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TODD O. MORKEN

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Spectir And SEBASS Analysis Of The National Mining District, Humboldt County, Nevada

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Dr. Wendy Calvin, Advisor

Dr. Jim Taranik, Committee Member

Dr. Danny Taylor, Graduate School Representative

Marsha H. Read, Ph. D., Associate Dean, Graduate School

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Abstract

The purpose of this study was to evaluate the minerals and materials that could be uniquely identified and mapped from measurements made with airborne hyperspectral SpecTIR VNIR/SWIR and SEBASS TIR sensors over areas in the National Mining District. SpecTIR Corporation and Aerospace Corporation acquired Hyperspectral measurements on June 26, 2008 using their ProSpecTIR and SEBASS sensors respectively. In addition the effects of vegetation, elevation, the atmosphere on spectral measurements were evaluated to determine their impact upon the data analysis and target identification. The National Mining District is located approximately 75 miles northeast of Winnemucca, Nevada at the northern end of the Santa Rosa Mountains. Precious metal mining has been dormant in this area since the 1940’s, however with increased metal prices over the last decade economic interest in the region has increased substantially. Buckskin Mountain has a preserved alteration assemblage that is exposed in topographically steep terrain, ideal for exploring what hydrothermal alteration products can be identified and mapped in these datasets. These Visible Near Infrared (VNIR), Short Wave Infrared (SWIR), and Long Wave Infrared (LWIR) hyperspectral datasets were used to identify and map kaolinite, alunite, quartz, opal, and illite/muscovite, all of which are useful exploration target identifiers and can indicate regions of alteration. These mapping results were then combined with and compared to other geospatial data in a geographic information systems (GIS) database. The TIR hyperspectral data provided significant additional information that can benefit geologic exploration and demonstrated its usefulness as an additional tool for geological exploration.
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CHAPTER 1: Introduction

Nevada has had a rich mining history since the 1860’s and is the nation’s highest producer of gold, silver, barite, lithium and mercury and a leading producer of geothermal energy as well (Price, 2004). Nevada has a high concentration of extensional geothermal resources and annually produces over $100 million dollars worth of geothermal power and $3 billion dollars of mineral production. Gold production in Nevada accounts for over 75% of the total United States production and approximately 10% of world production (Price, 2004). Prices for all of these materials have been increasing significantly over the past two decades. Currently prices for gold and silver have more than tripled in the last 10 years alone.

We are in the midst of one of the largest gold and precious metal mining booms in history and this has inspired a new flourish of interest in exploration for these minerals and resources. As the world population increases, global demand for these minerals is also expected to increase. With gold and silver prices rising at a near exponential rate there is both a need and motivation for finding new potential deposits of these precious minerals. In addition to exploring for new deposits, there is also increased interest in re-evaluating old mines previously taken out of production, as the National Mining District was in the 1940’s, due to unprofitability. Gold prices have increased by over 450% in the last 10 years and those resources once thought unprofitable to mine may be well worth renewed evaluation for development in the current and future precious metals market.

The term “Remote Sensing” refers to methods of using electromagnetic energy
(heat, light, and radio waves) as a means of measuring and detecting target spectral characteristics without being in physical contact with the target (Sabins, 1978). Optical multispectral (several wavelength channels) remote sensing has been available since the 1970’s and has been used successfully for a variety of purposes from geologic to military applications. Hyperspectral (hundreds of wavelength channels) data was first collected as the Airborne Imaging Spectrometer by the Jet Propulsion Laboratory of the California Institute of Technology in 1983 and is less abundant than multispectral data and less frequently used due to its higher cost and reduced spatial ground coverage (Crosta, 1998). Hyperspectral thermal datasets are even more rarely acquired than visible and near infrared datasets. However, to its advantage, hyperspectral data has greatly increased spatial and spectral resolution potentially providing an increased level of spectral measurement, material detection, and mapping delineation over multispectral data.

A multitude of rock forming and alteration minerals have wavelength-dependant absorption features that are diagnostic in various ranges of the electromagnetic spectrum (Green et al., 1998; Hunt, 1977; Salisbury, 1991). The spectra variations of many of these minerals in the visible, near infrared, mid-infrared, and thermal wavelengths are well characterized from previous work, though fewer studies have involved work with hyperspectral thermal datasets (Collins, 1991). In the past, the Visible Near Infrared (VNIR) and Shortwave Infrared (SWIR) data have been typically analyzed and treated separately from Thermal Infrared (TIR) data. However, using the two in combination allows for the identification and mapping of a wider range of minerals and mineral assemblages (Vaughan, 2005). Many of the absorption spectra for the minerals that result from hydrothermal alteration processes also have diagnostic spectra in
hyperspectral VNIR/SWIR/TIR data.

On June 26, 2008, hyperspectral VNIR/SWIR and TIR datasets were collected over the National Mining District located northeast of Winnemucca, Nevada. This was one of the first joint collections where both the SpecTIR VNIR/SWIR sensor and the SEBASS TIR sensor were placed in the same roll-stabilized mount in a Twin Otter aircraft and data from both sensors were collected at the same time along the same flight line. Usually hyperspectral VNIR/SWIR and TIR data are collected at different flight times, with spatial variation in areal coverage. The co-acquisition of this dataset makes them ideal for comparisons between the spectral ranges and to enhance the final result.

**The purpose of the study is to:**

(1) Evaluate what minerals and materials can be individually and uniquely identified and mapped from the hyperspectral SpecTIR VNIR/SWIR and SEBASS TIR datasets in the National District.

(2) Compare and contrast what is gained from the VNIR/SWIR and TIR datasets. Are their results redundant or does each bring something useful to mineral identification and mapping?

(3) Evaluate how and if it’s possible to improve the results through additional field sampling, and improved atmospheric correction techniques.

(4) Investigate the potential analysis complications of remote sensing in a region with moderate vegetation and significant elevation changes.

(5) Integrate results of the mapping with other spatial information into a professional Geographic Information Systems (GIS) map product that can be
integrated with both additional GIS data and remote sensing future results.

The goal of this research was to determine if the analysis of VNIR/SWIR and TIR data could provide useful and meaningful geologic information that can benefit mineral exploration while examining some of the potential complications using remote sensing in a moderately vegetated environment with high relief. It was neither expected nor likely to replace competent fieldwork by an exploration geologist, but merely demonstrate its usefulness as an additional tool not only for new exploration, but also to aid in the reevaluation and potential development of previously abandoned resources that may again be highly profitable in the current economic climate.
Chapter 2: Geologic Background

Regional Geology 2.1

The National Mining District is contained within the Great Basin drainage system. The Great Basin is the largest single watershed in the United States that has no outlet to an ocean. It encompasses most of the state of Nevada, and parts of California, Oregon, Idaho, and Utah. The Colorado Plateau and Wasatch Mountains in Utah surround the entire basin to the east, to the west by the Sierra Nevada Mountains, to the North by the Snake River Plain in Idaho, and to the south by the Mojave Desert (Figure 2.1). As a result of these surrounding barriers, all precipitation either drains to a series of inland lakes and playas where it evaporates or enters into various regional groundwater systems.

Since almost the entire Great Basin watershed lies within the Basin and Range providence, it is naturally dominated by Basin and Range topography. Basin and Range topography is characterized by active faults of which every north-south trending mountain range in the region is bounded by on at least one side. Over millions of years, these faults raised the mountains and dropped the valleys, that subsequently were filled in by erosional material. In some cases, these valleys are filled with sediments thousands of feet thick. In Nevada, which is the third most seismically active state in the United States, many of these range-bounding faults are normal and still active to present-day (Price, 2004). These mountain ranges in Nevada are usually not longer than 80 miles, and are separated by parallel valleys (Price, 2004).
2.2 National Mining District Geology

The National Mining District is located approximately 75 miles northeast of the city of Winnemucca in north central Nevada (Figure 2.1). It is contained within the northernmost part of the Santa Rosa Mountains, which structurally represent a north-south trending fault block and borders the western edge of the Goosey Lake Depression (Vikre, 2007). The National District has high relief with elevations in the district ranging from just over 4000 feet to over 8700 feet at Buckskin Mountain summit. This region also outlines the estimated southernmost extent of the McDermott caldera system. The volcanic layers in the district dip gently into this depression, a 15 to 20 mile wide volcanic basin to the southwest (Vikre, 1986). This volcanic basin is hypothesized to
have resulted from subsidence due to the removal of magma during volcanic eruptions that have deposited lava throughout the region.

Many ore deposits in northern Nevada are due to igneous activity, with metals coming from the magma itself or magma bodies providing heat to circulate metal-rich fluids (Price, 2004). The National District is an example of this type of metallogenesis; a large magma chamber is believed to be responsible for providing the heat that caused the hydrothermal fluids to circulate in the district, in some areas depositing metal-rich material. There is evidence that sinter formed at the paleosurface with disseminated gold and high grade gold and silver veins formed lower in the system beneath the surface (Wallace, 2003). The National District is considered a low-sulfidation epithermal deposit with reduced neutral pH fluids. This makes the relationships between the magma body chemistry and the resulting epithermal deposit less obvious because meteoric waters typically dominate the hydrothermal fluids (Simmons, 1995).

Basement rocks in the region are composed of Triassic-Jurassic age metasedimentary rocks represented mostly as phyllite at outcrops to the southwest. These basement rocks are overlain by up to 3000 feet of volcanic and intrusive rocks. The volcanic units are Miocene in age and range in composition from basalt to rhyolite. These mid-Miocene volcanics are common throughout much of Northern Nevada and are hypothesized to be directly related to the Yellowstone hot spot (Pierce and Morgan, 1992). During 17-14 Ma much of northern Nevada was characterized by bimodal basalt-rhyolite volcanism along with extensional faulting and sedimentation (John, 2001). Figure 2.2a shows a proposed representation of a bimodal basalt-rhyolite assemblage common to the northern Great Basin.
While the volcanics do vary in composition, andesite and rhyolite dominate, while lesser amounts of dacite, quartz latite, and basalt exist as well. Premineralization flows are comprised mostly of andesite with some dacite, basalt, quartz latite, and rhyolite flows, which have a maximum thickness of 150 feet per individual flow event (Vikre, 1985). The presence of easily identified flow tops, thin tuff layers interbedded between flows, and conformable flow units suggest they were emplaced within short intervals of geologic time of each other. All volcanic flows are nearly void of phenocrysts and thin section analysis shows that many of the flows in the district display significant alteration (Vikre, 1985).

![Bimodal Basalt-Rhyolite Magmatic Tectonic Setting](image)

**Figure 2.2a:** Bimodal basalt-rhyolite magmatic tectonic setting - (John, 2001).

Much of the district has been hydrothermally altered to various vein mineralization and all productive veins tend to be along the north-south trending faults.
and parallel range fronts to the west. Many of the dikes in the region also appear to trend north-south. East-west trending faults show no significant mineralization in the district. Displacement along these faults rarely exceeds several hundred feet and when east-west faults intersect north-south faults they appear to be the younger of the two (Vikre, 1985). Figure 2.2b displays a structural interpretation of the district produced by Vikre in 1985 and Figure 2.2c shows a geologic map also produced by Vikre.

The mines in the National Mining District produced approximately 200,000 ounces of gold and 750,000 ounces of silver during 1906-1941 (Vikre, 1987). However, those numbers are not well verified and there may be significant deviation from the actual production. Little official documentation has survived; so exact production numbers are not available, only secondhand estimates. In addition, there was minor mercury production from cinnabar deposits at the summit of Buckskin Mountain (Vikre, 1985). Since the early 1940’s there has been no significant production from the area and the old underground workings are inaccessible.

2.3 Buckskin Mountain Geology

Buckskin Mountain is of particular interest for various studies because it contains a virtually complete preserved hydrothermal alteration assemblage that is delineated by elevation and exposed at the surface (Vikre, 1987). The currently exposed summit surface of Buckskin Mountain represents a Miocene paleosurface of an environment that is similar to present-day Yellowstone. The sinter deposits at the summit at one time were exposed hot spring pools and now have created an erosion-resistant surface that over time, as the rest of the region eroded, have exposed what represents a well-persevered
fossilized hydrothermal system. Figure 2.3 shows a northeast-facing photo of Buckskin Mountain. While this region gains most of its precipitation from snowmelt, this picture also shows there is significant vegetation cover in the district as well.

