

Mineral Mapping Using Spectroscopy: From Field Measurements to Airborne and Satellite-Based Imaging Spectrometry

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Abstract

Mineral physics dictate the appearance of rocks and soils across the electromagnetic spectrum. In the Visible/Near-Infrared (VNIR) and Short Wave Infrared (SWIR), many materials absorb radiation at specific wavelengths, allowing their identification by the position and character of absorption features. Electronic processes at wavelengths less ~ 1.0 micrometers allow (in addition to others) identification of minerals containing Fe^{+3} . Molecular vibrational features at wavelengths between ~ 1.0 and 2.5 micrometers are diagnostic of minerals containing anion groups such as Al-OH, Mg-OH, Fe-OH, Si-OH, CO_3 , NH_4 , and SO_4 . Small differences in absorption band position and shape can be correlated with mineral compositional differences and variability. Imaging spectrometry (also known as “hyperspectral imaging” or HSI) has been used since the early 1980s to perform 2-dimensional mapping of mineral distribution based on spectroscopic characteristics. Field spectroscopy plays a critical role in the calibration, analysis, and validation of imaging spectrometer data. Imaging spectrometer datasets have been acquired around the world using airborne platforms and recent satellite systems provide spectral measurements for selected areas. The case history presented shows an example of the progression of imaging spectrometer data to its current state-of-the-art and demonstrates the link between laboratory, field, and imaging spectrometer data.

Introduction

The physics of visible/near-infrared (VNIR) and short-wave-infrared (SWIR) spectroscopy are well known. Key spectral features in these regions allow identification of a variety of materials using laboratory and field spectroscopy, including minerals, vegetation, man-made materials, snow and ice, and water (Clark et al., 2003, 2007). In geology, electronic processes at wavelengths less ~ 1.0 micrometers allow (in addition to others) identification of minerals containing Fe^{+3} , while molecular vibrational features at wavelengths between ~ 1.0 and 2.5 micrometers are diagnostic of minerals containing anion groups such as Al-OH, Mg-OH, Fe-OH, Si-OH, CO_3 , NH_4 , and SO_4 . Small differences in absorption band position and shape can be correlated with mineral compositional differences and variability (Gaffey, 1986; Duke, 1994).

Imaging spectrometry, “*the acquisition of images in hundreds of registered, contiguous spectral bands such that for each picture element of an image it is possible to derive a complete reflectance spectrum*”, is technology that has been available since the early 1980s (Goetz et al., 1985). It has also become known as “Hyperspectral Imaging” or ‘HSI’. Its utility for detailed materials mapping has been demonstrated for a variety of scientific disciplines (Goetz et al., 1985, Kruse, 1988; Hamilton et al., 1993; Clark et al., 1996; Green and Dozier, 1996; Kruse et al., 2006, Kruse and Perry, 2009). Current airborne HSI sensors provide high-spatial resolution (2-20m), high-spectral resolution (10-20nm), and high SNR ($>500:1$) data for a variety of scientific disciplines. AVIRIS: The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) represents the current state of the art. AVIRIS, flown by NASA/Jet Propulsion Laboratory (JPL) is a 224-channel imaging spectrometer with approximately 10 nm spectral

resolution covering the 0.4 – 2.5 micrometer spectral range (Green et al., 1998). The sensor is a whiskbroom system utilizing scanning foreoptics to acquire cross-track data. The IFOV is 1 milliradian. Four off-axis double-pass Schmidt spectrometers receive incoming illumination from the foreoptics using optical fibers. Four linear arrays, one for each spectrometer, provide high sensitivity in the 0.4 to 0.7 micrometer, 0.7 to 1.2 micrometer, 1.2 to 1.8 micrometer, and 1.8 to 2.5 micrometer regions respectively. AVIRIS is flown as a research instrument on the NASA ER-2 aircraft at an altitude of approximately 20 km, resulting in approximately 20-m pixels and a 10.5-km swath width. Since 1998, it has also been flown on a Twin Otter aircraft at low altitude, yielding 2 – 4m spatial resolution. There are also a number of other airborne instruments, both commercial and developed by various governments around the world (http://www.geo.unizh.ch/~schaep/research/apex/is_list.html). The launch of NASA's EO-1 Hyperion sensor in November 2000 marked the establishment of VNIR/SWIR spaceborne imaging spectrometer mapping capabilities. Hyperion is a satellite sensor covering the 0.4 to 2.5 micrometer spectral range with 242 spectral bands at approximately 10nm spectral resolution and 30m spatial resolution from a 705km orbit (Pearlman et al., 2003). Hyperion is a pushbroom instrument, capturing 256 spectra each with 242 spectral bands over a 7.5km-wide swath perpendicular to the satellite motion along an up to 160km path length. The system has two grating spectrometers; one visible/near infrared (VNIR) spectrometer (approximately 0.4 – 1.0 micrometers) and one short-wave infrared (SWIR) spectrometer (approximately 0.9 – 2.5 micrometers). Key Hyperion characteristics are discussed further in Green et al. (2003). Hyperion data are available for purchase from the U. S. Geological Survey (USGS EO-1 Website: <http://eo1.usgs.gov/>). Thousands of Hyperion scenes have been acquired for a variety of disciplines. The EO-1 Science Validation Team has evaluated and validated the instrument. Selected results have been published in various venues (Asner and Green, 2001; Hubbard and Crowley, 2001; Kruse et al., 2003). Also see Ungar (2003) for a summary along with associated papers.

