REFLECTANCE SPECTROSCOPY APPLIED TO EXPLORATION FOR MINERAL DEPOSITS AND GEOTHERMAL SYSTEMS, AND TO THE REMEDIATION OF MINED LANDS IN THE GREAT BASIN OF THE UNITED STATES

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Abstract

The Great Basin of the Western United States has thin continental crust and geologic structures that have controlled the emplacement of significant precious and base metal mineralization. Many of the mineral deposits in the Great Basin were emplaced by hydrothermal processes that altered the mineralogy of their host rock assemblages and facilitated concentration of metals. In the 1960’s and 1970’s research with laboratory spectrometers determined that some alteration minerals associated with mineral deposits have discrete spectral signatures that should permit their identification and mapping in the field. Research in the 1970’s found that clays and iron oxides, associated with mineralized systems, could be detected in multiband image data and mapped using their broad spectral signatures. Beginning in the 1980’s, research with prototype airborne imaging spectrometer data and ground-based spectrometers identified suites of alteration minerals that are key indicators of mineralized systems. Recent airborne and satellite systems have demonstrated that detailed mineral mapping is possible from aerospace measurements, as verified by ground-based spectrometer measurements. These spectral measurements document the zonation of low and high temperature mineral assemblages. Minerals like chlorite, epidote, calcite were found as propylitic alteration farther from igneous centers while quartz, quartz-alunite, and alunite were identified nearer the centers. Clay mineral assemblages were located between the two alteration zones, including: kaolinite, dickite, illite and montmorillinite. Iron oxide and iron sulfate minerals (hematite, goethite and jarosite respectively) were also found associated with alteration zones. There are now several reference spectral libraries and airborne/spaceborne case histories available that illustrate the unique spectral character of these distinctive mineral spectra and our ability to identify and map them from imagery. The technology and methods developed are used in a variety of related areas; mineral and geothermal exploration, detection of acid mine drainage, and the assessment of the effectiveness of mined-land reclamation.
The Great Basin of the Western United States

The Great Basin of the Western United States includes all of Nevada and portions of Idaho, Utah and Arizona, Figure 1. The Great Basin includes the Carlin Trend that is one of the five major precious metal districts in the world. It includes significant copper and molybdenum production and North America’s largest open pit copper mine, Bingham Canyon. The crust of the Great Basin is relatively thin and the structural framework has allowed mineralizing fluids to emplace significant deposits. The structural framework of the Great Basin, coupled with relatively shallow, high heat flow, have combined to make the Great Basin the “Saudi Arabia” of geothermal energy. The region is semi-arid, with vegetative cover frequently less than 30%, and sparse cloud cover throughout much of the year. Therefore, the Great Basin became the physiographic region of choice for testing new aerospace remote sensing techniques. When Landsat (formerly ERTS-1) data became available in the early 1970’s the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) investigators began to acquire aerospace image data over Goldfield and Cuprite, Nevada and later over Virginia City, Nevada. Today, the Great Basin remains as one of the most studied areas for evaluating the measurements made by spaceborne, airborne and ground-based electromagnetic remote sensing sensors.

Figure 1. Relief map with outline of the Great Basin.
History of Spectral Remote Sensing in the Great Basin

In the 1960’s laboratory research conducted mainly by Graham Hunt and John Salisbury (Hunt and Salisbury, 1970) made the pioneering laboratory reflectance measurements of reflectance variations from mineral and rocks. Their research at the Air Force Cambridge Laboratory demonstrated the potential for remote detection of important rock constituents and even specific minerals. They published their laboratory spectral measurements in Modern Geology, a journal that is no longer in print. Most of their laboratory spectra were measured under controlled conditions using dry, powdered samples of relatively pure mineral substances from a wide variety of localities. Their work laid the groundwork for the development of spectral libraries by the U. S. Geological Survey and the Jet Propulsion Laboratory (JPL) of the California Institute of technology (CIT).

In the 1970’s USGS and JPL research with aircraft and satellite multispectral image data over Goldfield, Nevada found that mineral groups, (clays and iron oxides) associated with hydrothermal alteration, could be detected and mapped (Rowan, et. al., 1974). However, the laboratory spectral measurements by Hunt and Salisbury showed promise of not only detecting the presence of clay and iron minerals, but also identifying clay and iron minerals, and mapping their abundances throughout areas being investigated. To understand dominant mineralogies and lithologies present in the field, ground-base reflectance measurements became necessary. Initially, simple handheld multiband instruments were developed for ground investigations of natural surface cover: rocks, unconsolidated rock materials, soils, coatings on rocks and soil, vegetation, human made materials and mixtures of the above. Many of these early instruments were first tested in the Great Basin.

