Structural Constraints of Buffalo Valley Hot Springs, North-Central Nevada

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Keywords

High-temperature geothermal sites, active faults, geothermal structural settings, Fish Creek mountains fault zone

ABSTRACT

The Humboldt Structural Zone (HSZ), located within a southwest-to-northeast oriented band that stretches from west-central to north-eastern Nevada and Idaho, is noted for abundant high temperature (>100° C) geothermal systems. This is generally attributed to the unique structural setting formed by the transfer of tectonic stresses from the Walker Lane right-lateral strike-slip regime into Basin and Range extension. The resultant faults may be both permeable and preferentially oriented for fluid flow in the present northwest-directed extensional strain field. A handful of structural settings have been found to control the majority of geothermal systems within the Basin and Range province. These settings are a) fault step-overs b) fault terminations c) fault intersections d) accommodation zones. Fault step-overs are the most common geothermal structural setting, controlling ~33% of known geothermal systems within the boundaries of the Great Basin. Hybrids of these settings are often even more accommodating to geothermal system generation.

Though a broad base geologic understanding of geothermal activity is well documented, investigations of individual systems are ongoing. The purpose of this study is to characterize the structural setting controlling secondary permeability at Buffalo Valley hot springs, Lander County, Nevada. This was accomplished through mapping of bedrock and surficial geologic units, at 1:24,000 scale, of eastern Buffalo Valley and west-central Fish Creek mountains. The slip and dilation tendencies of faults mapped proximal to Buffalo Valley hot springs (BVHS) were assessed to identify faults that may be favorably oriented to form fluid conduits, and temperature surveys, at 2-meter depth, were performed to isolate zones of geothermal upwelling and outflow.

Geologic mapping has revealed that Buffalo Valley's geothermal system is located within a right-step in the Fish Creek mountains western range-bounding fault. The stepping nature of this fault system has resulted in a diffuse zone of faulting referred to as the Fish Creek Mountains fault zone (FCMFZ). Within the FCMFZ, variability of individual fault-strike orientations result in secondary fault intersections within the larger right step-over. This creates a hybrid fault step-over/ fault intersection structural setting. Slip and dilation tendency calculations, for individual faults, have pinpointed faults preferentially oriented for slip and dilation in the current north-northwest directed extensional regime, however shallow temperature measurements indicate that primary geothermal upwelling is controlled by a fault intersection rather than dilation of an individual fault.

Introduction

Within the Basin and Range, the primary factors controlling secondary permeability are structural. North–northeast striking faults ((due) North-N60ºE) control ~75% of the geothermal fields within the Basin and Range (Faulds et al., 2004; 2011; Bell and Ramelli, 2007; 2009; Coolbaugh et al., 2002). Northeasterly striking faults are preferentially oriented to dilate in the current northwest- directed extensional strain field (Figure 1; Bell and Ramelli, 2007; 2009; Faulds et al., 2004; 2011). Though a strong correlation exists between north-northeast striking faults and geothermal systems, not all north-northeast striking faults host geothermal systems, nor are all Basin and Range geothermal systems associated with north-northeast striking faults (Bell and Ramelli, 2007; 2009; Faulds et al., 2011).

It is possible to narrow down preferential structural settings even further as a handful of structural settings have been found to host the majority of Basin and Range geothermal systems. Conducive structural settings include major fault terminations, fault intersections, discrete fault step-overs, accommodation zones, and hybrids of these structural settings (Faulds et al, 2006, 2010, 2011, 2013). These additional classifications can be utilized to facilitate recognition of geothermal activity hosting faults or fault segments (Figure 2).

In addition to fault orientation and structural settings, age of faulting is yet another factor that influences fault permeability. A strong statistical correlation has been observed between Holocene faulting (<10 ka) and geothermal activity (Bell and Ramelli, 2007; 2009). Out of 37 Basin and Range geothermal systems studied, 31 were closely associated with mapped Holocene faults (Bell and Ramelli, 2007). A subsequent investigation of 6 systems, seemingly void of Holocene faulting, yielded evidence of Holocene-age faults at all 6 sites (Bell and Ramelli, 2009). Holocene faults offer fresh conduits, not choked by gouge, and potential unimpeded fluid flow (Bell and Ramelli, 2007; 2009).

