

THE PYRAMID LAKE PAIUTE RESERVATION, WESTERN NEVADA (USA): EXPLORATION FOR BLIND GEOTHERMAL SYSTEMS IN A TRANSTENSIONAL DISPLACEMENT TRANSFER ZONE

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ABSTRACT

The Pyramid Lake region lies within a region of high geothermal potential in the northwestern part of the Great Basin in western Nevada (USA). It occupies a major displacement transfer zone, as the NW-striking right-lateral Pyramid Lake fault (PLF) ends northward and transfers strain to a major west-dipping normal fault system. Offset of an Oligocene paleovalley suggests ~10 km of dextral displacement on the PLF just south of its terminus. Cumulative normal displacement on west-dipping normal faults in the region is ~10.7-12.6 km, which is sufficient to have accommodated transfer of most of the dextral slip on the PLF. Enhanced extension results in high geothermal potential in the Pyramid Lake region. However, known high-enthalpy systems occur in culturally sensitive areas in the reservation and thus cannot be developed.

We have therefore embarked on a broad exploration program aimed at discovering blind geothermal systems within the reservation. This multi-disciplinary analysis includes identifying surficial features indicative of past geothermal activity (e.g., tufa towers) and favorable structural settings (e.g., relay ramps and fault intersections). The Astor Pass area directly northwest of Pyramid Lake was initially selected, because it contains two linear trends of tufa towers that mark a major fault intersection. Temperatures of 94°C were observed at 70 m depth proximal to the central tufa tower, but deeper drilling (>1 km) nearby has yet to yield higher temperatures despite promising geothermometry. Another promising area is a major step-over or relay ramp directly northeast of Pyramid Lake between the W-dipping range front faults of the Lake and Fox Ranges. Integrated geologic and geophysical studies are being employed to identify additional areas with high geothermal potential.

1. 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; Faulds et al., 2004). Volcanism in this region generally ceased ~3-10 Ma, suggesting that magmatism is not the heat source for most of the geothermal activity. Instead, major faults zones provide conduits for deeply circulating fluids within a broad extensional region of high heat flow (Faulds et al., 2004, 2005a).

The tectonic setting of the northwestern Great Basin probably accounts for the abundant geothermal activity (Fig. 1). Here, the Walker Lane terminates northwestward and is intimately tied to a broad zone of west-northwest-directed extension. The Walker Lane is a zone of dextral shear that accommodates ~20% (~1 cm/yr) of the Pacific – North America plate motion (Stewart, 1988; Oldow, 1992; Faulds et al., 2005a; Faulds and Henry, 2008; Hammond and Thatcher, 2004), with the bulk of plate boundary strain taken up by the San Andreas fault. As the Walker Lane terminates northwestward in northeast California, dextral shear is transferred into west-northwest-directed extension in the northwestern Basin and Range, which accentuates dilation on normal faults thereby generating a broad region of high geothermal potential in the transtensional to extensional northwestern Great Basin (Faulds et al., 2004). Although the broad tectonic setting is helpful in understanding the regional geothermal potential, it does not constrain the most favorable sites for developing an individual geothermal system.

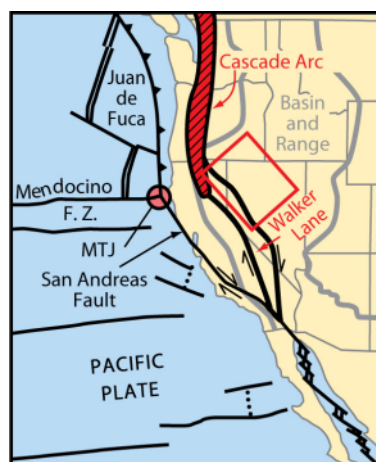


Figure 1: Present tectonic setting of western North America. The red box surrounds the locus of geothermal activity in the northwestern Great Basin. MTJ, Mendocino triple junction.