As the capabilities of airborne sensors increased in the 1970’s, and measurements in more spectral bands became possible, the need increased for the development of field instruments to measure solar reflectance from natural cover types in hundreds of spectral bands. Field spectrometers were first developed by the Jet Propulsion Laboratory and a private firm, Geophysical Environmental Research (GER). These spectrometers were first tested in Goldfield and Cuprite, Nevada. Airborne radiometers (not imagers) demonstrated the potential for measuring discrete spectra in hundreds of individual bands from airborne platforms. (Chiu and Collins, 1978). In the late 1970’s, developments in solid-state imaging technology made it possible to image terrain in tens of wavelength bands with optical-mechanical scanners (Kruse, et. al., 1990).

In the early 1980’s developments in solid-state imaging technology made possible spectral image measurements in hundreds of wavelength bands. During the early 1980’s the Jet Propulsion Laboratory, under the direction of Dr. Alex Goetz, developed the Airborne Imaging Spectrometer (AIS) using the JPL Director’s discretionary funds. The AIS measured reflectance in 128 spectral bands from 10 meter-sized areas. Some of the earliest overflights with this new instrument were over Cuprite and Goldfield, Nevada in the Great Basin.
Great Basin mineral deposits and geothermal occurrences are intimately linked to the evolution of volcanic-hydrothermal systems. Figure 2 illustrates linkages between silic magmatic fluids derived from evolving porphyry intrusives, structural control of the volcanic edifice, development of hot springs and low sulfidation base and precious metal deposits. Structurally controlled high sulfidation systems tend to form closer to the original volcanic center. The geochemistry of these systems dictates how the original host rocks are altered to produce mineral suites that can be detected in discrete spectral bands by aerospace measurements of solar reflectance, and subsequent earth emittance.

Figure 3 shows alteration mineral assemblages commonly found in low-sulfidation systems in the Great Basin. These systems are commonly characterized by hot springs, associated opaline silica, chalcedony, alunite and kaolinite. Frequently, native sulfur can be found in fractures near vents. Mixed layer clays, chlorite and epidote are found at distance from the main volcanic center. Ore found in these systems can be disseminated in permeable rocks surrounding the main fractures that delivered the mineralizing fluids, and often, high-grade mineralization is found at depth below the disseminated ore bodies. High-grade mineralization is often associated with quartz alunite and quartz veins.

Figure 4 shows alteration mineral assemblages commonly found in high-sulfidation systems found in the Great Basin. These systems have a distinct alteration zonation from propylitic (chlorite, epidote, calcite) through argillic (montmorillonite, illite and kaolinite) to, ultimately, quartz alunite and mineralized mineralized quartz veins.
Figure 3. Typical Mineralogy Found in Low-Sulfidation Systems in the Great Basin

Figure 4. Typical Mineralogy in High-Sulfidation Systems in the Great Basin.
Table 1 – General Characteristics of epithermal precious metal deposits

<table>
<thead>
<tr>
<th>Low Sulfidation</th>
<th>High Sulfidation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-space veins dominant, stockwork ore common</td>
<td>Disseminated ore dominant, replacement ore common</td>
</tr>
<tr>
<td>Disseminated and replacement ore minor</td>
<td>Stockwork ore minor, veins commonly subordinate</td>
</tr>
<tr>
<td>Veins, cavity filling (bands, colloforms, druses), breccias</td>
<td>Wallrock replacement, breccias, veins</td>
</tr>
<tr>
<td>Pyrite, electrum, gold, sphalerite, galena (arsenopyrite)</td>
<td>Pyrite, enargite, chalcopyrite, tennantite, covellite, gold, tellurides</td>
</tr>
<tr>
<td>Quartz, chalcedony, calcite, adularia, illite, carbonates (\text{KAISi}_2\text{O}_8)</td>
<td>Quartz, alunite, barite, kaolinite, pyrophyllite (\text{KAl}_{2}\text{(SO}_4\text{)}_2\text{(OH)}_6)</td>
</tr>
<tr>
<td>Au, Ag, Zn, Pb (Cu, Sb, As, Hg, Se)</td>
<td>Cu, Au, Ag, As (Pb, Hg, Sb, Te, Sn, Mo, Bi)</td>
</tr>
</tbody>
</table>

