

Structural Controls of the MacFarlane Geothermal System, Humboldt County, Nevada: A Progress Report

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ABSTRACT

The MacFarlane geothermal system is located ~85 km west of Winnemucca on the eastern margin of the Black Rock Desert, in Humboldt County, Nevada. An E-trending travertine mound, ~180 m long, and up to ~2 m tall and ~5 m wide, has a central fissure ridge along its long axis and an active hot springs flowing out of its west end. Reservoir temperatures were estimated at 80° – 140° C (Sibbett et al, 1982). Detailed geologic mapping, structural analysis and two-meter temperature data analysis integrated with previous datasets suggest the structural controls of the MacFarlane geothermal system, which include a NS-striking, west-dipping Tertiary fault east of MacFarlane hot springs, a NNE-striking, west-dipping Quaternary fault set directly surrounding the hot springs and a ENE-striking fault mapped just north of the hot springs by Sibbett et al. (1982). Although the highest temperature gradient is found at a proposed intersection between the Tertiary and Quaternary fault sets (Sibbett et al, 1982; Swanberg et al, 1982), other scenarios involving the geometry of the Quaternary faults and/or a combination of structural scenarios need to be considered. MacFarlane hot springs and the travertine mound lie between two Qua-

ternary faults, in a dextral step-over or relay ramp zone. The controls on the anomalously orientated travertine fissure ridges might be due to perturbations in the stress field during relay ramp formation, perturbations in the stress field related to a single fault termination, or a buried EW-striking fault. Many of these faults are covered in Quaternary sediments, so a geophysical survey and more detailed Quaternary mapping are in progress to resolve the specific structural setting here.

Introduction

Although the structural settings of many geothermal systems in the Basin and Range are well understood, the controlling factors for specific systems are often unclear. In the Basin and Range, geothermal systems are generally found in NNE-trending belts (e.g. Faults, 2004), near ranges bounded by normal faults; however, it is the smaller faults and fractures that commonly control the permeability in these systems. Therefore it is imperative to completely understand the structure of a system. Geothermal systems typically have upwelling and outflow zones, and it is important to distinguish these from each other in order to efficiently develop the geothermal resource.



Figure 1. Photo on left shows main travertine mound, looking west. The Southern Jackson Mountains are shown on the horizon on the left side of the photo. The photo on the right shows an example of fissure ridges within the large travertine mound.

MacFarlane hot springs, located in Humboldt County, Nevada, about 85 km west of Winnemucca, emerges from a prominent E-trending travertine mound; this suggests local NS extension, which is anomalous in the region. It has been shown that travertines with central fissure ridges are commonly structurally controlled (e.g. Brogi and Capezzuoli, 2009; Handcock et al, 1999; Altunel and Handcock, 1993), and the immediate structural control of the travertines at MacFarlane hot springs is not apparent. The largest travertine mound is ~180 m long, up to 5 m wide and 2 m tall, with 77° C water flowing at a rate of several gallons/minute out of its western end (Sibbett et al, Figure 1.) There are additional minor travertine features in the area, all of which exhibit a central fissure ridge (Figure 1), indicating local extension perpendicular to their current long orientation. Although there are other hot springs in the general area, none of them appear to have travertine fissure ridges or EW-striking structures (Figure 2).

This paper presents a preliminary report on the structural controls of the MacFarlane geothermal system. After a brief review of the necessary criteria for the formation of the geothermal system and the distinction between upwelling and outflow of geothermal water, a summary of the common structural controls on geothermal systems in the Great Basin is given. Next, the regional structural setting and the previous work done at MacFarlane hot springs is discussed. Finally, new data are discussed in the context of the regional setting and integrated with previous work.

Background

The main factors required for a geothermal resource to be developable include heat source, fluid to transport heat, and