Detailed studies of geothermal systems and broad inventories of favorable settings can, however, guide exploration strategies and reduce the risks of drilling a successful geothermal well. Particularly favorable structural settings for individual geothermal systems in extensional terranes include 1) relay ramps or step-overs in normal fault zones, 2) fault tips or terminations, 3) fault intersections, 4) accommodation zones (i.e., overlapping belts of oppositely dipping normal faults), 5) pull-aparts in strike-slip faults, and 6) displacement transfer zones

between strike-slip and normal faults zones (Faulds et al., 2006, 2011).

The major dextral faults in the northern Walker Lane form a left-stepping en echelon pattern and may be analogous to Riedel shears developing above a more through-going dextral fault at depth (Faulds et al., 2005a). Each dextral fault terminates in arrays of N- to NNE- striking normal faults and thus contributes incrementally to the overall transfer of dextral shear strain to extension within the northwestern Great Basin. We refer to these areas of strain transfer as transtensional displacement transfer zones. The Pyramid Lake region occupies a major displacement transfer zone at the northern end of the Pyramid Lake fault (Faulds et al., 2005b; Drakos, 2007). Major fault terminations, multiple fault intersections, and accentuated rates of extension indicate high geothermal potential in this and other major displacement transfer zones.

Several hot springs and a human-induced geyser occur in the Pyramid Lake region. The hot springs are commonly associated with structurally controlled tufa towers. Shallow-temperature surveys of both hot springs and wells in the area show temperature variations of 14°C to 117°C (Grose and Keller, 1975; Coolbaugh et al., 2006). However, geothermometers suggest temperatures between 131°- 213°C (Grose and Keller, 1975; Coolbaugh et al., 2006). Although the temperatures of the hot springs and geothermometers suggest possible economically viable geothermal systems, the areas associated with them (e.g., Needle Rocks and the Pyramid) are culturally sensitive to the Pyramid Lake Paiute Reservation and are therefore off limits for development. These restrictions have prompted exploration for a blind geothermal system in the region.

In this paper we present results of using structural and lithologic indicators to help locate blind geothermal systems within the Pyramid Lake area. We show that dilational fault intersections and tufa mark the location of a blind geothermal system and suggest the possible location of other blind systems based on structural settings.

2. STRATIGRAPHY

The Tertiary strata in western Nevada consist primarily of volcanic rock assemblages that rest nonconformably on Mesozoic granitic and metamorphic basement (Bonham and Papke, 1969; Dilles and Gans, 1995; Henry et al., 2004). In the Pyramid Lake area, Miocene basaltic-andesite (known as the Pyramid sequence) and lesser amounts of rhyolite lavas and domes dominate the Tertiary sections (Garside et al., 2003; Faulds et al., 2003; Henry et al., 2004). The Miocene section rests on Oligocene ash-flow tuffs in the southern part of the area. The Pyramid sequence 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 14.8 Ma tuff of Mullen Pass, a dacitic ash-flow tuff, and dacite lavas commonly separate upper and lower sequences of basaltic andesite lavas within the Pyramid sequence. The composite thickness of the Pyramid sequence typically exceeds 1 km.

Quaternary units in the 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. Lake deposits include beaches, bars, tufas, modified colluvium, shoreline sands and gravels, and silts associated with Lake Lahontan and Pyramid Lake (e.g., Adams et al., 1999).

3. STRUCTURAL FRAMEWORK

The Pyramid Lake region contains an intriguing structural intersection in the eastern part of the northern Walker Lane in northwestern Nevada. Here, the northwest-striking right-lateral Pyramid Lake fault ends to the north in conjunction with the southward termination of a west-dipping normal fault system that includes major range-front faults bounding the Lake Range and Nightingale Mountains (Fig. 2). Offset of a west- southwest-trending tuff-filled Oligocene paleovalley suggests ~10 km of right-lateral displacement on the Pyramid Lake fault just south of Pyramid Lake (Faulds et al., 2005a). In contrast, less than 1 km of dextral offset has been documented directly north of Pyramid Lake.

