Geothermal Resources Council Transactions, Vol. 27, October 12-15, 2003

Structural Analysis of the Desert Peak-Brady Geothermal Fields, Northwestern Nevada: Implications for Understanding Linkages between Northeast-Trending Structures and Geothermal Reservoirs in the Humboldt Structural Zone

James E. Faulds[1], Larry J. Garside[1], and Gary L. Oppliger[2]

[1]Nevada Bureau of Mines and Geology
[2]Department of Geological Sciences
University of Nevada, Reno, NV 89557

Keywords

Nevada, geothermal, Desert Peak, Brady, Humboldt structural zone, normal faults, folds, Hot Springs Mountains, extension

ABSTRACT

Detailed geologic mapping, delineation of Tertiary strata, analysis of faults and folds, and a new gravity survey have elucidated the structural controls on the Desert Peak and Brady geothermal fields in the Hot Springs Mountains of northwestern Nevada. The fields lie within the Humboldt structural zone, a region of high heat flow characterized by east-northeast to north-northeast-striking fault zones. The Tertiary section consists of late Oligocene ash-flow tuffs overlain by sequences of interfingering basalt lavas, diatomite, siltstone, sandstone, and limestone. The strata are fragmented into multiple north-northeast-trending fault blocks, which are bounded by en echelon, overlapping north-northeast-striking faults, most of which dip west-northwest. Slip data obtained from fault surfaces show that the north-northeast-striking faults generally accommodated dip-slip normal displacement, which is suggestive of a west-northwest-trending least principal stress. The strata are also deformed into north-northeast-trending, gently plunging folds. The folds are typically asymmetric with steeper and narrower west-dipping limbs found proximal to major west-dipping normal faults. These relations suggest that most folds resulted from a combination of east-tilting of fault blocks and drag along the west-dipping normal faults. The Brady field occurs along and near the north-northeast-striking, west-northwest-dipping, Brady fault zone, whereas the Desert Peak field may be localized near the northern end of the north-northeast-striking, west-northwest-dipping Rhyolite Ridge fault zone, which breaks into several strands (horse tails) as it loses displacement northward in the northern Hot Springs Mountains. Left-lateral shear along east-northeast-striking fault zones within the Humboldt structural zone may accentuate west-northwest-directed regional extension in the Hot Springs Mountains. This, combined with a greater density of faults and fractures induced by the transfer of strain between the en echelon overlapping normal faults, may promote deep circulation of fluids along the north-northeast-striking fault zones. Similar relations may characterize other geothermal fields within the Humboldt structural zone.

Introduction

We have undertaken integrated geologic, geophysical, and GIS investigations of the Desert Peak-Brady geothermal fields in the Hot Springs Mountains of northwestern Nevada. The geologic investigations include detailed mapping of a 3.5 km wide, northwest-trending transect between the Desert Peak and Brady fields, delineation of Tertiary strata, analysis of faults and folds, and ^{40}Ar/^{39}Ar dating and geochemical correlation of key units. The main objectives of this work are to delineate the late Cenozoic three-dimensional strain field, elucidate relations between faults, stratigraphic features, and thermal aquifers, and constrain stress orientations. Ultimately, we hope to utilize this information to assess controls on geothermal fields within the Humboldt structural zone of northern Nevada. Our transect of detailed mapping and analysis includes the Desert Peak East Enhanced Geothermal System (EGS) study area, a DOE-Industry co-funded project site in the Hot Springs Mountains (Schochet et al., 2002; Nathwani and Creed, 2002). The purpose of this paper is to provide a progress report of our multi-disciplinary investigations and discuss potential implications of our findings on understanding the structural controls of geothermal reservoirs in the northern Great Basin, where geothermal fields are commonly associated with north-northeast- to east-northeast-striking fault zones. The interpretations articulated in this paper are based on more thorough analyses and therefore supercede some of our preliminary findings described in Faulds et al. (2002).

