Characterizing Structural Controls of Geothermal Fields in the Northwestern Great Basin: A Progress Report

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ABSTRACT

Considering a lack of recent volcanism, the abundant geothermal activity in the northwestern Great Basin is somewhat anomalous. The prolific activity may result from enhanced dilation on N- to NNE-striking normal faults induced by a transfer of NW-directed dextral shear from the Walker Lane to NW-directed extension in the Great Basin. Although faults control most geothermal activity in the Great Basin, few detailed investigations have been conducted on the specific structural controls of individual fields. Because knowledge of such structures would facilitate exploration models, we have embarked upon a regional study of the controls on geothermal activity, which includes detailed analysis of several fields, reconnaissance studies of many other fields, and compilation of existing data. Our findings from the Bradys, Desert Peak, Needle Rocks, Salt Wells, and Gerlach geothermal systems suggest that many fields occupy discrete steps in fault zones or lie in belts of intersecting, overlapping, and/or terminating faults. In addition, most fields are associated with steeply dipping faults and, in many cases, with Quaternary faults. The structural settings favoring geothermal activity all involve subvertical conduits of highly fractured rock along fault zones oriented approximately perpendicular to the least principal stress. Features indicative of these settings that may be helpful in guiding exploration 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.

Introduction

Although volcanism generally ceased 3 to 10 Ma, the northwestern Great Basin contains abundant geothermal fields, many with subsurface temperatures approaching or exceeding 200°C. The fields are particularly abundant in northern Nevada and neighboring parts of northeast California and southern Oregon (Coolbaugh et al., 2002; Coolbaugh and Shevenell, 2004; Figure 1, overleaf). 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 source for most of the geothermal activity in this region. What accounts for the prolific geothermal activity in this region is therefore a major question.

On a grand scale, an unusual tectonic setting may facilitate much of the geothermal activity in the northwestern Great Basin. Here, a system of right-lateral strike-slip faults known as the Walker Lane (Stewart, 1988; Oldow, 1992; Faulds et al., 2005a) accommodates ~15-25% of the dextral motion between the Pacific and North American plates (Bennett et al., 2003; Hammond and Thatcher, 2004). Relatively high rates of recent (<10 Ma) WNW-directed extension (Henry and Perkins, 2001; Surpless et al., 2002; Colgan et al., 2004) absorb northwestward declining dextral motion in the Walker Lane, diffusing that motion into the Basin-Range. Abundant geothermal fields cluster in NE-trending belts in the northern Great Basin orthogonal to the extension direction (Figure 1). The Walker Lane begins losing displacement to the northwest in west-central Nevada near the southeast margin of the region with abundant geothermal activity. Individual fields appear to be largely controlled by NNE-striking normal faults (Blackwell et al., 2002; Johnson and Hulen, 2002; Waibel et al., 2003; Faulds et al., 2003, 2004). The prolific geothermal activity may therefore result from a transfer of NW-trending dextral shear in the Walker Lane to WNW extension in the northern Great Basin. Enhanced extension favors dilation and deep circulation of aqueous solutions along NNE-striking faults. The individual belts of geothermal fields may reflect loci of strain transfer (Faulds et al., 2004).

Despite mounting evidence suggesting that faults control most geothermal activity in the Great Basin, few detailed in-

