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Assessment of Favorable Structural Settings of Geothermal Systems in the Great Basin, Western USA

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ABSTRACT

We have undertaken a thorough inventory of the structural settings of known geothermal systems (>400 total) in the extensional to transtensional terrane of the Great Basin in the western USA. Of the more than 200 geothermal fields catalogued to date, we found that 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. Other common settings include a) intersections between normal faults and either transversely oriented strike-slip or oblique-slip faults (22%), where multiple minor faults typically 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 a myriad of closely-spaced faults and thus increased permeability. A major subset of fault intersections includes displacement transfer zones (5%) between strike-slip faults in the Walker Lane and N- to NNE-striking normal faults, with geothermal systems commonly focused along the normal faults proximal to their dilational intersections with nearby dextral faults. Other notable structural settings for geothermal systems in the Great Basin include accommodation zones (i.e., belts of intermeshing, oppositely dipping normal faults; 8%), major range-front faults (3%), salients or apices of major normal faults (3%), and pull-aparts in strike-slip fault systems (4%). Pull aparts and displacement transfer zones are more abundant within or along the margins of the Walker Lane, whereas step-overs and accommodation zones in normal fault systems are more prevalent within the extensional terrane that characterizes much of the Great Basin northeast of the Walker Lane. In addition, Quaternary faults typically lie within or near most of the geothermal systems. However, geothermal systems appear to be 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. Step-overs, terminations, intersections, and accommodation zones in normal fault systems would tend to correspond to long-term, critically stressed areas, where fluid pathways would more likely remain open in networks of closely-spaced, breccia-dominated fractures. It is also important to note that many of the higher enthalpy systems are characterized by more than one type of favorable setting at a single locality (e.g., Steamboat, Brady's, and Salt Wells).

Introduction

As stated in the Department of Energy (DOE) Geothermal Technologies Program Multi-year Research, Development, and Demonstration (MYRDD) Plan (p. 40), "the best EGS targets have high temperatures (> 200°C) at shallow depth (< 3 km) and a tectonic stress regime that keeps fractures open. Current technology cannot identify such sites with a high degree of certainty without drilling." Two major problems described in the MYRDD are 1) Barrier A, whereby "the ability has not been sufficiently demonstrated to assess potential EGS resources, prioritize potential sites for EGS, and achieve acceptable levels of site selection risk ahead of expensive drilling investments;" and 2) Barrier B, whereby "inadequate measuring techniques and knowledge preclude low-risk options to effectively select sites and characterize their physical parameters as potential EGS reservoirs before stimulation". Resolution of these barriers requires new and improved geological, geochemical, and geophysical techniques to find shallow hot rock and favorable crustal stress conditions where there is no surface manifestation. Even for conventional systems with surface manifestations, improved techniques are needed to locate the best sites for drilling into a sustainable subsurface reservoir.

In essence, the geothermal industry generally lacks a strong empirical database that qualitatively and quantitatively describes the most favorable settings for geothermal activity. Some generalized catalogues exist (e.g., Hurter and Haenel, 2002; Akkuş et al., 2005), but relatively little has been accomplished in data synthesis. Thus, robust conceptual models and favorable settings are generally not well defined and/or their broad applicability has not been well tested. The success of the best modelling techniques is limited without basic knowledge of which fault and fracture patterns, stress conditions, and stratigraphic intervals are most conducive to hosting geothermal reservoirs in various settings. The risk of drilling non-productive wells in a conventional system or a failed EGS experiment can therefore be high and impede further exploration. Better characterization of known geothermal systems in different settings (e.g., magmatic vs. nonmagmatic; transtensional vs. extensional) is therefore critical in discovering new systems, targeting the best drilling sites, and enhancement (EGS) or expansion of known systems. This is especially important in the Great Basin of the western USA, where the bulk of the geothermal resources may have little or no surface manifestation (i.e., blind or hidden; Coolbaugh et al., 2006a).

We are, therefore, systematically assessing the structural controls of geothermal systems within the Great Basin and adjacent regions. Most of the geothermal systems in the Great Basin are not related to obvious magmatic heat sources, but are instead fault-controlled. 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 (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). Identifying the favorable structural settings is particularly critical in amagmatic settings, such as most of the Great Basin, but also relevant to many systems with a magmatic heat source.

