Structural investigations of Great Basin geothermal fields: Applications and implications

James E. Faulds and Nicholas H. Hinz
Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557
Mark F. Coolbaugh
Great Basin Center for Geothermal Energy, University of Nevada, Reno, NV 89557

ABSTRACT

Because fractures and faults are commonly the primary pathway for deeply circulating hydrothermal fluids, structural studies are critical to assessing geothermal systems and selecting drilling targets for geothermal wells. Important tools for structural analysis include detailed geologic mapping, kinematic analysis of faults, and estimations of stress orientations. Structural assessments are especially useful for evaluating geothermal fields in the Great Basin of the western USA, where regional extension and transtension combine with high heat flow to generate abundant geothermal activity in regions having little recent volcanic activity.

The northwestern Great Basin is one of the most geothermally active areas in the USA. The prolific geothermal activity is probably due to 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. Analysis of several geothermal fields suggests that most systems occupy discrete steps in normal fault zones or lie in belts of intersecting, overlapping, and/or terminating faults. Most fields are associated with steeply dipping faults and, in many cases, with Quaternary faults. The structural settings favoring geothermal activity are characterized by subvertical conduits of highly fractured rock along fault zones oriented approximately perpendicular to the WNW-trending least principal stress. Features indicative of these settings that may be helpful in guiding exploration for geothermal resources include major steps in normal faults, interbasinal highs, groups of relatively low discontinuous ridges, and lateral jogs or terminations of mountain ranges.

Key Words: Geothermal systems, normal faults, kinematics, structural controls, Great Basin

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 1a). The geothermal systems cluster in discrete NNE to NE-trending belts (Faulds et al., 2004). The lack of recent volcanism suggests that upper crustal magmatism is not a source of heat for most of the geothermal activity in this region.

On a grand scale, an unusual tectonic setting may facilitate much of the geothermal activity in the northwestern Great Basin. The western margin of North America contains a broad zone of distributed shear from the San Andreas fault system to the Basin and Range province (Figure 2; Wernicke, 1992; Atwater and Stock, 1998). GPS geodetic results indicate that a system of right-lateral faults in the western Great Basin, known as the Walker Lane in its northern reaches (Locke et al., 1940; Stewart, 1988; Faulds et al., 2005; Faulds and Henry, 2008) and the eastern California shear zone to the south (Dokka and Travis, 1990), accommodates as much as 20–25% of the dextral motion (~1 cm/year) between the North American and Pacific plates (Thatcher et al., 1999; Dixon et al., 2000; Oldow et al., 2001; Bennett et al., 2003; Hammond and Thatcher, 2004). The Walker Lane essentially accommodates dextral motion of the Sierra Nevada block relative to the Great Basin and marks an abrupt physiographic change, with the predominant