Humboldt Structural Zone

A broad region of high heat flow, the Battle Mountain heat flow high (Lachenbruch and Sass, 1977), covers much of northern Nevada and includes an east-northeast-trending zone extending from near Reno to Elko (Figure 1, overleaf). This zone of faulting and high heat flow has been referred to as the Humboldt structural

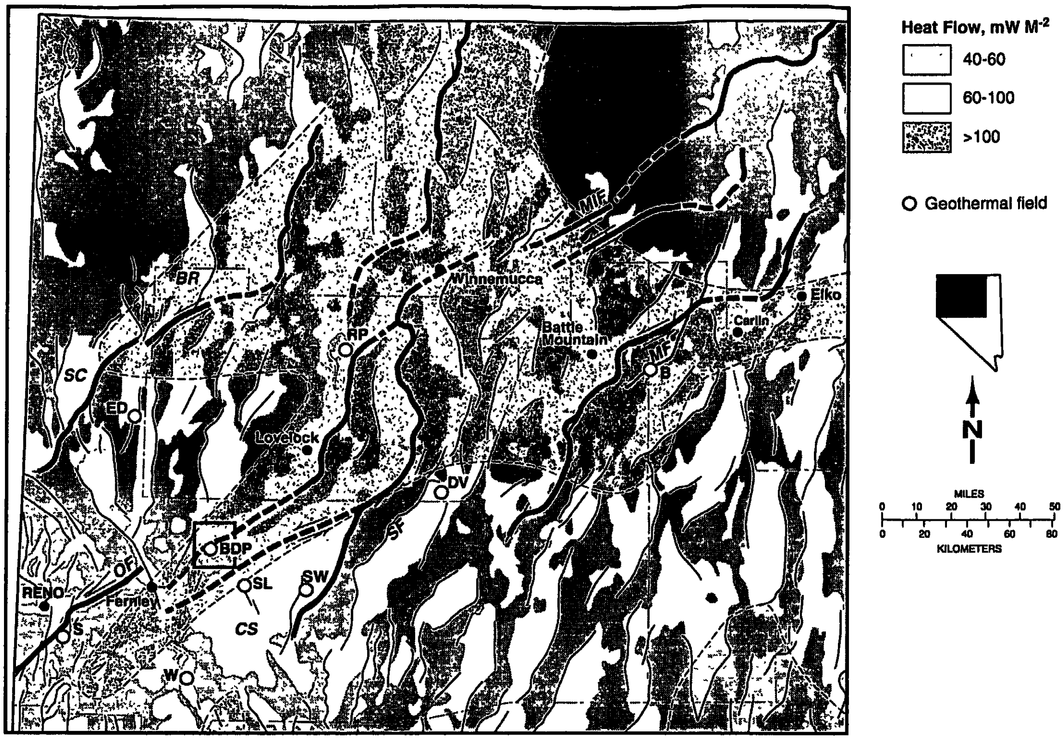

Figure 1. Generalized map of northern Nevada showing some of the major northeast-striking faults of the Humboldt structural zone in bold, Hot Springs Mountains (in box), and Battle Mountain heat flow high. Geothermal fields: BDP, Desert Peak-Brady; B, Beowawe; DV, Dixie Valley, ED, San Emidio Desert; RP, Rye Patch; S, Steamboat; SL, Soda Lake; SW, Stillwater; W, Wabuska. Other features: BR, Black Rock desert; CS, Carson Sink; MF, Malpais fault; MIF, Midas fault; OF, Olinghouse fault; SC, Smoke Creek Desert; SF, Stillwater fault.

zone (Rowan and Wetlaufer, 1981). Most of the major geothermal fields in northern Nevada, including Steamboat, Brady, Desert Peak, Soda Lake, Rye Patch, Dixie Valley, and Beowawe, occur along or near east-northeast- to north-northeast-striking faults in the Humboldt zone. The abundance of geothermal fields and regional extent of the heat flow anomaly indicate high potential of discovering additional geothermal reservoirs in this region.

From west to east, major east-northeast- to north-northeast-striking faults in the Humboldt structural zone include the Olinghouse fault, faults bounding the Smoke Creek and Black Rock Deserts, faults along the northern margin of the Carson Sink, Stillwater fault in Dixie Valley, Midas fault, and Malpais fault near Beowawe. Most of these faults accommodate left-lateral and/or normal slip. Normal slip is related to west-northwest-oriented extension in the Basin and Range province (e.g. Zoback, 1989; Thatcher et al., 1999). In the Walker Lane, some east-northeast-striking faults may serve as extensional transfer zones between right-stepping, northwest-striking dextral faults (Oldow et al., 1994). However, seismological data (Ichinose et al., 1998) and Quaternary studies (Sanders and Slemmons, 1979; Briggs et al., 2000) indicate recent left-lateral motion on many east-northeast-striking faults. Within the Walker Lane, such motion may accommodate the clockwise rotation of fault blocks in a region of dextral shear (Cashman and Fontaine, 2000). Northwest-striking dextral faults within the Walker Lane currently account for ~20% of the right-lateral motion between the North American and Pacific plates (e.g. Thatcher et al., 1999; Oldow et al., 2001). The reasons for sinistral displacement on east-northeast-striking faults within the Great Basin east of the Walker Lane are not entirely clear, but such faults may accommodate a small component of north-south shortening induced by broadly distributed constrictional strain (e.g. Dewey, 2002) within the evolving transform-plate boundary of western North America.