Spectral Investigations with AVIRIS in the Great Basin

During the late 1980’s and throughout much of the 1990’s NASA and JPL developed and perfected the AVIRIS system and began to acquire image data over Cuprite, Goldfield and the Virginia City areas. This system was flown in an Earth Resources U-2 high altitude aircraft, permitting coverage of large areas throughout the United States and, later around the World. AVIRIS collects its hyperspectral data in 224 spectral bands, in 9.2 nanometer bandpasses, with 10 to 20 meter ground instantaneous field of views, over about a 10 to 20-kilometer ground swath. Later in the 1990’s AVIRIS was alternatively mounted in a Twin Otter to acquire higher spatial resolution data. Development and flight of this hyperspectral system was paralleled by the development of portable ground-based spectrometers for verification of the spectral signatures of cover types. In the late 1980’s Greg Swayze, of the U. S. Geological Survey’s Spectral Laboratory in Denver, repeatedly acquired AVIRIS data over Cuprite and Goldfield, Nevada. As the instrument was improved, Swayze was able to show that the number of relatively pure mineral endmembers that could be detected in the Cuprite area increased from 8 to 64 (Swayze, 1998). Alvaro Crosta, on a sabbatical at the Desert Research Institute, collaborated with Chuck Sabine and Jim Taranik in a study of hydrothermal alteration in the Bodie mining district using 1992 AVIRIS data, (Crosta, 1998). This study utilized two different image data analysis procedures; spectral angle mapper (SAM), and Tricorder (Now Tetraorder) from the U. S. Geological Survey’s...
Spectroscopy Laboratory. Laboratory spectra was measured on a Beckman spectrometer and compared with X-Ray Diffraction measurements, (Crosta, et. al., 1998).

Spectral Research Related to Mineral and Geothermal Systems in Nevada

Virginia City, Nevada

Figure 7. Mineralizing structure

Figure 8. Location Map

Figure 9. Alteration minerals associated with the Comstock Fault, after Hudson, 1980.
The Virginia City mining district is located 27 km southeast of Reno, (Figure 8). This district produced over 225,000 kb of gold and 7 million kg of silver between 1862 and 1953. The oldest rocks are Mesozoic metasediments and metavolcanic rocks that have been intruded by Cretaceous granodiorite. These units are unconformably overlain by early Miocene silicic ash-flow tuffs, thick andesite flows and associated breccias of the Alta Formation. Overlying the Alta Formation, are andesite flows, breccias and accompanying dikes and stocks of the Kate Peak formation that are the main host for mineralization for the district (Thompson, 1956).

Mineralizing fluids that emplaced ore deposits in the Comstock Lode district were controlled by north-south trending listric faults, notably the Comstock and Occidental faults (Figure 7). Argillic and propylitic alteration are pervasive throughout the district. Occurrences of fine-grained alunite and kaolinite, resulting from supergene processes (oxidation of pyrite and the formation of low pH fluids), are localized in the district. Some of the areas described as “bleached” by earlier workers are hypogene quartz-alunite and clay minerals produced by fluids having lower pH than those that formed the Comstock deposits (Vikre, 1998). The main economic deposits of the district were found along the Comstock fault, often at the intersection of cross-faults. The main alteration assemblages noted in the district are: (1) Widespread propylitic assemblage not associated directly with ore mineralization. Propylitized rocks typically have a greenish color because of associated chlorite and epidote and these altered rocks commonly also have fractures that are filled with calcite; (2) A zeolitic assemblage superimposed on the propylitic zone; (3) Erratically distributed quartz-alunite alteration (of high-sulfidation type) and quartz-sericite-montmorillonite-pyrite alteration associated with gold-silver veins (Figure 9).

