1 **Remote Sensing of Geothermal-Related Minerals for Resource Exploration in Nevada**

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Abstract

We use remote sensing data from a variety of satellite and airborne instruments to characterize mineral and thermal properties as surface indicators of geothermal resources in Nevada. We generally use satellite data as a reconnaissance tool to target higher resolution airborne data collections. Spectral data are collected from field surface locations and samples to validate remote identifications and refine mineral maps. Spectral validation is done using an ASD portable spectrometer (0.4 – 2.5 μm) in both field and lab configurations. We also have a Thermo/Nicolet Nexus 6700 FTIR spectrometer and shared use of a Designs and Prototypes FTIR field instrument for thermal infrared data collection. Past work has identified sinter, tufa, travertine, argillic hydrothermal alteration minerals, evaporites, vegetation concentration near springs, and thermal anomalies as indicative of resource potential and structural controls on fluid pathways. Our methodology places mineral maps into GIS databases with other geologic information to make comparisons and site assessments. We recommend target areas for subsequent exploration including shallow temperature measurements, detailed geologic mapping, and structural analyses. This paper reviews over a decade of remote sensing geothermal exploration in Nevada and summarizes the common and unique features identified by our surveys.

Keywords: remote sensing; mineral mapping; hyperspectral; imaging spectrometer; geothermal; Nevada; Great Basin; sinter; hydrothermal alteration; hot springs

1. Introduction

Spectrally resolved remote sensing imagery has been used over a number of volcanic, active hydrothermal, and geothermal sites for temperature, structure, and mineral mapping. For example, Kruse [1999] compared the mineral mapping abilities of AVIRIS data collected in 1995 and 1998, and identified opaline sinter terraces and areas of alunite and kaolinite in data collected over Steamboat Springs, Nevada. Hellman and Ramsey [2004] used ASTER and AVIRIS to examine hot spring deposits in Yellowstone National Park. Vaughan et al. [2012] later used ASTER and MODIS data to estimate radiant heat flux at Yellowstone. Martini et al. [2003] used HyMap data to map hydrothermal alteration within the Long Valley Caldera, California. Silver et al. [2011] combined LiDAR data with imaging spectrometer data over the Humboldt-Rye Patch geothermal field.

For over a decade our group has used remote sensing data for geothermal exploration, focusing on sites within Nevada that have strong potential for electrical power production from modest to high-temperature systems at depth. We generally use satellite remote sensing data in combination with other existing geologic data to define targets for higher resolution, more expensive, airborne surveys. We have refined techniques to make remote sensing an efficient and effective way to do preliminary geothermal exploration over large areas of the Great Basin, western US. We have used these techniques on more than seven geothermal fields in Nevada, and have plans to continue to refine our methods and expand our data coverage (Figure 1).

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Figure 1. Map of Nevada showing the locations of geothermal fields studied using remote sensing data.

Geothermal systems in the Great Basin (a hydrologic province incorporating portions of the western states of Idaho, Utah, Oregon, California and most of Nevada) are generally amagmatic; water heated by deep circulation within the crust ascends along fault pathways produced by regional extension [Wisian et al. 1999]. Hot springs and fumaroles may be

surface indicators of a geothermal system, however blind geothermal systems may have very little or no surface expression at all. Our work indicates that remote sensing data can be used to identify both obvious and more subtle surface expressions of geothermal systems, including sinter deposits, evaporites, and hydrothermal alteration. We collect data in the field to confirm identifications made using satellite and aerial sensors. Field and lab measurements corroborate our detections and help refine mineral maps.

Although many of our techniques are similar to those used for other geological remote sensing applications, we have refined some for specific geothermal purposes and Basin and Range geology. We have also accumulated a working library of geothermally significant spectral signatures, including alteration minerals, hot spring deposits, and evaporites.

2. Background

2.1. Mineral Spectroscopy Overview

Many minerals have unique and diagnostic spectral properties, and features such as the band center, strength, shape, and width are used to identify species with high confidence. Both laboratory and remote sensing spectral data are commonly divided into wavelength ranges based on the cause of absorption features and the atmospheric windows through which the Earth's surface can be measured.