This DOE-ARRA (American Recovery and Reinvestment Act)-funded study consists of three discrete stages, which are an initial structural inventory, subsequent detailed study of representative fields, and finally 3D modeling of select systems. The ultimate goal of this project is to incorporate knowledge of favorable structural settings into refining exploration strategies and reducing the risks of geothermal drilling, particularly for blind or hidden geothermal systems.

Here, we report on the first phase of this project, which involves a broad but thorough inventory of structural settings of geothermal systems in the Great Basin, Walker Lane, and southern Cascades, with the aim of developing a structural catalogue and set of structural models of geothermal systems that documents the most favorable structural environments. Although the results in this paper should be considered preliminary, they may nonetheless facilitate both ongoing exploration in the region and selection of drilling sites within individual geothermal fields.

Previous Work

Substantial previous work on the structural controls of geothermal systems in the Great Basin and elsewhere has enabled this research. It has long been known that individual fields are commonly controlled by moderately to steeply dipping normal fault zones, as exemplified at the Dixie Valley (Blackwell et al., 1999; Johnson and Hulen, 2002; Wannamaker, 2003), Rye Patch (Waibel et al., 2003), Brady's, and Desert Peak fields (Figure 1) (Benoit et al., 1982; Faulds et al., 2010). Our initial regional assessment of structural controls in the Great Basin showed that N- to NE-striking faults (N0ºE-N60ºE) are the primary controlling structure for ~75% of the fields, and this control is strongest for higher temperature systems (Coolbaugh et al., 2002; Faulds et al., 2004). In the northwest Great Basin, the NNE-striking controlling faults are oriented approximately orthogonal to the crustal extension direction.