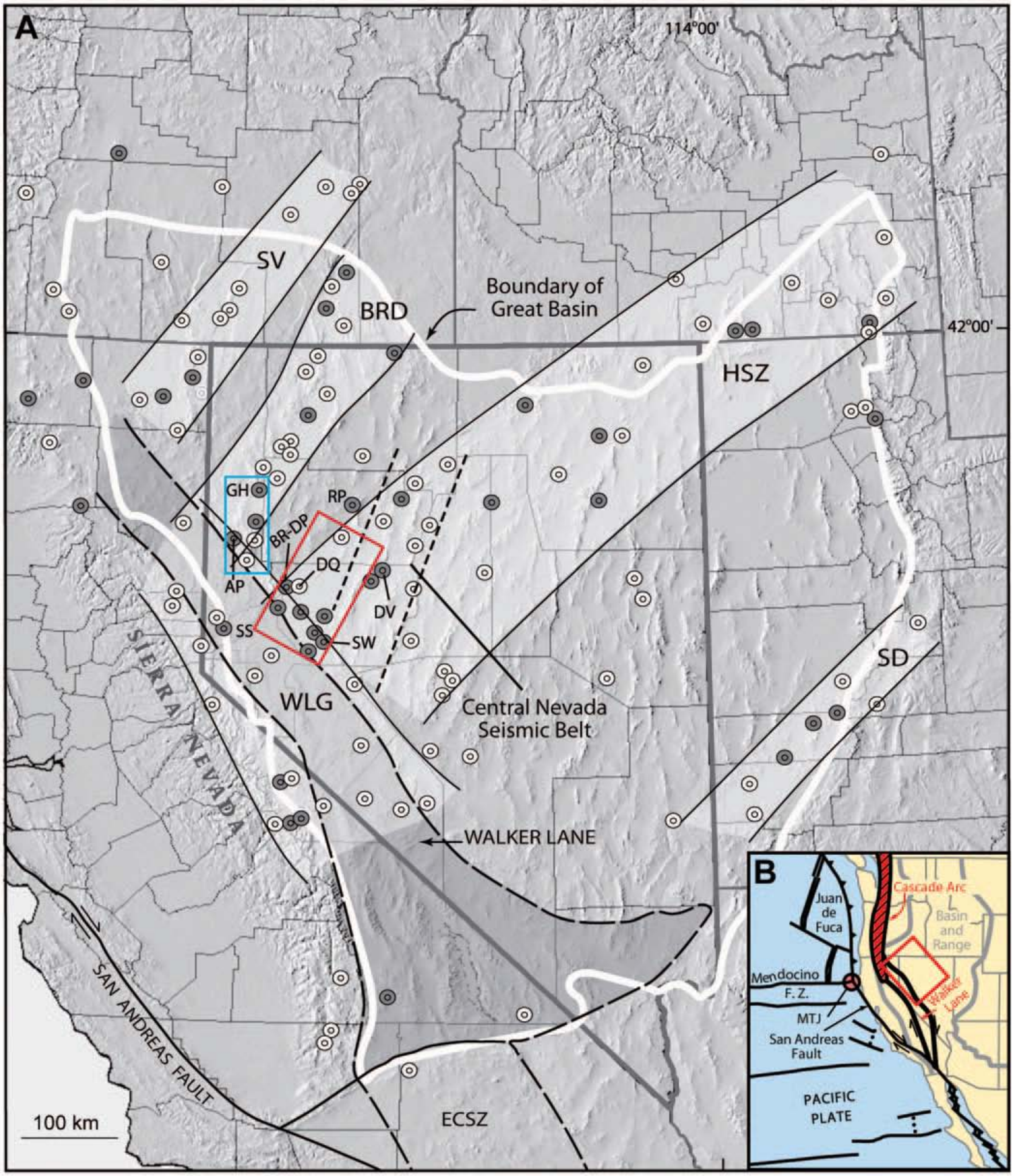

Figure 1. A. Geothermal belts in the Great Basin (from Faulds et al., 2004). Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. White circles are geothermal systems with maximum temperatures of 100–160°C; grey circles have maximum temperatures >160°C. ECSZ, eastern California shear zone. Dashed lines (short dashes) bound the central Nevada seismic belt. Red box surrounds Carson Sink region; blue box encompasses Pyramid Lake area. Abbreviations for individual geothermal fields: AP, Astor Pass; BR-DP, Brady's and Desert Peak; DQ, Desert Queen; DV, Dixie Valley; GH, Gerlach; RP, Rye Patch; SS, Steamboat; SW, Salt Wells. B. Present tectonic setting of western North America. Red box surrounds the locus of geothermal activity in the northwestern Great Basin. MTJ, Mendocino triple junction.

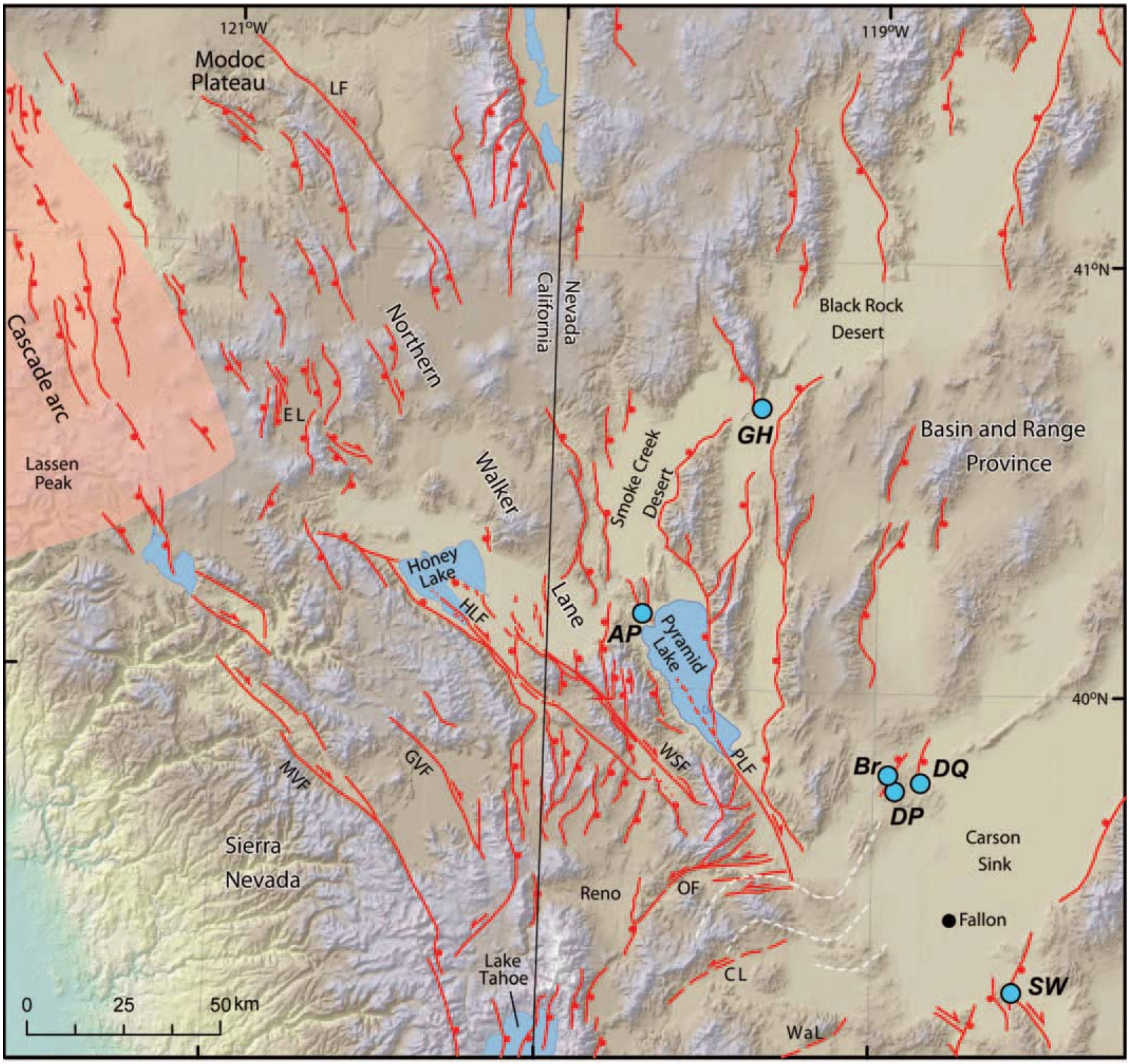

Figure 2. Shaded relief map of major faults and physiographic features of the northern Walker Lane (modified from Faulds and Henry, 2008); also shows selected faults of the adjacent Basin and Range Province and Cascade volcanic arc (from Gay and Aune, 1958; Lydon et al., 1960; Bonham and Papke, 1969; Stewart, 1988; Saucedo and Wagner, 1992; Grose, 2000; Henry et al., 2007). White dashed lines denote oroclinal flexure within the Walker Lane in the westernmost part of the Carson Sink. CL, Carson lineament; EL, Eagle Lake; GVF; Grizzly Valley fault; HLF, Honey Lake fault; LF, Likely fault; MVF, Mohawk Valley fault; OF, Olinghouse fault; PLF, Pyramid Lake fault; WaL, Wabuska lineament; WSF, Warm Springs Valley fault. In the Modoc Plateau area, dextral displacement is documented on only the Likely fault (Bryant, 1991; Grose, 2000; Poland et al., 2002) and a fault at Eagle Lake (Colie et al., 2002), but other faults probably have both dextral and normal displacement. Geothermal systems reviewed in this paper are shown with blue dots (AP, Astor Pass; Br, Brady's, DP, Desert Peak; DQ, Desert Queen; GH, Gerlach; and SW, Salt Wells).

