Regional Variations in Structural Controls on Geothermal Systems in the Great Basin

Patricia H. Cashman[1], James E. Faulds[2], and Nicholas H. Hinz[2]

[1]Dept. of Geological Sciences and Engineering
[2]Nevada Bureau of Mines and Geology,
University of Nevada, Reno

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ABSTRACT

Structural settings of geothermal systems in the Great Basin are known (e.g., Faulds et al. 2004, 2006, 2011), but regional variations in structural controls have not been systematically studied. There are several types of Quaternary faults in the Great Basin, including major north-striking normal fault systems along the east and west boundaries of the Basin and Range province, NNE-striking normal faults throughout the Basin and Range province, and several structural domains of strike-slip faults in the Walker Lane (e.g., Stewart, 1988; Faulds and Henry, 2008). These Quaternary faults are superimposed on different ages and styles of pre-existing rocks and structures, both of which may also influence the structural control of geothermal systems.

Analysis of data from four geologically distinct areas in the Great Basin reveals systematic differences in ages and orientations of faults. The dominant structural controls on geothermal systems differ between study areas, suggesting guidelines for geothermal exploration. Faults related to geothermal systems in southeastern Oregon preferentially strike northwest (an anomaly true only of this study area); step-overs and fault intersections are the most common structural controls. The Basin and Range of central Nevada has the strongest preferred fault orientation, NNE, and structural controls (step-overs, fault terminations and accommodation zones, in that order) are consistent with a dominant set of sub-parallel faults. Faults related to geothermal systems in western Utah have a N to NE preferred orientation, but there are subsidiary faults at a high angle to these. Fault intersections are the most common structural control in Utah, and are more prevalent here than in any of the other study areas; however, step-overs, fault terminations and accommodation zones are also relatively well represented. The Walker Lane of western Nevada exhibits the most diverse range of fault orientations and of structural controls on geothermal systems. Pull-aparts are the most common, and are unique to this study area; fault intersections and fault terminations are second in abundance. In summary, these preliminary results suggest that an improved understanding of regional variations in structural control will lead to region-specific exploration strategies for geothermal systems.

Introduction

Most of the geothermal systems in the Great Basin are amagmatic and fault-controlled. The specific structural settings favorable to development of these geothermal systems are known (e.g., Faulds et al. 2004, 2006, 2011), but regional variations in structural controls have not been systematically studied. There are several types of Quaternary faults in the Great Basin, including major north-striking normal fault systems along the east and west boundaries of the Basin and Range province, NNE-striking normal faults throughout the Basin and Range province, and several structural domains of strike-slip faults in the Walker Lane (e.g., Stewart, 1988; Faulds and Henry, 2008). These Quaternary faults are superimposed on different ages and styles of pre-existing rocks and structures, both of which may also influence the structural control of geothermal systems.

The regional structural and tectonic characteristics of the Great Basin govern the general types of rocks and faults at and near the ground surface. In the broadest sense, the Great Basin is in the wide zone of diffuse plate boundary deformation in western North America; this zone accommodates both WNW-ESE extension and, along its western edge, NW-trending dextral slip. The largest structural domain is the Basin and Range province, characterized by north-northeast-striking normal faults (Fig. 1). The Great Basin is bounded on the west by the active Sierran frontal fault system and the Mesozoic plutonic rocks of the Sierra Nevada. The Walker Lane, a northwest-trending zone of complex faulting with overall dextral motion, lies along the western edge of the Basin and Range province (Locke, et al. 1940; Stewart, 1988; Faulds and Henry, 2008). The active volcanoes of the Cascades are to the northwest, and volcanic rocks ranging from Eocene-Oligocene ignimbrites to the Neogene basalts of the Snake River Plain dominate the northern edge of the province. The active Wasatch normal fault system forms the northern part of the eastern boundary, exposing Proterozoic and Paleozoic rocks of the Mesozoic fold and thrust belt in its footwall. The Hurricane fault, Grand Wash fault and related structures form the boundary farther south, adjacent to Mesozoic rocks of the Colorado Plateau.

