REMOTE SENSING FOR EXPLORATION AND MAPPING OF GEOTHERMAL RESOURCES

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Abstract: The proposed work seeks to define surface identifiers of geothermal resources through analysis of remote sensing imagery to characterize mineral, vegetation, and thermal properties at known source regions to establish markers of potential in other areas. Geothermal identifiers include sinter, tufa (carbonate), hydrothermal alteration (clays, sulfates), vegetation stress due to near-surface saline waters, vegetation concentration near small surface seeps or springs, and thermal anomalies as mapped in both nighttime and corrected day/night imagery. Certain playa evaporites (borates) may also be diagnostic indicators of geothermal systems, where thermal springs discharge into closed basins. Mapped imagery will be geo-rectified to standard projections so that they can be readily included in regional and site specific databases. This work builds upon our previous funding which established the use of day/night imagery to identify surface thermal anomalies, mapping both known and hidden resources at Steamboat Springs and at Brady Hot Springs. Our proposed work extends our analysis to new basins at Buffalo Valley near Battle Mountain, NV, Dixie Valley past Fallon, NV and Fish Lake Valley west of Goldfield, NV. Buffalo Valley was identified by GBCGE work as a high strain location and of exploration interest. Dixie Valley is a known production site. The program continues collaborative efforts with remote sensing projects at LLNL and the University of Santa Cruz, through shared imagery and group visits of field locations. Modern high signal-to-noise hyperspectral data sets of Dixie, Fish Lake and Brady's have been delivered.

Response to RFP Focus Areas:

The proposed work directly responds to the first focus area of the RFP: Geothermal Resource Assessment and Exploration. In particular, we respond to both *B. Identification and Characterization of New Potential Geothermal Resource Targets* and *C. Geologic Mapping and Fault Characterization.* New potential targets will be identified using the complementary signatures identified above and geologic and fault mapping can be achieved using regional and local scale image information, coupled with other geophysical surveys. We have already demonstrated this type of result from our previously funded work. Interpretations gleaned from remote data will be verified through detailed field follow up on our own and through others with extensive knowledge of geology and structure of the target regions.

Introduction: Recent significant advances in the availability and quality of both short-wave and thermal infrared imagery has lead to the extensive use of these data sets as exploration and site characterization tools. Applications have included mineral and petroleum exploration and development (e.g. Sabine, 1999), targeting field intensive environmental remediation activities on the highest priority sites (Swayze et al. 2000), and hazard assessment. Well-established techniques in multispectral and hyperspectral analysis, coupled with new, state-of-the-art imagery from spaceborne and airborne sensor systems, allows their direct and immediate application to problems in geothermal energy exploration and development. For our analysis we use a variety of multispectral (several wavelength channel) and hyperspectral (hundreds of wavelengths) data sets. These data sets are sensitive to surface mineralogy and lithology as well as surface temperature. Instruments and data are summarized in Table. 1.

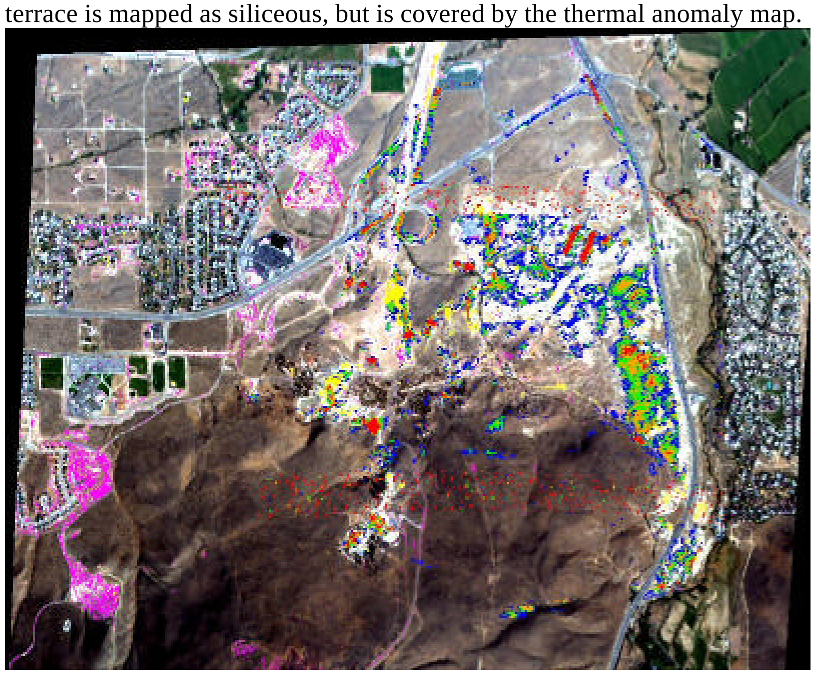
Table 1: Sensor Characteristics used in the proposed study