In the visible, near infrared, and short-wave infrared (VNIR/SWIR) (0.4 to ~2.5 μm), moderate and low-temperature surfaces are sensed due to the sunlight they reflect. Absorption features arise due the electronic orbital configuration of transition metals (generally iron or copper) in various crystallographic sites and from the combination and overtones of molecular vibrations from species such as hydroxyl, water, carbonate, and sulfate. This region of the electromagnetic spectrum is most sensitive to iron oxides, oxyhydroxides, and ligands resulting from high- or low-temperature alteration [Clark et al. 1990]. This region is especially useful for discrimination among sheet silicate (clay) minerals as well as argillic versus propylitic alteration. The former is dominated by kaolinite and smectite group minerals (montmorillonite, illite) and the latter by chlorite, epidote, and carbonate. In addition, opaline silica is determined by features arising from inclusion of water in the amorphous structure. The ready discrimination of these minerals has been the

basis for the use of the technique in economic mineral exploration [e.g. Thompson et al. 1999] as well as our own work in geothermal exploration.

The thermal infrared (TIR), typically 7 to 14 μm for terrestrial remote sensing, is so called because it senses the heat energy emitted by the Earth's surface. In this wavelength range the spectrum is sensitive to the fundamental molecular vibrations of ligand groups similar to the VNIR/SWIR. However in addition to water, carbonate, and sulfate, this region is sensitive to vibrations of Si-O bonds in silicates. All common rock-forming silicates have diagnostic absorption features in this spectral region and their shape and wavelength location are indicative of silicate structural classes [Estep-Barnes, 1977; Salisbury et al. 1991; Christensen et al. 2000]. We have successfully discriminated relative ages of the sinter terraces at Steamboat Springs based on the eventual change of opal to chalcedony [Vaughan et al. 2005]. Here, development of structural order of the SiO_2 causes clear separation of opal, cristobalite, and quartz [Michalski et al. 2003].

2.2 Geothermal Applications of Thermal and Spectral Data

Thermal infrared imagery has been used to sense small temperature anomalies associated with geothermal systems, but its usefulness in exploration has been limited because of the requirement for day and night image pairs and fairly extensive calibration to detect subtle temperature excursions. To date surface thermal anomalies have only been detected in the immediate vicinity of known hot springs or fumaroles [Coolbaugh et al. 2007]; though recent work is using FLIR imagery to quantify heat flux at known springs [Haselwimmer et al. 2013].

Detailed mineralogical studies of geothermal fields have revealed a wide array of alteration minerals in drill core and cuttings, and surficial deposits [Browne, 1978; Henley and Ellis, 1983] and the use of portable field spectrometers is advancing identification of alteration mineralogy in field settings [e.g. Yang et al. 2001]. The suite of alteration minerals associated with geothermal systems that are distributed on large enough scale to be apparent in remote sensing data sets is more limited. Table 1 shows minerals we have identified and Figures 2 and 3 show their characteristic spectra (see section 4 for discussion and detailed references).

Table 1. Common alteration minerals identified in remote sensing data of geothermal regions.

	Mineral	Chemical formula and geothermal relevance
Clay	Kaolinite	$\text{Al}_2(\text{Si}_2\text{O}_5)(\text{OH})_4$ Argillic alteration of feldspars.
	Illite	$\text{K}_{0.65}\text{Al}_2[\text{Al}_{0.65}\text{Si}_{3.35}\text{O}_{10}](\text{OH})_2$ Argillic alteration of feldspars or muscovite.
	Muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ Phyllic alteration of feldspars.
Sulfate	Alunite	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$ Advanced argillic alteration of potassium feldspars.
	Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ Evaporite deposited by sulfur-rich springs.
Carbonate	Calcite	CaCO_3 Comprises travertine and tufa, which are deposited by subaerial and sublacustrine calcium-rich springs, respectively; also occurs in veins.
Silica	Opal / Chalcedony	$\text{SiO}_2 \cdot n\text{H}_2\text{O}$ Amorphous silica gel; may fill fractures or be deposited as hot spring sinter. As sinter ages, develops structural order similar to quartz.
Borates	Tincalconite	$\text{Na}_2(\text{B}_4\text{O}_7) \cdot 5\text{H}_2\text{O}$ Evaporite formed near borate-rich springs; observed in playas.

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Figure 2. VNIR/SWIR spectra of geothermal indicator minerals. Most spectra were collected from field samples using an ASD spectrometer. Tincalconite, gypsum, and illite are from the U.S. Geological Survey (USGS) spectral library [Clark et al. 2007]. All spectra are displayed on the same 0 to 1 scale as noted for the bottom spectrum, and are offset for clarity.

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Figure 3. TIR spectra of representative geothermal indicator minerals. Spectra are from the emissivity library of Christensen et al. [2000] except for opal and alunite which are converted

from the reflectance data of Clark et al. [2007] ($\epsilon=1-r$). All spectra are displayed on the same 0.5 to 1 scale as noted for the bottom spectrum, and are offset for clarity.