Because of its close proximity to the University of Nevada, Reno, Virginia City, Steamboat and Geiger Grade became field laboratories for the Arthur Brant laboratory for Exploration Geophysics (ABLE). AVIRIS data were acquired over Virginia City in 1995 as a part of a “group shoot,” a group of firms interested in using the data for exploration. Initial data analysis was done by Joe Boardman and Jon Huntington. ABLE acquired the data from this study from Fred Kruse and when Amer Smailbegovic arrived in 1998 he began to analyze it with one of the first versions of the Environment for Visualizing Images (ENVI). Within just a few weeks of his arrival, his analysis mapped some of the mineral themes listed above and draped them on a false color image of AVIRIS data (Figure 10). These same mineral themes were then draped on a USGS 1:24,000 scale topographic map and the spectrally mapped themes from AVIRIS were then evaluated in the field using an ASD Full-Range Spectrometer. The ASD field measurements were used to collect samples which were, in turn, used for X-Ray Diffraction analysis in the Nevada Bureau of mines and Geology. Based on these studies, the investigators determined that the X-Ray Diffraction analysis was an unnecessary step to confirm the presence of alteration mineral suites (Smailbegovic, 2000).
The HyperSpecTIR (HST) is an airborne hyperspectral imaging spectrometer developed and operated by the SpecTIR Corporation. It measures solar reflected radiance in 227 continuous spectral channels between 0.45 and 2.45 μm (Table 2). It has an IFOV of 1 mrad (0.057°) and a TFOV that is selectable from 0 to 1 rad (57°) (Watts et al., 2001). The instrument is mounted on a tilting platform equipped with a "fast optical line-of-sight steering" system that allows for real-time compensation of aircraft motion (roll, pitch and yaw variations) in heavy turbulence, and increases the dwell time over the target (Watts et al., 2001). Images are acquired in a series of overlapping frames rather than a single, continuous strip. HST data were acquired over Virginia City in June 2002 from a Cessna 310 aircraft at an altitude of 2.5 km AGL. The images cover a swath of 1.1 km and have a spatial resolution of 2.5 m. Figure 11 shows one of these swaths which are scanned from left to right while the instrument collects spectra. The focal plane is motion stabilized. Although the HyperSpecTIR instrument is no longer flown by SpecTIR, it has been recently used for ground scans of road cuts and mine pits. Greg Vaughan used image data from the HST to map spectral alteration themes in Virginia City (Figure 11). In addition, Vaughan used the ASD to understand spectral mixing in AVIRIS pixel data at Wheeler Reservoir in Virginia City (Figure 12). AVIRIS pixels were plotted on an Orthophoto Quadrangle and then sampled with an ASD Spectrometer, shown in use by Greg Vaughan in Figure 12.
Figure 11. SpecTIR HyperSpecTIR (HST-3) sensor data processed with ENVI to produce spectra of typical high-sulfidation alteration mineral assemblages, Vaughan and Calvin, 2005.
Aurora, Nevada and Bodie, California

The Bodie Hills area is situated between the Wassuk Range on the North and Mono Basin on the South, split roughly in half by the Nevada-California state line. The area is mountainous with elevations ranging from 1,716 m (5,150 ft) in Fletcher Valley to 3,675 m (11,015 ft) on Potato Peak. The districts can be reached by improved gravel roads from Hawthorne, Nevada and Bridgeport, California. The roads are treacherous at times because they receive minimal or no maintenance and many have washed out over the years. The United States Forest Service (Bridgeport station) manages most of the land in the Bodie Hills, with the exception of Bodie (administered by the California State Parks), and small areas of patented land, primarily near the old mining works of Aurora, Paramount and Masonic.

The region is characterized by pre-Tertiary metavolcanic and granitic plutonic rocks, Tertiary and Quaternary volcanic rocks and occasional sedimentary rocks (Figure 13). Tertiary volcanics rocks form about three quarters of the rock types encountered.
Basement (pre-Tertiary) rocks are exposed only in a few isolated locales. Sedimentary rocks are conglomerates localized on the fringes of the Bodie Hills, formed from the erosion of (predominantly) Tertiary volcanic rocks.