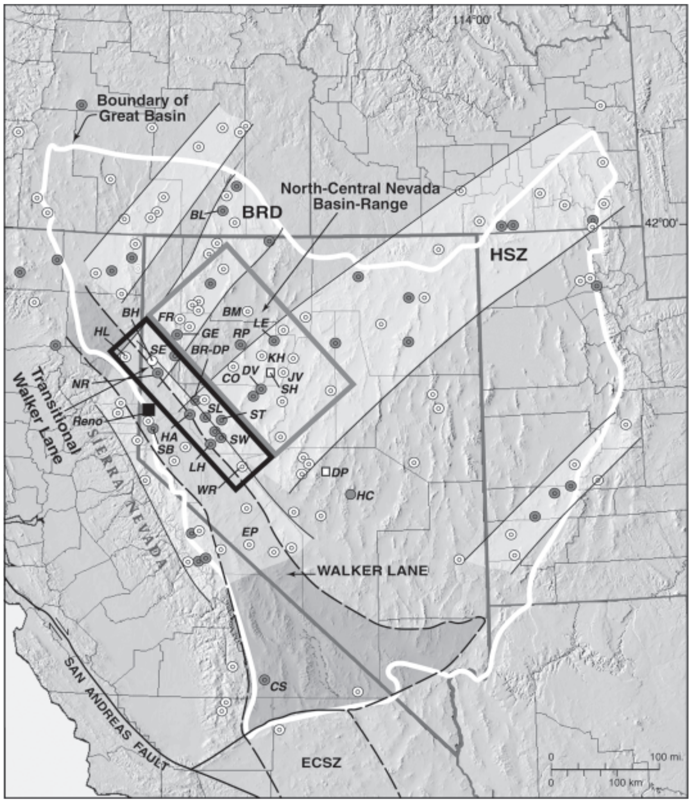

Figure 1. The northwestern Great Basin has the greatest concentration of geothermal fields in the western US. Gray circles have maximum temperatures >160°C; white circles are systems with maximum temperatures of 100-160°C; white squares are lower temperature systems briefly discussed in text. BRD, Black Rock Desert geothermal belt; ECSZ, eastern California shear zone; HSZ, Humboldt structural zone. Abbreviations for individual fields: BH, Bonham Ranch; BL, Borax Lake; BM, Blue Mountain; BR-DP, Brady-Desert Peak; CO, Colado; CS, Coso Range; DP, Diana's Punchbowl; DV, Dixie Valley; EP, Emigrant prospect, Fish Lake Valley; FR, Fly Ranch; GE, Gerlach; HL, Honey Lake; HA, Hazen; HC, Hot Creek; JV, Jersey Valley; KH, Kyle Hot Springs; LE, Leach Hot Springs; LH, Lee Hot Springs; NR, Needle Rocks; RP, Rye Patch; SB, Steamboat; SE, San Emidio; SH, Sou Hills; SL, Soda Lake; ST, Stillwater; SW, Salt Wells; WR, Wedell-Rawhide.

vestigations have been conducted on the specific controls of individual fields. Whether certain structures are particularly conducive for geothermal activity is therefore not known. 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. We have therefore embarked upon a regional study of the controls on geothermal activity in the northwestern Great Basin, which includes detailed analysis of several fields, reconnaissance studies of many other fields, and compilation of existing data. In this paper, we report initial findings for several fields and describe several structural settings that appear to favor geothermal activity.

Approach

To facilitate characterization of structural controls, we have focused on representative fields in two regions of the northern Great Basin (Figure 1). The first region lies within or directly adjacent to the Walker Lane and is termed "transitional Walker Lane". This transtensional setting contains both NW-striking right-lateral faults and northerly striking normal faults. Fields within the transitional Walker Lane include Lee Hot Springs, Salt Wells, Wedell/Rawhide, Stillwater, Soda Lake, Hazen (Patua Hot Springs), Desert Peak, Bradys, Needle Rocks at Pyramid Lake, Bonham Ranch, and Honey Lake. Only a few fields in this region (e.g. Desert Peak, Bradys, and Soda Lake) have been analyzed in detail (Benoit et al., 1982; McNitt, 1990; Faulds et al., 2003).

The second region is situated fully within the Basin and Range to the northeast of the Walker Lane in north-central Nevada and is referred to as the "north-central Great Basin". Here, NNE-striking normal faults dominate most areas but locally link with ENE-striking oblique-slip faults (left-lateral and normal components) in the Humboldt structural zone (Rowan and Wetlaufer, 1981; Faulds et al., 2003). Fields within this region include Gerlach, San Emidio, Fly Ranch, Blue Mountain, Kyle Hot Springs, Jersey Valley Hot Springs, Colado, Rye Patch, and Dixie Valley (Figure 1). Similar to the transitional Walker Lane, few fields (e.g. Dixie Valley and Rye Patch) have been studied in detail in the north-central Great Basin (e.g. Caskey and Wesnousky, 2000; Blackwell et al., 2002; Johnson and Hulen, 2002; Waibel et al., 2003; Schweickert et al., 2006).

Structural Controls

Regional assessments of structural controls show that N- to NE-striking faults (N0°E-N60°E) are the primary controlling structure for ~75% of geothermal fields in Nevada, and this control is strongest for higher temperature systems (Coolbaugh et al., 2002; Faulds et al., 2004). In the northwestern Great Basin, where the extension direction trends WNW, controlling faults generally strike NNE, approximately orthogonal to the extension direction. Other important structural trends include NW-striking faults in the Walker Lane and Black Rock Desert regions and ENE-striking faults in the Humboldt structural zone.