In this paper we address the question of whether geothermal systems are systematically controlled by different kinds of structures in different parts of the Great Basin, and if so, how and why. After a brief description of the Geothermal Database, a compilation of over 400 known geothermal springs and wells in the Great Basin, we explain our choice of study areas in southeastern Oregon, western Nevada, central Nevada, and west-central Utah. We present compilations of the ages of faults related to geothermal systems, orientations of faults related to geothermal systems, and probable structural controls on the geothermal systems for each of the four study areas. We conclude by reviewing the results in the context of the tectonic setting of each study area within the Great Basin.

Figure 2. GoogleEarth image from the Geothermal Database compiled by Coolbaugh, Faulds and others, with geothermal systems color-coded by temperature. Warmer colors correspond to higher temperatures.

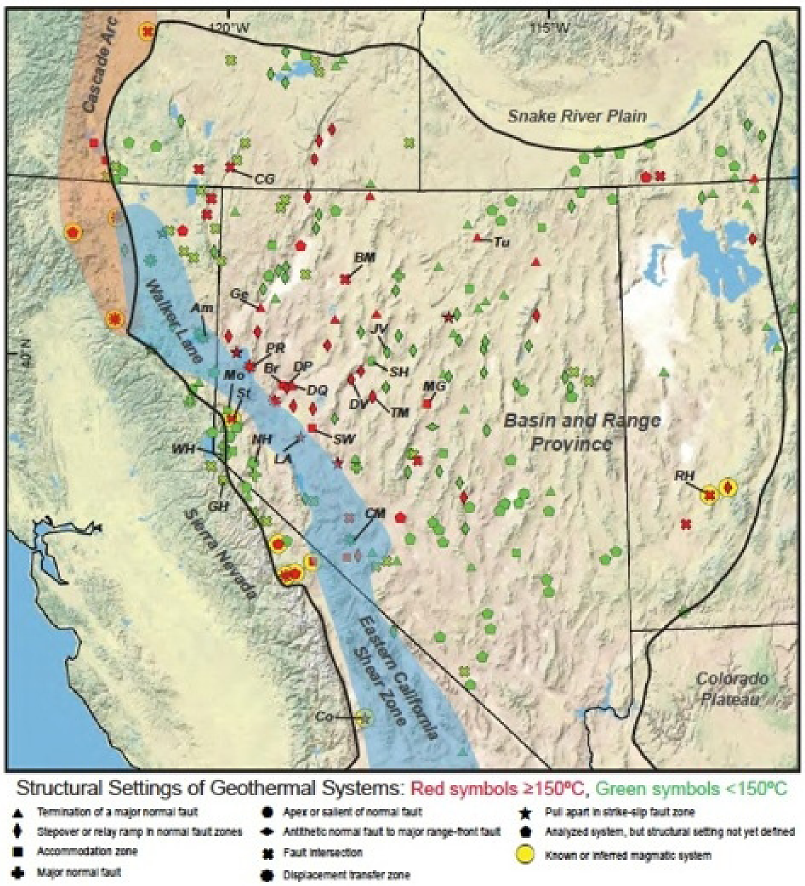

Figure 1. Regional location map, from Faulds et al. (2011), showing major geologic provinces, the boundary of the Great Basin, and the structural controls for over half of the geothermal systems in the Geothermal Database.

Methods

The analysis is based on data from a geothermal database of the Great Basin from Coolbaugh (2003), and a structural inventory of the geothermal systems by Faulds et al. (2011). The initial Geothermal Database (Coolbaugh, 2003) includes a compilation of more than 400 geothermal systems, with temperature estimates based on a combination of measured temperatures and multiple geothermometers (Fig. 2). Subsequent work (e.g., Faulds et al. 2011) has analyzed the structural setting of most of the geothermal systems in the database. The research started with a through literature review, and included examination of published geologic maps, Quaternary fault maps, the USGS Quaternary fault and fold database, air photos and imagery. Based on these data, we have systematically interpreted the structural settings of the geothermal systems, including many not previously evaluated for structural context. Although it is possible to interpret the structural setting for most geothermal systems within or near bedrock exposures, the same is not true for those in the basin-fill deposits of large basins (e.g., agricultural wells, or outflow springs at the toes of alluvial fans). The latter group, with structural setting classified as "undetermined", comprises approximately 25 % of the geothermal systems in the database. Further analysis, with geophysical tools, will be needed to evaluate the structural settings of these geothermal systems.

