# Geothermal Resource Characterization and Evaluation at Astor Pass, Nevada

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## ABSTRACT

A blind geothermal system adjacent to a large tufa tower at Astor Pass was characterized and evaluated according to a comprehensive field investigation consisting of geophysical and shallow temperature surveys, structural geological analysis, and reservoir characterization techniques. The geothermal reservoir system, located in basalts, basaltic-andesites and rhyolites of the Lower Pyramid Sequence, likely originated as the result of transfer of dextral shear to normal fault displacement creating a localized region of enhanced extension and fracture permeability. Shallow temperature and magnetotelluric surveys and seismic image interpretation informed the location of two exploration wells. These wells reached down to the underlying granodiorite basement, confirmed fault structures seen in the seismic images, and were used to characterize the reservoir through borehole fracture characterization and a long duration hydraulic reservoir

test. High fracture densities (0.7 m average spacing) were encountered in the reservoir rocks, and results from the hydraulic test indicate that the reservoir is well-connected with drawdown responses observed in a shallow water well located approximately 1 km from the pumping well. Borehole spinner log surveys with temperature probes and high resolution DTS measurements indicate that fracture inflows are relatively constant with isothermal temperatures ranging between 92 to 95°C along the exploration wells. Analysis of the reservoir drawdown response yields transmissivity values of  $4.8 \times 10^{-4}$  to  $6.7 \times 10^{-5}$  m<sup>2</sup>/s, with fracture transmissivity values ranging between  $1.0 \times 10^{-4}$  to  $7.2 \times 10^{-7}$  m<sup>2</sup>/s. This comprehensive set of data is used to conclude that the Astor Pass geothermal reservoir is a small, low-enthalpy system with relatively isothermal temperatures and high fracture connectivity and permeability.

# Introduction

Astor Pass is located approximately 50 km northeast of Reno, Nevada on the Pyramid Lake Paiute Reservation (Figure 1). In the absence of surficial geothermal expressions, such as hot springs, fumaroles and gysers, the Astor Pass area is considered a blind resource. Astor Pass is, however, located approximately 6 km northwest from the 'Needles', a culturally-sensitive area named after an impressive series of 90 m high calcium carbonate (tufa) towers along two northwest-trending subparallel ridges (Coolbaugh et al., 2006; Vice et al., 2007). Several hot springs and an abandoned geothermal well with artesian conditions, all with boiling water temperatures at the surface, are located at the basal area of the Needles. Tufa towers and mounds, though not as large as the Needles, are also present at Astor Pass. The formation of these tufa features along faults and fault intersections at both Astor Pass and the Needles likely resulted from hot springs discharging into Pluvial Lake Lahontan during the Pleistocene (Vice et al., 2007).

Previous geothermal resource investigations on the Pyramid Lake Paiute Reservation include: characterization of the Needles area (Garside and Schilling, 1979; Geothermal Development Associates, 1988); reservation-wide investigations utilizing



**Figure 1.** Aerial photograph (right) showing location of Astor Pass relative to the Needles and Pyramid Lake, and the location of Pyramid Lake relative to Reno, Nevada (left).

hyperspectral remote sensing, field, gravity, magnetic, and shallow temperature surveys (Kratt et al., 2005; Coolbaugh et al., 2006); and structural geologic analyses at various scales (Faulds et al., 2004, 2005, 2006, 2011; Vice et al., 2007). Coolbaugh et al. (2006) and Vice et al. (2007) provide detail on the first comprehensive field investigation of geothermal resources at Astor Pass. Two temperature-gradient wells were drilled to depths of approximately 130 m; the well closest to the largest tufa tower at Astor Pass yielded the higher temperature of the two wells, with a maximum temperature of 86°C at a depth of 60 m (Coolbaugh et al, 2006). A subsequent exploration well, APS-1, was drilled near the large tufa tower to further evaluate the geothermal potential at Astor Pass, but only reached a depth of 558 m when circulation was lost within a brecciated zone. The equilibrated temperature of APS-1 was approximately 90°C, and it was hypothesized that water exceeding 100 °C would have been encountered had the well been successfully drilled to greater depths (Vice et al., 2007).

The current study at Astor Pass is a collaboration between the Bureau of Indian Affairs, Desert Research Institute, Ehni Enterprises, Optim, Pyramid Lake Paiute Tribe, and University of Nevada, Reno. A comprehensive suite of geophysical and shallow temperature surveys, structural geological analyses, and reservoir characterization methods are utilized to further characterize and evaluate the resource potential of the geothermal reservoir adjacent to the large tufa tower at Astor Pass, herein referred to as the 'Astor Pass Geothermal Reservoir'. The focus of this paper is to provide study findings of the reservoir characterization consisting of borehole fracture log analyses, reservoir pressure and temperature responses during a 30-day reservoir test, and flow spinner logs and temperature profiles along boreholes. The reservoir characterization findings are then combined with relevant findings of the structural analyses, interpreted seismic profiles, and shallow temperature and magnetotelluric surveys to form a conceptual model of the geothermal reservoir.