2.3. Instruments and Methods

We have used a wide array of satellite, commercial and research airborne sensors. These encompass the wavelength regions noted above and range in spatial resolution (pixel size) from 2 to 90 m. These properties are summarized in Table 2. We commonly request satellite data for a regional overview and to help target more costly, higher spatial resolution airborne acquisitions. These aerial sensors offer much more detailed mineral mapping capability due both to higher spatial resolution and to the high-fidelity spectral coverage.

Table 2. Remote Sensing instruments used by our group for geothermal exploration.

Instrument name	Wavelengths (μm)	Operator Information	# of channels	Spatial resoluti on (m)	Geothermal sites
Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)	0.5 – 0.9	NASA & Japan instrument on the Terra	3	15	Steamboat Springs
	1.6 – 2.45	satellite	6	30	Brady's Hot Springs
	8 – 12	SWIR no longer working	5	90	Pyramid Lake
		asterweb.jpl.nasa.gov			Teels, Rhodes, Columbus
Thermal Infrared Multispectral Scanner (TIMS)	8.2 – 12.2	NASA & JPL airborne no longer flown	6	50	Steamboat Springs
Spatially Enhanced Broadband Array Spectrograph System (SEBASS)	7.8 – 13.5	Aerospace Corp airborne commercial https://www.aerospace.org/	128	2	Steamboat Springs
MODIS-ASTER Simulator (MASTER)	0.46 – 2.39	NASA & JPL airborne	25	5-10	Steamboat Springs
	7.76 – 12.88	research sensor masterweb.jpl.nasa.gov	10		Buffalo Valley Fish Lake Valley
Airborne Visible Infrared Imaging Spectrometer (AVIRIS)	0.45 – 2.5	NASA & JPL airborne research sensor aviris.jpl.nasa.gov	224	5, 20	Fish Lake Valley
HyperSpecTIR (HST)	0.47 – 2.4	SpecTIR Corp. airborne no longer flown www.spectir.com/	227	3	Brady's Hot Springs
HyMap	0.45 – 2.5	HyVista airborne	126	3-5	Brady's Hot Springs Desert Peak

		commercial www.hyvista.com			Fish Lake Valley Dixie Valley
ProSpecTIR	0.45 – 2.5	SpecTIR airborne commercial www.spectir.com/	< 400	2-3	Columbus Salt Marsh Fish Lake Valley

We use a combination of standard ENVI processing routines, and custom band combinations and ratios intended to highlight surface spectral features and alteration mineralogy. Data processing results are imported into ArcGIS for synthesis with other geologic and geothermal data, topography, and aerial photography. A variety of approaches have been used to process both VNIR/SWIR and TIR remote sensing data for mineral mapping purposes. We generally begin with the standard ENVI spectral hourglass approach [ENVI Tutorial: Spectral Unmixing <http://www.exelisvis.com/docs/SpectralUnmixing.html>, last accessed May 6, 2014]. A Minimum Noise Fraction (MNF) transform reduces the spectral dimensionality of the data by separating noise from data. A Pixel Purity Index (PPI) algorithm is then used to identify spectrally unique pixels, which are viewed in ENVI's n-dimensional visualizer to select classes. Classification is done using ENVI supervised classification methods or by thresholding Mixture Tuned Matched Filtering (MTMF) results.

We have also used a variety of experience-based approaches to processing remote sensing data. These techniques take advantage of well-known spectral absorption features using targeted image ratios or color combinations. Decorrelation stretches (DCS) are a useful way to increase color contrast in remote sensing images [Gillespie et al. 1986]. We use select input bands for DCS images to identify specific minerals. We then manually select classes from DCS images whose spectra are representative of target minerals. Relative band depth (RBD) mapping is similar to producing DCS images; band calculations targeting specific mineral spectra are used to produce greyscale images highlighting compositional differences. Thresholding RBD images or manual selection of pixels produces classes that may not be detected using other techniques. These spectral types are then identified using established spectral libraries and are mapped using spectral similarity tools such as the spectral angle, linear spectral mixing or matched filtering. Class averages of mapped similar pixels are calculated and are revised so that they still reflect known mineral features within one standard deviation of the mean.

