Identification of a New Blind Geothermal System with Hyperspectral Remote Sensing and Shallow Temperature Measurements at Columbus Salt Marsh, Esmeralda County, Nevada

Christopher Kratt[1], Mark Coolbaugh[2], Bill Peppin[3], and Chris Sladek[2]

[1]Desert Research Institute, Reno, NV
[2] Great Basin Center for Geothermal Energy, University of Nevada Reno, Reno, NV
[3]SpecTIR Corporation, Reno NV

Keywords

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ABSTRACT

Hyperspectral remote sensing-derived mineral maps and follow-up shallow temperature measurements were used to identify a new blind geothermal target in the Columbus Salt Marsh playa, Esmeralda County, Nevada. The hyperspectral survey was conducted with the ProSpecTIR VS2 instrument and consists of 380 km^2 of 4-meter spatial resolution data acquired on October 29, 2008, covering the playa and surrounding hills. Using these data, borate and sulfate evaporite minerals and opal/chalcedony, carbonates and argillic alteration were identified and mapped. Field samples were collected and validated with laboratory spectral measurements and x-ray diffractometer analysis. Mineral maps were then used to guide a shallow temperature survey with nearly 100 two-meter-deep measurements.

The largest area of sulfate and borate crusts identified with the hyperspectral survey occurs in the southwestern portion of the playa. Directly up the hydrologic gradient from these crusts, the 2-meter survey identified a 4.1 km by 1.7 km area of anomalous shallow temperatures. The shape of this temperature anomaly is elongate in an east-northeast direction parallel to, and along trend with, nearby Quaternary faults, and the down-slope direction of this trend points towards the area of sulfate and borate crusts. A cold spring associated with some of the sulfate and borate crusts yields anomalous geothermometer temperatures (115°C and 137°C, respectively for the quartz and Mg-corrected Na-K-Ca geothermometers), providing corroboration of a geothermal component to shallow groundwaters in the playa. A geothermal reservoir may exist at depth in the vicinity of, or laterally displaced from, the shallow temperature anomaly, in an area with a fanning strike pattern of Quaternary faults.

Introduction

Over the past decade several authors have reported on the use of airborne hyperspectral surveys in the Great Basin of the western United States for identifying and mapping geothermal indicator minerals (Martini et al., 2003; Kennedy-Bowdoin et al., 2003; Martini et al., 2004; MacKnight et al, 2004; Kratt et al., 2005; Kratt et al., 2006b). Examples include argillic alteration, silicification, tufa deposits, and evaporite crusts together with their associated minerals kaolinite, alunite, montmorillonite/illite, opal/chalcedony, gypsum, and tincalconite. Remote sensing data allows these and other minerals to be mapped over large areas where they can often reveal hidden fault structures and the potential presence of upwelling geothermal fluids. More recently Kratt et al. (2006a) successfully used satellite data to identify borate-rich Quaternary evaporite crusts in three different basins, including the Columbus Salt Marsh (CSM) playa. Borate-rich evaporite crusts are associated with geothermal activity around the world and Coolbaugh et al. (2006b) discuss the relationship of Quaternary borate deposits to geothermal systems in Nevada. Many warm spring and hot spring waters have high concentrations of boron; however, in some cases cold springs share this characteristic and where supported by favorable geothermometer temperatures may suggest the presence of a nearby geothermal reservoir. Both sulfate and borate evaporite minerals can precipitate by diffuse capillary evaporation and do not require flowing springs, hence, these minerals can serve as geothermal identifiers where thermal springs are not present.