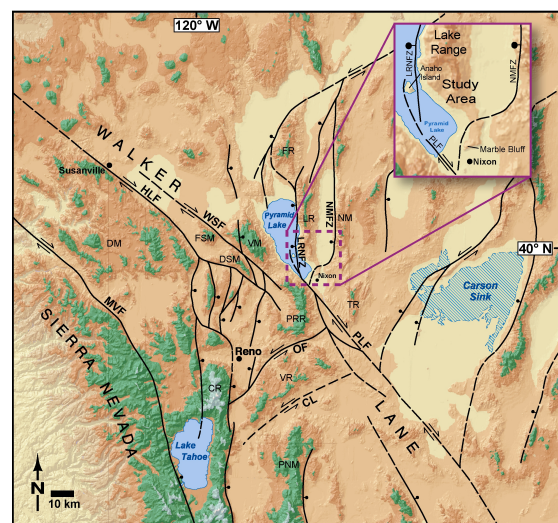


Figure 2. Structural map of the northern Walker Lane. Faults: CL, Carson Lineament; HLF, Honey Lake fault; LRNFZ, Lake Range fault; MVF, Mohawk Valley fault; NMFZ, Nightingale Mountains fault; OF, Olinghouse fault; PLF, Pyramid Lake fault; WSF, Warm Springs Valley fault. Mountain Ranges: CR, Carson Range; DM, Diamond Mtns.; DSM, Dogskin Mtn.; FSM, Fort Sage Mtns.; FR, Fox Range; LR, Lake Range; NM, Nightingale Mtns.; PNM, Pine Nut Mtns.; PRR, Pah Rah Range; TR, Truckee Range; VM, Virginia Mtns.; VR, Virginia Range. Inset marks the primary area for strain transfer.

The west-dipping normal fault system accommodated gentle to moderate east-tilting of fault blocks. The east-tilted Lake Range is the most prominent fault block in the region and is bounded on the west by a major west-dipping normal fault, here referred to as the Lake Range normal fault zone. This fault zone terminates southward against the dextral Pyramid Lake fault and steps to the left northward to the major range-front fault on the west flank of the Fox Range (Fig. 3). The basins are complex, east-tilted half grabens, bounded by west-dipping range-front faults along the Lake Range and Nightingale Mountains, and cut by systems of intrabasinal normal faults and in the case of Pyramid Lake basin also by NW-striking dextral faults. Concordant dips of strata throughout the Miocene and

Oligocene sections within the region indicate that major extension began after ~13 Ma.

Cumulative normal displacement on west-dipping normal faults in the southern Pyramid Lake region includes: 1) ~3.5 to 5.4 km in the Pyramid Lake basin and on the Lake Range normal fault zone, 2) ~1.8 km within the southern Lake Range, and 3) ~5.4 km in the Winnemucca basin and on the Nightingale Mountains fault zone (Drakos, 2007). Thus, total normal offset across the southern Pyramid Lake region is ~10.7 to 12.6 km. This amount is sufficient to have accommodated the transfer of ~9-10 km of dextral slip from the Pyramid Lake fault zone, as well as some regional extension that predates the onset of strike-slip faulting ~9 to 3 Ma.

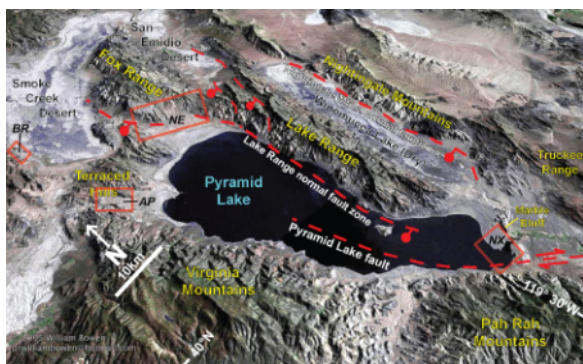


Figure 3. View looking northeast at the Pyramid Lake region showing major physiographic features and major fault zones (modified from a digital elevation model by Bowen, 2005). Light red boxes outline areas that contain favorable structural settings for geothermal activity. AP, Astor Pass; BR, Bonham Ranch; NE, northeast Pyramid Lake; NX, Nixon area.