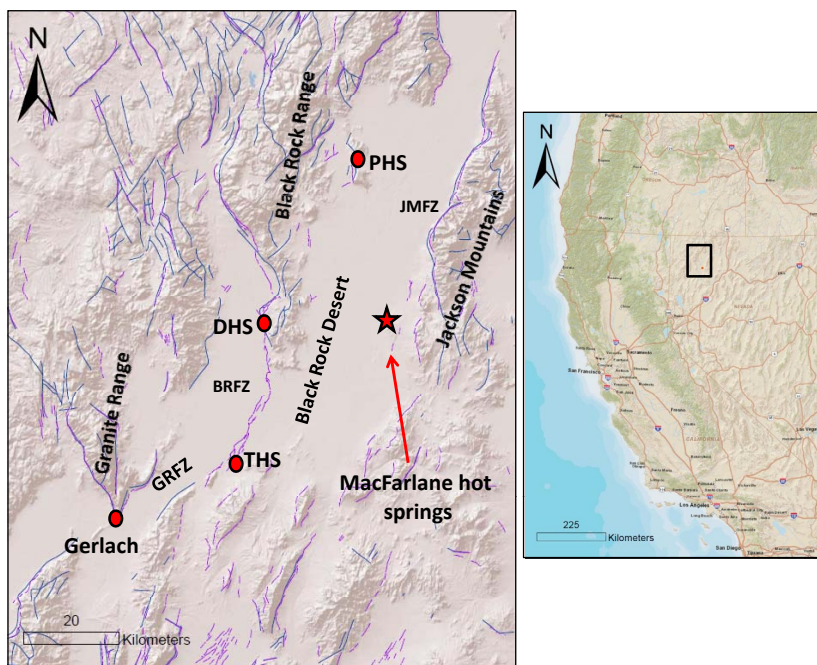


Figure 2. Location of MacFarlane hot springs, shown as a red star. Nearby hot springs shown as red dots and include: Gerlach, Tregos hot springs (THS), Double hot springs (DHS) and Pinto hot springs (PHS). Major fault zones include the Granite Range fault zone (GRFZ), the Black Rock fault zone (BRFZ), and the Jackson Mountain fault zone (JMFZ). Mapped faults are from the USGS fault database. Quaternary faults shown in purple, all other mapped faults shown in blue.

permeability. Heat sources for geothermal systems are generally magmatic and related to tectonic plate boundaries. However, amagmatic geothermal systems are encountered in continental areas where extension and thinning of the lithosphere occurs, such as in the Basin and Range Province in Nevada. Permeability in these systems permits for hot fluid circulation. Permeability is controlled by the subsurface geology and structure, including discrete joints, fractures and faults without extensive mineralization that create discrete zones of weakness through which fluids can flow (e.g. Hose and Taylor, 1974; Faulds et al, 2004; 2006; 2011).

A typical geothermal system in the Basin and Range has upwelling and outflow zones. An upwelling zone consists of hot geothermal fluids traveling upwards through structurally or lithologically controlled permeable areas, reaching the surface or near-surface (Richards and Blackwell, 2002). The fluid then commonly travels laterally, influenced by topography, groundwater and the hydrological gradient; this is referred to as the outflow zone (e.g. Richards and Blackwell, 2002). Upwelling zones get narrower with depth, while outflow zones typically form a broad, umbrella shape that changes over time and can produce surface manifestations, such as hot springs (Richards and Blackwell, 2002). It is important to know the locations of upwelling and distinguish them from outflow in order to efficiently develop a geothermal resource.

Specific structural scenarios have been shown to be favorable for geothermal systems in the Basin and Range Province. The most active geothermal systems are generally found in association with faults and fault zones oriented perpendicular to the least principal stress direction, and are typically related to NNE-striking normal and oblique-slip faults (e.g., Faulds et al, 2004). The specific structural settings that are favorable for these systems include: 1) overlapping synthetic normal fault systems with hard linkage (step-over); 2) overlapping antithetic fault systems (accommodation zones); 3) terminating or horse-tailing normal fault systems; and 4) multiple fault intersections (Faulds et al, 2006; 2011). The faults within these systems are often Quaternary in age, partly because permeability-inhibiting mineralization commonly associated with geothermal systems has not had time to develop. Often, a combination of the previously mentioned structural settings will result in permeability for a geothermal system (e.g. Faulds et al, 2011; Dering and Faulds, 2012).

Regional Setting

The northwestern Basin and Range lies in the transitional zone from the Basin and Range province to the south and east, and volcanic plateaus to the west (e.g. Lerch et al, 2008). The evolution of the northwestern Basin and Range is characterized by long-lived eruptive volcanism without tectonism between 35 to 16 Ma, followed by ongoing extension along high angle normal faults (e.g., Lerch et al 2007; 2008). Current GPS velocities suggest that $11.4 \pm .3$ mm/yr of relative extension oriented N47W between the Colorado Plateau and the Sierra Nevada is accommodated in the Basin and Range (e.g. Hammond and Thatcher, 2007). Strain rates

measured across the northwestern Basin and Range, specifically from Winnemucca west to the Sierra Nevada range front, indicate a vector sum slip rate of ~6 mm/yr (Hammond and Thatcher, 2007.)

