HYPERSPECTRAL EVALUATION OF MINE WASTE AND ABANDONED MINE LANDS NASA AND EPA SPONSORED PROJECTS IN IDAHO

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INTRODUCTION

The utilization of remotely sensed hyperspectral data for the evaluation of mine waste and the classification of abandoned mine lands (AML) is rapidly becoming a routine, commercial technology. Spectral International has assembled a consortium of companies and consultants to provide evaluation and monitoring capabilities through hyperspectral surveys using AVIRIS (Airborne Visible InfraRed Imaging Spectrometer) and new generation airborne sensors such as CASI (Compact Airborne Spectrographic Imager) and SFSI (SWIR Full Spectrum Imager).

Partly through the auspices of the NASA EOCAP program and the Environmental Protection Agency AML (Abandoned Mine Lands) Project, sites in Utah and Idaho are currently under investigation. This paper will present a preliminary look at the Idaho study and discuss the methods used. AVIRIS images and generalized analytical data will be shown in this paper as the hyperspectral CASI and SFSI images and most of the analytical data have yet to be released by the EPA

The EPA has made a commitment to the use of hyperspectral methods in the evaluation of mine waste distribution in the Coeur d'Alene River Basin project. The area under investigation is shown in **Figure 1**. This includes the lateral lakes area along the south fork of the Coeur d'Alene River from Rose Lake east to the Mission State Park, as well as the Canyon Creek and Nine Mile Canyon catchment areas and drainage.

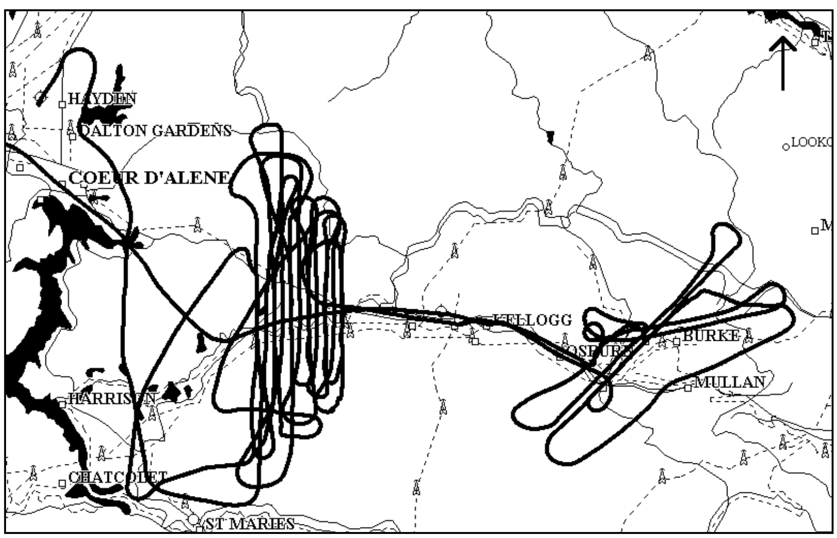

Figure 1. Coeur d'Alene river valley, showing SFSI/CASI flight lines.

OBJECTIVE OF THE STUDY

The objective of this study was to characterize and map the mine waste in the Coeur d'Alene River Basin and the mine sites in the contributing drainage. One way to accomplish this was by locating, and mapping areas of elevated lead and zinc concentrations and, if different, areas with low pH water (high iron). Cadmium and arsenic were secondary targets.

A second question to be addressed was whether or not vegetation could be used to map areas of high toxic metals and/or acidity. It would be of interest, for example, if we could associate stressed, dead or dying vegetation with high lead and zinc and/or low pH. Are there unique spectra signatures associated with this stressed vegetation that can be identified in the hyperspectral imagery?

OUTLINE OF THE METHOD

The use of Hyperspectral imagery for mineral mapping and identification is a relatively new methodology. Although the AVIRIS imaging spectrometer has been in existence for over ten years, work with this sensor has been largely experimental and developmental. The majority of the investigators working with the data have been from academic institutions and government research agencies. The past few years has seen the development of an increasing number of potentially commercial applications of AVIRIS at the same time as the appearance in the market of a new generation of commercial hyperspectral airborne instruments for routine operation.