A closer look at individual fields reveals that the controlling NNE-striking structures are typically 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), Bradys, and Desert Peak fields (Benoit et al., 1982; Faulds et al., 2003). However, most fields in the north-central Great Basin occur along or near major range-front faults, whereas fields in the transitional Walker Lane are typically situated along less prominent and, in some cases, somewhat innocuous normal fault zones. In the following sections, we report site-specific findings from five fields currently under study.

Desert Peak and Bradys

The Desert Peak and Bradys fields lie within the transitional Walker Lane in the northern Hot Springs Mountains ~80 km east-northeast of Reno (Figure 1). The geothermal system at Bradys Hot Springs has an estimated reservoir temperature of 181°C (Shevenell and DeRocher, 2005) and supports a combined flash and binary geothermal power plant with a total electrical generation capacity of 26.1 MWe. The surface expression of the Bradys geothermal system is a 4-km-long, NNE-trending zone of warm ground, fumaroles, and mud pots along the Bradys fault. The geothermal system at Desert Peak, with a reservoir temperature of 218°C (Shevenell and DeRocher, 2005), currently fuels a 12.5 MWe geothermal flash plant. The lack of a temperature/pressure drawdown over the last 20 years of production suggests that the Desert Peak system can support a higher rate of energy production, and a new 11 MWe binary power plant is under construction (Nevada Division of Minerals April 2006 Geothermal Update).

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 strata are cut by NNE-striking en echelon normal faults and deformed into a series of NNE-trending, moderately tilted fault blocks (Benoit et al., 1982; Faulds et al., 2003; Faulds and Garside, 2003). Kinematic data indicate essentially dip-slip normal displacement on the NNE-striking faults. Tilt fanning in the Miocene section, new $^{40}Ar/^{39}Ar$ dates, and tephrochronologic correlations bracket the major episode of extension between ~13 and 9 Ma. However, fault scarps indicate significant Quaternary extension in the area. The Miocene strata are also deformed into several NNE-trending folds. Some of these folds have been previously attributed to left-lateral faulting (Stewart and Perkins, 1999). However, the folds parallel major normal faults and are interpreted as extensional in origin, resulting from either fault-propagation folding (essentially fault drag) or reversals in the tilt direction of fault blocks.

Both geothermal fields occupy left steps or small stepovers in the en echelon, steeply dipping NNE-striking normal fault zones (Faulds et al., 2006; Figure 2)). The Bradys field lies along the Bradys fault zone, whereas the Desert Peak field occurs along the Rhyolite Ridge fault zone. Displacement on these faults is generally less than ~2 km. At least one segment of the Bradys fault has accommodated Quaternary normal displacement (Trevor and Wesnousky, 2001). Multiple fault strands in the stepovers provide subvertical conduits of high fracture density that probably enhance fluid flow and facilitate the rise of deep-seated thermal plumes. The NNE-striking faults are orthogonal to the regional WNW extension direction and are thus favorably oriented for fluid flow.