The basement of the Bodie Hills is comprised of pre-Cretaceous metavolcanic rocks and Cretaceous granitic plutons. The basement is exposed in the northern and eastern portions of the Bodie Hills. The plutons are intruding pre-Cretaceous metamorphic rocks of the Excelsior Formation chiefly composed of hornfels and greenstones (Smailbegovic, 2002). Two suites of Tertiary and Quaternary volcanics are present in the area: Calc-Alkaline (26 Ma – 4 Ma) and Alkali-Calcic. The Calc-Alkaline suite is dominated by porphyritic hornblende-pyroxene andesite and biotite-hornblende dacite. Lying unconformably on the Miocene assemblage are Pliocene and Pleistocene lava flows of basaltic-andesite and basalt, ranging in age from 3.5 Ma – 250 Ka (Smailbegovic, 2002).
Hyperspectral sensors used in this study (AVIRIS, HyperSpecTIR) are sensitive to the absorptions associated with iron (0.4 – 1.0 µm) and clay (2.1 µm to 2.4 µm) minerals and are capable of accurately recording them with the 10 nm wide band passes. By using hyperspectral imagery, the desire is to provide information on the type of alteration observed in the Bodie Hills (particularly Bodie-Aurora trend) and where possible differentiate high sulfidation from low sulfidation alteration assemblages. By understanding observed alteration assemblages, conclusions can be drawn as to their origin and possible temporal development.

Based on the available data and field observations, the types of hydrothermal alteration encountered in the Bodie Hills fit into the category of Epithermal vein deposits with two distinct subcategories: high sulfidation and low sulfidation. The minerals targeted for characterization of the low sulfidation assemblages are: illite, montmorillonite and sericite; for high sulfidation assemblages: alunite and kaolinite. It should be noted that kaolinite occurs in both low and high sulfidation assemblages but it is more pronounced in high sulfidation zones. A thematic mineral map produced from the endmember-class regions of interest derived from AVIRIS and HST data is shown on Figure 14. The mineral spectra directly associated with the alteration include kaolinite-type, alunite-type, illite/sericite-type (these two minerals are almost indistinguishable spectrally in the hyperspectral imagery) and “propylitic-type” spectra. The alunite areas dominate the ledge on top of the East Brawley Peak and also occur on top of the Sawtooth complex. Kaolinite closely follows (and often fringes) the distribution of alunite. However, kaolinite sometimes mixes with other clay minerals noted in the low sulfidation areas.

Illite, sericite and montmorillonite (Ca/Na) all exhibit the same absorption feature(s), hence the class should be thought of as a “mixed clay class.” The mixed clay are spatially associated with the mineralized areas in Aurora and Bodie and do not extend beyond the boundaries of the districts. On the high resolution imagery, it is narrowly constrained to the strike of veins observed in the Aurora district. The “propylitic” spectral endmember class has no apparent clay absorption bands and bears similarity to the absorption spectra for the chlorite-class minerals (amesite, clinochlore, chamosite etc.).

The analysis of hyperspectral data suggests two types of hydrothermal alteration present in the western portion of Bodie Hills. On the basis of spectral measurements – low sulfidation and high sulfidation types of hydrothermal alteration can be distinguished (Smailbegovic, 2002). Aurora and Bodie are very similar in their low-sulfidation system characteristics, showing significant argillic-sericitic alteration, closely associated with the vein systems and propylitic alteration in the general area.
Figure 14. Results of the Analysis of AVIRIS and SpecTIR HyperSpecTIR data over the Bodie-Aurora Area. Amer Smailbegovic, 2002.
Cuprite, Nevada

The Cuprite mining district is located approximately 65 km (40mi) south of Tonopah, Nevada (Figure 15). It consists of two spatially and temporally separate low-sulfur epithermal acid-sulfate systems separated by US Highway 95 (Swayze, 1997). Host rocks include Tertiary-age volcanic ash flow/air fall tuffs, flows, sedimentary conglomerates and sandstones and Cambrian-age carbonates, quartzites, siltstones (west side only). Abrams et al., 1977 mapped 3 alteration zones 1) Silicified (hydrothermal quartz +- calcite), 2) Opalized (opal, variable alunite and kaolinite), and 3) Argillized (kaolinite and/or montmorillonite) (Figure 16). Cuprite has been extensively used for over 30 years as a test site for remote sensing technology and algorithms for mineral mapping. Specific examples include multispectral remote sensing in the 1970s and 1980s, the Airborne Imaging Spectrometer (1983 - 1986), AVIRIS (1987 – Present), Hyperion (2001), and numerous other multispectral and hyperspectral sensors. It has been the focus of many geology studies, however, the most comprehensive are those by Ashley and Abrams (1980), and Swayze (1997). The U.S. Geological Survey has produced detailed mineral maps using their “Tetracorder” expert system and verified with field mapping, VNIR/SWIR spectral measurements, and other analytical methods.