Thermal evidence of the possible presence of geothermal waters may be achieved with two-meter-deep temperature surveys (Coolbaugh et al., 2007; Sladek et al, 2007). Shallow temperature surveys were recently used to identify thermal anomalies related to borate salt crusts at Teels and Rhodes Marsh playas in Mineral County, Nevada (Kratt et al., 2008). Similar to the Teels and Rhodes Marsh playas, the CSM playa also contains borate-rich evaporite crusts. These crusts are difficult to distinguish visually from common salt (NaCl). Spaceborne ASTER remote sensing measurements were used to approximately map some borate crusts at Teels, Rhodes, and Columbus Marshes (Kratt et al., 2006a). However, ASTER

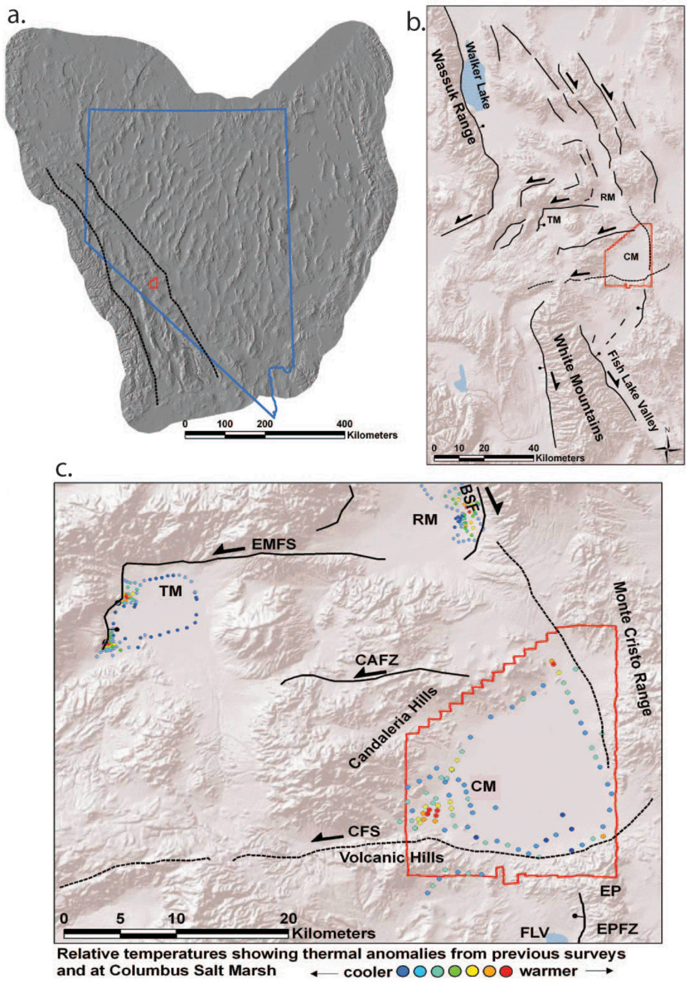

Figure 1. Red outline shows boundary of hyperspectral data coverage a.) Shaded relief map of Great Basin , Nevada state border outlined in blue, Walker Lane Belt approximated by black lines b.) major faults of the Mina Deflection shown in black , arrows show sense of motion c.) mountains and relevant features in the study area: CSM – Columbus Salt Marsh, EP – Emigrant Peak, FLV – Fish Lake Valley, EPFZ – Emigrant Peak Fault Zone, CFS – Coaldale Fault System, CAFZ - Candaleria Fault Zone, RM – Rhodes Marsh, TM - Teels Marsh, EMFS – Excelsior Mountain Fault System, BSF – Benton Springs Fault (faults modified from Wesnousky, 2005).

provides considerably less spatial detail and spectral resolution than is possible with airborne hyperspectral surveys, and its ability to distinguish borates from other salt minerals is imperfect. Thus, we were motivated to explore the ability of hyperspectral data to produce more accurate and higher-resolution maps of borates and sulfates at CSM playa, and then use these new mineral maps to help guide and focus follow-up shallow temperature surveys.