MacFarlane hot springs lies on the eastern margin of the Black Rock Desert within the northwestern Basin and Range (Figure 2). The Black Rock Desert is flanked by NNE-striking ranges to the east, and bounded on the west by N to NNW-trending ranges. The Jackson Mountain fault zone bounds the Jackson Mountains to the east, and the Black Rock fault zone cuts NNE through the center of Black Rock Desert to the west of MacFarlane hot springs (Figure 2). Both fault zones exhibit mainly normal to normal-oblique motion, down to the west. The geology in this region is characterized by Mesozoic granites overlain by a series of Tertiary rocks. The volcanics are divided into three groups: late Eocene basalt flows; Oligocene to early Miocene bimodal basaltic andesite flows with rhyolitic lavas and ash-flow tuffs; and middle Miocene rhyolitic ash-flow tuffs (e.g. Lerch et al, 2008). Local Neogene sedimentary units are present overlying the volcanic rocks. Lacustrine sediments related to numerous pluvial cycles overlie all older units; the most recent being those related to Lake Lahontan. The Lake Lahontan Seho highstand receded immediately prior to 13070 +/- 60 years ago; this was calculated by radiocarbon dating camel bones found behind a highstand barrier in a paleolagoon (Adams and Wesnousky, 1998). Quaternary alluvium and eolian deposits are the most recent units.

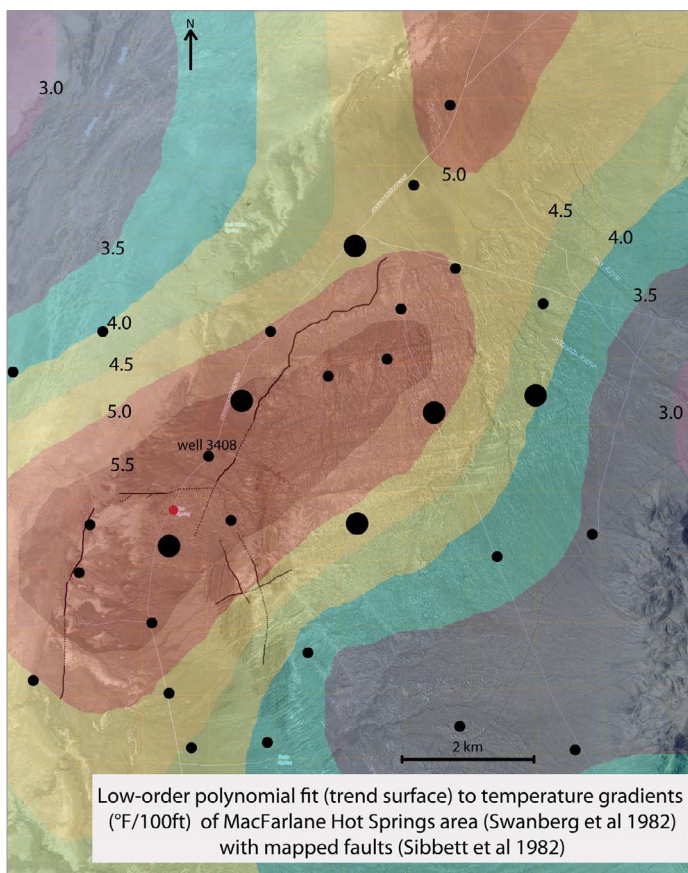


Figure 3. The high temperature anomaly is light red and trends NNE. Large black dots represent wells drilled to a depth of 1500-2000 ft; small black dots show wells with a depth of 100-500 ft. The well with the highest temperature gradient is labeled as 3408.

The geology specific to MacFarlane hot springs has been previously mapped. The majority of the bedrock units consist of Tertiary basalt flows overlain by tuffaceous sedimentary rock; both units have been tilted and now dip between 22° and 44° to the east (Sibbett et al, 1982). The sedimentary unit contains diatoms dated as late-middle Miocene to early Pliocene (Willden, 1963; Sibbett et al, 1982) and has local coquina dated as late Miocene to early Pliocene (e.g. Sibbett et al, 1982). These units are overlain along an angular unconformity by Lake Lahontan sediments, which consist of bar and shoreline deposits, as well as deep water sands and clays (Sibbett et al, 1982). Active alluvium is also mapped locally overlying all units.

