

Favorable Tectonic and Structural Settings of Geothermal Systems in the Great Basin Region, Western USA: Proxies for Discovering Blind Geothermal Systems

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ABSTRACT

We recently completed a comprehensive inventory of the structural settings of known geothermal systems (426 total, $\geq 37^{\circ}\text{C}$) in the extensional to transtensional terrane of the Great Basin region in the western USA. Of the known systems, $\sim 39\%$ are blind (no surface hot springs or fumaroles), but estimates suggest that as much as 75% of the geothermal resources in the region are blind. The density of geothermal systems and capacity of power plants correlate generally with tectonic strain rates. However, high-enthalpy geothermal activity is restricted to regions of extensional to transtensional strain, particularly the northwestern part of the Great Basin directly northeast of the dextral shear zone of the Walker Lane and pull-apart zones within both the Walker Lane and San Andreas fault system. We catalogued systems into eight major groups, based on the dominant pattern of faulting. Of the nearly 250 categorized geothermal fields, we found that step-overs or relay ramps in normal fault zones are the most favorable setting, hosting $\sim 32\%$ of the systems. Such areas are characterized by multiple, commonly overlapping fault strands, increased fracture density, and thus enhanced permeability. Other common settings include a) normal fault terminations (25%), where horse-tailing generates a myriad of closely-spaced faults and thus increased permeability; and b) fault intersections between two normal faults or between normal faults and transverse oblique-slip faults (22%), where multiple minor faults typically connect major structures and fluids can flow readily through highly fractured, dilational quadrants. Less common settings include: a) accommodation zones (9%); b) displacement transfer zones (5%); c) pull-aparts in strike-slip faults (3%); d) bends in normal faults (2%); and e) major range-front normal faults (1%). Pull-aparts and displacement transfer zones are more abundant in the transtensional western part of the Great Basin. Quaternary faults typically lie within or near most of the geothermal systems. Geothermal systems are rare along major range-front faults, possibly due to both reduced permeability in thick zones of clay gouge and periodic release of stress in major earthquakes. Step-overs, terminations, intersections, and accommodation zones correspond to long-term, critically stressed areas, where fluid pathways would more likely remain open in networks of closely-spaced, breccia-dominated fractures. Notably, many higher enthalpy systems are hybrids and contain more than one type of favorable setting (e.g. fault intersection within broad accommodation zone). These data can guide exploration strategies, especially for blind or hidden systems.

1. INTRODUCTION

Better characterization of known geothermal systems is critical for discovering new systems, expansion of known systems, selecting the best sites and development strategy for engineered geothermal systems (EGS), and reducing the risks in drilling in all systems. This is especially important in the Great Basin of the western USA, where most of the geothermal systems are not related to upper crustal magmatic heat sources but are instead fault-controlled. Moreover, the bulk of the geothermal systems ($\sim 75\%$) may have little or no surface manifestation (i.e. blind or hidden; Coolbaugh et al., 2006), and thus techniques must be developed to indicate the most favorable locations for targeting subsurface resources. Our approach has been to 1) relate the density of known systems and capacity of existing power plants to tectonic settings and regional strain rates, and 2) characterize and catalogue geothermal systems on the basis of the prominent fault pattern or structural setting (e.g., Faulds et al., 2011, 2012). These syntheses have been bolstered by detailed studies of individual representative systems across the region (e.g. Faulds and Melosh, 2008; Faulds et al., 2010; Hinz et al., 2008, 2010, 2011; Rhodes et al., 2010; Dering and Faulds, 2012; Edwards and Faulds, 2012; Siler et al., 2012; Anderson and Faulds, 2013). In this paper, we review the relations between tectonic strain rates and geothermal activity and summarize results of developing a catalogue of favorable structural settings for >400 geothermal systems in the Great Basin region.