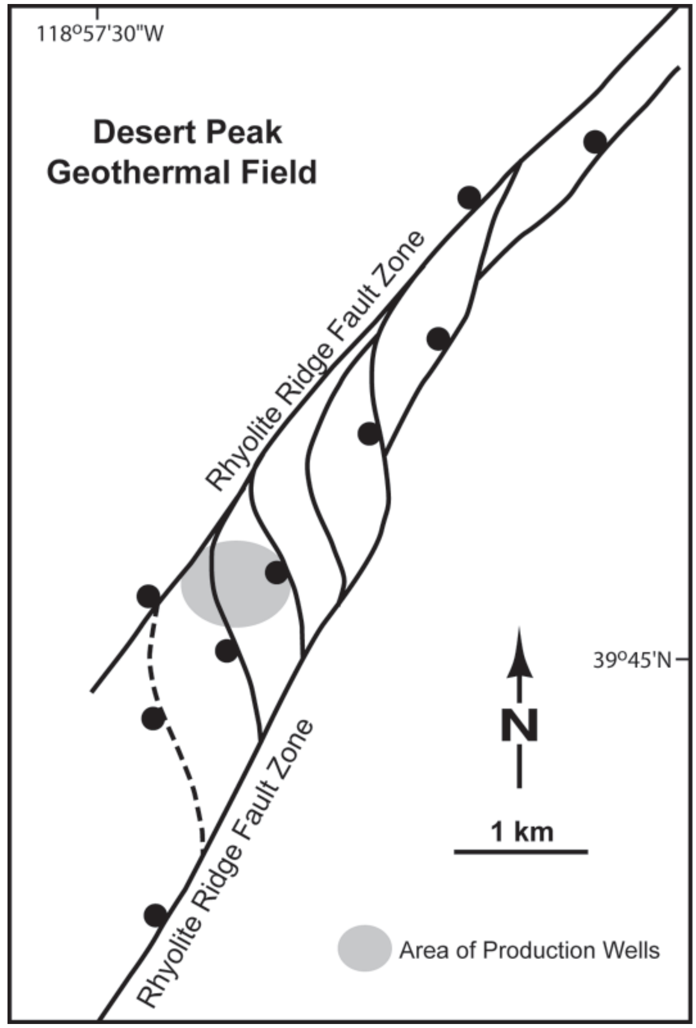

Figure 2. Structural map of the Desert Peak geothermal field (from Faulds and Garside, 2003). Production wells occur within a left step of the Rhyolite Ridge fault zone, where multiple fault strands connect the major overlapping fault segments. The faults shown with solid lines are defined by offset strata and/or well logs. Balls are shown on downthrown sides of normal faults. More detail is shown for the Desert Peak field (as compared to others discussed in this paper), because detailed geologic mapping and compilation of well data has been completed in this area. Numerous wells in the Hot Springs Mountains also facilitate more comprehensive subsurface interpretations as compared to most other geothermal fields within the Great Basin.

Needle Rocks

The Needle Rocks field occurs near the northwest shore of Pyramid Lake within the transitional Walker Lane ~70 km north-northeast of Reno (Figure 1). Two NW-trending belts of carbonate tufa towers (>2 km long and up to 90 m high) mark the Needle Rocks geothermal system. Several hot springs have temperatures as high as boiling. Geothermal wells drilled during the 1960s encountered water temperatures up to 117°C, and one well continues to spout boiling water. Geothermometry suggests reservoir temperatures of 143°C based on the quartz (no boiling) geothermometer and 213°C using the Na-K-Ca-Mg geothermometer (Mariner et al., 1974, 1975; Grose and Keller, 1975).

The Pyramid Lake area contains thick sequences (1-2 km) of mainly mafic middle Miocene volcanic rocks intercalated with thin lenses of sedimentary rock. In the vicinity of Needle Rocks, the Miocene section generally overlies Mesozoic granitic-metamorphic basement. NW-striking dextral faults and northerly striking normal faults dissect the Pyramid Lake area into a series of gently to moderately (~15-40°) E-tilted fault blocks. Most of the extension in the area postdates deposition of middle Miocene (~15-13 Ma) mafic lavas of the Pyramid Sequence, whereas strike-slip faulting probably began between ~9 and 3 Ma (Faulds et al., 2005a; 2005b; Henry et al., 2006).

Many faults in the area have Quaternary scarps (e.g. Bell, 1984; Briggs and Wesnousky, 2004).

The NW-striking right-lateral Pyramid Lake fault, which is one of the major strike-slip faults within the northern Walker Lane, terminates northwestward in the Pyramid Lake area. As much as 10 km of dextral slip along the Pyramid Lake fault appears to be transferred to normal slip along major northerly striking normal faults in the Pyramid Lake area, including range-front faults along the west flanks of the Nightingale Mountains and Lake Range (Faulds et al., 2005b). A major NW-striking right-lateral fault has not been identified to the north of Pyramid Lake. However, a series of steeply dipping NW-striking faults cut the Terraced Hills to the northwest of Pyramid Lake. Initial analysis of these faults suggests that they have accommodated components of both normal and dextral displacement. We interpret this fault system as the horse-tailing northwest end of the Pyramid Lake fault (Figure 3), whereby dextral slip along the Pyramid Lake fault is progressively transferred to N- to NNE-striking normal faults in the Smoke Creek Desert region to the north. Increased dilation induced by this strain transfer, combined with the close spacing of faults and/or intersecting faults, may have induced the geothermal activity in the Needle Rocks area.

