The Hybrid Model—The Most Accommodating Structural Setting for Geothermal Power Generation in the Great Basin, Western USA

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Great Basin, Nevada, structural setting, power plant, normal fault, accommodation zone, relay ramp

ABSTRACT

In our 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, we have found that step-overs or relay ramps in normal fault zones serve as the most favorable structural setting, hosting ~33% of the systems. Other common settings include a) intersections between normal faults and either transversely oriented strike-slip or oblique-slip faults (22%) and b) normal fault terminations or tip-lines (23%). A major subset of fault intersections includes displacement transfer zones (5%) between strike-slip faults in the Walker Lane and north-to northeast-striking normal faults, with geothermal systems commonly focused along the normal faults proximal to their dilatational intersections with nearby dextral faults. Other notable structural settings include accommodation zones (i.e., belts of intermeshing, oppositely dipping normal faults; 7%), major range-front faults (3%), major bends in normal faults (2%), 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. The more favorable settings correspond to long-term, critically stressed areas, where fluid pathways would more likely remain open in networks of closely-spaced, breccia-dominated fractures. Of the 27 power plants in the Great Basin region, however, the proportions differ, with step-overs hosting ~41% and accommodation zones and fault intersections each containing ~26%. Moreover, hybrid settings appear to characterize many of the producing systems, including some of the higher enthalpy systems (e.g., Brady’s and Steamboat). It would appear that the greater the structural complexity, the greater the likelihood of a geothermal system being robust enough to generate electric-

Introduction

Better characterization of known geothermal systems is critical for discovering new systems, reducing the risks in drilling, and enhancement (EGS) or expansion of known 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 may have little or no surface manifestation (i.e., blind or hidden; Coolbaugh et al., 2006a), and thus techniques must be developed to indicate the most favorable locations for targeting subsurface resources.

Our approach has been to characterize and catalogue geothermal systems on the basis of the prominent fault pattern or structural setting (Figure 1, next page). We have now catalogued ~300 systems in the Great Basin region and determined the relative proportions of various settings (Faulds et al., 2011), as well as regional trends in the types of settings (Cashman et al., 2012). These syntheses have been bolstered by detailed studies of individual representative systems across the region (e.g., Faulds et al., 2006, 2010; Faulds and Melosh, 2008; Hinz et al., 2008, 2010, 2011; Rhodes et al., 2010; Dering and Faulds, 2012; Edwards and Faulds, 2012; Siler et al., 2012; Anderson et al., this volume).

In this paper, we review the overall proportions for the favorable types of structural settings and then look at an important subset of systems, those that host producing power plants. Although this subset is relatively small (only 27; Table 1), the emerging pattern is potentially telling, as the relative proportions differ somewhat from the overall range. In addition, many of the producing systems appear to contain more than one favorable setting and are thus hybrids, making cataloguing more difficult but more importantly apparently generating more favorable conditions for fluid flow. We present examples of some of these hybrid systems and discuss their ramifications for exploration strategies.
Western North America contains a diffuse plate boundary, characterized primarily by dextral motion between the Pacific and North American plates (e.g., Atwater and Stock, 1998). Much of this 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 ~80% of the plate motion. The other ~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 fault junction, the Walker Lane dies out northwestward in northwest Nevada-northeast California. As the Walker Lane terminates, about 1 cm/year of dextral motion diffuses into west-northwest-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). Although the most prolific geothermal activity occurs in the northwestern part, geothermal systems are spread across the entire actively extending Great Basin, with activity focused in the higher strain regions (Faulds et al., 2012a).

It has long been known that individual geothermal fields in the Great Basin are generally controlled by moderately to steeply dipping normal fault zones (Benoit et al., 1982; Blackwell et al., 1999; Johnson and Hulen, 2002; Wannamaker, 2003; Faulds et al., 2006). In the northwest Great Basin, the predominant north-northeast-striking controlling faults are oriented approximately orthogonal to the regional extension direction. Because north-northeast-striking normal faults abound in the Great Basin, with many showing no signs of geothermal activity, it is important to determine which faults or which segments of individual faults are most likely to host a geothermal system. Our methodology for analyzing and cataloguing geothermal systems is described in Faulds et al. (2011).