Study Area Background

The study area is located in Esmeralda County, NV immediately to the northwest of Coaldale Junction where U. S. Highway 95 and U. S. Route 6 meet (Figure 1). CSM playa is bound to the north and west by the Candaleria Hills and to the northeast by the southwestern end of the Monte Cristo Range. The Volcanic Hills bound the southwest margin of the playa and the Emigrant Hills bound the southeast playa margin. Rhodes, Teels, and CSM playas are situated in a broad right-stepping transfer zone in the Walker Lane Belt referred to as the Mina Deflection (Oldow et al., 1994). Here, right-lateral strike-slip strain is transferred from the southern to the central Walker Lane along a series of east-northeast-striking left-lateral faults. This structural configuration has facilitated the development of extensional, "pull-apart" basins at all three playas, and the associated faults in each of these basins show evidence of Quaternary displacement (Wesnousky, 2005). Northeast-striking Quaternary faults are spatially associated with geothermal activity in much of Nevada (Coolbaugh et al., 2002; Faulds et al., 2006); thus from a regional perspective, Teels, Rhodes, and Columbus Marshes offer favorable settings for the possible development of geothermal systems.

The highly folded and faulted Ordovician Palmetto formation comprises the oldest exposed rocks in the study area (Albers and Stuart, 1972). These rocks are composed of shale and siltstone with interlayers of chert and limestone. Stratigraphically above the Palmetto formation is the Permian Diablo Formation, consisting of dolomite and conglomerate, which in turn is overlain by shale and sandstone of the Triassic Candaleria Formation. Overlying the Candaleria Formation are Tertiary basalts, andesites, rhyolites, ash flow tuffs, and lacustrine rocks that range in age from early Miocene to latest Pliocene (Albers and Stuart, 1972). Quaternary salt deposits and sediments are accumulating in the evaporitic basin that comprises the CSM playa.

Borate salts were mined at CSM during the 1870s, and in fact, Teels, Rhodes, and CSM playas once led the world in borate production for about a ten-year period beginning in the 1870s (Barker and Lefond, 1985). Kratt et al. (2006a) used ASTER images to approximately map the distribution of some of these borate occurrences. Evidence of geothermal activity was found at one cold spring surrounded by borate salt crusts, where the Mg-corrected Na-K-Ca and quartz geothermometers yielded subsurface temperatures estimates of 137º C and 115º C, respectively (Coolbaugh et al., 2006b).

Remote Sensing Background

More than 380 km^2 of 4-meter spatial resolution airborne hyperspectral data were acquired on Oct. 29, 2008 by SpecTIR Corp. of Reno, Nevada. These data cover CSM playa and the lower portions of the surrounding hills with eighteen flightlines, each approximately 1.2 km wide. The ProSpecTIR VS2 has 357**+** contiguous channels that cover the 0.40 – 2.5 μm wavelength region. The ProSpecTIR was flown aboard a Cessna 206 at an altitude of approximately 4,500 m above ground level and the survey was completed within a 3.5 hour period that bracketed the 24-hour solar maximum. The signal-to-noise ratio was 500:1 to 1,000:1 in regions away from the water absorption bands near 0.9, 1.1, 1.4, and 1.9 μm. The spatial accuracy of the data was +/- 8 meters (two pixels) after orthorectification using a USGS digital elevation model.

Mineral Mapping and Field Validation

Reflectance was derived from calibrated radiance data using two different methods: the MODTRAN-based Atmospheric

Correction (ATCOR) application (reference) which performs conversion to reflectance over the entire recording spectral region (0.4 to 2.5 μm), and the Virtual Empirical-Line Calibration (VELC) procedure in the Short-wave Infrared (SWIR) region (2.0 – 2.5 μm). The VELC method, developed by SpecTIR Corp., most closely resembles a flat-field calibration. It searches the entire image for pixels that are statistically "most generic," and then assumes that any spectral characteristics contained therein will not be of interest. From this group of pixels, the VELC calibration spectrum is determined as the average of the pixels found. The VELC reflectance is generated by dividing the calibrated radiance in (2.0 – 2.5 μm) by the VELC calibration spectrum. This is similar to the flat-field, empirical-line, and IARR calibrations available in the ENVI™ software package. The ATCOR output has the advantage of providing reflectance across the entire recording spectral region, but at lower spectral resolution. The VELC retains full resolution in the SWIR, and therefore provides much sharper discrimination of minerals with absorption features in this wavelength range, but with the disadvantage of being unusable in the lower wavelength region as the methodology presently is developed. The ATCOR reflectance can be used to determine the presence of minerals with iron signatures in the Visible Near-infrared (VNIR 0.4 – 0.9 μm) such as goethite, hematite, and jarosite; the VELC reflectance can be used for the identification of alteration clays, and sulphate and borate minerals, which have strong absorption features in the SWIR.

