Structural Controls of Geothermal Activity in the Northern Hot Springs Mountains, Western Nevada: The Tale of Three Geothermal Systems (Brady's, Desert Peak, and Desert Queen)

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ABSTRACT

The northwestern Great Basin in the western USA hosts abundant, generally amagmatic geothermal activity. Significant geothermal exploration is ongoing, but controls on fluid flow in the geothermal systems are generally poorly understood. To better elucidate the controls on fluid flow, we have been conducting a detailed structural assessment (detailed geologic mapping, structural analysis, gravity surveys, and stress determinations) of the northern Hot Springs Mountains ~80 km east-northeast of Reno, Nevada.

Three major NNE-striking normal fault systems dissect the northern Hot Springs Mountains, and each is associated with a distinct geothermal anomaly. From west to east, these are the Brady's, Desert Peak, and Desert Queen geothermal systems. The surface expression of the Brady's system is a 4-km-long, NNE-trending zone of extensive sinter, warm ground, fumaroles, and mud pots along the Brady's fault. In contrast, both Desert Peak and Desert Queen are blind geothermal systems with no obvious surface expression of hydrothermal activity. Kinematic data gleaned from fault surfaces in the area indicate essentially dip-slip motion along controlling faults and a WNW-trending extension direction, which is compatible with regional GPS geodetic data. Although spacing between the controlling fault zones is only ~3 to 6 km, available geochemical data suggest that each system is independent from the other. Both Brady's and Desert Peak are high enthalpy systems (175-215°C) that have operating power plants and are currently under study for expansion utilizing EGS technology. Both of these systems occupy left steps in the NNE-striking, west-dipping normal fault systems. The left steps appear to be linked by multiple minor, more northerly striking faults and thus mark steeply plunging conduits of highly fractured rock. The high fracture density in these steps enhances permeability and therefore accommodates the ascent of hydrothermal fluids. The Desert Queen system is marked by a 6-km-long shallow temperature anomaly with 2-meter temperatures as high as 42°C. These shallow temperatures overlie a shallow thermal aquifer at depths of roughly 70 m with temperatures as high as 90°C measured in shallow gradient holes. The Desert Queen system appears to occupy the southern, horse-tailing end of an east-dipping, NNE-striking normal fault zone, possibly where it intersects a major west-dipping antithetic fault. Increased fracture density associated with horse-tailing presumably generates a zone of high permeability conducive for deep circulation and fluid flow. The proximity of three independent geothermal systems in the northern Hot Springs Mountains demonstrates the high potential for geothermal development within the western Great Basin and suggests that favorable structural settings can be found along many normal fault zones.

Introduction

In the Great Basin, 20 geothermal systems have power plants either installed or under construction with a total capacity of approximately 760 MWe. Fifteen of these sites, with approximately 290 MWe capacity (installed or under construction) are not associated with young volcanism and are thought to owe their existence to active extensional or transtensional tectonics and high heat flow. Terrestrial surface heat flow ranges from 50 to ~120 mW/m^2, averaging roughly 90 mW/m^2 (Blackwell and Richards, 2004).

The majority of the higher temperature geothermal activity occurs in the northwestern part of the Great Basin even though volcanism generally ceased in this region 3 to 10 Ma. Many geothermal fields in the northwestern Great Basin have subsurface temperatures approaching or exceeding 200°C. The fields are particularly abundant in northwestern Nevada and neighboring parts of northeastern California and southern Oregon (Coolbaugh et al., 2002; Coolbaugh and Shevenell, 2004; Figure 1). The geothermal systems cluster in discrete NNE to NE-trending belts, including the Humboldt structural zone (which incorporates the central Nevada seismic belt) and Black Rock Desert region (Faulds et al., 2004). The lack of recent volcanism suggests that upper crustal magmatism is not a heat source for most of the geothermal activity in this region.

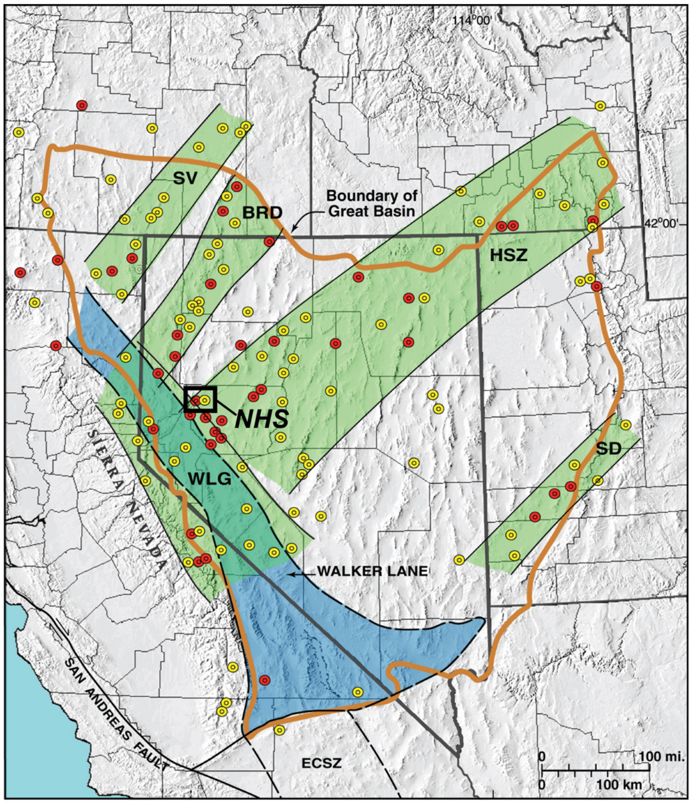

Figure 1. Geothermal belts in the Great Basin (from Faulds et al., 2004). Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. Yellow circles are geothermal systems with maximum temperatures of 100-160°C; red circles have maximum temperatures >160°C. ECSZ, eastern California shear zone. Black box surrounds the northern Hot Springs Mountains.

On a grand scale, the transtensional tectonic setting probably facilitates much of the geothermal activity in the northwestern Great Basin (Faulds et al., 2004). Relatively high rates of recent (<10 Ma) WNW-directed extension (Surpless et al., 2002; Colgan et al., 2004) in this region absorb northwestward declining dextral motion in the Walker Lane. The Walker Lane is a system of dextral faults that accommodates ~20% of the Pacific-North American plate motion (e.g., Hammond and Thatcher, 2004; Faulds and Henry, 2008). The NNE-trending belts of geothermal activity in the Great Basin are aligned orthogonal to the extension direction (Figure 1) and may therefore reflect loci of both strain transfer and extension (Faulds et al., 2004).