Despite the economic significance of the Humboldt structural zone, few detailed studies have been conducted on the Cenozoic stratigraphic and structural framework of the region. Although major contributions have recently been made (e.g. McNitt, 1990; Hickman et al., 1998, 2000; Blackwell et al., 1999, 2002; Caskey and Wesnousky, 2000; Blewitt et al., 2002; Johnson and Hulen, 2002), the temporal and spatial relationships between various structural features in the Humboldt structural zone and how individual faults, stratigraphic units, or sets of structures control fluid pathways and geothermal resources are generally poorly understood.

Of the developed geothermal fields, some of the best exposures of faults and folds occur in the Desert Peak and Brady fields in the Hot Springs Mountains. Thus, comprehensive analysis of this area has significant potential for characterizing both the structural setting (strain and stress fields) and structural controls on geothermal reservoirs in the Humboldt structural zone.

Hot Springs Mountains

The Desert Peak-Brady geothermal fields lie in the Hot Springs Mountains of northwestern Nevada, ~80 km east-northeast of Reno (Figure 1). The fields occur along or near an inferred, major east-northeast-striking fault zone that extends from near Fernley to Lovelock and bounds the Carson Sink on the north. Two power plants and one vegetable dehydration plant currently operate in the fields. The Brady power and dehydration plants are located at Brady's Hot Springs just southeast of I-80 along the north-north-east-striking Brady fault. The smaller Desert Peak power plant taps a *blind* geothermal reservoir ~6.8 km (4 miles) southeast of Brady's Hot Springs along or near the north-northeast-striking Rhyolite Ridge fault zone. Available aqueous chemistry and isothermal maps suggest that the Brady and Desert Peak fields are associated with essentially independent thermal plumes, at least at shallow depths (Benoit et al., 1982).

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. They concluded that the Desert Peak geothermal reservoir resides in pre-Tertiary rocks and further speculated that some mechanism other than Tertiary high-angle faulting localizes the heat, although such faults locally tap the reservoirs. However, the boundaries of the geothermal reservoirs in both the Brady's Hot Springs and Desert Peak areas remain poorly defined, which poses exploration challenges for further development of the field.

The Brady and Desert Peak geothermal fields have been operational for 11 and 18 years, respectively. The Desert Peak field has been very successful, utilizing the original two producing wells and one injector well for its entire life. However, this success has resulted in little study of the resource in the past two decades. Now that new power sales agreements are in place and exploration has resumed, it is important that the structural controls on this resource be reevaluated. In contrast, several problems have confronted geothermal operations in the Brady field. These include short residence times for fluids between recharge and intake wells and excessive draw-down in existing wells induced by nearby production. Such problems indicate a high level of fluid transmissivity. Known faults, such as the north-northeast-striking Brady fault, account for some of this high transmissivity. However, high transmissivity has also been documented across and within the hanging wall of the Brady fault, suggesting that stratigraphic units or obscure cross faults also channelize fluids. Drilling over the past 10 years has yet to be integrated into a structural model of the field. Thus, comprehensive 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 assessing some of the problems at the Brady field while also unraveling the fundamental stratigraphic and structural controls of both the Brady and Desert Peak fields.

Stratigraphic and Structural Framework

The detailed geologic mapping has revealed a relatively thick, complex, and laterally extensive Tertiary stratigraphy. In ascending order, the exposed Tertiary section along the transect consists of: 1) at least three ash-flow tuffs of presumed late Oligocene age, locally separated by thin sequences of volcaniclastic sandstone and megabreccia (several additional units of ash-flow tuff have been observed in cuttings and core from wells); 2) middle to late Miocene basaltic andesite or basalt lavas, 3) late Miocene diatomite and lesser intercalated siltstone, limestone, and basalt flows, 4) basalt lavas with lesser intercalated diatomite; 5) thin lenses of diatomite; 6) relatively thick section of siltstone and lesser basalt flows; 7) thin lenses of limestone; 8) local capping porphyritic basalt lavas of presumed late Miocene age (e.g. Desert Peak area), and (9) a capping, crystal-poor, fiamme-rich ash-flow tuff of presumed late Miocene age exposed only east and southeast of the Desert Peak geothermal field. Within these sequences, individual lithologic units have been mapped separately (e.g. individual ash-flow tuffs, intercalated basalts in diatomite, etc.). Several basalt plugs of probable late Miocene age 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. On the basis of tephrochronologic data from the northernmost Hot Springs Mountains and Trinity Range (Stewart and Perkins, 1999) and regional relations, the probable age of Miocene strata is ~14 to 8 Ma.

