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Mineral mapping in the Pyramid Lake basin: Hydrothermal alteration, chemical precipitates and geothermal energy potential

Christopher Kratt [a,*], Wendy M. Calvin [b], Mark F. Coolbaugh [b]

[a] Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, United States
[b] Arthur Brant Laboratory for Exploration Geophysics and the Great Basin Center for Geothermal Energy, MS-172, University of Nevada Reno, Reno, NV 89557, United States

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ABSTRACT

Geothermal resources exist on the Pyramid Lake Paiute Tribal Lands (PLPTL) in northwestern Nevada. We compiled numerous indicators of these resources into a geographic information system along with concurrent investigative results. This effort required acquisition and analysis of spaceborne multispectral and airborne hyperspectral remote sensing data for early-stage geothermal exploration. We identified minerals such as alunite, kaolinite, and montmorillonite through analysis of hyperspectral data indicating regions of hydrothermally altered rock associated with areas of geothermal potential. Tertiary volcanic and granitic rocks also contain these indicator minerals. Quaternary environments displayed gypsum-bearing evaporite crusts that we postulate were deposited by sulfate-rich thermal waters. Throughout the PLPTL, tufa towers and tufa shoreline deposits are extensively distributed as remnants of paleo-lake Lahontan. Based on measured spectra of calcium carbonate, we mapped tufa towers elucidating the strike direction of associated faults. Additionally, we correlated remotely-derived maps of shoreline tufa deposits with climate-related changes in lake level. Our mapping results helped guide detailed exploration efforts to areas with the most geothermal potential.

1. Introduction

High temperature springs and geothermal potential in the region surrounding Pyramid Lake, Nevada were noted as early as the 1960s, particularly near the Needles Rocks tufa formation (Garside & Schilling, 1979) (Fig. 1). Geothermal potential on the Pyramid Lake Paiute Tribal Lands (PLPTL) is considered to be high based on existing evidence of warm and hot springs, location of the lake along a major fault trend, and other known producing geothermal systems in the region along with the 3.6 MW San Emidio geothermal plant to the northeast of tribal lands. A detailed assessment of geothermal potential of the PLPTL was undertaken by the Great Basin Center for Geothermal Energy through the U. S. Department of Energy's GeoPowering the West program. We initiated the reconnaissance portion of phased exploration with acquisition of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) spacecraft data. We also collected HyVista Corp. HyMap imaging spectroscopy data by an aerial survey, covering the PLPTL. Using these data and others, we assembled a geographic information system (GIS) database including 1) well and spring locations, 2) drill hole and well temperature-gradients, 3) magnetic and gravity data, 4) nighttime Landsat thermal imagery, 5) shallow temperature data, 6) earthquake locations, 7) Quaternary fault locations, 8) topographic and aerial photographic base maps, and 9) hyperspectral imagery and derived mineral maps. Synthesis of these geothermal indicator data sets is provided by Coolbaugh et al. (2006). In this paper, we present detailed analysis of ASTER and HyMap data sets used in that study. The derived geothermal mineral indicator maps suggest promising sites for further exploration.

2. Geologic background

The Pyramid Lake basin is located within the Walker Lane Belt (WLB) system of northwest-striking right-lateral faults that generally parallel the eastern side of the Sierra Nevada mountain range. The WLB presently accounts for 15–25% of the motion between the North American and Pacific Plates (Thatcher et al., 1999). Offset movement in the southern WLB is between 50 and 100 km and decreases to ~20–30 km in the northern WLB where the study area is located. GPS-geodetic surveys (Kreemer et al., 2006) and structural evidence (Faulds et al., 2005) indicate that strain is partitioned into the Basin and Range from the northern WLB. Neotectonic faults on the Pyramid Lake reservation are characteristic of strain transfer relationships in the northern Walker Lane (Faulds et al., 2006). The northwest-striking, right-lateral Pyramid Lake fault (Fig. 1) extends southward more than 45 km and shows evidence of at least four different earthquake events in the past 15 ky (Briggs & Wesnousky, 2004). This fault accounts for 5–10 km of offset in the northern Walker Lane Belt (Faulds et al., 2005) as strain is transferred to N-NNE-striking normal faults to the north of Pyramid Lake (Faulds et al.,

* Corresponding author.
E-mail address: ckratt@dri.edu (C. Kratt).

