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Structural Controls of a Blind Geothermal System in the Northern Pyramid Lake Area, Northwestern Nevada

Garrett S. Vice¹, James E. Faulds¹, William J. Ehni², and Mark F. Coolbaugh³

¹Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557

²Ehni Enterprises, Inc. P. O. Box 4228 Carson City, Nevada 89702-4228

³Great Basin Center for Geothermal Energy, University of Nevada, Reno, NV 89557

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ABSTRACT

Most geothermal systems in the Great Basin are fault controlled. Ongoing studies suggest that many of these systems occupy discrete steps in fault zones or lie in belts of intersecting, overlapping, and/or terminating faults. Fault interactions within these settings generate subvertical conduits of highly fractured rock and increase dilation, thereby allowing geothermal fluids to approach the surface. Understanding the interaction between faults and geothermal systems can facilitate the identification of hidden or blind geothermal reservoirs.

Detailed geologic mapping and structural analysis has elucidated the links between faulting and a blind geothermal system in the northern Pyramid Lake region, northwestern Nevada. This system lies near the terminus of the Pyramid Lake fault zone, a transitional region between northwest-trending dextral shear in the Walker Lane and north-northeast striking normal faults in the northern Great Basin. The region is composed of intercalated Miocene basalt, rhyolite, and dacite flows with subordinate lenses of breccia, conglomerate, and diatomite. Structurally, the northern Pyramid Lake region contains north to north-northeast striking normal and north-northwest to west-northwest striking dextral-normal faults. Linear tufa towers mark some faults and fault intersections. Hot springs upwelling into Pleistocene Lake Lahontan probably formed many tufa towers, which were used as indicators for locating blind geothermal systems. The blind geothermal system at northern Pyramid Lake has no surficial hot springs but is marked by the intersection of linear north-northwest and west-northwest trending tufa towers that follow dextral-normal faults. Recent drilling adjacent to a large tufa tower confirms the presence of a geothermal system with temperatures of at least 90°C. Analysis of cuttings shows that the upper part of the reservoir lies in highly fractured, hydrothermally altered basalt and rhyolite units.

Introduction

The Great Basin in the western U.S.A. contains many geothermal fields. The majority are located in northern Nevada, northeastern California, and southern Oregon (Blackwell et al., 2002; Coolbaugh et al., 2002; Coolbaugh and Shevenell, 2004;

