Investigating *casi* Responses to Different Levels of Tailing Oxidation: Inco Copper Cliff Tailings Area, Northern Ontario, Canada

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Abstract

*Sulphide-rich tailings cause acid mine drainage (AMD) when they are in contact with oxygen and water. AMD can contaminate surface and ground water, which in turn can degrade the quality of the environment. Knowledge of the progress of oxidation and also the spatial distribution of tailings materials are of considerable importance when developing programs to provide effective control of tailings sites. In this paper, the potential of Compact Airborne Spectrographic Imager (*casi*) data for providing information on variations in the oxidation of tailings is investigated.*

Spectral-mode casi *data were acquired on August 19, 1998 in 72 bands covering the wavelength range of 400 nm to 950 nm. Twenty-one tailings samples were collected concurrently with the* casi *overflight. Reflectance was measured at all the sample locations using a GER 3700 spectrometer. Sample spectra from the GER were matched with the minerals from the USGS spectral library. Spectral matching revealed that the most likely minerals on this site are pyrite, pyrrhotite, jarosite, and goethite. Image spectra extracted from the casi data over the same sample locations were also matched to the USGS spectral library. Similar results were found in spite of the limited spectral coverage of the* casi*. Spectral unmixing of a test site within the* casi *imagery demonstrated the potential of this instrument to provide information on separating the zones of varying oxidation in the tailings. However, no direct relationships were found between the oxidation phases and the age of the tailings.*

Introduction

Most mine tailings contain a considerable amount of reactive sulphides which, when exposed to oxygen and water, will result in breakdown and oxidiation of the sulfide minerals that eventually lead to acid mine drainage (AMD) (Pearson *et al.*, 1997). AMD typically has pH values in the range of 2-4 and high concentrations of metals and dissolved salts which can cause ground- and surface-water contamination (Ash *et al.*, 1951; Nordstorm and Apers, 1999).

The occurrence of AMD has been identified as the largest environmental problem facing the Canadian mining industry. There is a clear need for developing methodologies for the repetitive, long-term monitoring of mine-tailing sites to ensure that

damage to the environment is kept to a minimum. In recent years, remote sensing techniques have gained increasing popularity over the traditional surface methods for monitoring mine-tailing sites (Farrand and Harsanyi, 1997; Lévesque *et al.*, 1997; Pearson *et al.*, 1997; Boine *et al*, 1999; Shang *et al.*, 1999; Swayze *et al.*, 2000). It is general believed that spectra covering both the visible and the short-wave infrared are needed for mineral mapping. Image data covering only the visible and near-infrared (VNIR) wavelengths are not considered adequate for mineral detection. This is because of the strong absorption features of minerals occurring in the short-wave infrared region of the electromagnetic spectrum. However, a study by Shang *et al.* (1999) revealed that Compact Airborne Spectrographic Imager (*casi*) data can be used to detect the occurrence of acid mine drainage through the association of oxidized tailings with iron oxides. Genesis of iron oxide minerals is a direct consequence of the chemical process leading to AMD generation. Iron oxides are optically typified by various shades of yellow, red, and brown colouration in rocks, soils, and water. They can be identified using the VNIR portion of the spectrum as recorded by the *casi* sensor. The results of this study will assist mining companies in monitoring the migration of AMD. Using remote sensing as a screening tool to identify possible affected sites, a more detailed survey can be conducted targeting these key areas in order to reduce the time and cost. Accordingly, proper control can be applied to mitigate the negative impact of mine tailings on the surrounding environment (Swayze *et al.*, 2000).

This current study investigates the potential of *casi* data for more detailed mine-tailing characterization and AMD detection. The data used are from three sources: high-spatial-resolution hyperspectral *casi* imagery, field spectra acquired with the GER, and mineral spectra from the United States Geological Survey (USGS; USGS, 2000) spectral library.

Study Site

The study site is located at Inco Limited's Copper Cliff tailings complex, Ontario, Canada. It is the largest acid-generating tailings site in Canada, approximately 22.3 km^2, and has resulted from approximately 100 years of mining operations (Puro *et al.*, 1995). Through the years, the tailings areas have been partitioned by tailing dams and have been named alphabetically, A to R, from the oldest to the most recent (Figure 1). Areas A to Q are inactive tailings and have been subjected to intensive reclamation activities, including liming and revegetation. Area R is still receiving tailings. This setting provides an excellent opportunity to study the evolution of tailings over time. Individual partitions within the tailings complex contains a range of mine-tailing compositions with different levels of vegetation regrowth. The major surface-cover types are fresh tailings, oxidized tailings, tailing-retention ponds, rock outcrops and vegetation. The average altitude is 300 m above sea level with an elevation range of 30 m.
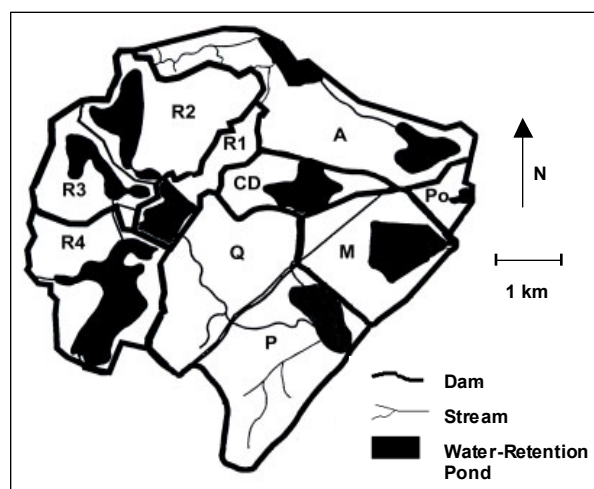