Field validation increases confidence in remote identification of minerals and helps to refine mineral maps. We use an Analytical Spectral Devices (ASD) FieldSpec Pro portable spectrometer to identify minerals in the field based on their VNIR/SWIR spectral signatures. We also collect samples in the field and use the ASD portable spectrometer in the lab with a halogen light source when access would be difficult while carrying the instrument. We also have a Thermo/Nicolet Nexus 6700 FTIR spectrometer and shared use of a Designs and Prototypes FTIR field instrument to collect TIR data. These instruments are used in the lab and field, respectively, to validate mineral maps by comparing instrument spectra with remote sensing spectra.

3. Survey Sites

3.1 Steamboat Springs

The Steamboat Springs geothermal field (Figure 1a) is home to Ormat's seven power plants that produce a total of 86 MW. The Steamboat complex is a primary energy source for the city of Reno. The Steamboat Springs site has numerous surface expressions of the geothermal system that also supports a spa. There is a well-developed sinter terrace and a full suite of geothermal indicator minerals are present, including advanced argillic alteration, mercury and antimony mineralization, and active fumaroles [Coolbaugh et al. 2000]. The site is a good example target for remote sensing work over a known geothermal resource. As noted in Table 1, our surveys of this site include the instruments MASTER (1999), SEBASS (1999 group data collect), and TIMS (archived data).

3.2 Brady's-Desert Peak

Brady's Hot Springs (Figure 1b) is home to Ormat's 14 MW geothermal powerplant and a direct-use vegetable dehydration plant. Mudpots and fumaroles with associated sinter and hydrothermal alteration trend linearly along 4 km of the Brady's Fault. The nearby Desert Peak geothermal field is blind system with no surface expression. Despite this, Ormat operates an 11 MW power plant at Desert Peak. The Brady's-Desert Peak location was identified for expansion and enhancement through creation of an enhanced geothermal system (EGS). Our study was an initial project to explore the utility of imaging spectrometer data over geothermal systems with both obvious surface expression and a blind field in close

proximity. Aircraft deployments collected HST data in 2002, and multiple HyMap flightlines were acquired in June of 2003.

3.3 Pyramid Lake

The Pyramid Lake Paiute Tribe is seeking development of geothermal resource on the Pyramid Lake Reservation (Figure 1c). Geothermal exploration initially focused on the north end of Pyramid Lake near the Needles Rocks (tufa) but this location is culturally sensitive and not open for development. A two-stage geothermal exploration program was conducted; the first phase involved a variety of techniques to identify high-potential locations [Coolbaugh et al. 2006a], and the second phase was drilling two deep wells in February 2011. Remote sensing data analysis was part of the first phase of exploration, acquiring HyMap data in fall of 2004.

3.4 Buffalo Valley

In Buffalo Valley (Figure 1d), hot springs and a chain of Quaternary cinder cones appear to be structurally controlled and possibly related to a geothermal system at depth. As part of a larger geothermal remote sensing program, MASTER data were acquired in 2006. No further geothermal exploration has occurred at Buffalo Valley, although in 2010 Ormat brought online a 15 MW power plant immediately to the south in Jersey Valley.

3.5 Teels, Rhodes, and Columbus Salt Marshes

Geothermal fluids in the Great Basin are associated with borate evaporite minerals [Coolbaugh et al. 2006b]. In an effort to identify additional blind geothermal systems ASTER VNIR/SWIR data were used to explore the presence of borate minerals in a number of playas within Nevada (Figure 1e, f, g) [Kratt et al. 2010]. Teels and Rhodes Marsh have structural similarities to Fish Lake Valley, a pull-apart basin to the southeast with two known geothermal systems. ProSpecTIR data were acquired in fall of 2008 and provided to the University of Nevada, Reno (UNR) at no cost, after the initial exploration was completed.

3.6 Fish Lake Valley

Fish Lake Valley (Figure 1h) was initially selected for geothermal exploration due to high temperatures in existing drill holes and recent large displacements along nearby faults. Although two undeveloped geothermal prospects were explored prior to our work, the

objectives of the remote sensing studies were to further define the extent of known resources and identify any additional target areas for geothermal exploration. Added commercial value could provide further incentive to build the costly transmission lines needed to develop geothermal resources in this remote valley. The area was part of a DOE-funded AVIRIS data collection in 2003. Also in this timeframe, HyVista flew a number of geothermal prospects on speculation, and UNR purchased the archived HyMap data in 2010. The ProSpecTIR data of Columbus Salt Marsh also covers a portion of the range surrounding Fish Lake Valley, which allowed a mapping comparison of two commercial sensors with AVIRIS [Littlefield and Calvin, 2014].