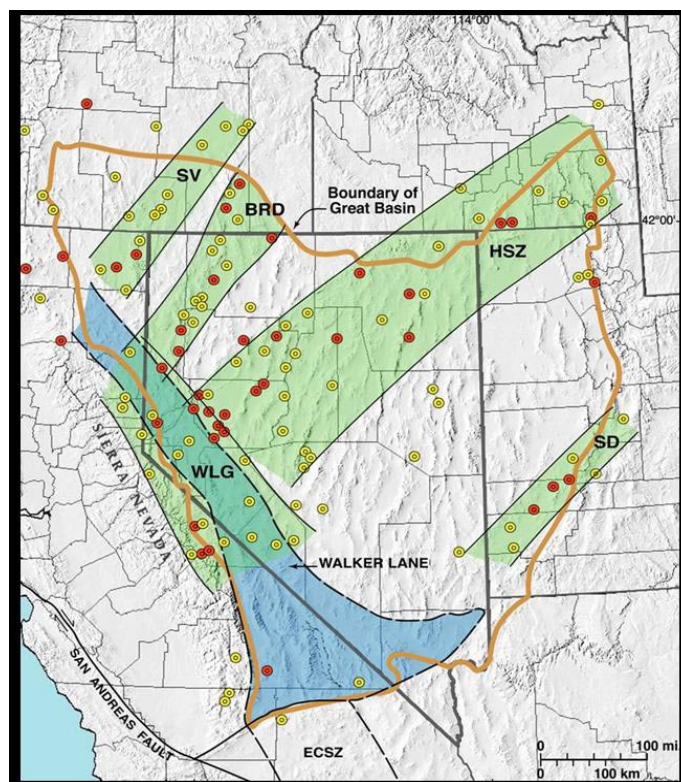


Figure 1. (from Faulds et al., 2004): Geothermal occurrences along structurally controlled belts in Utah, Nevada, and California. (green colored bands). BRD- Black Rock Desert; ECSZ- Eastern California Shear Zone; HSZ- Humboldt Shear Zone; SD- Sevier Desert; SV-Surprise Valley; WLG- Walker Lane (blue colored band). Red circles- Geothermal temperatures >160°C; yellow circles- geothermal temperatures = 100-160°C

Faulds et al., 2004). Within Nevada, geothermal fields can be grouped into four zones based on location and tectonic style (Faulds et al., 2004). These are the Walker Lane, Humboldt, Black Rock, and Surprise Valley belts (Figure 1). The belts occur in tectonically active regions, where volcanism generally ceased ~3-10 Ma, suggesting that many of the geothermal fields are not related to magmatism but are instead controlled by fault zones (Faulds et al., 2004, 2005a).

The tectonic setting of the northwestern Great Basin may account for the abundant geothermal activity. The northwestern Great Basin is in a transtensional region undergoing both northwest-southeast extension and northwest-directed dextral shear (Stewart, 1988; Oldow, 1992; Faulds et al., 2005a). The abundant regional geothermal activity may result from northwest-trending dextral shear in the Walker Lane transferring to north-northeast striking normal faults in the northern Great Basin (Faulds et al., 2005a, b). Recent studies suggest that geothermal fields in this region are most common along: 1) major steps in range-fronts, 2) interbasinal highs, 3) mountain ranges consisting of relatively low, discontinuous ridges, and 4) lateral terminations of mountain ranges (Faulds et al., 2006). These studies also suggest that fault intersections, terminations, steps, and overlaps are possible targets for geothermal exploration.

In this paper we present results using the above structural indicators to help locate a blind geothermal system within the Pyramid Lake area (Figure 2). We show that fault intersections in ranges with relatively low, discontinuous ridges can mark the location of a blind geothermal system.

Stratigraphy

The Tertiary strata in western Nevada consist primarily of volcanic rock assemblages (Bonham and Papke, 1969; Dilles and Gans, 1995; Garside et al., 2003; Faulds et al., 2003a, 2005a; Henry et al., 2004). This holds true in the Pyramid Lake area, where Oligocene to Miocene volcanic units dominate the Tertiary sections (Garside et al., 2003; Faulds et al., 2003a; Henry et al., 2004). The northern Pyramid Lake region is composed of Miocene basalt, basaltic-andesite, and rhyolite lavas and domes. The main basaltic unit in the area is the middle Miocene Pyramid sequence. The Pyramid sequence crops out in much of northwestern Nevada and is particularly thick in the Virginia Mountains and Lake Range (Garside et al., 2003; Faulds et al., 2003a; Henry et al., 2004; Drakos, 2007). This unit consists of multiple porphyritic and aphanitic basalt flows and intervening flow breccias, with subordinate lenses of conglomerate, diatomite, and sandstone. $^{40}\text{Ar}/^{39}\text{Ar}$ dates constrain the age of the Pyramid sequence between ~15.5 Ma and 13.2 Ma (Drakos, 2007).