Individual fields appear to be largely controlled by NNE-striking normal faults (e.g., Blackwell et al., 2002; Johnson and Hulen, 2002; Faulds et al., 2003, 2004, 2006). Enhanced extension favors dilation and deep circulation of hydrothermal fluids along faults oriented perpendicular to the extension direction. Although faults clearly control most geothermal activity in the Great Basin, many questions remain concerning the distribution of geothermal systems along fault zones in terms of overall spacing and which faults or segments of faults are most favorable for geothermal activity. Enhanced knowledge of such structures would facilitate exploratory drilling in known, but as yet undeveloped fields, expansion in producing fields, and identification of possible blind (or hidden) geothermal resources. Regional analyses indicate that blind geothermal systems likely comprise the majority of the geothermal resources in the Great Basin (Coolbaugh et al., 2007; Williams et al., 2009). We have therefore been analyzing and characterizing the structural controls on geothermal activity within the Great Basin (Faulds et al., 2003, 2004, 2005, 2006; Faulds and Melosh, 2008; Vice et al., 2007; Rhodes et al., this volume; Hinz et al., this volume).

In this paper, we describe our structural assessment of geothermal systems in the northern Hot Springs Mountains, ~ 80 km northeast of Reno in Churchill County, Nevada. Here, several independent geothermal systems are closely spaced and may provide clues to the overall geothermal potential of the region. The major goals of this paper are to summarize what is known about the structural controls of the geothermal systems and to provide an update of the stratigraphic and structural setting of the northern Hot Springs Mountains. This information can aid ongoing exploration aimed at expanding the Brady's and Desert Peak geothermal systems and developing the Desert Queen field.

Northern Hot Springs Mountains

The northern Hot Springs Mountains host at least three major geothermal anomalies and one apparently smaller, much less well documented system. From west to east, the major systems are the Brady's, Desert Peak, and Desert Queen geothermal fields (Figure 2). The fields are spaced ~5 km apart and respectively follow each of three major, similarly spaced, NNE-striking normal fault zones. Both the Desert Peak and Brady's systems support geothermal power plants. The Desert Peak and Desert Queen fields are *blind* geothermal systems, with no active hot springs or fumaroles and little, if any, fossil spring deposits. Available aqueous chemistry and isothermal maps suggest that the Brady's and Desert Peak fields are associated with essentially independent thermal plumes, at least at shallow depths (Benoit et al., 1982). The smaller system lies between Brady's and Desert Peak and is utilized by the Brady's power plant for injection purposes.

The Hot Springs Mountains are primarily composed of late Oligocene to late Miocene volcanic and sedimentary rocks that rest directly on Mesozoic metamorphic and granitic basement. Closely-spaced, north-northeast-striking faults dissect the range. In addition, the Tertiary rocks (some of which are less than 9 Ma) are deformed into closely spaced north-northeast-trending folds. Benoit et al. (1982) compiled isothermal maps, a near-surface thermal aquifer map, Bouguer gravity map (Desert Peak area only), and a generalized geologic map of the area. Faulds et al. (2003) and Faulds and Garside (2003) have more recently provided a detailed geologic map and more detailed gravity survey of the area, both aimed at elucidating the structural controls on the geothermal systems.

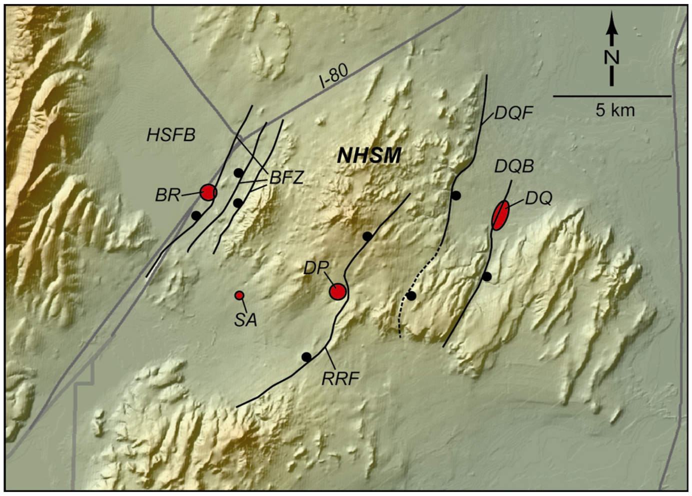

Figure 2. Digital elevation model of the northern Hot Springs Mountains (NHSM), showing major faults and geothermal fields. Ball shown on downthrown sides of faults. Each major fault zone in the northern Hot Springs Mountains contains a large independent geothermal field (marked by larger red circles) spaced ~5 km apart. BFZ, Brady's fault zone; BR, Brady's geothermal field (area of production wells); DP, Desert Peak geothermal field (area of production wells); DQ, Desert Queen geothermal field (area of shallow temperature anomaly); DQB, Desert Queen basin; DQF, Desert Queen fault zone; HSFB, Hot Springs Flat basin; RRF, Rhyolite Ridge fault zone; SA, small geothermal anomaly.

Stratigraphic Framework

The Hot Springs Mountains are dominated by a thick (>2 km) section of Miocene volcanic and sedimentary rocks resting on either Oligocene ash-flow tuffs or Mesozoic plutonic-metamorphic basement. The basement is only exposed in the Desert Queen area. Here, a diorite pluton of presumed Jurassic age intrudes a sequence of Triassic (?) weakly metamorphosed, but moderately altered siltstone, lesser quartzite and conglomerate, and a capping andesitic unit. An erosional surface of moderate relief (i.e., hundreds of meters) is developed on the Mesozoic rocks, above which rests the Oligocene and Miocene sections.

The Tertiary section is a heterogeneous mix of volcanic and sedimentary rocks, with a total of thickness of ~2-3 km. Only middle to late Miocene rocks are exposed, but Oligocene units have been observed in deep wells in the northern Hot Springs Mountains. Although significant lateral variations exist, the Neogene section can be grouped into several discrete packages. In ascending order, these include:

- Late Oligocene ash-flow tuffs, which are not exposed at the surface but are found in several wells in the Brady's and Desert Peak areas;
- A lower Miocene sequence of andesite, dacite, and rhyolite lavas and subordinate rhyolitic to dacitic ash-flow tuffs, ranging from ~16 to 13 Ma;
- A complex section of interfingering late Miocene diatomite, siltstone (commonly tuffaceous), limestone, sandstone, and basalt flows, ranging from ~13 to 10 Ma;
- A sequence of dominantly sedimentary rocks (mainly diatomite and tuffaceous siltstone) and lesser olivine basalt flows, ranging from ~12 to 9 Ma; includes dacite domes and flows to the south and southeast of the Desert Queen area;
- An ~10-9 Ma limestone unit that pinches out eastward and interfingers with the upper part of the underlying sedimentary suites;
- Capping ~9 Ma porphyritic basalt flows in the Desert Peak area;
- A 7.5 Ma aphyric dacitic ash-flow tuff that caps ridges and mesas to the southeast of the Desert Peak and Desert Queen fields;
- Late Miocene to Quaternary basin-fill sediments primarily in the Desert Queen basin and in the eastern Hot Springs Flat basin in the western part of the Brady's area.
- Quaternary sediments dominated by lacustrine deposits of late Pleistocene Lake Lahonton.

