STRUCTURAL AND TECTONIC CONTROLS OF GEOTHERMAL ACTIVITY IN THE BASIN AND RANGE PROVINCE, WESTERN USA

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ABSTRACT

We are conducting an inventory of structural settings of geothermal systems (>400 total) in the extensional to transtensional Great Basin region of the western USA. A system of NW-striking dextral faults known as the Walker Lane accommodates ~20% of the North American-Pacific plate motion in the western Great Basin and is intimately linked to N- to NNE-striking normal fault systems throughout the region. Overall, geothermal systems are concentrated in areas with the highest strain rates within or proximal to the eastern and western margins of the Great Basin, with the highest temperature systems clustering in transtensional areas of highest strain rate in the northwestern Great Basin.

Of the 250+ geothermal fields catalogued, step-overs or relay ramps in normal fault zones serve as the most favorable setting, hosting ~32% of the systems. Such areas have multiple, overlapping fault strands, increased fracture density, and thus enhanced permeability. Other common settings include a) intersections between normal faults and strike-slip or oblique-slip faults (22%), where multiple minor faults connect major structures and fluids can flow readily through highly fractured, dilational quadrants, and b) normal fault terminations or tip-lines (22%), where horse-tailing generates closely-spaced faults and increased permeability. Other settings include accommodation zones (i.e., belts of intermeshing, oppositely dipping normal faults; 8%), major normal faults (6%), displacement transfer zones (5%), and pull-aparts in strike-slip faults (4%). In addition, Quaternary faults lie within or near most systems (e.g., Bell and Ramelli, 2007). The relative scarcity of geothermal systems along displacement-maxima of major normal faults may be due to 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 are more likely to remain open in networks of closely-spaced, breccia-dominated fractures.

1. INTRODUCTION

In the western USA, more than 400 geothermal fields occur within the Great Basin region of the Basin and Range province, which includes most of Nevada, eastern California, western Utah, southern Oregon, and southern Idaho. The density of geothermal systems and associated power plants is greatest in northern Nevada and neighboring parts of northeast California and southernmost Oregon (Fig. 1). This clustering of geothermal fields lies within a much broader region of high heat flow (Blackwell and Richards, 2004). Geothermal power plants in the Basin and Range generally produce between ~2 and 100 MW. Although the density of geothermal fields is greatest in the northwestern Basin and Range, geothermal fields with the greatest electrical output in the western USA occur along the San Andreas fault system, including the Geysers in northern California and fields in the Salton Trough in southern California. Electrical output in these areas ranges from 200 to ~1,000 MW.

In the western part of the Great Basin, the Walker Lane is a system of dextral faults that accommodates ~20% of the motion between the North American and Pacific plates (e.g., Faulds and Henry, 2008; Kreemer et al., 2009). As the Walker Lane terminates northwestward in northwest Nevada-northeast California, about 1 cm/year of dextral motion diffuses into WNW-directed extension in the northwestern Great Basin. Enhanced extension and dilation within the northwestern Great Basin probably accounts for the abundance of fault-controlled geothermal activity in this region (Faulds et al., 2004).

Most of the geothermal systems in the Great Basin region are not related to obvious upper crustal magmatic heat sources, but are instead fault-controlled. Moreover, it is estimated that most of the geothermal resources in this region are blind or hidden, with no surface manifestations in the form of hot springs or fumaroles (Coolbaugh et al., 2006). Thus, identifying the favorable structural settings is particularly critical for refining exploration strategies in terms of discovering new hidden geothermal resources, selecting drilling targets at known systems, or enhancing production at existing power plants.

In this paper, we review the regional distribution of geothermal activity in the context of tectonic settings and strain rates, as well as the most favorable structural settings of individual geothermal fields. We conclude that there is a direct correlation between strain rates and geothermal potential. In addition, the most favorable structural settings for geothermal activity include: 1) step overs or relay ramps in normal fault zones, 2) terminations of major normal faults, 3) fault intersections, and 4) accommodation zones. Our findings may have implications for geothermal assessments in other parts of the world, especially for exploration for blind geothermal systems.