Instrument Name	Wavelength Coverage	Channels	Spatial Resolution	Data and Costs
ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer Yamaguchi et al. 1998 http://asterweb.jpl.nasa.gov	0.5 to 0.9 µm 1.6 to 2.45 µm 8 to 12 µm	3 6 5	15 m 30 m 90 m	Already acquired scenes on demand processing can be obtained at no cost through Calvin.
Master: MODIS and ASTER Airborne Simulator Hook et al. 2001 http://masterweb.jpl.nasa.gov	0.46 to 2.39 µm 7.76 to 12.88 µm	25 10	5m	New flight lines require a nominal contribution.
HyMap: www.hyvista.com	0.45 to 2.5 µm	126	3m	Flights already acquired in Dixie Valley through LLNL. New flights require a nominal contribution.
AVIRIS: Airborne Visible and Infrared Imaging Spectrometer Green et al. 1998 http://makalu.jpl.nasa.gov	0.45 to 2.5 µm	224	3m 20m	Flights already acquired in Fish Lake through LLNL
HyperSpecTIR: www.spectir.com	0.45 to 2.45 µm	227	3m	Brady's flights acquired but were low signal-to-noise. Reflight scheduled for summer '03.
Landsat ETM+	0.4-0.9 µm; 1.6 µm; 2.2 µm 10.4 to 12.5µm	6 1	30m 60m	Regional context for local, hi-resolution data. $600 per scene.

Past Progress:

An initial study was performed in the Steamboat Springs region that showed appropriate correction of thermal imagery for topographic slope orientation, albedo, and thermal inertia could increase the number of remotely detected thermal anomalies by an order of magnitude (Coolbaugh et al. 2000). This "hot spot" map was synthesized with our analysis of surface mineral characterization using MASTER data. This result is shown in Figure 1. We note that known vent sights are strongly associated with silicieous material. More detailed mineral mapping of a

Figure 1: TIMS derived thermal signatures over MASTER mineral mapping. Clay alteration is colored pink, silica rich material (quartz or sinter) are yellow. Colors blue, green, orange and red indicate thermal anomalies after correcting for surface characteristics. The main sinter terrace is mapped as siliceous, but is covered by the thermal anomaly map.



small portion of the region using a hyperspectral thermal imager clearly distinguishes sinter from quartz minerals and identifies sinter, alunite and kaolinite in regions of known venting (Vaughan et al. 2003). This includes the main terrace and vents to the west. Hot spots north and west of the main terrace were not covered by the hyperspectral data set and so only association with siliceous material can be determined using MASTER data. A paper comparing the mineral mapping capabilities between hyper and multi-spectral thermal data sets has been submitted to the *Journal of Geophysical Research* (Vaughan et al., submitted).