After identifying endmembers associated with vegetation and anthropogenic features, the remaining mineral spectra were consolidated to remove duplicates, resulting in the identification of 17 unique mineral endmember spectra. All eighteen flightlines were combined into a single file then processed with a matched-filtering algorithm in ENVI™ (Boardman et al., 1995) using the mineral endmember spectra as inputs. Matched-filtering provides a gradational scale for every pixel in the scene where the similarity to the input endmember is given a value from 0 (zero) to 1 (perfect). Comparison of the image spectra with the input endmember spectra was used to determine threshold values for each matched-filtered grayscale image. In the case of CSM, the threshold values were chosen conservatively, so that all pixels above the selected threshold value could be regarded as high-confidence matches to the endmember spectra and incorporated as mineral maps into Geographic Information Systems (GIS) software.

Over the course of three days during March and April 2009 more than 42 sample locations of remotely mapped minerals were field checked. Evaporite crusts were delicately removed and transported back to the laboratory along with samples collected in the surrounding hills. Using a halogen lamp as an illumination source and an Analytical Spectral Devices (ASD) Fieldspec Pro spectroradiometer, representative reflectance spectra for each of the field samples were collected. The ASD digitally records reflectance data for 2,151 spectral channels covering the 0.35-2.5 μm wavelength region. Reflectance calibration is achieved with a white reference panel that has a known reflectance across the entire measured spectrum. The laboratory ASD sample spectra were then compared to reference library spectra (Clark et al., 2003; Crowley, 1991).

Shallow Temperature Survey

During April 5-8, 2009 sixty-three 2 meter deep temperature measurements were recorded in the study area. Thirty-five additional measurements were made during May 2-4, 2009. Sladek et al. (2009) provide data showing that 2 meter deep temperatures in Nevada reach their annual low about the same time that the first part of this survey was conducted. From early May onward into the summer and fall, temperatures at a 2-meter depth progressively increase in response to warmer weather and increased solar radiation. Warm and cold base station measurements recorded during both survey periods were used to calibrate the temperatures from the first survey with temperatures of the second survey. During the survey, temperature variations of up to 1-2 degrees C were observed when moving from low-albedo (dark colored) rocks and soils into high-albedo (light colored) rocks and soils. These temperature variations are caused by the greater absorption of sunlight and retention as heat energy by darker materials compared to lighter materials. An algorithm was developed to compensate for this effect (see Sladek et al., 2009 for details).

Results and Conclusions

Hyperspectral mineral mapping and shallow temperature survey results identified an intriguing relationship between salt mineral crusts and thermal anomalies (Figure 2). We present only geothermal-related minerals of interest that were mapped with high confidence. Furthermore, we would fully expect the identification of more minerals if the data had been acquired under maximum solar irradiance during the summer months. Mapping results for