The Role of Field/Laboratory Spectroscopy

Field and laboratory spectroscopy serve several purposes in the context of imaging spectrometry data acquisition and analysis; 1) providing critical information for calibration of data and atmospheric removal, 2) acting as a source of library spectra for comparison to analysis results and identification of materials, and 3) assisting with validation of mapping results.

Calibration and Atmospheric Correction

Atmospheric correction is a requirement for most imaging spectrometer analysis applications. Early efforts at removal of atmospheric effects were empirical in nature, limited by the availability of adequate atmospheric models and correction software. Approaches such as the “flat field correction” and “empirical line correction” utilized information from the imaging spectrometer data themselves and field spectra respectively to estimate the atmosphere (Roberts et al., 1985). More recently, well-calibrated imaging spectrometer data and the availability of MODTRAN-based software such as ACORN, FLAASH, and ATCOR have produced excellent reflectance data without specifically requiring the use of ground spectral measurements (Kruse, 2004). These use water-vapor features near 0.9 and 1.1 micrometers (which are fully resolved using imaging spectrometer data) to estimate water vapor on a pixel-by-pixel basis. The water vapor estimates are used along with data characteristics (band centers, full-width-half-max response) and acquisition parameters (ground elevation, flight altitude, site latitude/longitude, date and time) with an atmospheric model (MODTRAN) to produce a per-pixel reflectance corrected dataset. Field spectra measured for targets occurring in the data still result in improvements, however, when used to refine the atmospheric correction.

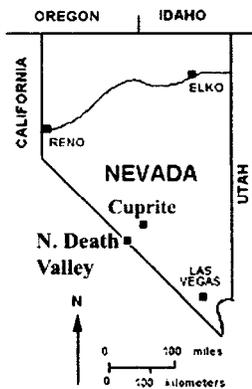
Spectral Libraries

Spectral libraries serve as the reference against which imaging spectrometer data are compared to determine surface composition. There are a variety of spectral libraries available for earth-surface materials (Salisbury et al. 1991; Grove et al., 1992; Clark et al., 2003, 2007; Baldridge et al., 2009). These are principally used for identification of mineralogy, but also contain some spectra of vegetation, man-made materials, snow-ice, and water. There is still considerable need for development of comprehensive spectral libraries that encompass these materials and specifically spectral variability.

Validation of Imaging Spectrometer Mapping Results

Field spectra are most commonly used to validate imaging spectrometer mapping results. A key factor is that the field instrumentation must have at least the same spectral resolution (or better) than the airborne/satellite data. Validation of imaging spectrometer results is complicated by spatial scaling effects. It is very difficult to characterize a surface in terms of the remote sensing footprint (picture element or pixel). Field spectrometers typically measure very small areas (on the order of centimeters), so most commonly, field measurements are made of all of the land surface components and these are compared to what usually amounts to a mixed spectrum from the imaging spectrometer data. It isn't possible to validate every pixel in an image dataset – spot measurements are usually made of key materials in key locations.

Historical Example



An example is presented for a geologic site in northern Death Valley, Nevada, USA to demonstrate the progression of imaging spectrometer capabilities and a selection of results. This site, located in south-central Nevada (Figure 1 at left), was designated part of a U.S. Geological Survey Wilderness Study Area in 1982. The USGS was charged with evaluating the economic mineral potential of the area by characterizing the surface geology, alteration, geologic structure, and existing prospects and claims. Remote sensing technology available at the time (Landsat MSS and TM data) was also used as part of this evaluation. Based on alteration mineralogy at the site, an airborne survey using Geophysical and Environmental Research's (GER's) 64 channel airborne spectral profiler was also flown. Results from the remote sensing analysis, field mapping and field spectral measurements,

laboratory analyses, and ancillary data led to removal of the site from consideration as a WSA in 1984 (Wrucke et al., 1984). Because the site was relatively well understood and mapped, repeated overflights have been made over the site for over 25 years with a variety of remote sensing instruments to evaluate remote sensing technology for resource assessment and to develop advanced analysis methodologies. Remote Sensing data available for the this site include Landsat MSS and TM, Thermal Infrared Multispectral Scanner (TIMS), Modis/ASTER Airborne Simulator data (MASTER), ASTER, JPL Airborne Synthetic Aperture Radar (AIRSAR) and SIR-C. Imaging spectrometer data flown for the site include GER Spectral Profiler (1982), Airborne Imaging Spectrometer (AIS) (1984 - 1986), Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (1987, 1989, 1992, 1994, 1995, 1998, 2000, 2005, 2006), HyMap (1999), and Hyperion (2000, 2004). The following sections describe selected data characteristics, analysis methods, and results – portions of this section have been previously published (Kruse, 1988, Kruse et al. 1999; 2003)

GER Spectral Profiler (1982)

The Geophysical Environmental Research Spectroradiometer (GERS) was an aircraft, non-imaging, spectral profiler (Collins et al., 1981) that collected data between 1.96 and 2.5 μ m in 64 contiguous, 8.6 nanometer-wide channels. A complete spectrum was measured with a 20 meter GFOV at 20 meter

intervals along the flightline. Fifteen flightlines of GERS data (approximately 3,500 spectra) were acquired for the this site during 1982, and color photographs acquired during the flight allowed compilation of a flightline map (Figure 2). The contributions of the atmosphere and the solar spectrum were removed using the IAR Reflectance method (a variation on the Flat Field method, Kruse, 1988) to get to reflectance spectra similar to laboratory measurements. The GERS data were analyzed by extracting individual spectra, preparing stacked spectra images, and along-flightline profiles of the data (Figure 3). Figure 4 shows the interpreted mineralogy overlain on the flightline map and topography (and interpolated between flightlines). The GERS allowed identification of individual minerals and mapping of the general distribution of surface materials. Targets were identified for more detailed study that were not identified in the previous Landsat analysis and subsequent field reconnaissance. The GERS data and basic analysis techniques developed served to demonstrate the utility of high quality aircraft spectrometer data for mineralogical mapping. The results provided sufficient new information that the USGS became involved in the NASA Airborne Imaging Spectrometer (AIS) program.

