Application of remote sensing technology to geothermal exploration

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ABSTRACT

Recent significant improvements in the wavelength coverage, spectral resolution and quality of remote sensing imagery have led to the extensive application of these data sets in exploration and site characterization. Traditional techniques in spectral and spatial analysis of imagery, coupled with new, high signal to noise data, allow their direct application to problems in geothermal energy exploration and development. Our work seeks to define surface indicators of geothermal resources at known source regions and to apply these tools to recognizing geothermal potential in other areas. Geothermal indicators include sinter, tufa (carbonate), hydrothermal alteration (clays, sulfates) and thermal anomalies. Our work responds to the need to identify new resources and to map the geology of these areas. In addition, we hope to bring down costs by helping to focus new development in existing resource areas. Our work demonstrates that airborne and spaceborne imagery can be used to map mineralogy and hot spots over broad and inaccessible regions. We have clearly associated indicator mineralogy with present and past geothermal activity. Remote sensing data have been able to identify fault extensions not previously mapped by field geologists. Future work will test these methods on new sites not yet producing power to confirm their predictive capabilities for new resources.

Key Words: Remote sensing, mineral mapping, thermal anomalies, Steamboat Springs, Bradys Hot Springs

INTRODUCTION

Renewable energy exploration and development is currently enjoying new interest as the nation seeks to lessen its dependence on foreign oil sources. Geothermal energy is competitive in areas where high heat flow and crustal water circulation combine to provide a readily accessible resource. Nevada in particular has abundant potential for geothermal energy development. The effort at present within the Department of Energy is focused on reducing the cost per kilowatt-hour (Kwh) by enhancing energy production at existing sites and bringing new resources on line.

Our work seeks to define surface indicators of geothermal resources through analysis of characteristic mineral, vegetation, and thermal properties at known source regions and to establish markers of potential in other areas. Geothermal indicators amenable to remote sensing include mineral spectral signatures as well as thermal anomalies mapped in both nighttime and corrected day/night imagery. For our analysis we use a variety of data sets from both airborne and spaceborne platforms.

Our research has concentrated on two established geothermal sites—Steamboat Springs and Bradys Hot Springs in Nevada. We have also examined data of the Dixie Valley and Buffalo Valley geothermal areas. We have used two primary methods of analysis: 1) combined day and nighttime imagery for thermal anomalies and 2) spectral analysis to determine diagnostic surface mineral absorption features to create mineral maps. These two methods have been merged using GIS techniques at Steamboat and Bradys.
INSTRUMENTS AND METHODOLOGY

We use a combination of optical, near-infrared and thermal infrared imagery that provides a multifaceted approach to identify geothermal resources and map geologic structures based on their surface expression. The data are both multispectral (several wavelength channels) and hyperspectral (hundreds of wavelengths). These data sets are sensitive to surface mineralogy and lithology as well as surface temperature. Derived image products include spatial maps of minerals and surface alteration, locations of thermal anomalies, and synthesis of remotely sensed thematic maps with field-based geologic maps. The data are geo-rectified to standard projections so that they can be readily included in regional and site specific databases.

Airborne and spaceborne sensors used include ASTER, MASTER, AVIRIS, HyMap, and SEBASS. Wavelength coverage, number of channels, and ground spatial resolution for these instruments are summarized in Table 1. The first two are multispectral systems and the last three are hyperspectral. All except SEBASS measure in the reflected solar portion of the spectrum (0.4 to 2.5 μm, the combined optical and near-infrared), and ASTER, MASTER and SEBASS observe surfaces at thermally emitted infrared wavelengths (7 to 15 μm). ASTER is the only spaceborne data set used. While we often acquire Landsat coverage over our target sites, we typically do not spend much time on image processing and analysis of that coverage because ASTER offers improved spatial resolution in the visible and more spectral channels in the near-infrared than Landsat.

Identification of Thermal Anomalies

Surface temperature depends on numerous physical parameters. These include albedo (brightness), slope, compaction and coherence (soil vs rock) as well as recent insolation history. A light colored surface will reflect more sunlight and hence be cooler during the day (a darker one is warmer). A slope facing the sun receives more direct solar energy per unit area and hence is also warmer. Soil compaction and rock coherence are combined into a physical property known as thermal inertia or resistance to change in temperature. A fine grained surface (low inertia) will heat up and cool down quickly, while a competent rock will heat up but also cool down more slowly (high inertia), so that low inertia surfaces will be warmer during the day, but cooler at night. The surface temperature also depends on the amount of solar insolation reaching the surface (has it been cloudy?) and convective transport to the atmosphere (winds) can also affect surface temperature.

