Active Faults and Neotectonics at Geothermal Sites in the Western Basin and Range: Preliminary Results

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ABSTRACT

Although a general association of high-temperature geothermal sites and the structural controls provided by faults is evident in the spatial patterns of the western Great Basin, the ages of these faults are poorly known. In this study, we utilize low-sun-angle aerial photography together with field investigations to characterize the age and recency of faulting associated with selected geothermal sites. Although many Quaternary-age faults are distributed across the western Great Basin, nearly all high-temperature sites are spatially associated with Holocene (<10-13 ka) faults.

Preliminary results show that of a total of 37 high-temperature sites, 31 sites occur directly on, or in close proximity, to seismically active Holocene faults. Five of these sites are on faults that are structurally related to historical surface ruptures produced by large magnitude earthquakes. New Holocene fault traces have been detected at several sites, including sites in the Needle Rocks, Empire, and Kyle thermal areas. Further work is being conducted on other similar sites, but these preliminary results suggest that the age of faulting, in particular the occurrence of Holocene activity on the fault, is an indicator of recent levels of crustal strain release and may provide an exploration tool in assessing geothermal potential along a given fault structure.

Introduction

The association of non-magmatic geothermal resources and geologic structure in the western Great Basin is well known, with most exploration efforts directed toward targeting the controlling fault structure. A spatial comparison of high-temperature geothermal sites with known Quaternary-age faults in the western Great Basin (Figure 1) shows that many of the sites are located along faults, in particular, many are located along range-bounding faults. Previous studies have noted this relation, but they have largely focused on localized fault stress-strain relations that would account for the dilation of fault apertures permitting upward movement of geothermal water. A common approach in these studies has been the application of state-of-stress models that predict favorable coulomb stress changes occur-

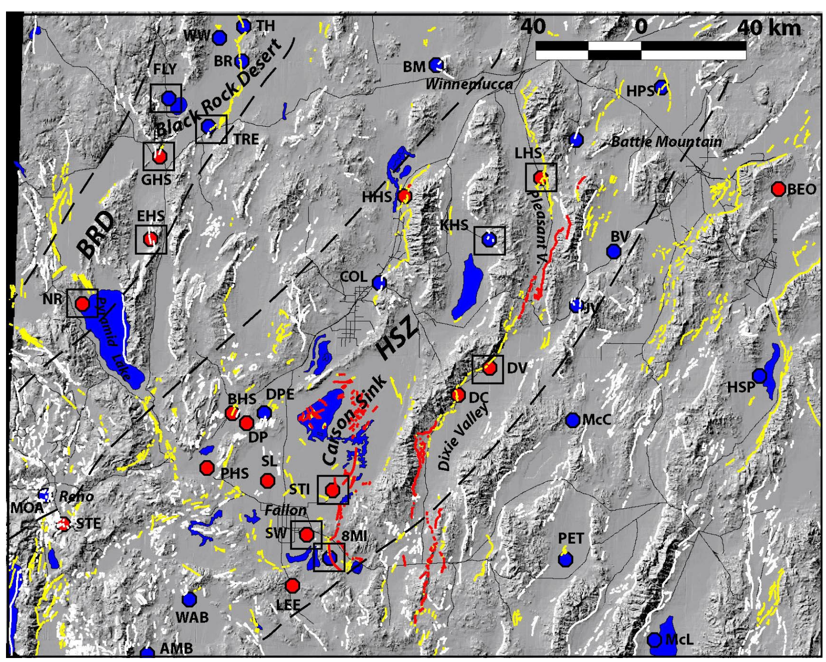


Figure 1. Principal high-temperature (>100°C) geothermal sites in the western Nevada region; blue dots indicate temperatures of 100-160°C; red dots indicate temperatures >160°C (data from Coolbaugh *et al.,* 2003). The Black Rock Desert (BRD) and Humboldt structural zones (HSZ) are from Faulds *et al.,* 2005). Pleistocene-age faults (pre-Holocene) shown in white; Holocene faults (<10-13 ka) shown in yellow; historical fault ruptures shown in red (Bell, 1984; USGS, 2003). Sites currently under investigation are marked by boxes; site labels are listed in Table 1.

ring at fault rupture endpoints (Caskey and Wesnousky, 2000; Wesnousky and Tempel, 2004). These studies have generally concluded that no first-order associations between observed and predicted sites occur.