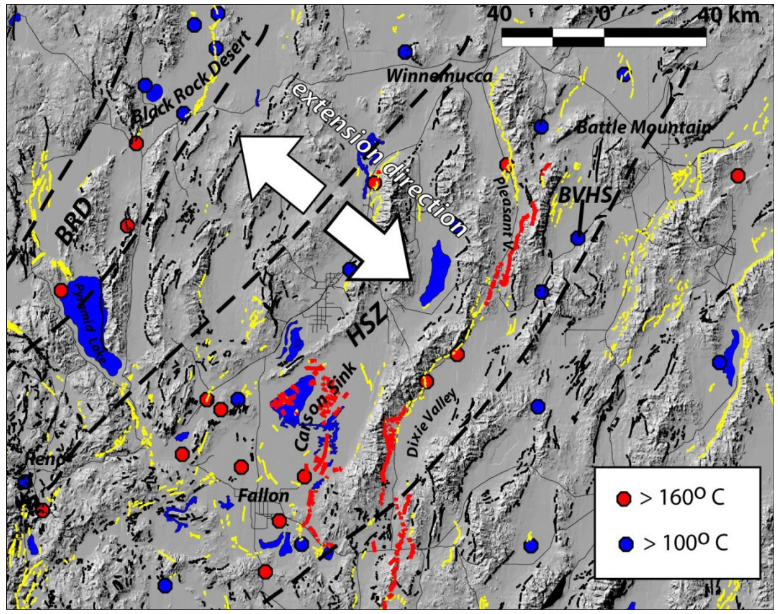

Figure 1. Figure after Bell and Ramelli (2007; 2009). High temperature geothermal sites in north-western Nevada (>100ºC), blue dots indicate geothermal systems 100ºC-160ºC, red dots indicate geothermal systems >160ºC, historical fault ruptures are indicated in red and Holocene faults are indicated is yellow. BVHS = Buffalo Valley hot spring, HSZ = Humboldt Structural Zone, current extension direction is indicated by white arrows.

BVHS is a high temperature geothermal system (>100ºC) that lies within the boundaries of the Humboldt Structural Zone (HSZ). The HSZ is a band that stretches from west-central Nevada to south-western Idaho, noted for abundant high temperature geothermal systems including Dixie and Jersey Valleys (Figure 3; Faulds et al., 2004). Geothermometric calculations indicate reservoir temperatures equal to 125ºC at BVHS (Mariner et al., 1974). This system is expressed surficially, on the eastern valley basin floor, as abundant hot seeps emerging from a ~600 meter diameter travertine mound. This mound rises subtly above the modern playa deposits and Pleistocene Buffalo lake lacustrine sediments, beach deposits, and near shore dunes.

Prior to this study, very few Quaternary faults were mapped in the eastern Buffalo Valley and Fish Creek mountains (Figure 4). Likewise, a geophysical survey interpreted the valley as an asymmetrical graben with a large normal fault along the eastern Tobin range and no major faulting along the eastern basin boundary (Wollenberg et al., 1975).