Geothermal anomalies are sometimes found in nighttime images (being warmer than the surroundings). However, we desired a more robust method that would account for the various aspects contributing to surface temperature and help identify anomalously warm regions with confidence. This method employs both day and night imagery so that the varying contributions cited above can be accounted for. Daytime imagery provides information on albedo and day/night comparisons can provide temperature differences and hence estimate thermal inertia. Digital elevation data (DEM) allows correction for slope and solar incidence angle. Full details of the parametric model that was developed are described in Coolbaugh et al. (2000) and Coolbaugh (2003). Results from both Steamboat Springs and Bradys Hot Springs are described later.

Mineral Mapping

Optical and infrared spectroscopy has been used for over 40 years to identify rocks and minerals. Beginning in the 1970’s, imaging spectral instruments were deployed on aircraft and multi-spectral image platforms have been in orbit since that time. The technique relies on a combination of absorption features that arise from primary rock-forming elements (especially iron), and molecules and anions such as water, hydroxyl, carbonate and sulfate. In the thermal infrared the fundamental absorptions of the \( \text{SiO}_4 \) tetrahedra also cause absorption features that vary with the crystallographic co-ordination of the mineral (e.g., Farmer, 1974; Hunt, 1977). Remote spectral data sets have been successfully used to identify and map numerous mineral species.

### Table 1: Spectral and Spatial Properties of Remote Image Data Sets

<table>
<thead>
<tr>
<th>Data Sets Used</th>
<th>Wavelength Coverage</th>
<th>Channels</th>
<th>Spatial Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
<td>0.5 to 0.9 μm, 1.6 to 2.45 μm, 8 to 12 μm</td>
<td>3, 6, 5</td>
<td>15 m, 30 m, 90 m</td>
</tr>
<tr>
<td>MASTER: MODIS and ASTER Airborne Simulator</td>
<td>0.46 to 2.39 μm, 7.76 to 12.88 μm</td>
<td>25, 10</td>
<td>5m</td>
</tr>
<tr>
<td>HyMap:</td>
<td>0.45 to 2.5 μm</td>
<td>126</td>
<td>3m</td>
</tr>
<tr>
<td>AVIRIS: Airborne Visible and Infrared Imaging Spectrometer</td>
<td>0.45 to 2.5 μm</td>
<td>224</td>
<td>3m</td>
</tr>
<tr>
<td>SEBASS: Spatially Enhanced Broad Array Spectrograph System</td>
<td>7.5 to 13.5 mm</td>
<td>128</td>
<td>2m</td>
</tr>
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</table>
of interest in geothermal exploration including sinters, carbonates, sulfates, and native sulfur (e.g. Hellman and Ramsey, 2004; Kruse, 1999; Martini et al. 2003; Nash et al. 2004).

Sinter, carbonate and hydrothermal alteration minerals, such as clays and sulfates, are identified by their unique spectral signatures from visible through infrared wavelengths, identified in Figure 1. These materials are spatially mapped in the airborne and spaceborne imagery and identifications are validated through field and laboratory spectral measurements as well as x-ray diffraction and thin section analyses.

RESULTS

Steamboat Springs

In a pilot study for thermal anomaly identification, Coolbaugh et al. (2000) found that the main sinter terrace did not appear warm in uncorrected day/night thermal images. However, analysis that accounted for slope, albedo, and thermal inertia provided an accurate map of the main terrace as an anomalously warm region (Fig. 2). In this study the optical and infrared images were from different sensors and seasons, limiting the temperature difference that could be classified as anomalous. For our thermal anomaly analysis at Brady’s we used ASTER data where optical and infrared data are acquired simultaneously.

We performed mineral mapping at Steamboat Springs using the thermal spectral channels of both MASTER and SEBASS. MASTER was able to separate clay dominant surfaces from quartz/sinter surfaces; however the data could not discriminate between quartz and sinter. Also, MASTER mineral maps did not show unique relationships to regions of known geothermal activity. The SEBASS instrument has much higher spectral resolution that allowed detailed separation of quartz from sinter deposits as well as distinguishing the evolution of sinter deposits with age. Vaughan et al. (2003, 2004) and Vaughan (2004) summarize the results and note that alunite, kaolinite, and transient hydrous sulfates are uniquely found in regions of geologically recent venting or forming around active fumaroles. These mineral identifications have been confirmed in the field and with XRD. Synthesis of SEBASS mineral maps with thermal anomaly maps shows a clear relationship between indicator minerals and geothermal activity.