3.7 Dixie Valley

Dixie Valley (Figure 1i) is home to one of the highest temperature geothermal resources in Nevada, with temperatures reaching 285°C at 3 km depth. The area is host to one of the oldest geothermal power plants; Terra-Gen Power's 63 MW power plant was built in 1988 in northern Dixie Valley. Numerous hot springs exist in the region and historic fault ruptures suggest potential pathways for fluid flow. Kennedy-Bowdoin et al. [2003, 2004] used 2003 HyMap data to map geothermal alteration minerals at Dixie Meadows in the central portion of Dixie Valley. In 2010 a project was initiated to study geothermal potential in southern Dixie Valley with a focus on Navy Air Station (NAS) Fallon land, in conjunction with the Navy Geothermal Program Office. In 2010 we collected additional HyMap data covering southern Dixie Valley and Fairview Valley; HyVista also provided preliminary mineral maps generated using their proprietary automated classification software.

4. Summary of Results

4.1. Modest Resolution Data for Thermal Mapping

We have used the satellite sensor ASTER over nearly every site we have studied (Table 2), but have only used TIR data in ASTER and TIMS to map thermal anomalies over two sites, Steamboat and Brady's Hot Springs [Coolbaugh et al. 2007]. Coolbaugh et al. [2000] mapped thermal anomalies at Steamboat using two approaches with TIMS data. The first method used a nighttime TIMS band 5 image with corrections for elevation and high albedo sinter, which was estimated using AVIRIS data. The second, more effective method averaged daytime and nighttime TIMS images, and then corrected for elevation and albedo. This

thermal anomaly mapping approach was refined and performed for Brady's Hot Springs using ASTER thermal data. Thermal anomalies were identified along the Brady's Fault, but the approach also highlighted previously unknown hot spots, interpreted as extensions of the fault. In general there was very good correspondence between the thermal anomalies identified remotely with locations identified in the field, as shown in Figure 4.

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Figure 4. Map of thermal anomalies at the Brady's site, adjacent to Interstate Highway 80 northeast of Fernley, NV. The highway is the linear diagonal feature crossing the scene. Warm colors indicate temperature anomalies derived from ASTER imagery at 90 m/pixel (after Coolbaugh et al. 2007 and Calvin et al. 2005). Small black and brown circles indicate steam vents or surface hot spots located using GPS in the field [Coolbaugh et al. 2004]. Transparent anomaly map is overlain on Google Earth image using USDA Farm Service Agency information to show surface features.

4.2. Modest Resolution Data for Mineral Mapping

We commonly use the VNIR and SWIR portions of ASTER to highlight broad regions of alteration and to target higher spatial and spectral resolution airborne flights. ASTER SWIR data were used to identify hydrothermal alteration on a regional scale both at Brady's and Desert Peak [Kratt et al. 2003] and at Pyramid Lake [Kratt et al. 2010]. Kratt et al. [2003] used ASTER SWIR data at Brady's to map minerals including calcite, opal, and kaolinite. These minerals were validated in the field, and the calcite was found to be linearly trending tufa deposits on strike with the surface expression of the known fault. At Pyramid Lake regional alteration associated with clays and sulfates was identified using a DCS of ASTER bands 4, 6, and 9 (spectral ranges 1.60–1.70, 2.18–2.22, and 2.36–2.43 μm , respectively). In a search for blind systems using ASTER, Kratt et al. [2006b] found tinalconite at Teels, Rhodes, and Columbus Salt Marshes; its presence was confirmed with the ASD portable spectrometer in the field. Geothermometry of nearby fluids suggested possible hidden geothermal reservoirs at these locations. Kratt et al. [2008 and 2009] performed subsequent shallow temperature surveys identified two shallow temperature anomalies in Teels Marsh

that were adjacent to a Quaternary fault. A thermal anomaly was identified near opalized sands at Rhodes Marsh.

As part of a multiple site data collect in 2006 we acquired MASTER data over Steamboat, Brady's-Desert Peak, Buffalo Valley, and Fish Lake Valley. Littlefield and Calvin [2009] examined the Buffalo Valley data. Calcite and vegetation were identified in the VNIR/SWIR data, and the DCS defined by Vaughan et al. [2005] was used to identify clay-dominated and silica-dominated areas with the TIR data. Calcite surrounds the Buffalo Valley Hot Springs, indicative of a travertine mud that was verified in the field using the ASD portable spectrometer. No geothermal minerals were mapped near the Buffalo warm springs on the western side of the valley, although remotely mapped healthy vegetation confirmed the presence of springs.