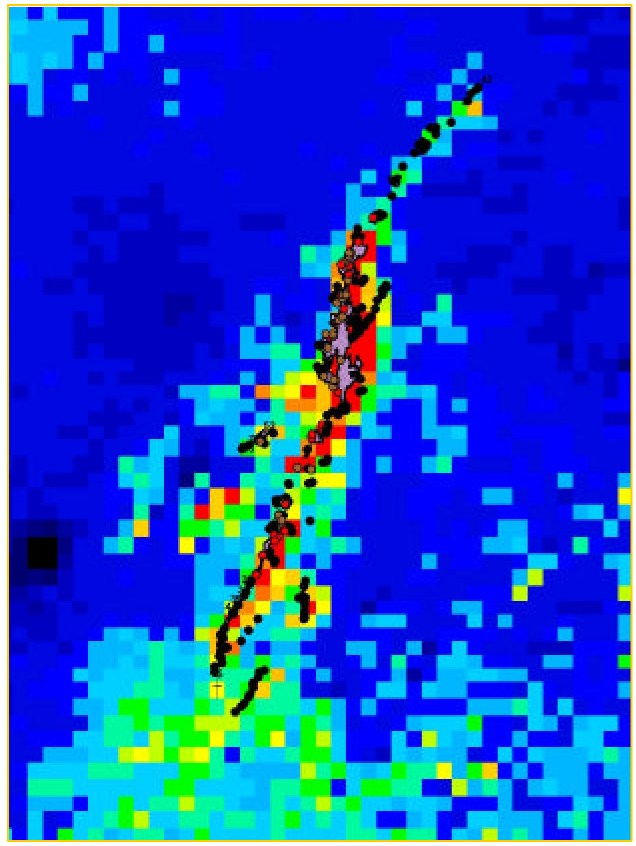


Figure 2: Thermal anomaly map from ASTER day/night processing at Brady. Warm colors indicate hotter temperatures. Black and brown points are GPS locations of fumeroles/vents seen at the surface. ASTER thermal spatial resolution is 90m. Future data will seek to map these types of anomalies at 5m resolution.

The thermal anomaly analysis was extended over the Brady location using day/night ASTER imagery to simultaneously account for albedo. Data were registered to (DEM) and field measurements of surface albedo and diurnal temperature cycling were used to empirically constrain these corrections in the anomaly calculation. Figure 2 shows that even at 90m/pixel this spaceborne data easily identified a thermal outcrop ~4 km in length. Field checking of vents and fumeroles in the region show that the linear fault previously assumed instead had a more complex structure. A paper summarizing these results is in preparation for *Remote Sensing of Environment* and will be submitted in the next month.

Subsequent work has potentially identified carbonate tufas as a surface marker of the Brady fault extension. We are currently exploring the mineralogic expression of vent features and possible fault extensions in ASTER mineral/lithologic maps and in hyperspectral data from SpecTIR Corporation. We have found potential fault extensions using the signature of columnar tufas that has been corroborated in the field. This work will be summarized in a paper to the GRC in Morelia, Mexico (due May 9) and will presented at the Fall meeting.

Industry Collaborations:

Co-Investigator Mark Coolbaugh has been the primary interface to geothermal industry collaborators, providing awareness of our analysis and results and obtaining authorization as required to field check and validate the remote sensing results. In our first year we have worked with:

1) Ormat at the Brady's Power Plant - providing thermal images and GPS maps of fumaroles and warm ground that they can use to help locate secondary structures at depth. Interfacing with field geologist in mapping possible fault extensions.
2) Gilroy Foods at the Brady's Hot Springs using thermal images and GPS maps of fumaroles and warm ground.
3) Nevada Department of Transportation, provided thermal images of Steamboat Springs to be used in on-going engineering studies for the freeway extension in that area.

Proposed Work:

Our proposed work seeks to extend and enhance this analysis by: 1) Providing detailed mineralogic mapping and relation to structure using a series of already acquired hyperspectral data sets. 2) Assessment and request of new imagery over Buffalo Valley which has emerged from the work of Blewitt as a high priority site. 3) Continuing thermal anomaly mapping using higher spatial resolution imagery by requesting day/night MASTER coverage for selected sites.

The proposed work extends our local scale studies into Dixie Valley, Fish Lake Valley and Buffalo Valley. By comparing magmatic systems (Steamboat as recently inferred by geochemical studies) with extensional systems (Brady, Dixie) we can begin to define surface alteration patterns and characteristics that may help distinguish these types of systems. For example, ground water geochemistry has noted that Ca and SO_4 are higher in extensional systems. This could lead to enhanced precipitation of sulfates in addition to sinter or other markers of activity. Fish Lake is similar to Steamboat in that it is situated along range front faults but also has young volcanics in the area.

