Structural Controls of Lee Hot Springs, Southern Churchill County, Western Nevada: A Small Pull-Apart in the Dextral Shear Zone of the Walker Lane

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Keywords

Nevada, geothermal, Lee Hot Springs, Blow Sand Mountains, White Throne Mountains, Desert Mountains, Walker Lane, strike-slip faults, normal faults, pull-apart

ABSTRACT

Allen Springs and Lee Hot Springs provide an opportunity to evaluate a geothermal reservoir model relative to structures of the Walker Lane. Allen Springs is a cool-temperature, natural seep, and Lee Hot Springs is a hot spring, emanating from a well drilled in the 1930s. These springs have been used for livestock water for much of the past century, and thermal applications have been explored periodically since the 1930s. Both springs are probably part of a single geothermal system with a reservoir temperature estimated at ~170° C. Detailed geologic mapping and geophysical investigations were used to investigate the structural controls of these springs. The study area is cut by multiple northeast-striking, southeast dipping normal faults that repeat Tertiary volcanic sequences. A series of northwest-striking dextral faults intersect these normal faults. Geologic and geophysical data suggest that these normal and dextral faults comprise a right step or small pull-apart, in a northwest-striking dextral shear zone of the Walker Lane. The geothermal reservoir is hosted in shallow basement rocks, and fluid flow is controlled by the northeast-striking normal faults with greatest documented displacement. The distribution of spring deposits along this normal fault indicate that fluid flow is also concentrated along intersections with the northwest-striking dextral faults.

Introduction

We have undertaken detailed geologic and geophysical investigations of the Allen Springs and Lee Hot Springs area, northwest of the Blow Sand Mountains, western Nevada. The geologic investigations included structural analysis of faults and detailed geologic mapping of ~75 km^2. This area includes Mesozoic basement, Tertiary volcanic rocks, and Quaternary deposits. $^{40}Ar/^{39}Ar$ dating was used to correlate Tertiary volcanic units both within the study area and with the regional stratigraphy of western Nevada. For the regional and detailed studies, existing aeromagnetic data (U.S. Geological Survey, 2006) were reprocessed as reduced-to-pole (RTP) magnetic anomalies. Moreover, ~150 new gravity stations were collected in the study area and integrated with other existing datasets to form a database of approximately 2300 gravity stations, which were processed to complete a Bouguer anomaly map (CBA).

This study is part of a larger project aimed at characterizing the structural controls of geothermal systems in the northwestern Great Basin (e.g., Faulds et al., 2003, 2006; Vice et al., 2007). Most of the related studies have focused on areas within the Basin and Range province directly northeast of the Walker Lane. However, the Lee-Allen area lies within the belt of strike-slip faulting within the Walker Lane, which is a major dextral fault system within the western Great Basin (Figure 1). The purpose of this paper is to present a conceptual structural model for the structural controls of Allen springs and Lee Hot springs and compare this setting to others within the western Great Basin.

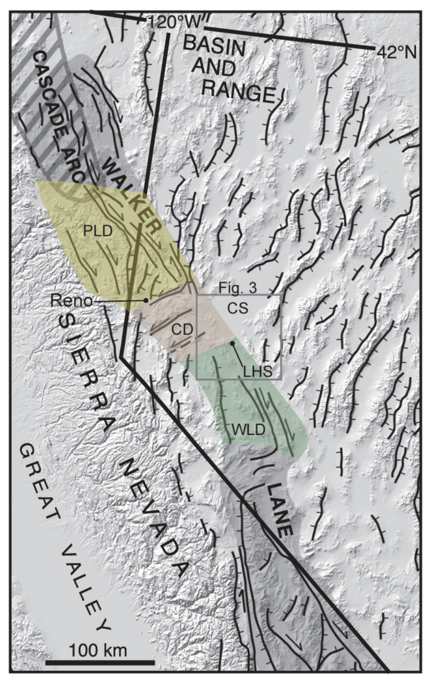

Figure 1. Faults of the Walker Lane (modified from Stewart, 1988) on shaded elevation model (modified slightly from Faulds et al., 2005). LHS, Lee Hot Springs; CD, Carson domain; CS, Carson Sink; PLD, Pyramid Lake domain; WLD, Walker Lake domain. Gray box corresponds to Figure 3.