Calibration, atmospheric correction algorithms and processing software are still relatively new and improving. Nevertheless, it is still necessary to "truth" the airborne data with field studies, and by using various analytical techniques. Different applications require slightly different approaches. For the Coeur d'Alene study, the following was used:

1. Geologic Background and Historical Information
2. Field Reconnaissance
3. Airborne Data Acquisition
4. Analytical Support
5. Integration of data sets – Spectral Library
6. Image processing
7. Field check images
8. Results and Products

BACKGROUND AND HISTORICAL INFORMATION

When a study is first started, an attempt is made to assemble as much definitive background information as possible. The resulting informational framework is used to provide the context for interpreting the remote sensing data. Such contextual information would include mining and metallurgical processing history, economic geology, and geochemistry.

Mining History

Researching mining in the Coeur d'Alene area involved a literature review going back to the last century, and included visits to old mine and mill sites. Mining was underground which generally kept waste rock movement to a minimum. The early treatment processes used gravity methods. This produced waste ("jig" tailings) with high concentrations of unrecovered lead and zinc minerals, which was dumped into the streams, and allowed to migrate down river. Later milling processes were more efficient but still failed to recover ultra-fine free and locked sulfides. Until the 1960s, the tailings were often unmanaged, and much was dumped into the drainage system.

Geological Summary

Folded and faulted Precambrian sediments of the Belt Supergroup dominate the geology of the area. These include clastic sediments (argillites, siltstones, sandstones and quartzites) in the lower part (Prichard, Burke, Revett and St. Regis Formations), and more carbonates (dolomites) in the upper part (Wallace and Striped Peak Formations). The lead-zinc-silver mineralization is hosted predominantly in the lower formations, where they occur as vein-type deposits. These veins are filled with a quartz-siderite (±ankerite±Mn-dolomite) gangue, with associated Al-rich mica (muscovite) mixed with chlorite in the immediate wall-rock. Sphalerite, galena and tetrahedrite dominate the ore mineralogy. Pyrite, pyrrhotite and chalcopyrite also occur but may only be important locally. From this mineralogy, the main toxic metals are lead, zinc and cadmium. Iron and sulfur are ubiquitous but not necessarily abundant (Gott and Cathrall, 1980).

The secondary (oxidized) mineralogy includes anglesite and cerrusite, as well as hematite and goethite in gossans. There is limited jarosite as the pH in the study area was not generally acid. Illite occurs as a result of the degradation of the mica. In the soils, smectite occurs as a weathering product.

FIELD RECONNAISSANCE

The first field reconnaissance was done in early October. The following types of information were collected:

- SWIR range reflectance spectra from rocks, soils, sediments and vegetation
- Solar spectra for reflectance calibration and vegetation spectra.
- Portable X-Ray Fluorescence chemical analyses of the same
- Digital and film photographs of sample sites;
- GPS coordinates for the sample locations and control points.

The **PIMA** (portable infrared field spectrometer) was used to collect infrared reflectance spectra of tailings, ore, rocks and soils. Representative spectra were chosen from this data set and used to construct a spectral reference calibration library for the Coeur d'Alene project. This information was then used to determine the minerals present and to spectrally calibrate the airborne data. The target minerals that have been identified with the tailings and the dump materials, are degraded, yet still identifiable, aluminum-mica and siderite. **Figure 2** shows PIMA spectra for the more common infrared active, mineral, species encountered in the Coeur d'Alene study.

The **GER 2600** (Geophysical Environmental Research) is a solar-illuminated, field spectrometer with VIS through SWIR range. It was used to collect field spectra of trees, grass and bushes in the study area as well as calibration data for the airborne sensor. Selected field collected spectra were used in the vegetation solar illuminated spectra reference library. It was considered very important, however, to have an accurate representation of plant reflectance properties. The GER data were supplemented with CARY laboratory data as weather conditions during the fieldwork were generally cloudy, and solar instruments are very sensitive to cloud cover.

A portable **X-Ray Fluorescence (XRF)** unit was used in the field to acquire chemical information on the distribution of the toxic metals. Extensive analyses were performed on the country rocks, ore, dumps, tailings, wastes, and soils, as well as the trees, bushes and grasses. This information was then integrated with the infrared data and overlain, together with the mineralogy, on the images.