Figure 15: Location map, Cuprite and Goldfield, Nevada
For the purposes of this study, AVIRIS data collected for the Cuprite site during 2002 were run through the ENVI “hourglass” procedures. The data were corrected to apparent reflectance using the ACORN atmospheric correction software, Mode 1 (calibrated hyperspectral data). The atmospheric correction was further refined using a USGS-measured spectrum for Stonewall Playa at Cuprite (Figure 17), used to “bootstrap” the correction, thus removing residual artifacts from the atmospherically corrected AVIRIS data. The MNF Transform was run on 48 SWIR bands from approximately 2.01 – 2.48 micrometers; the results are approximately 20 coherent MNF bands. These 20 MNF bands were used for 25,000 iterations of the Pixel-Purity-Index (PPI), producing an image band with all of the “pure” pixels ranging from 1 up, with “hits” coded as a grayscale image. ENVI’s Region of Interest (ROI) utility was used to extract only those pixels with more than 25 hits in the PPI image to form an ROI with approximately 4000 pixels. These were loaded into the ENVI n-D Visualizer and interactive n-Dimensional scatterplot analysis was used in conjunction with spectral plots for the highlighted pixels identify and extract the purest pixels (endmembers) for 12 spectral classes. An ROI was created for each endmember and the mean spectrum was extracted from the atmospherically corrected AVIRIS data for each class. In this case, the Spectral Analyst was used along with expert knowledge of mineral spectroscopy and a new Plug-In to ENVI the “Spectral Expert” (Kruse, 2003) to identify the endmembers at Cuprite from their reflectance spectra and absorption features. Mixture-Tuned-Matched-Filtering (MTMF) was run on the 20 significant MNF bands using the endmember ROIs (ENVI extracts MNF spectra automatically during analysis). The output of the MTMF is a series of Matched Filter (MF) images and “Infeasibility” images, one for each endmember. The MF images allow an estimate of mineral abundance (Figure 18). The infeasibility images improve the MF results by causing improved rejection of false alarms using mixture feasibility constraints. The two images (for each endmember) were
used in ENVI’s interactive 2D scatterplotting function to extract pixels with high MF and low Infeasibility scores for each endmember. The output is a ROI for each endmember showing those pixels in the image that most closely match the spectral signature of each specific endmember. The ROIs are then combined into a classified image using ENVI’s ROI-to-Classification function, and can be overlain on a single band image for spatial location (Figure 19).

Figure 17: Photograph of Stonewall Playa at Cuprite, NV (Stop #2) and USGS Spectral Library Reflectance Spectrum used for improved reflectance correction of Cuprite AVIRIS data.

Figure 18: MF filter images for selected endmembers at Cuprite, NV: (left: kaolinite, center: alunite, right: silica) showing estimated abundance color coded from blue to red (low to high).
Field investigations were conducted at Cuprite, NV during January and February 2009 to verify imaging spectrometer analysis results. An ASD FieldSpec Pro spectrometer was used to make reflectance measurements of selected sites illustrating the key alteration types and occurrences in the Cuprite Mining District, Figure 20). These included (Figures 21 - 25) a silica pit showing hydrothermal silica alteration (Stop #3), alunitic alteration (Stop #4), kaolinitic alteration (Stop #5 – “Kaolinite Hill”), a second silica occurrence (Site #6), and buddingtonite (Stop #7, “Buddingtonite Bump”). Unaltered volcanic rocks were also observed at Stop #7. Scaled, printed image alteration maps were reviewed and compared to the on-the-ground alteration. The ASD field spectrometer was used to verify selected mineralogies and to illustrate the effects and scale of spectral mixing.
Figure 20: Orthophoto showing location of and access to ASD measurement sites at Cuprite, NV. Numbers refer to stops/ASD Spectra discussed in the text.