Four areas, from different tectonic settings across the Great Basin, were further analyzed in this study (Fig. 3). The purpose of the study was to quantify differences in fault orientations, fault ages, or structural settings of geothermal systems that might result from geographical (and therefore, structural or tectonic) differences across the Great Basin. Since the database can be sorted by county, each selected study area comprises two or three contiguous counties within a major tectonic province. Lake, Harney and Malheur counties in southeastern Oregon represent the northwestern Great Basin, bounded on the west by the Cascade Range. Lander and Pershing counties in central Nevada represent the central Basin and Range province. Millard and Beaver counties in southwestern Utah represent the southeastern Great Basin, adjacent to the Colorado Plateau. A fourth group, Esmeralda, Mineral and Lyon counties in western Nevada, represents the Walker Lane; however, county lines here cross geologic boundaries, so this group includes parts

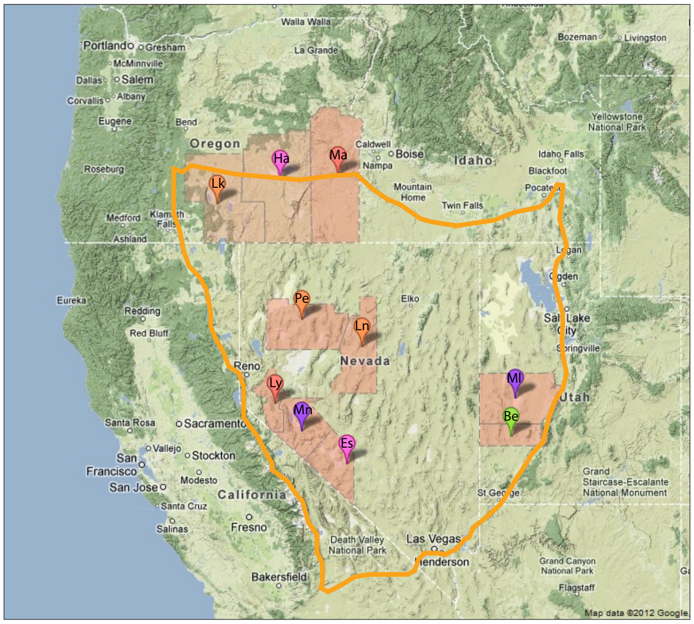

Figure 3. Location map showing the counties used in this analysis. Be = Beaver Co., Es = Esmeralda Co., Ha = Harney Co., Lk = Lake Co., Ln = Lander Co., Ly = Lyon Co., Ma = Malheur Co., Mi = Millard Co., Mn = Mineral Co., Pe = Pershing Co.

of the Basin and Range province and the Walker Lane. These study areas contain roughly equivalent numbers of geothermal system-related faults in the database: southeast Oregon (25), central Nevada (16), southwest Utah (17) and western Nevada (25).

The ages of controlling faults, orientations of controlling faults, and structural settings were quantified for the geothermal systems in each of the study areas. The faults were separated into the age categories used in the USGS Quaternary fault and fold database. This is compilation of information on faults and associated folds