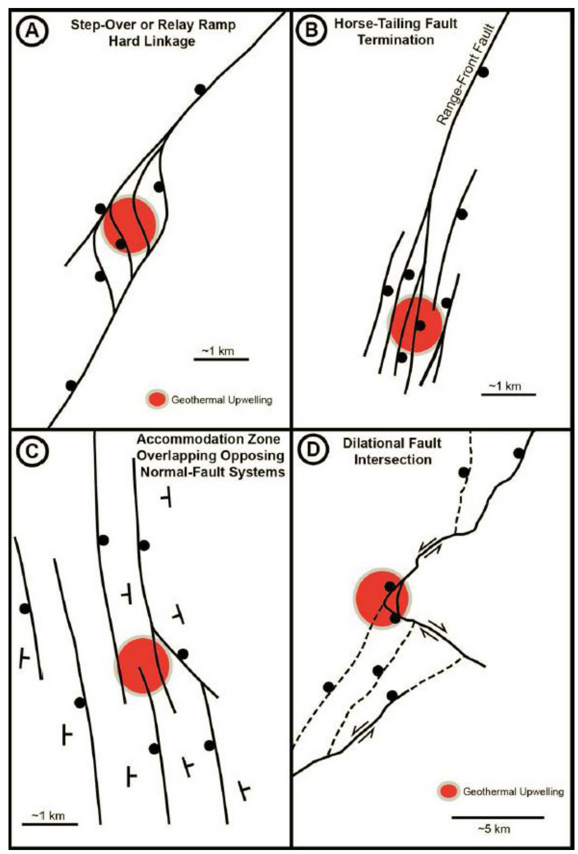

Figure 2. From Faulds et al. (2010; 2011; 2013), showing four of the most common structural setting for geothermal occurrence within the Basin and Range province. Fault step-overs are most prevalent, controlling ~33% of known Basin and Range geothermal systems (Cashmen et al., 2012).

Methodology

Geologic Mapping

Aerial photography has been utilized for many years in mapping and surveying of the Earth. Stereo pairs of photos taken at high elevation are exceptionally helpful in discerning faults and lineaments that may not be obvious from the ground. This method is particularly useful when dealing with surficial and poorly indurated geologic units. It is often advantageous to pair aerial photo mapping with field investigations for enhanced structural understanding of a study area, as was done during this investigation. Approximately 100 km^2 of both bedrock and surficial geologic units were mapped at 1:24,000 scale using both aerial photos and topographic maps as bases, during this study. Mapping formed the basis of funding for this project, and was provided by the U.S. Geological Survey EdMAP program (Agreement No. G14AS00005). Strong emphasis was placed on recognition of previously unrecognized faulting in the vicinity of BVHS.

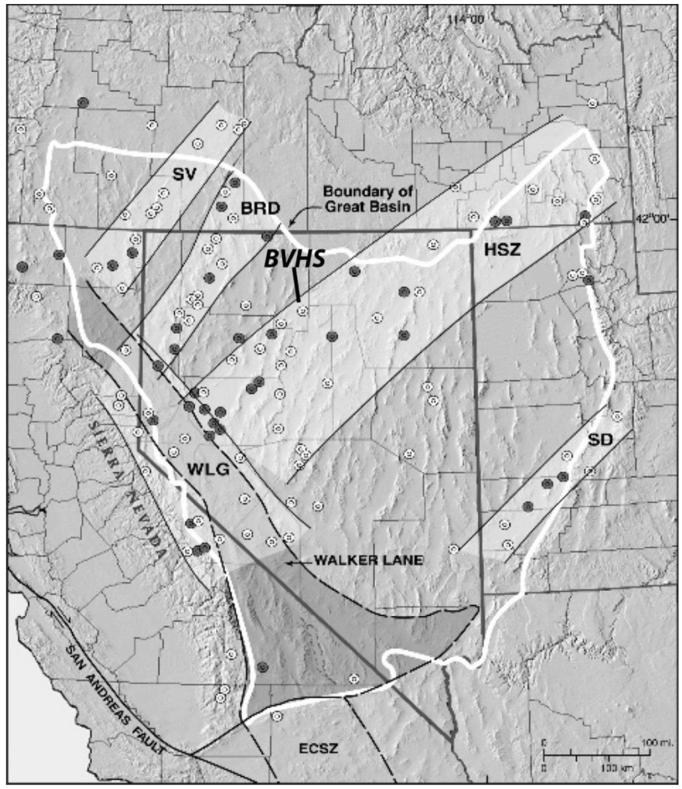

Figure 3. Figure after Faulds et al. (2004). Known geothermal systems located within the Great Basin. Shown geothermal fields are grouped in the Sevier Desert (SD), Humboldt Structural Zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. White circles represent geothermal systems with maximum temperatures of 100°C-160°C; Gray Circles have maximum temperatures >160°C, ECSZ = Eastern California Shear Zone, White solid outline = boundary of the Great Basin, BVHS = Buffalo Valley hot spring.

