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Geothermal Potential of the Pyramid Lake Paiute Reservation, Nevada, USA: Evidence of Previously Unrecognized Moderate-Temperature (150-70°C) Geothermal Systems

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ABSTRACT

At least two and possibly three previously unrecognized moderate-temperature (150-165°C) geothermal areas have been identified during a geothermal exploration program on the Pyramid Lake Paiute Reservation (PLPR) in west-central Nevada, USA. At each of these new areas -- Pyramid Rock, the southwestern Smoke Creek Desert (SWSMD), and east Astor Pass, -- as well as at the known Needle Rocks geothermal area, hot springs and/or near-surface upwellings of hot water are associated with calcium carbonate (tufa) towers forming today in Pyramid Lake or formed in late Pleistocene Lake Lahontan. The structural controls on geothermal fluid flow are still being investigated, but the intersection of Quaternary faults appears to have localized the shallow upwelling of thermal fluids. Near-surface thermal waters, where identified, have temperatures ranging up to 49-97°C, whereas quartz and Na-K-Ca-Mg geothermometers suggest reservoir temperatures on the order of ~150 to 165°C.

Exploration work began with compilation of existing data into a geothermal geographic information system (GIS), and acquisition of an airborne hyperspectral remote-sensing survey of the entire reservation. These efforts were followed by a reconnaissance field survey that prioritized the investigation of anomalies identified in the initial GIS and hyperspectral work. The field survey, which included temperature measurements of springs and existing wells; reconnaissance structural and geological assessments; and geochemical analyses of selected spring and well waters, identified the current areas of interest.

Two promising areas have been investigated in detail with magnetic and gravity surveys; shallow temperature measurements from 2-meter-deep auger holes; detailed geologic mapping; and temperature-gradient drilling. Temperature-gradient drilling in progress, and early results include the intersection of near-boiling waters within 60 m (200 ft) of the surface just east of Astor Pass, ~6 km northwest of Needle Rocks in an area with no springs.

Introduction

A favorable overview of the renewable energy potential on the PLPR by the Department of Energy’s (DOE) GeoPowering the West (GPW) program in 2001 led to funding of a detailed geothermal resource assessment (Clutter, 2005). To conduct the assessment, the tribe chose High Desert GeoCulture, LLC, to provide overall technical management, and selected the Great Basin Center for Geothermal Energy (GBCGE) at the University of Nevada, Reno (UNR) to help design and implement a geothermal exploration program. Exploration activities began in the fall of 2004, with data acquisition and a remote-sensing survey, and continued through 2005 with a variety of field geological, geophysical, and geochemical surveys. Temperature-gradient drilling began in late 2005 before being temporarily suspended by wet winter weather. This paper presents exploration program results as of late 2005.
Regional Structure

Pyramid Lake, which forms the heart of the 1,800 km² PLPR in west-central Nevada (Figure 1), is the largest body of water remaining from late Pleistocene Lake Lahontan. The bottom of Pyramid Lake, elevation of 3,450 ft, is second only to Dixie Valley in terms of low elevation in the northern half of the Great Basin. This low elevation helps explain why the lake is the final discharge point of the Truckee River, whose waters originate from the Sierra Nevada Mountains and Lake Tahoe to the west. The low elevation also provides a clue to the area’s high geothermal potential, because the same tectonic forces and faults responsible for forming deep valleys in northern Nevada can also provide deep conduits for geothermal fluids.

A complex pattern of Quaternary faulting on the PLPR provides a particularly favorable setting for the formation of geothermal systems. The reservation lies along the northeastern boundary of the Walker Lane, a zone of northwest-striking dextral faults related to the San Andreas fault (Stewart, 1988). In west-central and northwestern Nevada, evidence suggests that a portion of this strike-slip motion transfers to northerly striking normal faults of the Great Basin interior (Faulds et al., 2004, 2005a). This zone of transfer, which parallels the northeastern margin of the Walker Lane, is associated with a relatively large number of geothermal systems (Figure 1), perhaps because the transfer from strike-slip to extensional faulting promotes a more complex pattern of deep faulting and greater dilation on the normal faults (Faulds et al., 2004; Coolbaugh et al., 2005). In any case, the PLPR appears to lie within a major zone of strain transfer, as the right-lateral Pyramid Lake fault terminates northward and merges with a complex system of normal faults (Faulds et al., 2005b).