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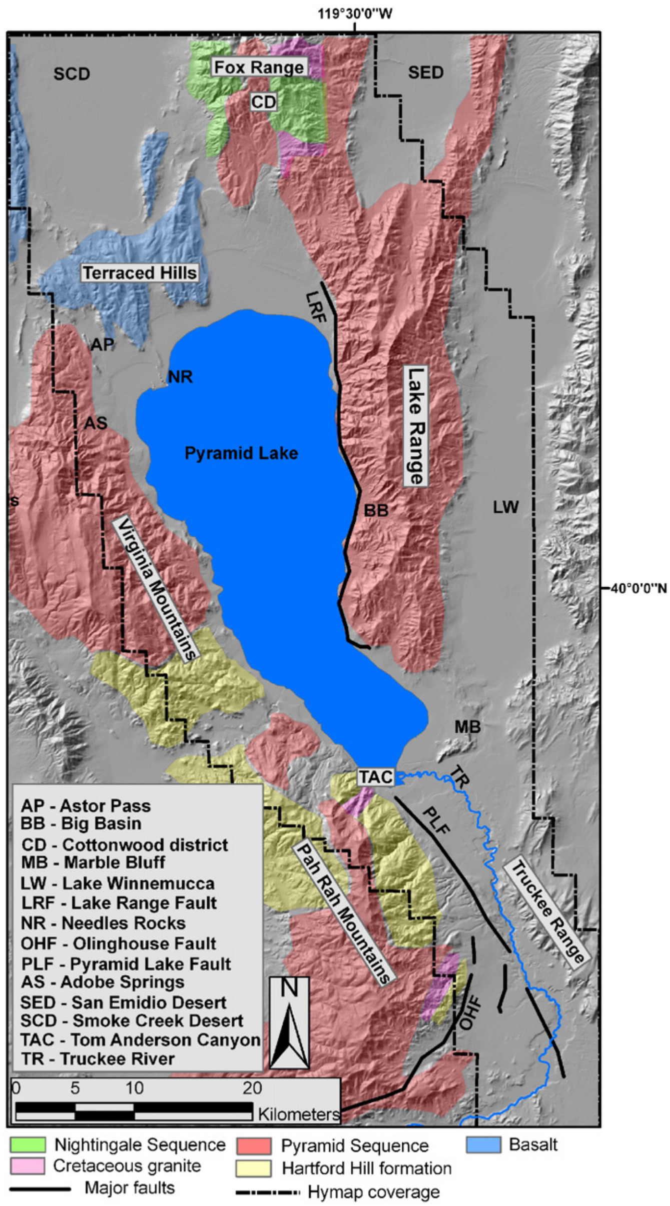

Fig. 1. Shaded relief image shown with generalized geologic map modified from Bonham and Papke (1969) and approximate locations of other areas referenced in the text, dashed line is boundary of area imaged by the hyperspectral survey.

2006). The Olinghouse fault (Fig. 1) is a northeast-striking, left-lateral fault that can be traced for 25 km and has ruptured at least twice during the past 4 ky (Briggs & Wesnousky, 2005). Other, less active, predominantly N-NW-striking faults offset mostly east-dipping Tertiary basalts, rhyolite, lacustrine deposits, and limited metamorphic outcrops (Bonham & Papke, 1969). Association of the northern WLB with the Pyramid Lake basin promotes crustal dilation and deeper penetration of fluids along these steeply dipping faults (Faulds et al., 2005). This structural relationship enables increases in higher local heat flux and, therefore, increased potential for geothermal energy production (Faulds et al., 2005).