Slip and Dilation Tendency

Critically stressed faults are more likely to be utilized as fluid conduits. These faults have a history of rupture, are actively accommodating crustal stresses, and are primed for future rupture. Active faults are not likely to be choked by fault gouge and offer clear paths for fluid circulation (Bell and Ramelli, 2007). Likewise faults that are preferentially oriented to be dilated in the current north-northwest directed extension are likely sources of lithospheric permeability.

3D Stress is a computer program that facilitates rapid calculations of fault shear and normal stresses, slip tendency, and dilation tendency. To begin calculations, a three dimensional stress field must be input into the program. The stress field utilized for this study was published by Zoback (1989) at Cortez, NV (Sigma 1=188/84; Sigma 2=43/-05; Sigma 3=133/04). Using this stress field, slip and dilation tendency calculations were modeled for faults located within 5 km of BVHS. These faults were identified during the mapping phase of this project.

Two-Meter Temperature Survey

Shallow temperature surveys are an effective method for delineating thermal aquifers, and their reduced cost and time commitment, when compared to deep drill temperature surveys, give this technique distinct advantages (LeSchack and Lewis, 1983; Coolbaugh et al., 2007b; and Sladek et al., 2007). In addition to time and monetary advantages, this method also allows for flexibility during field execution. Drill-hole locations can be easily adjusted to accommodate field conditions and additional data sets can be painlessly related to previously collected data.

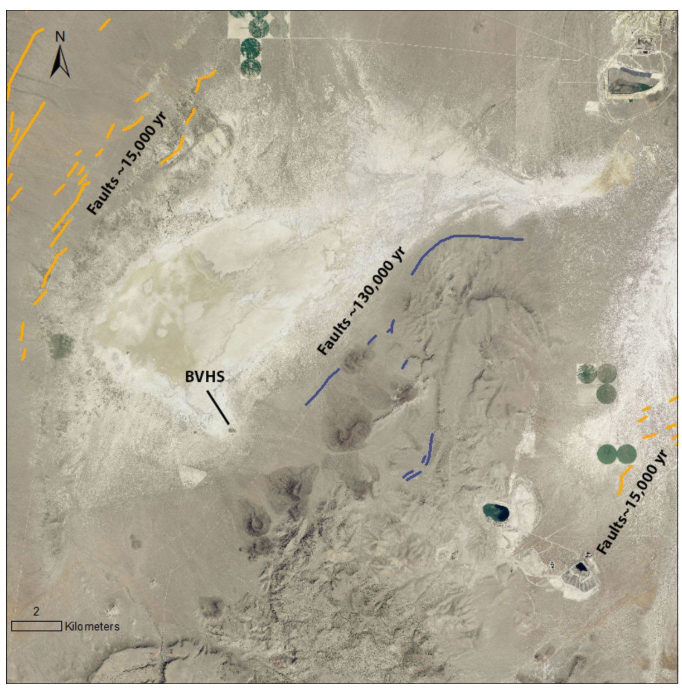

Figure 4. NAIP imagery of eastern Buffalo Valley and northern Fish Creek Mountains with faults from the U.S.G.S. Quaternary Fault and Fold database displayed. The estimated age of blue faults ~130,000 years and yellow faults ~15,000 years , BVHS = Buffalo Valley hot springs. According to the U.S.G.S. Quaternary Fault and Fold Database, no faulting is currently recognized within 3.75 km of Buffalo Valley hot springs, and no Holocene faults are recognized in the vicinity of the BVHS or northern Fish Creek mountains (U.S. Geological Survey, 2006).