The faults directly surrounding MacFarlane hot springs, identified in previous mapping, include a NS-striking Tertiary graben, a minor NE-striking Tertiary fault set, and a series of NNE-striking Quaternary faults with a dextral step (Sibbett et al, 1982). The fault on the east side of the proposed NS-striking Tertiary graben is west-dipping and has 335 m of offset based on cross sections (Sibbett et al, 1982). A projected fault intersection between the Tertiary graben and the Quaternary normal fault corresponds with high temperature gradient (Sibbett et al, 1982). The Quaternary faults are exposed northwest of the hot spring and offset algal tufa mats about 6 meters down to the west (Sibbett et al, 1982). A dextral step mapped just north of the hot springs is thought to control the location of the travertines (Sibbett et al, 1982). Although the step-over might be related to the travertines, it does not specifically explain their unique orientations.

Forty-four temperature gradient wells were drilled near MacFarlane hot springs, varying in depth from 100-500 feet to 1500-2000 feet (Figure 3). The majority of the gradient profiles show a linear relationship between temperature and depth. There is a large NNE-trending high temperature anomaly centered near the hot springs, associated with the step-over and Quaternary faults (Swanberg et al, 1982; Figure 3), and another high temperature gradient area, defined by one gradient well, NNE of MacFarlane hot springs; the second area does not seem to be associated with mapped faults or springs. The highest temperature gradient is 5.5° F/100 ft, which is about ½ C/m (Swanberg et al, 1982); this was observed at well 3408 (Figure 3), which is thought to be the intersection of the NNE-trending Quaternary fault and the older normal fault mapped in the bedrock units (Sibbett et al, 1982; Swanberg et al, 1982).

Geothermometry work was done at MacFarlane hot springs using Na-K-Ca and quartz values, which agreed with each other and gave a maximum reservoir temperature of 140° C (Sibbett et al, 1982). Quartz, Na/K and chalcedony calculations were also done and gave reservoir temperatures of 80° - 120° C (Sibbett et al, 1982). The MacFarlane thermal anomaly is not considered a very high temperature system, but could potentially be developed using a binary power plant system for electrical production.

New Data

Geologic Mapping

There is a mappable internal stratigraphy of the Tertiary sedimentary unit southeast of MacFarlane hot springs that demands a reinterpretation of the faults expressed in this unit (Ts, Figure 4). The sedimentary sequence overlies the basalt in a depositional con-

tact. The unit varies from white diatomite to tuffaceous sandstone, with local coquina and silicified resistant layers. The coquina unit is reddish tan to white, locally silicified, and contains shells that are between 2-5 mm in diameter. The coquina is distinct within the sedimentary stratigraphy and makes a mappable marker unit.

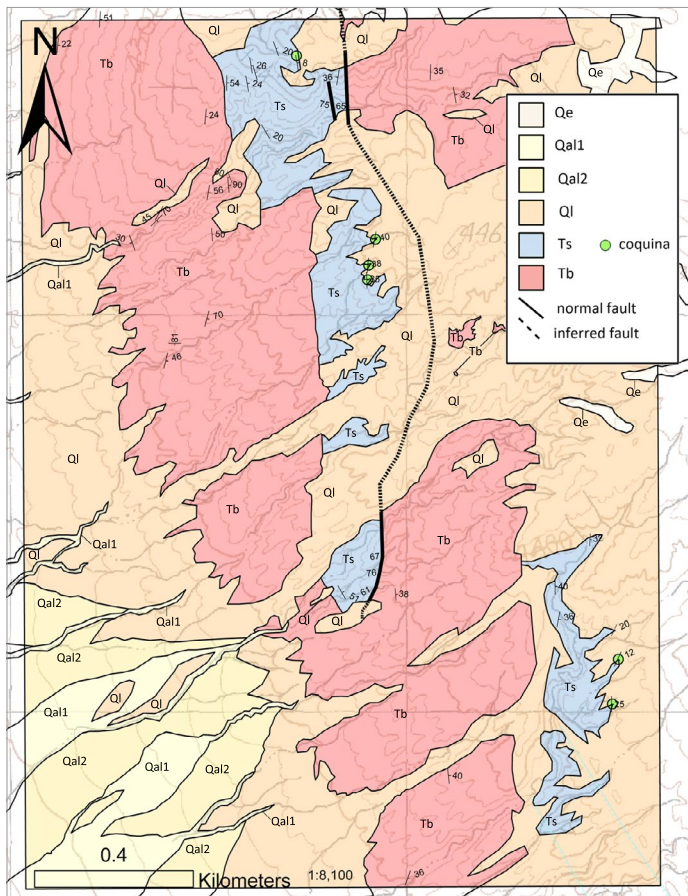


Figure 4. Preliminary geologic map of the bedrock east of MacFarlane hot springs. Units shown include: Qe – eolian deposits; Qal1 – active alluvium; Qal2 – relict alluvium; Ql – Lake Lahontan recessional beach deposit; Ts – tuffaceous sedimentary unit with diatomite and local coquina; and Tb – basalt. Green dots show coquina beds. Location of map shown as black box in Figure 6.