Figure 2.2b: Structural map of National Mining District – (Vikre, 1985).
Figure 2.2c: Geologic map of the National Mining District, grey box indicates remote sensing data collection area – (Modified from Vikre 1985).
The proposed duration of the hydrothermal system that altered Buckskin Mountain is from 50,000 to 200,000 years (Vikre, 1985). The minimum for this estimate was based on the thickness of the sinter layer still in place (~100 feet) using estimates of sinter formation from modern day analogs. The maximum duration was determined using heat and water flow values using an estimated magma reservoir that the current geology could have supported. Using this information, Vikre also estimated the size of the magma body that drove the hydrothermal events at Buckskin Mountain was approximately 0.8 to 1.6 cubic miles (Vikre, 1987).

Figure 2.3: Photo facing northeast toward Buckskin Mountain.
Buckskin Mountain exhibits hydrothermal alteration by two main fluid events. The first event had fluid temperatures from 295° to 250° C and caused the brecciation of some units of rhyolite in the area. In the second event, fluid temperatures varied from 100° C at the paleosurface to 250° C at depth (Vikre, 1995). These fluid temperature estimates were evaluated primarily from fluid inclusion studies. Fluids from the second event at temperatures of approximately 250° C at depth emplaced the gold and silver deposits by precipitation at an estimated pressure of 40 bars (Vikre, 1985). In the case of Buckskin Mountain, there were two main sources of hydrothermal fluids. Fluid inclusion studies from drill core samples indicate that the deepest source fluids, located from 1200 to 2400 feet below the estimated paleosurface, were composed of a deep quartz fluid and the hydrothermal fluids above that zone to the paleosurface were a mixture of deep quartz fluid and Miocene ground water (Vikre, 1987). Productive veins and some of the intrusive rocks at Buckskin Mountain have been localized by orthogonal faults that are related to larger scale basin and range structures in the region (Vikre, 1986).

The productive veins of the region are dated at approximately 15 Ma and are associated with intrusive rhyolite volcanics in the district (Vikre, 1985). The National and Birthday veins were the most productive and at times yielded an ounce of gold per pound of ore in the electrum drift of the National vein. However, silver was the major component from which most of the veins derived their value (Vikre, 1985). Expected minerals in the region are: kaolinite, chlorite, illite, cinnabar, pyrite, stibnite, alunite, barite, calcite, electrum, quartz, and sinter in varying abundances. No placer gold deposits have been found in any of the National District drainages (Vikre, 1985).
Vikre identified four stages of hydrothermal alteration at Buckskin Mountain, using sample and drill core data. However, not all stages or their minerals exhibit significant surface exposure, therefore not all stages or their alteration products would be expected to be identified and delineated in the hyperspectral datasets. Stage 1 is quartz and the oldest hydrothermal stage, which is restricted to elevations less than 7000 feet. Stage 2 is banded quartz + silver sulfides-selenides + electrum and is restricted to elevations from 6400 feet to 8000 feet. Stage 3 is massive sulfide + chalcedony and Stage 4 is silica + stibnite above 7300 feet of elevation. In addition to the four stages, chalcedonic silica + quartz + cinnabar caps Buckskin Mountain with a summit elevation of 8743 feet.
3.1.1 Electromagnetic Radiation

Electromagnetic radiation refers to a phenomenon of self-propagating waves composed of orthogonally orientated electric and magnetic fields. This energy moves in a harmonic wave pattern traveling at the velocity of light (Sabins, 1987). Commonly, many of the properties of electromagnetic radiation are defined and described by wave theory; however, particle theory suggests electromagnetic radiation is made up of photons (Lillesand, 1987). The energy of these photons is inversely proportional to their wavelength so that longer wavelengths contain less energy. Wave theory describes how electromagnetic energy propagates; however, the energy itself can only be detected as it interacts with matter (Sabins, 1987). It is in this later process that remote sensing instruments are able to detect and measure electromagnetic radiation. Figure 3.1.1a shows the components of an electromagnetic wave.

Figure 3.1.1a: Diagram of electromagnetic wave – (modified from Lillesand, 1987).
Before electromagnetic radiation interacts with matter it is referred to as *incident* radiation. This interaction between radiation and matter can result in five possible processes: transmission, absorption, emission, scattering, and reflection (Sabins, 1987). Figure 3.1.1b shows a diagram of these possible interactions. These five types of interactions are classified into two categories; emission, scattering and reflection are surface phenomena, and transmission and absorption are volume phenomena (Sabins, 1987). More than one of these processes occurs simultaneously when solar radiation is incident upon a surface and each process can be affected by the composition and physical properties of the surface, the wavelength of the incident radiation, and the potential interaction of these processes with each other.

**Figure 3.1.1b:** Interactions of incident radiation with matter – (modified from Sabins, 1987).

### 3.1.2 Electromagnetic Spectrum

In remote sensing, electromagnetic radiation is typically referred to and classified by either its frequency or wavelength (Lillesand, 1987). The visible and reflected light
regions used for this study includes the Visible Near Infrared (VNIR), with wavelengths ranging from 0.4 to 1.0 µm and the Short Wave Infrared (SWIR), ranging from 1.0 to 2.5 µm (Clark, 1999). The thermal infrared region used includes the Long Wave Infrared (LWIR) region ranging from 8 to 16 µm. Figure 3.1.2a shows a diagram of the entire electromagnetic spectrum.

Figure 3.1.2a: Electromagnetic spectrum. Wavelength regions used for this study include the VNIR(0.4-1.0 µm), SWIR (1.0-2.5 µm), and LWIR (8.0-16.0 µm).

Absorption and scattering of electromagnetic radiation from the sun as it passes through the atmosphere is one of the largest limiting factors in terrestrial remote sensing. Atmospheric gasses such as ozone (O₃), oxygen (O₂), carbon dioxide (CO₂), and water
vapor (H₂O) and solid particles suspended in the atmosphere (aerosols) create regions that are effectively opaque to incoming radiation by attenuating and scattering certain wavelengths (Clark, 1999). Large continuous regions of the electromagnetic spectrum that have high transmission of solar radiation, ideal for remote sensing data acquisition, are referred to as atmospheric windows (Lillesand, 1987). Figure 3.1.2b shows a diagram of atmospheric transmission in the electromagnetic spectrum.

![Atmospheric transmission windows](image)

**Figure 3.1.2b:** Atmospheric transmission windows - (Sabins, 1987).

### 3.2.1 VNIR, SWIR, and LWIR Mineral Spectroscopy

The interaction of electromagnetic radiation incident upon matter activates electronic and vibrational processes from within that matter. These processes in turn create the spectral minima seen in hyperspectral data (Clark, 1999). The dominating electromagnetic absorption process is the fundamental vibrational node and is responsible for the absorption features seen in the LWIR. Electronic processes are responsible for absorption features in the VNIR and combinations and overtones from the fundamental vibrational nodes are responsible for SWIR absorption features. Many of the minerals
resulting from hydrothermal alteration display diagnostic absorption features in the VNIR, SWIR, and LWIR regions of the electromagnetic spectrum due to these processes.

The location and depth of the absorption features is directly influenced by the mineral’s molecular structure, bonding, and chemical composition. Surface roughness, grain size, mineral mixtures, atmospheric effects, and changes in viewing geometry all can affect measured spectral signatures as well (Clark, 1999). The result of all of these possible processes and combinations can cause significant complexity in a mineral’s spectral signature. Some of these minerals and the processes responsible for their diagnostic absorption features are discussed in further detail in the following sections.

3.2.2 Electronic Processes

Electronic processes are caused by isolated ions and atoms in a mineral changing from a lower energy state to a higher one through the absorption of photons incident upon them (Clark, 1999). Absorption features seen in the VNIR wavelengths commonly result from the presence of iron or copper (affecting electronic process) or water (affecting vibrational processes) in the mineral structure. The absorption features seen in the VNIR region of the electromagnetic spectrum can result from several types of electronic processes. These processes are: crystal field effects, charge-transfer, color centers, and conduction bands (Hunt, 1977).

Crystal field effects are the most common electronic process in the VNIR and are due to the unfilled electron shells of transition elements such as iron (Clark, 1999). Charge-transfer processes occur when absorbed photon energy forces an electron to shift between multiple ions or between ions and ligands and is responsible for absorption
features in goethite and jarosite (Hunt, 1977). Color center electronic processes are created by the irradiation of structural crystal lattice defects and are responsible for the range of colors displayed in fluorite (Clark, 1999). Conduction band transitions occur when electrons may occupy two energy levels and are responsible for the yellow color of sulfur and red color of cinnabar (Clark, 1999). Figure 3.2.2 shows absorption features of sulfate and goethite due to various electronic processes.

Figure 3.2.2: VNIR electronic processes.
3.2.3 Vibrational Processes

The bonds in a molecule or lattice structure have the ability to vibrate as a system and may cause new vibrations in multiples of the original fundamental node frequency. These additional vibrations are referred to as overtones when they are multiples of a single fundamental vibration and combinations when they are composed of different modes of multiple vibrations (Hunt, 1977). Combination and overtone vibrational features are responsible for absorption minima in the SWIR wavelengths. Muscovite, alunite, and kaolinite absorption minima located near 2.2 µm are a direct result of these combination and overtones from presence of the hydroxide ion (Hunt, 1977). Figure 3.2.3a shows some minerals of interest for exploration that have SWIR spectral absorption minima resulting from combination and overtone vibrational processes.

LWIR spectral absorption features result from radiant energy being emitted from matter as heat (Adams, 2006). The deviation from a theoretical blackbody emittance curve allows for the characterization of a mineral’s distinct spectral absorption features (Sabins, 1987). Silicates are easily distinguished in the LWIR due to the fundamental vibration node for the Si-O bonds occurring in this wavelength region. This allows for identification particularly of ring and framework silicates that are not easily detectable in the VNIR/SWIR regions (Christensen et al., 2000). Figure 3.2.2b displays several exploration minerals and their LWIR absorption minima resulting from fundamental vibrational processes.
Figure 3.2.3a: SWIR vibrational spectral absorption features.
3.3 Spectral Libraries

Properly and positively identifying spectral absorption features displayed in unidentified endmembers requires the use of a reference spectral library for comparison.
Spectral reference libraries are compiled by using laboratory hyperspectral spectrometers and other laboratory tests on pure mineral endmembers under controlled environments to obtain highly accurate reference spectral signatures. These libraries typically also provide additional parameters for each mineral sample including, but not limited to, an indication of sample purity, spectral resolution, collection location, and sample description. Two libraries were used in this study, the USGS spectral mineral library (Clark et al., 2007) with over 1300 spectral signatures covering the VNIR and SWIR and the ASU Spectral Library containing approximately 200 minerals and their representative LWIR spectral signatures (Christensen et al., 2000).

3.4 Remote Sensing Instrumentation

Passive sensors used in this study are sensitive only to radiation from an outside illumination source, in this case the sun. The ground surface provides the radiance signal resulting from its interaction with the incident solar radiation (Jong, 2004). When these photons enter the sensor optics they are spectrally separated using a prism or grating and the signal at each wavelength is converted to a charge representing the intensity (Borengasser, 2008). An analog-to-digital converter is used to convert the charge to an intensity number known as the Digital Number (DN), which is later converted to absolute radiance using radiometric calibration against standard sources of known intensity.

Atmospheric correction can then be performed on the radiance data to correct for absorption and scattering effects of gasses and particles contained in the atmosphere. This correction yields a reflectance product in the case of the VNIR/SWIR or an
emissivity and estimated ground temperature product in the case of the LWIR (Clark, 1999).

Clark defines four general parameters to describe a spectrometer: spectral range, spectral bandwidth, spectral sampling, and signal-to-noise ratio. Spectral range is the wavelength range the sensor can reliably and accurately measure. Spectral bandwidth is the width of an individual spectral channel in the sensor. Spectral sampling is the width from one spectral bandpass to the next and along with spectral bandpass creates spectral resolution (Clark, 1999). A higher signal-to-noise (S/N) ratio indicates that the sensor can more accurately record details in spectrum it measures.