In contrast to the prominent east-tilted fault block of the Lake Range, the northern Pyramid Lake region consists of a series of fault bounded, relatively low, north-northwest-trending discontinuous ridges (Vice et al., 2007). The ridges generally follow the strike of the faults and are tilted gently to moderately eastward. Some faults in this area are marked by Quaternary scarps. Based on limited kinematic data, morphology of Quaternary fault scarps, and offset of Miocene volcanic units, the faults accommodated normal and/or dextral-normal displacement. Normal displacement has probably dominated, as evidenced by large normal separations (~400-500m) and steep escarpments along many of the north-northwest-trending ridges. However, one north-northwest striking fault in this area accommodated ~600 m of dextral offset of a rhyolite plug. In addition, subvertical dips of north-northwest-striking faults imaged in seismic reflection profiles across the Pyramid Lake basin suggest that some of the faults accommodated strike-slip displacement (Shane Smith, personal communication, 2007; G. Kent, unpublished data). 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.

Another defining characteristic of the region are the linear belts of tufa towers. There are two distinct sets in the northern Pyramid Lake region, the Needle Rocks and Astor Pass. Both sets project toward faults cutting Miocene

volcanic units, suggesting that they are structurally controlled.

4. GEOTHERMAL SYSTEMS

The broad displacement transfer zone within the Pyramid Lake region favors geothermal activity due to the transfer of dextral shear to extension. However, individual geothermal systems in this region probably reside within local fault terminations, steps, and/or intersections within the displacement transfer zone. Detailed geologic mapping, shallow-temperature surveys, gravity data, seismic reflection surveys, and well data are therefore being integrated to elucidate the structural framework and identify potential blind geothermal systems in the region. Favorable settings were found in the Astor Pass area (Vice et al., 2007) directly northwest of Pyramid Lake and in several other parts of the reservation.

4.1 Astor Pass

The Astor Pass tufa tower (Fig. 4) marks the intersection of linear north-northwest- and west-northwest-trending belts 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 the series of en echelon faults that primarily accommodated normal slip with lesser dextral offset. It parallels a southwest-dipping fault bounding the west flank of the ridge directly east of the tufa towers (Fig. 5). The west-northwest-trending tufa spires mark the approximate trace of a dextral, down-to-the-northeast, oblique-slip fault. Exposures of this fault in a clay pit to the northwest of Astor Pass indicate a primary component of dextral slip with minor normal displacement.



Figure 4. View looking northeast at intersecting linear belts of tufa towers at Astor Pass. The tufa alignments probably mark the traces of NNW-striking normal and WNW-striking dextral faults.

The 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 belts of tufa towers (Fig. 5).

Since 2006, three wells have been drilled in the southwest quadrant of this fault intersection. The northernmost well

was the first drilled and was located ~150 m southwest of the central tufa tower. It penetrated to a depth of ~558 m, crossed multiple fault zones, and reached temperatures of ~90°C at ~200 m, suggesting a potentially viable geothermal system. Furthermore, the cuttings showed that hydrothermally altered basalt and rhyolite, locally including sulfides (e.g., pyrite or chalcopyrite), was common beneath the intersecting tufa towers. Considering the lack of any surface hot springs in the area, the first well was considered a success, as it demonstrated 1) the presence of a 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. Surface expression of these hot springs may simply be stymied by the dryer Holocene climate.