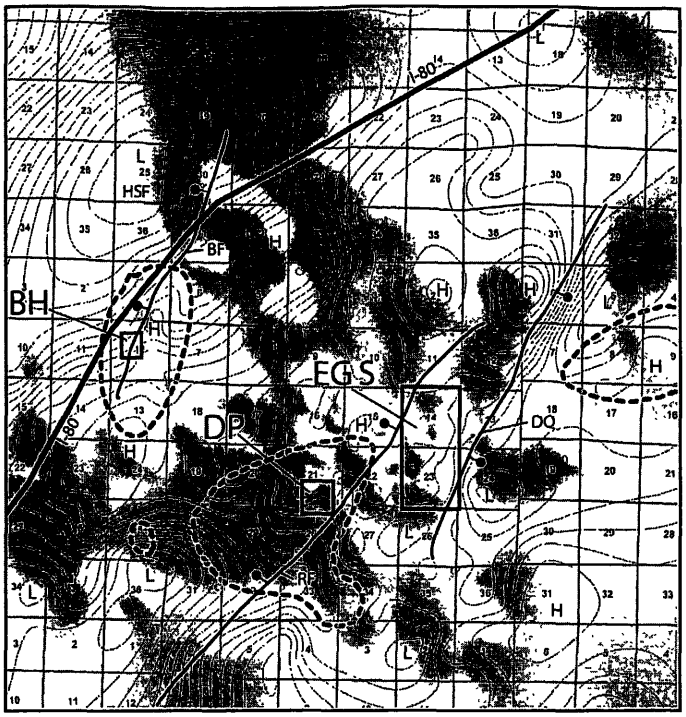

Figure 2. Gravity anomaly image of the Desert Peak and Brady geothermal fields. Complete Bouguer gravity anomaly reduced at 2.4g/cc; contours are 1 milligal. Shown are: Desert Peak (DP) and Brady (BH) geothermal plants, EGS project study area (EGS), 160° F iso-temperature contour at 300 ft depth (dashed lines), Hot Springs Flat basin (HSF), and the Brady (BF), Rhyolite Ridge (RF), and Desert Queen (DQ) faults (bar and ball on downthrown side). H and L represent gravity highs and lows, respectively. Also shown are land-survey mile sections and Interstate 80 (I-80).

The Hot Springs Mountains are fragmented into multiple north-northeast-trending fault blocks, which are bounded by numerous en echelon, overlapping north-northeast-striking faults, most of which dip west-northwest. Major faults include 1) the north-northeast-striking, west-northwest-dipping Brady fault zone, which bounds much of the northern Hot Springs Mountains on the northwest and Hot Springs Flat basin on the southeast; 2) north-northeast-striking, west-northwest-dipping Rhyolite Ridge fault zone, which appears to terminate northward in the northern Hot Springs Mountains; and 3) north-northeast-striking, east-southeast-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, including much of the EGS site, the Miocene section appears to be somewhat thinner (~1 km). A north-northeast-trending horst block, which forms the bulk of the EGS site, lies between the oppositely dipping Rhyolite Ridge and Desert Queen faults.

Over 300 bedding attitudes (Figure 3, overleaf) and more than 20 fault surfaces were measured along the transect. The bedding typically dips ~20-45° east-southeast and strikes north-northeast