The main vegetation types were conifers (white pine, lodgepole pine, western red cedar, Douglas fir), aspen, larch, cottonwoods, fragmeites and grasses. Gott and Cathrall (1980) showed that the Douglas Fir and White pine assimilate lead. This is supported by field XRF analyses, as one of the objectives of this study was to correlate vegetation with lead distribution. It is probable, however, that most of the lead intolerant species have been eliminated from this ecosystem through lethal exposure, resulting in the development of high tolerance levels in the survivors. An alternative attempt is being made to evaluate the distribution of lead tolerant species to verify the correlation.

GPS (Global Positioning System) was used to collect geographic location information for control and calibration points, and sample locations. The Trimble unit used was accurate to better than 3 meters.

It was considered important to have a **photographic record** of the locations sampled as well as the general aspects of the terrain and vegetation in the area. This provided a visual reference to investigators involved in data compilation and evaluation, and assisted image processors when classifications were determined. Moreover, it stands as a visual archive for future utilization and interpretation. For this study, both digital and film photographs were taken. The digital photographs were transmitted electronically to the airborne survey crew and the image processors to familiarize them to the survey area.

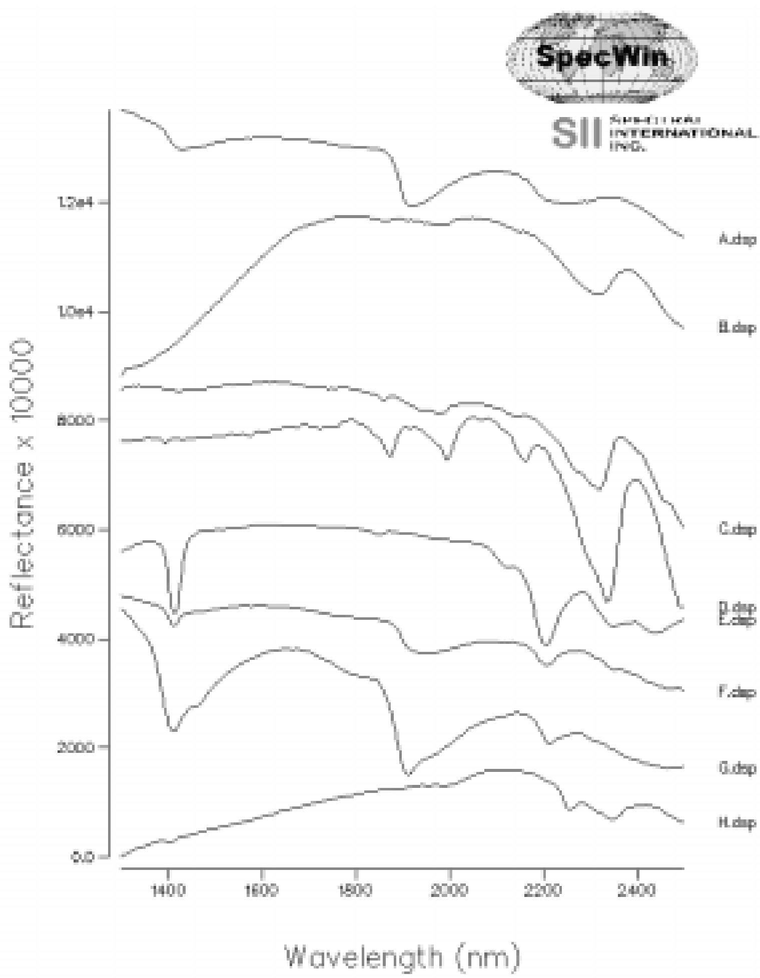

Figure 2. Representative PIMA spectra of minerals from the Coeur d'Alene survey. These include [A] silica, [B] siderite, [C] dolomite, [D] calcite, [E] muscovite, [F] illite, [G] montmorillonite and [H] Fe-chlorite.

ANALYTICAL SUPPORT

The advantage of field portable, or hand-held, internal light-source spectrometers is that they provide a rapid, in-situ analytical method. With experienced users, appropriate software and spectral libraries, most infrared active mineral suites can be identified in the field. However, there are situations where it is prudent to verify the identification with laboratory analysis. For the Coeur d'Alene project, X-ray diffraction was used to verify and supplement mineral identifications. The CARY laboratory spectrometer was used to acquire spectra and identify vegetation types and iron compounds.