Task 1: Hyperspectral Mineral Mapping

Our first task focuses on detailed analysis of hyperspectral data sets that have recently been acquired or delivered. These data sets include Hymap acquisitions over Dixie Valley, and AVIRIS data over Fish Lake Valley. We will continue working on data from Brady's provided by SpecTIR corporation. We hope to extend our demonstrated ability to characterize sinter and tufa deposits to other infrared data sets and explore the ability to discriminate various playa salts. There has been noted a correlation between the appearance of ferric "gels", most likely ferrihydrite, with known geothermal centers (Coolbaugh and Raines, unpublished data). Ferrihydrite has a distinct spectral signature in the visible (e.g. Bishop et al. 1993) which readily separates it from other iron oxides such as goethite and hematite. We will seek to establish correlations between these properties and known sources as a way to assess their utility in regional data sets as an exploration tool for finding unknown sources.

Brady's Hot Springs

SpecTir corporation acquired data over Brady's in the summer of 2002, but did not deliver either corrected radiance or reflectance until the first quarter of 2003. Unfortunately, the focal plane was not sufficiently cool at the time of the acquisition and this has led to poorer signal-to-noise in the 2 to 2.5 µm spectral range which is crucial to the discrimination of mineral signatures. In the absence of hyperspectral data we began mineral assessments using the same ASTER scenes that had been used for the thermal anomaly analysis. Using a decorrelation stretch (e.g. Gillespie et al., 1986) we identified carbonates around the Brady's fault at the coarse 30m spatial scales of

ASTER. This result focused both field work and subsequent analysis of the SpecTIR data once this was made available. In initial hyperspectral mapping we are able to identify both tufa (carbonate) and sinter signatures as possible markers of the fault extension. We have used several playas in the area as calibration sites and note an unusual spectral signature. We are currently working to determine what salts are contributing to the observed spectra. Crowley (1991) and Crowley and Hook (1996) have shown that evaporites have unique spectral signatures. Our proposed work will continue refining the field/remote mapping correlations and look for zoning or compositional variation among the playa salts. SpecTir Corp has promised a reflight of the area in the summer of 2003.

Dixie Valley

18 Flightlines of the HyMap sensor were acquired over Dixie Valley on September 1, 2002. Figure 3 shows a color composite of the data draped over topography, courtesy of Brigette Martini of HyVista Corp. The flightlines corrected to surface reflectance were delivered from collaborator Bill Pickles of LLNL in January of 2003. Initial assessment shows that the data are very high quality, and HyMap has provided geolocation of the scenes simplifying fusion of the mapping results with other data surveys of the region. In particular aeromagnetic surveys have occurred here and can be incorporated with hyperspectral mapping results. Detailed field work with UCSC/LLNL is planned for early June. In addition to salt and sulfate species we expect to use presence of green vegetation to help uncover springs or other near-surface water. Salt grass or vegetation type may also lead to identification of potential sources or vegetation stress may identify geothermal waters with high temperatures or high dissolved concentrations of metals.

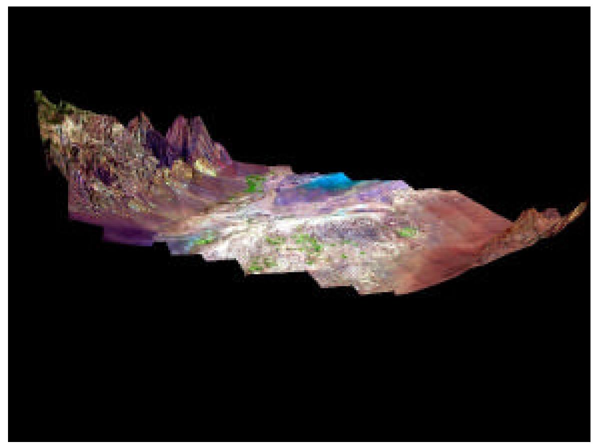


Figure 3: HyMap swaths over Dixie Valley cover known seeps and springs and can be related to structure across the valley floor.