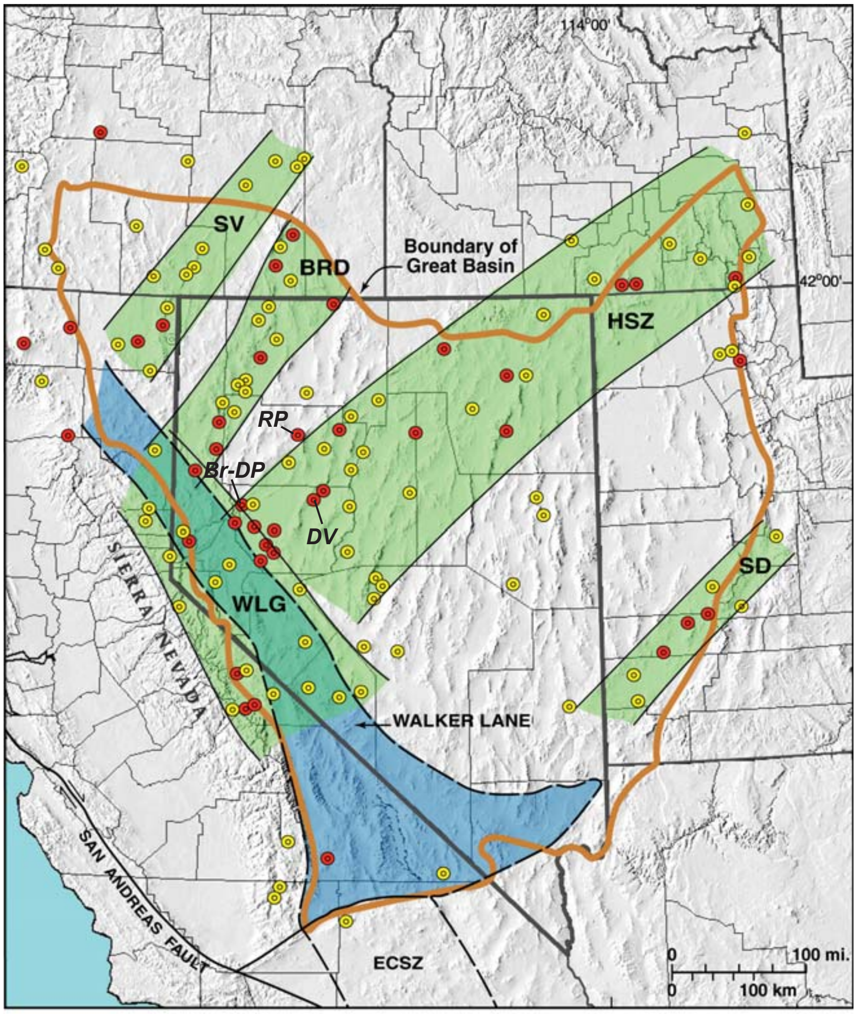

Figure 1. General representation of geothermal systems in the Great Basin, as portrayed prior to this project (from Faulds et al., 2004). Yellow circles are systems with maximum temperatures of 100-160ºC; red circles have maximum temperatures >160ºC. BRD, Black Rock Desert geothermal belt; ECSZ, eastern California shear zone; HSZ, Humboldt structural zone; SD, Sevier Desert belt; SV, Surprise Valley belt; WLG, Walker Lane belt. Abbreviations for individual fields: Br-DP, Brady's-Desert Peak; DV, Dixie Valley; RP, Rye Patch.

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. In an effort to better characterize structural controls on geothermal activity in extended terranes, we have therefore analyzed numerous fields in the western Great Basin (USA) and western Turkey through integrated geologic and geophysical investigations (Faulds et al., 2004, 2005, 2006, 2010; Faulds and Garside, 2003; Faulds and Melosh, 2008; Vice et al., 2007; Hinz et al., 2008, 2010, this volume; Rhodes et al., 2010). Methods have included detailed mapping, structural analysis, gravity surveys, studies of surficial geothermal features (e.g., travertine, sinter, springs, and fumaroles; Coolbaugh et al., 2006b), shallow temperature surveys (Coolbaugh et al., 2007), and geochemical analyses.

Our findings suggest that many fields occupy a) discrete steps in normal fault zones, b) intersections between normal faults and transversely oriented oblique-slip faults, c) overlapping oppositely dipping normal fault zones, d) terminations of major normal faults, or e) transtensional pull-apart zones (Figure 2). All of these settings are typically associated with steeply dipping faults, most commonly involving subvertical conduits of highly fractured rock along or near Quaternary fault zones oriented approximately perpendicular to the least principal stress. General topographic features indicative of these settings include: 1) major steps in range-fronts, 2) interbasinal highs, 3) mountain ranges consisting of relatively low, discontinuous ridges, and 4) lateral terminations of mountain ranges. Surficial features, such as tufa towers, travertine spring mounds, and sinter deposits, are also associated with many systems. These structural, topographic, and surficial features may indicate hidden or blind geothermal fields, which have no surface thermal waters or steam (i.e., hot springs, fumaroles, or geysers).

Our findings are compatible with the conclusions of Curewitz and Karson (1997) and Micklethwaite and Cox (2004). In a global survey, Curewitz and Karson (1997) found that hot springs are generally concentrated near the ends of faults or at fault intersections. Micklethwaite and Cox (2004) found that zones of high permeability in fault systems correspond to paleo-rupture arrest areas at the ends of fault segments. The rupture-arrest regions mark areas of aftershocks and multiple interconnecting fault splays, where fluid flow is favored. In normal fault systems, these rupture arrest regions commonly correspond to discrete step-overs in fault zones or reversals in the dominant dip direction of systems of faults (Roberts and Jackson, 1991; Faulds and Varga, 1998). Such rupture arrest regions may also account for high-permeability flow paths occurring in spatially discrete but negligible overall fractions of individual faults, as documented in the Borax Lake geothermal field in southern Oregon (Fairley and Hinds, 2004).

It is noteworthy that magmatic systems like those in Iceland are also controlled by tensional fractures (Gudmundsson, 2000). However, dilational fault segments (i.e. faults with low normal stress) are not the only type of conduit for hydrothermal systems. In some fields, like the EGS site at Coso, critically stressed faults (faults with high shear stress) can also control fluid flow (Sheridan and Hickman, 2004).