1. DISTRIBUTION OF GEOTHERMAL FIELDS

Figure 1 shows the locations of major geothermal systems and power plants with respect to major tectonic features and strain rates within and adjacent to the Great Basin region of the Basin and Range province. The parameters of the geothermal database utilized in our plots were described by Coolbaugh et al. (2002) and Faulds et al. (2011). Figure 2 illustrates the density of known geothermal systems.

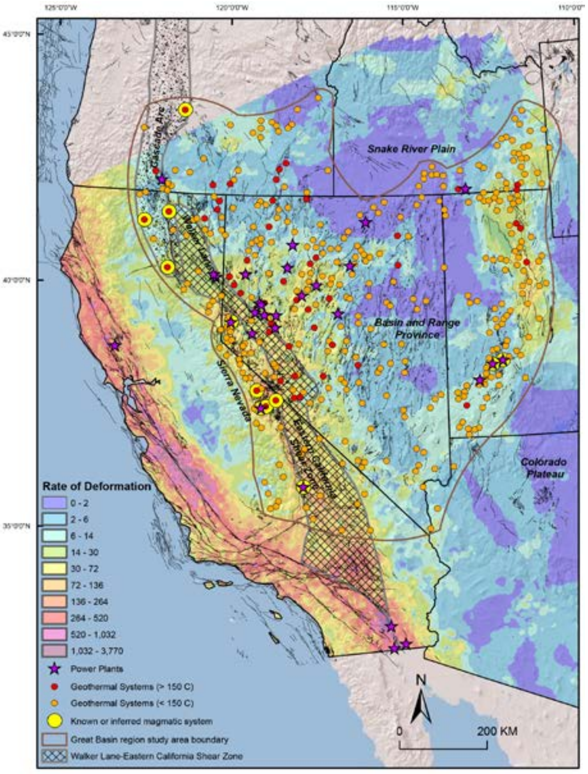

Figure 1. Map showing strain rates and geothermal systems in the Great Basin and adjacent regions. Strain rates reflect the second invariant strain rate tensor (10^{-9}/yr; from Kreemer et al., 2012).

The known geothermal systems cluster in several discrete belts: 1) Wasatch geothermal belt: This belt extends along the Wasatch Front in Utah following the eastern margin of the Basin and Range province, with an arm extending westward directly southeast of the Snake River Plain (Fig. 2). 2) Walker Lane geothermal belt: This NW-trending cluster occupies the central to northern Walker Lane extending westward through the Sierra Nevada-Basin and Range transition zone. 3) Humboldt geothermal belt: This NE-trending zone extends from western to north-central and northeastern Nevada. The Humboldt belt essentially forms a bridge between the Walker Lane and Wasatch geothermal belts, suggesting that the corresponding Humboldt structural zone (cf., Rowan and Wetlaufer, 1981) facilitates geothermal activity. The Humboldt structural zone is a broad area of ENE- to NE-striking sinistral-normal faults stretching across much of northern Nevada. 4) Black Rock Desert geothermal belt: This NNE-trending belt extends through the Black Rock Desert region of northwest Nevada northward into the Alvord basin of southern Oregon. 5) Surprise Valley geothermal belt: This relatively small belt encompasses the Surprise Valley area of northeastern-most California and the Warner Valley region of southern Oregon.

There are direct correlations between the distribution of geothermal systems, especially high-temperature fields, with both the density of Quaternary faults and strain rates. For example, geothermal fields cluster in the broad transtensional setting directly northeast of the Walker Lane and along the Wasatch Front. Strain rates and Quaternary faulting in both of these areas are significantly higher compared to other parts of the Basin and Range (Fig. 1).