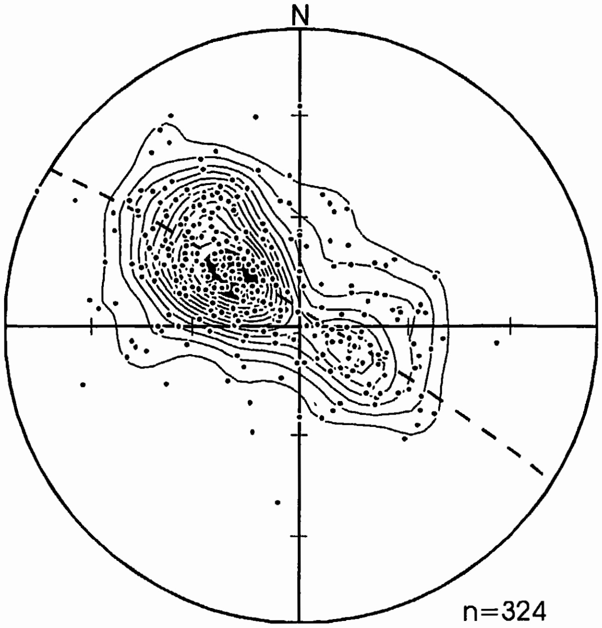

Figure 3. Density contour plot of poles to bedding and layering in Tertiary strata, northern Hot Springs Mountains. Π circle (dashed great circle) defines an average, gently plunging, north-northeast-trending fold axis. Poles are shown by small dots (n=number of poles).

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. Slip data obtained from fault surfaces (Figure 4) show that the north-northeast-striking faults generally accommodated dip-slip normal displacement. The north-northeast strike of the normal faults indicates a west-northwest-trending least principal stress, which is compatible with the regional extension direction inferred from geodetic data (e.g. Thatcher et al., 1999). It is important to note, however, that a west-northwest-striking joint set was observed in the late Oligocene ash-flow tuffs. This may imply an earlier episode of mild ~north-south extension, which has been noted elsewhere in the Basin and Range province (e.g. Best, 1988; Faulds et al., 2001).

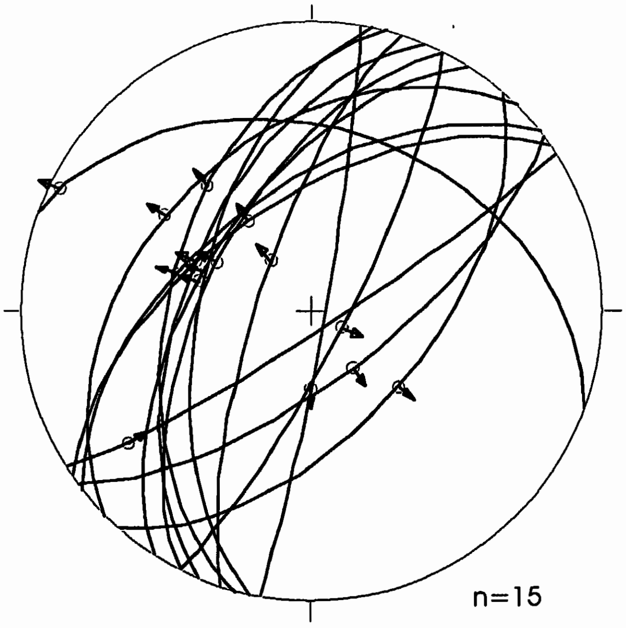

Figure 4. Great circles of faults showing slip sense (arrow) inferred from striae (i.e. slickenlines) and other kinematic indicators. n=number of faults.

As noted originally by Cunningham et al. (1958) and later by Hiner (1979), the strata are deformed into several north-northeast-trending folds. The Π circle defined by poles to bedding indicates gently plunging, N30°E-trending fold axes (Figure 3). 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).

Gravity Data

The gravity anomaly pattern (Figure 2) largely reflects the relief on the buried pre-Tertiary bedrock in the northern Hot Springs Mountains. It defines the form of the Desert Peak horst system interpreted from drilling by Benoit et al. (1982). It is also in harmony with a narrow pre-Tertiary bedrock horst occurring at 1350 m depth at the Brady field and with granitic basement outcrop at the Desert Queen mine. The density contrasts of the overlying sedimentary and volcanic units against the pre-Tertiary basement ranges between 0.0 and -0.65 g/cc. The weighed average is about -0.34 g/cc which translates into an average depth response of 70 m per 1 milligal of the gravity anomaly. This basic result offers considerable utility in projecting where potential reservoir rocks may be shallowest and corrects a largely contrary conclusion based on a 1979 gravity survey over the Desert Peak field described by Benoit et al. (1982). That survey covered too little of the horst system to identify its form and was corrupted by a few large measurement errors, which have been corrected by the data and analysis of this study.