Of the geothermal fields analyzed to date, we found that step-overs or relay ramps, fault intersections, and normal fault terminations or tip-lines host most of the geothermal systems (Figures 1 and 2). Step-overs in normal fault zones serve as the most favorable structural setting, hosting ~33% 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, Neal Hot Springs, and Tuscarora. Intersections between normal faults and either transversely oriented strike-slip or oblique-slip faults account for ~22% of the systems (34% if subsets included). Normal fault terminations or tip-lines, where horse-tailing generates a myriad of closely-spaced faults (Figure 2B) and thus increased permeability, also represent ~23% of the systems. Systems that occupy such tip-lines include Gerlach, Desert Queen, and Grover’s Hot Springs. Quaternary faults typically lie within or near most of the geothermal systems in the Great Basin (Bell and Ramelli, 2007). 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 rocks remain critically stressed and fluid flow is therefore favored.

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 ~7% of the systems, including Salt Wells (also known as Eight-Mile Flat), Steamboat, Tuscarora, and McGinness 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 Patua, Wild Rose, and Pyramid Rock. Pull-aparts in strike-slip fault systems represent only 4% of the systems overall but are more common in the Walker Lane-eastern California shear zone (e.g., Coso and Lee-Allen). Major range-front faults account for 3% or less of the systems. The relative paucity of systems in such areas probably results from the abundance of clay gouge on large offset faults, which can serve as a barrier to fluid flow, and the periodic release of stress in large earthquakes.

### Table 1. Structural Settings of Geothermal Systems with Power Plants.

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For status: C; under construction; P, Producing; S, Standby status. Type of structural setting (from left to right): FT, fault tip or termination; FI, fault intersection; SO, step-over or relay ramp; AZ, accommodation zone; DTZ, displacement transfer zone; PU, pull-apart; H, hybrid; U, undetermined.
Structural Settings for Producing Fields

We include 27 localities in our analysis of producing geothermal systems (Table 1). This includes 23 systems currently producing geothermal power, 2 under construction, and 1 in standby status. Of the 27 systems, 11 occupy step-overs (i.e., relay ramps, ~41%), 8 lie at fault intersections (~30%), 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 contain more than one type of structural setting. Notable within this distribution is the large proportion of producing accommodation zones, which only represent ~8% 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.

In essence, the structural settings group themselves into a hierarchical pattern with respect to fault complexity. Despite the horse-tailing nature of a fault termination, such structures are probably the simplest and notably contain relatively few developed systems. A fault intersection is generally more complex, as it typically contains both multiple fault strands and can include a distinct dilational quadrant depending on the kinematics of the intersecting faults. A step-over or relay ramp essentially consists of two overlapping fault terminations and thus involves additional complexity, especially in cases where the relay ramp is breached by multiple fault splays that provide hard linkage between the main overlapping faults and produce multiple fault intersections. Accommodation zones involve further complexity, as they consist of multiple fault terminations and fault intersections. Although there are fewer accommodation zones across the Great Basin as compared to fault terminations, intersections, and step-overs, the additional structural complexity of an accommodation zone leads to a greater proportion hosting a producing geothermal system. Displacement transfer zones and pull-aparts in strike-slip fault systems are also complex zones, typically consisting of multiple fault intersections. However, these settings are largely restricted to the Walker Lane belt and thus less common than favorable extensional settings in the broader Great Basin region. Nonetheless, it would appear that, throughout the Great Basin region, the greater the structural complexity, the greater the likelihood of a geothermal system being robust enough to generate electricity.

Hybrid Systems

It is notable that many of the producing geothermal systems are characterized by more than one type of favorable setting at a single locality (Table 1). This relationship is in accord with the interpretation that increasing structural complexity correlates with the probability of hosting a geothermal system capable of generating electricity. Here, we review 4 systems that fit this hybrid model.