All aircraft flown hyperspectral data obtained for this study were collected with pushbroom type sensors. In a pushbroom instrument scanner, rows of a CCD are arranged perpendicular to the flight direction in a linear array (Borengasser, 2008). They image as a group across the flight path as the platform moves forward. One spatial dimension (cross-track) is provided by the line array and the spectral dimension is recorded in the second dimension of the CCD. The second spatial dimension (along-track) is provided by the forward motion of the aircraft. The detailed design parameters for these instruments (swath, field of view, spectral resolution and signal to noise) are provided in Table 3.5 below.

### 3.5 Hyperspectral Airborne Sensors

Approximately 22 km² of hyperspectral VNIR/SWIR and LWIR data representing five flight lines were flown and collected by SpecTIR Corporation and Aerospace Corporation on June 26, 2008. What makes these datasets unique was that both the
ProspecTIR VNIR/SWIR and SEBASS LWIR sensors were mounted fore and aft in the same Twin Otter aircraft and flown at the same time over the National Mining District. The aircraft is flown to achieve some spatial overlap in adjacent flight lines, however, the swath for the LWIR sensor is 1/3 that of the SWIR. So when flown to achieve overlap in the LWIR this results in extensive spatial overlap from flight line to flight line in the VNIR/SWIR data.

Having both sensors mounted in the aircraft in this configuration assures that the following variables are common among the two wavelength ranges during the data acquisition: vegetation, ground disturbance, soil moisture, and atmospheric conditions. Frequently hyperspectral data collections may have long temporal separations that can further complicate data analysis due to environmental and atmospheric changes over time. This was one of the first datasets that SpecTIR Corporation and Aerospace Corporation flew with this dual sensor joint project to collect VNIR/SWIR and LWIR data during the same flight. This type of collection is very cost effective, as only one flight is needed to get a larger spectral range of data. Figure 3.5 shows a close up detail of the two sensors mounted in the aircraft.

Spectral data covering the VNIR/SWIR regions over the National Mining District was acquired from the ProSpecTIR VS sensor. Built and operated by SpecTIR Corporation (www.spectir.com) it combines the ProSpecTIR V (VNIR) and S (SWIR) sensors into a single aircraft mountable option. Spatial resolution is dependant upon the altitude of the aircraft and ground elevation during collection. Many studies have been done showing the usefulness of hyperspectral VNIR/SWIR data for identifying and mapping alteration minerals (Bedell 2005; Crosta, 1998; Rowan, 2003). SpecTIR
provided radiometrically corrected radiance data, along with two atmospherically corrected products.

Figure 3.5: ProSpecTIR and SEBASS sensors (SpecTIR and Aerospace Corporations).

For hyperspectral data acquisition of the LWIR region the Spatially Enhanced Broadband Array Spectrograph System (SEBASS) sensor was used. The SEBASS sensor is a Mid-Wave Infrared (MWIR) and LWIR sensor with 128 channels in the MWIR and 128 LWIR channels with similar spectral, spatial, and S/N qualities to the ProSpecTIR VS sensor.

While there have been limited studies using hyperspectral LWIR data for geologic mapping purposes, they do indicate SEBASS LWIR data should be able to identify silica and clay minerals accurately ( Vaughan, 2002). In addition, many studies have proven the
validity and usefulness of using multispectral thermal infrared data for detecting silicates and oxides (Hook, 1994; Rowan, 2003; Sabine, 1994). Recently it has also been shown that integrating VNIR/SWIR hyperspectral data with multispectral thermal data can yield large improvements in the identification of silicate and oxide minerals (Chen, 2007). It is anticipated that the hyperspectral thermal data, used in combination with hyperspectral VNIR/SWIR data, will prove even more useful. SpecTIR provided radiance, atmospherically corrected apparent emissivity, and ground temperature data products covering the LWIR region. Table 3.5 shows various parameters of the data collections used for this study. These datasets will be covered in more detail in chapter 5 and detailed specifications for the sensors can be found in Appendix I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ProSpecTIR</th>
<th>SEBASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range</td>
<td>MODTRAN 0.407 - 2.4518 µm</td>
<td>128 Bands 7.6309-13.5360 µm</td>
</tr>
<tr>
<td></td>
<td>VELC 1.894 - 2.397 µm</td>
<td></td>
</tr>
<tr>
<td>Average Ground Resolution</td>
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<td></td>
</tr>
<tr>
<td>Dataset Size (GB)</td>
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<td>1.2</td>
</tr>
<tr>
<td>Flight Line Swath Width</td>
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<td>~ 400 meters</td>
</tr>
<tr>
<td>Total Scene Width</td>
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<tr>
<td>Flight Line Overlap</td>
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<td>~ 25 %</td>
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<tr>
<td>Flight Lines</td>
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<td></td>
</tr>
<tr>
<td>Average Aircraft Elevation (AGL)</td>
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</tr>
<tr>
<td>Ground Elevation (AMSL)</td>
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</tr>
<tr>
<td>Collection Date/Time</td>
<td>June 26, 2008 / 12:20:05 - 1:46:27 pm PST</td>
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</tr>
</tbody>
</table>

Table 3.5: Study dataset parameters.
3.6 Analytical Spectral Devices (ASD) Field Spectrometer

Designed and built by Analytical Spectral Devices Incorporated (www.asdi.com) the FieldSpec Pro measuring from 0.350 to 2.499 µm with a 0.001 µm step size sampled in 2151 channels is the industry standard for a wide range of VNIR/SWIR laboratory and field remote sensing applications. Light, either from a solar or artificial source incident to the sample enters the unit though fore-optics attached to a fiber optic cable. This radiance measurement is then converted to reflectance by using a spectralon panel as a white reference standard to remove the effects of the illumination source (Arthur, 2007).

For the purposes of this study, the FieldSpec Pro was only used to make VNIR and SWIR reflectance measurements in the laboratory from whole rock and powdered samples collected in the field using a halogen illumination source. The collected spectra were used both for spectral comparison to the aircraft hyperspectral collected data and for identification of potential unknown endmember using reference spectral libraries. Figure 3.6 shows an image of the FieldSpec Pro being used in laboratory to measure a spectralon white reference panel.

3.7 Nicolet 6700 Fourier Transform Infrared (FTIR) Spectrometer

The laboratory based Nicolet 6700 FTIR is an advanced research spectrometer measuring 1869 bands from 2.499 to 25.050 µm and is a standard for mid-infrared measurements in the research community. The Nicolet 6700 was used to provide LWIR spectral signatures for samples collected in the field in both chip and powdered forms. The results of that analysis were then compared to the collected hyperspectral LWIR image data and used to identify potential unknown endmembers and further verify known samples. Figure 3.7 shows the Nicolet 6700 FTIR in the laboratory.
Figure 3.6: FieldSpec in the laboratory (modified from NERC).

Figure 3.7: Nicolet 6700 FTIR in University of Nevada, Reno laboratory.
Chapter 4: Image Processing and Mapping

This chapter will outline and describe the processing methods that were used to obtain the results that will be discussed in detail in Chapter 5. All data processing for this study was completed using two primary industry and research accepted software packages. Hyperspectral image data manipulation and processing was performed with the Environment for Visualizing Images version 4.3 (ENVI) software package. ENVI allows for image manipulation using general inspection techniques, color Red, Green, Blue (RGB) composites, Decorrelation Stretching (DCS), Relative Band Depth ratios (RBD) and the ENVI Hourglass structured processing flowchart, Spectral Angle Mapper (SAM), and Mixture Tuned Matched Filtering (MTMF) that will be discussed in further detail later in this chapter.

ArcGIS version 9.3 geographical information systems (GIS) software package was also used exclusively in order to compile, and integrate mapping results with other geospatial resources. These various datasets may include, but are by no means limited to: Digital Elevation Models (DEM), geologic maps, roads, streams and rivers, soil maps, watershed maps, slope aspect maps, along with all of the mineral mapping results from the analysis of the hyperspectral data in ENVI. Some processing steps were performed only on specific datasets and those are discussed under each dataset that they apply to.
4.1.1 SpecTIR VNIR/SWIR Data Processing

The SpecTIR provided datasets contain 5 flight lines covering the VNIR/SWIR wavelengths in three products: radiance, and two atmospherically corrected datasets using MODTRAN and VELC (methods described below). Each flight line had a cross-track illumination correction applied to them individually. Cross-track illumination attempts to correct for the illumination variations across the scene to compensate for vignetting, instrument scanning, off-nadir view angles and reflections. The data was georeferenced using the SpecTIR provided Input Geometry Table (IGT) and Geometry Lookup Table (GLT) files using ENVI georeferencing tools. Overall for this study the accuracy of the georeferencing was more than adequate and correlated well in ArcGIS with other geospatial data layers. The five flight lines were then mosaicked into a single scene for further analysis. Multiple iterations of different mosaics with various settings were created and processed using the same endmembers as were applied to the individual flight lines early in this study for a comparison. While the research standard is to process every flight line individually for this dataset the results were not significantly affected by working with a single mosaic versus individual flight lines. This could be due to the small number of flight lines and the short amount of time covering their acquisition.

4.1.2 VNIR/SWIR Atmospheric Correction

Three approaches were used to correct the atmospheric contribution to the data. The Moderate Resolution Atmospheric Transmission radiative transfer fortran code (MODTRAN), was developed by the Air Force and is publically available and used as the basis for a number of commercially available atmospheric correction routines
including ACORN (Atmospheric Correction Now, available through http://www.imspec.com/) and the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) module in ENVI. MODTRAN provides a method to correct for water vapor, oxygen, carbon dioxide, methane, and ozone in addition to molecular and aerosol scattering effects in the atmosphere. SpecTIR has developed their own, proprietary correction algorithm based on the MODTRAN code and an additional in-house proprietary algorithm called VELC (Virtual Empirical Line Calibration). These SpecTIR provided corrections differ in approach as well as the wavelength subset used (Kratt et al. 2009). We refer to the SpecTIR derived reflectance products as "MODTRAN" and "VELC" in subsequent discussion. MODTRAN reflectance data uses the entire VNIR/SWIR spectral range, 0.4 to 2.45 µm while VELC uses only the subset from 2 to 2.5 µm.

During initial analysis of the SpecTIR provided MODTRAN dataset it was noted that excessive spectral smoothing from atmospheric correction processing might have been applied. Excessive spectral smoothing would reduce the spectral resolution and the ability to detect spectral absorption features in the data. The SpecTIR provided VELC dataset, while also corrected for atmospheric effects, shows excellent spectral absorption feature resolution in the 2.0-2.5µm spectral region. However, the VELC dataset covers a smaller spectral range, which reduces its overall usefulness compared to the MODTRAN provided product to detect certain endmembers. Certain diagnostic oxide absorptions features appear at wavelengths below 1.0µm. Since these iron oxide alteration features are typically subtle in their spectral expression excessive smoothing in the MODTRAN
product could have been obscuring the absorption feature completely making identification and mapping of potential iron oxide alteration impossible.

In order to explore if it was possible to find a better balance between correcting for the atmospheric effects while avoiding the excessive smoothing problems another atmospheric corrected dataset was produced using the SpecTIR provided radiance dataset and the software package Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH). FLAASH is available as an add-on to ENVI and includes user defined parameterized input for typical water vapor (season, latitude band) and aerosols (urban, rural, visibility) to the MODTRAN code. FLAASH offers the derivation of water vapor, aerosols, and the ability to select among several strong water features to define the column abundance of water vapor, in addition to the calculation of reflectance from the radiance data. Significant work in this area has shown that improved atmospheric correction yields a more useful end product for endmember identification and mapping (Kruse, 2004).

In order to use FLAASH processing the input radiance image must be in a floating-point, long integer (4-byte signed), or integer (2-byte signed or unsigned) data type. The interleave for the image must be BIL or BIP and FLAASH requires input data to be floating-point values in units of W/cm2*nm*sr. In the case of this SpecTIR radiance dataset a scale factor is 1000.00 was applied for all bands to meet this requirement. Because of this input requirement, data are output with wavelength in nm, in contrast to the SpecTIR reflectance, which is reported in µm, so that subsequent results will use both types of units. The atmospheric model chosen was Mid-Latitude Summer. The Rural aerosol setting was selected, as the aerosols in the scene should not be
significantly affected by urban or industrial sources in this particular field area. Since visibility conditions were clear during collection a visibility value of 120 km was used. Table 4.1.2 shows the parameters used for the National District dataset.