The gravity data place important constraints on pre-Tertiary basement depth in basins adjacent to the Hot Springs Mountains, which, in turn, elucidates the magnitude of offset on bounding normal fault zones. For example, the gravity anomaly over the Hot Springs Flat basin northwest of the Brady field (Figure 2) indicates a depth of ~2 km to pre-Tertiary basement, which suggests at least 1.0 km of cumulative down-to-the-west throw across the bounding Brady fault system. It is important to note, however, that the actual Brady fault within the Brady geothermal field only accommodates ~150 m of throw (Benoit et al., 1982) and is therefore interpreted to be one segment of a larger fault system. Similarly, a minimum of 1 km of offset is inferred for the northern part of the Desert Queen fault. The gravity data also indicate that displacement on the Rhyolite Ridge fault zone increases southward in the northern Hot Springs Mountains 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.

The northwest-trending gravity contours across the Desert Peak field (Figure 2) may reflect a relay ramp (cf. Larsen, 1988) associated with southward increasing displacement on the Rhyolite Ridge fault zone.

Implications

The data acquired in this study have significant implications for understanding the structural controls on geothermal fields in the Hot Springs Mountains and elsewhere in the Humboldt structural zone. For example, both the Brady and Desert Peak fields are associated with north-northeast-striking normal faults. The Brady field occurs along and near the north-northeast-striking, west-northwest-dipping, apparently left-stepping Brady fault zone, whereas the Desert Peak field may be localized near the northern end of the north-northeast-striking, west-northwest-dipping Rhyolite Ridge fault zone, which breaks into several strands (horse tails) as it loses displacement northward in the northern Hot Springs Mountains. North-northeast-striking faults also play a role in controlling geothermal reservoirs in other geothermal fields within the Humboldt structural zone (e.g. Dixie Valley; Hickman et al., 1998, 2000; Blackwell et al., 2002).

The west-northwest trend of the minimum horizontal principal stress within the region (Zoback, 1989) can account for the association of geothermal fields with the north-northeast-striking faults (e.g. Hickman et al., 1998, 2000). Fluids can simply flow more readily along moderately to steeply dipping faults oriented perpendicular to the least compressive stress. However, north-northeast-striking normal faults characterize much of the Great Basin, and yet many parts of the Great Basin do not contain geothermal fields. Why such structures are particularly favorable for localizing geothermal reservoirs within the Humboldt structural zone is therefore an important question.

A possible explanation is that left-lateral shear along the east-northeast-striking fault zones within the Humboldt structural zone may accentuate west-northwest-directed regional extension (Figure 5). The east-northeast trend of the northern margin of the Carson Sink and related east-northeast-trending fault blocks (e.g. West Humboldt Range) suggest that east-northeast-striking fault zones are present near the Hot Springs Mountains. On the basis of regional relations, these faults zones may accommodate a significant component of left-lateral displacement. Thus, the Hot Springs Mountains may lie within a broad zone of left-lateral shear within the Humboldt structural zone. A small component of sinistral shear, combined with both regional west-northwest-directed extension and greater fault and fracture density associated with the transfer of strain between the many en echelon overlapping normal faults, may promote the deep circulation of fluids along north-northeast-striking fault zones within the Hot Springs Mountains and other parts of the Humboldt structural zone. However, favorable stratigraphic horizons, such as the nonconformity between Tertiary and Mesozoic basement in the Hot Springs Mountains, are also critical for localizing geothermal reservoirs and cannot be overlooked in exploration efforts within the Humboldt structural zone.

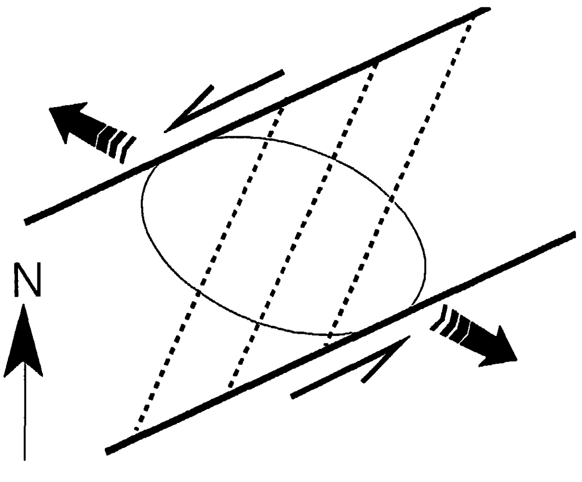

Figure 5. Schematic portrayal of accentuation of WNW-directed extension in an ENE-trending zone of left-lateral shear. This may partly account for the propensity of geothermal fields along NNE-striking fault zones in the Humboldt structural zone.

Acknowledgments

This research was supported by the U.S. Department of Energy under instrument number DE-FG07-02ID14311. We thank Dick Benoit, Jim Combs, and Lisa Shevenell for helpful comments that improved this manuscript.

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