north-northeast-trending topographic grain in the Great Basin giving way westward to more heterogeneous terrain (Figure 1a). To the south, the Walker Lane/eastern California shear zone merges with the San Andreas fault in southern California. To the north, it terminates in northeast California near the southern end of the Cascade arc. The most prolific geothermal activity lies directly northeast of the northern part of the Walker Lane dextral shear zone (Figure 1b).

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, thereby diffusing that motion into the Basin-Range. The region of abundant geothermal activity lies directly northeast of the northern part of the Walker Lane, where dextral shear is decreasing to the northwest. The NNE- to NE-trending geothermal belts in the Great Basin are oriented orthogonal to the WNW-trending extension direction (Figure 1a). 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 allowing deep circulation of hydrothermal fluids along the NNE-striking faults. The individual belts of geothermal fields may reflect loci of strain

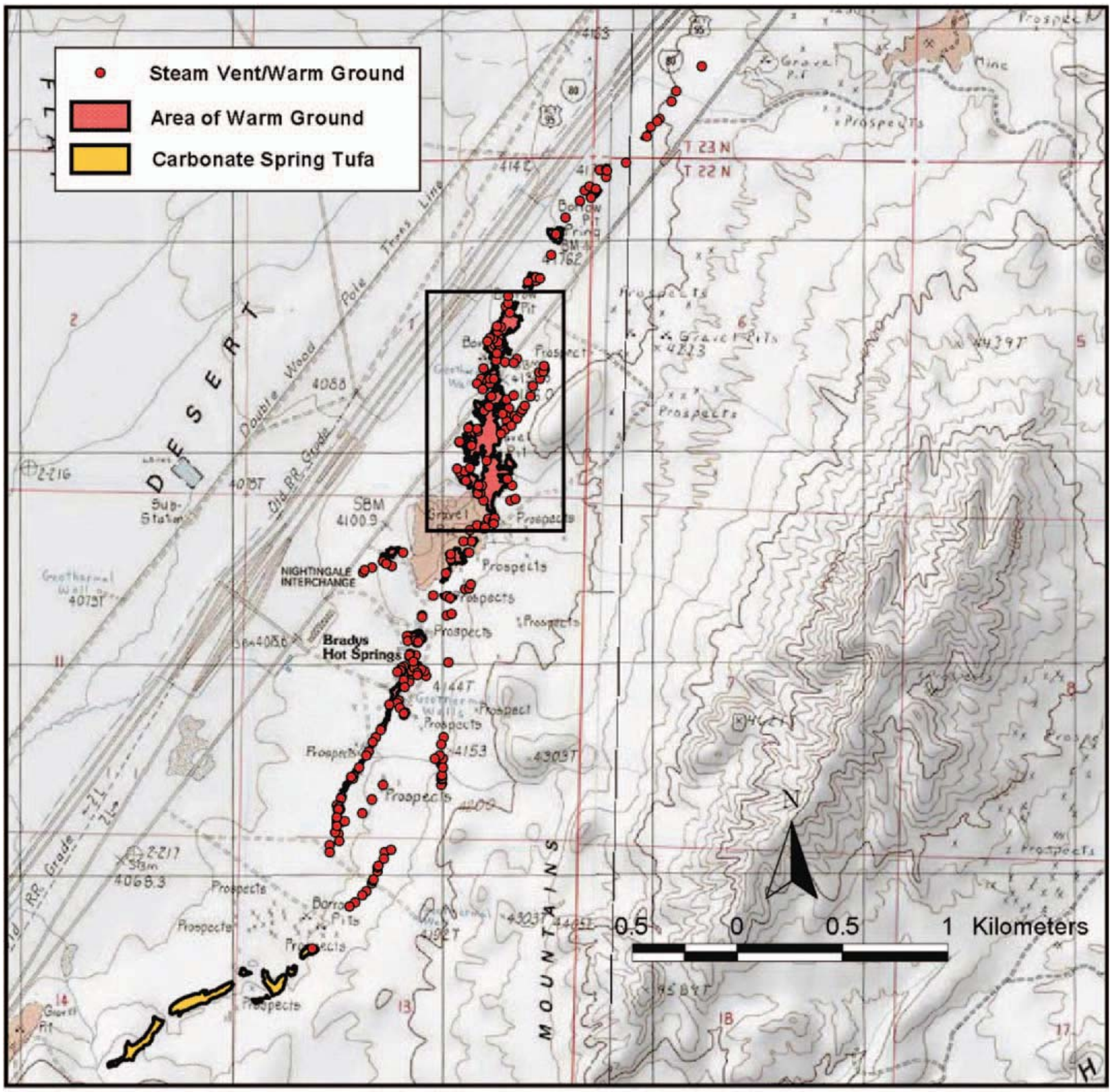

Figure 3. Brady's field, surface geothermal features. The Brady's system is marked by a linear zone of hot springs, fumaroles, warm ground, and sinter along the WNW-dipping, NNE-striking Brady's fault zone. The main production wells are located up to ~1 km to the west of a small left step in the fault zone (encompassed by black box) and presumably penetrate the down-plunge projection of a highly fractured step-over at depth.

transfer between the Walker Lane and Great Basin (Faulds et al., 2004).