The electrical-generating capacity of individual power plants or groups of plants within a geothermal field is also proportional to strain rate (Figs. 1 and 2). All fields with capacities of 200-1,000 MW lie within large transtensional pull-apart basins along the San Andreas fault (Salton Trough), on strands of the San Andreas system (The Geysers), or in pull-apart basins within the Walker Lane-eastern California shear zone (Coso). Strain rates in these areas range from ~1 cm/yr at Coso to ~4 cm/yr in the Salton Trough. It should also be noted that all of these systems also have a magmatic component contributing to the heat source. To the east within the bulk of the Basin and Range province, where strain rates are much less (typically less than a few mm's/yr) and upper crustal magmatic heat sources are scarce, geothermal fields produce from 2 to 100 MW.

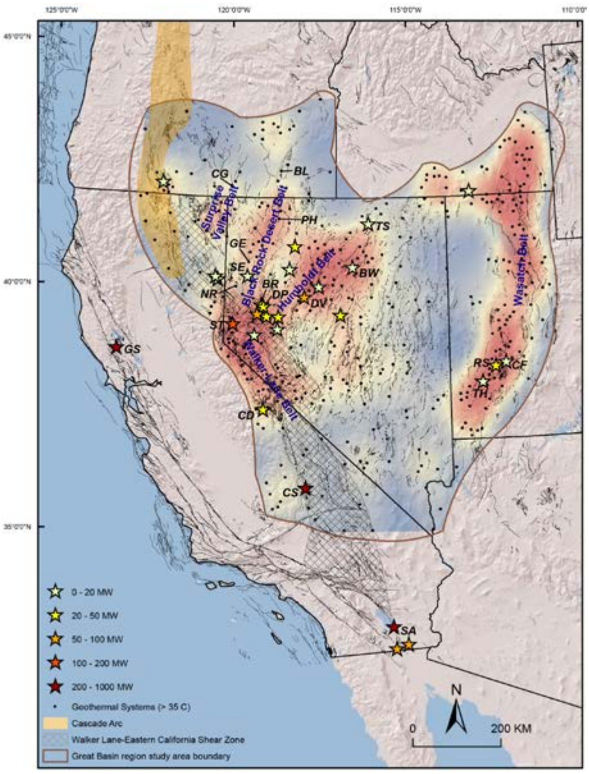

Figure 2. Density of known geothermal systems (≥37°C) in the Great Basin region. Density values were calculated using a kernel density plot in which the number of geothermal systems with temperatures ≥37°C within a radius of ~30 km was calculated for each 3 km cell in a grid. Warmer colors represent progressively greater geothermal system densities. Power plants and relative capacities are shown by stars. Geothermal systems: BL, Borax Lake; BR, Bradys; BW, Beowawe; CD, Casa Diablo; CF, Cove Fort; DP, Desert Peak; DV, Dixie Valley; CG, Crump Geyser; CS, Coso; GE, Gerlach; GS, The Geysers; NR, Needle Rocks, Pyramid Lake; PH, Pinto Hot Springs; RS, Roosevelt; SA, Salton Trough; SE, San Emidio; ST, Steamboat; TS, Tuscarora; TH, Thermo.

2. STRUCTURAL SETTINGS

The structural settings of ~300 geothermal systems have been reviewed utilizing published literature, air photos and imagery, geologic maps, and/or field visits (Fig. 3). Higher temperature systems (>150^{o}C) were prioritized in our analysis. Many of the “known” systems consisted of individual wells within basins and were therefore difficult to evaluate.