2. REGIONAL SETTING

Western North America contains a diffuse plate boundary, characterized by dextral motion between the Pacific and North American plates (e.g. Atwater and Stock, 1998) and west- to northwest-directed extension within the Basin and Range province (e.g. Wernicke, 1992). Much of dextral plate motion is taken up by the Queen Charlotte and San Andreas fault systems, including a system of pull-aparts within the Gulf of California and Salton Trough of southern California. However, within the western USA, the San Andreas fault system accommodates only $\sim 80\%$ of the plate motion. The other $\sim 20\%$ is distributed across the western Great Basin in a system of dextral faults known as the Walker Lane in the north and eastern California shear zone in the south (e.g. Faulds and Henry, 2008; Kreemer et al., 2009). In concert with the San Andreas fault terminating northward at the Mendocino triple junction, the Walker Lane dies out northwestward in northwest Nevada-northeast California. A broad zone of active extension stretches eastward across the Great Basin region from the Sierra Nevada and Walker Lane in eastern California to the Wasatch Front in Utah (Figure 1).

Although geothermal systems are spread across the entire actively extending Great Basin region (Figure 1), they are most abundant in discrete belts along the eastern margin of the Basin and Range (Wasatch Front) in western Utah and southeastern Idaho and in western to north-central Nevada within and directly northeast of the Walker Lane. The loci of geothermal activity in the Great Basin largely correlate with regions of higher strain rates, as derived from GPS geodetic data. Enhanced extension and dilation within the northwestern Great Basin probably results from the northwestward termination of the Walker Lane and diffusion of

~1cm/yr of dextral shear into west-northwest directed extension (Faulds et al., 2004). High-temperature systems in particular cluster within the zones of highest strain directly northeast of the Walker Lane, as well as in areas of recent magmatism or in transtensional pull-apart basins along the Walker Lane or San Andreas fault system.

The capacity of geothermal power plants also correlates with strain rates, with the largest (hundreds of megawatts) along the Walker Lane or transtensional/magmatic parts of the primary Pacific-North American plate boundary (e.g. Salton Trough and the Geysers), where strain rates range from 10-100 nanostrain/yr to 1,000 nanostrain/yr, respectively. Lesser systems (tens of megawatts) reside in the Great Basin region of the Basin and Range province (outside the Walker Lane), where local strain rates are typically < 10 nanostrain/yr.