Thermal data from MASTER and ASTER over Steamboat were studied by Vaughan et al. [2005]. MASTER was used to map geothermal mineral groups such as clays, and more siliceous material in sinters; however opaline and chalcedonic sinters were not distinguishable using MASTER data. It was found that ASTER could not distinguish clay-rich from silica-rich areas due to the low spectral resolution; clays were not identified because ASTER lacks a spectral channel between 9.1 and 10.6 μm , as shown in Figure 3 this is where clay minerals have their strongest absorption features.

4.3 Imaging Spectrometer VNIR/SWIR Mineral Mapping

The majority of our studies have been conducted using commercial imaging spectrometer data sets mapping minerals using diagnostic features in the VNIR/SWIR. We here briefly summarize the results, and Figure 5 provides a schematic overview of common minerals found at Brady's-Desert Peak, Pyramid Lake, Fish Lake Valley, and Dixie Valley.

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331 **Figure 5.** Mineral maps produced using imaging spectrometer VNIR/SWIR data over (a)
332 Brady's-Desert Peak, (b) Pyramid Lake, (c) Fish Lake Valley, and (d) Dixie Valley, Nevada.
333 Key shows color for each mineral mapped. Faults are from the USGS Quaternary fault and
334 fold database distributed on-line.

335

336 Kratt et al. [2006] used HyMap data at Brady's-Desert Peak (Figure 5a) to map kaolinite,
337 gypsum, opaline sinter, and tufa (calcite). Kaolinite and gypsum corresponded to active
338 geothermal vents, but remotely mapped opal highlighted previously unmapped sinter linearly
339 distributed along a potential extension of the Brady's Fault. Some of the sinter discoveries
340 also coincided with thermal areas identified by Coolbaugh et al. [2007] and Figure 4.
341 Structurally controlled tufa was also mapped, indicative of fluids leaking along a fault.
342 Siliceous root casts were mapped near the blind Desert Peak geothermal system and were
343 associated with mercury soil gas anomalies that also suggest a geothermal system at this site
344 [Kratt et al. 2006], and additional faults were proposed that are not found in the USGS
345 database.

346

347 Kratt et al. [2010, 2005] analyzed the large Pyramid Lake HyMap collection (Figure 5b).
348 Regions of hydrothermal alteration were remotely mapped as clays and alunite. Gypsum was
349 mapped within the Smoke Creek Desert in close correlation with young fault scarps. Tufa
350 was also mapped around Pyramid Lake; much of this tufa is not related to spring activity and
351 instead formed at paleoshorelines of pluvial Lake Lahonton. Field validation helped to
352 determine if tufa deposits were spring-related or formed along paleoshorelines. Geothermal
353 indicator mineral maps helped elucidate structural controls and fault orientation, or were
354 found to be in close association with thermal springs [Coolbaugh et al. 2006a]. Structurally
355 controlled tufa was identified at Astor Pass along strike with the Needles Rocks. Geothermal
356 wells were eventually drilled at Astor Pass, largely due to the remotely identified tufa.

357

358 Littlefield and Calvin [2014] examined multiple data sets over Fish Lake Valley (Figure 5c),
359 including AVIRIS, MASTER, HyMap, and ProSpecTIR. Remotely mapped geothermal
360 minerals included opal, calcite, alunite, kaolinite, and muscovite. Two areas of opaline sinter

and travertine deposits (calcite) were identified along the west edge of the playa, likely deposited around structurally controlled hot springs during the Pleistocene when the water table was higher. Argillic alteration was mapped within the rhyolite tuff of the surrounding ranges; kaolinite and muscovite were used as indicator minerals for hydrothermal alteration. Alteration minerals generally occur in linear trends, indicative of thermal fluids being discharged along faults. In total, four new targets were identified for future exploration including detailed geologic mapping and structural analyses. This study emphasized the use of DCS images to highlight compositional differences in the multispectral and hyperspectral datasets and created several new combinations relevant to geothermal exploration. Of particular significance was the DCS of HyMap bands 105, 108, 110 (2.16, 2.21, 2.24 μm , respectively) displayed as RGB highlighted several geothermal minerals (opal, kaolinite and alunite, muscovite, calcite) each as different colors.