Several late Miocene basalt plugs intrude the Tertiary strata mainly in the area between the Desert Peak and Brady fields. Desert Peak itself is composed of a large basalt plug capped by an 8.9 Ma porphyritic basalt flow.

Tephras (i.e., ash-fall deposits) are common in the late Miocene section of the northern Hot Springs Mountains (Stewart and Perkins, 1999) and greatly facilitate detailed dating and correlation of stratigraphic units through geochemical fingerprinting (i.e., tephrochronology; Perkins et al., 2002). The tephras provide critical markers in the numerous fault blocks with which to gauge offset on bounding normal faults. For example, a 9.8 Ma tephra

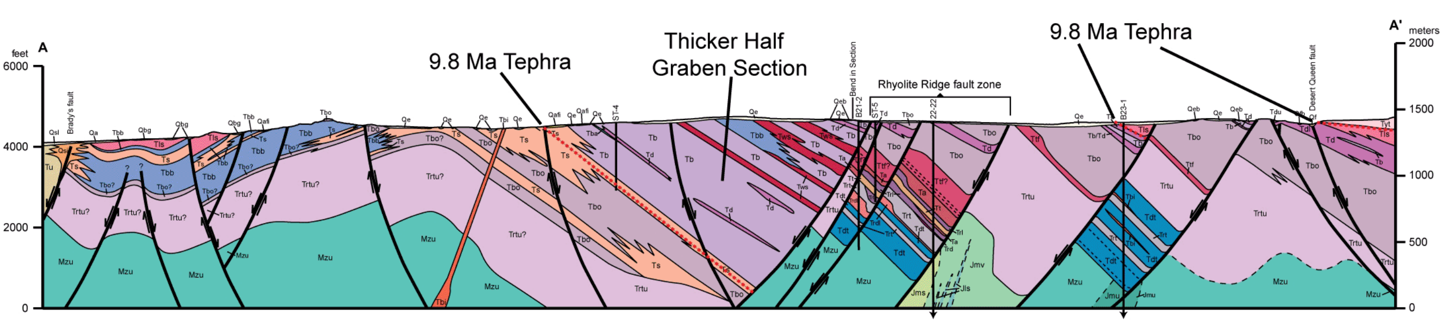

Figure 3. WNW-trending geologic cross section (WNW on left; ESE on right) of the northern Hot Springs Mountains (from Faulds and Garside, 2003). No vertical exaggeration. Note distribution of 9.8 Ma tephra (red dashed line), which serves as an important marker with which to gauge offset on major faults. In ascending order, unit abbreviations: Mzu, Mesozoic basement, undifferentiated; Jmv, Jms, and Jmu-Jurassic metamorphic rocks; Trtu, Oligocene tuffs, undifferentiated; Tdt, Trt, Oligocene ash-flow tuffs; Trdl, Oligo-Miocene rhyolite-dacite lavas; Trl, Oligo-Miocene rhyolite lavas; Trdl; Tt, late Oligocene-early Miocene tuff; Ta, early to middle Miocene andesite-dacite lavas; Ttf, middle Miocene ash-flow tuff; Tbo, older basalt lavas; Tbb, basaltic breccia; Td, diatomite; Ts, lacustrine sediments; Tb, basalt lavas; Tls, limestone, Tyt, 7.5 Ma ash-flow tuff; Qsi, sinter; Qe, eolian deposits; Qfb, Qafi, and Qa-alluvial fan and recent wash deposits; Qsl, Lake Lahonton sediments.

has been correlated across several fault blocks in the Desert Queen area and helps to constrain the magnitude of offset on major faults, such as the Rhyolite Ridge fault zone (Figure 3).

The capping ~7.5 Ma ash-flow tuff is one of the youngest pyroclastic deposits in the region and is the youngest known volcanic deposit in the northern Hot Springs Mountains. This ash-flow tuff forms a resistant cap on the ridges and mesas to the south of the Desert Queen basin and appears to underlie the basin itself, as evidenced by several small exposures along the western margin of the basin. It provides an important marker from which to gauge the magnitude of late Miocene to recent extension.

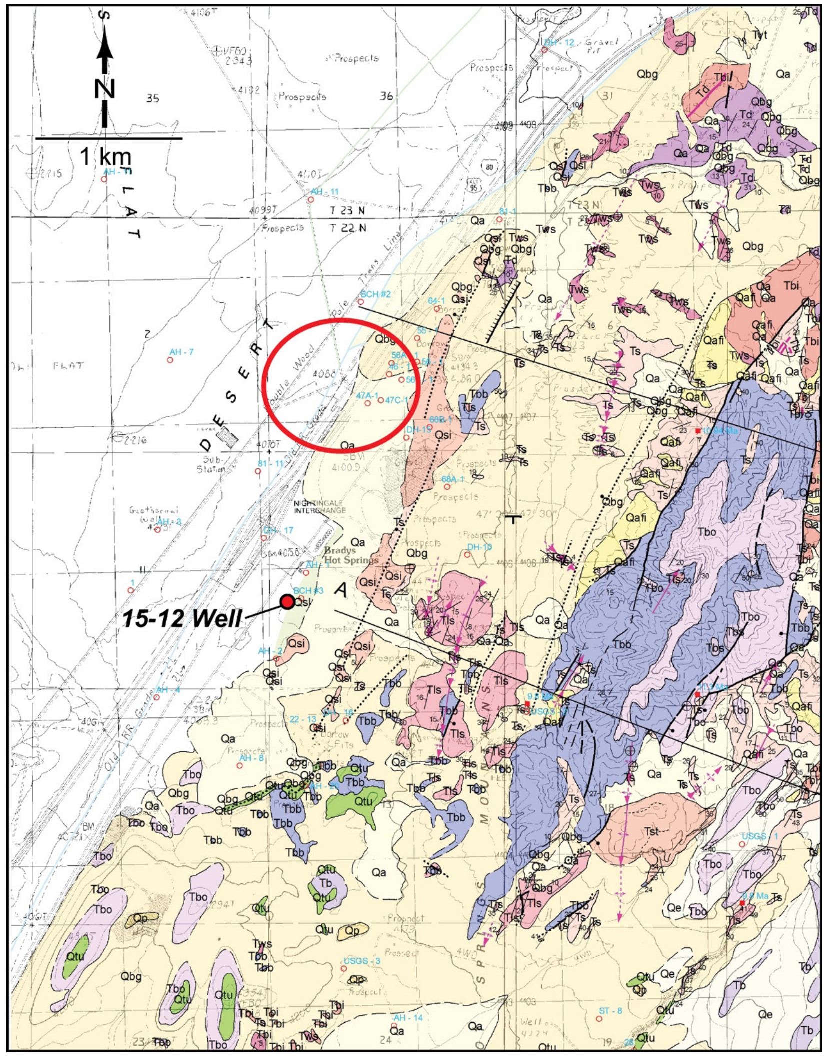

Figure 5. Geologic map of the Brady's geothermal field (modified from Faulds and Garside, 2003). See Faulds and Garside (2003) for description of units. Red circle encompasses area of production wells. These wells appear to tap the down-plunge projection of a small step-over in one strand of the Brady's fault system, although intersecting oppositely dipping normal faults may also channel hydrothermal fluids in the area. Well 15-12 is currently under study for an EGS experiment. Note that cross section A-A' (Figure 3) ends directly east of the well 15-12.