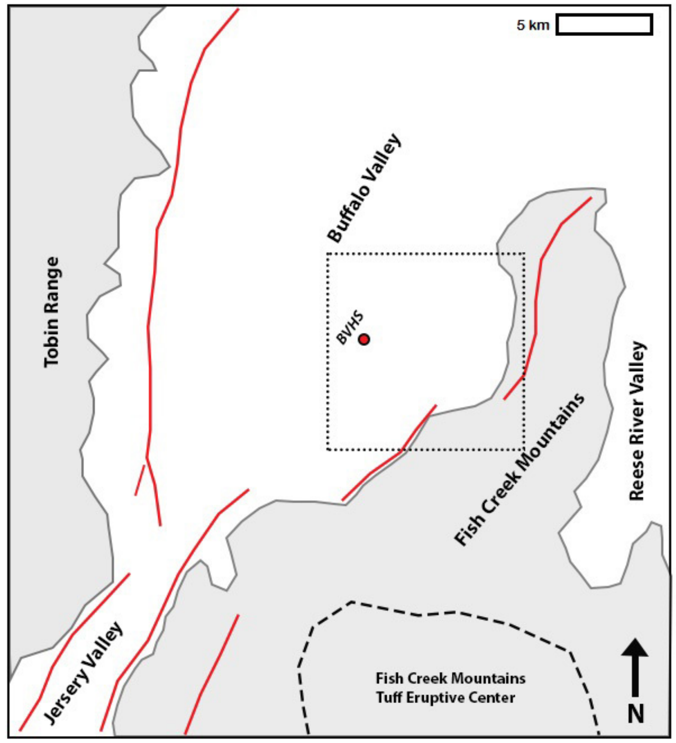

Figure 5. Diagram showing the major Buffalo and Jersey Valley basin-bounding geologic structures. Along the Tobin range a nearly continuous single fault trace is visible. Conversely, the eastern basin boundary is characterized by multiple right step-overs. The dotted box outlines the area covered by Figure 6.

An eighty-two point shallow temperature survey was conducted, at two-meter depth, during this investigation. Temperatures recorded at two-meter depth are not subject to diurnal changes, but are subject to seasonal changes. Data was collected at three different dates and corrected using simple seasonal temperature calibration equations prior to converting measurements to Degrees Above Base (DAB). Once data sets were converted to DAB, they could be directly related to each other.

Results

Fault Architecture, Locations, and Orientations

Jersey Valley is located immediately south of Buffalo Valley and is bounded to both the east and west by normal faults. These faults continue into Buffalo Valley forming the east and west boundaries of this valley, as well. The Tobin Range front fault, forming the western basin boundary, is active with well-formed faceted spurs and a linear near-continuous alluvium-rupturing fault trace. Rather than a single linear fault, the eastern bounding fault is made of several right-stepping normal faults (Figure 5). One of these fault step-overs is located up-gradient and adjacent to Buffalo Valley hot springs.

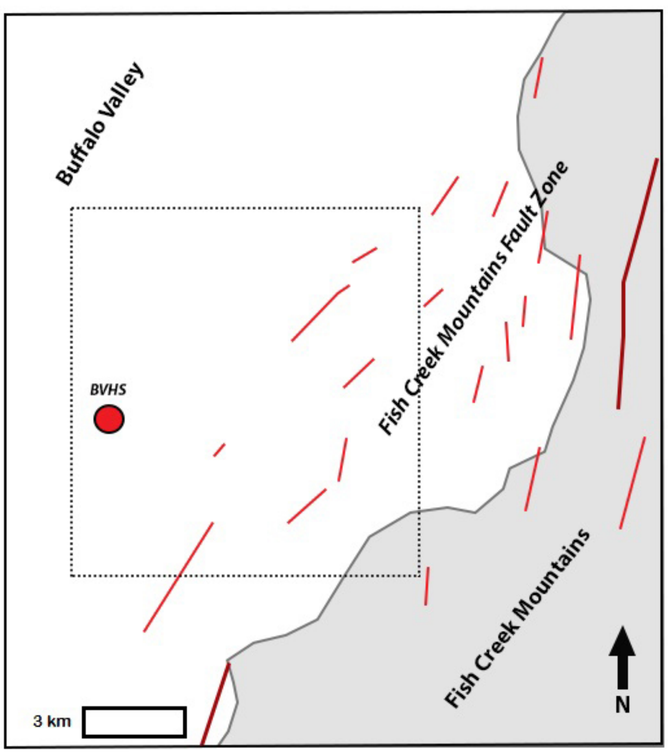

Figure 6. Diagram of the west-central Fish Creek mountains and a small portion of the eastern Buffalo Valley basin. Dark red faults represent large step-over faults and lighter red faults represent smaller faults within the step-over system. This diffuse zone of faulting makes up the Fish Creek Mountains Fault Zone (FCMFZ). The dotted box outlines the area covered by **Figure 8**.