Geologic Setting

Allen Springs and Lee Hot Springs occupy the boundary between the Carson and Walker Lake structural domains of the Walker Lane (Figure 1; e.g., Stewart, 1988). Since the Oligocene, six major northwest-striking dextral faults have accommodated ~48–100 km of cumulative offset across the Walker Lake domain (e.g., Ekren and Byers, 1984; Hardyman and Oldow, 1991). To the north in the Pyramid Lake domain, four major northwest-striking dextral faults have accommodated ~20–30 km of cumulate dextral offset since 9–3 Ma (Faulds et al. 2005). The dominant northwest-trending structural fabric of the Walker Lane is conspicuously absent within much of the Carson domain, and instead, three northeast-striking fault zones and lineaments of known or presumed left-lateral offset dominate. In contrast to the strike-slip faults of the Pyramid Lake and Walker Lake domains, clockwise vertical axis rotation of fault-bounded blocks (Cashman and Fontaine, 2000) and oroclinal flexure (Faulds and Perkins, 2007) accommodate dextral shear within the Carson domain.

Allen Springs and Lee Hot Springs

Thermal Springs

Allen Springs and Lee Hot Springs reside in a pass between the Blow Sand Mountains to the southeast, the White Throne Mountains to the north, and the Desert Mountains to the west (Figure 2). The Carson Sink, one of the most aerially extensive basins in western Nevada, abuts the north sides of the Desert and White Throne Mountains, and another smaller basin, known as Rawhide Flats, lies to the south of the Blow Sand Mountains. Exposures in the White Throne and Desert Mountains are composed entirely of Tertiary volcanic rocks. The Blow Sand Mountains consist primarily of Tertiary volcanic rocks, but also contain several small exposures of Mesozoic metasedimentary rocks along the north and northwest margins. A small north-northeast-trending ridge composed of Mesozoic diorite (informally referred to as "Allen Ridge" in this paper) rises steeply to the north of Allen and Lee Springs and forms a conspicuous high point between the surrounding mountain ranges.

Thermal applications of Allen Springs and Lee Hot Springs have been explored sporadically since the 1930s (Miller, 1978). In the 1930s, Fallon residents Bob Lee and Frank Inman drilled to a depth of more than 20 m and encountered boiling water and geyser activity, resulting in the "Lee Hot Springs" of today. From 1951 to 1977, a dozen shallow wells were drilled to 10 to 50 m depth near Lee Hot Springs and one well was drilled to 177 m at Allen Springs. The majority of these wells encountered flowing hot or boiling water, and several wells experienced geyser activity and flows up to 60 lpm. In 1978, Oxy Geothermal Inc. drilled an exploratory well, the Federal No. 72-33(K) to 919 m between Allen Springs and Lee Hot Springs encountering a maximum flow of 160 lpm at 610 m and maximum temperature of 119º C at the bottom.

Today, water only flows from Allen Springs and Lee Hot Springs; all other exploration wells have been capped, pulled, naturally plugged, or are dry. Water temperatures for Lee Hot Springs have been recorded between 88º to 100º C (Mariner et al., 1974; Glancy and Katzer, 1975; Miller, 1978; Great Basin Center for Geothermal Energy, 2007). Water temperatures for Allen Springs have been reported at 15º C to 24º C (Miller, 1978; Great Basin Center for Geothermal Energy, 2007).