The spectral polishing algorithm is a linear renormalization method that attempts to reduce spectral artifacts in data using only the original data itself. Selecting a larger value for the width parameter yields more spectral polishing, which increases the amount of smoothing applied to the data. After several iterations it was determined the lowest width setting of 1 increased the potential for absorption feature detection and identification. FLAASH corrections were performed for each of the five flight lines individually, which were then corrected for cross-track illumination, georeferenced, and combined into a single scene mosaic for further processing.

<table>
<thead>
<tr>
<th>FLAASH Parameters Used in Atmospheric Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Type</td>
</tr>
<tr>
<td>Average Sensor Altitude</td>
</tr>
<tr>
<td>Flight Date</td>
</tr>
<tr>
<td>Flight Time</td>
</tr>
<tr>
<td>Ground Elevation</td>
</tr>
<tr>
<td>Average Pixel Size</td>
</tr>
<tr>
<td>Atmospheric Model</td>
</tr>
<tr>
<td>Aerosol Model</td>
</tr>
<tr>
<td>Spectral Polishing</td>
</tr>
<tr>
<td>Polishing Width</td>
</tr>
<tr>
<td>Water Retrieval</td>
</tr>
<tr>
<td>Aerosol Retrieval</td>
</tr>
<tr>
<td>Water Absorption Feature</td>
</tr>
<tr>
<td>Initial Visibility</td>
</tr>
<tr>
<td>Wavelength Recalibration</td>
</tr>
</tbody>
</table>

*Table 4.1.2: FLAASH atmospheric correction parameters.*
I found that the FLAASH corrected data did improve the identification and mapping of many minerals, although not the iron oxides. The significance of having the best atmospheric correction possible while preserving spectral absorption features cannot be overstated. More accurate atmospheric correction allows for identification and detection of more endmembers in the scene and aids in more accurate mapping and mixture separation. The results of minerals mapped using the FLAASH correction and comparisons to maps derived from the MODTRAN and VELC products will be shown in detail in Chapter 5. Subsequent image processing, described next, was performed on all three atmospherically corrected data sets.

4.1.3 Color Infrared (CIR) Image

Producing a Color InfraRed (CIR) image allowed for an additional tool to map vegetation in the scene. ENVI creates this image by creating a RGB color composite image that maps the near-infrared region (0.76 to 0.9 µm) in red, the red (0.6 to 0.7 µm) region to green, and the green region (0.5 to 0.6 µm) to blue from the original dataset. Regions that show up pink to red in the scene represent various increasing density of healthy green vegetation.

4.1.4 Normalized Difference Vegetation Index (NDVI)

The NDVI index is one of the best-known and frequently used vegetation indexes available (Schowengerdt, 1997). ENVI can produce a NDVI image as long as the original dataset contains the proper near infrared and red wavelengths. The equation ENVI uses for calculating the NDVI is: (Near Infrared band – Red band) / (Near Infrared
band + Red band). NDVI results were used in conjunction with the CIR image to try and get an accurate threshold for masking the heaviest densities of green vegetation from the scene. Green vegetation adversely affects the VNIR/SWIR scene analysis by having its own distinct spectral signature and increasing volume scattering effects. The NDVI and CIR results were used to create a mask that was applied to the scene to remove the regions dominated by dense green vegetation. This allowed for reduced scene inspection and processing time by removing areas of the scene that would not yield useful endmember spectra. Various thresholds were tested during this processing in order to identify a threshold that balanced removal of healthy green vegetation but retained regions that still contained useful mineral spectral signatures.

4.2 SEBASS LWIR Data Processing

The Aerospace Corporation provided SEBASS LWIR dataset was adequately corrected for atmosphere and water vapor effects so no additional atmospheric correction was attempted. Flight lines were georeferenced individually using GLT files after cross-track illumination corrections were performed. As with the SpecTIR data flight lines multiple iterations of mosaics were created and tested in comparison to processing individual flight lines and showed that using a single georeferenced mosaic would not negatively affect the results. Georeferenced accuracy was not as high as for the SpecTIR datasets, but was still more than adequate for the requirements of this study. No vegetation removal masking was performed for the LWIR data.
4.3 Color Composites

ENVI can assign any three wavelength bands to the colors red, green, and blue to create an RGB color composite image of the scene. These RGB combinations are used with specific wavelengths that tend to highlight individual minerals or classes of minerals in the scene. For example in the SEBASS dataset an RGB combination using band 48 (10.235 µm) for red, band 27 (9.166 µm) for green, and band 14 (8.434 µm) for blue was created. In the resulting image silica was represented by red, alluvium by cyan, and areas of bleached rocks by blue-purple colors in the scene. (Vaughan et. al., 2003).

Once an area of interest was found the Pixel Locator tool was used to record the exact pixel location that may represent a mineral endmember for later mapping. The pixel locator also indicates the Datum coordinates that were then used to reference the pixel location on other geospatial resources. These coordinates were then used with a Garmin handheld GPS in the field to locate sampling sites. For each pixel of interest its spectral signature was displayed using the ENVI Z profile tool. The Spectral Analyst and Spectral Library viewer could then be used to attempt to identify the potential endmembers by comparison to reference library spectra.

4.4 Decorrelation Stretch (DCS)

Variations in mineralogy are frequently expressed very subtly in hyperspectral data. An enhancement to a simple color composite described above is to apply a Decorrelation Stretch (DCS) to make it easier for the analyst to differentiate the mineral variation in the scene. The technique uses a principal component transformation on the acquired data. The main advantages are the contrast of the entire RGB scene is
enhanced and the original hue of the image is preserved allowing for easier scene interpretation (Gillespie, 1986).

In the thermal wavelength regions data correlation is typically very high and using DCS can greatly improve the analysis of the data. In thermal images emissivity and temperature control the brightness of each band but emissivity may not vary much across the spectrum while temperature may vary largely across the scene (Adams, 2006). The DCS process when used in thermal datasets subdues the temperature variations while trying to increase the variation in emissivity component in the scene.

4.5 Relative Band Depth (RBD)

Relative Band Depth (RBD) mapping seeks to take advantage of the fact that many minerals have sharp narrow absorption features. The method involves a ratio expressed as: (band x + band y) / (band z). Bands x and y represent the shoulders of the absorption feature and band z represents the absorption feature minima (Rowan and Mars, 2003). Clays typically have an absorption feature located at approximately 2.2 µm and using RBD can attempt to delineate clays in the scene. RBD returns a single grey scale image in which the highest values represent the highest absorption depths and should indicate regions of interest for the mineral or minerals in question. Figure 4.5 shows a comparison of a color composite image, a DCS on the color composite, and a RBD image. The color composite bands chosen tend to highlight clays in magenta, the DSC increases the overall visible scene diversity (though magenta colors no longer relate to clays), and the RBD attempts to use the narrow diagnostic feature of kaolinite to help highlight only kaolinite regions in the scene.
Figure 4.5: Comparison of color composite to highlight clays in magenta, DCS performed on the color composite to enhance visible scene diversity, and RBD results to highlight kaolinite in magenta for the same region.

4.6.1 Spectral Hourglass

In order to more efficiently process hyperspectral data methods for reducing the data dimensionality were designed to reduce processing time and more efficiently detect and delineate endmembers in the scene. The spectral hourglass method described by Kruse et al. (1996) is the most established "recipe" for reducing data dimensionality without loosing crucial information in the scene.

4.6.2 Minimum Noise Fraction (MNF)

Minimum Noise Fraction transform (MNF) reduces the amount of data dimensionality by performing two separate principal components rotations (Carr, 2002). MNF effectively attempts to segregate and remove noise from the dataset. It reduces the
total number of bands with useable scene information in them so fewer bands can be used in future processing steps, reducing the processing time in subsequent steps.

The MNF transform also returns the eigenvalues used for the principal component rotations in a plot that helps to identify the number of bands of the MNF transform that may have useful data in them. Visual inspection of the MNF results was performed to see where the bands degraded to noise in the scene by loading them into an animation to evaluate where the bands degraded to mostly noise. The number of bands for further processing was reduced by approximately 75%. Performing the next processing steps on 30-40 bands from the MNF analysis compared to 128-178 channels in the original data saved significant time. It’s important not to remove too much data as any band reduction processing probably removes some useful scene information, but performed correctly will not negatively impact the results.

4.6.3 Pixel Purity Index (PPI)

Pixel Purity Index (PPI) analysis selects the most spectrally “pure” pixels in the image, which aids in scene endmember selection. The MNF results are projected onto random unit vector scatter plots. Those pixels that are spectrally pure plot towards the ends of these unit vectors (Boardman et al., 1995). The number of times a specific pixel is determined to be spectrally pure is recorded and the total value is assigned to the pixel (Kruse et al., 1996).

The PPI processing allows four main variables to be manipulated. The first is the selected number of bands from the MNF transform. The second is the number of iterations, 5000 iterations seemed to work best and reduce processing time. The third
variable is the number of iterations per block; the default of 250 was used. The last variable is a threshold setting. The default value of 2.5 was used, other values were experimented with but the results were similar. Too many pure pixels can overly complicate processing in later steps. The Region Of Interest (ROI) tool was used to reduce the PPI results for further analysis using a threshold factor in order to yield the most pure 500-1000 pixels in the scene.

4.6.4 N-Dimensional Visualizer (n-DV)

The MNF and PPI results were used in the n-Dimensional Visualizer (n-DV) to define classes that would later be analyzed as representing the most unique endmembers. The N-Dimensional Visualizer allows viewing the PPI results in N-d space in which N is the number of bands used from the MNF analysis. It is interactive in that it displays a “cloud” of pure pixels that can be rotated in N-d space. Distinct corners of the cloud or tight groupings could represent potential endmembers. These regions were outlined and a class was created from them. Statistics and spectral averages for each class were then evaluated and the spectral analyst was used to attempt to identify each class. The best classes were then used with other endmembers for unmixing and mapping. Keeping in mind that most pixels on the ground are actually not a single pure mineral but a mixture of minerals and other soil and vegetation components in various amounts.

Throughout all processing steps endmembers were located and the best representative pixels of those endmembers were selected and evaluated. Once processing was completed the remaining endmembers could be identified either by spectral libraries, or field sampling and laboratory analysis. Spectral Analyst was a good first attempt to
find possible matches but manual inspection of the suggested match is required to make sure it is a good fit. In addition field sampling of unknown endmembers also yielded identification through laboratory spectral analysis or other methods such as XRD. Once a collection of identified and unknown endmembers for each dataset could be compiled the next step in the processing was to map the endmember extent in the scene.

4.7.1 Endmember Mapping

Once the endmembers were reduced and identified their extent was mapped in the scene. The process of mapping endmembers is influenced by analyst bias as the thresholds chosen dominate the extent of the mapped endmember in the scene. It's important for the to keep in mind the desired focus the mapping and that the thresholds used to map locations for pure endmember sampling need to be more strict than those used to just map the extent of a minerals present in the scene. Even with high-resolution hyperspectral data every pixel on the ground certainly represents a mixture of minerals, vegetation, etc.

Most natural surfaces display macroscopic linear mixing that is representative of combination of their spectra according to their fractional abundance in the field of view (Singer et al., 1979). Pixels in the data used for this study represent 3.5 square meters on the ground. Most likely every pixel in the scene is not a single mineral but mixtures of various minerals and vegetation. However many pixels in the scene may be dominated by a single mineral endmember to the extent they can be considered to be "pure" pixels of that mineral endmember for mapping purposes. There may also be scene endmembers
that are combinations of materials that also yield a diagnostic mineral spectral signature in the scene and can be mapped but do not represent a clear dominant single mineral.

4.7.2 Spectral Angle Mapper (SAM)

Spectral Angle Mapper (SAM) compares the image pixel spectra with the endmember spectra and calculates the spectral angle between them. Pixels in the scene within the analyst specified angle threshold are classified as their matching endmember and those that are not are left as unclassified pixels. SAM performs this by using endmember spectral signatures as vectors in space with dimensionality representing the number of bands. SAM only uses the vector direction and not its length and as a result SAM is it is not affected by scene illumination variations (Kruse, 1996). Individual rules are returned for each endmember used in the classification output. These rules can be adjusted or modified by a histogram stretch within ENVI. The rules can be narrowed to return only those areas with the most pure concentrations of each endmember, or widened to show greater extent of each endmember and allow the delineation of endmember mixing.