This paper provides an overview of the local structural controls of geothermal systems in the northern Great Basin. We review the structural settings of representative geothermal fields in two of the major geothermal belts. The first is the Carson Sink region, which lies in the southern part of the Humboldt geothermal belt (red block in Figure 1a). The second region includes the Pyramid Lake and Gerlach areas, located in the southern part of the Black Rock Desert geothermal belt (blue block in Figure 1b).

CARSON SINK GEOTHERMAL SYSTEMS

The Carson Sink is a broad region of the western Great Basin consisting of a large composite, internally drained basin and multiple small mountain ranges. It lies directly northeast of the northern Walker Lane. Normal faults dominate the area, but major range-front faults, common in much of the Basin and Range province, are largely confined to the margins. In the western part of the Carson Sink, the structural grain changes eastward from ~E-W to NNE (Figure 3), as an oroclinal flexure within the Walker Lane (Faulds and Henry, 2008) gives way to the extension-dominated Basin and Range province, as epitomized by NNE-striking normal fault zones.

The Carson Sink is marked by abundant geothermal activity, including five operating power plants and several promising geothermal fields. We have analyzed the structural controls of several geothermal fields within the Carson Sink region and conclude that the geothermal activity is controlled primarily by NNE-striking normal fault zones (Faulds et al., 2003, 2006; Hinz et al., 2008). Cumulative dextral shear along the Walker Lane appears to be greater to the southeast of the Carson Sink than to the northwest (Faulds and Henry, 2008). We therefore speculate that the abundant geothermal activity in the Carson Sink region may be associated with a transfer of some of the NW-directed dextral shear in the Walker Lane to WNW extension in the interior of the Great Basin.

Hot Springs Mountains: Brady's, Desert Peak, and Desert Queen Geothermal Fields

The Brady's, Desert Peak, and Desert Queen fields lie in the northern Hot Springs Mountains ~80 km east-northeast of Reno, Nevada, along the northern margin of the Carson Sink (Figures 1 and 2). The geothermal system at Brady's Hot Springs has estimated reservoir temperatures of 175–205°C at 1-2 km depth (Shevenell and DeRocher, 2005) and supports a combined flash and binary geothermal power plant with a total electrical generation capacity of ~16–17 MWe.

The surface expression of the Brady's system is a 4-km-long, NNE-trending zone of warm ground, fumaroles, mud pots, and silicified sediments along the Brady's fault (Figure 3). Approximately 7 km to the southeast lies the geothermal system at Desert Peak, which has a reservoir temperature of 218°C (Shevenell and DeRocher, 2005) and currently fuels a 12.5 MWe geothermal flash plant. The Desert Queen field, approximately 9 km east-northeast of the Desert Peak power plant, is not yet developed, but Magma Energy Corporation is currently exploring there. Both the Desert Peak and Desert Queen fields are *blind* geothermal systems, with no current hot springs.

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. Fault scarps indicate significant Quaternary extension in the area.

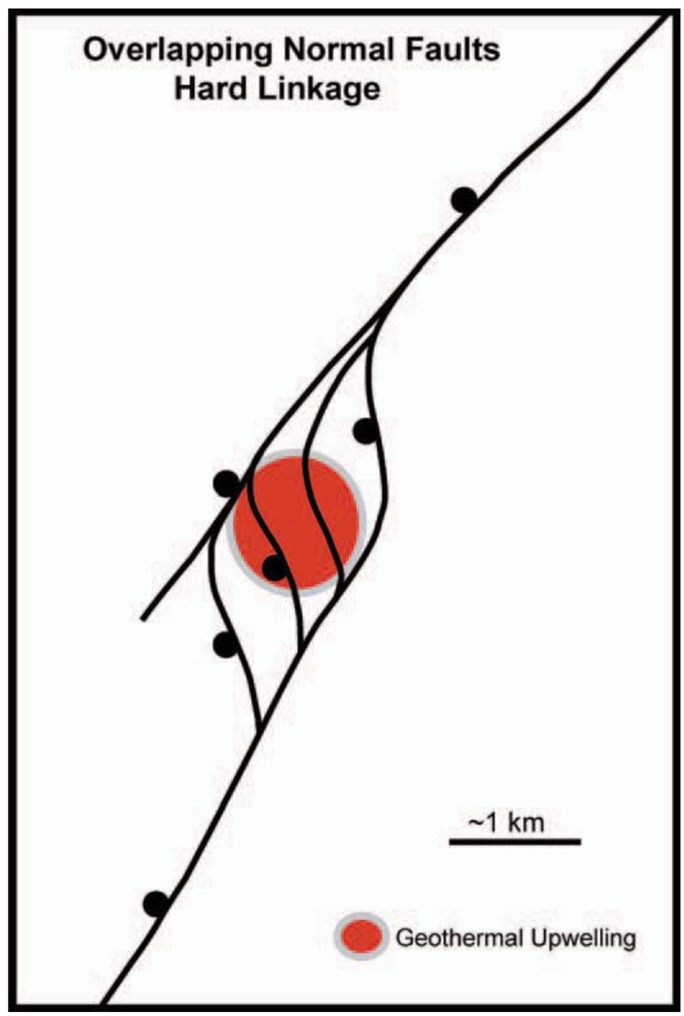

Figure 4. Step-over in normal fault zone. Step-overs appear to control the geothermal systems at Desert Peak and Brady's. Scale and fault pattern modeled after features at Desert Peak. Multiple minor faults provide hard linkage between two major strands and serve to increase fracture density, thus providing an avenue for the ascent of geothermal fluids.