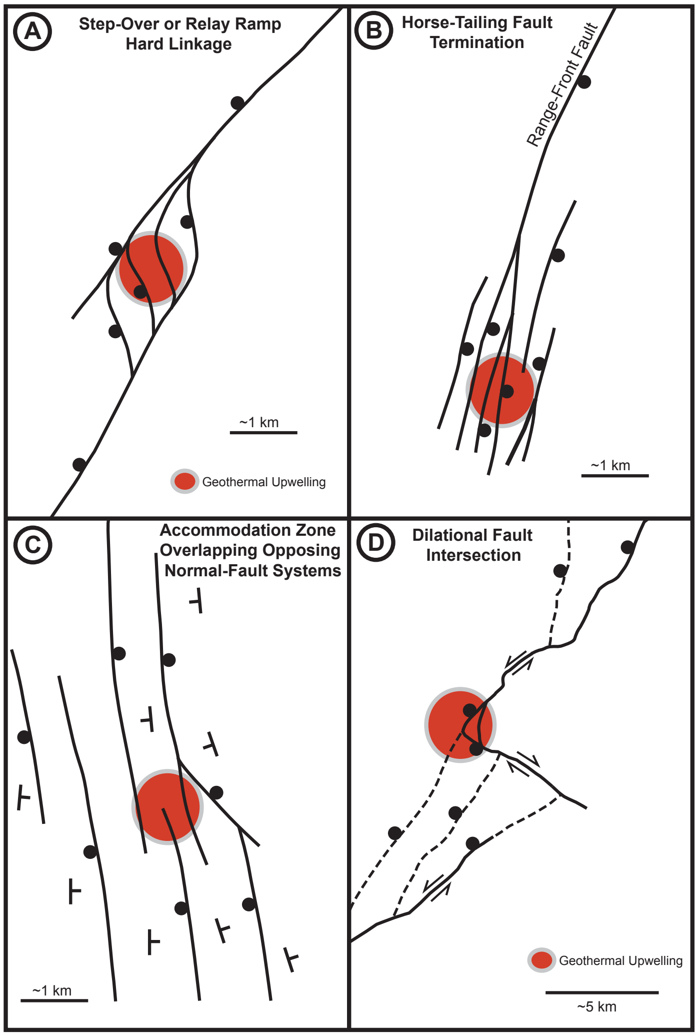

Figure 2. Examples of favorable structural settings for geothermal systems. Areas of upwelling geothermal fluids are shaded in red. A. Step-over or relay ramp between two overlapping normal fault segments with multiple minor faults providing hard linkage between two major faults. B. Terminations of major normal faults, whereby faults break up into multiple splays or horsetail. C. Overlapping, oppositely dipping normal fault systems (accommodation zones) that generate multiple fault intersections in the subsurface. Strike and dip symbols indicate tilt directions of fault blocks. D. Dilational fault intersection between oblique-slip normal faults.

Although a variety of structural settings has been documented for geothermal systems in extensional terranes and conceptual models developed for some of these settings, no general synthesis has been completed that describes which settings are most favorable for geothermal activity. Thus, it is difficult to determine the likelihood of finding a geothermal system in a particular structural setting or determine the risk of drilling in a particular location even within a known geothermal field, as that field might contain more than one type of structural feature. Our results below represent a first attempt to catalogue >400 geothermal systems in the Great Basin based on structural setting.

Database

An initial database of geothermal systems in the Great Basin was taken from Coolbaugh (2003), who used it to evaluate relationships between geothermal activity and geospatial data such as young fault orientations and crustal strain rates and generate predictive maps of geothermal potential for Nevada (Coolbaugh et al., 2002; Coolbaugh, 2003) and the Great Basin (Coolbaugh et al., 2005). Coverage of the initial database was limited to the confines of the Great Basin as defined by Fenneman (1928), with a 70-km-wide buffer added. The buffer made possible the evaluation geothermal activity in the geologically complex margins of the Great Basin, which hosts a number of magmatic heated geothermal systems (e.g. Coso, Mammoth, Mt. Lassen, and Mt. Shasta in California; Newberry Crater in Oregon, Roosevelt Hot Springs in Utah, and arguably, Steamboat Springs in Nevada (Arehart et al., 2003)).

For the purposes of the database, a geothermal system was defined as the occurrence of hot water either in springs or wells at temperatures of at least 37°C. Multiple hot springs and/or hot wells were grouped into individual "geothermal systems" and a central point was chosen to represent the loci of springs and wells. A minimum 10-km-distance between geothermal systems was required; otherwise the data points were considered part of the same geothermal system, unless geothermal production well data were available to demonstrate that adjacent thermal wells were not in communication with each other.