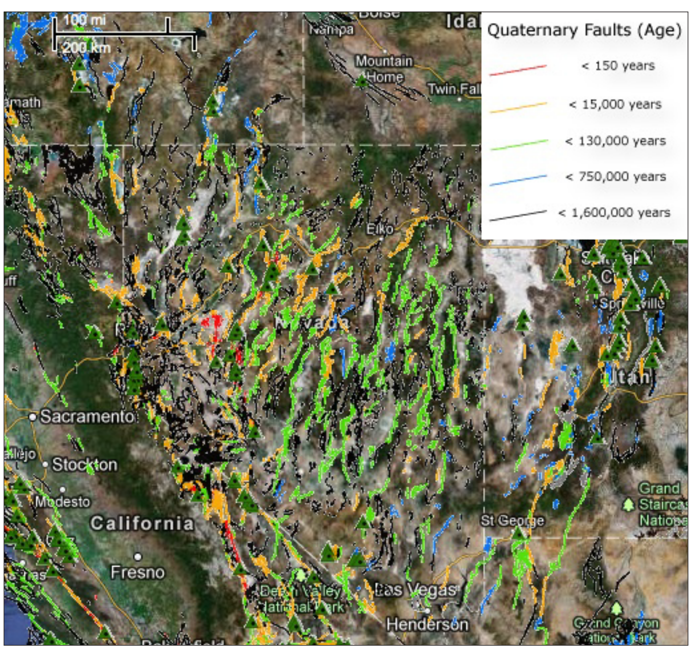

Figure 4. GoogleEarth image showing Qhaternary faults from the USGS Quaternary fault and fold database, color-coded by age.

in the United States that are believed to be sources of M>6 earthquakes during the Quaternary (the past 1,600,000 years) (Fig. 4). The fault age categories are: historic (< 150 years), Holocene-Latest Pleistocene (<15,000 years), Mid-Late Quaternary (<130,000 years), Late Quaternary (<750,000 years), Quaternary (<1,600,000 years), and older than Quaternary (>1.6 Ma).

The strike directions of the faults controlling geothermal systems are divided into sixteen segments of the compass rose (N, NNE, NE, ENE, etc.). Where two faults form the structural control on a geothermal system (e.g., a fault intersection), both faults are included in the rose diagram of fault orientations.

The structural settings of the geothermal systems are divided into ten classes, consistent with those used by Faulds et al. (2011):

1 - termination of normal fault
2 - stepover
3 - accommodation zone
4 - major normal fault
5 - apex of normal fault
6 - antithetic normal fault
7 - fault intersection
8 - displacement transfer zone
9 - pull-apart
10 - undetermined

Structural setting interpretations were made independently by at least two people, and discrepancies were compared in order to make a final interpretation. Many of the discrepancies were a function of the scale of observation (e.g., a minor step-over within a larger accommodation zone).

Results

Orientations of Faults

As expected, the orientations of faults related to geothermal systems differ between the study areas (Fig. 5). The dominant fault strikes in southeast Oregon are NW, with a subsidiary peaks at NNW and N-NNE. The dominant fault strike in central Nevada is NNE-NE; this is the strongest structural orientation in the study, with 63% of the faults in this range. The dominant fault strikes at the southeast edge of the Great Basin, in Utah, are NNE-NE and N-NNE; small subsidiary orientations of ENE and NW are also present. The Walker Lane sample from western Nevada shows the widest spread of fault orientations: about 25% of the

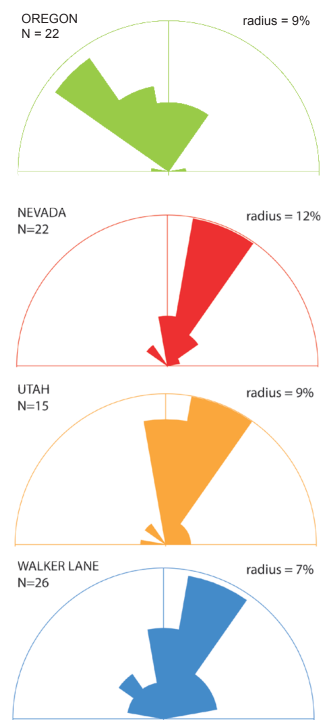

Figure 5. Rose diagrams of the strike directions for faults interpreted to control the geothermal systems in each of the four study areas: SE Oregon, central Nevada, western Utah, and western Nevada (Walker Lane).