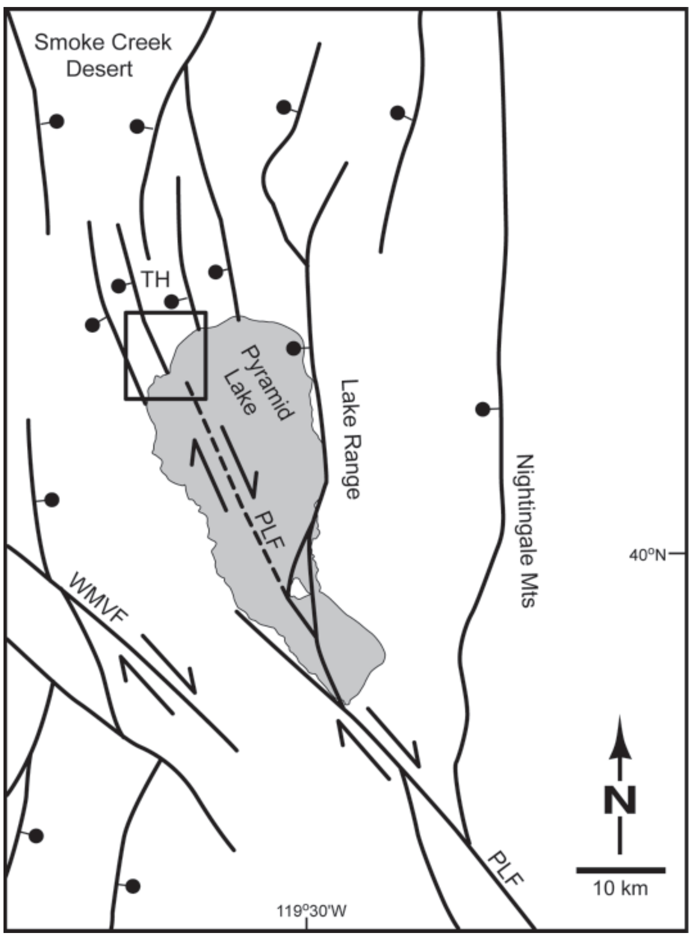

Figure 3. Generalized structural map of the Pyramid Lake area. Box roughly outlines the Needle Rocks geothermal field, which appears to lie within the horse-tailing northern end of the right-lateral Pyramid Lake fault. Dextral slip on the Pyramid Lake fault diffuses northward into northerly striking range-front faults along the west flanks of the Lake Range and Nightingale Mountains and oblique-slip (dextral-normal) NNW-striking faults in the Terraced Hills. PLF, Pyramid Lake fault; TH, Terraced Hills; WMVF, Warm Springs Valley fault

Salt Wells

The Salt Wells geothermal field occupies the west-southwest margin of the Salt Wells basin ~20 km southeast of Fallon, Nevada, along the east flank of the Bunejug Mountains and north edge of the Cocoon Mountains (Figure 1). This area lies near the intersection of the Walker Lane and central Nevada seismic belt. Temperature gradient drilling has defined a large, 12-km-long heat flow anomaly at the Salt Wells geothermal system (Edmiston and Benoit, 1984). Amp Resources, LLC, are currently constructing a 10 MWe binary power plant that will develop a shallow geothermal reservoir with an estimated temperature of ~140°C. Geothermometry suggests that a deeper reservoir may exist at temperatures of 180-190°C.

The stratigraphy of the Bunejug and northern Cocoon Mountains consists of a thick sequence of middle to late Miocene basalt lavas (~13 to 8 Ma) and minor amounts of interbedded volcaniclastic sandstone, conglomerate, and siltstone. Available well data suggest that the basalt exceeds 400 m in thickness. Regional relationships indicate that the basalt overlies Oligocene (~30 to 25 million years old) ash-flow tuffs and/or Mesozoic granitic and metamorphic basement. The basalts are overlain by Quaternary alluvial fans and lacustrine deposits associated with Pleistocene Lake Lahontan.

Gently tilted fault blocks and steeply dipping northerly striking normal fault zones characterize the structural framework of the area. Most of the fault blocks are tilted gently eastward (<30°), but one small block in the southeastern Bunejug Mountains exhibits gentle westward tilts. On the basis of the predominant east-side-down tilts, major faults in the Bunejug and Cocoon Mountains are inferred to dip steeply westward. In contrast, a major northerly striking fault zone along the east flank of the Bunejug Mountains and west side of the Salt Wells basin (here referred to as the Salt Wells fault zone) dips steeply eastward, as evidenced by unpublished gravity data and several scarps cutting Lake Lahontan silicified sand deposits. Several segments of this fault zone have northwest strikes. It is possible that a major northwest-striking splay continues to the southeast of the geothermal field along the northeast flank of the Cocoon Mountains (Figure 4).