Fish Lake Valley

This valley is a relatively unexplored geothermal center with active agriculture along the eastern flank of the White Mountains. The site is of potential interest as it shows up on GIS maps of "potential favorable development" by Coolbaugh and lies along a northeast trending fault zone that may be related to Mammoth. AVIRIS data were acquired on March 20, 2003, and the approximate area of the coverage is shown in Figure 4. Calibrated data have not yet been delivered. During a field trip to the Cuprite area, just south of Goldfield, we performed a preliminary field reconnaissance of the acquisition site. Similar to Dixie Valley these data can be used to assess surface mineral alteration, presence of

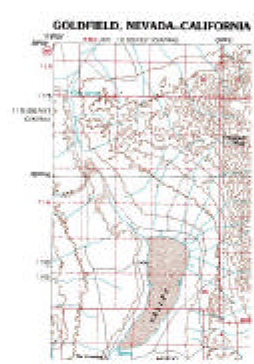


Figure 4: Approximate location of AVIRIS flights. Extends west across valley ~ same distance onto adjacent map.

enhanced sulfates or other salts, vegetation stress or possible indicators of geothermal extent.

Task 2: Regional Assessment of Buffalo Valley

One site that emerged as a high potential region from the funded work of Blewitt was the Buffalo Valley area near Battle Mountain. This region was noted as having high strain which may be one factor in creating productive geothermal systems. We will perform an initial regional survey using Landsat and ASTER data in order to identify high priority targets for hyperspectral acquisitions of this area to be analyzed in year 2. We have acquired some of the initial ASTER data, but will have to merge several scenes to cover the southern end of the valley. Landsat coverage of the area includes both this region and Dixie Valley so that we can look at broad regional alteration patterns in addition to detailed local surveys. Conversations with HyVista Corporation suggest that if they are acquiring other flightlines in the area we can get an acquisition similar to Dixie Valley for a nominal fee. As these data are delivered corrected and geo-located this acquisition has significant advantage over SpecTIR, who are still working on product development. This task will proceed from regional assessment (year 1) to detailed local mapping in year 2.

Task 3: Additional thermal anomaly work with MASTER

Our work with coarse resolution thermal data suggests that both known and hidden thermal sources can be uncovered using day/night imagery to enhance thermal anomaly detection. While the method has sufficient uncertainty that it may not be a useful tool on a regional or statewide basis, the method has significant potential to help identify expansion zones in existing fields. We will continue thermal anomaly mapping using day/night airborne MASTER acquisitions. These data sets have the advantage of significantly improving spatial resolution over that obtained from orbit (5m vs 90m). As MASTER acquires concurrent VNIR/SWIR and TIR data we can simultaneously do low resolution mineral mapping along with thermal anomaly studies. The concurrent acquisition of visible data markedly simplifies corrections for surface albedo and other factors that go into the anomaly correction routine. Our understanding is that we have the potential to acquire new MASTER flights for a nominal contribution. As our investigators are not currently funded by NASA Earth Science programs, some financial contribution is required in order to show NASA program managers that UNR is serious about data analysis and reduction. Conversations with the MASTER program scientist Simon Hook, have encouraged our submission of flight requests that may be acquired as targets of opportunity as the instrument/aircraft fly out of NASA-Ames. The relationship of airborne remote sensing data to other geophysical measurements at geothermal sites is considered compelling.

Schedule, Milestones and Deliverables:

Calvin - Remote Sensing	Duration or Date
Task 1: Hyperspectral Data Analysis	6/03-9/05
Brady's analysis of sinter, carbonate, playas	6/03-3/04
Dixie Valley HyMap Data	6/03-6/04
Fish Lake Valley AVIRIS data	9/03-12/04
Task 2: Buffalo Valley	
ASTER/Landsat Data Acquisition/Analysis	6/03-12/03
Identify targets for hyperspectral	6/03-12/03
Hyperspectral acquisitions/analysis	4/04-9/05

Task 3: MASTER Day/Night	
Request acquisitions: Steamboat, Dixie, Fish Lake, Buffalo.	6/03
Data analysis for thermal anomalies	12 months from delivery
Deliverables:	
Quarterly Progress Reports	Quarterly
Contributions to GRC Mexico: Dixie, Brady	Sept 03
Contributions to GRC 2004, San Francisco	May/Sept 04
DOE annual review	Jul 03,04,05
Presentations at annual AVIRIS Workshop (Dixie yr 1, Fish L yr2)	Feb 04, 05
Peer reviewed publication(s) for RSE or similar.	Fall 04, Summer 05

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