Lamb et al. [2011] explored all of the HyMap data acquired in Dixie Valley. Automated processing of the 2010 flights accurately identified areas of calcite associated with playas and various clay mineral alteration, but was not tuned to identify geothermally relevant minerals opal or gypsum. We validated HyVista mineral maps and produced new maps using techniques described in this paper. Remotely mapped geothermal indicator minerals included calcite, opal, gypsum, kaolinite, and alunite. These were found in several locations, including Dixie Meadows, Pirouette Mountain, and Elevenmile Canyon (Figure 5d). Geothermal minerals in Dixie Meadows were consistent with the previous work of Kennedy-Bowdoin [2003, 2004] showing alunite and kaolinite related to a geothermal system at depth. Pirouette Mountain and Elevenmile Canyon are blind thermal anomalies identified through drilling [e.g. Williams and Blackwell, 2012]. Minerals mapped near the Pirouette Mountain prospect were found in the nearby portions of the Clan Alpine Mountains and are unrelated to the geothermal target. Near the Elevenmile Canyon prospect remotely mapped minerals included kaolinite, gypsum, calcite and opal, though the opal material was not sinter from a hot spring deposit. A shallow temperature survey was completed in Dixie Valley [Skord et al. 2011] and additional faults were identified using LiDAR and low sun angle aerial photography [Helton et al 2011]. These studies were used to target locations for exploratory deep drilling, which has not yet occurred.

4.4 Imaging Spectrometer TIR Mineral Mapping

Vaughan et al. [2003, 2005] were among the first to use SEBASS, an airborne TIR imaging spectrometer, to establish methods of data validation and calibration as well as mineral identification capabilities. The narrow spectral channels of SEBASS allowed the development of a unique DCS band combination of thermal radiance data (SEBASS bands 6, 35, and 24 as RGB) that Vaughan et al. [2005] also applied to MASTER data to distinguish silica-rich versus clay-rich regions. Vaughan et al. [2005] also used SEBASS data to map more specific minerals including opal, quartz, alunite, anorthite, albite, and kaolinite. Unique sulfates (alunogen and tamarugite) were identified around active fumaroles. Hot spring activity at Steamboat Springs is associated with opaline sinter, whereas chalcedony comprises the ancient sinter deposits. That study also found that opaline and chalcedonic sinters were separable in this high spectral resolution data set.

5. Summary of Mineral Associations and Sites

Table 3 lists which common geothermal indicator minerals were observed at each site. Opal and chalcedony/quartz comprise recent and ancient sinter deposits. At several locations within Nevada, hot silica-saturated water moves upward along faults; sinter is deposited when the water cools below 100°C. Sinter was remotely mapped at Steamboat Springs, Brady's-Desert Peak, and Fish Lake Valley (Figure 1a,b,h) and in all these instances was deposited from geothermal fluids.

Travertine and tufa are composed of calcite. Travertine is deposited as hot calcium- and bicarbonate-rich water is depressurized subaerially [Pentecost, 1995]. Tufa is deposited as calcium-rich spring water reacts with carbonate-rich lake water [Benson, 1994]; springs may be hot or cold. We identified travertine at Buffalo Valley and Fish Lake Valley (Figure 1d,h). Also at Fish Lake Valley we identified a mixed spectrum of opal and calcite, which suggests sinter and travertine were both precipitated. Tufa was remotely mapped at Brady's Hot Springs and Pyramid Lake where it was precipitated at springs beneath pluvial Lake Lahonton. Calcite identified in Dixie Valley (Figure 5d) may be related to shoreline deposits or regional carbonate units rather than geothermal systems.

Quaternary borates are statistically linked to moderate to high temperature geothermal systems in the Great Basin [Coolbaugh et al. 2006b]. Fluids that have interacted with boron

have experienced deep circulation and therefore heating. Remotely mapped borates include borax and tincalconite; these minerals are bright white and occur in playas. Borates were identified at Teels, Rhodes, and Columbus Salt Marshes and Fish Lake Valley (Figure 1e,f,g,h). Gypsum also occurs in playas and can be a geothermal indicator mineral. Although gypsum is not exclusively a geothermal mineral, it is associated with young faults leaking fluids and hot springs at Brady's Hot Springs, near Pyramid Lake, and at Columbus Salt Marsh (Figure 1b,c,g).

A variety of hydrothermal alteration minerals have been mapped during our geothermal exploration studies. Advanced argillic alteration minerals include alunite and kaolinite. Alunite is a sulfate that indicates alteration of potassium feldspars as a reaction with sulfuric acid, or it can form near fumaroles. Kaolinite is a clay product of low temperature alteration of feldspars, and can also form near fumaroles. We remotely mapped argillic alteration at Steamboat Springs, Brady's Hot Springs, Pyramid Lake, Fish Lake Valley, and Dixie Valley (Figure 1a,b,c,h,i). Illite and muscovite were identified at Pyramid Lake, Fish Lake Valley, and Dixie Valley respectively. These minerals are also alteration products of feldspars so that not all occurrences are necessarily related to geothermal systems. In particular, the muscovite identified near Elevenmile Canyon in Dixie Valley was associated with weathering [Lamb et al. 2011].