More recent studies have begun to focus on the role that regional crustal strain plays in controlling geothermal sites. The tectonic framework of the western Great Basin is driven largely by the Walker Lane belt, a broad zone of northwest-oriented dextral shear. Currently favored models which utilize the strain relations associated with the Walker Lane belt in predicting preferred geothermal sites show that fault structures optimally oriented in the Walker Lane belt extension direction (north-northeast-striking) are likely to exhibit dilational strain, and that more than 75% of the geothermal fields in Nevada and western California are controlled by north-northeast-striking structures (Faulds *et al*., 2005. The principal geothermal sites can be broadly grouped into two regional trends in the western Nevada region: the Humboldt structural zone, and the Black Rock Desert structural zone (Figure 1). Contemporary geodetic strain (GPS) measurements support this model and also predict that extensional strain on northeast-trending structure is a major component controlling geothermal activity (Blewitt *et al*., 2003).

Although these regional tectonic models can account for many geothermal occurrences, not all geothermal sites are on north-northeast-striking faults, and conversely, not all northeast-striking faults are preferred geothermal sites (Figure 1), indicating that there are other contributing factors. In this study, we propose a simple model in which the age of most recent faulting is a criterion for potential geothermal resources occurring along fault structure. Surface fault ruptures in the Basin and Range province are generally associated with large earthquakes, in the magnitude range of M6.5-7.6 and typically occurring at crustal depths of 10-15 km. Such earthquakes release comparably large amounts of crustal strain, most of which is localized along or near the fault rupture, likely providing a mechanism for opening new pathways for geothermal water to reach the surface from deep crustal depths. In order to further investigate the validity of this model, we have been examining spatial and temporal characteristics of faults at selected geothermal sites and investigating the neotectonic behavior, in particular the age of most recent faulting, in order to better understand how this relation may be a potential exploration tool. In this paper, we present the preliminary results of our analysis of fault and neotectonic characteristics associated with several high-temperature geothermal sites.

Methodology

Holocene-age (<10-13 ka) faults display geologically recent surface ruptures and are considered to be seismogenic features in the Great Basin, that is, faults along which crustal strain is likely to be released again in the near future. Such faults are easily identified throughout most of the western Nevada basins because of the widespread distribution of lake strandlines associated with the last major cycle of pluvial Lake Lahontan at about 13 ka. Fault traces which post-date these shorelines can thus be differentiated from older Pleistocene faults that pre-date this lake cycle. In addition, detailed Quaternary stratigraphic studies have provided age data on young faults further allowing the age classification of most faults in the region (cf., Bell, 1984; USGS, 2003).

Based on the compilation by Coolbaugh et al. (2003), there are 37 geothermal sites within the western Nevada region that have maximum temperatures of 100º C or greater (Table 1). In this study, we have focused on these 37 sites in order to determine the relation of selected sites to young fault structures. A spatial comparison of these sites with known Holocene faults shows that many of the sites are associated with these faults (Figure 1). In order to further characterize the faults at these sites, we have conducted more detailed studies to determine the presence and age of the associated faults.

Table 1. Holocene faults associated with geothermal systems having maximum temperatures of 100°C or greater (Coolbaugh *et al.,* 2003). Site labels correspond to Figure 1 location map. New faults identified by low-sun-angle aerial photography are noted.