# **Geological Setting**

The Astor Pass area is comprised of Tertiary basalts, basalticandesites, and rhyolite lavas and domes of the Lower Pyramid Lake Sequence which overlie granodiorite and metavolcanic basement rocks (Faulds et al., 2005; Vice et al., 2007). The Lower Pyramid Lake sequence contains subordinate lenses of flow breccia and volcaniclastic sedimentary rocks, and is overlain in the northern Pyramid Lake area by Quaternary deposits of alluvium and Pleistocene Lake Lahontan and contemporary Pyramid Lake deposits (Faulds et al., 2005; Vice et al., 2007). Tufa formations, as previously mentioned, are also present at the surface and near-surface. The characterization efforts detailed in this study primarily focus on the fractured basalts, basaltic-andesites, and rhyolite lavas of the Lower Pyramid Lake Sequence.

Astor Pass is located within the northwestern portion of the Basin and Range tectonic province, a transtensional region subjected to both northwest-southeast extension and northwest-directed dextral shear (Faulds et al., 2005; Vice et al., 2007; Faulds et al., 2011). The northern Pyramid Lake area lies within the northern Walker Lane, a system of right-lateral strike-slip faults in the western Great Basin that accommodates approximately 15-20% of the dextral motion of the North American and Pacific plates (Faulds et al., 2005; Vice et al., 2007). The Pyramid Lake fault, which strikes approximately northwest-southeast and has approximately 10 km of cumulative offset, is the northeastern-most, right lateral strike slip fault of the Walker lane (Faulds et al., 2005; Vice et al., 2007). The northernmost trace of Pyramid Lake Fault terminates under Pyramid Lake, and Astor Pass to the northwest is considered a location where dextral shear is transferred to normal faults. This localized enhanced extension is thought to favor geothermal activity (Faulds et al., 2004, 2006, 2011; Vice et al., 2007). This interpretation is consistent with the faulting inferred from the seismic surveys, high degree of fracturing and faulting present in the area, and relatively high reservoir permeability as discussed in the following section.

# **Reservoir Exploration and Characterization**

The evaluation of the Astor Pass geothermal resource consisted of an exploration stage followed by a second stage involving well drilling and reservoir characterization. The exploration stage consisted of seismic and shallow temperature surveys, and combined with an updated structural geological analysis and an older magnetotelluric survey, guided the location and depth of two exploration wells. Exploration wells at the site consist of two new wells that were drilled as part of the project, APS-2 and APS-3, and an older exploration well from the previous investigation, APS-1. These wells were used to monitor reservoir pressure and temperature responses during a long-duration reservoir test.

### Seismic Surveys

Seismic surveys were conducted along a series of approximate north-south and east-west oriented seismic lines in the Astor Pass area (Figure 2). Advanced imaging techniques were used to process the seismic profiles as outlined in Eisses et al. (2011), Frary et al. (2011), and Louie et al. (2011). Interpreted seismic profiles, combined with a structural analysis, indicate a complicated mechanical linkage between predominately northwest-southeast trending fault structures with dextral strike-slip and dip-slip displacement (Figure 2). Prior to the reservoir test the potential of these faults to compartmentalize the reservoir were unknown.

#### Shallow Temperature and Magnetotelluric Surveys

A shallow temperature survey, intended to be a surrogate for deeper temperature-gradient drilling, was conducted to provide further insight into drilling locations for the two exploration wells. The shallow temperatures were measured approximately 2 meters below land surface in a manner consistent with that described in Coolbaugh et al. (2006). Measured temperatures range from 16.5°C to 26.7°C with the highest temperatures clustered around the tufa tower (Figure 3a). The high temperature anomaly is consistent with an older magnetotelluric (MT) survey conducted by Zonge Geosciences, Inc. that indicates a low resistivity anomaly in the vicinity of the tufa tower. This is interpreted as a localized region of convective circulation of geothermal fluid.

## **Exploration Wells**

Two exploration wells, APS-2 and APS-3, were drilled to a total depth of 1315 and 1378 m below land surface, respectively.







**Figure 3.** Results from shallow (2 m) temperature survey (a) with temperature values given in degrees Celcius. Note the highest temperatures are adjacent to the tufa tower (gray outline in upper portion of figure). Resistivity contours from magnetotelluric survey (b) showing low resistivity anomaly near the tuff tower (outline near 'bullseye' of low resistivity). The low resistivity anomaly is interpreted to be an area of convective circulation of geothermal fluids.