Figure 1. Map of the study site (Modified from Puro et al., 1995)

Data Acquisition and Preprocessing

Hyperspectral *casi* imagery was acquired over the study site on August 19, 1998 from an altitude of 2100 m. The entire tailings were covered with eight flightlines. The data were collected in 72 bands between 400 nm and 950 nm. The bandwidth at full width of half maximum (FWHM) is 10 nm with a spectral sampling interval of 10 nm. The spatial resolution is 4 m by 4 m, resulting in a swath width of 1.6 km (406 pixels).

Tailings samples were collected at 21 locations through the study site concurrently with the *casi* data acquisition. The samples cover different tailings areas within the mining complex to include

tailings of various mineral compositions and oxidation stages. Locations of the sample points are shown in Figure 2. Each sample was gathered from the top of the tailings surface. Reflectances of the tailings samples were measured in the laboratory using a GER 3700 spectroradiometer. The measured reflectance covers 400 nm - 2500 nm of the electromagnetic spectrum.
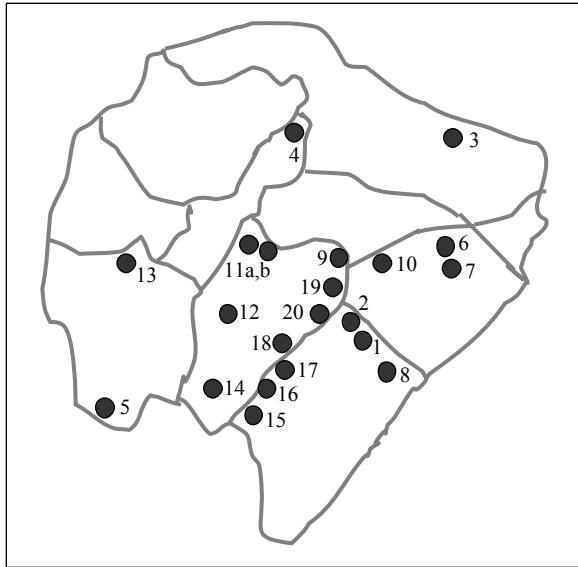

Figure 2. Locations of the tailings samples

Preprocessing of the *casi* data involves three steps: noise removal, atmospheric correction and spectral post-processing. These preprocessing steps will ensure the later extraction of clean endmember spectra which will subsequently lead to better unmixing results.

Noise Removal: This step was carried out in principal component (PC) feature space using the unstriping module implemented in the Imaging Spectrometer Data Analysis System (ISDAS: Staenz *et al*., 1998). Initially, a PC transformation was performed on the original *casi* radiance data. By doing this, the striping (non-periodic banding noise) and random noise inherent in the original radiance data were enhanced and separated from the signal. The first 6 PC features are of good quality; therefore, they were excluded from this process. The unstriping procedure adjusts the mean of the stripes by applying a gain to that stripe to remove the striping. This is achieved by

initially plotting the mean of each line for the remaining PC features against the line number. A triangular smoothing was then applied to the mean curve to remove the spikes in the spatial domain. This enabled the computation of a correction factor (gain) for each line to adjust the original mean values to the smoothed ones. Random sensor noise was eliminated by passing a 3 by 3 average filter through the data. The noise-removed data cube was then inverse-transformed back to its original band form. Figure 3 shows the effect of noise removal from the *casi* data.
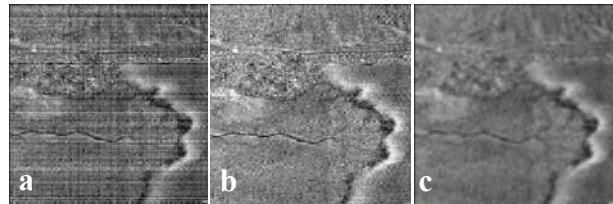

Figure 3. Principal component feautre 9 of casi radiance data of the test site a) original, b) unstriped, and c) spatial averaged

Reflectance Retrieval: The noise-removed *casi* radiance data were converted to reflectance using the surface reflectance retrieval procedure in ISDAS. This procedure, developed by Staenz and Williams (1997), is based on a look-up table (LUT) approach to remove atmospheric effects. It considers the wavelength, pixel position, atmospheric water vapour, aerosol optical depth, and terrain elevation for the generation of the LUTs. The MODTRAN3 radiative transfer code was used to create the LUTs. Figure 4 shows a retrieved *casi* reflectance image of the test site.
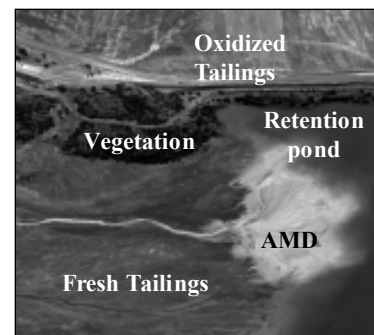