Previous Geothermal Work

Previous geothermal exploration on the PLPR was largely limited to the Needle Rocks area on the north edge of Pyramid Lake, where a spectacular series of 90 m (300 ft) tall calcium carbonate towers form two northwest-trending subparallel ridges more than 2 km long (Figure 2). Hot springs at the base of the Needle Rocks near lake level have temperatures as high as boiling (Garside and Schilling, 1979) and yield geothermometer reservoir temperature estimates ranging from 143°C for the quartz geothermometer to 213°C for the Na-K-Ca-Mg geothermometer (Table 1). Western Geothermal, Inc. drilled three wells at the Needles in the 1960s. The deepest well was 5,930 feet (1,807 m) deep and encountered a flow of 400 gpm at a temperature of 242°F (117°C), and boiling water continues to geyser from the well today. The potential for producing geothermal power at Needle Rocks is considered good (Geothermal Development Associates, 1988), but important cultural features in the area preclude development.

Reconnaissance Exploration

The possibility of finding geothermal targets outside of Needle Rocks was considered good from the beginning of this study because of the large size of the reservation (1,800 km²), its location in a very favorable tectonic setting, and the fact that very little exploration had been conducted outside the Needle Rocks. Consequently the reconnaissance phase of exploration was designed to be as thorough as possible given the time and budgetary constraints.

Reconnaissance exploration began with the compilation of relevant data into a computerized geothermal GIS, and acquisition and analysis of hyperspectral remote-sensing imagery of the entire reservation. These efforts were followed by a field reconnaissance survey and additional regional gravity measurements to supplement the limited existing data. A description of each step is given below.
The GIS served as a focal point for gathering data relevant to geothermal exploration into a digital format, allowing relationships between data types to be easily viewed and assessed in a continually evolving flexible map format. Ultimately, the GIS permitted the team to become aware of information gaps, so that the field reconnaissance program could be appropriately targeted. Also, maps could be rapidly updated as more detailed information became available to facilitate planning of temperature-gradient holes. ESRI’s ArcGIS® 9.0 and ArcView® 3.3 software platforms were used. To date, the GIS includes 22 Gb of files, including: 1) well data and spring data from state and federal governments and the PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 2) temperature-gradient holes, geothermal wells, and PLPR; 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Ave Temp = average of quartz and Na-K-Ca-Mg geothermometers.
Detailed Exploration

The Astor Pass and southwestern Smoke Creek Desert (SWSCD) areas are being investigated with detailed gravity and magnetic surveys, shallow temperature surveys, detailed geological mapping, geochemical analyses, and temperature-gradient drilling. Procedures and methodologies of the geophysical work and shallow temperature surveys are discussed below.

Detailed Gravity and Magnetics Surveys

At the east Astor Pass and SWSCD target areas, approximately 1,000 new gravity stations were collected on 400 by 400 meter grids by Magee Geophysical Services LLC. Each detailed survey covered about 75 km². As with all new gravity data collected for this project, the measurements were acquired using state-of-the-art gravity and GPS survey methods and processed with full terrain corrections. UNR students also collected 50 additional high detail (100 m spacing) stations over the Astor Pass target. The detailed-scale gravity-station data were combined with the regional-scale data and a series of derivative products were generated, including the complete Bouguer anomaly, isostatic residual, total horizontal gradient, first derivative of the upward-continued isostatic residual, and Euler de-convolutions to estimate the depth to basement. Gravity reductions for the complete Bouguer data were evaluated using several density estimates for the surface terrain, including 2.3, 2.4, and 2.5 g/cm³.