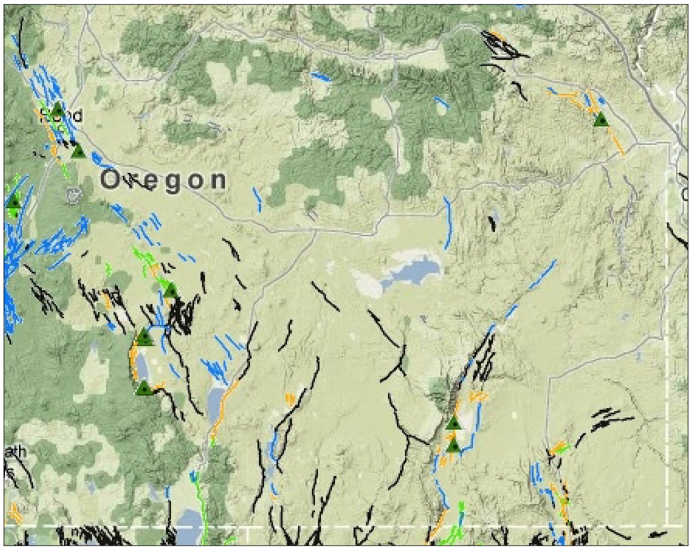

Figure 6. Map of Quaternary faults, color-coded by age, for the southeastern Oregon study area. See Figure 3 for the location of these counties. Faults and ages are from the USGS Quaternary fault and fold database; see Figure 4 for explanation of colors.

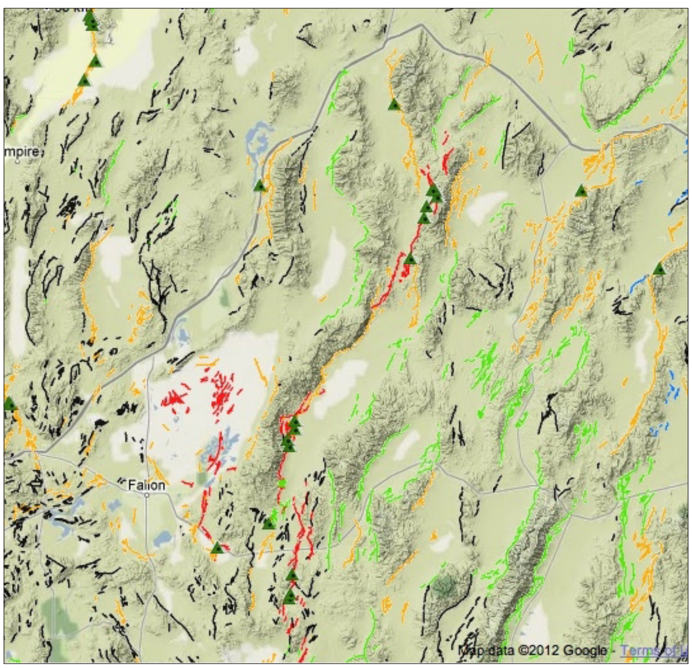

Figure 7. Map of Quaternary faults, color-coded by age, for the central Nevada study area. See Figure 3 for the location of these counties. Faults and ages are from the USGS Quaternary fault and fold database; see Figure 4 for explanation of colors.

faults strike generally NW, while the remainder strike N-ENE (and dominantly NNE-NE). Quaternary faults from these counties as shown in the USGS fault and fold database illustrate that the faults associated with geothermal systems are not necessarily representative of the average fault distribution (Fig.s 6-9).

Ages of Faults

The ages of faults associated with geothermal systems also differ between study areas (Fig. 10; see also figures 6-9). For