Pyramid Lake is the largest of the few remaining vestiges of Pleistocene Lake Lahontan that once covered 22,500 km^2 during its high stand at ~13 ky (Adams & Wesnousky, 1999). The presence of Lake Lahontan gave rise to the prolific deposition of tufa in the region. These calcium-carbonate deposits are precipitated when calcium-rich spring waters mix with atmospherically derived CO_2 dissolved in lake water (Coolbaugh et al., 2009). The mixing zone commonly occurs at sublacustrine springs, and paleo-shorelines where tufa forms a hard coating on surface materials that can be greater than 1 m in thickness. Sublacustrine tufa towers may indicate that structural control was aligned with identified faults (Benson, 1994; Hancock et al., 1999; Kratt et al., 2005).

A series of structurally controlled tufa towers stand up to 90 m tall at the northern edge of Pyramid Lake where both spring and well waters can be found at boiling temperatures. Pyramid Rock, an island in the central part of the lake, is another tall tufa tower where a 97 °C spring issues from its base (Coolbaugh et al., 2006). Numerous other tufa towers, tens of meters tall, are found around the margins of the lake and adjacent basins, in addition to prolific tufa encrustations on paleo-shorelines.

3. Data sets and processing methods

Due to the size of the PLPTL (~1800 km^2), we employed remote sensing data sets to provide a general survey of the area as well as direct field reconnaissance and mapping to the sites with the highest geothermal potential. The ASTER instrument on the NASA Terra satellite provides images in 14 wavelength channels from the optical to thermal infrared (Yamaguchi et al., 1998). Our analysis focused on the combination of visible/near-infrared (VNIR; 0.5–0.8 µm) and short-wave infrared (SWIR; 1.6–2.4 µm) channels. The three VNIR channels are acquired at a spatial resolution of 15 m/pixel spatial resolution and the six SWIR channels at 30 m/pixel. The VNIR and SWIR data were analyzed separately to provide initial surface cover and thematic maps. We used the AST-07 at-surface reflectance data product provided by the USGS Land Processes Distributed Archive Center, which provides on demand processing of ASTER high-level data products (http://asterweb.jpl.nasa.gov). We selected an ASTER scene from 6/04/04 for the similar seasonal coverage to that of the hyperspectral aerial survey described below. Eighty percent of the reservation was imaged by the ASTER scene, with minimal cloud cover. Past analysis has shown that simple color composites and band ratios can be used to refine targets for detailed analysis (e.g. Rowan & Mars, 2003). We applied decorrelation stretches (Gillespie et al., 1986) to various VNIR and SWIR band combinations to help identify areas of hydrothermally altered rock and tufa deposition.

The HyMap sensor is an airborne imaging spectrometer flown by HyVista Corporation that measures radiance in 127 contiguous channels with 13–17 nm sampling intervals that span the 0.45–2.5 µm range. We acquired more than 2000 km^2 of hyperspectral data over the PLPTL on Sept. 23, 2004 from an approximate altitude of 2500 m above ground level with spatial resolution of 5 m/pixel. Twenty-six overlapping flightlines were acquired, and each flightline was approximately 2.2 km wide by at least 60 km long. HyVista used in-house instrument calibration and atmospheric modeling routines to deliver calibrated at-surface reflectance data.

For spectral analysis, we individually processed each flightline by masking the lake and then using statistical methods described by Green et al. (1988) to reduce spectral coherence and noise, as well as enhance identification of surface spectral endmembers. These methods follow those successfully used by others (e.g. Kratt et al., 2005; Kennedy-Bowdoin et al., 2004; MacKnight et al., 2004; and Martini et al., 2003) to identify unique mineral signatures associated with geothermal systems. Data processing used algorithms found within the commercial software ENVI®, but relied on our previous experience analyzing this type of data to deliver high confidence map products. Unique spectral signatures identified in the airborne image data were corroborated with field and laboratory analyses.

Due to variation in sun angle and flight direction, we processed each flightline separately. Our analytical methods relied on a series of principal component transforms that segregate noise and concentrate unique elements of the data cloud into low order components (Green et al., 1988). We visually inspected these “Minimum-Noise Fraction”