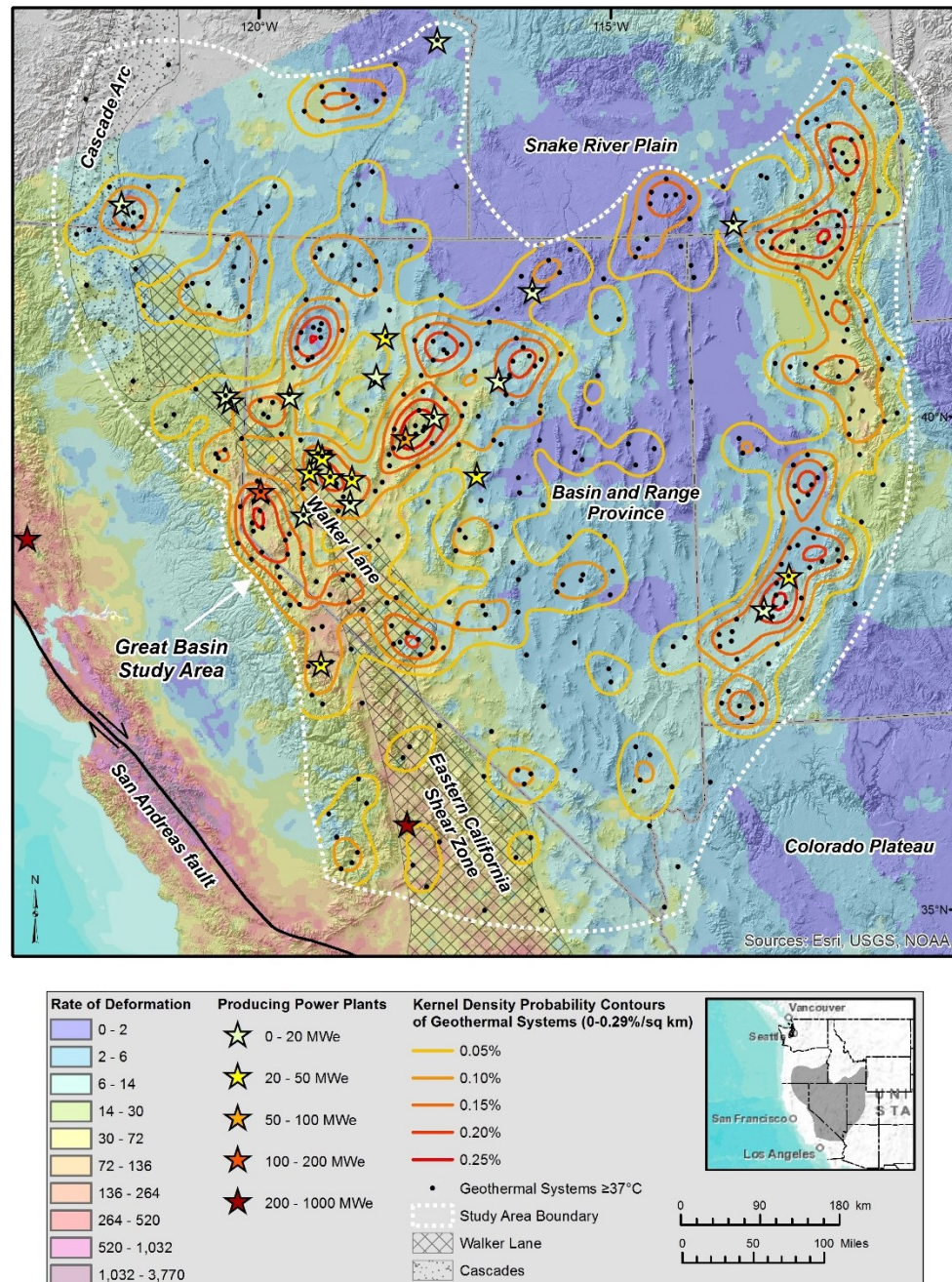


Figure 1: Density of known geothermal systems ($\geq 37^{\circ}\text{C}$) in the Great Basin region plotted on a map showing strain rates. Density contours were derived from a kernel probability estimate in which the distribution of geothermal systems was evaluated within a 50 km radius from a 5x5 km cell size within the Great Basin study area (white outline in figure). This yielded a 0.00 to 0.29% probability range of a geothermal system per square kilometer in the study area, average is 0.06%. Contours in this figure are at 0.05% intervals. Strain rates reflect the second invariant strain rate tensor (10⁻⁹/yr; from Kreemer et al., 2012). Power plants and relative capacities are shown by stars.

3. FAVORABLE STRUCTURAL SETTINGS

Individual geothermal fields within the Great Basin region are primarily controlled by moderately to steeply dipping normal fault zones (Benoit et al., 1982; Blackwell et al., 1999; Johnson and Hulen, 2002; Wannamaker, 2003; Waibel et al., 2003; Faulds et al.,

2010). Regional assessments of structural controls in the Great Basin have shown that N- to NE-striking faults (N0°E-N60°E) are the primary control for ~75% of the fields (Coolbaugh et al., 2002; Faulds et al., 2004). In the northwest Great Basin, the NNE-striking controlling faults are approximately orthogonal to the crustal extension direction. However, NNE-striking normal faults abound in the Great Basin, and many show no signs of geothermal activity. Thus, it is important to determine which faults or which segments of individual faults are most likely to host geothermal activity, especially in a region where the bulk of the geothermal resources are likely blind or hidden.

We have therefore completed an inventory of the structural settings of geothermal systems in the Great Basin region. Of the 426 known systems, ~39% are blind with no surface hot springs or fumaroles. We catalogued systems into eight major groups, based on the dominant pattern of faulting (Figure 2): 1) major normal fault segments (i.e., near displacement maxima), 2) fault bends, 3) fault terminations or tips, 4) step-overs or relay ramps in normal faults, 5) fault intersections, 6) accommodation zones (i.e. belts of intermeshing oppositely dipping normal faults), 7) displacement transfer zones whereby strike-slip faults terminate in arrays of normal faults, and 8) transtensional pull-aparts. These settings form a hierarchal pattern with respect to fault complexity (Figure 2). Major normal faults and fault bends are the simplest. Fault terminations are typically more complex than mid-segments, as faults commonly break up into multiple strands or horsetail near their ends. Fault intersections are also complex, as they generally contain both multiple fault strands and can include discrete dilational quadrants. A step-over consists of two overlapping fault terminations and thus involves additional complexity, especially where the relay ramp is breached by multiple fault splays between the main overlapping faults and thus contains multiple fault intersections. Accommodation zones involve further complexity, as they consist of multiple fault terminations and fault intersections (Figure 2).