Of the geothermal fields analyzed to date, we found that step-overs or relay ramps, fault intersections, and normal fault terminations or tip-lines hosted most of the geothermal systems (Figs. 3 and 4). Step-overs or relay ramps in normal fault zones served as the most favorable structural setting, hosting ~32% of the systems. Such areas are characterized by multiple, commonly overlapping fault strands, increased fracture density, and thus enhanced permeability. Examples of geothermal systems within normal fault step-overs include Desert Peak, Jersey Valley, and Tungsten Mountain. Intersections between normal faults and either transversely oriented strike-slip or oblique-slip faults accounted for ~22% of the systems. Within such intersections, multiple minor faults typically connect major structures and fluids can flow readily through highly fractured areas or dilational quadrants. Examples include Roosevelt Hot Springs, Blue Mountain, and Crump Geyser. Normal fault terminations or tip-lines, where horse-tailing generates a myriad of closely-spaced faults and thus increased permeability, also represented ~22% of the systems. Systems that occupy such terminations include Gerlach, Desert Queen, and Grover’s Hot Springs.

Two other types of fault interactions, accommodation zones and displacement transfer zones, host many geothermal systems. Accommodation zones (cf., Faulds and Varga, 1998) are belts of intermeshing, oppositely dipping normal faults and therefore include multiple fault intersections. These zones host ~8% of the systems, including Salt Wells (also known as Eight-Mile Flat), Sou Hot Springs, and McGinness Hills. Displacement transfer zones link strike-slip and normal fault systems (e.g., northeastern margin of the Walker Lane). Geothermal systems in displacement transfer zones are commonly focused along the normal faults proximal to dilational intersections with nearby strike-slip faults. About 5% of the systems were found in displacement transfer zones, including Columbus Marsh, Amedee, and Pyramid Rock. Other observed settings for geothermal systems include major range-front faults (3%; e.g., parts of Dixie Valley), bends in major normal faults (3%; e.g., Walley’s Hot Springs and Nevada Hot Springs), and pull-aparts in strike-slip fault systems (4%) (e.g., Coso and Lee-Allen).

It is notable that many of the higher enthalpy systems are characterized by more than one type of favorable setting at a single locality. For example, the Salt Wells geothermal system in west-central Nevada occurs within an accommodation zone between east- and west-dipping normal faults, at the south end of a major east-dipping normal fault zone, and possibly within a small displacement transfer zone. The Brady’s system lies within a discrete left step in a NW-dipping normal fault zone within a broader accommodation zone. Steamboat appears to occupy a broad accommodation zone between overlapping east- and west-dipping normal fault zones at the south end of the Truckee Meadows while also containing discrete fault intersections that control fluid flow within the developed part of the field.

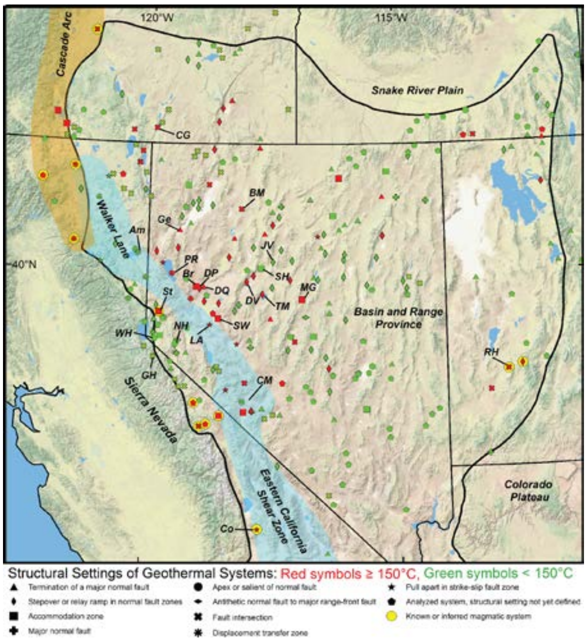

Figure 3. Structural settings of geothermal systems. Major types of structural settings are shown on a digital elevation model of the Great Basin and adjacent regions. Geothermal systems discussed in the text include: Am, Amedee; BM, Blue Mountain; Br, Brady’s Hot Springs; CG, Crump Geyser; CM, Columbus Marsh; Co, Coso; DP, Desert Peak; DQ, Desert Queen; DV, Dixie Valley; Ge, Gerlach; GH, Grover’s Hot Springs; JV, Jersey Valley; LA, Lee-Allen; MG, McGinness; NH, Nevada Hot Springs; PR, Pyramid Rock; RH, Roosevelt Hot Springs; SH, Sou Hot Springs; St, Steamboat; SW, Salt Wells (Eight-Mile Flat); TM, Tungsten Mountain; WH, Walley’s Hot Springs.