Geothermometers have also been applied at Lee Hot Springs and the surrounding area. Respective silica and Na-K-Ca geothermometry temperatures of 162º C and 173º C to 178º C have been calculated for Lee Hot Springs (Mariner et al., 1974; Great Basin Center for Geothermal Energy, 2007). Water samples from springs and temperature gradient holes directly south of Lee Hot Springs at the Fallon Naval Air Station Bombing Range Bravo 19 (Figure 2) yielded geothermometer temperature ranges of 115º to 164º C for silica and 152º to 216º C for Na-K-Ca (Whelan et al., 1980). Whelan et al. (1980) concluded that the thermal source of these waters are part of the Allen Springs and Lee Hot Springs geothermal reservoir and estimated an overall reservoir temperature of ~170º C.

The previous exploration of the geothermal potential for Allen Springs and Lee Hot Springs has located hot water, but not in great quantities. However, little to no

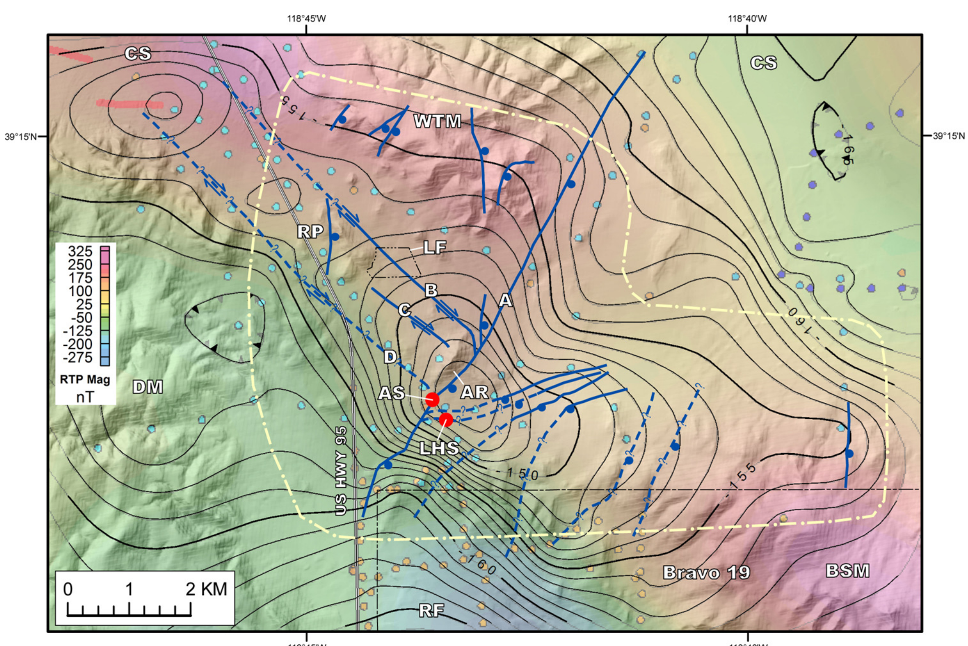

Figure 2. Map of the Allen Springs and Lee Hot Springs area showing major faults and gravity and aeromagnetic anomalies overlain on shaded topography. Dashed light yellow line shows approximate extent of detailed geologic mapping. A, B, C, D, correspond to major faults described in text; AR, Allen Ridge; AS, Allen Springs; Bravo 19, Fallon Naval Air Station Bombing Range Bravo 19, BSM, Blow Sand Mountains; CS, Carson Sink; DM, Desert Mountains; LF, Churchill County Landfill; RF, Rawhide Flats; RP, Russell Pass; WTM, White Throne Mountains. Blue and yellow dots represent gravity stations from this and previous studies, respectively. Contours are 1 mGal CBA. Color anomalies are RTP aeromagnetic intensity data reprocessed from U.S. Geological Survey (2006).

attempt has been made to understand the structural setting for these springs. Thus, the detailed geological mapping, structural analysis, and gravity studies conducted in this study have significant potential for advancing our understanding of the geometry, extent, and structural controls of this geothermal reservoir.