Structural Framework

The Hot Springs Mountains are fragmented into multiple NNE-trending, gently to moderately tilted fault blocks, which are bounded by numerous en echelon, overlapping NNE-striking faults, which dip both WNW and ESE (Benoit et al., 1982; Faulds et al., 2003; Faulds and Garside, 2003). Major faults include 1) the NNE-striking, WNW-dipping Brady's fault zone, which bounds much of the northern Hot Springs Mountains on the northwest and Hot Springs Flat basin on the southeast; 2) NNE-striking, WNW-dipping Rhyolite Ridge fault zone, which appears to terminate northward in the northern Hot Springs Mountains; and 3) NNE-striking, ESE-dipping Desert Queen fault in the eastern part of the northern Hot Springs Mountains (Figure 2). West of Desert Peak, in the hanging wall of the Rhyolite Ridge fault zone, the Miocene section exceeds 2 km in thickness. To the southeast in the footwall of this fault, the Miocene section appears to be thinner (~1 km). A broad NNE-trending horst block lies between the oppositely dipping Rhyolite Ridge and Desert Queen faults.

Figure 4. Exposed fault surface along the Desert Queen fault zone. Fault strikes northerly. Striae, rough facets, and Riedel shears indicate normal-dextral motion (with normal component dominating), followed by late stage dip slip normal movement. Fault surfaces in the area provide an independent means of determining stress directions.

Over 500 bedding-layering attitudes and numerous fault surfaces have been measured in the northern Hot Springs Mountains. The bedding typically dips ~20-45º ESE or WNW and strikes NNE parallel to the faults. Lower parts of the section are, at least locally (e.g. west of Desert Peak), tilted more steeply than upper parts. Kinematic data gleaned from fault surfaces (Figure 4) indicate essentially dip-slip normal displacement on the NNE-striking faults and a WNW-trending extension direction, which is compatible with both the regional extension direction inferred from geodetic data (e.g., Hammond and Thatcher, 2004) and borehole breakout data from wells in the area (Hickman et al., 2010).

The Tertiary strata are also deformed into several north-northeast-trending, gently plunging folds (Hiner, 1979; Faulds and Garside, 2003). In the Desert Peak area, the folds are typically asymmetric with steeper and narrower west-dipping limbs found proximal to major west-dipping normal faults. Fold axes parallel these north-northeast-striking faults. These relations suggest that most folds are coeval with, and genetically related to, the normal faults. The broader east-dipping limbs of the folds are essentially east-tilted fault blocks modified in some areas by roll-over into slightly curved, concave upward west-dipping normal faults. The narrower west-dipping limbs are drag folds along the west-dipping normal faults and ostensibly represent a type of forced fold, similar to that suggested by Benoit (1995).

Major extension began in the northern Hot Springs Mountains at ~13 Ma and has continued at least episodically into the Quaternary. Much of the Miocene section is clearly syntectonic, as evidenced by greater thicknesses in the hanging walls of the major normal faults (Figure 3). Tilt fanning in growth-fault basins suggests that extension began ~13 Ma. The capping 7.5 Ma ash-flow tuff is tilted and faulted much less than underlying units, indicating that the bulk of extension occurred between ~13 and 8 Ma. However, the capping tuff is cut by many faults, suggesting significant extension since 7.5 Ma. Several faults in the area are also marked by Quaternary scarps, including the Brady's fault (Wesnousky et al., 2005).

Brady's Geothermal Field

The Brady's geothermal field 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. An ongoing EGS project is targeting well 15-12 in the southern part of the field (Figure 5).

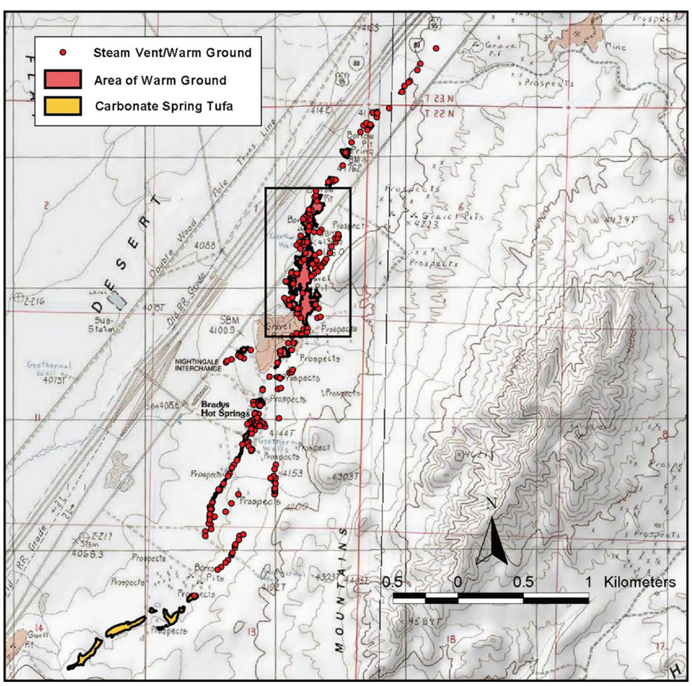

Figure 6. Brady's field, surface geothermal features. The Brady's system is marked by a linear zone of hot springs, fumaroles, warm ground, and sinter along the WNW-dipping, NNE-striking Brady's fault zone. The main production wells are located up to ~1 km to the west of a small left step in the fault zone (encompassed by black box) and presumably penetrate the down-plunge projection of a highly fractured step-over at depth.

The Brady's area is dominated by NNE-trending gently to moderately tilted fault blocks bounded by moderately to steeply dipping normal faults. Faults in the area dip both WNW and ESE and have respectively accommodated both E- and W-tilting of fault blocks. West-tilted fault blocks predominate suggesting that ESE-dipping faults have accommodated the bulk of extension in the area. No major transverse or cross faults have been observed at the surface.