AIRBORNE SENSORS AND DATA ACQUISITON

Data from three sensors was used in this study: AVIRIS, SFSI and CASI. The AVIRIS was flown for NASA, by the Jet Propulsion Laboratory at 65,000 feet over the Coeur d'Alene valley in September 1995. GA Borstad Associated flew the SFSI/CASI combination in late October of 1998. This was flown over limited areas as this was a test flight to demonstrate the application of a refined hyperspectral sensor to this type of study. The principal areas flown were the lateral lakes (Mission Flat-Cataldo-Rose Lakes) and in Canyon and Nine-Mile Creeks.

Table 1. Airborne instrument configurations

	AVIRIS	SFSI	CASI
Band width	12 nm	10 nm	2-4 nm
Spectral range	400–2500nm	1220-2320 nm	403-1000 nm
FoV		35^o	35^o
Ground pixel size	17 m	4 m	4 m
Swath width	11 km	2 km	2 km

IMAGE PROCESSING

There are numerous government, university and commercial image processing programs available. The ENVI program, with custom modifications to the data sets, was the main program used to process the data in this application. Hyperspectral image processing is still a relatively new discipline. The production of a high quality hyperspectral image is a process requiring numerous calibrations, calculations and refinements.

One of these refinements is the integration into the images, of spectral data from high resolution field spectrometers. This allows a more precise determination of end-members for the program to map and use in "unmixing" algorithms. It also pre-supposes an in-depth understanding of mineralogy and the local geology. In theory, the ideal situation would be to allow the computer program to search, identify and classify the components of the image. In practice, this does not yet work effectively. When the investigators have an idea of what is on the surface or what particular mineral or material is targeted, and have spectra of the targets, processing will be more accurate.

The Coeur d'Alene Project required very complex and detailed image processing as there are numerous diverse components to these images including vegetation, wetlands, mine waste dumps, tailings dumps, disseminated tailings, stream sediments, iron coated surfaces on river gravels, precipitates, algal mats and soils.

Three different approaches were used to analyze this data and produce images of varying complexity. The first employed general processing techniques based more on the Landsat methods. This was followed by Classification procedures. These are done with a less conventional approach utilizing field spectral data collected before processing starts and integrated with the images. To validate this technique, the pure pixel end member Boardman method was implemented (Boardman, 1993).

The raw data was first calibrated using proprietary internal programs. An IARR correction was next applied to correct to relative reflectance. The image was warped to control points chosen from topographic maps, ortho-digital photographs and GPS points. It is not unusual to use hundreds of control points to correctly rectify an image. The initial images were created through a general processing technique, which chose contrasting bands to a target material band. This created a pseudo-false color. The Crosta processing algorithm was used to highlight the iron minerals. These two images provide a coarse idea of what materials are present and their distribution.

AVIRIS False Color (Lateral Lakes)

This rectified image is a pseudo-false color (**Figure 3**), using 1200, 1700, 2200 nanometer bands as RGB. These were chosen to highlight the Al-OH absorption, shown by field work to be characteristic of tailings, and some soils. These appear in the original images as blue pixels but are circled in this reproduction. This spectral signature is interpreted to be from muscovite (mica) that weathers to illite.