**Figure 2.** Fault trace map (a) showing location of seismic transects (green) and interpreted faults (dotted lines). Example of seismic reflection profile (b) showing strong reflectivity of Tertiary basalts along with interpreted faults. Note the complex configuration of normal and strike-slip faulting at Astor Pass shown in (a).

The depth and spatial location of these wells was selected to optimize the intersection of these wells with numerous fault planes at depth as informed by the seismic profiles. The seismic imaged reservoir fault structures were confirmed during drilling. Both wells are located on the west side of the large tufa tower (Figure 4) and are approximately 125 m apart. The short distance between the wells reflects the uncertainty in the potential for fault compartmentalization of the reservoir, and hence, the close proximity was intended to ensure hydraulic communication between the wells.

The design of the two wells consists of large diameter surface casing, followed by intermediate casing, and a steel liner that extends from the bottom of the intermediate casing down to terminal depth. The intermediate casing extends beyond the zones of lost circulation encountered within 330 m and 480 m below land surface and is cemented in place. The liners are slotted with 300 m of open interval that is positioned at the bottom of the wells. Both boreholes encountered granodiorite basement rocks at approximately 1250 m below land surface.

## Wellbore Geophysics and Reservoir Fracture Characterization

Borehole geophysical surveys were conducted by Baker Hughes, Inc. to collect information on fractures and breakouts along the deeper sections of the two wells. The surveys used a combination of micro-resistivity and accoustic methods to both detect and distinguish between open, partially-open and closed fractures. The longest survey was conducted along the APS-3 borehole and forms the basis of the borehole fracture analysis.

A total of 973 fractures were encountered along a 710 m interval corresponding to an average fracture spacing of 0.7 m for all fractures, 1.3 m for either partially open or open fractures, and 15 m for open fractures. Analysis of fracture orientations yields

two fracture sets, both of which are oriented northwestsoutheast and dipping steeply to either the southwest or northeast (Figure 5). Analysis of breakouts confirms that the majority of fractures are oriented in the direction of the least compressive horizontal stress, and are consistent with the orientations of the larger faults inferred from the seismic profiles in Figure 2.

**Figure 4.** Photograph of drilling rig near tufa tower at Astor Pass (left) along with sample output from the borehole geophysical survey (right). Borehole survey output courtesy of Baker Hughes, Inc.



**Figure 5.** Lower hemisphere stereonet plots of all fracture orientations (a) indicate two steeply dipping fracture sets oriented northwest-southeast. Bore breakouts (b) confirm that the majority of fractures are located in the direction of least compressive horizontal stress.

## Thermal and Hydraulic Reservoir Testing

A reservoir test that involved pumping APS-3 at a constant rate of  $2.8 \times 10^{-2}$  m<sup>3</sup>/s (450 gpm) was conducted over a period of 30 days to characterize the thermal and hydraulic properties of the Astor Pass geothermal reservoir. Wells APS-1, APS-2 and a water well completed in the unconsolidated alluvium approximately 1 km in distance from APS-3 were used as monitoring wells. Temperatures in APS-2 were monitored via a distributed temperature system (DTS) cable at a spatial resolution of 1 m along the borehole and at a temporal resolution of 15 minutes. Borehole flow meter 'spinner' surveys were conducted during the pump test along APS-1, APS-2 and APS-3. The spinner tool also contained a temperature probe that collected temperature profiles along the exploration wells.

Strong drawdown responses were observed in APS-1 and APS-2 (Figure 6), and surprisingly, even the water well located approximately a kilometer away (not shown). These results indicate that the background network of fractures and faults is highly connected and the larger faults detected in the seismic profiles do not compartmentalize the reservoir and may actually promote long range flow connectivity. While APS-2 and APS-3 are open to the reservoir at the same depth and located only 125 m apart, APS-1 is completed 550 m above the open interval of

APS-3. The drawdown in the water well in unconsolidated sediment above the basalt, basaltic-andesites and rhyolites of the Lower Pyramid Sequence further demonstrates the large-scale connectivity of the reservoir.

The borehole 'spinner' and temperature surveys (both DTS and temperature probe on the spinner tool) conducted in APS-1, APS-2 and APS-3 during the pumping test indicate that inflows into the open interval of the wells are relatively constant (not shown). This implies that fracture transmissivity of the reservoir open to the wells is relatively constant. Temperatures in the boreholes are isothermal and range from 92 to 95°C, and that fracture inflows are of relatively constant temperature (Figure 7).