4.7.3 Mixture Tuned Matched Filtering (MTMF)

Mixture Tuned Matched Filtering (MTMF) uses the results from MNF analysis along with previously chosen endmembers to “unmix” and map these endmembers by suppressing the background. It is a hybrid algorithm that combines well-established signal processing methods with linear mixture theory to help reduce the level of false positives inherent in some other unmixing methods. Two images are returned for each
endmember during the analysis. The first is the MF score and the second is the infeasibility image. The MF score represents pixels that have the highest match for the endmember spectra. The infeasibility image represents Root Mean Square (RMS) error in which higher numbers indicate higher RMS error. Ideally a high MF score and a low infeasibility value indicate high confidence that the pixel in question is a good match. High infeasibility numbers mean the pixel in question is probably a false positive and not actually representative of the endmember. As with the SAM mapping by applying interactive linear stretches to the results can tailor the output to the specific requirements for the study.
Chapter 5: Processing Results

The processing steps described in chapter 4 were used to locate, extract, identify, and map endmembers in the National District datasets. Those results were integrated with other geospatial data in a GIS database to combine a variety of other geospatial products covering the National District region. The remainder of this chapter will discuss maps arising from analysis of the different sensors as well as different atmosphere corrected data products.

5.1.1 SpecTIR VNIR/SWIR FLAASH Correction

Initial inspection of the SpecTIR provided MODTRAN and VELC products showed that the MODTRAN product had a high level of spectral smoothing applied during the atmospheric correction process. In an attempt to analyze a product with improved spectral resolution covering the entire 0.4 to 2.5 µm range the radiance provided data was corrected manually with FLAASH. The parameters used for the FLAASH correction can be seen in Figure 4.1.2b. The results of the FLAASH processing using reduced spectral polishing provided an improved dataset with better spectral resolution compared to the provided MODTRAN product. Figure 5.1.1a shows a comparison for the same pixel in the MODTRAN, VELC, and FLAASH corrected datasets. The FLAASH spectra clearly show the diagnostic kaolinite doublet while the MODTRAN spectra shows a very slight doublet effect but would not be diagnostic. The VELC also shows a very diagnostic kaolinite doublet and showed improved endmember identification and mapping than even the FLAASH dataset did in the 2.0–2.4
µm range. The main motivation for doing the FLAASH correction was the expectation that it would yield a dataset with similar spectral quality to the VELC but with wider spectral coverage. This should have helped in indentifying and mapping iron oxide spectral features in the 0.4 to 1.0 µm range. However, this turned out not to be the case as the FLAASH data did not yield any additional iron oxide endmembers in the scene.

**Figure 5.1.1a:** MODTRAN, VELC, and FLAASH spectral comparison showing the affects of various atmospheric correction models.

Figure 5.1.1b shows a comparison of the mapping variations using each of the three datasets. The same kaolinite endmember made up of 28 selected pixels were used for all 3 datasets with the same threshold settings for SAM mapping. There were 43439 pixels mapped as kaolinite in the MODTRAN dataset, 24781 pixels mapped as kaolinite in the VELC dataset, and 4397 pixels mapped as kaolinite in the FLAASH dataset. In the lower spectral graphs showing the ROI statistics the red lines represent the minimum and maximum variance in spectral signatures, the green lines represent the upper and lower standard deviation, and the black line the average spectral signature for all the pixels mapped. FLAASH maps the fewest pixels as kaolinite but the minimum, maximum and
average statistical spectral curves have the best match for the USGS reference library spectrum for kaolinite. While FLAASH mapped fewer pixels the confidence is higher that they actually represent the kaolinite endmember. MODTRAN maps the most pixels in the scene however; neither the average of the mapped pixels or the extremes show the diagnostic kaolinite feature. So while MODTRAN maps a much larger region as kaolinite, the confidence that those pixels actually represent kaolinite is very low. The VELC is somewhere in the middle, mapping fewer pixels than the MODTRAN but more than FLAASH. The VELC mapped region average and +/- standard deviation spectral statistic curves do show diagnostic kaolinite spectral features but the minimum and maximum still have significant variation from the expected kaolinite spectra. For these reasons most of the VNIR/SWIR analysis was done using the FLAASH and VELC products. The MODTRAN was also processed for endmembers, however, no endmembers derived from this method had good spectral characteristics for mapping.

**Figure 5.1.1b:** Comparison of endmember mapping results for MODTRAN, VELC, and FLAASH datasets.
5.1.2 True Color Image Creation

Creating a true color image from the scene dataset is useful as a first look into the scene to get an idea of vegetation or scene variability. Frequently some of the variations in vegetation, rock type, and structure can be seen in true color images. In addition a true color image makes a good background for mapping results and for planning fieldwork for endmember sampling. Unfortunately for this dataset the results were less than ideal and the colors in results were skewed from what was expected creating an image that was not a good true color representation of the scene. This could be due to errors made in the calibration of the sensors during collection or errors made during the post collection correction of the data or additional unknown factors. Figure 5.1.2 shows the results of the ENVI true color image processing. Due to this issue for mapping and fieldwork planning needs that required a true color scene data from the National Agriculture Imagery Program (NAIP) was used. The NAIP dataset is a 2-meter resolution color orthophoto that has been georectified and was also used as a basemap for the mineral maps.

5.1.3 Color Infrared and Normalized Difference Vegetation Index

Similar to the true color image ENVI was used to create both Color Infrared (CIR) and Normalized Difference Vegetation Indexes (NDVI). They were used in coordination to create a mask to remove dense healthy green vegetation from the scene. Figure 5.1.3a shows the results of the CIR processing in which increasing shades of red indicated more dense regions of healthy green vegetation.
The results of the NDVI processing are shown in Figure 5.1.3b. In this image, regions of lighter shades indicate higher density of healthy green vegetation. Using the histogram stretching function of ENVI the NDVI image was adjusted until it was a similar fit to the CIR image. A mask could then be applied to the entire dataset removing those areas that contain high-density vegetation cover. Figure 5.13c shows the results of the vegetation masking for the dataset extent indicated by the red outline. Those regions in black have been removed from all further processing steps, decreasing analysis time.
Figure 5.1.3a: Color Infrared (CIR) analysis results.
Figure 5.1.3b: NDVI analysis results.
Figure 5.1.3c: Scene vegetation removal mask results. Red outline shows the approximate extent of the dataset, and black areas represent regions of healthy green vegetation removed from further processing.

5.1.4 VNIR/SWIR RGB, DCS, and RBD Results

RGB, DCS, and RBD processing were all used in order to locate and refine potential endmembers in the scene. Figure 5.1.4a shows the DCS results after being applied to a RGB combination using band centers of 0.66, 0.80, and 0.55 µm,
respectively that tends to highlight areas of iron oxide in the scene represented by yellow-orange colors. Figure 5.1.4b shows a similar DCS of an RGB combination using band centers of 2.0, 2.2, and 2.4 µm, respectively that tend to highlight clays in magenta.

**Figure 5.1.4a:** DCS of RGB using bands 29 (0.66 µm), 44 (0.80 µm), and 17 (0.55 µm). Yellow and red regions of the image tend to represent areas of iron oxides.
Figure 5.1.4b: DCS of RGB using bands 143 (2.0 µm), 158 (2.2 µm), and 174 (2.4 µm). Presence of clay minerals tends to be indicated by magenta colors in the scene.

Using Relative Band Depth analysis was employed successfully to better identify areas of a particular mineral’s spectral signature. An RGB image is created using bands that will highlight the shoulders and minima for a diagnostic spectral feature, this new RGB
composite image highlights areas in the scene that contain the feature of interest in magenta. Figure 5.1.4c shows a spectral profile with the red, green, and blue lines representing bands chosen to highlight the diagnostic spectral feature of kaolinite. A DCS was performed on the results to further enhance regions in the scene that might share a similar absorption feature by reducing correlation in the data. Figure 5.1.4d shows the DCS results from a RBD chosen to highlight kaolinite. Regions of the scene in magenta are statistically likely matches for kaolinite, but also include false positives from other clays with similar spectral absorption minima. Taken as a whole the clay areas highlighted are good indications of regions of alteration in the scene.

Figure 5.1.4c: Relative Band Depth (RBD) example to highlighting a spectral feature in the scene.
Figure 5.1.4d: DCS stretch of RBD using bands 18 (2.0 µm), 50 (2.2µm), and 79 (2.4 µm). Magenta colors represent a good match for the spectral feature of kaolinite. Regions of dark blue correlate well with alunite, and bright red colors correlate well to quartz/sinter regions.

These processes along with the Spectral Hourglass processing methods discussed in chapter 4 were used in order to identify minerals in the scene and also help to find the
best spectral representation of those minerals in order to select the best endmember for
unmixing and mapping purposes.

5.1.5 VNIR/SWIR Scene Endmembers

Using combinations of the processes and results discussed previously many
possible endmembers were derived from the scene. Some of those endmembers turned
out to be the same mineral and were combined. Some were not identified with specific
minerals, perhaps representing complex mixtures. Endmember identification was
attempted through lab analysis along with comparison to spectral reference libraries.
Some endmembers with spectral features that could not be identified turned out to be
from mine dumps or leaching sites. It was decided to only use those endmembers that
were identified with high confidence for further unmixing and mapping processing. The
underlying emphasis of this study was to determine what could be mapped in the scene
through analysis of remote sensing data alone. To further this goal, detailed analysis of
field and lab samples was not the focus and supports using only those endmembers that
were easily identified with high confidence from the provided scene data and existing
reference libraries.

Four endmembers were chosen in the VNIR/SWIR analysis and these are shown
in figure 5.1.4a. They include kaolinite, alunite, muscovite, and illite. The figure shows
the scene spectral signature for the endmember in black and the USGS spectral library
signature for its match in red. Muscovite and illite were combined into a single
endmember for mapping purposes. As seen in Figure 5.1.4.a, the spectral signatures of
these phyllosilicates are very similar and it was concluded they could not be accurately
delineated as separate endmembers in these data. It's common in previous studies to make
a single combined group of illite/muscovite/montmorillonite endmembers as well
(Rowan, 2003). Figure 5.1.5a shows a comparison of the USGS libraries for the spectral
signatures of illite, muscovite, and montmorillonite demonstrating their similar diagnostic
spectral features in the VNIR/SWIR.

Figure 5.1.5a: USGS Spectral library comparison of illite, montmorillonite, and
muscovite.
5.1.6 VNIR/SWIR SAM Mapping Results

The three final endmembers were used with SAM mapping using the default spectral angle of 0.10. Thresholds were used with the resulting rule images for each endmember in order to create an ROI that best represented the endmember in the scene. Accuracy of the potential thresholds was evaluated by manual inspection of the spectral signatures for the resulting pixels mapped in the scene and also by using the statistical analysis of the ROI to view the minimum, maximum and standard deviations and comparing them to the desired endmember reference spectral signature. Selected ROI's
were then exported to a class image, converted to a vector image, and imported into GIS and overlaid onto the NAIP color orthophoto background. Figure 5.1.6a and 5.1.6b show the results of the SAM endmember mapping. Alunite and kaolinite map to the southeast primarily in the Buckskin Mountain area and the Muscovite/Illite endmember to the northeast by the National Mine location.

**Figure 5.1.6a**: VNIR/SWIR SAM mapping results, box insets show zoomed in regions shown in figure 5.1.6b.
Figure 5.1.6b: VNIR/SWIR SAM mapping results. Image on the left is from the National Mine region and the image on the right is from Buckskin Mountain.

5.1.7 VNIR/SWIR MTMF Mapping Results

MTMF mapping was carried out using the 45 bands selected from the MNF spectra hourglass processing and the same ROIs used in the SAM mapping processing. Figure 5.1.7a and 5.1.7b show the results of the MTMF mapping. The kaolinite endmember extent approximately similar to the SAM results however by manually
inspecting the mapped regions spectral signatures and looking at the ROI statistics for those regions the alunite extent was determined to be less accurate with MTMF than the SAM results. If the threshold was reduced to include all the manually inspected known areas of the scene with alunite spectral signatures too much of the scene was incorrectly mapped as alunite. The illite/muscovite/montmorillonite endmember mapped more accurately using the same evaluation with MTMF than the SAM results.