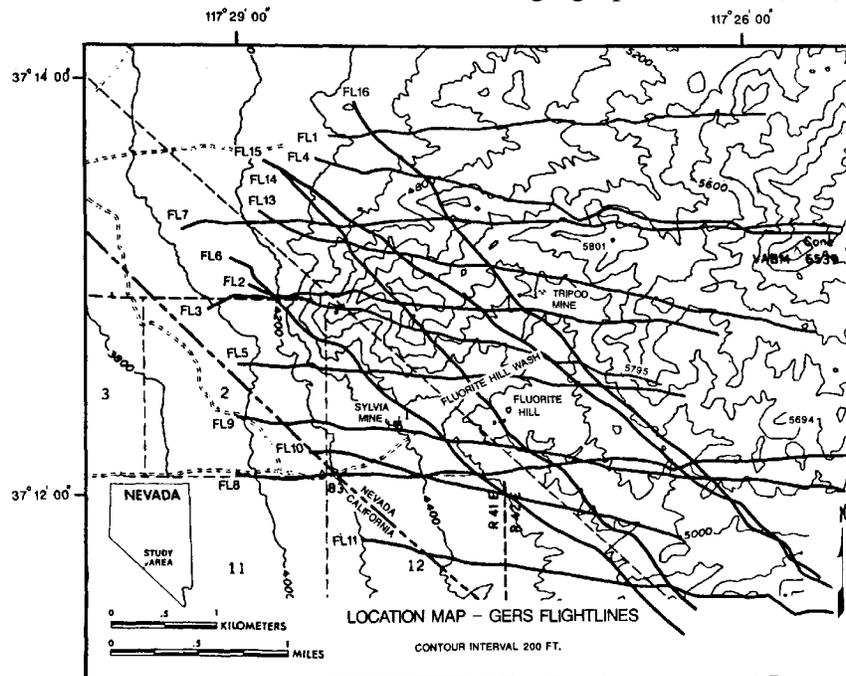


Figure 2: GERS Flightline map for northern Death Valley, NV site.

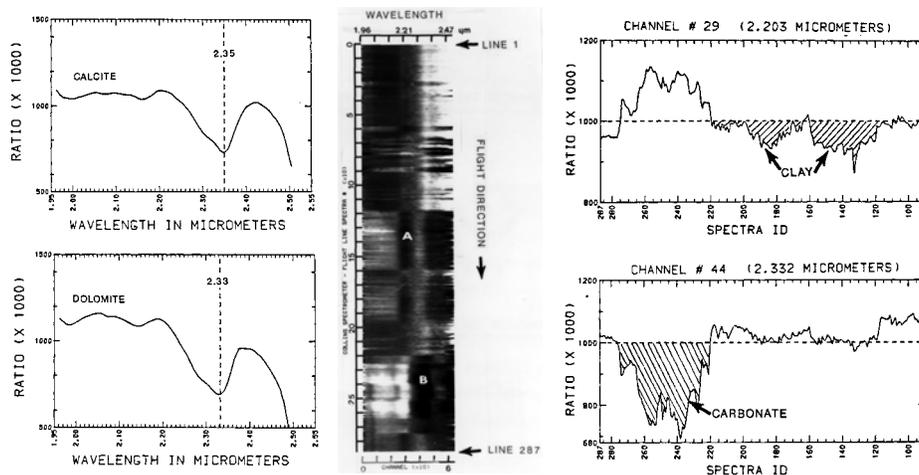


Figure 3: GER spectral plots, stacked grayscale spectra, and flightline profiles for flightline 6.

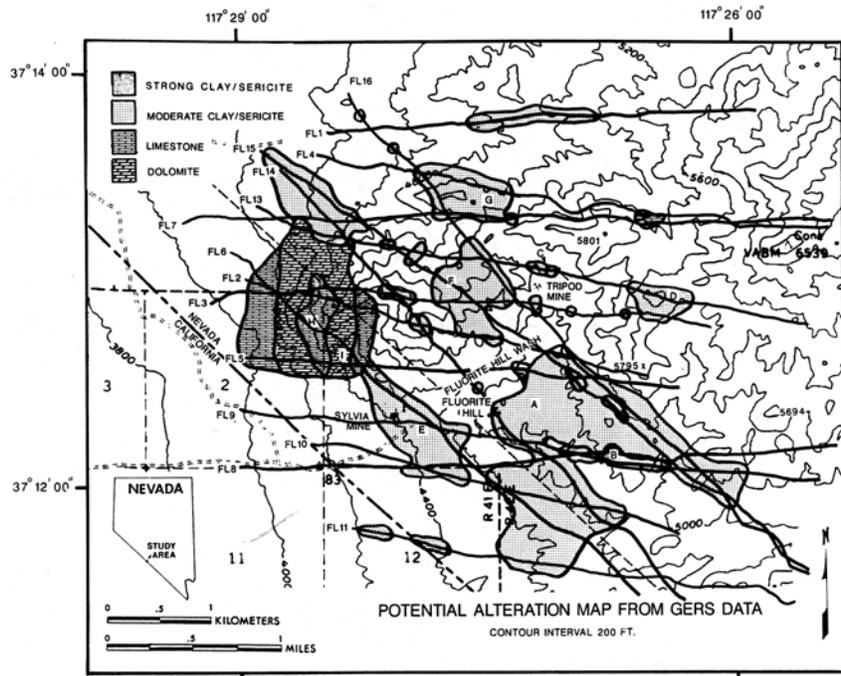


Figure 4: GER Spectral Profiler Interpreted Mineralogy

Airborne Imaging Spectrometer (AIS) (1984 - 1986)