Stratigraphic Framework

Mesozoic basement, Tertiary volcanic rocks, and Quaternary spring and lacustrine deposits crop out in the vicinity of the Lee-Allen springs. The basement consists of diorite, limestone, phyllite, and chert. Four principal sequences of Tertiary volcanic rocks were distinguished within the study area and include from oldest to youngest: 1) five late Oligocene ash-flow tuffs locally separated by rounded fluvial gravels, course mega-breccias, and hornblende-bearing andesite lavas; 2) late Oligocene to early Miocene (?) hornblende-bearing andesite lavas, locally separated by thin layers of fluvial gravels; 3) middle Miocene rhyolite domes and associated coarse clastic sedimentary rocks; and, 4) olivine-bearing basaltic andesite lavas of probable middle to late Miocene age, locally separated by thin layers of fluvial gravels and/or diatomite. Silicified sediments and tufa were mapped around both Allen Springs and Lee Hot Springs, near the northeast end of Allen Ridge, and in combination with siliceous sinter along fault traces in the area of low topography between this ridge and the Churchill County landfill (Figure 2). The most areally-extensive outcrop of silicified sands abuts the north side of Allen Springs and measures ~300 m across.

Several new $^{40}Ar/^{39}Ar$ dates on the volcanic rocks were obtained for this project. These include a 13.83±0.03 Ma age for a rhyolite lava and a date of 5.57±0.14 Ma from the overlying basaltic andesite lavas. A sample of the middle unit (i.e., third from bottom) of five ash-flow tuffs was also processed for $^{40}Ar/^{39}Ar$ analysis and yielded an age of 28.55±0.10 Ma. Petrographic analysis implies correlation with the 28.8 Ma tuff of Campbell Creek. The uppermost tuff in this sequence correlates texturally and petrographically with the distinctive 25.3 Ma Nine Hill Tuff (Deino, 1989). Both of these tuffs are widespread across much of western Nevada (e.g., Deino, 1989; Faulds et al., 2005).

Structural Framework

The Blow Sand and White Throne Mountains are fragmented into multiple northeast-trending fault blocks, which dip northwest 25º to 45º and are bounded by subparallel north-northeast to east-northeast-striking normal faults with southeast dips (Figure 2). The most prominent normal fault (Fault A, Figure 2) strikes northeast across the study area from near the northwest corner of Bombing Range Bravo 19, through the vicinity of Allen Springs and Lee Hot Springs, along the southeast flank of Allen Ridge, and then along the southeast flank of the White Throne Mountains to the southeastern part of the Carson Sink. This fault subparallels a northeast-trending trough directly east of Allen Ridge; this trough may have been partially cut by Lake Lahontan currents. Stratigraphic throw on this major normal fault is estimated at ~1000 m adjacent to Allen Ridge. Other normal faults in the Blow Sand and White Throne Mountains exhibit up to 300 m of displacement.

A series of right-lateral faults, striking ~N45ºW intersect fault A and extend northwest to, and possibly through, the Russell Pass area (Figure 2). As with the normal faults, these strike-slip faults are largely concealed by Quaternary deposits. Silicified sands, tufa mounds, and locally steeply-inclined Tertiary volcanic units constrain the junction of faults A and B at the north end of Allen Ridge. A northwest-striking reverse fault offsetting poorly consolidated early Pleistocene or late Pliocene sediments was observed in the Churchill County landfill excavation on strike with the trace of fault B near the north end of Allen Ridge. Fault C is accompanied locally by siliceous sinter and is exposed in bedrock in two shallow washes and in a prospect pit surrounded with minor silicified lacustrine sediments. Riedel shears along fault surfaces exposed in this prospect pit indicate a right-lateral sense of slip. Fault D is a queried strike-slip fault marked by linear bedrock features in the Russell Pass area, Allen Spring, and the outcrop of silicified sands northwest of Allen Spring. Evidence for magnitude of slip has not been observed on any of these strike-slip faults.