Detailed-scale aeromagnetic surveys using ultralight aircraft were flown by Pearson DeRidder and Johnson Inc. over the same areas as the detailed-scale gravity surveys. Each aeromagnetic survey consisted of about 1,280 line-kilometers flown at a typical sensor height of 100 m above ground, with 100-meter line spacings and 300-meter-spaced cross lines. Operating at a 70 to 100 km per hour air speed, this system employed a 10 Hz sample-rate cesium-vapor magnetometer, differential GPS navigation and positioning, and a radar altimeter.

Shallow Temperature Surveys

The discovery of a very high temperature gradient (85°F/100 ft or 950°C/km) in the first temperature-gradient hole east of Astor Pass suggested the possibility of augmenting temperature-gradient drilling with much shallower temperature measurements. An initial attempt at measuring temperatures at a 36 inch (0.9 m) depth did not yield good anomaly definition, but 84 inch (2.2 m) auger holes were much more successful. Because of time constraints and equipment availability, the normal methods of measuring temperatures in shallow holes (Olmsted, 1977; LeSchack and Lewis, 1983; Trexler et al., 1982) were modified for the Pyramid Lake surveys. The procedure involved drilling holes with Eijkelkamp hand-auger equipment. Immediately after hole completion, temperatures were measured at two locations: 1) at the bottom of the open hole; and 2) in the middle of the soil held by the core barrel. This technique is subject to a variety of temperature-measurement errors, including those caused by core-barrel friction, variations in pre-drilling temperature of the coring device, collapse of shallow soil into the bottom of the hole, changes in air temperature that affect instrument temperature compensation, and changes in ground temperature due to changes in weather. The primary advantage of the technique is obtaining a temperature in real-time, which can be used to optimize the location of the remaining auger holes.

A shallow temperature survey at Astor Pass (25 holes) was completed under relatively constant weather conditions over a 10 day period in late November, 2005, using a digital K-type thermocouple meter and probe with a precision of approximately +/-1 to2°C. The survey at SWSCD (29 holes) was completed in 11 days in the first half of December, 2005 under deteriorating weather conditions which eventually forced a suspension of auger drilling when duplicate holes revealed an appreciable change in subsurface temperatures. A 3-wire Pt-RTD (platinum resistance temperature device) with a precision of ~ 0.1°C was used at SWSCD, which is relatively unaffected by surface temperature variations. Both surveys were success-

Figure 3. a) Pyramid Rock viewed looking north from Anaho Island. b) Boiling spring on west side of Pyramid Rock at arrow in a).
ful in outlining pronounced subsurface temperature anomalies; temperatures (at a depth of 2.18 m) ranged from 14 to 26°C at Astor Pass and 14 to 24°C at SWSCD.

**Results: Geothermal Prospects**

Three areas outside the immediate Needle Rocks geo-

thmal area were identified as having potential for moder-

ate-temperature geothermal fluids, defined here as containing

temperatures approaching or exceeding 150°C. They are
discussed below.

**Pyramid Rock**

Pyramid Rock, the namesake of Pyramid Lake, is the tall-
est and most massive single calcium carbonate (tufa) tower

in Nevada (Figure 3). It projects 110 meters above an 1157-

meter-elevation lake level, but most of the mass is below the

water surface. Lake-bottom bathymetry suggests that the base

of the spire is 85 m below the surface (and is 400 m long by

200 m wide), which, if correct, implies a total tower height of

nearly 200 m.

The Paiute Tribe has undoubtedly known since antiquity

of the existence of a hot spring at Pyramid Rock. In the En-

glish literature, however, reports are conflicting about the nature

of springs here and on nearby Anaho Island. Garside and

Schilling (1979) described them as “warm”, while an NBMG
database listed temperatures of 59°C. In contrast, Benson et

al. (1995) ascribed an 89°C temperature to the Pyramid Rock

spring. No previous chemical analyses are known.