Geothermal Site	Holocene Fault
Ambassador AMB	Smith Valley
Beowawe BEO	Beowawe (Malpais)
Black Rock Hot Springs BR	Black Rock; new faults found
Blue Mountain BM	Blue Mountain
Bradys Hot Springs BHS	Bradys
Buffalo Valley Hot Springs BV	North Fish Creek Mountains
Colado COL	West Humboldt Range
Desert Peak DP	Hot Springs Mtns
Desert Peak East DPE	Hot Springs Mtns
Dixie Comstock DC	Stillwater Range; 1954 ruptures
Dixie Valley DV	Stillwater Range; 1954 ruptures; new faults found
Eightmile Flat 8MI	Eightmile Flat; new 1954 ruptures found
Empire EHS	San Emidio; new faults found
Fly Ranch (Wards) Hot Springs FLY	None previously mapped; new faults found
Gerlach GHS	Gerlach; new faults found
Hot Pot Hot Springs HPS	Ellison Siding
Hot Springs Point HSP	None mapped
Humboldt House HHS	West Humboldt Range
Jersey Valley JV	Jersey Valley
Kyle Hot Springs KHS	East Range; new faults found
Leach Hot Springs LHS	Tobin Range; 1915 ruptures
Lee (Allen's) Hot Springs LEE	None mapped
McCoy McC	None mapped
McLeod 88 McL	None mapped
Moana MOA	Sierra Nevada
Needle Rock NR	Terraced Hills; new faults found
Patua (Hazen) Hot Springs PHS	Hot Springs Mtns
Peterson PET	Desatoya Mountains
Salt Wells SW	None previously mapped; new faults found
Soda Lake SL	None mapped
Steamboat STE	Sierra Nevada
Stillwater STI	1954 ruptures
TH Hot Springs TH	Black Rock
Tipton TIP	Edna Mountain
Trego Hot Springs TRE	Black Rock; new faults found
Wabuska WAB	Wabuska
WW 392 WW	None mapped

Low-sun-angle (LSA) aerial photography is commonly utilized in neotectonic studies to identify and map small, young, fault ruptures not visible on standard aerial mapping photography. LSA photography is commonly flown when the sun is between 10-25° above the horizon in early morning and late afternoon, resulting in illumination or shadowing of the fault scarp depending on the orientation of the fault. The photography is flown at large scale (1:12,000) to enable the detection of fault scarps 30 cm or less in height. Previous experience with LSA photography in the western Great Basin has shown that additional new fault traces are very commonly detected in areas previously mapped, and that many areas thought to be lacking Holocene faults are found to have faults present.

Following the identification of fault traces on LSA aerial photography, field studies were conducted to examine and radiometrically date the fault-stratigraphic relations, including the detailed analysis of fault relations exposed through exploratory trenching. These studies are currently in progress.

Preliminary Results

A comparison of the distribution of high-temperature geothermal sites with faults (Figure 1) indicates that while the sites are associated with only a minor fraction of the total number of Quaternary faults (Figure 1), they are clearly associated with Holocene faults. Of the 37 high-temperature geothermal sites shown in Figure 1, 31 of these sites are associated with Holocene faults (Table 1). In many cases, the association is direct, that is, the geothermal site lies directly on the fault trace, or is in close proximity, such as occurring on the hanging wall block of the fault trace. Examples include the Empire, Kyle Hot Springs, and Needle Rocks sites, discussed below. Importantly, five of the sites occur within historical fault rupture zones: Dixie Comstock and Dixie Valley (between 1915 Pleasant Valley and 1954 Dixie Valley rupture zones), Leach Hot Springs (at north end of 1915 Pleasant Valley rupture zone), Eightmile Flat and Stillwater (within 1954 Rainbow Mountain rupture zone).

Eightmile Flat

Examination of the Eightmile Flat geothermal site now indicates that the 1954 Rainbow Mountain fault ruptures (Caskey *et al.*, 2004) extend directly through the site (Figure 2). The thermal springs were the site of an 1870 borate mine, and right-lateral displacement of the berms associated with mining activity are visible on the LSA photography and on the ground.