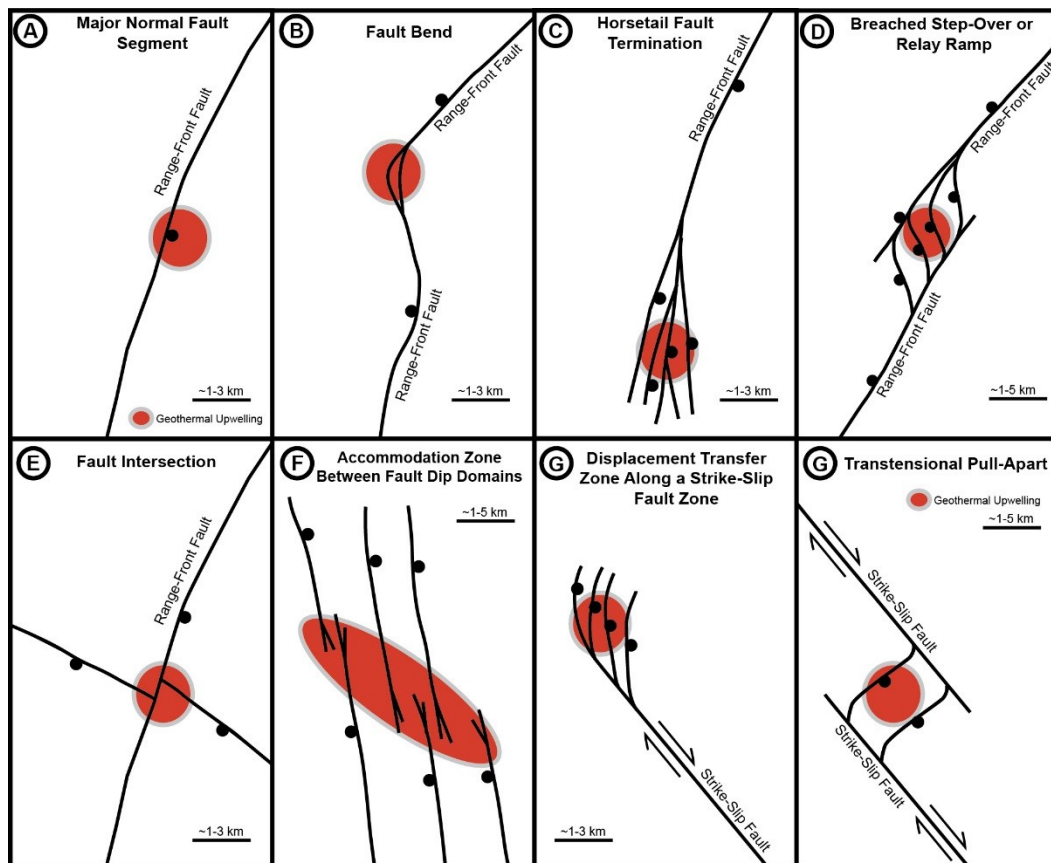


Figure 2: Characteristic structural settings for geothermal systems in the Great Basin region. A. Major normal fault. B. Bend in major normal fault. C. Fault tip or termination with main fault breaking into multiple strands or horsetailing. D. Fault step-over or relay ramp breached by minor connecting faults. E. Fault intersection. F. Accommodation zone, consisting of belt of intermeshing oppositely dipping normal faults. G. Displacement transfer zone, whereby major strike fault terminates in array of normal faults. H. Transtensional pull-apart in major strike-slip fault zone.

Of the nearly 250 categorized geothermal fields (Figure 3), we found that step-overs or relay ramps in normal fault zones are the most favorable setting, hosting ~32% of the systems. Such areas are characterized by multiple, commonly overlapping fault strands (Figure 2D), increased fracture density, and thus enhanced permeability. Other common settings include a) normal fault terminations (25%), where horse-tailing generates a myriad of closely-spaced faults (Figure 2C) and thus increased permeability; and b) fault intersections between two normal faults or between normal faults and transverse oblique-slip faults (22%), where multiple minor faults typically connect major structures and fluids can flow readily through highly fractured, dilational quadrants. Less common settings include: a) accommodation zones (9%); b) displacement transfer zones (5%); c) pull-aparts in strike-slip faults (3%); d) bends in normal faults (2%); and e) major range-front normal faults (1%). Pull-aparts and displacement transfer zones are more abundant in the transtensional western part of the Great Basin. Quaternary faults typically lie within or near most of the geothermal systems (Bell and Ramelli, 2007). We should note that the structural setting for ~25% of the systems could not be

determined. In most cases, undetermined systems reside in the central part of a basin (commonly warm wells), where geophysical data are inadequate for elucidating the subsurface structure.