Figure 5.1.7a: VNIR/SWIR MTMF mapping results, box insets show zoomed in regions shown in figure 5.1.7b.
Figure 5.1.7b: VNIR/SWIR MTMF mapping results. Image on the left is from the National Mine region and the image on the right is from Buckskin Mountain.

5.1.8 VNIR/SWIR SAM and MTMF Composite Mapping Results

The composite map for the VNIR/SWIR region analysis was produced using the kaolinite and alunite results from the SAM mapping and the illite/montmorillonite/muscovite result from the MTMF mapping. Each was chosen because they were the best ROI statistical average spectra in comparison to the matching
library spectra for their respective mapped regions. Figure 5.1.8a and 5.1.8b show the results of the mapping.

**Figure 5.1.8a:** VNIR/SWIR composite map, box insets show zoomed in regions shown in figure 5.1.8b.
Figure 5.1.8b: VNIR/SWIR composite map. Image on the left is from the National Mine region and the image on the right is from Buckskin Mountain.

5.2.1 LWIR RGB, DCS, and RBD Results

The SEBASS LWIR dataset was processed using similar methods to the VNIR/SWIR data. However, based on the emissivity evaluation the atmospheric correction was deemed acceptable so no attempts to do further correction were performed and vegetation was not removed from the scene. An RGB composite using bands 67
(11.1 µm), 36 (9.6 µm), and 25 (9.1 µm), were used as a first look at the thermal scene diversity. Vaughan in 2003 and others have shown that this RGB combination does a particularly good job of separating clays from unaltered quartz minerals in the scene. A DCS was also performed on this RGB in order to increase the contrast for better discrimination of scene diversity. Figure 5.2.1 shows the results of the DCS on the RGB combination mentioned above. Yellow colors tend to indicate sulfates, opalized silica, and quartz minerals, purple colors indicate clay-dominated materials, and green or cyan colors show vegetation and spectrally neutral surfaces.

As with the VNIR/SWIR data many DCS results were used on different RGB combinations for analysis to locate, identify potential endmembers in the scene. RBD was also used once specific minerals of interest were identified to further refine the endmembers. These methods were combined with the results from the spectral hourglass processing flow in order to further detect and refine the scene endmembers.

5.2.2 LWIR Scene Endmembers

Potential scene endmembers that were identified and refined were then evaluated in order to make sure they were unique and the best spectral representation in order to be the best candidates for further mapping. Some endmembers were unable to be identified as unique minerals even using lab identification methods so they were not used for mapping. Most of these areas, when investigated in the field, were old ore leach pads or mine dumps similar to the VNIR/SWIR endmembers. It is thought the diagnostic mineral spectral features from those areas may be related to chemicals used in ore processing or
the process of their weathering products over time. It was decided to only map those endmembers that could be uniquely and reliably identified. This yielded six

**Figure 5.2.1:** SEBASS DCS of RGB using bands 67 (11.1 µm), 36 (9.6 µm), and 25 (9.1 µm). Yellow colors tend to indicate sulfates, opalized silica, and quartz minerals, purple colors indicate clay-dominated materials, and green or cyan colors show vegetation and spectrally neutral surfaces.
endmembers for SAM and MTMF mapping; corrugated metallic surface (abandoned building roof), water, jarosite, alunite, quartz, and opal sinter. Figure 5.2.2 shows the scene endmember spectra in black and the matching spectral library spectra in red. In the case of the metallic surface and water endmembers fieldwork was used to identify them and since they are not related to geologic processes no matching reference library spectra is shown.

Figure 5.2.2: SEBASS endmembers used for mapping.
5.2.3 LWIR SAM Mapping Results

The six endmembers were mapped using SAM with the default spectral angle setting of 0.10. The resulting rule images had various thresholds applied in order to increase the accuracy of the mapped endmembers in the scene. Accuracy was evaluated by manual inspection of the spectral signatures in the scene, comparing the results to those of the VNIR/SWIR mapping for endmembers mapped in both datasets, and evaluating the minimum, maximum, and standard deviation statistical information for the ROI. SAM mapping had difficulty with delineating the quartz endmember from alunite and some unknown dark regions of the scene even when high thresholds were applied. The same issue occurred when trying to map the alunite endmember. Figure 5.2.3a and 5.2.3b show the results of the SAM mapping when overlaid on the NAIP orthophoto background.

5.2.4 SEBASS MTMF Mapping Results

The same endmembers were used along with 30 bands from the MNF spectral hourglass processing for the MTMF mapping. MTMF also had problems delineating alunite, quartz, and opal sinter in the scene. As with the SAM mapping regions were evaluated by manually inspecting the spectral signatures of the mapped regions to ensure the pixels mapped contained diagnostic spectral features of the representative endmember and by evaluation of the ROI statistics for each region. The only way to ensure each region yielded very high confidence of being representative of its endmember and to reduce large scale overlap between mapped units that did not display diagnostic features from both endmembers was to set thresholds so high almost none of the scene would
have been mapped to any of the endmembers. A compromise was chosen so while the thresholds are still high, and fewer pixels were mapped than in the VNIR/SWIR they retain a higher level of accuracy with fewer false positives as evaluated by manual pixel inspection and ROI statistics. Figure 5.2.4a and 5.2.4b show the results of the MTMF mapping.

**Figure 5.2.3a:** SEBASS SAM mapping results, box inset shows zoomed in region shown in figure 5.2.3b.
Figure 5.2.3b: SEBASS SAM mapping results showing Buckskin Mountain Region.
Figure 5.2.4a: SEBASS MTMF mapping results, box inset shows zoomed in region shown in figure 5.2.4b.
Figure 5.2.4b: SEBASS MTMF mapping results showing Buckskin Mountain Region.
5.3 VNIR/SWIR/LWIR Final Composite Map

Using the best results from all the datasets in order to provide the most information on a single background a final composite map was produced. Table 5.3 shows each of the endmembers, the number of scene pixels mapped to that endmember, and the source of their mapped result. Figure 5.3.1a to 5.3.1c show the final composite maps displaying the extent of all mapped endmembers.

<table>
<thead>
<tr>
<th>Mineral/Material</th>
<th>Pixels Mapped</th>
<th>Processing Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alunite</td>
<td>19983</td>
<td>VNIR/SWIR SAM</td>
</tr>
<tr>
<td>Jarosite</td>
<td>865</td>
<td>LWIR SAM</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>27890</td>
<td>VNIR/SWIR SAM</td>
</tr>
<tr>
<td>Illite/Muscovite/Montmorillonite</td>
<td>9823</td>
<td>VNIR/SWIR MTMF</td>
</tr>
<tr>
<td>Quartz</td>
<td>11951</td>
<td>LWIR SAM</td>
</tr>
<tr>
<td>Opal Silica</td>
<td>633</td>
<td>LWIR MTMF</td>
</tr>
<tr>
<td>Water</td>
<td>2023</td>
<td>LWIR MTMF</td>
</tr>
<tr>
<td>Metal Roof</td>
<td>62</td>
<td>LWIR MTMF</td>
</tr>
</tbody>
</table>

Table 5.3: Final composite map scene endmembers.
Figure 5.3.1a: Final VNIR/SWIR/LWIR composite endmember map, box insets show zoomed in regions shown in figure 5.3.1b and 5.3.1c.
Figure 5.3.1b: Final VNIR/SWIR/LWIR composite endmember map from the National Mine region.
Figure 5.3.1c: Final VNIR/SWIR/LWIR composite endmember map from the Buckskin Mountain region.
Chapter 6: Field Sampling and Lab Analysis

In order to validate the remote sensing identifications, two field trips to the study area were made. The first was in July 2008 and the second was in October of 2009. Samples were collected during both field visits and were later used for lab analysis in order to verify endmembers and attempt to identify unknown endmembers. Validation was performed on scene endmembers originating from processing analysis that contained diagnostic spectral features that yielded a high confidence mineral identification only from the scene data. The following sections will discuss the fieldwork that was performed and results of that work in both identifying and verifying potential endmembers in previous data analysis.

6.1 July 2008 Fieldwork

The first visit, performed before the remote sensing data was in hand, was used as an opportunity to spend some time in the field area and get an idea of the geologic structure and diversity. Samples were collected of each of the geologic units mapped on the 1985 geologic map created by Dr. Peter Vikre. Originally it was envisioned that sampling each major rock type in the area would allow exploring the ability to map the geologic units using the lab spectral signatures from those samples.

Samples from thirteen geologic units were collected, and processed in the lab. Each sample was measured using the ASD in both whole rock and powder form and with the Nicolet FTIR in both powder and chip form to cover the entire spectral range of the remote sensing data, as described in Chapter 3. Many of these samples were from areas
outside the dataset coverage because the full extent of the data was unknown at the time and sampling location was referenced from the outcrop location mentioned in Vikre's work, where possible.

This provided a great opportunity to get introduced to the field area, and it also allowed for experimentation and experience using the lab equipment to process field samples. Table 6.1 shows an overview of the samples collected during July 2008. Figure 6.1 shows a geologic map with a NAIP color orthoimage background and collected sample locations. Appendix III will show a comprehensive collection of sample photos, and their laboratory collected spectral signatures in the VNIR/SWIR and LWIR. One sample of epiclastic sinter was also selected for XRD analysis.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Geologic Unit</th>
<th>Unit Description</th>
<th>UTM Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samp2</td>
<td>Tbx</td>
<td>Ryholite</td>
<td>11 T 454598 4623889</td>
</tr>
<tr>
<td>Samp3</td>
<td>Tql2</td>
<td>Quartz latite flow</td>
<td>11 T 455084 4623206</td>
</tr>
<tr>
<td>Samp4</td>
<td>Twt</td>
<td>Crystal-lithic rhyolite tuff</td>
<td>11 T 456860 4622674</td>
</tr>
<tr>
<td>Samp5</td>
<td>Tql1</td>
<td>Quartz latite flow</td>
<td>11 T 454536 4623876</td>
</tr>
<tr>
<td>Samp6</td>
<td>Tr3</td>
<td>Rhyolite</td>
<td>11 T 454500 4624024</td>
</tr>
<tr>
<td>Samp7</td>
<td>Tr2</td>
<td>Crystal-lithic rhyolite tuff</td>
<td>11 T 454565 4625782</td>
</tr>
<tr>
<td>Samp8</td>
<td>Tcs</td>
<td>Epiclastic and Sinter</td>
<td>11 T 454310 4626156</td>
</tr>
<tr>
<td>Samp9</td>
<td>Tri2</td>
<td>Vitrophyric rhyolite</td>
<td>11 T 454399 4623540</td>
</tr>
<tr>
<td>Samp10</td>
<td>Tmt</td>
<td>Tuff</td>
<td>11 T 453730 4624210</td>
</tr>
<tr>
<td>Samp11</td>
<td>Tmi</td>
<td>Andesite</td>
<td>11 T 453649 4624496</td>
</tr>
<tr>
<td>Samp12</td>
<td>Ta1</td>
<td>Andesite flow</td>
<td>11 T 453377 4624699</td>
</tr>
<tr>
<td>Samp13</td>
<td>Tr4</td>
<td>Rhyolite flow</td>
<td>11 T 453143 4624722</td>
</tr>
<tr>
<td>Samp14</td>
<td>Ta2</td>
<td>Andesite flow</td>
<td>11 T 452670 4624514</td>
</tr>
<tr>
<td>Samp15</td>
<td>JMS</td>
<td>Phylite</td>
<td>11 T 450355 4624448</td>
</tr>
<tr>
<td>Samp16</td>
<td>None</td>
<td>Silica/opal</td>
<td>11 T 453378 4624925</td>
</tr>
</tbody>
</table>