With help from a Pyramid Lake search and rescue boat,

the Pyramid Rock hot spring was visited in the spring of 2005,

and at that time it was vigorously spouting from a vertical

rock face a few centimeters above lake level (Figure 3). A

temperature of 97°C was measured (boiling) and steam was

observed issuing from a crack 4 m above the spring. However,

the reported spring on Anaho Island could not be located dur-
ings a several-hour search during which many pelicans, geese,

and rattlesnakes were sighted, but no thermal springs. The

only original published reference to springs on Anaho Island,

by Waring (1965), is sufficiently vague that the reference could

actually apply to Pyramid Rock.

Although the existence of thermal springs on Anaho Island

remains uncertain, other features indicate thermal activity on

the east side of Pyramid Lake in addition to the Pyramid Rock

spring. Garside and Schilling (1979) reported divers finding

underwater hot springs near Pyramid Rock. John Jackson,

Water Resources director, Pyramid Lake Paiute Tribe (PLPT;

verbal communication, 2005) reported observations of bub-

bling waters at an unspecific location on the lake surface north

of Pyramid Rock near Red Bay (along what would be the Lake

Range fault zone), although the authors did not find these

phenomena during a brief 15-minute boat search in 2005.

The tectonic setting of the Pyramid Rock area appears

complicated. The island is situated at a point where the geo-

morphic expression of the north-striking Lake Range fault

zone (on west side of Lake Range; Figure 2) dies out to the

south as it meets what appears to be a northeast-striking fault

defined by the subaqueous northern base of Anaho Island.

Pyramid Island itself appears to lie near the western end of an

almost 1-km-long line of tufa towers, which strikes an unusual

(for Quaternary structures in western Nevada) N80°W. More

regionally, Pyramid Rock lies within a complex transfer zone of

fault motion between the dextral Pyramid Lake fault to the

west and the Lake Range normal fault to the east (Faulds et

al., 2005b; Drakos et al., 2005).

A hot spring water sample from Pyramid Rock yielded a

153°C estimate of reservoir temperature based on both the

quartz and K-Na-Ca-Mg geothermometers (Table 1), sug-

gesting the potential for generating electricity. For religious

reasons, the PLPT has excluded this area from development.

**Southwestern Smoke Creek Desert**

Two warm springs (Rotten Egg Spring and Round Hole

Spring) and several warm artesian wells with temperatures

up to 37°C were previously documented along the southwest

margin of the Smoke Creek Desert (Garside and Schilling,

et al.).
The reconnaissance team was attracted to this area because no geothermometer temperature estimates were available, and because the area contained the largest gypsum anomaly detected by the hyperspectral survey. Field investigations rapidly confirmed a large sulfate-rich soil area on the western margin of Smoke Creek Desert above the elevation of the playa. A 49°C artesian well, not in any known database, was soon located. In addition, a conspicuous area of tufa towers was noted along an apparent 600-meter stepover in the range-front fault to the west (Figure 4, 5). Geochemical analyses of artesian well water revealed a correlation between water temperatures, chloride contents, and discrepancies between the Na-K-Ca-Mg and quartz geothermometers (Table 1) suggesting mixing of near-surface cold groundwaters with deeper geothermal fluids. In spite of the apparent mixing, geothermometer temperatures of well waters reach and exceed 150°C. Thus, this area was selected for further study.