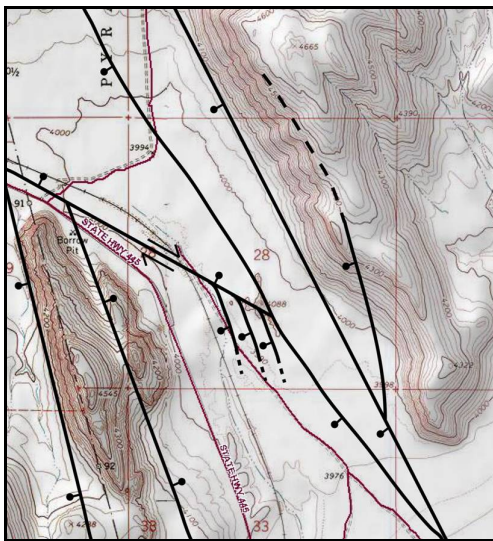


Figure 5. Structure map of the Astor Pass area. The two linear belts of tufa mounds (shown in Fig. 4) are located in the central part of the map at the intersection between the NNW-striking normal and WNW-striking dextral-normal faults. The southwest quadrant of this fault intersection probably has a dilational component.

Two subsequent vertical wells were drilled a few hundred meters to the south of the first well and penetrated to depths of ~1315 m and 1379 m, respectively. Highest temperatures recorded in these wells were ~95°C. It therefore seems likely that the present geothermal system is a relatively small plume centered beneath the central tufa tower along steeply dipping intersecting faults. The quartz and Mg-corrected Na-K-Ca geothermometers have suggested temperatures of 131-132°C for the area (M. Coolbaugh, written communication), so we are encouraged that subsequent drilling beneath the main tufa tower and along the primary fault intersection may tap into a higher temperature geothermal system.

4.2 Other Prospects

Favorable structural settings for geothermal activity occur in several other parts of the Pyramid Lake Paiute Reservation. Foremost among these is the northeastern Pyramid Lake area, which contains a large step or relay ramp between major west-dipping, range-front normal faults on the west sides of the Lake and Fox Ranges (Figs. 2

and 3). Steps in normal fault systems are the most common structural setting for geothermal systems in the Great Basin (Faulds et al., 2011). A shallow temperature survey (2 m probe) indicates a thermal anomaly in the Emerson Pass area in the northern part of this broad step-over. Similarly, the Bonham Ranch area in the northwestern part of the reservation (Fig. 3) lies along the down-dip projection of a small step or relay ramp along an east-dipping normal fault zone.

The area directly west of Nixon to the southeast of Pyramid Lake (Figs. 2 and 3) probably marks a major intersection between the Pyramid Lake fault, N-striking normal faults, and NE-striking oblique-slip faults and may therefore host a blind geothermal system. However, a cool shallow aquifer associated with the Truckee River may effectively mask this geothermal system.

Finally, several warm springs along an apparent east-dipping antithetic fault on the east flank of the Lake Range (Fig. 3) may mark a high-temperature system at depth. Detailed mapping and reconnaissance are needed along this fault to determine the locations of possible steps or terminations that may contain the most robust geothermal system.

5. CONCLUSIONS

The Pyramid Lake region occupies a broad displacement transfer zone that accommodates the transfer of dextral shear from the Pyramid Lake fault to a west-dipping normal fault system. Accentuated extension in this area favors geothermal activity.

Due to the cultural value of surface hot springs to the Pyramid Lake Paiute Reservation, geothermal development must occur on blind systems away from the culturally sensitive areas. Our work has helped to identify a geothermal system at a major fault intersection in the Astor Pass area. Other potentially favorable areas for blind geothermal activity include 1) a large step (or relay ramp) between west-dipping range-front faults flanking the Lake and Fox Ranges directly northeast of Pyramid Lake, 2) the Nixon area, and 3) parts of an apparent antithetic, east-dipping normal fault on the east flank of the Lake Range.

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