In terms of hydrothermal activity, the most significant fault in the area is the Brady's fault zone, which consists of a complex system of en echelon, primarily WNW-dipping faults. The surface expression of the Brady's geothermal system is a 4-km-long, NNE-trending zone of extensive sinter, warm ground, fumaroles (Figure 6), and mud pots along the Brady's fault system. The gravity anomaly over the Hot Springs Flat basin northwest of the Brady's field (Figure 7) indicates a depth of ~2 km to pre-Tertiary basement, which may imply ~1.0 km of cumulative down-to-the-

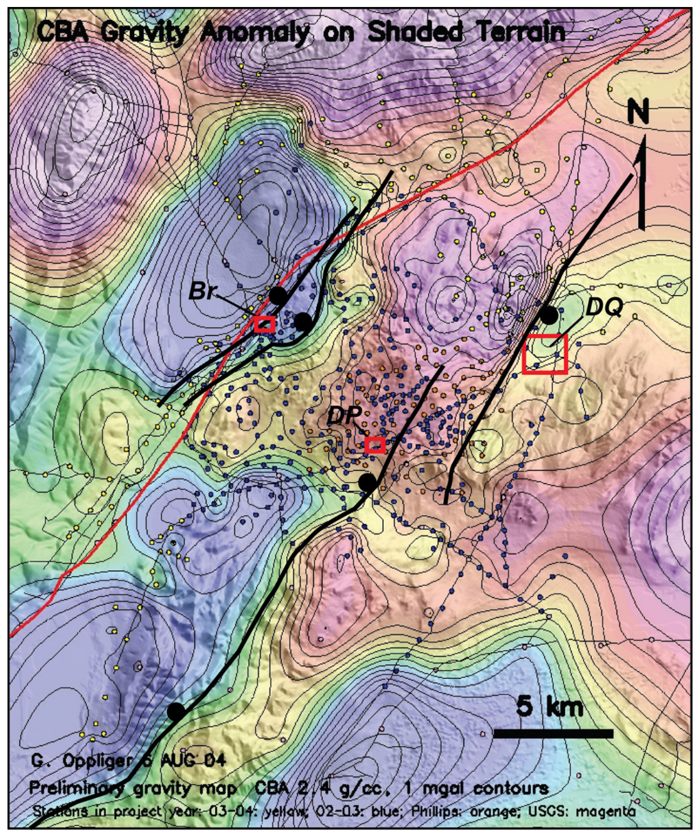

Figure 7. Bouguer gravity shown as color anomalies on a shaded terrain background reduced at a density of 2.4 g/cc and contoured at intervals of 1 mgal . To a first-order, the anomaly approximates the pattern of pre-Tertiary basement depth, although thick sequences of Miocene basalt lavas and basalt intrusions correspond to some of the gravity highs. The lowest anomalies, colored blue, correspond to structural basins with relatively thick sequences of tertiary sediments and volcanics and recent alluvium. These geologic units typically have effective density contrasts with the pre-Tertiary basement in the range of 0.2 to 0.4 g/cc. Pre-Tertiary basement, associated with light pink, is exposed only over a few percent of this map area, i.e., in the extreme north and north-west parts of the map and at Desert Queen. Gravity proved particularly effective in this study for tracing hidden segments of the Brady's, Desert Peak and Desert Queen faults as well as identifying basement cutting normal faulting at the geothermal prospect scale.

west throw across the bounding Brady's fault system, although this estimate is complicated by the WNW tilt of fault blocks in the area. 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 main hot springs at Brady's have been the site of a resort and spa for many years (1930s to 1950s). The main production wells at Brady's appear to penetrate the down-plunge projection of a small left step in a major splay of the Brady's fault zone (Figure 5; Faulds et al., 2006). The NNE-striking Brady's fault zone is orthogonal to the regional WNW-trending extension direction and is thus favorably oriented for fluid flow. We suggest that multiple fault intersections at depth between the WNW-dipping Brady's fault zone and presumably older ESE-dipping faults, as well as multiple fault strands in the step-over, produce a zone of high fracture density that enhances fluid flow and facilitates the rise of a deep-seated thermal plume.

Several problems have confronted geothermal operations in the Brady's field. These include short residence times for fluids between injection and production wells and excessive draw-down in existing wells induced by nearby production. Such problems demonstrate high fluid transmissivity. Known faults, such as the NNE-striking Brady's fault, account for some of this high transmissivity. However, high transmissivity has also been documented across and within the hanging wall of the Brady's fault, suggesting that stratigraphic units or obscure cross faults also channelize fluids. Drilling data from the past 20 years have yet to be integrated into a comprehensive structural model of the field. Thus, detailed geologic and geophysical studies of the northern Hot Springs Mountains together with incorporation of existing subsurface data (Benoit et al., 1982; NBMG well data files) has significant potential for improving conceptual models of the Brady's field and enhancing production in the field utilizing EGS technologies.

Desert Peak Geothermal Field

The geothermal system at Desert Peak, with a reservoir temperature of 207°C, currently fuels a 12.5 MWe geothermal flash plant. The maximum measured temperature at Desert peak is 218 °C (Shevenell and DeRocher, 2005). The Desert Peak system is a blind geothermal system that has no surface hot springs or fumaroles. Silicified late Pleistocene sands crop out ~1.3 km west-southwest of the production wells (Figure 8) and probably resulted from prehistoric outflow from the hydrothermal system into former Lake Lahontan when water tables were higher than today. The Desert Peak system was first identified in a regional temperature gradient drilling program in the 1970s (Benoit et al., 1982). The Desert Peak field has been very successful, utilizing