The detailed gravity survey subsequently revealed that displacement along the western range-front fault of the Smoke Creek Desert was at a maximum immediately north of the aforementioned range-front stepover (Figure 6), and that this range-front fault splays southward into several subsidiary southwest to southeast-striking faults (Figure 6). The westernmost of these fault-splays forms the step-over in the range-front fault, which corresponds to a change in dip of volcanic rocks in the range, suggesting a possible change in dip of normal faults along the range front (i.e. more structural complexity). In the piedmont east of the range front, several Quaternary fault scarps are present, accompanied by shallow slump failures and karst-type topography in water-soluble sulfate-rich soils. The complete Bouguer gravity anomaly and its derivative anomaly maps further suggest a buried mini-graben adjacent to the western edge of the valley (Figure 6), similar to that documented for Dixie Valley (McKenna et al., 2005). The detailed aeromagnetic anomaly shows two distinct magnetic lows, one near the exposed stepover along the western range front and a second one further east in the eastern part of the splayed fault zone (Figure 6).
To help locate future temperature-gradient holes, a shallow auger-hole temperature survey was completed. The survey (Figure 4) encountered shallow cold groundwater in the eastern half of the survey area (in the area of artesian wells), underneath which the shallow temperature survey cannot see. In the western half of the survey area, a temperature anomaly was detected near the calcium carbonate tufa towers. An anomalous 35°C temperature measured in a 16-ft (5 m)-deep abandoned dry well (in December, 2005) confirms this temperature anomaly.

One possible exploration model for the SWSCD involves thermal waters rising within the stepover in the range-front fault. At the time of Lake Lahontan, these fluids would have reached the surface to form hot springs and tufa towers. Radiometric dating of tufa towers in the vicinity of Pyramid Lake using 14C (Benson et al., 1995) and uranium-series (Szabo et al., 1996) methods indicates that the towers are up to 60,000 years in age. More recently, when the lake dried up, the hot waters may have begun infiltrating near-surface sediments and flowing eastward down the hydrologic gradient toward the playa, where they could develop artesian pressures beneath clay-rich sediment layers in the playa. Some of these thermal waters could mix with shallower colder groundwaters before reaching the surface in wells. Preliminary chemical modeling of the artesian well waters predicts that the discrepancy between cation and quartz geothermometers can be resolved if cold waters with a chemistry similar to water in the coldest artesian well (20°C) mix with a 65°C thermal water. Required mixing ratios do not exceed roughly 1:1 (in the 37°C artesian well), and in this mixing scenario, the cation and quartz geothermometers both predict reservoir temperatures of roughly 165°C in the parent thermal fluid.

The structural complexity of this area suggests several alternative exploration models in which potential geothermal reservoirs could lie significantly east of the range front fault. Evidence for such models include: 1) Quaternary fault scarps in the piedmont, 2) a possible buried mini-graben and fault splays east of the range front as indicated by the gravity survey, and 3) a magnetic low east of the range front, which may indicate subsurface hydrothermal alteration.

**East Astor Pass**

A 75-km² area northwest of Needle Rocks, which includes much of the Terraced Hills (Figure 2, 7), is also being explored in greater detail. This area attracted initial interest because large areas of argillic alteration were found in Miocene volcanic rocks of the Terraced Hills, and because a series of young northwest-striking faults cut the volcanic rocks. These faults could potentially provide fluid conduits between the clay-altered areas and hot springs at Needle Rocks farther to the south, as first hypothesized by Bonham and Papke (1969).

The hyperspectral remote-sensing survey identified a number of previously unmapped kaolinite/halloysite outcrops in the Terraced Hills, significantly expanding the distribution of documented occurrences beyond an active halloysite mine.
on the western edge of the hills (Bonham and Papke, 1969). Other clues to the presence of thermal activity beneath or near the Terraced Hills include a large tufa tower 6 km northwest of Needle Rocks (Figure 8) and two warm cattle wells, one of which is 26°C and yielded a 143°C K-Na-Ca-Mg geothermometer temperature (Table 1).

After reconnaissance survey completion and detailed gravity and magnetic geophysical work, two temperature-gradient wells were drilled east of Astor Pass at the southwestern edge of the Terraced Hills (Figure 7). The southern hole tested a hypothesized intersection of a northeast-trending topographic lineament with a northwest-striking fault defined by the detailed gravity and magnetic surveys. The northern hole tested the same northwest-striking fault where it passes near a 30-m-tall tufa tower (Figure 8). Both holes encountered high temperature gradients at shallow depths, with peak temperatures at ~ 60 m (200 ft), and became isothermal from 60 to 140 m (200 to 450 ft). Temperatures in the northern hole were hottest, peaking at 86°C at a 60 m depth near bedrock.