Late Pleistocene and Holocene units include Lake Lahontan lacustrine deposits, travertine mounds and post-Lahontan deposits; these constrain the relative ages of young faults. The Lake Lahontan deposits can be separated into two main units: lake sediments and recessional barrier beach and bar deposits. The approximate age of these units correlates with the Lake Lahontan Seho highstand, radiocarbon dated at ~13,000 years (Adams and Wesnousky, 1998). The post-Lake Lahontan deposits include eolian dune deposits and various cycles of fan alluvium (Qe, Qal1 and Qal2, Figure 4). These units are generally fan-shaped in the aerial photos and have a lower albedo due to their basaltic clast composition.

The travertine ridges exposed at MacFarlane hot springs exhibit a variety of orientations and sizes (Figure 5). All travertines show a linear central opening, or fissure ridge, though which water flowed and deposited calcium carbonate on the flanks of the mound. Many travertine mounds have internal parallel laminations in the fissure ridges that record multiple dilational fracturing

events. Detailed mapping shows mainly E-trending travertine mounds, with minor travertine mounds oriented NNW and NW, shown in Figure 6. The largest travertine mound is ~180 m long and 2 m high, with active hot springs flowing out of its west end. The other travertines are much smaller, and vary in length from 9 m to 33 m, and are typically less than 1 m wide (Figure 5).

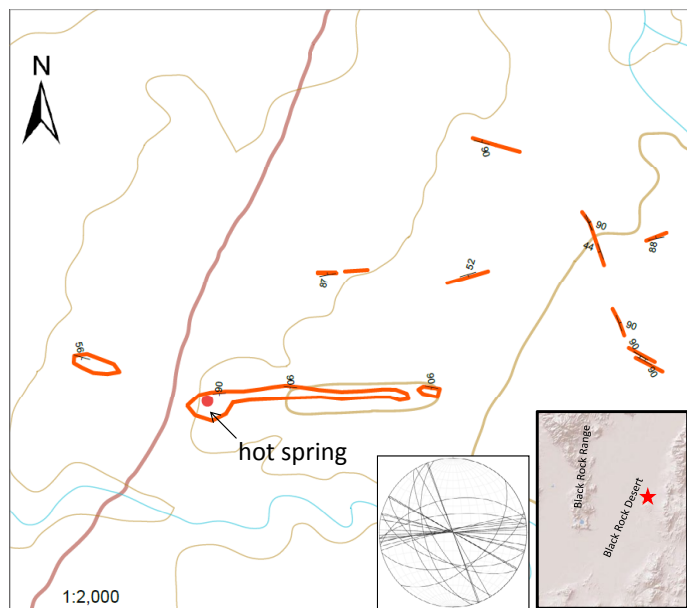


Figure 5. Orientations of travertine fissure ridges near MacFarlane hot springs. Actual hot spring is shown as a red dot on the west end of the large travertine mound. Road shown in reddish brown, topographic contour lines (20 ft interval, thick line is 4100 ft) shown in brown. All orientations of fissure ridges shown on stereonet, n=30.

Structural Data

Based on kinematic and geologic data, there are four main fault sets near MacFarlane hot springs (Figure 6). Fault sets can be differentiated based on ages and the orientations of the faults and include a: A.) NS-striking Jackson Mountain fault zone; B.) NS-striking fault expressed in bedrock just east of MacFarlane hot springs; C.) NNE-striking fault set surrounding MacFarlane hot springs; and D.) possible ENE-striking fault mapped by Sibbett et al. (1982) and visible as a lineament in color aerial photos. A NE-striking fault set and a NS-striking, east-dipping normal fault were previously mapped (Sibbett et al, 1982) but are not present based on recent detailed geologic mapping.

The first fault set (A) is exposed at the western boundary of the Jackson Mountains (Figure 6). These faults are steeply west-dipping, NS-striking, and have a normal sense of motion (e.g. Lerch et al, 2008). This fault system is ~ 60 km long, and has local splays and discrete steps. The total amount of offset is unknown, but hopefully will be resolved with continued mapping. The faults are expressed as scarps in Quaternary alluvium and locally cut Lake Lahontan lacustrine sediments, which means that this fault has been active post ~13,000 years ago.