A key characteristic of geothermal systems is reservoir temperature. In a few cases where deep wells are present, the reservoir temperature can be directly measured, but in most cases, especially where no wells are present, it must be estimated using fluid geothermometry. Fluid geothermometry is an imperfect estimator of reservoir temperatures, but the use of geothermometry is considered essential in this study for two reasons: 1) to minimize temperature bias between wells and springs, because well temperatures commonly exceed the surface boiling point, but spring temperatures rarely do, due to the effects of evaporative cooling during boiling, and 2) to make it possible to assess relationships between structural environments and reservoir temperatures, with the expectation that reservoir temperatures are influenced by the depth of penetration of meteoric fluids into the crust. Some oil and gas wells have relatively high temperatures by virtue of their great depths, but where these temperatures do not exceed the regional background crustal temperature gradient, they do not indicate by themselves the presence of geothermal activity. For this reason, data from oil and gas wells were excluded if depths exceeded 500 m.

In the database constructed by Coolbaugh (2003), the temperature assigned to a geothermal system was the maximum of the measured temperature and the average of two or more geothermometers. Geothermometer-based temperatures for geothermal systems >160°C were taken from Mariner et al. (1983), by averaging temperature estimates based on the quartz (Fournier and Rowe, 1966; Fournier, 1981), Mg-corrected Na-K-Ca (Fournier and Potter, 1979), and SO_4-H_2O (McKenzie and Truesdell, 1977) geothermometers. Following the methodology of Mariner et al. (1983), the chalcedony geothermometer (Fournier, 1981) was used in place of the quartz geothermometer when the Mg-corrected Na-K-Ca geothermometer was less than 100°C. For geothermal systems <160°C, the SO_4-H_2O geothermometer was not included in the averaging, because of limited data availability, but otherwise the geothermometer methodology remained the same.

Data sources included, for all states, the Geo-Heat Center State Geothermal Database (2002) and Blackwell (2002). For Nevada, additional data were taken from Garside (1994) and Mariner et al. (1983). For Utah, additional data were taken from Blackett and Wakefield (2002), NOAA and Utah Geological and Mineral Survey (1980), and Edmiston and Benoit (1984). For California, Idaho, and Oregon, additional data were respectively taken from DOE (1980), Mitchell et al., 1980, and DOE (1982).

Results

The structural settings of ~245 geothermal systems were reviewed with published literature, air photos and imagery, geologic maps, and/or field visits (Figure 3). Higher temperature systems (>150°C) were prioritized in our analysis. Many of the "known" systems consisted of individual wells within basins and were therefore difficult to evaluate. As we conducted our analysis, we also refined the locations and names of many of the geothermal systems in the initial database.

Although faults are the major controlling feature of fluid flow within geothermal systems in this region, the literature on structural settings of individual systems is relatively scant. Thus, we have made the first interpretations of the structural settings for many geothermal fields. In general, it was possible to make such determinations if the systems were situated within or near bedrock exposures, but further analysis utilizing geophysical data is needed to determine the settings for many systems in the central parts of large basins. Thus, more than 20% of the systems reviewed were not initially catalogued.

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. 2 and 3). 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 (Figure 2B) and thus increased permeability, also represented ~22% of the systems. Systems that occupy such tip-lines include Gerlach, Desert Queen, Grover's Hot Springs, and possibly Tuscarora. It is noteworthy that Quaternary faults typically lie within or near most of the geothermal systems in the Great Basin, as previously noted by others (Bell and Ramelli, 2007).

Two major subsets of fault intersections include accommodation zones and displacement transfer zones. Accommodation zones are belts of intermeshing, oppositely dipping normal faults (Figure 2C) 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, Moana, and McGin-