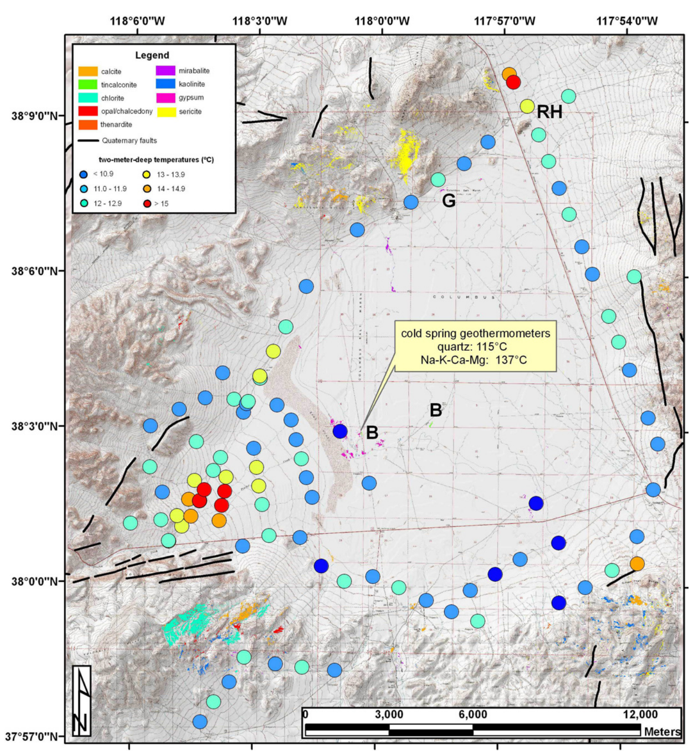

Figure 2. Mineral mapping and temperature survey results, B – tincalconite, RH – Rock Hill, G - gypsum.

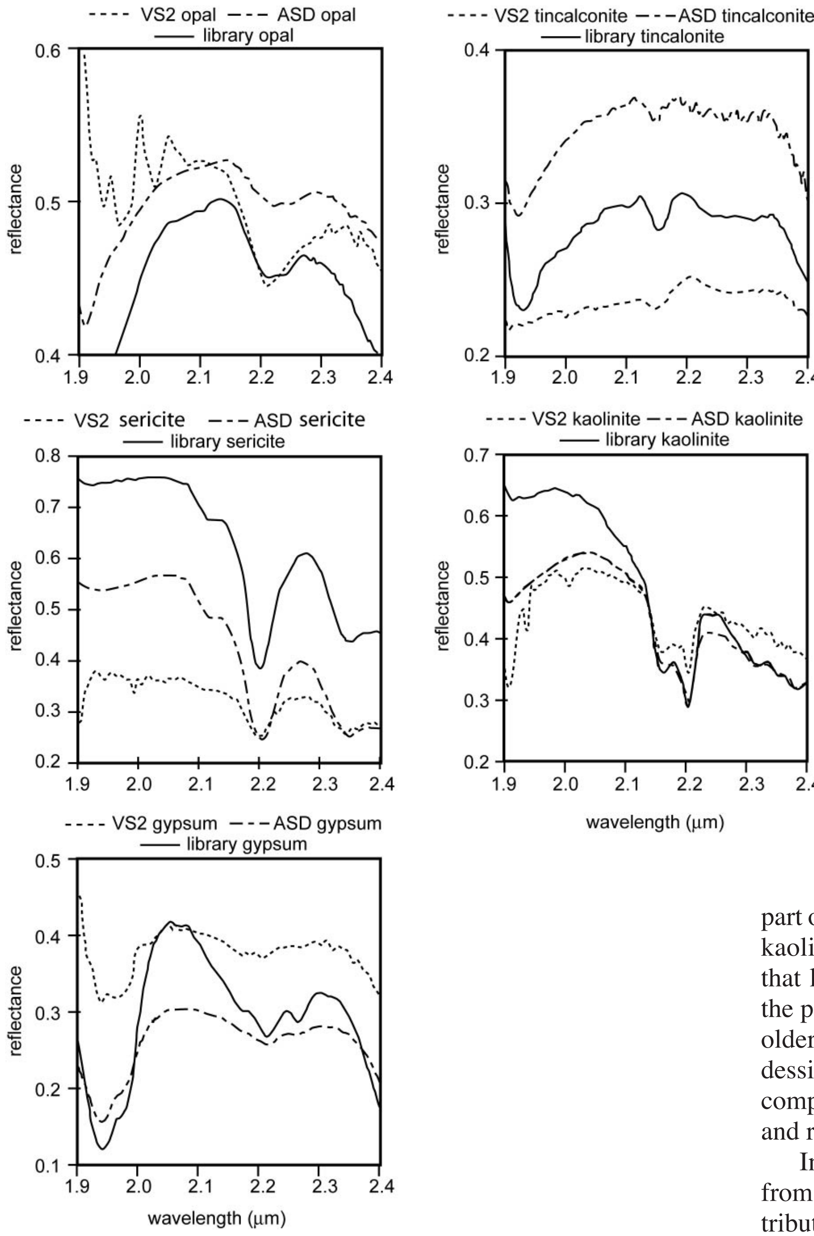

Figure 3. Comparison of selected mineral spectra.