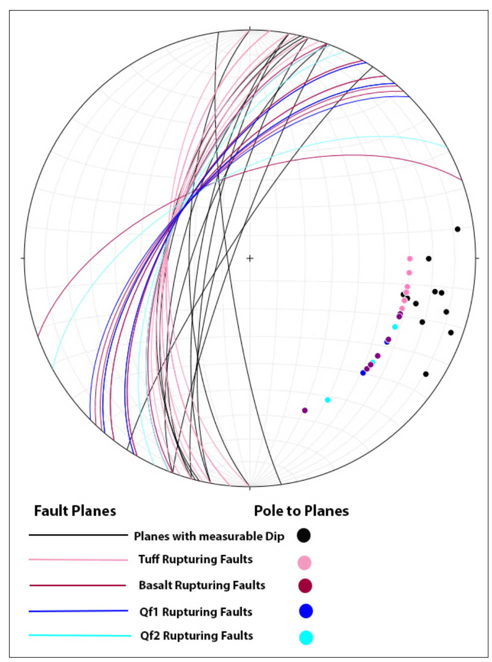

Figure 7. Allmendinger stereonet displaying the orientation of 40 mapped faults along the western Fish Creek mountains range front. Fault planes are indicated as great circles on the stereonet and poles indicated by circles. Faults are color coded by observable geologic units that are ruptured. Faults without a measurable dip are assumed to dip 60°, the textbook dip of normal faults. Units: Tuffs- ash flow tuffs of Eocene to Oligocene age; Basalts- cinder cones and flows of Pleistocene age; Qf1- older fan deposits of late Pleistocene age; Qf2- younger fan deposits of Holocene age.

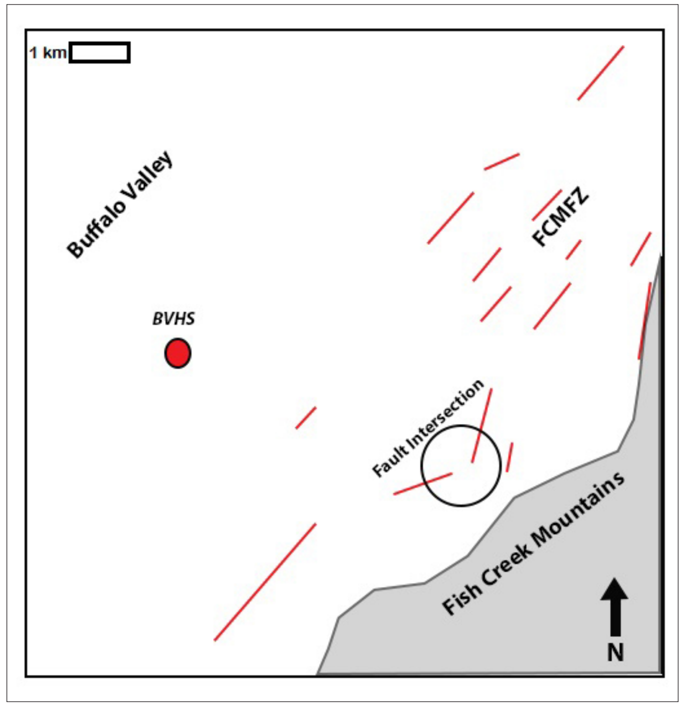

Figure 8. Diagram of proximal faults to BVHS with probable fault intersection that is located 3.5 km up-gradient of BVHS delineated by a circle. BVHS= Buffalo Valley hot spring, FCMFZ= Fish Creek mountains fault zone.