Figure 21: Stop #3: Silica Pit 1: Opaline Silica, Kaolinite, Alunite
Figure 22: Stop #4: Alunite Hill

Figure 23: Stop #5: Kaolinite Hill

Figure 24: Stop #6: Silica Pit 2
Beginning in 2006, SpecTIR, LLC, based in Reno, Nevada began flying a dual hyperspectral sensor, manufactured by Specim in Finland, and called ProSpecTIR. ProSpecTIR uses two separate sensors, one for the Visible and Near-Infrared and one for the Short-Wave Infrared. These sensors combined can make measurements at bandwidths of 5 nm, at spatial resolutions of 2 meters, in over 350 spectral bandpasses. The sensors are easily mounted in a light aircraft, Figure 26. ABLE began working with ProSpecTIR data beginning in 2007 and test flights were flown over Cuprite, Nevada. A preliminary analysis of this data was done by Amer Smailbegovic, Figure 27. In 2008, SpecTIR and Aerospace Corporation began co-mounting both ProSpecTIR and SEBASS in the same stabilized mount in Aerospace’s Twin Otter aircraft.

Figure 25: Stop #7: Buddingtonite Bump: verify NH4 minerals, view unaltered Tuffs

Figure 26. SpecTIR’s ProSpecTIR instrument consists to two solid state imaging sensors manufactured by Specim in Finland (left). Operator shown in Cessna 206 (right).
Goldfield, Nevada

Goldfield, a historic mining district discovered in 1902, is located approximately 40 km (25mi) south of Tonopah, Nevada (Previous Figure 15). It has been described as the type locality for the Epithermal Bonanza deposit of the enargite-gold or quartz-alunite type (Berger 1992, Model 25e). Mineralization occurs primarily in Tertiary-age calc-alkalic volcanic rocks (porphyritic trachyandesite, rhyodacite, quartz latite, and rhyolite). Some minor ore at depth occurs in Ordovician argillite and Jurassic quartz-monzonite (Ashley, 1990). Goldfield displays two ages of volcanism 1) Oligocene silicic ash flow tuffs, air-fall tuff, and flows associated with development of an inferred caldera and associated ring-fracture zone followed by extensive erosion and 2) emplacement of Lower Miocene flows, tuffs, and breccias with formation of rhyolite and rhyodacite domes along the ring-fracture zone. Prominent early-Miocene normal faults (mostly NE-trending, east dipping) formed late in the second episode of volcanism. Less well-defined fault sets appear to follow the ring-fracture zone. Extensive hydrothermal alteration, principally occurring in and around the ring-fracture zone is dated at about 20.6 Ma (lower Miocene). The principal alteration consists of intense acid-sulfate alteration and bleaching. Several recognized zones include: 1) Advanced argillic (quartz+alunite+kaolinite+pyrophyllite+sericite+diaspore+leucoxene+pyrite), 2) Phyllic-argillic (quartz+kaolinite+sericite+adularia+opal+pyrite), 3) Argillic (quartz+montmorillonite+illite+kaolinite+relict feldspar+pyrite), and 4) Propylitic (Chlorite+albite+epidote+montmorillonite+caclite+zeolite+pyrite), (Figure 28).
Figure 28: Goldfield, NV, alteration map (from Ashley, 1990).

Figure 29: Left: Goldfield, NV, 2002 AVIRIS Endmembers, Right: Goldfield, NV, 2002 AVIRIS MTMF Mineral Map: The minerals mapped were extracted using 2D Scatterplotting of high MF score versus low Infeasibility Score for endmembers extracted from the AVIRIS data. Endmember were identified by visual and numerical comparison to the USGS Spectral Library splib06. Only the best mineral matches are shown.
Field verification of the Goldfield, NV site was conducted during January and February 2009 (Figure 30). At an overlook point (Stop #1, Figure 30), topographic, geologic, and image maps and perspective views were used to provide an overview of the geology and alteration at Goldfield. The results of the AVIRIS mineral maps were compared to field ASD spectral measurements for selected sites for comparison of on-the-ground mineralogy. A prospect pit (Stop #2) was investigated and kaolinite, alunite, and jarosite alteration spectra measured (Figure 31) using an ASD FieldSpec Pro spectrometer. Stop #3 provided an overlook of the Florence Pit and ASD measurements of extensive tailings piles confirmed principally kaolinite/jarosite mineralogy (Figure 32). Stop #4 was at a road cut overlooking the Jumbo Pit, where host rocks and alteration were measured and a variety of minerals identified including kaolinite and jarosite (Figure 33). Stops #5 (northeast flank of Vindicator Mtn) and #6 (Ruby Hills) provided access to alunite alteration (Figure 34).