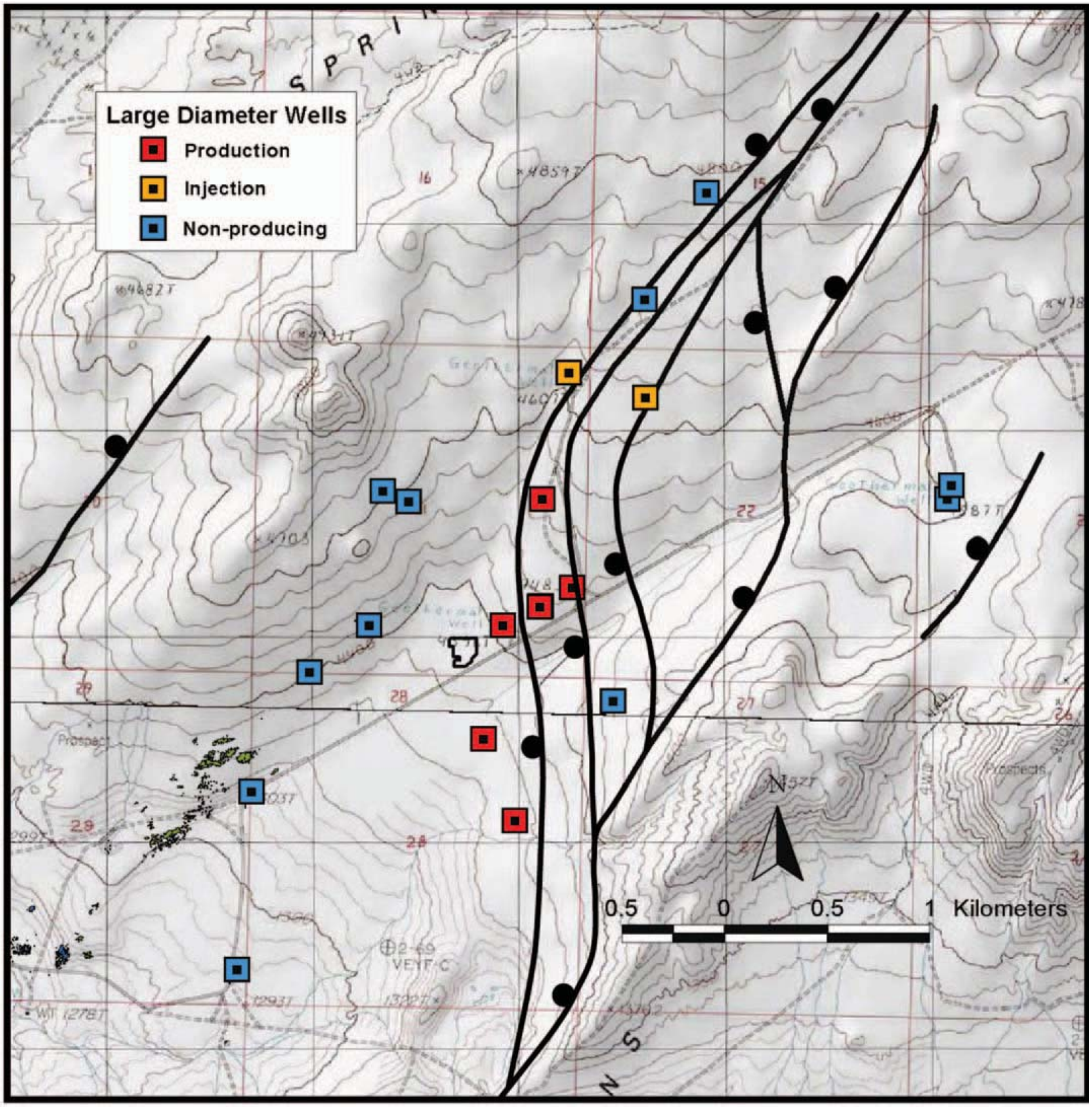

Figure 5. Geothermal wells, Desert Peak. All production wells at the Desert Peak geothermal system occur in a large left step in the NNE-striking Rhyolite Ridge normal fault zone. Stratigraphic relations gleaned from detailed geologic mapping (Faulds and Garside, 2003) and well data indicate that the step-over contains multiple fault strands. Balls shown on downthrown sides of normal faults.

Both the Brady's and Desert Peak fields occupy left steps or small step-overs in the en echelon, steeply west-dipping NNE-striking normal fault zones (Faulds et al., 2006; Figure 4). The Desert Peak field occurs along the Rhyolite Ridge fault zone (Figure 5), whereas the Brady's field lies along the Brady's fault zone (Figure 3). Displacement on these fault zones locally exceeds ~2 km. At least one segment of the Brady's fault has accommodated Quaternary normal displacement (Wesnousky et al., 2005). Multiple fault strands in the step-overs (Figures 4 and 5) provide subvertical conduits of high fracture density that probably enhance fluid flow and facilitate the rise of deep-seated thermal plumes. Intersecting, oppositely dipping

NNE-striking normal faults may also play an important role in channeling fluids at Brady's. The NNE-striking faults are orthogonal to the regional WNW extension direction and are thus favorably oriented for fluid flow.

The Desert Queen system was first identified by temperature gradient drilling (Benoit et al., 1982). It is marked by a shallow 2-meter temperature anomaly (Coolbaugh et al., 2007) near the southern end of the steeply east-dipping Desert Queen fault zone. As this fault zone terminates southward, it breaks into multiple splays. The higher fracture density associated with the horse-tailing end of the fault may provide a channel way for the hydrothermal fluids.

Salt Wells Geothermal Field

The Salt Wells geothermal field occupies the southwestern margin of the Salt Wells basin ~20 km southeast of Fallon in the southeastern part of the Carson Sink (Figures 1 and 2). In early 2009, ENEL completed construction of a 14 MWe binary power plant that taps a shallow geothermal reservoir with an estimated temperature of ~145°C. Geothermometry suggests that a deeper reservoir may exist at temperatures of 180–190°C. This area lies near the intersection of the Walker Lane and central Nevada seismic belt, where several historic 6.0 to 7.0 magnitude normal and normal-dextral earthquakes have occurred (Caskey et al., 2004).

The local stratigraphy consists of middle to late Miocene basalt lavas and lesser interbedded sedimentary rock. Well data suggest that the basalt exceeds 400 m in thickness and overlies Oligocene ash-flow tuffs and/or Mesozoic granitic and metamorphic basement. The basalts are overlain by Quaternary alluvial fans and lacustrine deposits from Pleistocene Lake Lahontan.