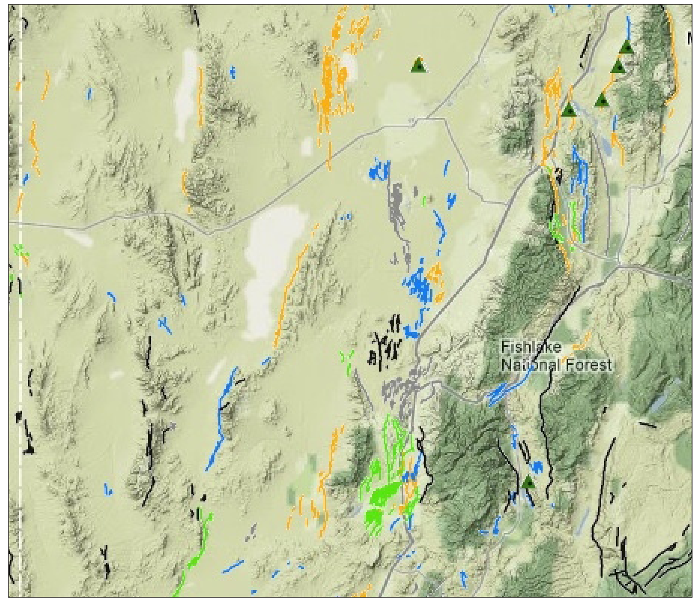

Figure 8. Map of Quaternary faults, color-coded by age, for the western Utah study area (from the NV-UT state line to the eastern edge of the Basin and Range). See Figure 3 for the location of these counties. Faults and ages are from the USGS Quaternary fault and fold database; see Figure 4 for explanation of colors.

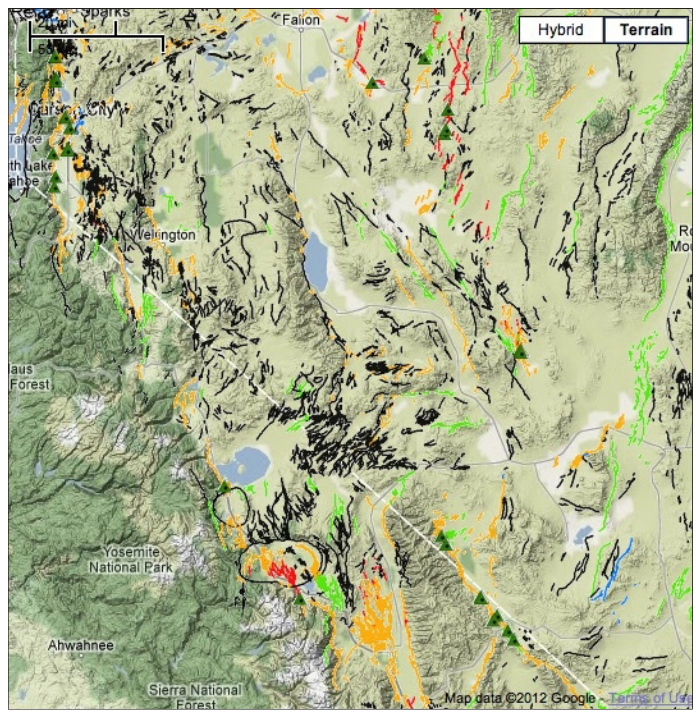

Figure 9. Map of Quaternary faults, color-coded by age, for the western Nevada study area (counties northeast of the CA-NV state line). See Figure 3 for the location of these counties. Faults and ages are from the USGS Quaternary fault and fold database; see Figure 4 for explanation of colors.

consistency, we use the fault ages on the USGS Quaternary fault and fold database in this analysis. Southeast Oregon has the largest percentage of faults in the >1.6 Ma category, with considerably fewer faults in the Holocene (<15,000 years) and Quaternary (< 1,600,000 years) age brackets. Central Nevada,