On a regional scale, two of the six major dextral faults of the Walker Lake domain, the Benton Springs and Gumdrop Hills faults have been mapped and/or interpreted to extend northward to near the southern latitude of this study area (Figure 3; Ekren and Beyers, 1984; Hardyman et al., 1992). However, much of the northwest-trending structural grain of the Walker Lake domain ceases near the Carson/Walker Lake domain boundary. The southeastern Carson domain contains several discontinuous sets of east-northeast-striking faults, punctuated by minor north- to northwest-striking faults (Stewart and Carlson, 1978), the most notable of which are the northwest-striking dextral faults mapped in this study.

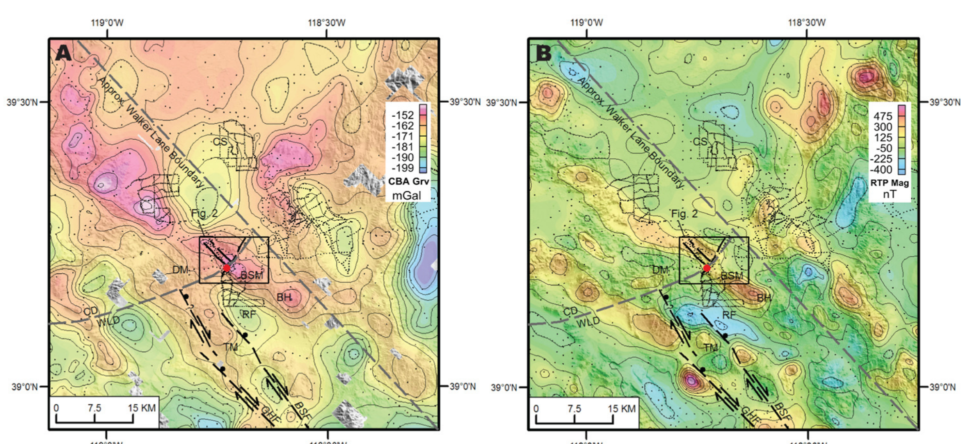

Figure 3. Regional gravity anomaly map (A) and regional aeromagnetic anomaly map (B) overlain on shaded topography with Walker Lane and both Carson (CD) and Walker Lake (WL) domain boundaries after Stewart (1988). Interpreted northerly extensions of the Benton Springs fault (BSF) and the Gumdrop Hills fault (GHF) are after Ekren and Beyers (1984) and Hardyman et al. (1992). Gray box corresponds to Figure 2. BH, Barnett Hills; BSM, Blow Sand Mountains; CS, Carson Sink; DM, Desert Mountains; LHS, Lee Hot Springs; RF, Rawhide Flats; TM, Terrell Mountains. 3A) Black dots, gravity stations from this and previous studies; color anomalies, CBA gravity; contours are 4 mGal. 3B) Color anomalies, RTP magnetic intensity; contours are 100 nT.

Gravity and Magnetic Anomaly Data

The gravity anomaly pattern (Figures 2, 3A) largely reflects relief on the buried pre-Tertiary bedrock and aides with interpreting the structural model for this geothermal area. The magnetic anomaly pattern (Figures 2, 3B) mainly shows contrasts between highly magnetic rocks, such as thicker sequences of Tertiary basalts or mafic crystalline basement rocks, and low-magnetic units, including basin fill deposits or felsic volcanic rocks. Both data sets reflect the broad-scale northwest-trending structural grain in the Walker Lane and the north-northeast-trending structural grain to the east of the Walker Lane.