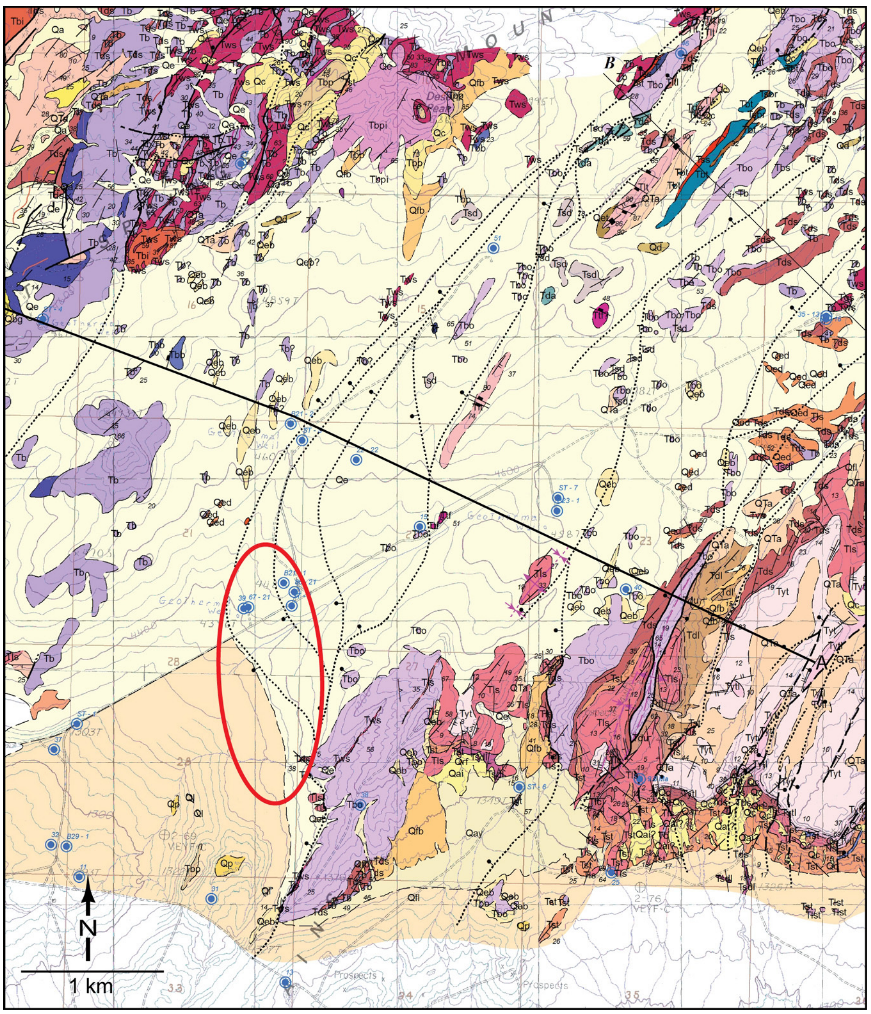

Figure 8. Geologic map of the Desert Peak geothermal field (modified from Faulds and Garside, 2003). See Faulds and Garside (2003) for description of units. Red ellipse encompasses area of production wells. These wells appear to tap the down-plunge projection of a large step-over in the Rhyolite Ridge fault zone. Note that cross section A-A' (Figure 3) projects through the central part of this area.

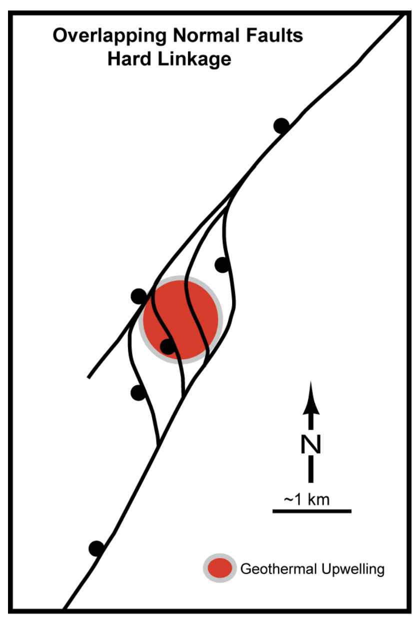

Figure 9. Geothermal wells, Desert Peak. All production wells at the Desert Peak geothermal system occur in a large left step in the NNE-striking Rhyolite Ridge normal fault zone. Stratigraphic relations gleaned from detailed geologic mapping (Figure 8, Faulds and Garside, 2003) and well data indicate that the step-over contains multiple fault strands. Balls shown on downthrown sides of normal faults.

the original two producing wells and one injector well for the first 20 years of its life. A recent drilling program increased production 2 years ago.

The Desert Peak area is dominated by NNE-trending gently to moderately ESE-tilted fault blocks bounded by moderately to steeply WNW-dipping normal faults. The most significant fault in the area is the WNW-dipping Rhyolite Ridge fault zone, which consists of several strands and steps to the left in the vicinity of the geothermal field. Gravity data indicate that displacement on the Rhyolite Ridge fault zone increases southward by as much as 840 m. This is compatible with a progressive southward increase in depth to pre-Tertiary basement noted in wells in the vicinity of the Desert Peak field. NW-trending gravity contours across the Desert Peak field may reflect a relay ramp (Larsen, 1988) associated with southward increasing displacement on the Rhyolite Ridge fault zone. No major transverse or cross faults have been observed in the Desert Peak area. In addition, there appears to be no surface evidence for a horst block in the Desert Peak area. The gravity high in the Desert Peak area appears to be associated with a thick sequence of synextensional late Miocene basalt flows that filled the half graben in the hanging wall of the Rhyolite Ridge fault zone.

The geothermal field at Desert Peak occurs in the major left step in the Rhyolite Ridge fault zone (Figure 8). All production wells occur with this step-over. Multiple fault strands in the step-over (Figure 9) produce a subvertical conduit of high fracture density that probably enhances fluid flow and facilitates the rise of a deep-seated thermal plume. The NNE-striking fault zone is orthogonal to the regional WNW extension direction and is thus favorably oriented for fluid flow.

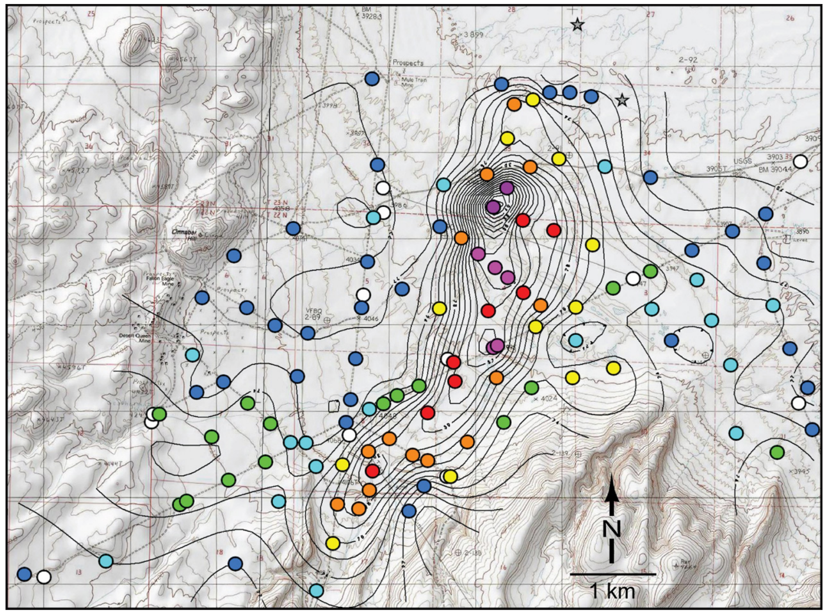

Figure 10. Shallow temperature anomaly at the Desert Queen area as determined from measurements made at a 2-meter depth (Coolbaugh et al., 2007a). Warmer colors + purple represent progressively warmer 2-meter temperatures, as follows: dark purple > 39°C, light purple 33-38.9°C, red 30-32.9°C, orange 27-29.9°C, yellow 25-26.9°C, green 24-24.9°C, light blue 23-23.9°C, dark blue < 23°C. Black contour line interval is 1°C. White circles are temperature gradient holes.

Desert Queen Geothermal Field

The Desert Queen field has not been developed yet, but is currently being explored by Magma Energy Corporation. The Desert Queen system is a blind geothermal system that has no surface hot springs or fumaroles. It was first identified by temperature gradient drilling (Benoit et al., 1982) and is marked by a 6-km-long shallow temperature anomaly with temperatures as high as 42°C at 2 m depth (Coolbaugh et al., 2007a; Figure 10). These shallow temperatures overlie a shallow thermal aquifer at depths of roughly 70 m with temperatures as high as 140°C measured in shallow gradient holes.