Much of the Salt Wells fault zone is obscured by the effects of shoreline processes and eolian deposition, but a north-striking, left-stepping fault zone is nonetheless indicated by wave-modified fault scarps, tilted Quaternary deposits, fault brecciation, and silica deposition. Offset of both playa muds and silicified Lahontan sands indicates some Holocene offset on the Salt Wells fault zone. The fault zone has down-to-the-east vertical displacement, but the linearity of individual traces and left-stepping pattern of the zone suggest it also has a right-lateral component, similar to the 1954 earthquake ruptures along the east flank of Rainbow Mountain 15 km to the north (Caskey et al., 2004). This E-dipping fault zone appears to die out southward and break into several splays (i.e., horse-tailing) in the southern part of the Salt Wells basin, as evidenced by multiple subparallel fault scarps.

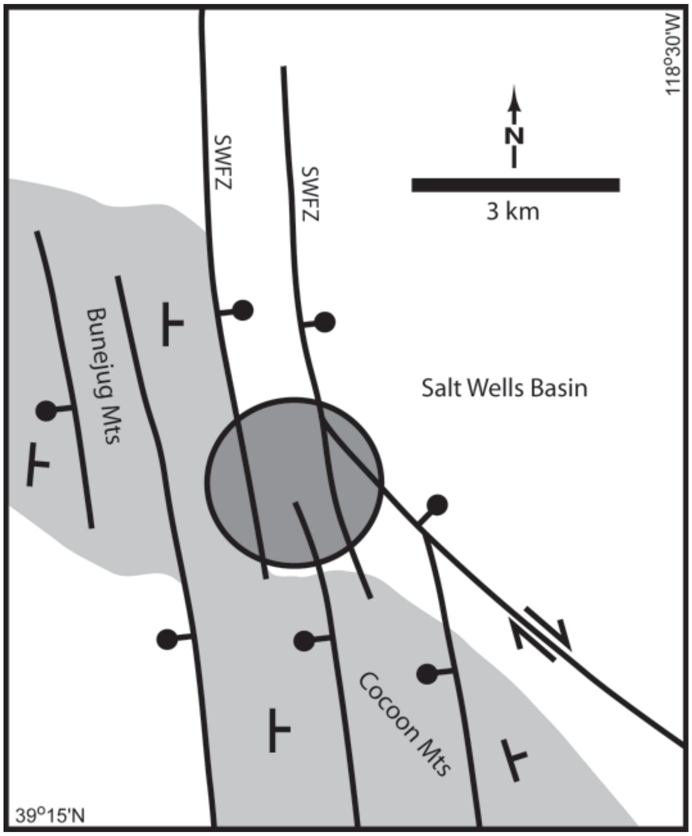

Figure 4. Generalized structural map of the Salt Wells area. Shaded circle roughly outlines the locus of the geothermal field. Lightly shaded area denotes the Bunejug and Cocoon Mountains. The geothermal field occurs near the apparent southern end of the east-dipping Salt Wells fault zone (SWFZ), where it probably overlaps and intermeshes with a west-dipping fault system that bounds east-tilted fault blocks in the Cocoon and Bunejug Mountains. In addition, the SWFZ may intersect a northwest-striking dextral-normal (?) fault that bounds the northeast flank of the Cocoon Mountains, generating a small pull-apart in the western part of the Salt Wells basin. Bar-and-balls are shown on downthrown sides of normal and oblique-slip faults.

The Salt Wells geothermal field appears to be localized along the steeply E-dipping Salt Wells fault zone as it loses displacement southward and possibly intermeshes with a W-dipping fault system emanating from the Cocoon Mountains (Figure 4). The increased fracture density generated by the multiple intersecting faults probably produced greater permeability in the area, which has in turn provided convenient channelways for the geothermal fluids. The steeply dipping geometry of the faults suggests subvertical conduits of highly fractured bedrock. Dilation in the Salt Wells geothermal field may be further enhanced by the merging of part of the Salt Wells fault zone into a right-lateral, NW-striking fault along the northeast flank of the Cocoon Mountains, as this geometry would generate a small pull-apart in the southwest corner of the Salt Wells basin (Figure 4).