Needle Rocks

Although the Needle Rocks geothermal site was known to be structurally controlled (Faulds *et al.*, 2005), the age of most recent faulting was previously unknown. Through the use of LSA photography, we have identified and dated three separate Holocene fault traces that lie immediately east of Needle Rocks: the Terraced Hills, Fox Canyon, and Fox Range fault traces. These are all west-dipping fault structures, and the Needle Rocks area lies in the hanging wall of this fault set. The youngest fault of this set is the Terraced Hills trace which cuts late Holocene shoreline deposits of Pyramid Lake (Figure 3, overleaf).

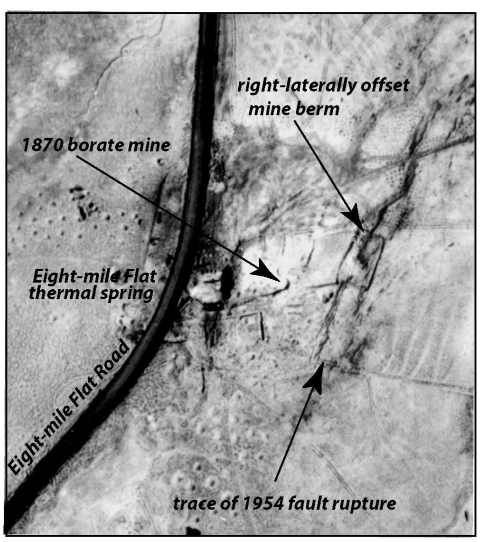
Empire

The distribution and age of faults associated with the Empire geothermal site were previously poorly known (USGS, 2003). New LSA photography now reveals that multiple Holocene fault traces extend from the Pyramid Lake area through the southern San Emidio Desert into the Empire thermal site (Figure 4, overleaf). These faults are of similar mid- to late Holocene age and are possible structurally connected with the faults near Needle Rocks.

Kyle Hot Springs

The Kyle Hot Springs geothermal site is one of several sites (including Needle Rocks) where the thermal spring is located directly on a northwest-striking fault (in contrast to the dominant northeast-striking pattern), and prior to this study the age of the faulting was believed to be pre-Holocene (Figure 1). Our study now shows that this fault exhibits a Holocene rupture history (Figure 5). Although the site lies above the 10-13 ka shorelines of Lake Lahontan, mapping of faulted alluvial fan deposits indicates that the faulted deposits are younger than the Lahontan shorelines.

Our fault study also suggests that the occurrence of



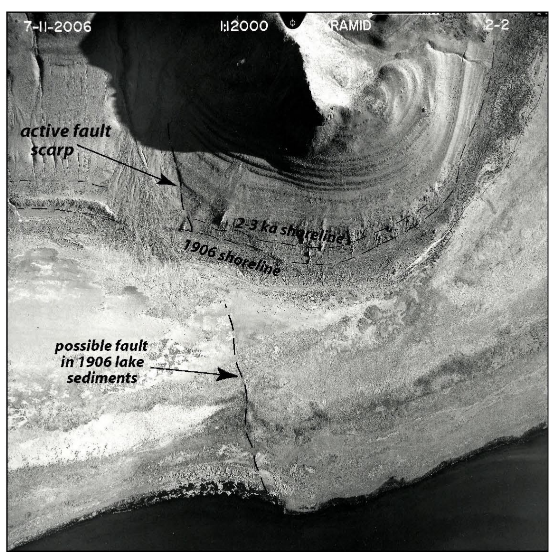
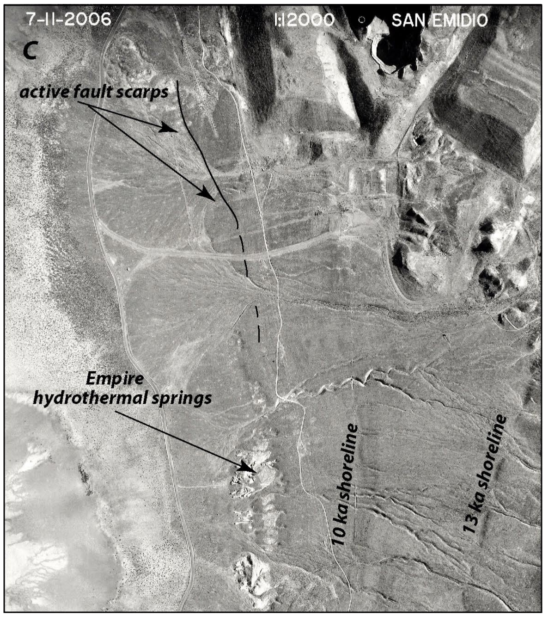


Figure 2 (left). Low-sun-angle aerial photograph of the Eightmile Flat geothermal site. Fault traces from the 1954 Rainbow Mountain event extend through the site and laterally offset berms constructed around the borate mine at the spring site.