Gently to moderately E-tilted fault blocks bounded by steep W-dipping northerly striking normal fault zones characterize the structural framework of the southern portion of the Salt Wells area. To the north, a major east-dipping, northerly striking normal fault zone (here referred to as the Salt Wells fault zone) bounds the west side of the Salt Wells basin and is marked by several Holocene scarps cutting Pleistocene silicified sand deposits. Temperature gradient drilling has defined a large, 12-km-long, heat flow anomaly along this fault zone (Edmiston and Benoit, 1984), which dies out southward where it merges with the west-dipping fault system in the vicinity of the geothermal system.

The productive geothermal wells appear to be localized along the steeply E-dipping Salt Wells fault zone as it loses displacement southward, breaks into several splays (i.e., horsetails), and intermeshes with the W-dipping fault system (Figure 6). The increased fracture density generated by the multiple intersecting faults produced greater permeability in the area, which has in turn provided convenient channel ways for geothermal fluids. The steep dips of the intersecting faults may have produced both subvertical and subhorizontal conduits of highly fractured bedrock, which may have generated multiple geothermal reservoirs at depth. However, some of these reservoirs may be limited in lateral or vertical extent. A key for further development at Salt Wells will be locating the primary upflow zone of hydrothermal fluids from greater depths.

BLACK ROCK DESERT BELT

The Black Rock Desert belt is a NNE-trending zone of abundant geothermal activity in the northwestern part of the Great Basin (Figure 1). At least 18 geothermal fields lie in this belt, including seven high temperature systems (>160°C). Only one small power plant and associated vegetable dehydration facility have been developed in this region, but significant geothermal exploration is now underway with anticipated future development in several areas.

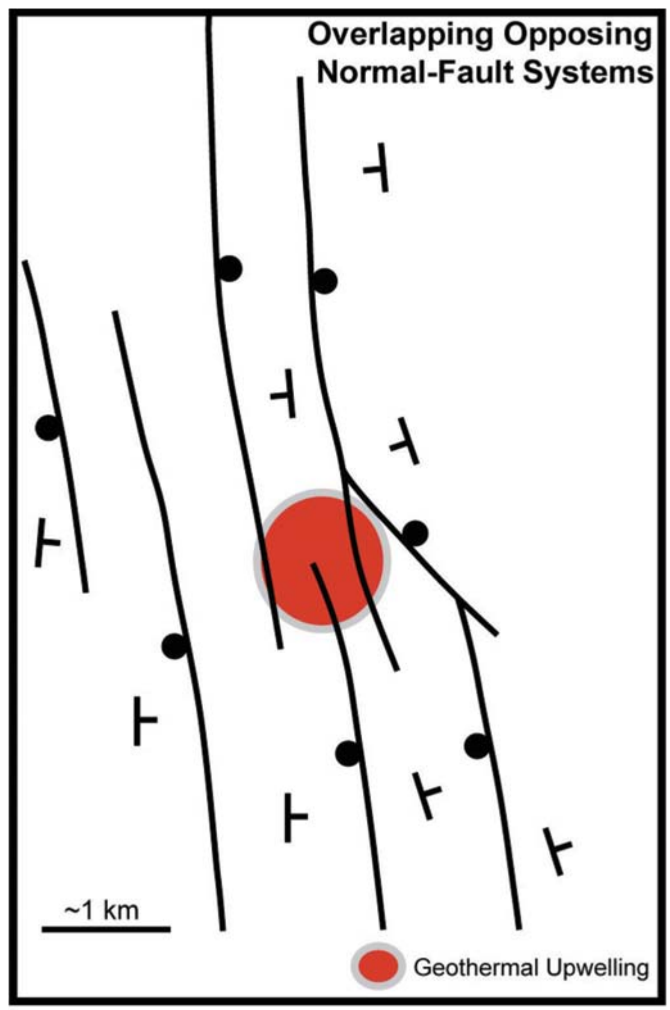

Figure 6. Overlapping, opposing fault systems. Overlapping, oppositely dipping normal fault systems generate multiple fault intersections in the subsurface, thus increasing fracture density and providing pathways for geothermal fluids, as exemplified at Salt Wells. Strike and dip symbols indicate tilt directions of fault blocks.

At the southern end of the Black Rock Desert belt, the Pyramid Lake fault, a major dextral fault in the northern Walker Lane accommodating ~10 km of right slip since ~6 Ma (Faulds et al., 2005) terminates northwestward beneath Pyramid Lake. Similar to other major strike-slip faults in the Walker Lane, the Pyramid Lake fault ends in complex arrays of normal faults. Slip on the Pyramid Lake fault appears to be transferred to west-dipping range-front normal faults that bound the Lake Range and Nightingale Mountains on the west (Figure 3). Cumulative slip on the west-dipping normal faults in the area is comparable to the mag-