The second fault set (B) is located in the Tertiary units south-east of MacFarlane hot springs. The main fault is exposed at the contact between the basalt and the sedimentary unit, with a minor synthetic fault observed only in the sedimentary unit. The main

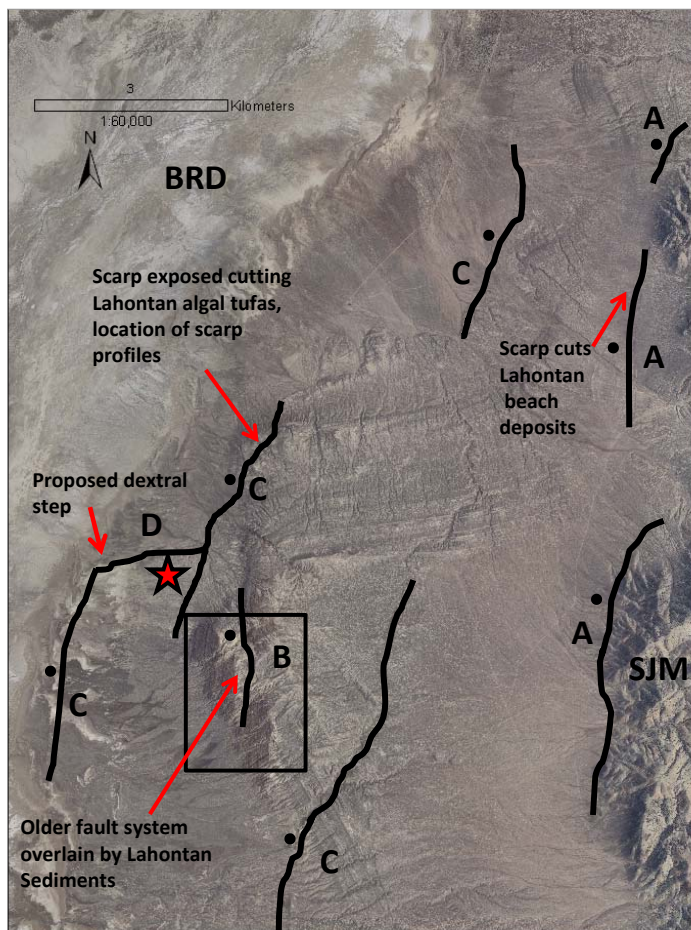


Figure 6. Fault sets (A, B, C and D) near MacFarlane hot springs (shown as red star) in a regional context. Dot displayed on hanging wall, and sense of motion for set D is unknown. SJM = Southern Jackson Mountains, BRD = Black Rock Desert. Black box represents area mapped in Figure 4.

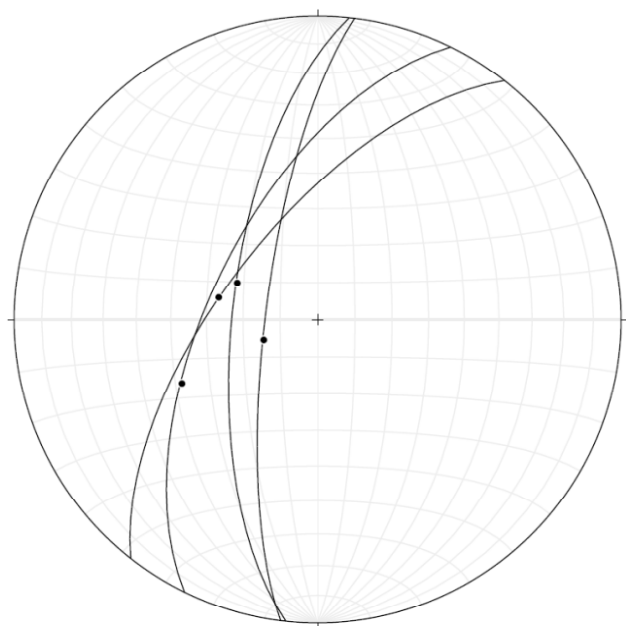


Figure 7. Fault planes with lineations shown on fault set B. Lack of lineation data due to severely weathered outcrop (n=4).



Figure 8. Drag folding within the sedimentary unit at the fault and contact with basalt.