Gerlach

The Gerlach geothermal field lies within the north-central Great Basin directly east of the southern end of the Granite Range on the northwest side of Gerlach, Nevada (Figure 1; Keller and Grose, 1978). Boiling springs, mud pots, and siliceous sinter mark the Gerlach Hot Springs. The quartz and K-Na-Ca-Mg geothermometers indicate a possible reservoir temperature for geothermal fluids of ~160-200°C, which is consistent with the occurrence of siliceous sinter at the springs. The stratigraphy of the Gerlach area consists of middle to late Tertiary volcanic and sedimentary rocks that rest directly on Mesozoic granitic and Permian-Triassic metamorphic basement. Just to the west of Gerlach along the southwest flank of the Granite Range, the Tertiary section includes sequences of 1) interbedded tuffaceous siltstone, sandstone, conglomerate, and sparse ash-flow tuff; 2) dacite lavas; 3) rhyolite lavas and domes; and 4) olivine basalt to basaltic andesite flows (Faulds and Ramelli, 2005). On the basis of similarities with sections described elsewhere in western Nevada (e.g. Stewart and Perkins, 1999; Trexler et al., 2000; Henry and Perkins, 2001; Faulds et al., 2003; Faulds and Garside, 2003), most of the Tertiary rocks in this area are probably middle to late Miocene

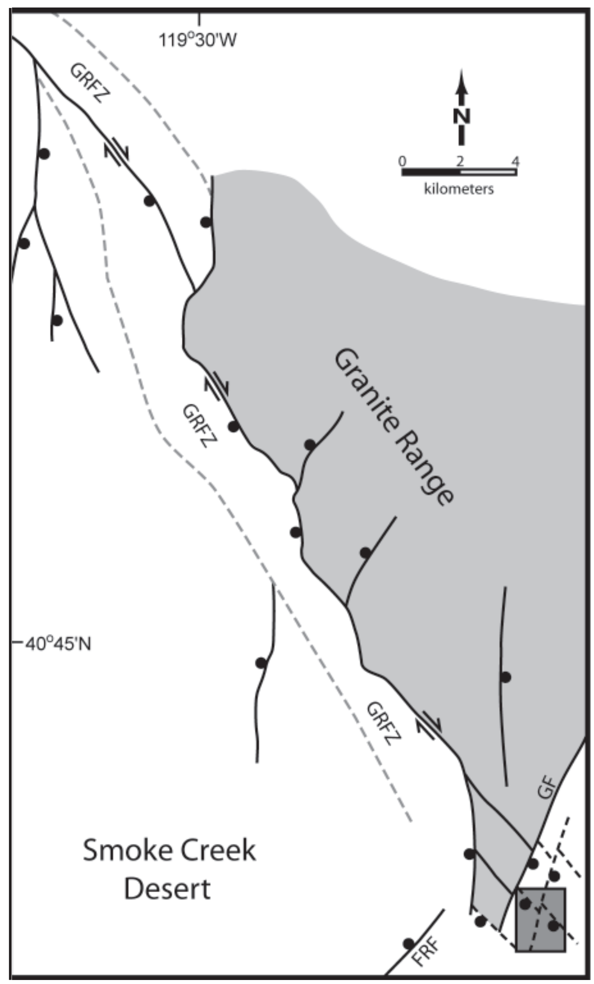

Figure 5. Generalized structural map of the Granite Range and Gerlach area. Shaded box roughly outlines geothermal field. Lightly shaded area denotes the Granite Range. The geothermal field lies near the intersection of two southward terminating range-front faults. FRF, Fox Range fault; GF, Gerlach fault, which is the range-front fault on the east side of the Granite Range; GRFZ, Granite Range fault zone, which forms the range-front fault on the southwest margin of the Granite Range. Balls shown on downthrown sides of normal or oblique-slip faults.

in age. The Tertiary rocks are overlain by Quaternary alluvial fans, lacustrine deposits associated with late Pleistocene Lake Lahontan, and eolian deposits. The Gerlach area is dominated by alluvial fans shed from the Granite Range, which consist primarily of granitic detritus. Lacustrine deposits crop out just to the east and south of Gerlach within the playas of the Black Rock and Smoke Creek Deserts, respectively.