Figure 30: Orthophotograph showing the location of specific mineral alteration sites measured using the ASD field spectrometer.
Figure 31: Goldfield Stop #2, Prospect pit with alunite, kaolinite, and jarosite

Figure 32: Spectrum of typical Goldfield tailings material, Stop #3 near Florence Pit (Kaolinite + Jarosite)

Figure 33: Stop #4, Roadcut overlooking Jumbo Pit, Kaolinite and Jarosite
Spectral Studies of Geothermal Systems in the Great Basin

Hymap (hyperspectral mapper) image data were used to remotely map unique geothermal indicator minerals over the Brady–Desert Peak geothermal fields. Geothermal-related minerals and rocks such as sinter, tufa, and sulfates, display diagnostic characteristics in the visible and shortwave infrared; their presence and distribution can be used to guide more detailed field work for geothermal exploration. The Brady–Desert Peak geothermal fields are located about 80 km east of Reno, Nevada in the Hot Springs Mountains, (Figure 35). North–northeast-striking en-echelon faults offset Tertiary volcanic and lacustrine rocks. Two geothermal power plants produce...
electricity from two separate geothermal systems, one with numerous fumaroles and mudpots, the other showing no active surface expression of geothermal activity. Surface occurrences of gypsum, calcium–carbonate, hematite, and opaline silica were identified at both sites with the hyperspectral data; these minerals when considered together are indicative of geothermal activity at both sites. Mapping results were synthesized with other spatial data in a geographic information systems (GIS) database that was used to help draw structural interpretations of faulting and fault controls at the Brady–Desert Peak area, (Figures 36 and 37).

Figure 36. Brady Geothermal Field in the Western Great Basin

Figure 37. Cross-section of Brady Geothermal Field after Faulds, 2004
Temperature zonation of alteration assemblages is well known in the exploration of hydrothermal systems for economic metals. The use of these alteration facies in geothermal systems has been less studied, particularly as it relates to borehole geology and system temperature. Several studies have explored the use of both silica and chlorites as geothermometers and alteration zonation, particularly of clay mineral type (illite, montmorillonite, beidellite), can characterize the temperature of alteration in geothermal systems. Infrared spectroscopy is particularly good at identifying a wide variety of alteration minerals especially clays that are difficult to distinguish in hand samples. Several promising pilot studies were performed that suggest the power of the technique to sample continuously and provide mineral logs akin to geophysical ones (Kratt et al., 2004; Calvin et al., 2005), (Figure 38). These studies demonstrated that core and drill chips can be rapidly surveyed, acquiring spectra every few to tens of cm of section. Preliminary work has helped to establish appropriate measurement techniques using the ASD field spectrometer and we are actively developing core and chip spectral logs that can be related to other borehole measurements (Figure 39).
Figure 39. Incorporation of ASD measurements in core analysis at Bradys Geothermal Field.

Figure 40. ASD measurements of geothermal lithologies near Bradys Geothermal Field.
Conclusions

Beginning in the 1980’s, remote imaging spectroscopy emerged as a transformational technology. Early experiments with the Airborne Imaging Spectrometer (AIS) at Cuprite showed that it was not only possible to identify specific minerals using a spectral library, but it was spectrally possible to measure unknown spectra and later determine the minerals (Buddingtonite) associated with that spectra. Although studies of laboratory spectra done a decade earlier on dry mineral powders indicated the potential of identifying and mapping mineral spectra in the field, in situ measurements were necessary to evaluate the effects of weathering, mineral coatings and the distribution of different cover types within an imaged ground instantaneous field of view. Early field spectrometers were often heavy and cumbersome to use in the field. The development of the ASD series of portable spectrometers was a breakthrough that enabled one person to collect the necessary ground spectral data that was important for image processing and analysis of hyperspectral image data. Even when ground spectrometers were used to confirm airborne spectral measurements, most traditional exploration geologists questioned the measurements and insisted on X-ray analysis of field samples to “confirm” correct identification of alteration mineral. X-ray analysis uses small samples that are prepared in a laboratory setting and it makes a different measurement than ground-based and airborne spectrometers. Over the past two decades, most mineralogists now agree that X-ray analysis is not needed to confirm mineral compositions determined through remote sensing techniques. ASD spectrometers are commonly used in the laboratory to make measurements of whole-rock samples collected in the field. Precision measurements of sub-centimeter samples are now done with a Nicolet spectrometer system in ABLE’s spectroscopy laboratory at the University of Nevada, Reno.
Key References

**Mineral Spectroscopy - Selected References**


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