**Table 6.1:** July 2008 sample summary.
Figure 6.1: July 2008 sample locations.

6.2 October 2009 Fieldwork

The focus of this field visit was to sample endmembers chosen in the processing of the VNIR/SWIR/LWIR datasets both for verification and identification of the
endmembers. As the field area is at high elevation and it was late in the season field conditions were not ideal for sample collection as there was significant snow cover in much of the higher elevations. Due to the poor conditions it was decided not to try and obtain in situ field measurements with the ASD instrument but instead concentrate on obtaining field samples for later laboratory analysis. Eighteen potential endmembers samples were targeted, but due to the rugged terrain and poor conditions some sample locations could not be accessed. Using GIS location results for samples a handheld Garmin 60CSx GPS unit along with printed aerial photos for navigation 10 sites were located and sampled. Jarosite and opal sample locations used in the final mapping were unable to be accessed due to poor field conditions and high relief terrain. Comprehensive results from the lab analysis and sample photos are located in Appendix IV. Table 6.2 shows a summary of the endmembers sampled in the field, and figure 6.2 shows their locations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Remote Sensing Target</th>
<th>Description</th>
<th>Origin of Endmember</th>
<th>XRD</th>
<th>UTM Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay2</td>
<td>None</td>
<td>Unknown Clay</td>
<td>VNIR/SWIR</td>
<td>Yes</td>
<td>11 T 455104 4626192</td>
</tr>
<tr>
<td>Alunite</td>
<td>None</td>
<td>Alunite</td>
<td>VNIR/SWIR/LWIR</td>
<td>Yes</td>
<td>11 T 453757 4626395</td>
</tr>
<tr>
<td>Sample1</td>
<td>None</td>
<td>Unknown</td>
<td>VNIR/SWIR</td>
<td>Yes</td>
<td>11 T 452068 4631323</td>
</tr>
<tr>
<td>Sample2</td>
<td>None</td>
<td>Unknown</td>
<td>VNIR/SWIR</td>
<td>Yes</td>
<td>11 T 452307 4631873</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Kaolinite</td>
<td>Unknown</td>
<td>VNIR/SWIR</td>
<td>Yes</td>
<td>11 T 454346 4627235</td>
</tr>
<tr>
<td>Quartz</td>
<td>None</td>
<td>Quartz</td>
<td>LWIR</td>
<td>Yes</td>
<td>11 T 454181 4626623</td>
</tr>
<tr>
<td>Sunk1</td>
<td>None</td>
<td>Unknown</td>
<td>LWIR</td>
<td>Yes</td>
<td>11 T 452462 4631433</td>
</tr>
<tr>
<td>Sunk5/6</td>
<td>None</td>
<td>Unknown</td>
<td>LWIR</td>
<td>Yes</td>
<td>11 T 452462 4631433</td>
</tr>
<tr>
<td>Sunk8</td>
<td>None</td>
<td>Unknown</td>
<td>LWIR</td>
<td>Yes</td>
<td>11 T 452815 4631918</td>
</tr>
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<td>Sclay1</td>
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<td>Unknown Clay</td>
<td>LWIR</td>
<td>Yes</td>
<td>11 T 452314 4631768</td>
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</table>

Table 6.2: October 2009 field sample summary.
6.3 Scene Endmember Validation

Samples were prepared in the lab for analysis using the ASD and Nicolet instruments to produce spectral signatures in both whole rock and powdered form. In the
case of whole rock samples an effort was made to take the measurement from a weathered surface similar to what would be exposed in the field area. All XRD samples were prepared in powdered form. Samples were crushed, and sieved with a #35 screen and then powdered using a mortar and pestle. In the case of the kaolinite endmember from the VNIR/SWIR data initial identification on the in scene spectra did not agree with the results from the collected field sample. It turns out the kaolinite sample collected yielded a spectral signature that matched alunite. Since the kaolinite spectral feature is extremely diagnostic it's much more likely that some error in the sample collection location occurred. This could be due to a GPS location error or simply not collecting enough individual samples from the location to ensure a representative sampling. This is especially true in that much of the Buckskin Mountain region kaolinite areas intermix with alunite regions and there is extensive mass wasting occurring that can transport and mix surface materials. It is also possible that the kaolinite signatures in the field area were actually only a thin coating instead of bulk kaolinite and were overprinted during sample preparation. However, the ASD measurements taken on the field collected kaolinite whole rock samples on exposed undisturbed surfaces also yielded alunite spectral signatures. Figure 6.3a shows the VNIR/SWIR analysis results for the alunite endmember, Figure 6.3b shows the LWIR analysis results, and figure 6.3c the XRD analysis. The scene spectra indicate a good alunite match and the VNIR/SWIR ASD, LWIR FTIR, and XRD lab analysis also validate the presence of alunite in the field sample. Not all evaluations were this successful in some cases for unknown scene endmembers that were located in areas of mind dumps, leaching sites, or other ground disturbance areas field samples were still unable to be uniquely identified when compared
to reference libraries or using XRD analysis results. Appendix V contains more complete VNIR/SWIR/LWIR lab sample analysis verification results for the endmembers sampled along with XRD lab analysis results for the 10 samples selected for further XRD analysis.

![VNIR/SWIR in scene endmember spectra](chart.png)

**Figure 6.3a:** VNIR/SWIR dataset, field sample, and reference library spectral comparison.

Figures 6.3d to 6.3k show sample photos, ASD lab spectra, and Nicolet lab spectra from samples collected in the field for the alunite, kaolinite, quartz, and opal scene endmembers used in the final composite mapping from chapter 5. The jarosite and illite/muscovite/montmorillonite scene endmembers were not sampled due to poor field conditions making those regions inaccessible during the October 2009 field visit. As was mentioned previously the kaolinite sample turned out to be alunite so it’s results are not representative of the scene endmember.
Figure 6.3b: LWIR dataset, field sample, and reference library spectral comparison.

Figure 6.3c: XRD results confirming presence of alumite in field sample.

The “opal” sample is from the July 2008 collection and was identified in lab analysis as not being opal but quartz. The sample was not taken from a location resulting from scene
data analysis of the “opal” scene endmember. XRD analysis for the alunite, kaolinite, quartz, and opal samples can also be found in Appendix VI.

Figure 6.3d: Alunite field sample photo.

Figure 6.3e: Alunite field sample ASD and Nicolet lab spectra.
Figure 6.3f: Kaolinite field sample photo.

Figure 6.3g: Kaolinite field sample ASD and Nicolet lab spectra.
Figure 6.3h: Quartz field sample photo.

Figure 6.3i: Quartz field sample ASD and Nicolet lab spectra.
Figure 6.3j: “Opal” field sample photo.

Figure 6.3k: “Opal” field sample ASD and Nicolet lab spectra showing lab identification as quartz.
Chapter 7: Summary and Discussion

7.1 Discussion

7.1.1 Alunite mapping VNIR/SWIR/LWIR results comparison.

The alunite endmember made the best candidate in this study to compare the mapping results from the VNIR/SWIR and LWIR in both SAM and MTMF mapping as it is the only endmember that was mapped in all spectral regions used for this study. Figure 7.1.1 shows a zoomed in region from the Buckskin Mountain area using the VNIR/SWIR and LWIR alunite endmembers that were mapped in both the SAM and MTMF.

While they all show some of the same regions mapped as alunite there are significant differences in the total scene area mapped as alunite. The VNIR/SWIR MTMF result maps the least amount of scene as alunite while the LWIR MTMF maps the largest scene area as alunite. The LWIR also seems to show more consistency in the regions mapped as alunite compared to the VNIR/SWIR. In the LWIR the differences could easily be explained by slight threshold differences as the SAM results map nearly identical areas just not quite the total extent as the MTMF. In the VNIR/SWIR there is less agreement in what regions actually contain alunite or not. There are numerous possible reasons for these discrepancies. First and foremost there is the level of threshold applied by the analyst when mapping the endmember and the differences in the endmember mapping algorithms of SAM and MTMF. Even small differences in threshold that may not be easily apparent in statistical averages across thousands of pixels or manual scene spectral evaluation can greatly impact the amount of the scene mapped as the endmember of interest.
Figure 7.1.1: Alunite endmember mapping results in the VNIR/SWIR and LWIR using both SAM and MTMF.
There are also differences in the spatial resolution, strength of the spectral feature of interest, sensor signal to noise ratio, spectral sampling and resolution, accuracy of the atmospheric corrections, and applied calibrations made at the time of collection. Any one of which can effect how well endmember mapping results would correlate from one dataset to another. There is also the issue of the diagnostic spectral feature of the endmember itself and how it relates to the spectral features of other minerals. An endmember may not have a very distinct spectral feature or features, making it easy to confuse with other spectra in the scene. Even if the scene endmember does have a very distinct feature it may not be unique compared to other endmember spectral features. The issue of multiple minerals having similar diagnostic spectral features was clearly demonstrated in the illite/montmorillonite/muscovite endmember spectral comparison in Figure 5.1.5a. They all have diagnostic absorption features, but due to their overlap and similarity it’s difficult to identify which mineral is which without additional information or field sampling.

Take for example a potential worst-case scenario of a field area that is known to have illite, montmorillonite, and muscovite contained within it. Attempting to delineate these endmembers from each other would be extremely difficult without extensive field sampling in the VNIR/SWIR data alone. However, this is another benefit of having LWIR data as two minerals may have very similar diagnostic features in the VNIR/SWIR but may have very different features in the LWIR. Having the LWIR dataset can allow for an attempt at delineating the two minerals from each other as long as they can be separated by distinct spectral absorption differences in those wavelengths. So while a
comparison of regions mapped as the same mineral across wavelength regions can be extremely complicated, and may not even be possible, having multiple wavelength regions available can help delineate minerals that have similar spectral features in another wavelength region and could not be delineated.

There are also georeferencing issues, in both cases of the SpecTIR VNIR/SWIR and SEBASS provided datasets the endmember mapping results had to be adjusted to the NAIP background image due to georeferencing errors. This was found to be less of an issue with the SpecTIR data than with the SEBASS data, but both datasets needed some adjustment to overlay accurately with other geospatial datasets, in some cases over 100 meters of error was corrected for with the SEBASS results. In the National District there is extensive terrain and vegetation variation and many roads, etc. that can be used to accurately adjust the alignment of the mapped results in GIS. However, for regions that may be more featureless or are very homogeneous in nature it may make exact location of the mapping results very difficult especially if the mapped regions are very small. This further complicates field sampling as well since georeferencing errors in the data end up being sample location errors on the ground when trying to sample an endmember of interest.

7.1.2 Geologic Mapping Comparison

An attempt was made to compare the results of the mineral maps resulting from VNIR/SWIR/LWIR to a georeferenced version of Dr. Vikre’s geologic map produced in 1985. Three comparison images were produced and are shown in figures 7.1.2a to 7.1.2c. Only two correlations in comparing the results appear to be well supported. The
first is that the quartz/sinter mineral endmember is well correlated with the geologic maps epiclastic hydrothermal quartz and sinter unit (Figure 7.1.2b) in the Buckskin Mountain region. The second less directly correlated item of interest is that the illite/montmorillonite/muscovite mapped endmember in the National Mine region follows a very linear trend that overlays directly onto the mapped National Vein structure (7.1.2c). However, this trend of linear mineral exposure may be due to past mining processes along the vein. A more broad relation is that the mineral endmember mapping also shows quartz/sinter at the highest elevations of Buckskin Mountain, followed by kaolinite clays, and alunite as elevation decreases. This sequence is the same as is mentioned in Vikre’s study of the alteration products of Buckskin Mountain that are controlled by their original subsurface elevations to the hydrothermal system that drove the alteration 15-16 million years ago.

It’s important to keep in mind that there are fundamental differences between a remote sensing mineral endmember map and a geologic map. The geologic map used here is not concerned with minerals created by hydrothermal alteration processes and lumps together regions of mass wasted or erosional processes in the field area. Regions in the geologic map that have high levels of mass wasting, such as the Buckskin Slide are mapped entirely as a single landslide debris unit where the remote sensing results map variations in the surface minerals in these mass wasting areas. The geologic map units are regional bedrock units and for the most part do not take into account their alteration products aside brief mentions in the unit descriptions, and may have little to no surface expression throughout most of the field area. On the other hand the remote sensing results do not easily identify the bedrock units, in fact sinter/quartz was the only
Figure 7.1.2a: VNIR/SWIR/LWIR composite map results compared to Vikre’s 1985 geologic map of the same region. Quartz unit on left (magenta) correlates well to the epiclastic sinter unit on the right (dark grey).

unit that was identified in the endmember map that is the same in the geologic map. The remote sensing maps also do address mass wasting and mineral transportation issues as well. A sub millimeter coating of clays on a rock from weathering or eolian transportation and remote sensing analysis will map the rock as a clay endmember. So in many ways the geologic map and the remote sensing mineral endmember map are mapping different things, however used in conjunction with each other they can supplement each other.
These differences can be used to an advantage in that they both can provide useful information about a region. Certainly bedrock geologic maps can provide structural and fundamental lithologic information, however they are not as useful for identification of alteration products that can be used to help identify targets of interest for exploration. The remote sensing mineral maps produced here consistently showed endmembers that were results of hydrothermal alteration processes and were located within close proximity to known resources at both the National Mine and Buckskin Mountain areas.