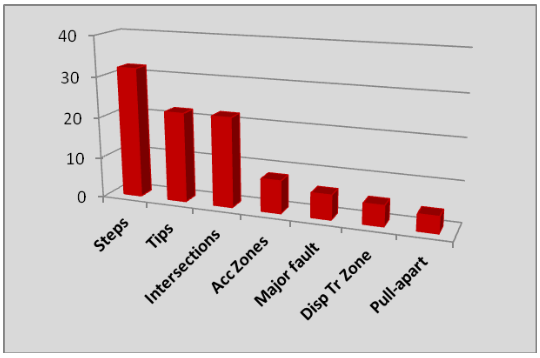

Figure 4. Favorable structural settings of geothermal fields in the Great Basin region. Bar graph shows the relative proportions of the most favorable settings. Discrete steps or relay ramps in normal fault zones are the most common setting, followed by fault terminations (or fault tips), fault intersections, accommodation zones, mid segments and bends along major normal faults, displacement transfer zones, and pull-aparts in strike-slip fault zones. About 300 systems have been analyzed.

2. DISCUSSION

Regional tectonism appears to be the primary driving force for geothermal activity in the western USA, as evidenced by the correlations between strain rates and the distribution of geothermal fields (Figs. 1 and 2). Although geothermal fields are found throughout the Great Basin region, the greatest concentrations occur in western to north-central Nevada (Walker Lane and Humboldt geothermal belts) and in western Utah to southeastern Idaho (Wasatch geothermal belt), where strain rates are generally higher than other parts of the region. Furthermore, the majority of high-temperature systems occur in western to north-central Nevada, which has the highest strain rates in the region east of the Walker Lane.

The locus of geothermal activity in western to north-central Nevada corresponds to the active transtensional setting situated directly northeast of the central and northern parts of the Walker Lane (e.g., Faulds et al., 2004; Blewitt et al., 2005; Kreemer et al., 2006; Hammond et al., 2007), where dextral shear associated with plate boundary motions decreases northwestward and is transferred to west-northwest-directed extension in the Basin and Range. The NNE to NE trends of the major geothermal belts in this region (e.g., Humboldt and Black Rock Desert belts) are oriented approximately orthogonal to the west-northwest-trending extension direction and may therefore reflect loci of strain transfer from the Walker Lane into the Great Basin.

Lower strain rates and the associated lower power-plant capacities in the Basin and Range should not deter exploration and development. Although individual systems with hundreds to thousands of megawatts may be unlikely in much of the Basin and Range, the distribution of 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. The northern Hot Springs Mountains in western Nevada exemplify this potential, as each major normal fault zone in this area hosts a high-temperature geothermal system (e.g., Bradys, Desert Peak, and Desert Queen systems; Faulds et al., 2010).

One of the most striking aspects of the inventory of structural settings is that geothermal systems are relatively rare along the displacement-maxima zones or mid-segments of major normal faults (i.e., major range-front faults). This may result from both reduced permeability in thick zones of clay gouge and periodic release of stress in major earthquakes. Instead, geothermal systems most commonly occur in belts of intermeshing, overlapping, or intersecting faults. Step-overs (or 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.

These findings may help to guide geothermal exploration in the Great Basin and aid in tapping into the presumably vast amount of blind geothermal systems that underlie the region. This includes planning the location of individual production wells within a broader thermal anomaly. These results are also applicable to other extensional settings, such as western Turkey, the East African Rift, and the Taupo Zone of New Zealand.

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