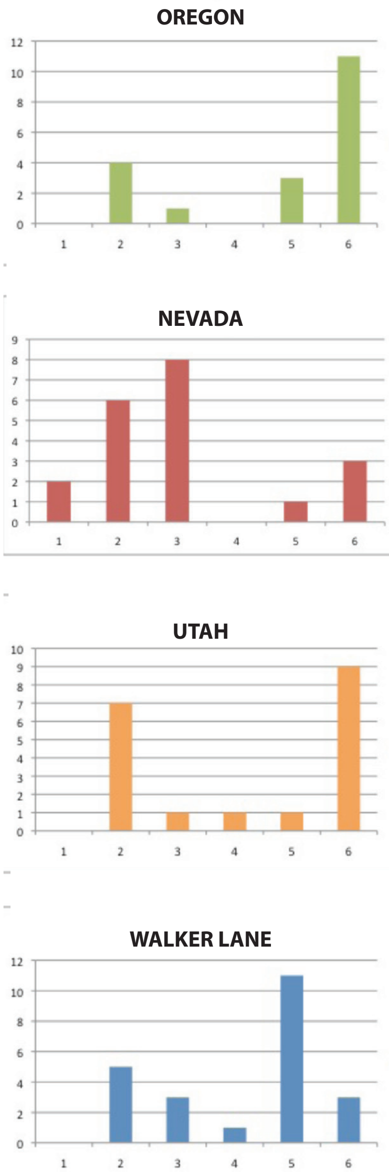

Figure 10. Histograms of the ages of faults interpreted to control the geothermal systems in each of the four study areas: SE Oregon, central Nevada, western Utah, and western Nevada (Walker Lane). The categories for fault ages follow those of the USGS Quaternary fault and fold database (see caption of Fig. 4).

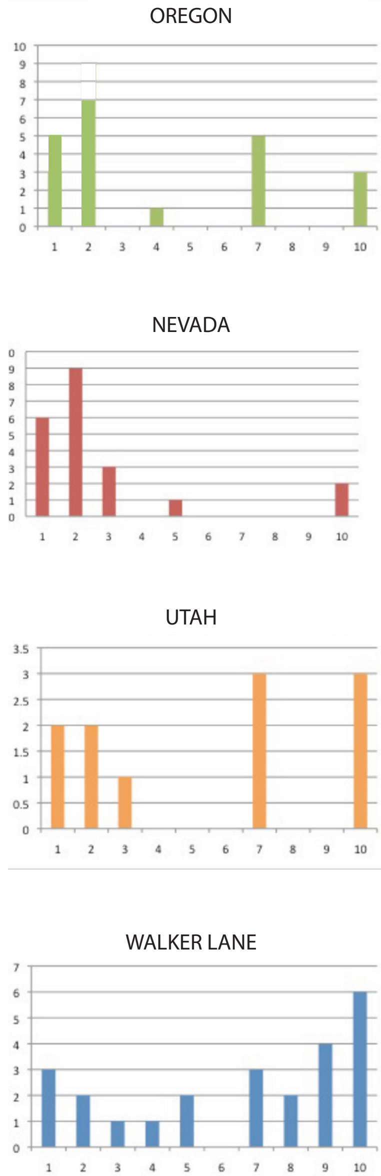

Figure 11. Histograms of the structural settings interpreted to control the geothermal systems in each of the four study areas: SE Oregon, central Nevada, western Utah, and western Nevada (Walker Lane). The structural settings of the geothermal systems are divided into ten classes, consistent with those used by Faulds et al. (2011):

squarely in the Basin and Range province, has the most recently active faults of any of the study areas, including two historic faults and a large majority between Holocene (<15,000 years) and Mid-Quaternary (<130,000 years) in age. Southwestern Utah has a strongly bimodal distribution of fault age, with roughly half Holocene-Latest Pleistocene (<15,000 years) and the other half older than 1.6 Ma. The Walker Lane study area has a majority of Quaternary faults (< 1.6 Ma), but also includes populations of Holocene (<15,000 years) and Mid-Quaternary (<130,000 years) faults.

Structural Settings of Geothermal Systems

The most interesting comparisons are the structural controls on geothermal systems in different parts of the Great Basin (Fig. 11). The structural settings are "undetermined" for a relatively large percentage of the southwest Utah and Walker Lane groups; these are not included in the following summary. The dominant structural control for geothermal systems in the southeastern Oregon study area is step-overs, with fault intersections and terminations of major normal faults second. Structural controls in the central Nevada (Basin and Range) study area are most commonly step-overs, followed by fault terminations and then accommodation zones. Fault intersections are the most common structural control in western Utah, with fault terminations and step-overs second in importance. The Walker Lane study area in western Nevada has by far the most diverse structural controls on geothermal systems. Every kind of setting except one (antithetic normal fault) is represented. Pull-aparts are the most common, followed by fault intersections and fault terminations, then by step-overs, apexes of normal faults and displacement transfer zones, and then by fewer of the remaining types.