The Desert Queen area is dominated by NNE-trending gently to moderately tilted fault blocks bounded by moderately to steeply dipping normal faults (Figure 11). Most of the faults accommodated relatively minor offset (i.e., hundreds of meters or less), but the east-dipping Desert Queen fault zone accommodated 2-3 km of normal displacement. West-tilted fault blocks dominate the northern part of the area within and marginal to the Desert Queen basin, whereas both east and west tilts occur to the south of the basin (Figure 11). A few NNE-striking faults appear to cut late Pleistocene shoreline deposits of Lake Lahonton in the Desert Queen basin. No major transverse or cross faults were observed.

A major, NNE-striking, ESE-dipping normal fault zone bounds the west side of the Desert Queen basin (Figure 11) and is here

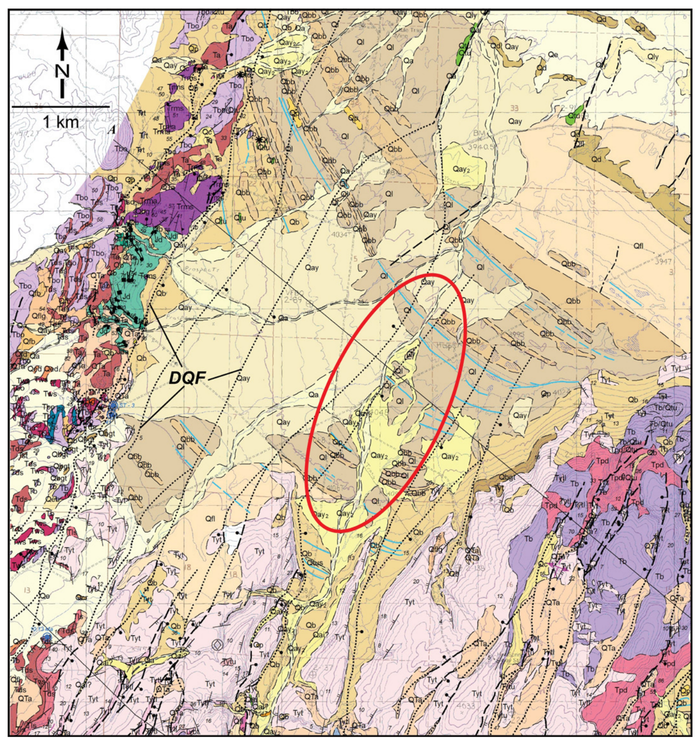

Figure 11. Geologic map of the Desert Queen geothermal field (mainly from Faulds and Green, unpublished map). See Faulds and Garside (2003) for description of bedrock units. Red ellipse encompasses area of shallow temperature anomaly (Figure 10). The Desert Queen geothermal field may be associated with the horse-tailing southern part of the Desert Queen fault zone (DQF) as it loses displacement southward. Note that cross section lines shown on this map are not the same as that in Figure 3.

referred to as the Desert Queen fault zone. This fault zone consists of at least four major strands, including one strand west of the mountain front, one at the mountain front, and two poorly exposed strands east of the mountain front. The eastern two strands are obscured by a thin veneer of Lake Lahontan gravels, which largely cover a bedrock pediment extending eastward from the mountain front. Collectively, the major strands accommodated >2.5 km of down-to-the-east displacement in the vicinity of the Desert Queen Mine. This fault zone loses significant displacement southward and nearly terminates. It has <200 m of offset 4 km south of the Desert Queen basin.

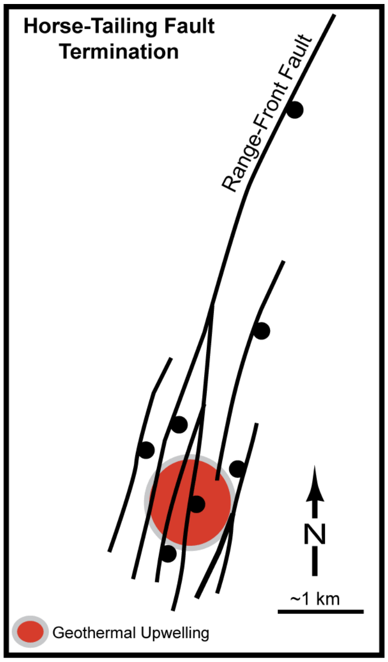

Figure 12. Schematic termination of a major normal fault, whereby faults break up into multiple splays or horsetail. Closely-spaced faults in such areas generate a broad, steeply dipping zone of high fracture density and high permeability, which facilitates the rise of geothermal fluids.

The geothermal field occurs near the southern end of the Desert Queen basin near where the Desert Queen fault zone loses significant displacement toward the south. As this fault zone terminates southward, it breaks into multiple splays. We suggest that higher fracture density associated with the horse-tailing end of the fault (Figure 12) may provide a channel way for the hydrothermal fluids. In addition, a major antithetic fault zone appears to intersect multiple splays of the southward terminating Desert Queen fault, which may also facilitate fluid flow in the southern part of the basin.

Discussion and Conclusions

Optimum permeability in the Great Basin primarily requires a favorable structural environment involving high fracture density. It would appear that fault zones are far more important in hosting geothermal reservoirs within this active transtensional to extensional setting than are specific stratigraphic horizons. The trick is determining which parts of normal fault systems contain the highest fracture density and are oriented favorably to accommodate dilation and/or shear. As demonstrated in the Hot Springs Mountains, irregularities in normal fault zones (e.g., steps), lateral terminations of major normal faults, and intersections between oppositely dipping fault zones all provide adequate hosts for geothermal reservoirs.

The proximity of three independent, large geothermal systems in the northern Hot Springs Mountains demonstrates the high potential for geothermal development within the northwestern Great Basin. The fact that two of these three systems are blind implies even greater potential for discovering hidden systems elsewhere in the region. All fault zones have lateral terminations, and most contain major irregularities and/or intersections with other faults. This begs the question as to whether most fault zones in the northwestern Great Basin actually host viable, albeit commonly hidden, geothermal resources. If so, the geothermal potential of the region may be grossly underestimated.

To fully realize the geothermal potential of the region, including discovery and exploitation of new systems (e.g., Desert Queen) and optimal utilization of mature fields (e.g., Brady's and Desert Peak) necessitates a detailed 3D understanding of the complex fault systems and their impacts on channeling fluids. Three-dimensional geological modeling in these areas requires integration of all detailed surface, well, and geophysical data available. For the Brady's EGS site, we are therefore synthesizing detailed geological field mapping, fault plane analysis, stress inversion, 3D structural geological modeling, and stress modeling to contribute to EGS development (Faulds et al., 2010). Our integration of detailed field studies, stress modeling, and 3D structural modeling (e.g., Moeck et al., this volume) may be valuable for geothermal development wherever cost-effective exploration strategies are needed.

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References Cited

Benoit, D., 1995, Forced folding and Basin and Range geothermal systems: Geothermal Resources Council Transactions, v. 19, p. 155-163.