Figure 9. A small synthetic fault observed in the sedimentary unit. Fault plane is overlain by Lake Lahontan sediments.

fault strikes between 186° and 206° azimuth and dips between 61° and 76° to the west. Slickensides show mainly dip-slip motion, with a minor sinistral oblique component trending to the southwest (Figure 7). Drag folding in the sedimentary unit also indicates down to the west motion (Figure 8). The actual exposed length of the fault is about 300 m, but the extent of the fault is projected to be about 2 km (Sibbett et al, 1982). The stratigraphy, including the coquina marker, is offset and found repeated to the east (see coquina, Figure 4). The offset on this fault is about 335 m (Sibbett et al, 1982), while the offset on minor synthetic fault is less than 1 m. The entire fault system is covered by Lake Lahontan sediments (Figure 9). The age of this fault set is older than $\sim 13,000$ years but younger than 4-11 (Late Miocene to early Pleistocene), based on age control given from the stratigraphy.

Fault set (C) is located ~ 7 km west of the Southern Jackson Mountains, in close proximity to MacFarlane hot springs (Figure 6). These faults are NNE-striking and west-dipping, as

observed in scarps that are visible in the aerial photographs and on the ground. This fault system is at least 15 km long based on imagery, although the exact locations of the northernmost and southernmost fault terminations are unknown. The fault directly east of MacFarlane hot springs terminates to the south, based on linear traces observed on aerial photos, locations of scarps, and confirmed with drill data (Sibbett et al, 1982). The fault just west of the hot springs appears to terminate to the north, based on linear traces on aerial photos and locations of scarps. Based on drill data, the basalt unit has been offset 400 m down to the west across the fault east of the hot springs (Sibbett et al, 1982). Northeast of MacFarlane hot springs, Lake Lahontan algal tufa mats are offset about 6 m down to the west across the fault, and west of the springs tufa is offset at least ~2 m. Scarps are covered by recent eolian deposits and show substantial degradation and drainage dissection.

A possible fault set (D) is located between the NNE-striking faults in set B (Figure 6). This fault set is ENE-striking and dips

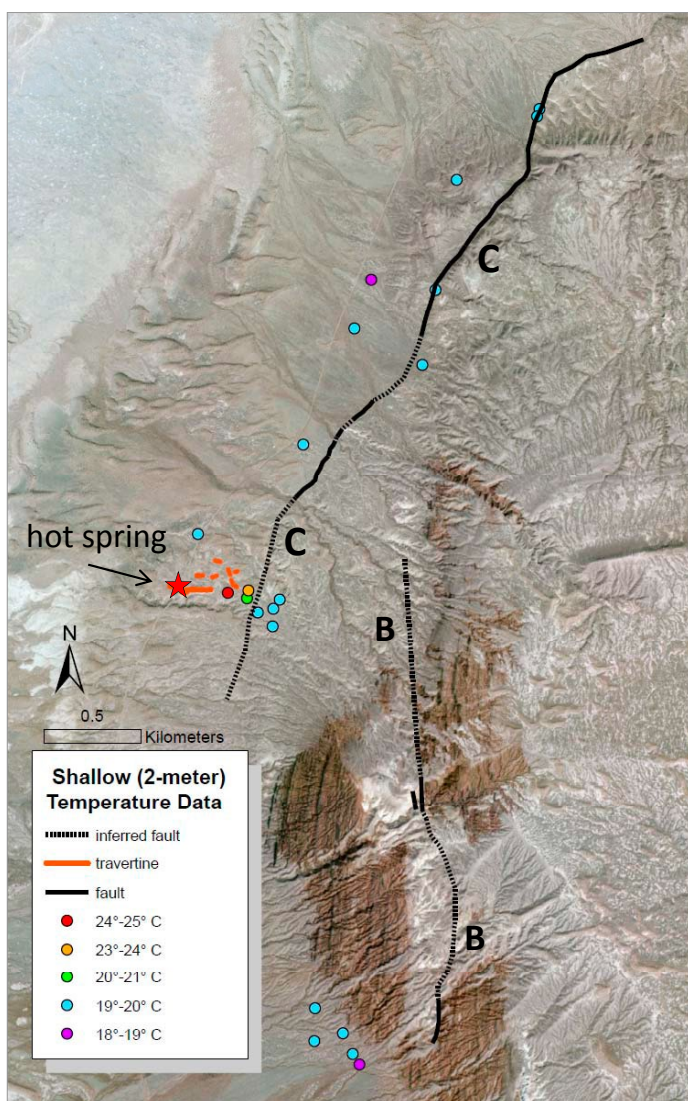


Figure 10. Shallow (two-meter) temperature data at MacFarlane hot springs. Faults sets shown in black, labeled B and C, and travertines shown in red. Hot spring is shown as a red star.

north (Sibbett et al, 1982). The fault is shown as a lineament in aerial photos with little to no ground expression. The lineament is expressed in Quaternary Lake Lahontan sediments; therefore the interpreted age is younger than ~13,000 years.