1 - termination of normal fault
2 - stepover
3 - accommodation zone
4 - major normal fault
5 - apex of normal fault
6 - antithetic normal fault
7 - fault intersection
8 - displacement transfer zone
9 - pull-apart
10 - undetermined

Discussion

Southeastern Oregon

Perhaps the most surprising aspect of the southeast Oregon geothermal systems is the most common age of faults associated with these systems, i.e., >1.6Ma according to the USGS Quaternary fault and fold database (Fig. 10). Note, however, that some workers have documented Holocene activity on both NNW-striking and NNE-striking faults in southeast Oregon (e.g., Pezzopane, 2001), so younger faulting may be more prevalent. The prevailing NW strike of the faults is also anomalous when compared to the other areas analyzed (Fig. 5). This orientation is not surprising, however, in the context of the location -- the western part of this study area is along strike of the Walker Lane, and all of it is southeast of the rotating Coast Ranges block (e.g., Wells et al., 1998; McCaffrey et al., 2000b; Hammond and Thatcher, 2005b; McCaffery et al., 2007). North- and NNE-striking faults are also present; these are consistent with the northward continuation of Basin-and-Range-style normal faulting. The most common structural setting of southeast Oregon geothermal systems in the database is step-overs (Fig. 11). Fault intersections (commonly between the NW- and NNE-striking faults) are second in abundance, and terminations of major normal faults are third.

Central Nevada

The central Nevada study area is within the Basin and Range province, and the structural controls on the geothermal systems are consistent with this setting. Faults associated with geothermal systems overwhelmingly strike NNE (Fig. 5), exhibiting the strongest preferred orientation found in this study. This orientation is perpendicular to the modern extension direction. The central Nevada study area is the only one to include historic faults, and virtually all of the other faults related to the geothermal systems are also relatively young -- either Holocene or Mid- to Late Quaternary in age (Fig. 10). Structural controls on the geothermal systems are most commonly step-overs, but also include a significant number of normal fault terminations and a smaller number of accommodation zones (Fig. 11). All of these structural controls are consistent with a dominant set of sub-parallel normal faults.

Western Utah

The structural controls on geothermal systems in western Utah have several characteristics in common with those in southeastern Oregon, on the opposite side of the Great Basin. The majority of the faults are older than 1.6 Ma (Fig. 10); the other faults are almost exclusively Holocene-Latest Pleistocene. Faults have a strong preferred orientation (in this case, N to NE), but there are subsidiary systems at a high angle to these (Fig. 5). The NNE-striking faults parallel the fault boundary with the Colorado Plateau. Fault intersections are the most common structural control, and are more prevalent here than in any of the other study areas; however, the structures that can be associated with a dominant fault set -- step-overs, fault terminations and accommodation zones -- are also relatively well-represented (Fig. 11).

Western Nevada (Walker Lane)

The western Nevada study area straddles parts of two tectonic provinces, the Walker Lane and the Basin and Range, and structures related to geothermal systems include characteristics of each. Not surprisingly, this study area exhibits the most diverse range of fault orientations and of structural controls on geothermal systems. Although the dominant strike of faults related to geothermal systems is N to NE (typical of the Basin and Range province), several other fault orientations occur as well (Fig. 5). The latter include NW and ENE, each of which typifies one of the strike-slip-dominated structural domains within the Walker Lane (e.g., Stewart, 1988). Pull-aparts are the most common structural control in this study area. Fault intersections and fault terminations are second in abundance.

In summary, there are systematic regional variations in structural controls of geothermal systems in the Great Basin, and the broader tectonic setting puts these observations in perspective. This preliminary study shows the potential for further regional analysis, and demonstrates the need for better precision in defining domains based on regional structural history and tectonic setting. An improved understanding of regional variations in structural control will lead to better exploration strategies for geothermal systems.

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