Benoit, W.R., Hiner, J.E., and Forest, R.T., 1982, Discovery and geology of the Desert Peak geothermal field: A case history: Nevada Bureau of Mines and Geology Bulletin 97, 82 p.

Blackwell, D.D., Leidig, M., and Smith, R.P., and Johnson, S.D., 2002, Exploration and development techniques for Basin and Range geothermal systems: Examples from Dixie Valley, Nevada: Transactions Geothermal Resource Council, v. 26, p. 513-518.

Blackwell, D.D., and Richards, M., 2004, Geothermal Map of North America: American Association of Petroleum Geologists, scale 1:6,500,000.

Colgan, J.P., Dumitru, T.A., and Miller, E.L., 2004, Diachroneity of Basin and Range extension and Yellowstone hotspot volcanism in northwestern Nevada: Geology, v. 32, p. 121-124.

Coolbaugh, M.F., Taranik, J.V., Raines, G.L., Shevenell, L.A., Sawatzky, D.L., Minor, T.B., and Bedell, R., 2002, A geothermal GIS for Nevada: defining regional controls and favorable exploration terrains for extensional geothermal systems; Proceedings, Annual Meeting, Reno, NV., Sept. 22-25, 2002, Geothermal Resources Council Transactions, v. 26, p. 485-490.

Coolbaugh, M.F. and Shevenell, L.A., 2004, A method for estimating undiscovered geothermal resources in Nevada and the Great Basin: Geothermal Resources Council Transactions, v. 28, p. 13-18.

Coolbaugh, M.F., Sladek, C., Faulds, J.E., Zehner, R.E., and Oppliger, G.L., 2007a, Use of rapid temperature measurements at a 2-meter depth to augment deeper temperature gradient drilling: Proceedings, 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan. 22-24, 2007, p. 109-116.

Coolbaugh, M.F., Raines, G.L., and Zehner, R.E., 2007b, Assessment of exploration bias in data-driven predictive models and the estimation of undiscovered resources: Natural Resources Research, v. 16, n. 2, p. 199-207.

Faulds, J.E., and Garside, L.J., 2003, Preliminary geologic map of the Desert Peak – Brady geothermal fields, Churchill County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 03-27.

Faulds, J.E., Garside, L.J., and Oppliger, G., 2003, Structural analysis of the Desert Peak-Brady geothermal fields, northwest Nevada: Implications for understanding links between northeast-trending structures and geothermal reservoirs in the Humboldt structural zone: Geothermal Resources Council Transactions, v. 27, p. 859-864.

Faulds, J.E., Coolbaugh, M., Blewitt, G., and Henry, C.D., 2004, Why is Nevada in hot water? Structural controls and tectonic model of geothermal systems in the northwestern Great Basin: Geothermal Resources Council Transactions, p. 649-654.

Faulds, J.E., Henry, C.D., Coolbaugh, M.F., and Garside, L.J., 2005, Influence of the late Cenozoic strain field and tectonic setting on geothermal activity and mineralization in the northwestern Great Basin: Geothermal Resources Council Transactions, v. 29, p. 353-358.

Faulds, J.E., Coolbaugh, M.F., Vice, G.S., and Edwards, M.L., 2006, Characterizing Structural Controls of Geothermal Fields in the Northwestern Great Basin: A Progress Report: Geothermal Resources Council Transactions, v. 30, p. 69-76.

Faulds, J.E. and Melosh, G., 2008, A Preliminary Structural Model for the Blue Mountain Geothermal Field, Humboldt County, Nevada: Geothermal Resources Council Transactions, v. 32, p. 273-278.

Faulds, J.E., and Henry, C.D., 2008, Tectonic influences on the spatial and temporal evolution of the Walker Lane: An incipient transform fault along the evolving Pacific – North American plate boundary, *in* Spencer, J.E., and Titley, S.R., eds., Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits: Tucson, Arizona Geological Society, Digest 22, p. 437-470.

Faulds, J., Moeck, I., Drakos, P., and Zemach, E., 2010, Structural assessment and 3D geological modeling of the Brady's geothermal area, Churchill County (Nevada, USA): Proceedings, Thirty-Fifth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 1-3, 2010 SGP-TR-188, 5 p.

Hammond, W.C., and Thatcher, W., 2004, Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the Global Positioning System: Journal of Geophysical Research, v. 109, B08403, doi: 10.1029/2003JB002746.

Hickman, S.H., and Davatzes, N.C., 2010, In-situ stress and fracture characterization for planning of an EGS stimulation in the Desert Peak geothermal field, Nevada: PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 1-3, 2010, SGP-TR-188.

Hiner, J.E., 1979, Geology of the Desert Peak geothermal anomaly—Churchill County, Nevada [M.S. thesis]: University of Nevada, Reno.

Johnson, S.D., and Hulen, J.B., 2002, Subsurface stratigraphy, structure, and alteration in the Senator thermal area, northern Dixie Valley geothermal field, Nevada: Transactions Geothermal Resource Council, v. 26, p. 533-542.

Larsen, P.H., 1988, Relay structures in a Lower Permian basement-involved extensional system, East Greenland: Journal of Structural Geology, v. 10, p. 3-8.

Perkins, M.E., and Nash, B.P., 2002, Explosive silicic volcanism of the Yellowstone hotspot: The ash fall tuff record: Geological Society of America Bulletin, v. 114, no. 3, p. 367-381.

Shevenell, L. and De Rocher, T., 2005, Evaluation of chemical geothermometers for calculating reservoir temperatures at Nevada geothermal power plants: Geothermal Resources Council Transactions, v. 29, p. 303-308.

Stewart, J.H., and Perkins, M.E., 1999, Stratigraphy, tephrochronology, and structure of part of the Miocene Truckee Formation in the Trinity Range-Hot Springs Mountains area, Churchill County, east-central Nevada: USGS Open-File Report 99-330, 23 p.

Surpless, B.E., Stockli, D.F., Dumitru, T.A., and Miller, E.L., 2002, Two-phase westward encroachment of Basin and Range extension into the northern Sierra Nevada: Tectonics, v. 21, no. 1, p. 2-1 to 2-13.

Vice, G.S., Faulds, J.E., Ehni, W.J., and Coolbaugh, M.F., 2007, Structural controls of a blind geothermal system in the northern Pyramid Lake area, northwestern Nevada: Geothermal Resources Council Transactions, v. 31, p. 133-137.

Wesnousky, S.G., Barron, A.D., Briggs, R.W., Caskey, J., Kumar, S., and Owen, L., 2005, Paleoseismic transect across the northern Great Basin: Journal of Geophysical Research, v. 110, B05408, doi:10.1029/2004JB003283.

Williams, C.F., Reed, M.J., DeAngelo, J., and Galanis, S.P. Jr., 2009, Quantifying the undiscovered geothermal resources of the United States: Geothermal Resources Council Transactions, v. 33, p. 995-1002.