The Airborne Imaging Spectrometer (AIS) was similar to the GERS in spectral resolution (9.3nm cf. 8.6nm) and spatial resolution (10 to 15m cf. 20m) but unlike the GERS the AIS was designed specifically as an imaging device. The AIS was an experimental sensor designed to test two dimensional, near-infrared area array detectors. This instrument imaged 32 (AIS-1, 1983-1985) or 64 (AIS-2, 1986) cross-track pixels simultaneously, collecting data in 128 contiguous narrow (AIS-1 [9.3nm], AIS-2 [10.6nm]) channels from approximately 1.2 to 2.5 μ m (Vane et al., 1983; Goetz et al., 1985; Vane, 1986). The AIS-1 was flown on a NASA C-130 aircraft at an altitude of approximately 4,500 meters above mean terrain, resulting in an average ground pixel size of about 10.9 X 10.9 meters and a swath width of about 350 meters. The AIS-2 was flown at a similar altitude, but the revised instrument characteristics resulted in an average ground pixel of about 14.4 X 14.4 meters and swath width of about 920 meters. Locations of the 1984 through 1986 AIS data registered to a topographic map are shown in Figure 5 (Right).

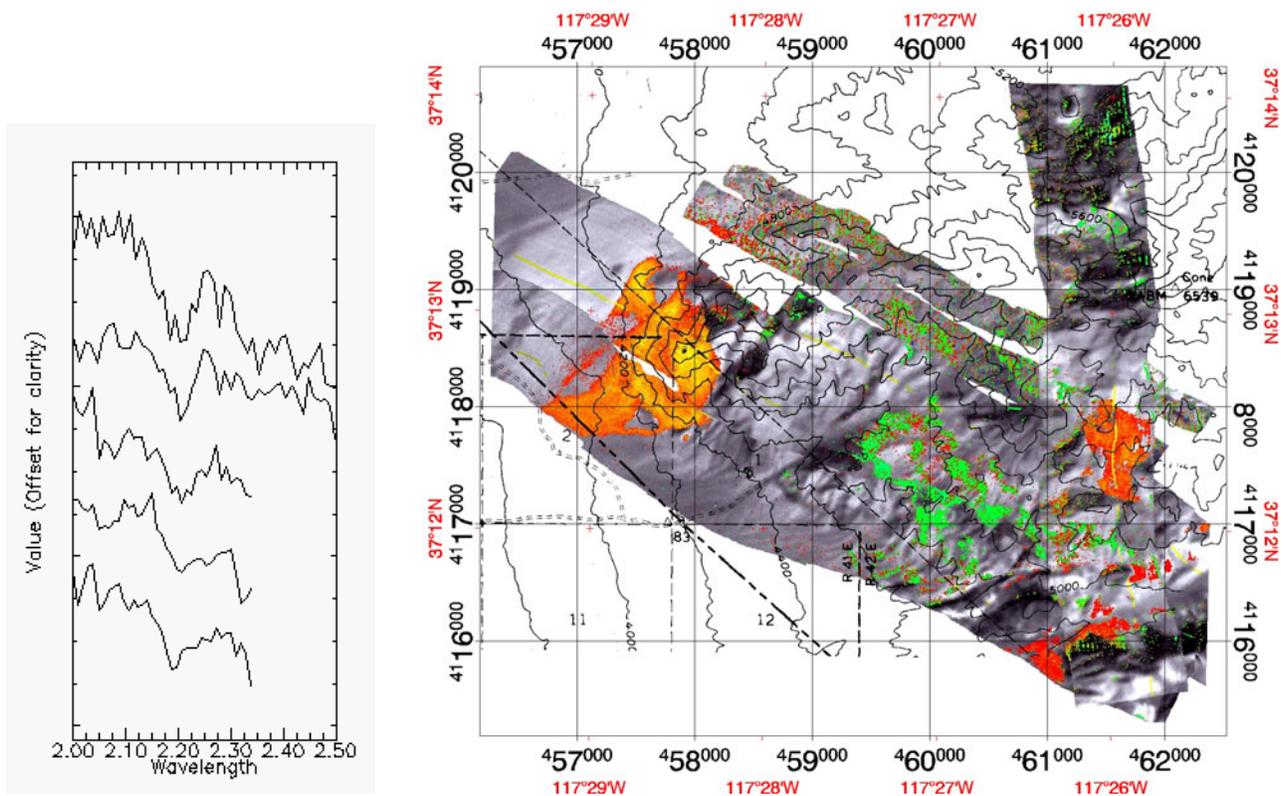


Figure 5: Left: AIS Spectra of the mineral Sericite (Illite/muscovite). Right: AIS Flightlines at northern Death Valley, 1984 – 1986. Mineralogy superimposed – Red=2.35 micrometers (Calcite), Green=2.2 micrometers (Muscovite), Yellow=2.32 micrometers (Dolomite).