The Pyramid sequence along northern Pyramid Lake can be divided into two units, separated by the tuff of Mullen Pass (a dacitic ash-flow tuff) and a dacite flow. The lower sequence is ~400 m thick and composed of intercalated aphanitic and porphyritic basalt to basaltic-andesite lavas, lesser rhyolite flows, and subordinate lenses of flow breccia and volcanoclastic sedimentary rocks. A suite of porphyritic basalt and rhyolite intruded the lower part of the Pyramid sequence. The upper

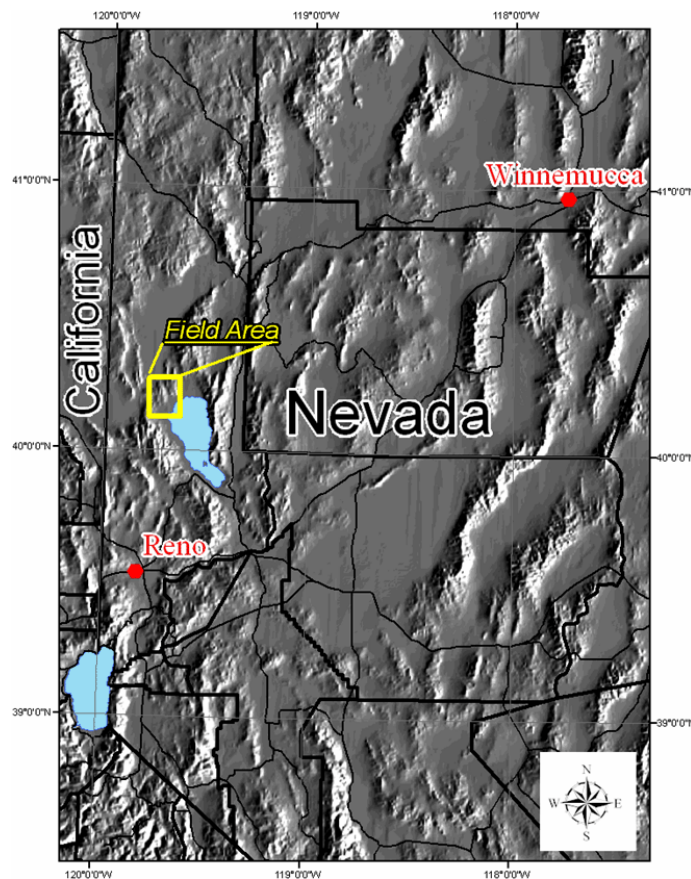


Figure 2. Location of study area outlined in yellow.

Pyramid sequence is ~600 m thick and consists primarily of aphanitic basaltic-andesite flows.

Quaternary units in the northern Pyramid Lake region are dominated by alluvial and lacustrine deposits from both Pleistocene Lake Lahontan and the contemporary Pyramid Lake. Alluvial deposits include alluvial fans and fluvial gravels along ridge flanks. These deposits also extend downward to various levels in the Pyramid Lake basin (Bonham and Papke, 1969; Faulds et al., 2003a). Lake deposits include beaches, bars, tufas, modified colluvium, shoreline sands and gravels, and silts associated with Lake Lahontan and Pyramid Lake (Adams and Wesnousky, 1998; Adams et al., 1999).

Structural Setting

Two major tectonic domains contribute to the faulting style of northwestern Nevada, the Walker Lane and the Basin and Range. The Walker Lane is a system of right-lateral strike-slip faults in the western Great Basin that accommodates ~15-20% of the dextral motion between the North American and Pacific plates. It generally straddles the California-Nevada border (Stewart, 1988; Oldow, 1992; Faulds et al., 2005). Both geologic and geodetic studies suggest that the Walker Lane loses displacement northward as dextral shear dissipates into north-northeast-striking normal fault zones within the western Great Basin (Faulds et al., 2005b). The northern Pyramid Lake area lies within the northern Walker Lane near the north end of

the northwest-striking right-lateral Pyramid Lake fault zone. Geodetic studies show that the northern Walker Lane accommodates ~ 8 mm/yr of northwestward translation between the Sierra Nevada and central Great Basin (Oldow et al., 2001; Bennett et al., 2003; Hammond and Thatcher, 2004).