**Figure 7.1.2b:** Buckskin Mountain VNIR/SWIR/LWIR composite map compared to Vikre’s 1985 Geologic map unit. The Quartz endmember from the VNIR/SWIR/LWIR result on left (magenta) correlates well to the epiclastic quartz/sinter unit from the geologic map (dark grey unit in center) on right.
In addition, the initial RGB composite and DCS images also successfully highlighted broad areas of alteration in scene at both the National Mine and Buckskin Mountain regions. This type of broad first look analysis is useful for looking for targets of interest in a region to focus further analysis on and typically may not require hyperspectral data but can be performed with multispectral data as well. Further hyperspectral analysis such as was performed in this study can provide more detailed mineral endmember maps and yield additional information about those regions and the alteration itself that may help support or reject possible targets of interest for further exploration.

**Figure 7.1.2c:** National Mine VNIR/SWIR/LWIR mapping result compared to Vikre’s 1985 geologic map. Illite/montmorillonite/muscovite endmember shown in green on the right correlates well to the National Vein linear NW trending structure shown in the black dashed line on the left.
7.2 Summary

This study examined the VNIR/SWIR and LWIR wavelength regions of hyperspectral datasets covering the National Mining District in order to explore their usefulness and their potential to complement each other for the purposes of mineral resource exploration. The evaluation of the results of processing each dataset and comparing the minerals each was capable of identifying and mapping has shown that having hyperspectral LWIR data certainly can add unique and useful information to the more commonly evaluated hyperspectral VNIR/SWIR data.

The VNIR/SWIR data was capable of identifying several important alteration products in the National District such as alunite, kaolinite, and illite/muscovite/montmorillonite. The LWIR data was able to map quartz, opal sinter, and jarosite endmembers and provide additional verification and increased confidence to the VNIR/SWIR mapped regions of alunite. The progression of mapped minerals seen at Buckskin Mountain constrained by elevation from quartz/sinter to kaolinite to alunite also followed the expected pattern of elevation controlled alteration products from previous work in the area done by Dr. Vikre. However the surface extent of these alteration minerals is greatly exaggerated by transportation and mass wasting in high-relief regions of the Buckskin Mountain area. So while the minerals identified and the progression of them generally agrees with other studies the mapped extent is not representative of their actual alteration surface expression. This may seem like a disadvantage and does limit the accuracy of mapping the extent and location of the various alteration stages and their products. However, the ability to map the general
alteration products and their progression successfully is more than adequate to identify a target of interest for further exploration.

While this study concluded that having both hyperspectral VNIR/SWIR and LWIR datasets offers many advantages to maximize the number of minerals that could be identified and mapped, there were challenges as well. The first and foremost issue for exploration with hyperspectral data is simply the cost versus coverage problem. Hyperspectral flight lines cover only a few hundred meters of width and cost thousands of dollars per flight line so that purchasing large regions of hyperspectral coverage may not be financially possible for many companies. However, as the technology increases in demand and more and more uses are developed for the data better collection methods will improve the efficiency and lower the costs of data collection. In addition, some hyperspectral satellite instruments are being developed for deployment in the near future. While the ground resolution of satellite systems will be larger than the datasets used for this study, the ability to use hundreds of bands of hyperspectral data will undoubtedly provide a wealth of information and new findings beyond that currently available with multispectral satellite data.

The additional atmospheric correction required for the VNIR/SWIR dataset clearly showed that having the best calibrated and atmospherically corrected product yields significant improvements in the results for detection, identification, and delineation of scene endmembers. Georeferencing errors in the datasets, specifically the SEBASS data made comparing and overlaying exact mapped regions from the VNIR/SWIR and LWIR datasets difficult to do with high confidence. As this was one of the first datasets collected with both sensors at the same time, procedures and calibration methods will be
and already have been improved, and future datasets will have better georeferencing, sensor calibration, and atmospheric correction applied. Hopefully these advances will come with ever increasing speed as interest in hyperspectral datasets for the purposes of exploration continues to increase.

The National District study area was also a good analog for investigating the effects of moderate vegetation cover and high relief on the hyperspectral datasets and how it would impact endmember detection and mapping. The National District has almost 5000 feet of elevation change, which makes accurate georeferencing and atmospheric correction much more difficult, but also various levels of vegetation resulted in almost 40% of the scene containing no diagnostic mineral spectral information. In many previous studies flat non-vegetated regions are usually chosen because they are ideal areas for dataset collection. While that may be ideal for working with the data itself it’s certainly not typical of real world settings for most exploration targets.

Remote sensing is not likely to replace the results that an expert field geologist it can be a valuable tool in the exploration process. Remote sensing can relatively quickly identify potential targets of interest for further exploration. It is not feasible, in terms of expense or time, to send teams of geologists to map and explore hundreds of square miles of remote terrain. However, in areas that are reasonable candidates for remote sensing analysis, entire geographical regions can be looked at in a relatively short amount of time and at less expense. Remote sensing can also identify and delineate minerals that even the best field geologist would not be able to detect in the field using typical geologic field identification and mapping techniques. As hyperspectral datasets become more widely available and at lower cost they will provide a wealth of new information helping to
identify new targets of interest for exploration and further establishing itself as an essential tool for exploration.
References Cited and Additional Sources


Hunt, G. R. (1979), Near-infrared (1.3-2.4 \mu m) spectra of alteration minerals-- potential for use in remote sensing, Geo- physics 44:1974-1986.


Appendix I: Dataset Coverage

SpecTIR and SEBASS Dataset Coverage

SpecTIR VNIR/SWIR
SEBASS LWIR

1:50,000
Time sequence of the genesis of Buckskin Mountain from 16.5 Ma to present (modified from Vikre (2007),
Buckskin proposed paleosurface cross section (modified from Vikre, 2007).
# Appendix II: Sensor Specifications

## ProspektTIR-V (VNIR) Sensor

<table>
<thead>
<tr>
<th>Sensor head</th>
<th>Typical specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrograph</td>
<td>High efficiency imaging spectrograph. Smile and keystone &lt; 2 microns, F/2.4</td>
</tr>
<tr>
<td>Spectral range</td>
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**Fore optics options**

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</table>

**Camera**

- Progressive scan CCD camera

**Output**

- 12 bits digital

**Integration time**

- Selectable independent of image rate

**Shutter**

- Electromechanical shutter for dark background registration, user controllable by software

## ProspektTIR-S (SWIR) Sensor

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**Fore optics options**

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**Camera**

- Progressive scan MCT camera

**Output**

- 14 bits digital

**Integration time**

- Selectable independent of image rate

**Shutter**

- Electromechanical shutter for dark background registration, user controllable by software

## SEBASS TIR Sensor

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Appendix III: VNIR/SWIR/LWIR Scene Endmembers

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VNIR/SWIR Scene Endmember Spectra
LWIR Scene Endmember Spectra
Appendix IV: Summer 2008 Collected Sample Photos and Lab Analysis

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<td>Samp10</td>
<td>Tmt</td>
<td>Tuff</td>
<td>11 T 453730 4624210</td>
</tr>
<tr>
<td>Samp11</td>
<td>Tmi</td>
<td>Andesite</td>
<td>11 T 453649 4624496</td>
</tr>
<tr>
<td>Samp12</td>
<td>Ta1</td>
<td>Andesite flow</td>
<td>11 T 453377 4624699</td>
</tr>
<tr>
<td>Samp13</td>
<td>Tr4</td>
<td>Rhyolite flow</td>
<td>11 T 453143 4624722</td>
</tr>
<tr>
<td>Samp14</td>
<td>Ta2</td>
<td>Andesite flow</td>
<td>11 T 452670 4624514</td>
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<tr>
<td>Samp15</td>
<td>JMS</td>
<td>Phyllite</td>
<td>11 T 450355 4624448</td>
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<tr>
<td>Samp16</td>
<td>None</td>
<td>Silica/opal</td>
<td>11 T 453378 4624925</td>
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</table>

Sample Photos:

Samp2 - Tbx - Rhyolite Breccia
Samp3 - tql2 - Qtz Latite Flow

Samp4 - twt
Crystal Lithic Rhyolite Tuff
Samp7 - TR2 - Rhyolite Flow

Samp8 - Tes - Epislastic Sinter
Samp9 - Tri2
Vitrophyric Rhyolite

Samp10 - tmt - Tuff
Samp11 - tmi - Andesite

Samp12 - Ta1 - Andesite Flow
Samp13 - Tr4 - Rhyolite Flow

Samp14 - Ta2 - Andesite Flow
ASD VNIR/SWIR Spectra
Nicolet LWIR Spectra
Appendix V: Fall 2009 Collected Sample Photos and Lab Analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>Remote Sensing Target</th>
<th>Description</th>
<th>Origin of Endmember</th>
<th>XRD</th>
<th>UTM Coordinates</th>
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</thead>
<tbody>
<tr>
<td>Clay2</td>
<td>None</td>
<td>Unknown Clay</td>
<td>VNIR/SWIR</td>
<td>Yes</td>
<td>11 T 455104 4626192</td>
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<td>Alunite</td>
<td>Alunite</td>
<td>Alunite</td>
<td>VNIR/SWIR/LWIR</td>
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<tr>
<td>Sample1</td>
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<td>Unknown</td>
<td>VNIR/SWIR</td>
<td>Yes</td>
<td>11 T 452068 4631323</td>
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<tr>
<td>Sample2</td>
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<td>Unknown</td>
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<td>11 T 452307 4631873</td>
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<td>Kaolinite</td>
<td>Kaolinite</td>
<td>Kaolinite</td>
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<td>11 T 454346 4627235</td>
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<td>Quartz</td>
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<td>LWIR</td>
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<td>11 T 454181 4626623</td>
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<tr>
<td>Sunk1</td>
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<td>11 T 452462 4631433</td>
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<tr>
<td>Sunk5/6</td>
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<tr>
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<td>Unknown Clay</td>
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<td>Yes</td>
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</tbody>
</table>

Sample Photos:

![Clay2](image_url)
Alunite

Sample 1
ASD VNIR/SWIR Spectra

ASD Spectra October 2009 Samples

Value (Offset for clarity)

Wavelength - Micrometers

0.5  1.0  1.5  2.0  2.5
Nicolet LWIR Spectra
# Appendix VI: XRD Sample Analysis Results

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Source</th>
<th>XRD Analysis Results</th>
<th>UTM Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alunite</td>
<td>VNIR/SWIR/LWIR</td>
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</tr>
<tr>
<td>Clay2</td>
<td>VNIR/SWIR</td>
<td>Quartz, Muscovite, Calcite</td>
<td>11 T 455104 4626192</td>
</tr>
<tr>
<td>Quartz</td>
<td>LWIR</td>
<td>Quartz</td>
<td>11 T 454181 4626623</td>
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<td>Opal</td>
<td>2008 Field Work</td>
<td>Quartz</td>
<td>11 T 453378 4624925</td>
</tr>
<tr>
<td>Sample1</td>
<td>VNIR/SWIR</td>
<td>Calcite, Quartz, Ankerite</td>
<td>11 T 452068 4631323</td>
</tr>
<tr>
<td>Sample2</td>
<td>VNIR/SWIR</td>
<td>Quartz, Muscovite</td>
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</tr>
<tr>
<td>Sclay1</td>
<td>LWIR</td>
<td>Muscovite, Quartz</td>
<td>11 T 452314 4631768</td>
</tr>
<tr>
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<td>LWIR</td>
<td>Quartz, Orthoclase, Muscovite</td>
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<td>Sunk8</td>
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<td>11 T 452815 4631918</td>
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</table>

![XRD analysis graph for Alunite](image)