The Gerlach Hot Springs occur at the south end of the Granite Range near the intersection of two major range-front faults, both of which are marked by Quaternary fault scarps. The Granite Range is a large gently NE-tilted horst block bounded by the NW-striking oblique-slip Granite Range fault zone on the southwest and major NNE- to NNW-striking normal fault zones on the east and northeast. The E-dipping fault zone on the east flank of the range dies out southward toward Gerlach, giving way to a major W-dipping fault zone along the west side of the Fox Range. Although the SW-dipping normal-dextral Granite Range fault essentially terminates ~5 km west of Gerlach, several minor strands of this fault zone appear to cut the southern end of Granite Range and extend into the Gerlach area. Although bedrock exposures are not present in the vicinity of the hot springs, we infer that the geothermal activity is controlled by the intersection of steeply dipping NW- and northerly striking fault zones along the horse-tailing ends of the two major range-front fault zones (Figure 5). The intersections of these steeply dipping faults generates highly fractured subvertical conduits that accommodate the ascent of the hydrothermal fluids.

Summary

Although many more fields need to be analyzed to fully characterize the structural controls on geothermal systems in the Great Basin, several major themes are emerging. First, many of the fields do not reside on major range-front faults but rather on less conspicuous normal fault zones. This is especially true for the geothermal systems within the "transitional" Walker Lane (e.g. Salt Wells, Desert Peak, Bradys, Needle Rocks). Despite differences in overall structural setting between the transitional Walker Lane and north-central Great Basin, many geothermal fields in both regions appear to occupy discrete steps in fault zones or lie in belts of intersecting, overlapping, and/or terminating faults. Although only one field from the north-central Great Basin was discussed in this report, many fields in this region appear to be focused near apparent steps in major range-front normal faults (e.g. Jersey Valley, Dixie Valley, and Hot Creek) or within zones of overlapping, oppositely dipping range-front faults (e.g. Diana's Punchbowl in Monitor Valley). Even some fields within strike-slip dominant settings, such as the eastern California shear zone, occur along steps in range-front faults, as exemplified by the Emigrant prospect in Fish Lake Valley (Hulen et al., 2005). It is important to note that major normal fault zones, including many range-front faults, typically horsetail, or splay into multiple strands, near their terminations. In addition, nearly all faults hosting geothermal activity in the Great Basin appear to dip steeply. Furthermore, many of the systems occur along faults with Quaternary scarps. In nearly all cases analyzed to date, the structural settings favoring geothermal activity generate subvertical conduits of highly fractured rock along fault zones oriented approximately perpendicular to the least principal stress (i.e. approximately north-northeast in the northwestern Great Basin).

Our initial findings are also compatible with the conclusions of Micklethwaite and Cox (2004), who found that zones of high permeability around fault systems can be predicted if fault segments and likely locations of paleo-rupture arrest can be located. The rupture-arrest regions correspond to 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 stepovers in fault zones or reversals in the dominant dip direction of entire systems of faults (e.g. Roberts and Jackson, 1991; Faulds and Varga, 1998). Because of their tendency to mark the termination of significant fault ruptures (i.e. the boundary of a zone of collapse), these arrest regions can gradually develop a topographic expression in the form of interbasinal highs. Such rupture arrest regions may also account, at least in part, 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).

Our conclusions clearly have implications for exploration strategies for blind geothermal resources within the Great Basin. Considering the typical constraints on time and resources, it is difficult for industry to conduct detailed investigations across broad expanses of the Great Basin. Thus, exploration strategies need to focus on features indicative of intersecting, terminating, and overlapping fault systems. Such features may include: 1) major steps in range-fronts that typically correspond to stepping or overlapping range-front faults (e.g. Hot Creek (Nye County), Jersey Valley, and possibly Dixie Valley), 2) interbasinal highs, which characterize overlapping oppositely dipping normal fault systems (e.g. Salt Wells, Steamboat Springs, and Sou Hills), 3) mountain ranges consisting of relatively low, discontinuous ridges, which commonly signify en echelon normal fault systems (e.g. Bradys, Desert Peak, and possibly Bonham Ranch), and 4) lateral terminations of major mountain ranges, which are typically associated with the horse-tailing ends of range-front faults and/or intersecting normal and strike-slip to oblique-slip fault zones (e.g. Gerlach). It is also noteworthy that pull-apart zones are an additional feature in strike-slip dominant settings conducive to geothermal activity, as exemplified at Coso (Unruh et al., 2002) and in the Salton Trough area (Herzig and Mehegan, 1987; Hiriart-LeBert and Gutiérrez-Negrin, 1994).

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