The Pyramid Lake fault zone is the northeasternmost, right-lateral fault in the northern Walker Lane (Bell, 1984; Faulds et al., 2005a). It has accommodated ~ 10 km of right-lateral offset since ~ 3 -9 Ma (Faulds et al., 2005a). As the Pyramid Lake fault zone continues northward, its trace is lost under Pyramid Lake, and the fault has not been identified on the north end of the lake. However, several north-northwest-striking faults cut the hills north of Pyramid Lake and may indicate a transfer of right-lateral shear from the Pyramid Lake fault zone to the northern Pyramid Lake region.

The northern Pyramid Lake region consists of a series of fault bounded, relatively low, north-northwest-trending discontinuous ridges. The ridges generally follow the strike of the faults. Based on limited kinematic data, morphology of Quaternary fault scarps, and offset of Miocene volcanic units, the faults probably accommodated either normal or dextral-normal displacement.

The faults can be separated into two sets based on general strike, kinematic data, and occurrences of structurally controlled tufa: 1) the northwest Pyramid Lake and 2) northeast Pyramid Lake groups. The northwest Pyramid Lake group contains at least twelve well-defined faults, which range in strike from west-northwest to north-northeast. Well-exposed fault surfaces containing kinematic indicators, such as fault striae and Riedel shears, are sparse. However, fault surfaces exposed in a clay pit have striae and Riedel shears indicative of dextral-normal oblique-slip movement. Another north-northwest striking fault in this region accommodated ~ 600 m of dextral offset of a rhyolite plug. The other defining characteristic of the northwest region are the linear tufa towers. There are two distinct sets, the Needle Rocks and Astor Pass. The linear trends of the tufa towers project toward faults cutting volcanic units, suggesting that they are structurally controlled.

Well-preserved fault surfaces and tufa towers have not been observed in the northeast Pyramid Lake group. However, two west-facing Quaternary fault scarps were found in this area, and both are associated with right steps in the Pyramid Lake shoreline. Faults in this region strike from northwest to northeast (with an average strike of north) and generally dip to the west. Faulting style is probably dextral oblique-slip, with possibly more of a normal movement. Evidence for faulting style includes displaced units, seismic reflection data from Pyramid Lake, and morphology of fault scarps. Normal separation characterizes all faults in the area. However, subvertical dips of north-northwest-striking faults imaged in seismic reflection profiles across the northern part of Pyramid Lake suggest that some of the faults accommodated strike-slip displacement (Shane Smith, personal communication, 2007). One of the faults has an ~ 0.5 m down-to-the-west scarp cutting Lake Lahontan shorelines, making it one of the youngest faults in the area. The right steps in the Pyramid Lake shoreline along the two Quaternary faults probably result from down-to-west normal displacement (thus generating shallow embayments

on the downthrown western sides of the faults), as opposed to dextral offset of the shorelines.

Geothermal Characteristics

Several hot springs and a human-induced geyser occur in the northern Pyramid Lake region. The hot springs and geyser lie along the northwestern shore of Pyramid Lake in association with structurally controlled tufa towers. Shallow-temperature surveys of both hot springs and wells in the area show temperature variations of 14 to 117°C (Grose and Keller, 1975; Coolbaugh et al., 2006). However, geothermometers suggest temperatures between 143°- 213°C (Grose and Keller, 1975; Coolbaugh et al., 2006). Although the temperatures of the hot springs and geothermometers suggest a possible economically viable geothermal system, the areas associated with them (e.g., Needle Rocks and the Pyramid) are culturally sensitive and off limits for development. These restrictions prompted the exploration for a blind geothermal system in the region.