The AIS data were calibrated to apparent reflectance using the IAR Reflectance technique (Kruse, 1988). Selected reflectance spectra for 1984 through 1986 data at the northern Death Valley site are shown in Figure 5 (Left). Algorithms were developed to identify automatically the strongest absorption feature in the 2.1 to 2.4 μm portion of each AIS spectrum. Removal of a continuum (Clark and Roush, 1984) was used to place all of the absorption features on a common reference plane. The continuum was calculated using a second order polynomial fitted to selected channels (channels without absorption features) in the relative reflectance spectra. The continuum then was "removed" by dividing the polynomial function into the actual data. A color image showing absorption band information was designed using an intensity, hue, saturation (IHS or "Munsell") color transform (Raines, 1977; Kruse and Raines, 1984; Kruse et al., 1986) to map the three band parameters band position, band depth, and band asymmetry into red, green, blue (RGB) color space (Figure 5, Right). The band depth was mapped into intensity, the band width was mapped into saturation, and the band position was mapped into hue. Transformation of the IHS-encoded spectral information into the RGB color space produced an image in which all of the absorption band information for the strongest absorption feature in each pixel was present in the image colors (Figure 5, Right). The registered AIS images and spectra were used to identify areas for further detailed investigation. Individual spectra and groups of spectra were extracted from the AIS data (Figure 5, Left) and comparisons were made to absorption band parameters extracted from spectra of laboratory standards and to published spectra to identify alteration minerals. An interpretive map of the site mineralogy using the AIS data is shown in Figure 6.

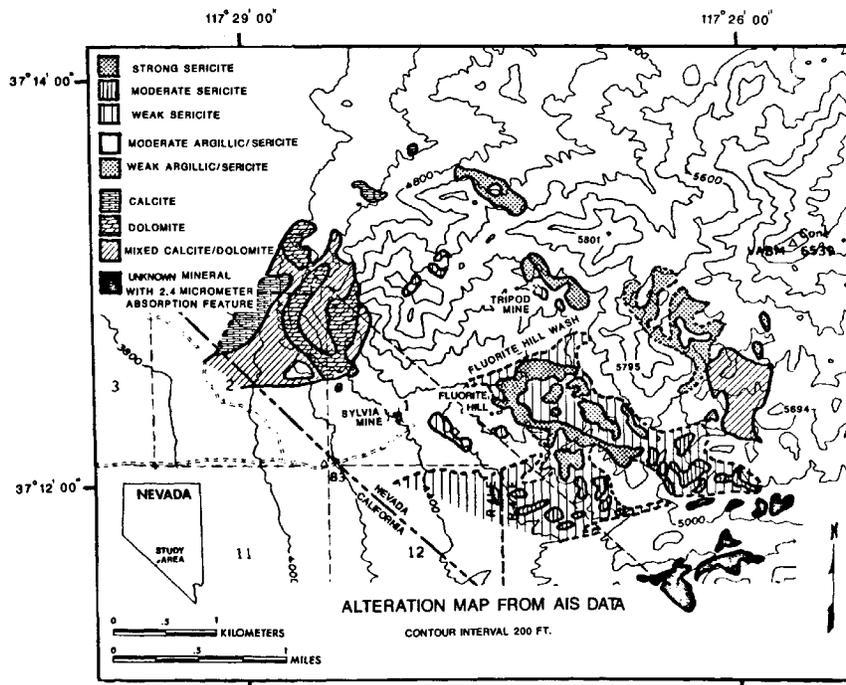


Figure 6: Interpreted alteration mineralogy from AIS data.

The AIS alteration map was field checked during 1986 and generally showed good correspondence with field mapping. Two types of alteration were mapped with the AIS data and subtle differences in surficial mineralogy were observed. Areas of sericite (illite/muscovite) alteration could be identified based upon a strong absorption feature near $2.21 \mu\text{m}$, a weak shoulder near $2.25 \mu\text{m}$, a weak absorption band near $2.35 \mu\text{m}$ and an additional weak band near $2.44 \mu\text{m}$. In one area of weakly sericitized rock, X-ray diffraction analysis demonstrated that the predominant soil clay mineral was montmorillonite. Although this soil contained less sericite than montmorillonite, the spectral character of the sericite dominated the near-infrared spectra and montmorillonite was not identified using field, laboratory, or aircraft spectra; X-ray diffraction was required to identify the montmorillonite. Areas of argillic alteration were identified by the presence of a weak to moderate absorption feature near $2.21 \mu\text{m}$ caused by montmorillonite; identification of montmorillonite was possible only when no masking minerals (such as sericite) were present. Calcite and dolomite were identified based on a sharp absorption feature near 2.34 and $2.32 \mu\text{m}$, respectively, and other weak absorption features that are at shorter wavelengths in the dolomite spectra than in the calcite spectra. Fan gravels derived from both dolomite and limestone bedrock have shallow, broad absorption bands near $2.34 \mu\text{m}$; these bands resemble those for calcite rather than dolomite. The position of the absorption feature in the fan gravels (near $2.34 \mu\text{m}$ regardless of provenance), may be caused by a shift towards calcite composition in the development of soil. Isolated spectra having some characteristics of skarn minerals, such as epidote, tremolite, and actinolite, were observed in the AIS data but could not be confirmed independently. An unknown $2.4 \mu\text{m}$ mineral (later lab verified via X-Ray diffraction as Zeolite) was also mapped using the AIS data (Kruse, 1988).

Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (1987 – Present)

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) became operational in 1987. AVIRIS measures near-laboratory-quality spectra in 224 10 nm-wide channels in the spectral range 0.41 to 2.45 μm (Porter and Enmark, 1987). From 1987 – 1998, AVIRIS was flown aboard the NASA ER-2 aircraft at an altitude of 20 km, with an instantaneous field of view of 20 m and a swath width of about 10 km. Subsequent flights have been flown mostly on a Twin Otter aircraft with pixels sizes on the order of 2m.

AVIRIS data for the site were initially obtained during May 1987, however, with very poor signal-to-noise performance. After enhancements to the instrument, data were again acquired in 1989 with signal-to-noise ratios of approximately 50/1 at 0.70 μm and 20/1 at 2.20 μm for targets with reflectances of 0.5 (Kruse, unpublished data). The Spectral Image Processing System (SIPS) (Kruse et al., 1993b) was used to preview the AVIRIS radiance images and to extract image radiance spectra for calibration. The data were calibrated to apparent reflectance using ground targets and the empirical line method (Ballew, 1975, Roberts et al, 1985; Kruse et al., 1993a). Once the data were calibrated to reflectance, interactive analysis using SIPS was used to determine the principal minerals at the surface. Extraction of average spectra from areas with spectral character allowed comparison to library spectra of specific minerals for identification. A simple, commonly used method for analysis of imaging spectrometer data, binary encoding and spectral matching using a reference library (Mazer et al, 1988) was used to make mineral maps. The binary encoding method was selected for analysis of the 1989 AVIRIS data because it is robust in the presence of noise. Laboratory spectra for calcite, dolomite, illite (sericite), hematite, and goethite were used as references for the classification. The 2.0 - 2.4 μm region was selectively used for the carbonates and sericite, while the 0.4 - 1.0 μm range was used for the iron oxide minerals. These regions were chosen for encoding because of observed diagnostic spectral characteristics limited to these wavelength ranges of the spectrum. Selected examples comparing Fe Oxide spectra from the AVIRIS data to those in the spectral library are shown in Figure 7. Analysis results for these data have been published in Kruse et al., 1993a.

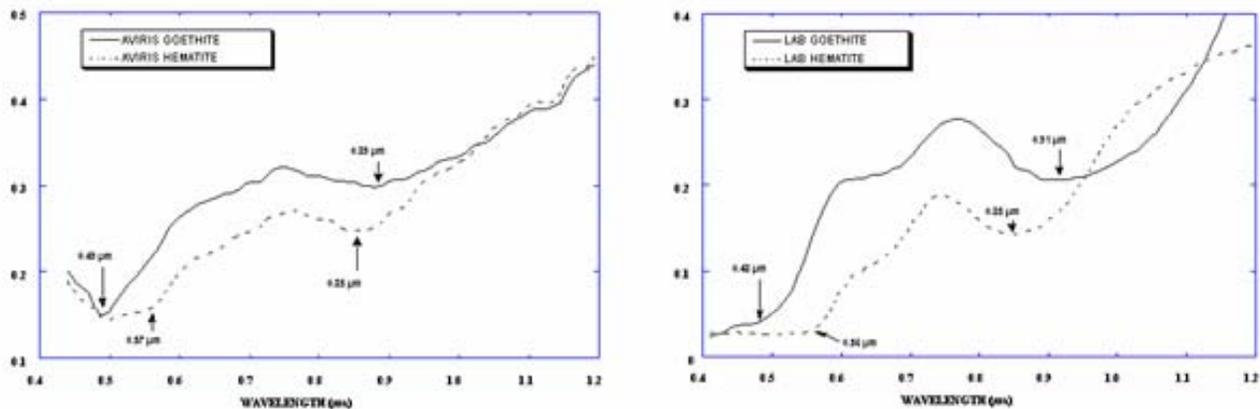


Figure 7: AVIRIS spectra for Hematite and Goethite compared to laboratory spectra

Additional AVIRIS datasets were acquired in 1992, 1994, 1995, 1998, 2000, 2005, and 2006). As the sensor matured, SNR improved, and new atmospheric correction capabilities were developed, additional detailed mapping was possible. Boardman and Kruse, 1994 and Boardman et al., 1995 summarize a comprehensive methodology for analyzing imaging spectrometer data. These methods rely on atmospherically corrected data and concentrate on finding the key endmember spectra defined by the data space, identifying them, mapping their spatial distributions, and quantifying abundances for each pixel. Approaches used include algorithms such as the Spectral Angle Mapper (SAM) (Kruse et al.,

1993b; Boardman, unpublished data), an expert system approach (Kruse et al., 1993a, Kruse 2008), and spectral unmixing (Boardman, 1989, 1993) (Figure 8).