down the hydrologic gradient from a 4.1 km x 1.7 km thermal anomaly identified by the shallow temperature survey (Figure 2). This location appears to coincide with a radiating, fan-shapped pattern of Quaternary extensional faults that define the southwestern margin of the basin. A second temperature anomaly of similar magnitude was identified at the extreme northern end of Columbus Marsh, near Rock Hill (Figure 2). The fact that this second anomaly is indeed caused by geothermal activity is evidenced by drilling conducted on the north side of Rock Hill in the 1980s, which encountered hot water at the bedrock-alluvium interface (Nevada Bureau of Mines and Geology web site).

Our hyperspectral mineral maps in the hills that bound the southern portion of the study area generally correspond to alteration zones reported by Martini et al. (2004). The north-striking Emigrant Peak Fault Zone and northeast-striking faults in the Volcanic Hills intersect the east-striking Coaldale Fault. This structural complexity provides a favorable environment for enhanced fluid flow and may explain the presence of broadly distributed kaolinite, chlorite, calcite, and more restricted occurrences of opal/chalcedony. Field validation revealed that areas where calcite was identified corresponded with limestone beds possibly belonging to the Palmetto Formation. Areas that displayed alteration were associated with Tertiary volcanic units and did not appear to be the result of recent geothermal activity. Furthermore, there were no strong indications of 2 meter deep thermal anomalies in this part of the study area. In the Candaleria Hills sericite and limited kaolinite outcrops corresponded with hydrothermal alteration that likely occurred in the mid Tertiary. On the eastern side of the playa several exposures of thenardite were identified. These older evaporite deposits seemed to be exhumed by the eolian dessication of younger halite deposits. Figure 3 shows selected comparisons of ASD sample spectra, ProSpecTIR image spectra, and reference spectra.

Inter-seasonal two-meter background temperature variations from previous surveys show less variability than at CSM. We attribute this to the greater variability of albedos and slope aspects on which this survey was conducted. In the case of albedo, darker surfaces absorb more sunlight energy than light colored slopes. An approximate correction for this effect (Sladek et al., 2009) was applied to the data shown in Figure 2. In the case of slope aspects, temperatures on the north-facing slopes that bound the southern end of the basin are cooler overall than temperatures on west-facing slopes that bound the east side of the basin. The east side of the basin shows the least variability in slope, aspect and elevation. This may explain why temperatures here are within one degree of each other. Southeast-facing slopes that bound the north side of the basin have somewhat higher 2-meter temperatures than other aspects and this may be explained by a greater heat loading on south-facing slopes.

The mapping of evaporite minerals with hyperspectral imagery and results of a shallow temperature survey have directly led to the identification of a previously unrecognized geothermal system in the southwestern portion of the Columbus Marsh valley. These and past results have proven the usefulness of hyperspectral remote

the borate mineral tincalconite were in close correspondence to tincalconite evaporite crusts identified with satellite data (Kratt et al., 2006a). In the two areas where tincalconite was identified, the mineral displays fluffy efflorescent surfaces that seem to be fresh and actively precipitating, compared to the dusty and desiccating evaporite crusts that are characteristic of older surfaces. Widespread gypsum crusts occur adjacent to a spring near one of the tincalconite occurrences and from where favorable geothermometer temperatures were reported (Coolbaugh et al., 2006b). The presence of gypsum on playa surfaces does not imply exclusive precipitation by geothermal fluids; however, gypsum and other sulfate crusts, identified with remote sensing, have been associated with young faults and thermal springs at other areas (Kratt et al., 2005; Kratt et al., 2009, accepted). Most of the gypsum identified at CSM playa forms parallel to the toe of an alluvial fan that is sensing and shallow temperature surveys. When combined, data from one can be leveraged by data from the other to help optimize geothermal exploration.

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