The shallow auger-hole temperature survey (Figure 7) indicates the first two temperature-gradient holes were drilled along the axis of a northwest-trending zone of maximum shallow temperatures. The fact that the shallow survey found the highest temperatures and highest horizontal temperature gradients in the immediate tufa tower vicinity suggests that the tufa tower represents the surface expression of a subsurface conduit for rising thermal groundwater. At some time in the past, but likely within the last 60,000 years (Benson et al., 1995; Szabo et al., 1996) when lake levels were higher, thermal groundwater reached the surface to form the towers, but now the rising thermal groundwater appears to bleed off into unconsolidated sediments near the top of bedrock before reaching the surface.

The location of the tufa tower at a change in the trend of the Astor Pass valley, and the fact that the radial arms of the tufa tower are subparallel to each of the valley trends, suggests that the location of the tower is controlled by the intersection of west-northwest and northwest-striking faults. More structural-setting knowledge of this geothermal area will be gained as detailed mapping and temperature-gradient drilling continue. At the moment, the location of a possible deeper geothermal reservoir is unknown, but it could exist either nearby or farther to the north in the Terraced Hills.

Other Areas

A number of other areas with varying geothermal potential have been identified on the reservation. A warm spring (27°C) and warm well (28°C) were found east of the Truckee River and east of the Numana Fish Hatchery (Figure 2) with hyperspectral imagery help that detected sulfate crusts in the area. The warm spring is relatively saline (Table 1) and would have generated a high cation geothermometer (170°C) temperature were it not for its high Mg content. Possible mixing of shallow high-Mg groundwater with deeper thermal waters could produce the observed chemistry. The Numana area lies near the intersection of the right-lateral Pyramid Lake fault and the left-lateral Olinghouse fault, and topographic lineaments suggest that several north-northeast-striking normal faults may splay from the Pyramid Lake fault in this area.

Several warm springs with temperatures up to 24°C occur along the east side of the Lake Range (Figure 2). Topographic lineaments suggest these springs are controlled by a small-displacement range front fault with at least one en echelon step-over near the north end of the reservation. Geothermometer temperature estimates are low, however. Several warm wells are known in the Nixon area; geochemical analyses of these waters are needed to help assess the potential for district heating or electrical energy production. Gravity surveys indicate the area between Nixon and Pyramid Rock is characterized by large magnitude variations in the depth to bedrock, in turn suggesting a complex structural pattern associated with fault motion transfer from the strike-slip Pyramid Lake fault to more northerly striking normal faults along the Lake Range and Winnemucca Lake (Drakos, 2006). Other potential environments for geothermal activity that warrant further investigation include high-displacement normal faults along the western margins of the Lake and Fox Ranges, a potentially large step-over in normal faulting in the Fox Canyon area, and northeast-striking normal faults at the extreme southern end of the San Emidio Desert.

Discussion and Conclusions

The discovery of additional geothermal resource areas on the PLPR indicates significant potential for geothermal energy development on the reservation. It also illustrates that it is possible to use modern grass-roots-style reconnaissance exploration techniques to find previously unknown geothermal systems in the Great Basin that have the potential to produce electricity. Future exploration on specific areas of interest discussed herein should help clarify the geological and structural controls on geothermal fluid flow, and hopefully lead to identification of deeper geothermal reservoirs.

It is noteworthy that two of the geothermal areas of interest (SWSCD and Numana) have surface sulfate crusts detectable with remote sensing, and that in four areas (Needle Rocks, Pyramid Rock, SWSCD, and East Astor Pass), near-surface thermal waters are associated with calcium-carbonate tufa towers. In two of these areas (SWSCD and East Astor Pass), hot waters that formerly reached the surface to form tufa towers no longer reach the surface today. Such tufa towers abound in the Great Basin. Further exploration of tufa towers and additional searches for sulfate anomalies, both on the reservation and elsewhere, is likely to lead to the discovery of additional geothermal systems.

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