Brady’s

The Brady’s geothermal field lies ~80 km northeast of Reno in west-central Nevada (Figure 1). It has a reservoir temperature of 180-193°C at 1-2 km depth (Benoit et al., 1982) and supports a combined dual flash and binary geothermal power plant with a total installed capacity of 26 MWe. The power plant has been in operation since 1992. It is also the site of an ongoing EGS project in the southern part of the field.

The Brady’s area is dominated by north-northeast-trending gently to moderately tilted fault blocks bound by moderately to steeply dipping, primarily north-northeast-striking normal faults. Faults in the area dip both west and east and have respectively accommodated both east- and west-tilting of fault blocks. The stratigraphic section consists of middle to late Miocene volcanic and sedimentary strata, Oligocene-early Miocene ash-flow tuffs, and Mesozoic metasedimentary basement locally intruded by Jurassic and Cretaceous plutons.

The most significant fault in the area for hydrothermal activity is the Brady’s fault zone, which consists of a complex system of en echelon, primarily west-northwest-dipping faults (Figure 3). The surface expression of the Brady’s geothermal system is a 4-km-long, north-northeast-trending zone of extensive sinter, warm ground, fumaroles, and mud pots along the Brady’s fault system. The Brady’s fault zone has accommodated ~500 m of...
cumulative down-to-the-west throw. Several segments of this fault zone channel hydrothermal fluids. Wesnousky et al. (2005) documented one Holocene, normal dip-slip rupture along the fault zone.

The Brady’s geothermal system lies within a discrete left step in the west-northwest-dipping Brady’s fault zone but also within a broader accommodation zone consisting of overlapping west- and east-dipping faults (Figure 3). The main production wells at Brady’s appear to penetrate the down-plunge projection of a small left step in the Brady’s fault zone (Faulds et al., 2006). The north-northeast-striking Brady’s fault zone is orthogonal to the regional west-northwest-trending extension direction and is thus favorably oriented for fluid flow. We suggest that multiple fault strands in the step-over combined with some intersections between the west- and east-dipping faults produce a zone of high fracture density that enhances fluid flow and facilitates the rise of a deep-seated thermal plume.

**Salt Wells**

The Salt Wells (or Eight-Mile Flat) geothermal field occupies the west-southwest margin of the Eight-Mile Flat basin ~20 km southeast of Fallon, Nevada, along the east flank of the Bunejug Mountains and north edge of the Cocoon Mountains (Figures 1 and 4). Temperature gradient drilling has defined a large, 12-km-long heat flow anomaly at the Salt Wells geothermal system (Edmiston and Benoit, 1984). The Salt Wells geothermal system has been described as a blind geothermal system, but surface warm springs, warm ground, argillic alteration of bedrock, silicified Quaternary sediments, and opaline sinter are present in the area (Coolbaugh et al., 2006b). Anadarko first conducted geothermal exploration in the area in the early 1980’s. ENEL recently developed a 14MWe power plant, which came on line in 2009 and taps a shallow (150-225 m) geothermal reservoir with an estimated temperature of ~140°C. Geothermometry suggests that a deeper reservoir may exist at temperatures of 180-190°C. The area is dominated by gently to moderately east- and west-tilted fault blocks bound by both west- and east-dipping normal faults, respectively, and consisting of middle to late Miocene volcanic and lesser sedimentary strata, onlapped by Quaternary sediments.

The Salt Wells system appears to be controlled by at least two structural settings. The broader setting is an accommodation zone between east- and west-dipping normal fault systems, with geothermal activity focused in the axial part of the accommodation zone within a northerly trending extensional syncline developed between east- and west-tilted fault blocks (Figure 4; Hinz et al., 2011). East- and west-dipping faults overlap and cross-cut each other in the hinge zone of the syncline, yielding a zone of high fracture density. The system also occupies the southern horse-tailing tip of a major east-dipping normal fault zone, the Rainbow Mountains fault. Much of this fault ruptured in a M 6.9 earthquake in 1954. In addition, the southern part of the Rainbow Mountains fault may curve into a northwest-striking dextral-normal fault that bounds the northern Cocoon Mountains, thus forming a small displacement transfer zone. The structural complexity of this area, including multiple splaying faults and fault intersections, presumably generates a zone of subvertical conduits of highly fractured rock that accommodate upflow of hydrothermal fluids.