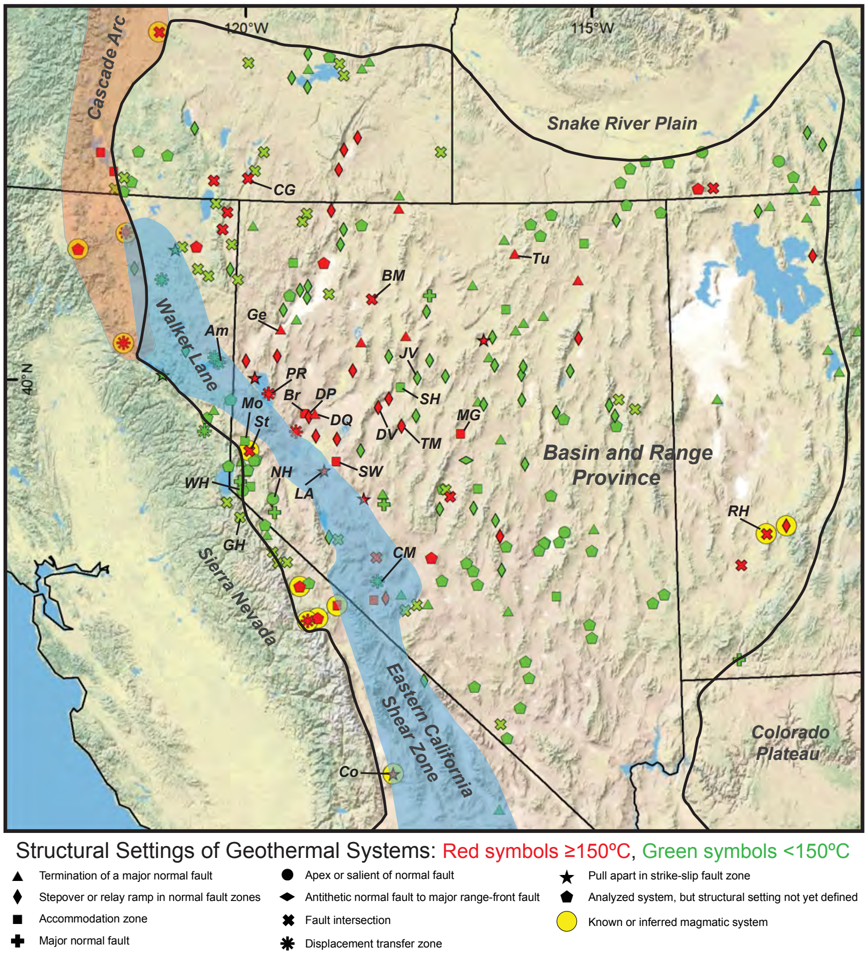

Figure 3. Structural settings of geothermal systems, as deduced in this study. Major types of structural settings are shown on digital elevation model of the Great Basin and adjacent regions. Red symbols – high-temperature systems (≥150°C); green symbols – low-temperature systems (<150°C); yellow circles represent known or inferred magmatic systems. 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; Mo, Moana; 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; Tu, Tuscarora; WH, Walley's Hot Springs.

ness Hills. Displacement transfer zones accommodate a transfer of strain between strike-slip and normal faults (e.g., northeastern margin of the Walker Lane). Geothermal systems in displacement transfer zones are commonly focused along the normal faults proximal to their 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), salients or apices of 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 or Eight-Mile Flat 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 with 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.

Discussion and Implications

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. Instead, geothermal systems most commonly occur in belts of intermeshing, overlapping, or intersecting faults. 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.

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 geothermal anomaly. For example, a logical site for a production well within an anomaly may be the horse-tailing end of a major normal fault or dilational part of a fault intersection. This work should, of course, be coupled with slip and dilation tendency analysis of fault zones and where possible 3D modeling (Moeck et al., 2009, 2010), so as to not only select the best well sites but also estimate the best well paths.

Comparative analysis of favorable settings between different parts of the Great Basin and between different types of systems (e.g., magmatic vs. amagmatic) is also important. It is obvious, for example, that geothermal systems within pull-aparts and displacement transfer zones are more abundant within or along the margins of the Walker Lane, whereas systems within step-overs and accommodation zones in normal fault systems are more prevalent within the extensional terranes. However, the initial findings show no apparent patterns in the abundance of systems in step-overs vs. fault terminations, for example, in different parts of the Great Basin. Also, structural settings in the magmatic-heated systems appear to be as varied as those in the non-magmatic. Ultimately, another key component will be estimating what proportions of certain structural settings might contain geothermal activity in a given area. In the near future, however, any such estimate will be hampered by the likelihood of abundant undiscovered, blind geothermal systems in the region.

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