Results

Geologic mapping, shallow-temperature surveys, gravity data, and well data have been integrated to elucidate potential blind geothermal systems in the northern Pyramid Lake region. The Astor Pass tufa tower (Figure 3) marks the intersection of linear north-northwest- and west-northwest-trending belts

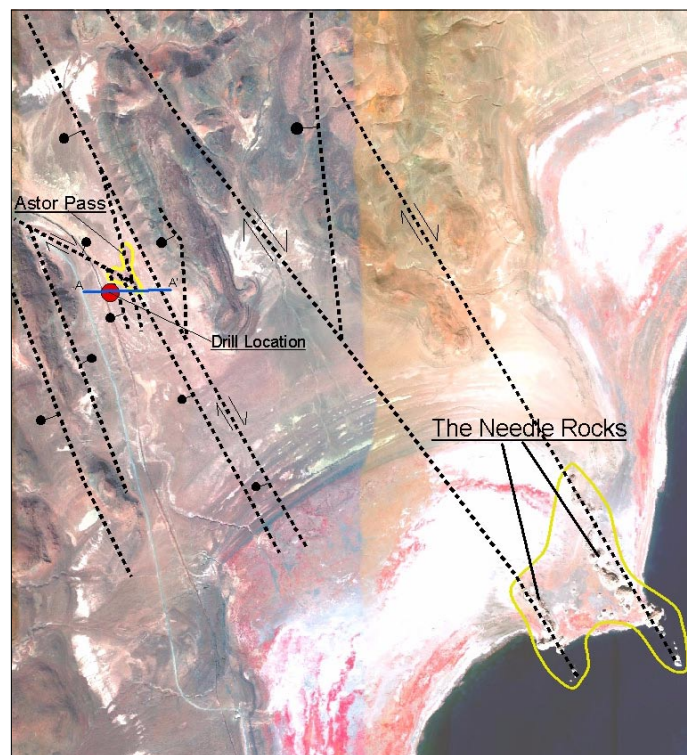


Figure 3. Generalized map showing inferred major faults near the blind geothermal system in the northern Pyramid Lake area. Linear trends of tufa towers near the fault intersection are outlined in yellow. Red circle marks the location of geothermal well described in text and shown in Figure 4. Blue line denotes cross section (Figure 4).

of tufa towers. The linear tufa trends were probably produced by the upwelling of geothermal fluids along major fault zones, into Pleistocene Lake Lahontan. The north-northwest-striking fault is part of a series of en echelon faults that accommodated dextral-normal oblique-slip, with possibly a greater normal than dextral component, as evidenced by large normal separations (~400-500m) and steep escarpments along many of the north-northwest-trending ridges. However, a north-northwest striking fault, ~1 km east of the Astor Pass tufa tower, did accommodate ~600 m of dextral offset of a rhyolite plug. The fault controlling the north-northwest-trending tufa towers presumably parallels a southwest-dipping fault bounding the west flank of the ridge directly east of the tufa towers (Figure 4).

The west-northwest-trending tufa spires mark the approximate trace of a dextral, down-to-the-northeast, oblique-slip fault. Total offset along the fault is uncertain. However, the fault is part of a series of en echelon faults, some of which contain kinematic data. Kinematic data from one of these faults indicates subequal components of dextral and normal slip. Normal movement is down-to-the northeast.

The apparent kinematics of the north-northwest- and west-northwest-striking faults suggest a zone of increased fracturing near their intersection in the vicinity of the Astor Pass tufa towers. This zone of fracturing is probably composed of multiple fault splays. Assuming a dextral component of slip on at least the west-northwest-striking fault implies a greater dilational component on the southwest side of the intersecting trends of tufa towers (Figure 3).