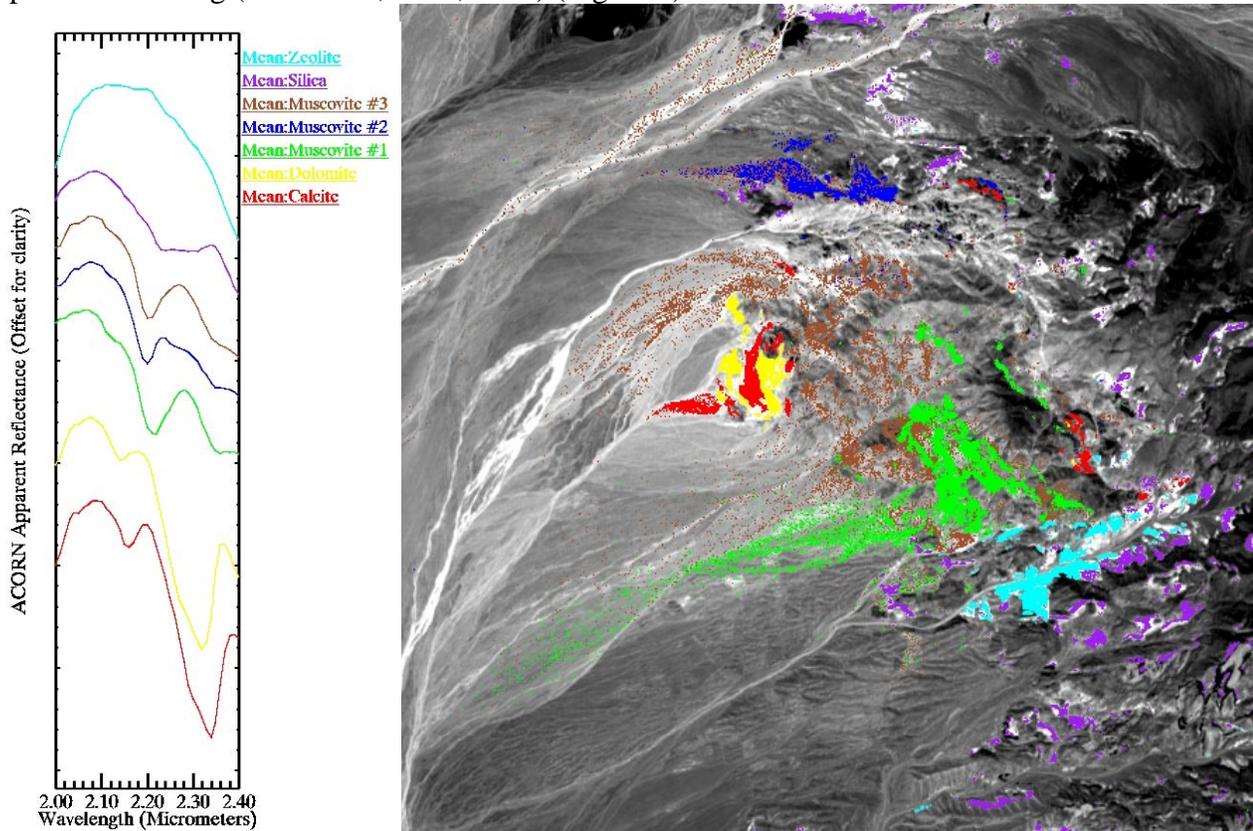


Figure 8: Left: Endmember spectra extracted from the AVIRIS data collected June 9, 2000. Right: Mixture-Tuned Matched Filtering (MTMF) Mineral mapping results for the June 9 2000 AVIRIS (15m) data utilizing the endmember spectra at left.

Analysis of the 1989 – 2006 AVIRIS confirmed and refined the zoned alteration patterns at the site, including the predominance of quartz-sericite-pyrite alteration. The AVIRIS data confirmed separation of calcite and dolomite based on a 10 nm band position shift and allowed identification of some skarn mineralization as well as confirming zeolite identification and distribution. AVIRIS data also showed that goethite is generally associated with intruded, altered rocks and with Ag-bearing veins, while hematite is generally associated with later volcanic rocks. The 1992 and 2006 data also confirmed that several sericite (illite/muscovite) endmembers exist and allowed expansion of the study to a larger area.

The ability to map materials at the sub-pixel level was also clearly established with the 1995 AVIRIS data. Several areas of subpixel dolomite occurrence were selected from the 1995 results for field checking. Boardman and Kruse located these subpixel occurrences in the field, and verified their mineralogy using a field spectrometer. Figure 9 shows two sub-pixel outcrops of dolomite at the approximately 3% and 1% levels respectively.



Figure 9: Field verification of spectral mixing results. Left photo shows an approximately 3 x 3 meter outcrop (3% of a pixel) of dolomite found using sub-pixel detection. Right photo shows approximately 1 x 3 meter outcrop (1% of a pixel) of dolomite.

EO-1 Hyperion (2001 and 2004)

Hyperion data were acquired for the northern Death Valley site during 2001 and 2004. The same standardized imaging spectrometer data processing methods applied to the AVIRIS data were applied to the Hyperion data, leading to the definition of a similar set of specific key minerals (Figure 10).