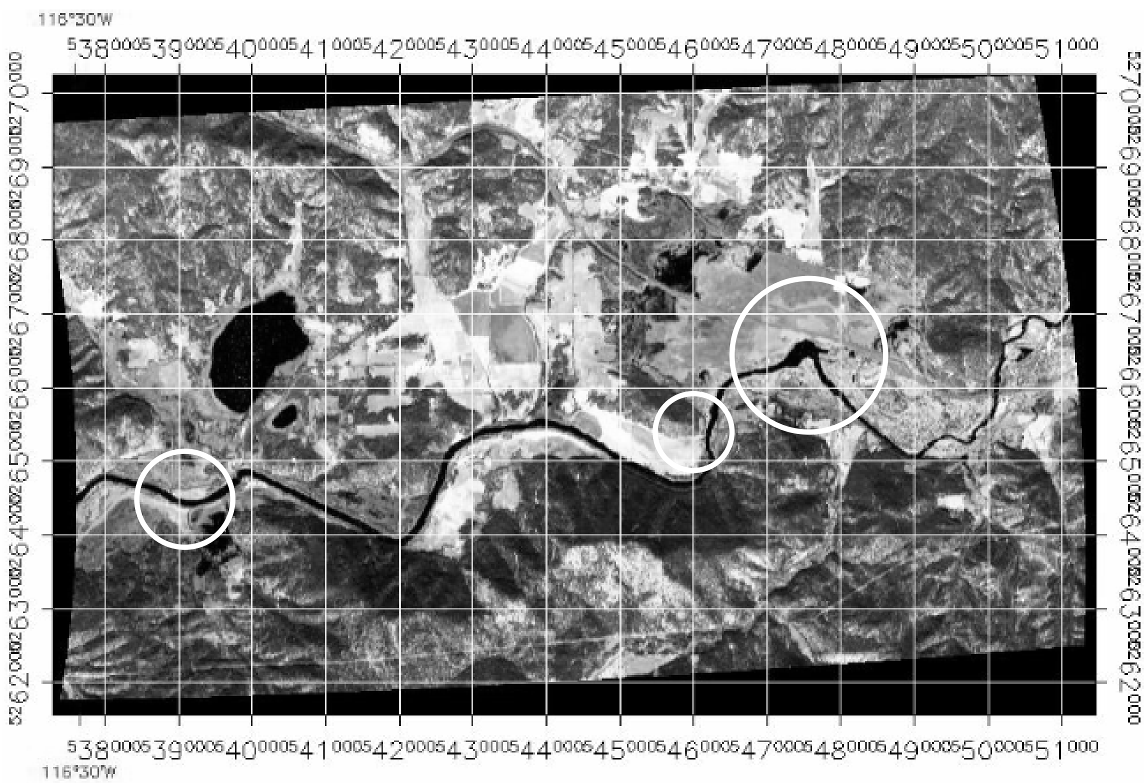

Figure 3. Rectified pseudo-false color image of the lateral lakes along the Coeur d'Alene River. Blue pixels in the original image appear in this reproduction as light gray but are circled.

The reworked tailings in the dredged area at the Old Mission State Park are an intense blue, potentially indicating a higher concentration of the mica constituent. The tailings are spread along the interstate highway, which is a ribbon through the image. `Note how they are trapped in the river bends especially at ^{52}64000x ^{5}39000; at ^{52}65000 x ^{5}46000 and ^{52}65000 x ^{5}49000 – east. The Forutchey Farm Field at ^{52}65000 x ^{5}46000 shows a break out of the river and dissemination of the tailings into the soil of the fields. There is a delta at ^{52}66000 x ^{5}49000; a marsh at ^{52}68000 x ^{5}46000; and Bull Run Lake with floating algae just to the right of ^{52}64000 x ^{5}39000. Agricultural fields dominate the central part of the images and show tans and browns and orange coloration. Care must be taken in the interpretation of the slopes, especially in the southern part of the scene where shadow and oblique angles can distort the data.

AVIRIS Crosta/Iron (Lateral Lakes)

Several Crosta technique images were created to generally show and enhance the iron mineral distribution. The distribution of much of the iron should link to the oxidized ore minerals and their by-products and thus link to the toxic metals. The problem is that the iron is, for the most part, amorphous and it is very difficult to isolate a diagnostic spectral signature for the different phases that might exist. Farrand and Harsany (1995) processed the same AVIRIS data, and remarked on the inability of highly specialized algorithms to discriminate the iron species. The first Crosta images produced were dominated by clay.

AVIRIS False Color (Canyons)

The same type of processing (geocorrection; IARR correction to relative reflectance) was applied to the segment of the AVIRIS flight lines (Scene 7 with part of scene 6 spliced on the western edge) that covered Canyon Creek and Nine Mile Canyon, just north out of Wallace. **Figure 4** is RGB with AVIRIS bands 89, 142, 191 (SFSI bands 10, 48, 94). There are only nine control points for the warp of this image. A first order linear warp was done and the fit is very good, especially along the creek bottoms. This is important because much of the contamination occurs in narrow zones (< 4 meters wide) that define creek beds and their banks, where toxic metals are carried in the bed load, and adsorbed into iron precipitates and algal matter

Because the terrain in this image is mountainous and largely forested, the general appearance is quite different from the flatter, lateral lakes area. However, it can be seen from the distribution of the blue color (circled on the figure), that the streambeds contain significant amounts of the 2200-nanometer band region clays. The very bright, whiter patches, are for the most part, bare ground and scree slopes. Most of the areas of intense blue (also circled) contain mine dumps. The higher resolution sensors (SFSI and CASI) have been able to should highlight these mines, dumps and waste in greater detail.