During the fall of 2006, drilling took place ~150 m southwest of the central tufa tower. The well penetrated to a depth

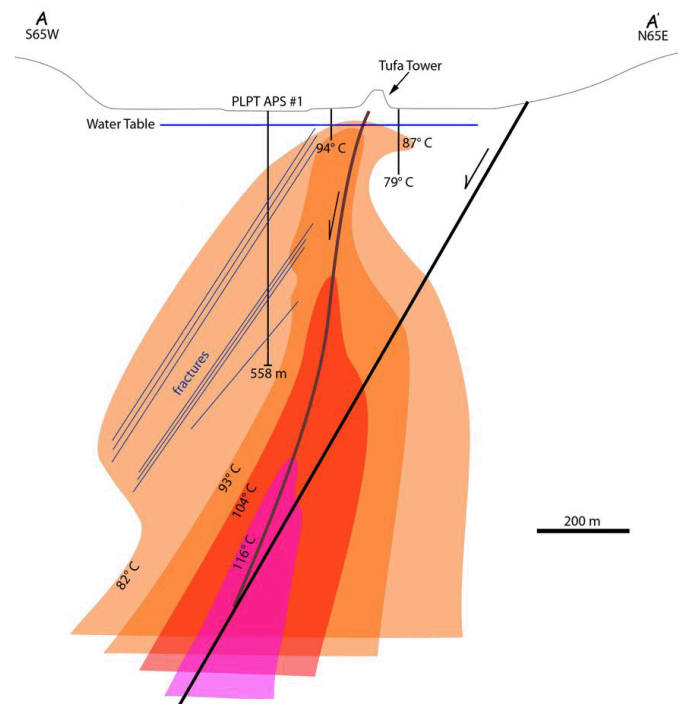


Figure 4. Schematic of subsurface across geothermal system in the northern Pyramid Lake region. Colored areas represent geothermal temperatures.

of ~550 m and crossed multiple fault zones (Figure 4). Temperatures reached ~90° C at ~200 m in the well, suggesting a potentially viable geothermal system. Furthermore, the cuttings showed that hydrothermally altered basalt and rhyolite, locally including sulfides (e.g., pyrite or chalcopyrite), were common beneath the intersecting tufa towers. The well data demonstrate 1) a relatively robust hydrothermal system beneath the intersecting tufa towers, and 2) fault control for the linear belts of tufa towers. Thus, it seems likely that the linear belts of tufa towers were indeed generated by hot springs issuing along faults into Pleistocene Lake Lahontan. Current surface expression of these hot springs may simply be stymied by the dry Holocene climate.

We therefore suggest that deeper drilling southwest of the central tufa tower may encounter higher temperatures, which may in turn permit geothermal development. Similar to some other geothermal fields in the region (e.g., Desert Peak; Benoit et al., 1981; Faulds et al., 2003b), the main geothermal reservoir at Astor Pass may reside in Mesozoic basement rocks near the nonconformity with Miocene strata. On the basis of regional stratigraphic relations (e.g., Faulds et al., 2003a; Drakos, 2007), we estimate that the depth of the nonconformity is less than ~1.2 km. Thus, the inferred geothermal reservoir may be an economically feasible target.

Conclusions

The relationships described above indicate a link between high temperatures and intersecting dextral-normal faults in the northern Pyramid Lake region. Abundant en echelon west-northwest-striking to north-northwest-striking dextral-normal faults indicate that the northern Pyramid Lake area occupies a transitional zone between the Walker Lane and extension-dominated northwestern Great Basin. Enhanced geothermal activity in this area may therefore be induced by a transfer of dextral shear in the Walker Lane, particularly to the north-northwest-striking right-lateral Pyramid Lake fault, to north-northwest-striking normal faults in the northwestern Great Basin. Thus, ranges of low discontinuous ridges, multiple intersecting faults, and small pull-aparts in the systems of oblique-slip faults are all potentially fruitful zones for geothermal exploration in this region.

In the case of Astor Pass, intersecting linear trends of tufa towers mark both the intersection of west-northwest- and north-northwest-striking dextral-normal faults and a blind geothermal system. A small pull-apart zone on the southwest side of the intersecting faults may mark the most promising target for geothermal activity. Additional drilling is needed, however, to further define and characterize the blind geothermal reservoir, which may be centered near the nonconformity between Miocene strata and Mesozoic basement rocks. The additional data will provide the parameters needed for determining the engineering and economic feasibility for development.

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