Figure 3 (right). Low-sun-angle aerial photograph of the Terraced Hills fault trace east of Needle Rocks at the north end of Pyramid Lake. Fault cuts 2-3 ka shoreline deposits and may extend into 1906 lake sediments that are now exposed.



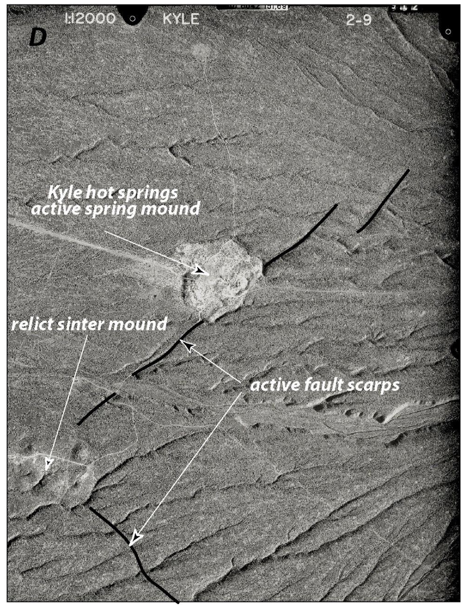


Figure 4 (left). Low-sun-angle aerial photograph of the Empire geothermal area showing previously undated fault scarp extending through the spring site. Fault is mid- to late Holocene age based on the fact that it post-dates several shorelines that are younger than 10-13 ka.

Figure 5 (right). Low-sun-angle aerial photograph of Kyle Hot Springs. Active and relict spring mounds are located directly on Holocene fault scarps which at this location exhibit a zigzag fault geometry.

the thermal area along a northwest-striking fault can be in part explained by the irregular geometry of the fault trace. Although the overall strike of the fault is northwest-trending, the detailed fault geometry exhibits a salient-reentrant pattern (zigzag geometry); a similar geometry is seen at the Leach Hot Springs site. Such zigzag geometry may facilitate the mechanical dilation of the fault and fracture system as the fault blocks move down along a saw-tooth range-front fault trace during normal faulting events.

Conclusions

A preliminary analysis of the structural controls on high-temperature geothermal sites in the western Great Basin using low-sun-angle aerial photograph methodologies coupled with field investigations indicates that most of the sites are spatially associated with seismically active Holocene-age faults. Out of a total of 37 high-temperature sites, 31 sites are located directly on or in relative close proximity to Holocene faults. Five of the sites are associated with fault structures that have ruptured during large magnitude earthquakes during the last 100 years. Although the study is in progress, it is highly likely that further analysis will show that other sites not presently associated with any obvious faults will also be found to contain unrecognized faults of Holocene age.

This spatial association of high-temperature geothermal sites with seismically active faults supports the conceptual model that geothermal potential may be related to recent crustal strain release along faults. Although there are many Quaternary faults in the western Great Basin, not all are sites for geothermal activity, including faults which are in favorable north-northeast-striking orientations. This suggests that other variables are present which further control whether certain faults will provide apertures for the upward movement of thermal fluids. Further work may reveal a consistent relation between the youngest age of faulting, or the timing of most recent strain release on the fault, and the occurrence of thermal sites. This work will include the collection of neotectonic data which can show how much of the faulting at geothermal sites has occurred in the last 1,000-2,000 years. These results may lead to the utilization of active fault behavior as an exploration tool in identifying and segregating sites of potential geothermal resources.

Acknowledgments

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