Two-Meter Temperature Data

A reconnaissance shallow (two-meter) temperature survey shows one area of elevated temperatures, just east of MacFarlane hot springs (Figure 10). This survey was designed to: 1) test hypotheses on locations of shallow fluid flow related to faults or other permeable units and 2) discover areas of high temperature that might have been overlooked in previous work. No elevated temperatures were measured along Quaternary fault traces and at the location of the proposed step-over, and no other high-temperature areas were discovered. The high temperatures measured just east of the hot springs were 23°-25° C, and trend east up-topography.

Discussion

The travertine fissure ridges at MacFarlane hot springs are dominantly EW-striking, and record multiple dilational events based on their internal laminations. The hot spring at MacFarlane was active during the Lake Lahontan Seho highstand recession, based on wave-rounded travertine clasts (Sibbett et al, 1928). The orientations of the dilational fissure ridges do not match extensional trends in the northwestern Basin and Range, and there are multiple hypotheses to explain this. The anomalous orientations might be related to small fractures caused by perturbations in the stress field related to relay ramp geometry between two terminating faults, or specifically related perturbations in the stress field caused by a single fault termination on the NNE-striking Quaternary fault just east of MacFarlane hot springs. There could also be an EW-striking fault buried under Quaternary sediments that is interacting with the NNE-striking Quaternary fault.

The reconnaissance shallow temperature data show that hot fluid circulation is not controlled at a shallow depth by the NNE-striking Quaternary fault and proposed step-over. The hot water is controlled by these faults at depth, based on temperature gradient data (Swanberg et al, 1982). The high temperatures found directly east of the travertine mound show that the hot springs is related to fluid that is flowing east to west, most likely as part of an outflow system. Further shallow temperature data will help constrain the location of this anomaly and help relate it to structure in the area. Another line of evidence that the hot springs is likely related to outflow is the location of the highest temperature gradient well ~2.5 km to the NE.

New mapping for this study reveals that there are no NE-striking faults in the Tertiary and basalt sedimentary section east of MacFarlane hot springs, based on lack of kinematic indicators and offset units found when mapping the basalt and sedimentary units in detail. The offset coquina marker bed within the Neogene sedimentary unit records a single W-dipping normal fault; it forms the eastern contact of the Neogene sedimentary section (Figure 4). The apparent offset observed in aerial photos is misleading; they are depositional contacts of lacustrine sediments overlying the basalts rather than being structure-related.

The new data from this study require reconsideration of the structural controls previously interpreted for MacFarlane hot

spring. A fault intersection between the NS-trending Tertiary fault and the NNE-trending Quaternary fault was previously proposed as a structural control on the highest temperature gradient at MacFarlane hot springs (Sibbett et al, 1982; Swanberg et al, 1982). However, the Quaternary faults in the proximity of MacFarlane have a number of geometries that are ideal for permeability. These include a hard-linking step-over and/or relay ramp related to the possible northward and southern terminations of two distinct faults, or permeability increase due to one fault termination. These Quaternary faults are more likely to control permeability, based on their age and the abundance of geothermal systems related to Quaternary faults in the Basin and Range. A combination of scenarios involving both Tertiary and Quaternary fault sets might also be favorable for controlling the geothermal system.

Conclusion

Preliminary interpretations of new two-meter temperature data, geologic mapping and kinematic data integrated with previous work suggest that there are four distinct fault sets at MacFarlane hot springs; sets B, C and D (Figure 6) might play a role in controlling the high temperatures of the geothermal system. Possible structural controls on the geothermal fluid flow include a: 1) fault intersection; 2) relay ramp and associated small fractures within the ramp; 3) step-over linking the relay ramp; 4) combination of fault terminations associated with the relay ramp, or one fault termination; 5) unknown fault or faults covered by Quaternary sediments increasing permeability; or 6) combination of some or all of the previously mentioned scenarios. Many of these faults are at least partially covered by Quaternary sediments, so a geophysical survey and more detailed Quaternary mapping are in progress to resolve the specific structural setting here.

There are several plausible causes of local NS extension exhibited in the travertine fissure ridges, based on geologic mapping and kinematic data. These include: 1) dilational fractures caused by perturbations in the stress field related to relay ramp formation, allowing for fluid flow; 2) perturbations in the stress field related to a single fault termination; and 3) an EW-striking fault buried under Quaternary sediments interacting with the NNE-striking Quaternary fault. With further geologic mapping, integration using GIS, structural analysis, generation of cross sections in the area, and a possible geophysical survey hopefully the causal mechanisms can be resolved.

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