It is also noteworthy that many of the higher enthalpy systems are hybrids, meaning that they are characterized by more than one type of favorable setting at a single locality (e.g. Steamboat, Brady's, Coso, and Salt Wells). This is especially true for systems that host geothermal power plants in the region. Of the 27 producing systems (Figure 2), 11 occupy step-overs (i.e., relay ramps, ~41%), 8 lie at fault intersections (~30%), and 7 occur in accommodation zones (~26%). Fault terminations, displacement transfer zones, and pull-aparts each host ~11-14% of the systems (3 to 4 each). The total number in these counts exceeds the total number of systems, because at least 10 (~37%) of the systems are hybrids and contain more than one type of structural setting. Notable within this distribution is the large proportion of producing accommodation zones, which only represent ~9% of the total geothermal fields in the Great Basin region, yet host ~26% of the producing systems. On the other hand, fault terminations account for ~22% of the total systems in the Great Basin, but only host ~11% of the producing fields. Although this subset is relatively small (only 27), the large amount of hybrids in the producing systems further demonstrates that structural complexity is one of the most critical factors for geothermal activity in the Great Basin region. Overall, ~21% of the known geothermal fields are hybrid or compound systems.

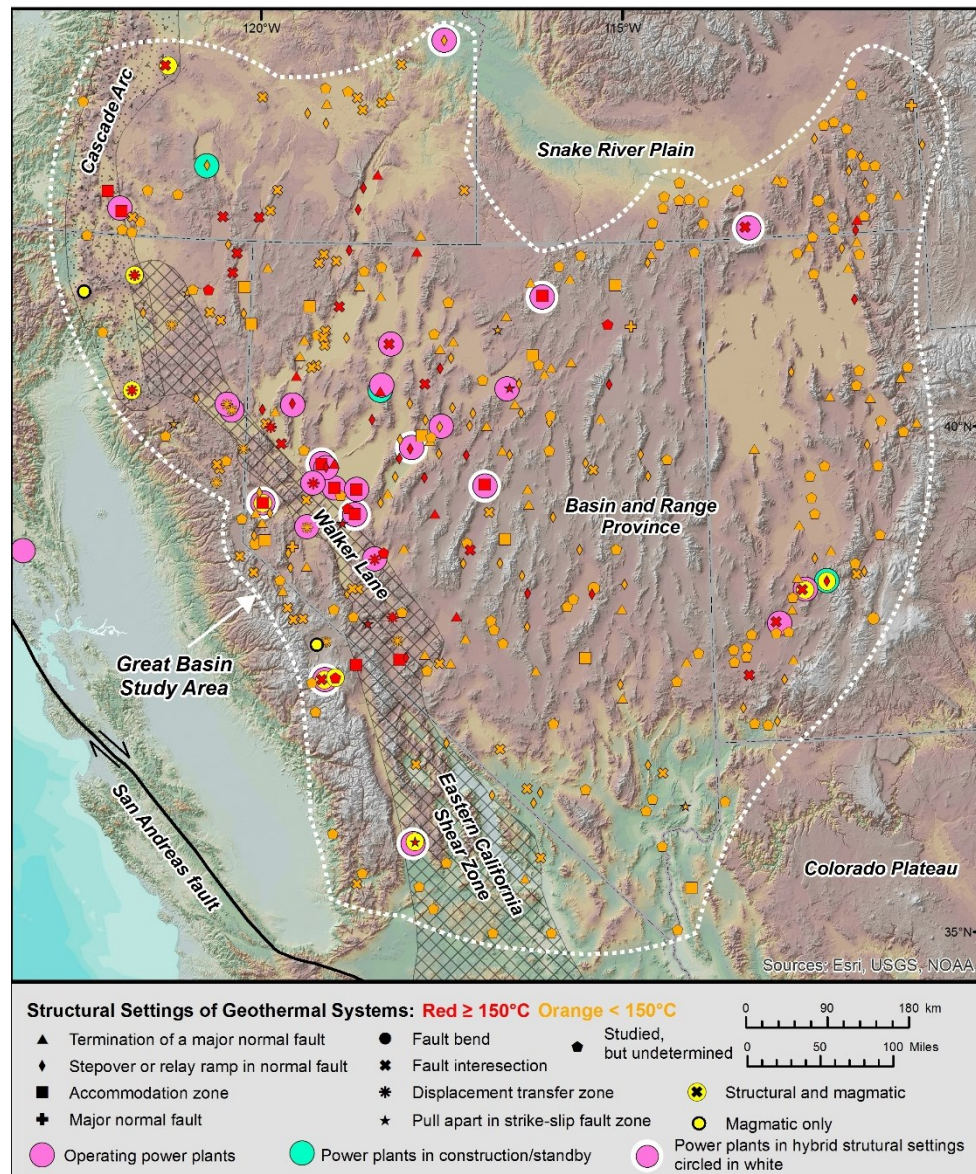


Figure 3: Structural settings of geothermal systems in the Great Basin region (white outline), as deduced in this study. Major types of structural settings are shown on digital elevation model of the Great Basin and adjacent regions. See Figure 2 and text for descriptions of structural settings. Red symbols – high-temperature systems ($\geq 150^{\circ}\text{C}$); orange symbols – low-temperature systems ($< 150^{\circ}\text{C}$); yellow circles represent known or inferred magmatic systems; lavender circles are sites for operating geothermal power plants.

4. DISCUSSION AND CONCLUSIONS

Regional tectonism appears to be the primary driving force for geothermal activity in the western USA, as evidenced by strong correlations between strain rates and the distribution of geothermal fields (Figure 1). The correlation between strain rates and