Allen Springs and Lee Hot springs reside in a local 4 km-wide gravity maximum, coincident with local basement exposure along a greater 60 km-long regional gravity high trending N55ºW. Strong positive magnetic anomalies residing to the northwest and southeast of Allen Lee Springs are offset from the gravity highs. Geologic mapping indicates that these magnetic highs correspond to locally thick (250+ m) sections of basaltic andesite lavas. Locally, the regional gravity high decreases steeply to the south into a strong gravity low associated with the Rawhide Flats basin. We interpret this steep gradient as a northwest-striking fault, bounding the northeast side of this basin. Fault A corresponds to a minor downward step in the gravity gradient across the northwest-trending local gravity high. The Benton Springs fault appears to parallel gradients between the gravity low of Rawhide Flats to the northeast and the moderate gravity and magnetic high of the Terrill Mountains to the southwest. The geometries of mapped faults and faults interpreted from geophysical data (Figures 3A, B) suggest that the Rawhide Flats basin has developed in a right step in the dextral Benton Springs fault system. Moreover, this fault system takes another right step through the Allen Springs and Lee Hot Springs study area into the southern Carson Sink, as illustrated in Figure 4.

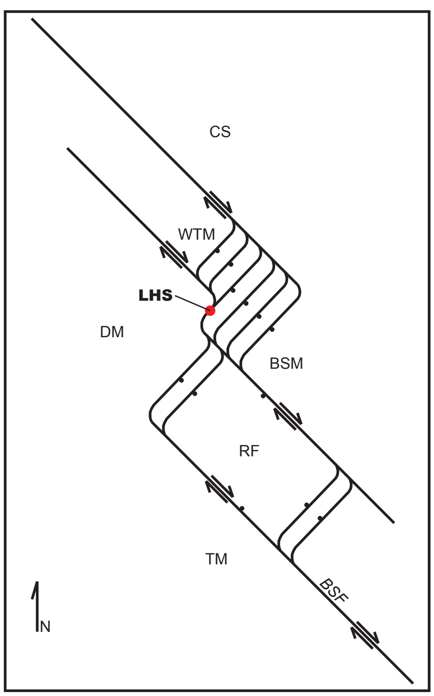

Figure 4. Schematic fault model for the Lee-Allen geothermal area showing a series of right steps along a dextral fault system, interpreted as the northerly extent of the Benton Springs fault. Abbreviated physiographic features are the same as in Figures 3 and 4.

Discussion

Based on the geologic mapping, structural analysis, and geophysical investigations undertaken in this study, we interpret the Allen Springs and Lee Hot Springs geothermal system as residing in a right step, or small pull apart, along a northwest-striking dextral fault zone within the Walker Lane (Figure 4). The overlapping dextral faults are connected by orthogonal sets of normal faults. The basement exposure at Allen Springs and Lee Hot Springs corresponds to the intersection of the pull-apart zone with a more regional, N55ºW-trending gravity high. The distribution of exposed basement and the extent of the gravity high in the Allen Springs and Lee Hot Springs area indicate that the geothermal reservoir is hosted in basement rocks. The distribution of Quaternary spring deposits further suggests that hydrothermal fluid flow is controlled largely by Fault A and the intersection of Fault A with Faults B, C, and D.

These findings are compatible with other parts of the Pacific-North American transform boundary (e.g., eastern California shear zone, San Andreas fault system), where pull-aparts along right steps in dextral shear zones are commonly loci for geothermal activity (e.g., Hulen and Norton, 2000; Monastero et al., 2005). In contrast to these other well known areas, however, the Lee-Allen springs system occurs along a relatively small and heretofore unrecognized pull-apart within the Walker Lane. More thorough studies of the region may reveal many other small pull-aparts, each of which may have a high potential of hosting a viable geothermal system. It is also noteworthy that the setting at Lee-Allen springs contrasts somewhat with those just to the northeast within the Basin and Range, where geothermal activity is commonly focused at discrete steps in normal fault zones, near the ends of major range-front faults, or at the intersections of normal and transverse faults. Thus, the structural setting and controls of geothermal activity may differ somewhat depending on proximity to the Walker Lane.

Acknowledgements

This research was supported by a grant from the Department of Energy through the Great Basin Center for Geothermal Research (DE-FG36-02ID14311). This manuscript benefited from discussions with Larry Garside and Mark Coolbaugh and a thoughtful review by Frank Monastero.

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