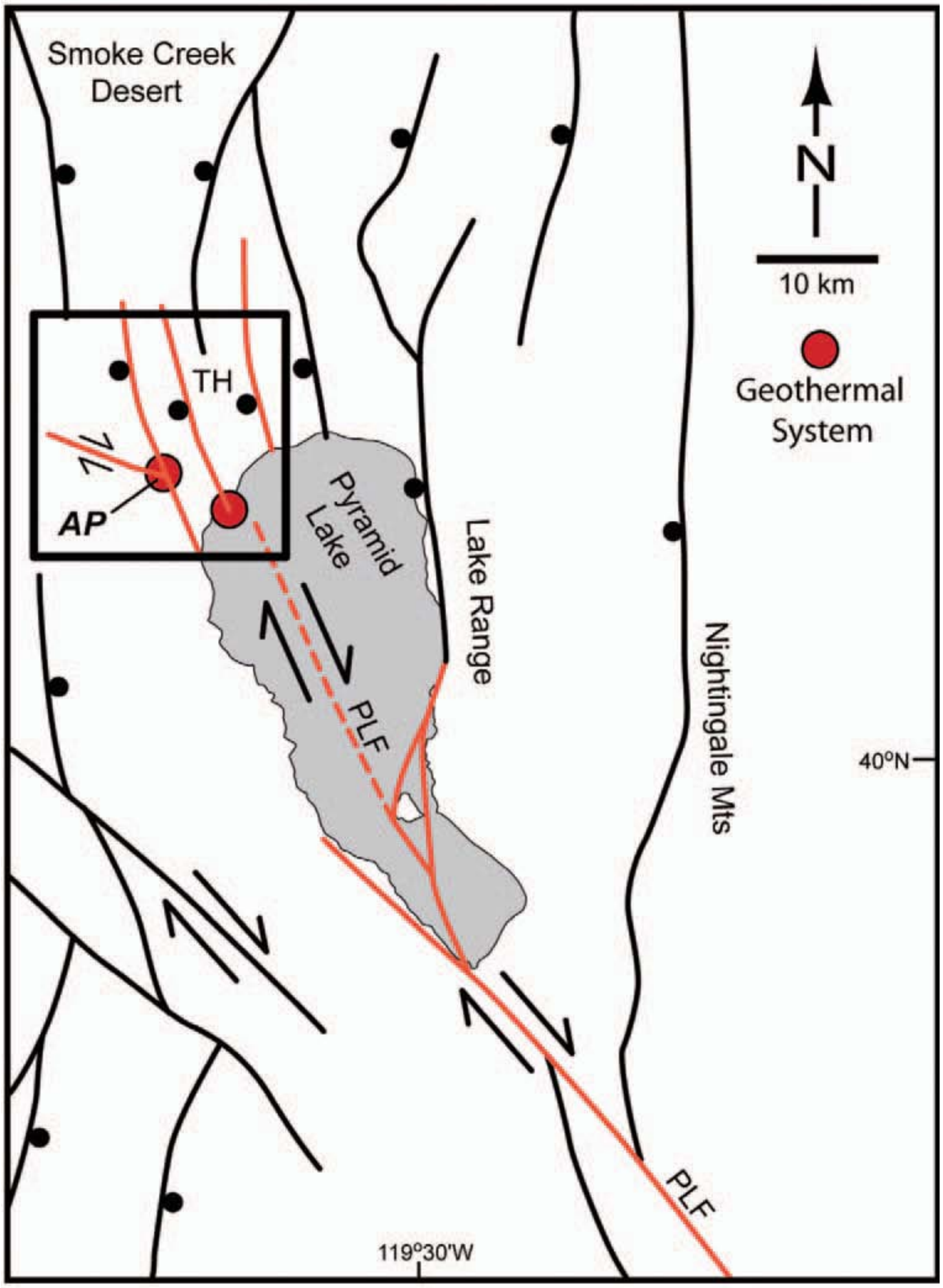

Figure 7. Generalized map of Pyramid Lake area. Two geothermal fields lie in the horse-tailing north end of the right-lateral Pyramid Lake fault (PLF). Dextral slip on PLF diffuses northward into northerly striking range-front faults along the west flanks of the Lake Range and Nightingale Mountains and oblique-slip (mainly normal with minor dextral component on some strands) NNW-striking faults in the Terraced Hills. The Astor Pass geothermal system (AP) occurs at the intersection between a NNW-striking, primarily normal fault and WNW-striking mainly dextral fault. Box surrounds study area of Vice et al. (2007). TH, Terraced Hills.

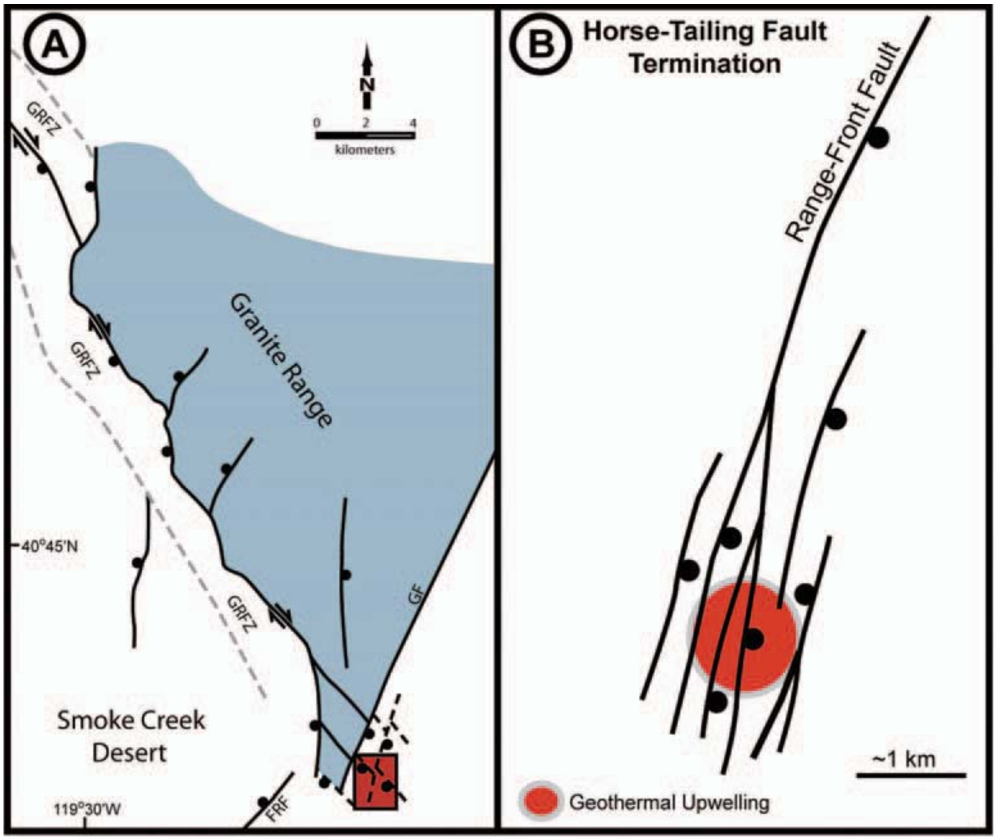

Figure 8. A. Generalized structural map of the Gerlach area. Red box roughly outlines geothermal field. Lightly shaded area denotes the Granite Range. The geothermal field lies near the intersection of two southward terminating range-front faults. FRF, Fox Range fault; GF, Gerlach fault, which is the 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. B. Schematic termination of a major normal fault, whereby faults break up into multiple splays or horsetail.