Figure 1: Visible and infrared spectral properties of common geothermal minerals (from top to bottom in the plot): carbonate (calcite), sulfate (alunite), clay (montmorillonite) and sinter (opal). Band center position, band shape, and width are diagnostic of specific minerals and can be mapped in hyperspectral data sets.
We reproduced the thermal anomaly analysis at Bradys Hot Springs using ASTER with two scenes, one acquired during the day, and one at night, within a 24-hour period. In addition surface temperature data was gathered in the field during the overflight along with diurnal temperature measurements at 15 to 30 minute intervals to establish thermal inertia curves of representative surfaces. Although the spatial footprint of ASTER is large, 90m/pixel, the data set easily identified the main structures and vents along the primary fault, extending over 4 km in length (Fig 3). Outlier patches of warm ground were confirmed in the field and there is a precise correspondence between the remotely derived hotspot map and fumaroles and hotspots identified and located using GPS in the field. Several anomaly outliers pointed to potential complexity in the fault system that was subsequently examined at higher spatial resolution with mineral mapping techniques.

We obtained optical and near infrared spectral coverage using the HyMap instrument (Fig. 4). Kratt et al. (2003, 2004) and Kratt (2005) summarize the results of mapping both sinter and carbonate tufa in the area. Sinter was mapped using a diagnostic absorption feature at 2.25 µm and identification was confirmed with laboratory analysis and XRD. Large areas of silicified diatomite were also mapped using this technique and significant field validation was performed in order to optimize detection thresholds and localize true sinter deposits. Figure 5 shows large deposits of sinter, mapped in red, that mark an extension of the fault line south of the main plant that was not previously recognized from field mapping. Structurally controlled tufa mounds trending from the main fault were also identified.

**Brady’s Hot Springs**

We reproduced the thermal anomaly analysis at Brady’s Hot Springs using ASTER with two scenes, one acquired during the day, and one at night, within a 24-hour period. In addition surface temperature data was gathered in the field during the overflight along with diurnal temperature measurements at 15 to 30 minute intervals to establish thermal inertia curves of representative surfaces. Although the spatial footprint of ASTER is large, 90m/pixel, the data set easily identified the main structures and vents along the primary fault, extending over 4 km in length (Fig 3). Outlier patches of warm ground were confirmed in the field and there is a precise correspondence between the remotely derived hotspot map and fumaroles and hotspots identified and located using GPS in the field. Several anomaly outliers pointed to potential complexity in the fault system that was subsequently examined at higher spatial resolution with mineral mapping techniques.

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CONCLUSIONS

Our work demonstrates that spaceborne imagery can be used to map mineralogy and hot spots over broad and inaccessible regions. We have successfully mapped thermal anomalies at Steamboat Springs. Hyperspectral thermal infrared data can differentiate sinter deposits of opaline silica from massive chalcedony, thus separating recent from older deposits. More detailed mineral mapping shows clay alteration and sulfates are uniquely mapped in regions with current or geologically recent geothermal activity.

At the Bradys location, detailed thermal anomaly and mineral mapping found extensions of the main fault not previously mapped by field geology and suggest more complicated underlying structure at the site. Here the SWIR spectral region was able to locate sinter and structurally controlled sub-lacustrine tufa associated with current and historical geothermal activity.

Ongoing work is testing these methods at Pyramid Lake, in regions without any current power production, to analyze their effectiveness in a predictive mode for drilling and site placement of new power plants.

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REFERENCES


Figure 4: Flightline coverage of HyMap data at Bradys shown over topography. Actual lines are marked by flags at their north and south ends. The right 5 lines were offset south in order to cover the enhanced geothermal plant at Desert Peak, a geothermal resource with no obvious surface expression.
Figure 5. Sinter map at Bradys Hot Springs. Portions of I-80 cross the image from left to upper right. The main plant is identified by small white rectangular features below the highway. Sinter outcrops are mapped in red. Small outcrops in the lowest portion of the image identified relic fault structures not previously recognized in field mapping.