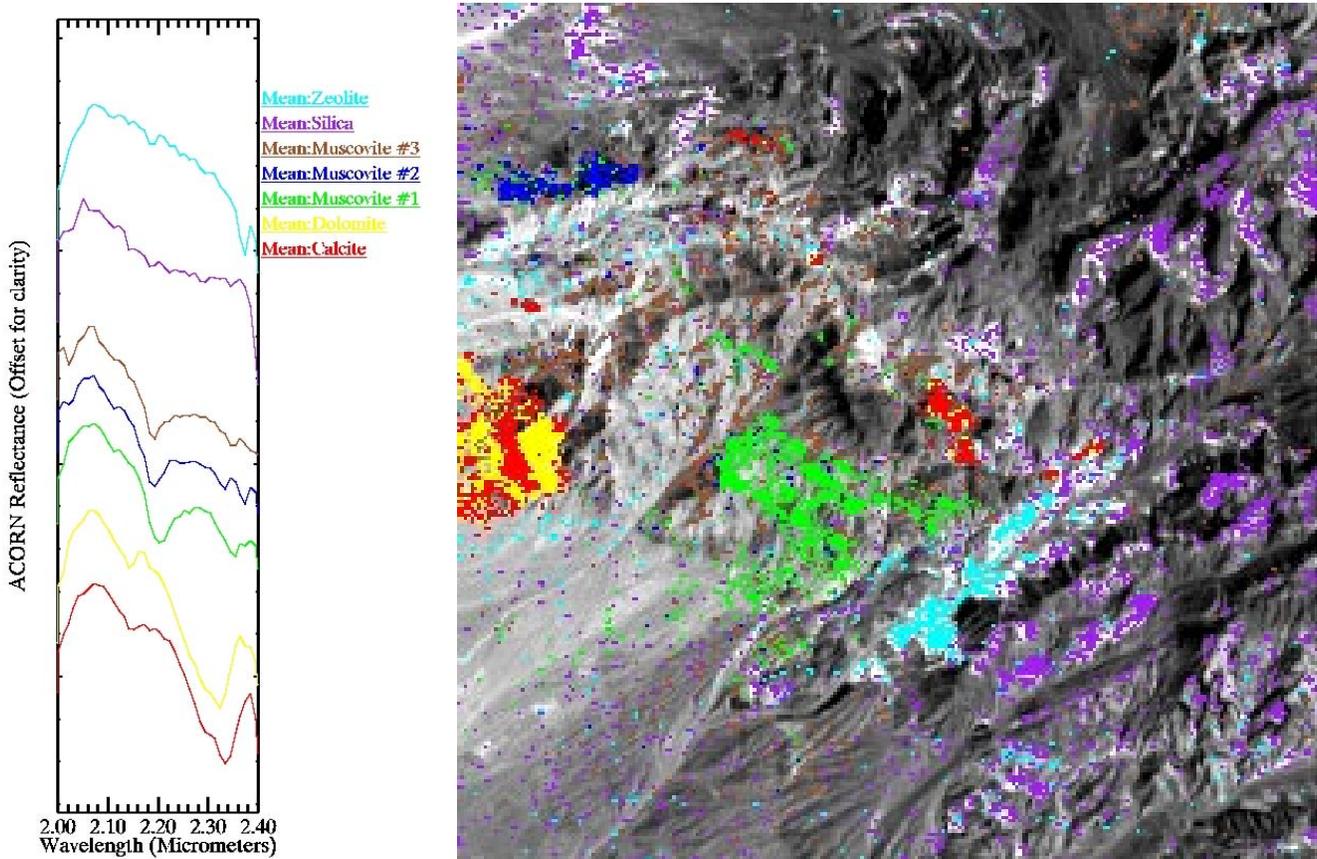


Figure 10: Left: Endmember spectra extracted from the Hyperion (29m) data collected July 23 2001. Right: Mixture-Tuned Matched Filtering (MTMF) Hyperion Mineral mapping results utilizing the endmember spectra at left.

It was, however, more difficult (than for AVIRIS) to extract the information because of the Hyperion data's lower SNR. The effect of this reduced response compared to AVIRIS is lower data dimensionality; thus, fewer endmembers can be identified and mapped than with AVIRIS. Accuracy assessment and error analysis indicates that with Hyperion data that, in many cases, mineral identification is not possible where specific minerals are known to exist (Kruse et al., 2003). In addition, Hyperion often confuses similar minerals that are separable using AVIRIS. Note that some of the differences could also possibly be attributable to spectral mixing due to differences in pixel size (approximately 30 m for Hyperion versus approximately 15 m for AVIRIS), which cause slight loss of spatial detail in Hyperion results. Comparison of Hyperion results to the known mineralogy derived from the AVIRIS data (and verified in the field using field spectrometry and in the laboratory using X-Ray diffraction) generally validate on-orbit mineral mapping and Hyperion performance (Kruse et al., 2003).

Summary and Conclusions

Laboratory and field spectroscopy form the basis for imaging spectrometry analysis for a wide variety of disciplines. Geologic materials are well characterized, extensive spectral libraries exist, and there is a good understanding of the nature and source of spectral features in rocks and minerals in the VNIR/SWIR. There is a requirement, however, for additional spectral measurements in support of calibration and atmospheric corrections, for further understanding spectral variability and mixtures, and for field validation of analysis results. A summary of imaging spectrometer data and processing from 1982 to present at a site in the northern Death Valley region, Nevada, USA, serves to illustrate the advances made in imaging spectrometer sensor systems and analysis algorithms over the last approximately 25 years. Availability of high quality reflectance spectra for mapping began with the GERS spectral line profiler. This instrument produced data with an excellent SNR that demonstrated the potential of the technology. The AIS system, an area-array imaging spectrometer, provided the first imaging spectrometer images of the area, but detector and software limitations made analysis of these data difficult and lack of complete spatial coverage prevented full understanding of the hydrothermal system. Good-quality AVIRIS data became available in 1989 and were subsequently acquired through the 1990s and between 2000 and 2006. Each improvement to the sensor required that additional analysis techniques be developed and each improvement in the algorithms spurred further sensor improvements. The AVIRIS system has now progressed to the state where it can be used to produce laboratory quality spectra without any ground measurements. The net result of repeat acquisitions at this site and others was that AVIRIS became an operational system capable of producing detailed geologic and alteration maps that could not be obtained by any other means. The advent of the Hyperion spaceborne system demonstrated the viability of imaging spectrometers in space, but also the importance of high SNR performance for extraction of high-quality reflectance spectra. There are a number of planned satellite systems that will build on this technology to provide widespread imaging spectrometer data for important Earth observation tasks.

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