nitude of dextral slip on the Pyramid Lake fault (Drakos, 2007). Many faults in the area have Quaternary scarps (e.g., Bell, 1984; Briggs and Wesnousky, 2004; Vice, 2008). Enhanced extension, induced by the transfer of dextral shear along the Pyramid Lake fault to ~E-W- to WNW-directed extension, is probably responsible for geothermal activity in the Black Rock Desert geothermal belt. We review two undeveloped geothermal systems in this belt, the Astor Pass and Gerlach geothermal fields.

Astor Pass Geothermal Field

The Astor Pass field lies at the north end of Pyramid Lake in the southern part of the Terraced Hills (Figures 2 and 7). The area contains thick sequences (1–2 km) of predominantly mafic, middle Miocene volcanic rock intercalated with thin sedimentary lenses, all overlying a Mesozoic granitic to metamorphic basement. At least six geothermal systems occur in the Pyramid Lake area. Although none of the systems have been developed, significant exploration has occurred. Hot springs upwelling into Pleistocene Lake Lahontan formed many tufa towers in this region. These tufa towers may indicate blind geothermal systems.

The Astor Pass area lies near the northwest shore of Pyramid Lake (Figure 7). Intersecting linear WNW- and NNW-trending belts of tufa towers at Astor Pass suggest the presence of an underlying or blind geothermal system, but no hot springs or other clear-cut geothermal features are present. Nearby hot springs along Pyramid Lake have surface temperatures as high as boiling and geothermometer temperatures of 143°–213°C (Mariner et al., 1974; Grose and Keller, 1975) but development is precluded because of the cultural significance of the area to the Pyramid Lake Indian Reservation.

Detailed geologic mapping and structural analysis demonstrate links between faulting and the inferred blind geothermal system at Astor Pass (Vice et al., 2007). Closely spaced N- to NNE-striking normal and NNW- to WNW-striking dextral-normal faults fragment the area into a series of gently to moderately (~15–40°) E-tilted fault blocks. The intersecting belts of tufa towers probably mark intersecting WNW- and NNW-striking normal-dextral fault zones.

The southwest quadrant of this fault intersection is probably dilational and was therefore recommended for drilling. Drilling to 558 m depth confirmed a geothermal system with temperatures exceeding 90°C. Analysis of cuttings shows that the upper part of the reservoir lies in highly fractured, hydrothermally altered, basalt and rhyolite units. The closely-spaced dextral-normal faults in the Astor Pass area may represent the horse-tailing northwest end of the Pyramid Lake fault (Figure 7), where dextral slip is progressively transferred to N- to NNE-striking normal faults. Dilational fault intersections or fault geometries appear to be particularly favorable for geothermal activity within this region of enhanced extension.

Gerlach Geothermal Field

The Gerlach geothermal field lies in the south-central part of the Black Rock Desert belt on the southeast flank of the Granite Range (Figure 2; Grose and Keller, 1975). Boiling springs, mud pots, and siliceous rock mark 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 deposition of silica at the surface.

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. The Tertiary rocks are overlain by Quaternary alluvial fans, lacustrine deposits derived from Pleistocene Lake Lahontan, and eolian deposits. The field 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 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 (normal-dextral) Granite Range fault zone on the southwest (Faulds and Ramelli, 2005) 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. 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 (Figure 8).

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 8). The intersections of these steeply dipping faults generate highly fractured subvertical conduits that accommodate ascent of the hydrothermal fluids.

CONCLUSIONS

Although more analysis is required to fully understand the structural controls on geothermal systems in extended terranes, several major themes are emerging from our work in the Great Basin. These include:

1) Many fields do not reside on the main segments of major range-front faults but rather on the horse-tailing ends of major faults or on less conspicuous normal fault zones.
2) Many geothermal systems occupy discrete steps in fault zones or lie in zones of intersecting, overlapping, and/or terminating faults.
3) Favorable structural settings commonly involve steeply dipping Quaternary fault zones.

In general, structural settings that produce conduits of highly fractured rock along fault zones oriented approximately perpendicular to the least principal stress are conducive for geothermal activity. Our findings have potentially important implications for geothermal exploration in extended terranes, especially for blind systems. Exploration strategies should focus on intersecting, terminating, and overlapping features of fault systems including the following:

- Discrete steps in range-fronts that typically correspond to stepping and overlapping range-front faults or possibly to intersections between major normal faults and oblique-slip transfer faults.
- Interbasinal highs, which characterize overlapping oppositely dipping normal fault systems.
- Mountain ranges consisting of relatively low, discontinuous ridges, which commonly signify en echelon normal fault systems with multiple fault terminations and intersections.
- Lateral terminations of major mountain ranges, where the horse-tailing ends of major normal faults and/or intersecting normal and strike-slip to oblique-slip fault zones occur.

Structural studies are critical to evaluating known geothermal systems and selecting locations for geothermal wells. Fractures and faults generally provide the primary pathways for deeply circulating hydrothermal fluids in both magmatic and amagmatic settings. Important tools for structural analysis include detailed geologic mapping, kinematic analyses of faults, and estimation of stress orientations. Detailed characterization of local structural settings will determine areas with the highest fracture density and where faults show the greatest tendency for slip or dilation (e.g., Moeck et al., 2009). Integration of field-derived information with 3-D stress-strain models will predict the location and orientation of deep permeable fractures.

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