**McGinness Hills**

The McGinness Hills geothermal system is in central Nevada ~20 km northeast of Austin (Figure 1). It is a blind system, with no surface hot springs or fumaroles, but is marked by extensive alteration and large (1 km²) silica sinter deposits (Casaceli et al., 1986). Gold exploration in the 1980’s led to the discovery of hot artesian water. Geothermometry studies by Coolbaugh et al. (2006a) indicated temperatures of ~150 to 214°C at depth. These studies prompted Ormat to explore the area, and a 30MWe capacity binary power plant came online in 2012.

The McGinness area is dominated by gently east-tilted fault blocks bound by moderately to steeply west-dipping faults. Fault blocks consist of Oligocene-early Miocene ash-flow tuffs and andesite lavas that nonconformably overlie Paleozoic metasedimentary rocks locally intruded by Jurassic plutons. Quaternary alluvial fan deposits onlap all older rock units.

The McGinness Hills geothermal system lies in a hybrid structural setting. On a regional scale, the structural setting of McGinness Hills is characterized by a broad accommodation zone,
which includes the west-dipping range-front fault of the Simpson Park Range and a major east-dipping fault on the east side of the Toiyabe Range (Figure 5). The geothermal system essentially occupies an interbasinal high between the Big Smoky and Grass Valley basins at the confluence of the Toiyabe and Simpson Park Ranges. On a local scale, however, the McGinness Hills system occupies a left step-over within a north-northeast-striking normal fault in a belt of overlapping east- and west-dipping faults. Highest permeability appears to reside at the intersections of the north-northeast-striking faults with steeply dipping northwest-striking faults.

Tuscarora

The Tuscarora geothermal field lies in the northeastern Tuscarora Mountains in northeastern Nevada ~90 km northwest of Elko (Figure 1). It is marked by surface hot springs and a large (~700 m long) silica sinter terrace. Extensive geothermal exploration in the area from 1978-1981 included the drilling of 32 temperature gradient holes peripheral to and within the known thermal anomaly. Ormat Technologies, Inc., conducted recent exploration and drilling and in 2011 constructed a binary power plant, which currently produces 18 MWe from an ~170°C reservoir in Paleozoic metasedimentary rocks at a depth of 1740 m. The Tuscarora area is dominated by late Eocene to middle Miocene volcanic and sedimentary rocks, all overlying Paleozoic metasedimentary rocks exposed in gently to moderately east- and west-tilted fault blocks bound by moderately to steeply dipping normal faults.

Two distinct structural settings at different scales appear to control the geothermal field (Dering, 2013). The regional setting is a 10-km wide complexly faulted left step or relay ramp between the west-dipping range-bounding normal faults of the Independence Range and Bull Run Mountains (Figure 6). However, geothermal activity on a local scale occurs within a small northerly trending accommodation zone within the step-over, where sets of east- and west-dipping normal faults intermesh. The distribution of hot wells and hydrothermal surface features, including boiling springs, fumaroles, and siliceous sinter, indicate that the geothermal system is restricted to the narrow (< 1 km) axial part of the
accommodation zone, where permeability is maintained at depth around complex fault intersections. Shallow up-flow appears to be focused along several closely spaced steeply west-dipping, north-northeast-striking normal faults within the axial part of the accommodation zone. These faults are favorably oriented for extension and fluid flow under the present-day northwest-trending regional extension direction.

Conclusions

Of the 27 geothermal systems that generate electricity in the Great Basin region, most occupy step-overs, fault intersections, and accommodation zones. Hybrid systems, which incorporate more than one type of structural setting, are particularly favorable for geothermal power. Increasing structural complexity clearly favors geothermal systems, especially robust systems capable of generating electricity. Displacement-maxima zones or mid-segments of major normal faults (i.e., major range-front faults) lack producing geothermal systems, possibly due to both reduced permeability in thick zones of clay gouge and periodic release of stress in major earthquakes. Instead, geothermal power plants 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 vast amount of blind geothermal systems that underlie the region. This includes targeting of the most promising sites within broad accommodation zones and step-overs.

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