capacity of existing geothermal power plants further suggests that it may be possible to relate strain rate to geothermal potential. However, higher strain rates do not automatically equate with resource potential. For example, higher strain along the San Andreas fault system and Walker Lane-eastern California shear zone generally does not equate with geothermal activity, because strike-slip faulting includes a component of shortening, which tends to restrict fluid flow. Large geothermal systems in these zones of dextral shear appear to be restricted to transtensional pull-apart basins and/or to areas of recent volcanism (e.g. Salton Trough, The Geysers, and Coso). It would appear that without recent magmatism, extensional or transtensional deformation is required to generate a productive geothermal system (e.g. Blewitt et al., 2002, 2005; Faulds et al., 2004; Kreemer et al., 2006; Hammond et al., 2007). Enhanced extension promotes both high heat flow and dilation on normal faults, thus inducing deep circulation of meteoric waters and up-flow along fault zones.

We should stress that lower strain rates and the associated lower power-plant capacities in the Basin and Range (Figure 1) should not deter exploration and development. Although systems with hundreds to thousands of megawatts seem unlikely in the Basin and Range, the distribution of the known systems indicates strong potential for development of many additional systems in the tens of megawatts range. Furthermore, relatively closely-spaced fault zones can host separate exploitable geothermal systems, whose combined capacity can rival that of regions with higher strain rates, as exemplified in the northern Hot Springs Mountains in west-central Nevada (Faulds et al., 2010).

Geothermal systems most commonly occur in belts of intermeshing, overlapping, or intersecting faults. Similar relations have been observed in other extensional settings around the world (Curewitz and Karson, 1997), such as the Taupo volcanic zone in New Zealand (Rowland and Sibson, 2004; Rowland and Simmons, 2012) and Aegean extensional province in western Turkey (Faulds et al., 2009). Step-overs (relay ramps), terminations, intersections, and accommodation zones in fault systems correspond to long-term, critically stressed areas, where fluid pathways are more likely to remain open in networks of closely-spaced, breccia-dominated fractures. Although exceptions exist, geothermal systems are relatively rare along the displacement-maxima zones or mid-segments of major normal faults (i.e., major range-front faults), possibly due to both reduced permeability in thick zones of clay gouge and periodic release of stress in major earthquakes. These findings may help to guide geothermal exploration and aid in development of the presumably vast amount of blind geothermal systems that underlie the Great Basin region.

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