During mapping, many smaller faults were identified between the discrete right-stepping faults, along the eastern basin boundary, that are not currently included in the U.S. Geological Survey's Quaternary Fault and Fold Database (U.S. Geological Survey, 2006). These smaller faults are part of a diffuse fault zone referred to as the Fish Creek Mountains Fault Zone (Figure 6; FCMFZ). The dominant strike direction of the faults within the FCMFZ, varies between 172º and 220º, averaging 200º. These faults rupture Paleozoic, Tertiary, Pleistocene, and Holocene age units. Two discordant faults strike at 241º and 250º and rupture Holocene and late Pleistocene fan units and Quaternary basalt flows respectively (Figure 7). Variations of individual fault strikes within the larger fault step-over provide the opportunity for secondary fault intersections. One such fault intersection is located ~3.5 km east and up-gradient from BVHS (Figure 8).

Potential Fluid Conduits

Slip and dilation tendency calculations were performed on fifteen faults located within 5 km of BVHS (Figure 9). Of fifteen analyzed faults only fault #6 provided measurable dip. Slip and dilation tendencies were calculated assuming a dip of 60º for the other fourteen faults without field verifiable dip. These calculations were performed using the program 3D Stress assuming the stress regime published by Zoback (1989) at Cortez, NV. During analysis in 3D Stress, all fifteen faults were found to have dilation tendencies higher than 0.674 on a 0-1 scale, and slip tendencies greater than 1.141 on a 0-2.12 scale. Fault #6 possessed both the highest slip and dilation tendency with values of 1.935 and 0.955 respectively (Figure 9).

Upwelling Zones

Temperature readings were collected at two-meter depth from 82 locations across an area of ~28 km^2, focusing on the area between Buffalo Valley hot springs and the Fish Creek mountains. Care was taken to collect readings down gradient of observed Quaternary fault scarps and within drainages. Several attempts to emplace probes in drainages were unsuccessful due to alluvium obscured lava flows. Elevated temperatures were found just east of the travertine mound, near the base of several cinder cones, and in a channel-like pattern down the length of the fan located directly east of the springs. The highest thermal readings were detected east of the springs and at the mouth of the fan (+2.0< DAB<+3.9) (Figure 10). Temperature measurements from all three campaigns were analyzed in relation to background temperatures. Resulting temperature calculations ranged from -2.4 to 3.9 Degrees above Base (DAB).