Classification Processing

The authors preferred the classification format because it allowed more interaction with and control of the images. Additionally, there were varied and specific targets, which could be better addressed, in separate images. One of the most effective ways of doing classifications was to use PIMA spectrometer field data. The PIMA data were analyzed, identified and representative spectra chosen. These spectra were then imported into the image-processing program.

At this stage, the background knowledge of the area became important and was used to evaluate the best choices in the PIMA site library. Those choices were compared and matched to SFSI / AVIRIS spectra, in the image, at sites where selected PIMA spectra were collected. The sensor spectra were then used to train the image, by selecting comparable spectra, matching them with varying degrees of confidence and integrating them into a classification image.

One important target was the tailings, as these are a recognized source of toxic metal contamination in the area. The reworked tailings at Mission Flats were chosen as a pilot study area although several other sites were also visited and tested. It was determined from the spectra that the major mineral in the tailings at this site, are degraded muscovite mica, silica and the iron carbonate, siderite (confirmed by X-ray Diffraction Analysis by Anne Thompson of Petrascience in Vancouver, B.C). Several XRDs were able to duplicate this and other identifications.

The hypothesis made with the tailings at Mission Flats is that the combination of the siderite carbonate and mica would be the easiest spectrum to identify associated with the tailings. Numerous close matches were made between the spectra from AVIRIS pixels extracted from the center of the dredge tailings and PIMA spectra from pits in those tailings and SFSI pixels from the same location. The closest match was chosen as a reference for processing. The resulting classified image is shown on **Figure 5**. Tailings in the original are colored with a distinctive yellow but here are circled.

INTEGRATION OF DATA SETS

Mineralogical, chemical, botanical and spectra data sets were compiled together with their GPS coordinates. These have been overlain upon processed images, in a GIS format, as part of the final product.