Reservoir drawdown trends from APS-1 and APS-2 suggest that the background fault and fracture network is highly connected and functions approximately as an equivalent porous medium. Drawdown data from APS-2 was analyzed according to a variety of aquifer test methods including Theis, Jacob-Cooper and Neuman (e.g., Fetter, 2001) and yielded reservoir transmissivity values in the range of  $4.8 \times 10^{-4}$  to  $6.7 \times 10^{-5}$  m<sup>2</sup>/s (Walsh et al., 2011). Analysis of drawdown at APS-1 yielded similar results. The isothermal temperature profiles made this analysis straightforward as water density and viscosity values corresponded to temperatures of 95°C.

Information on fracture aperture in the boreholes was not collected during the analysis of the borehole geophysics. The lack of data on fracture length and aperture precluded a discrete fracture analysis of the hydraulic properties of the reservoir (e.g., Reeves et al. 2010, 2012). Instead, average or equivalent fracture transmissivity was computed by normalizing the reservoir transmissivity values by the number of open (n=47)and combined open and partially open fractures (n=936). This corresponds to a range of effective and fracture transmissivity values of  $1.0 \times 10^{-4}$  to  $1.4 \times 10^{-5}$  m<sup>2</sup>/s and  $5.1 \times 10^{-6}$  to  $7.2 \times 10^{-7}$  $m^2/s$ , respectively. The cubic law (Snow, 1965) was then used to compute average fracture apertures from the above fracture transmissivity values, resulting in 260 to 340 microns if only open fractures are included and 65 to 125 microns if open and partially open fractures are included in the analysis. The use of all partially open fractures most likely overestimates the connectivity of the background network, as observed by the low fracture aperture range; whereas, the exclusive use of open fractures underestimates the connectivity of the network, as observed by the



Fracture networks exhibit complex geometry (e.g., Reeves et al., 2012) and in all likelihood, the background network responsible for fluid flow consists of both open and partially open fractures identified from the borehole fracture analysis. This implies that the fluid conducting fractures have density and transmissivity values that lie between the two end member estimates.

high fracture aperture range.

**Figure 6.** Drawdown profiles along APS-2 and APS-1 located approximately 150 and 330 meters away from the pumping well, respectively. The recovery spikes occurred during periods in which the pump had to be shut down for maintenance.

## **Borehole Temperature Profiles**



**Figure 7.** Temperature profiles for APS-1, APS-2 and APS-3 showing a more or less isothermal temperature profile of approximately 95°C down to 1300 meters. The water table is located at approximately 30 meters below land surface.

### Conceptual Model of the Astor Pass Geothermal Resource

The Astor Pass geothermal reservoir is a small, low-enthalpy system with relatively isothermal temperatures of 95°C. The shallow temperature and magnetotelluric surveys outline a circular to elliptical convective plume of geothermal fluid circulation. Well bore hydraulic testing with a spinner tool and temperature probe indicates that the granodiorite basement rocks have insufficient permeability to serve as a laterally extensive reservoir, suggesting that a discrete fault or fault intersection (the geometry of Astor Pass tufa tower suggests a fault intersection) is responsible for providing a pathway for upwelling of geothermal fluids through the basement and into the geothermal reservoir located in the overlying Tertiary volcanics of the Lower Pyramid Lake sequence.

There is a strong correlation between tufa formations and geothermal activity on the Pyramid Lake Paiute Reservation (Coolbaugh et al., 2006; Eisses et al., 2011). In addition to the Needles and Astor Pass, a hot spring discharges from Pyramid Rock, the largest massive tufa tower in Nevada and the namesake of the Pyramid Lake area. Eisses et al. (2011) conducted seismic Compressed High Intensity Radar Pulse (CHIRP) surveys to image fault structures at the base of Pyramid Lake. Washouts and formation of tufa in the processed CHIRP images along normal or dip-slip fault structures, the same structures that formed the tufa features at Astor Pass and the Needles, indicate that these structures are permeable and conduct hot fluid.

The high fracture permeability and large-scale connectivity of the basaltic, basaltic-andesite and rhyolite reservoir rocks of the Pyramid Lake sequence support findings from the structural geologic analysis that Astor Pass is in a region of enhanced extension. The reservoir rocks offer little resistance to the upward migration of geothermal fluids. Upon encountering cooler, nearsurface temperatures, the geothermal fluids cool, and migrate downward along the outline of the convective cell due to density contrasts. The long duration of the reservoir hydraulic test and the high resolution monitoring of fracture inflow locations and borehole temperatures eliminate the possibility of preferential flow of geothermal waters exceeding 100°C. These features would have been intersected as the cone of depression (which spread to a radial distance of at least 1 km as evidenced by drawdown in the water well), and hotter inflow temperatures would have been detected during the temperature surveys and high resolution DTS measurements.

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