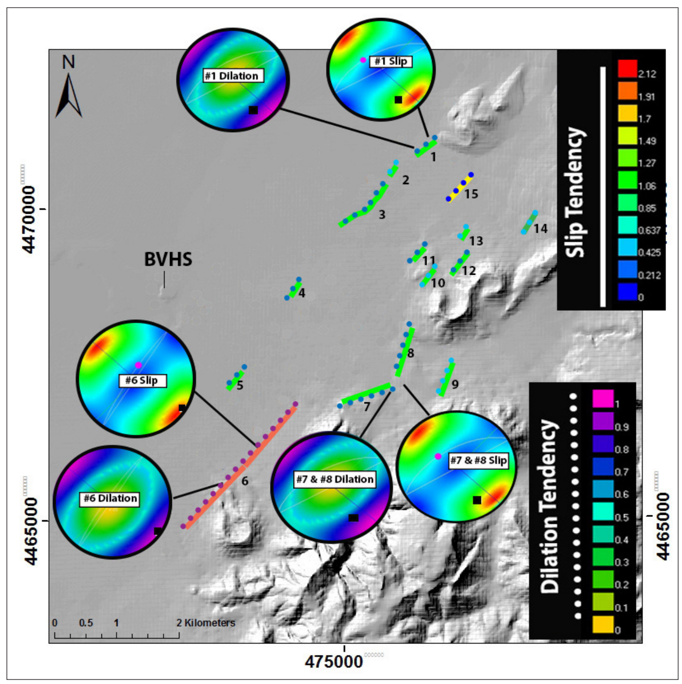

Figure 9. Figure shows fifteen faults that are located proximal to BVHS color coded by slip and dilation tendency. Slip tendency is indicated by the solid fault line color and dilation tendency is indicated by the color of the overlying dotted line. A key is included for both data sets above. Stereonet slip and dilation plots are also provided for faults #1, #6, and #8 that were generated using the program 3D Stress. The black square located in each stereonet diagram represents the pole to the fault plane represented by the diagram. The color zonations indicate the magnitude of slip and dilation tendencies calculated by 3D Stress and follow the relative keys included in the figure above. Fault #6 possesses both the highest slip and dilation tendency and Fault #15 has the second highest slip and dilation tendency. Faults #7 and #8 form a fault intersection located up-gradient from BVHS (Figure 8), but do not show notably high slip or dilation tendencies.

Conclusions

Upwelling at the Buffalo Valley geothermal system sits within a large right step-over in the eastern Buffalo Valley basin bounding fault. This is one of the four most common structural settings to host Basin and Range geothermal systems (Faulds et al, 2006, 2010, 2011, 2013). Within this larger fault step-over, strike orientations of smaller faults vary forming at least one fault intersection (faults 7, 8). These two settings together form a hybrid geothermal structural setting. Hybrid settings are the most accommodating structural scenario for geothermal systems and subsequent geothermal exploration (Faulds et al., 2013).

Though individual faults within the FCMFZ are found to have higher slip and dilation tendencies than faults 7 and 8, the primary zone of upwelling appears to be controlled by this fault intersection as demonstrated by the two-meter ground temperatures. This can be explained by increased permeability and/or dilation formed by the physical interaction of these two faults. Two minor heat anomalies were also identified during the shallow temperature survey. These more subtle anomalies are directly down gradient from faults 6 and 15. Faults 6 and 15 were found to have the highest and second highest slip and dilation tendencies of the 15 faults analyzed. These anomalies may be related to lesser zones of upwelling caused by dilation of faults 6 and 15, but do not have independent surficial expressions.

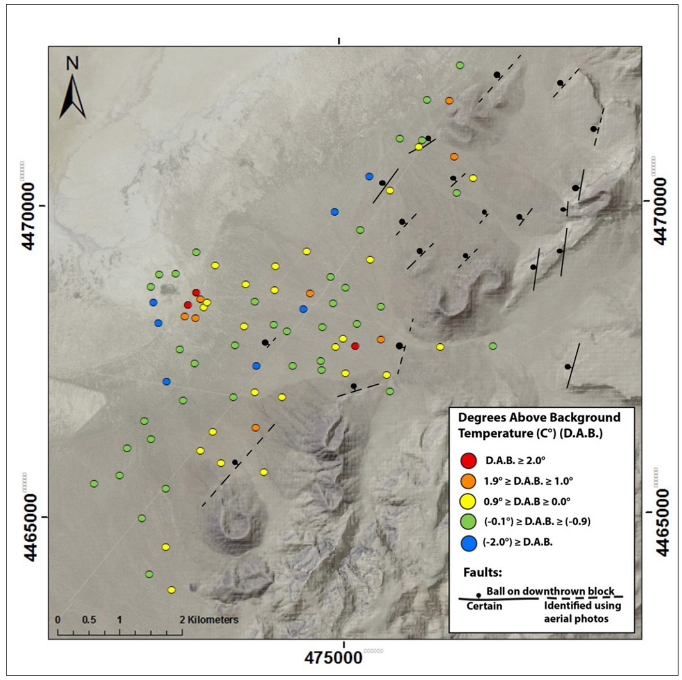

Figure 10. Results of the two-meter temperature survey plotted by GPS coordinates in ArcMAP. Normal faults are indicated by solid and dashed lines. Solid faults=field proven; Dotted= identified using aerial photos. The primary heat anomaly is observed down gradient of the identified fault intersection (Figures 8 & 9) and below Fault #6 & #15 following the fault numbering of Figure #9.

Acknowledgments

This study was supported by EdMAP Agreement No. G14AS00005 for the geologic mapping of eastern Buffalo Valley and western Fish Creek mountains.

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