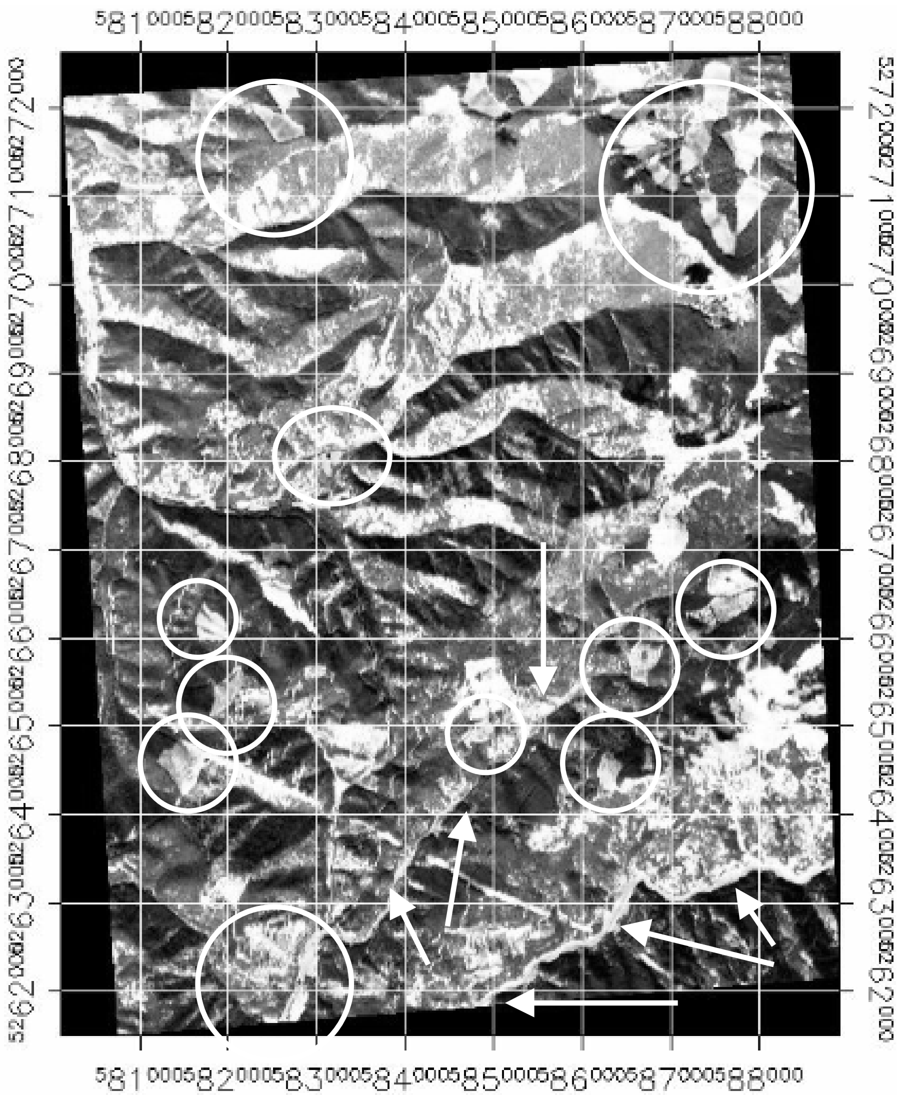

Figure 4. Rectified pseudo-false color image of the Canyon Creek and Nine-Mile Creek drainage. The 2200-nm spectral highlights (blue on the original image) are indicated with arrows and circles.

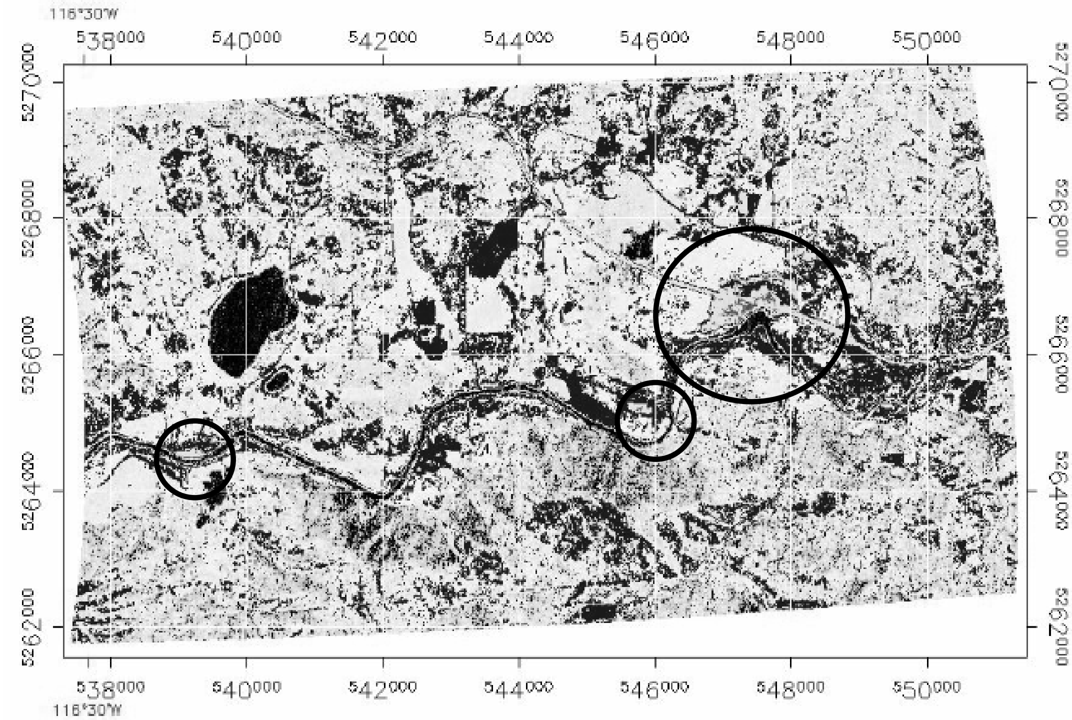

Figure 5. Classified image showing 2200 nm band, representing tailings (circled). These are a distinctive yellow color in the original image.

RESULTS AND PRODUCTS

The last stage prior to printing the final product is field checking of images and integrated data maps for accuracy, consistency and common sense. After that additional corrections and refinements can be applied if required. We have a high rate of success and usually get a 90% match between the field data and the images.

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