Table 3. Summary of locations and mapped geothermal related mineral deposits.

Site	Kaolinite	Illite or muscovite	Gypsum	Alunite	Travertine or tufa	Borate	Sinter	Shallow temp survey
Steamboat	✓			✓			✓	
Brady's-Desert Peak	✓		✓		✓		✓	
Pyramid Lake	✓	✓	✓	✓	✓			✓
Buffalo Valley					✓			
Teels, Rhodes, Columbus			✓			✓		✓
Fish Lake Valley	✓	✓		✓	✓	✓	✓	
Dixie Valley	✓		✓	✓				✓

5. Conclusions

We identified geothermal indicator minerals at all sites we explored using visible, near, shortwave, (0.4 – 2.5 μm) and/or thermal infrared (8 – 12 μm) remote sensing data. To best understand geothermal systems and constrain fluid pathways underground, surficial mineral maps are integrated with a strong understanding of local structural geology. Modern remote sensing tools provide a rapid regional assessment to help define high priority targets for additional studies including field geologic and structural mapping, shallow temperature surveys, geophysical surveys, geochemistry, and lastly drilling.

Thermal anomalies found using remote sensing techniques have only identified regions with active surface features thus far. Shallow temperature measurements, specifically done using the 2m depth temperature survey method developed by Sladek et al. [2007], have been more effective at identifying small near-surface thermal anomalies than remote sensing studies. We have completed 2m temperature surveys at many geothermal sites in the Great Basin and find the method is rapid, inexpensive, and effective. Table 3 notes the sites where such surveys have been conducted, concurrent with or following on the remote sensing analysis. High shallow temperatures identified using the 2m survey method have been consistent with high temperature gradients observed in later drilled deeper holes [Kratt, 2011; Coolbaugh et al. 2007b].

Mineral mapping for geothermal targets is best considered as part of a multi-faceted approach to geothermal exploration. As an initial exploration approach, we suggest the use of remote sensing and 2 m temperature measurements; so far, we have paired these techniques at Desert Peak, Pyramid Lake, Teels, Rhodes, and Columbus Salt Marshes, and Dixie Valley (Table 3). Additionally, due to the association between Quaternary faults and potential geothermal systems [Bell and Ramelli, 2009], we typically include in our assessments the relationship of these minerals to known fault structures or possible fault features identified in the field. While a large fault structure controls the surficial deposits at Brady's (Figure 5a) many systems are associated with small or indistinct surface expressions. Identification of recent, small-offset faults (<1m) is successfully accomplished through remote sensing techniques such as low-sun angle photography or LiDAR [Bell and Ramelli, 2009; Helton et al. 2011].

Remote sensing work and related geothermal exploration studies are ongoing, for example, Kratt [2011] recently used ProSpecTIR data for geothermal indicator mineral mapping at several Nevada sites that was coupled with 2 m temperature and gravity surveys. Kruse et al. [2011] demonstrated that global mapping anticipated by the proposed NASA HypSIRI instrument will be able to identify these common geothermal surface minerals. We recently began using these tools for characterizing core and cuttings from geothermal wells; pilot studies have used core from the Great Basin and elsewhere [Calvin et al. 2010; Littlefield et al. 2012]. We use the ASD portable spectrometer to collect VNIR/SWIR spectra and then apply modified remote sensing methods to map mineralogy as a function of depth. Preliminary studies are demonstrating the ability to map a wide range of temperature-dependent alteration minerals, many of which are not expressed in our surface exploration analyses.

These techniques are effective in the arid setting of Nevada where there is sparse vegetation cover. Similar techniques have worked well in moderately vegetated settings such as Yellowstone, WY and Long Valley Caldera, CA [Hellman and Ramsey, 2004; Martini et al. 2003]. In geothermal settings that are highly vegetated, LiDAR may be the most effective aerial remote sensing tool to use first, coupled with field spectral analysis of mineralogy [e.g. Canet et al., 2015]. The emerging field of unmanned aerial systems (UAS), coupled with imaging spectrometers [e.g. Lucieer et al., 2014] will also improve our ability to map small-scale surface features associated with geothermal systems in remote, rugged or vegetated terrain.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5