Figure 4. Sub-scene of the casi reflectance image (band 35 centred at 661 nm)

Methods

The study is intended to investigate the potential of *casi* data for mapping variations in tailings

oxidation. This was accomplished through two approaches. First of all, fraction maps of the test site were studied to reveal the spatial relationship of the endmembers. Secondly, GER spectra and *casi* image spectra were compared with minerals from the USGS spectral library.

Spectral Unmixing: Using the *casi* reflectance data, constrained linear spectral unmixing was performed with 10 endmembers on the test scene. These endmembers were selected from the image data with the automated endmember selection tool implemented in ISDAS. This technique applies an iterative error analysis (IEA) scheme to automatically extract endmembers from an image cube (Szeredi *et al.*, 2000). The IEA method performs a series of constrained unmixings, each time choosing as endmembers those pixels with the largest errors.

Spectral Matching: Spectral matching was conducted on all of the GER-measured spectra by comparing them with the 498 mineral spectra from the USGS library. Both spectral angle and correlation measures were used to perform the spectral matching.

Spectral matching was also conducted using spectra extracted from the *casi* data at the same locations where the samples were taken. The *casi* spectra were then compared with the USGS spectral library to investigate whether the spectral matching will reveal similar results to the GER spectra.

Results and Discussion

Spectral Unmixing: The results of the constrained linear unmixing using the 10 endmembers were examined in the form of fraction maps. Endmember fraction maps permit the comparison of the variabilities of fractions of the endmembers in a spatial context. The resulting fraction maps discriminate between surface cover types: vegetation, fresh tailings, various oxidized tailings, and water. Among the 10 endmembers, endmembers 2, 5, 8 and 10 were of most interest since they revealed a unique pattern of a mixture of oxidized tailings (em5, 8, 10) and water (em2). The spectra of these four endmembers are shown in Figure 5.
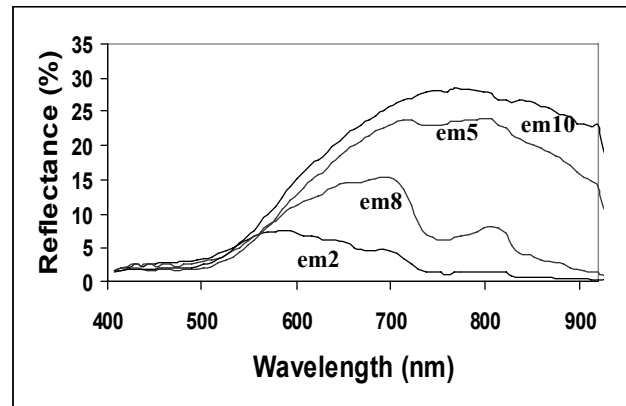

Figure 5. Selected endmember (em) spectra derived from the casi data covering the scene shown in Figure 4

It can be seen from Figure 6 that these four endmembers form a concentrically zoned fan-shaped pattern at the point where a surficial stream discharges into a retention pond. The zonation defined by these endmembers may depict differences in concentration of the sediments (oxidized tailings) in water, or deposition of minerals of different grain sizes. They may also outline the progressive interaction between differing chemistries of the surface run-off (AMD) and the retention pond (water).
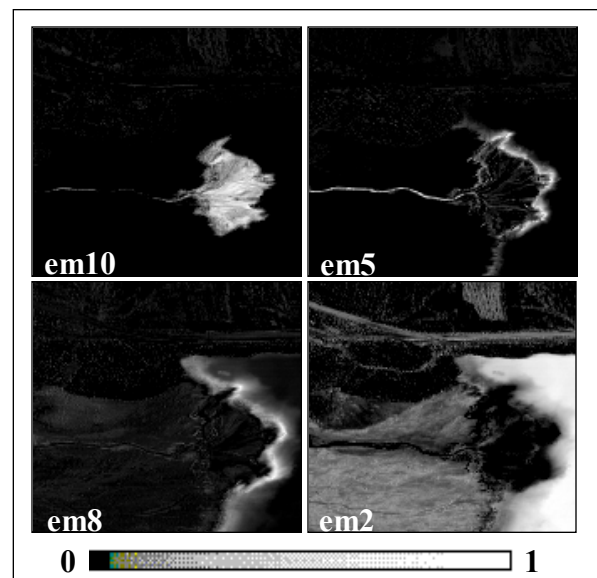

Figure 6. Fraction maps of endmenbers (em) 2, 5, 8, and 10.

Visual examination of the endmember spectra of AMD (em10) and water (em2) in Figure 5 suggests that the intermediate endmember spectra (em5 and 8) are not a simple combination of the outer spectra (em2 and 10). For instance, the em8 spectrum has an apparent broad absorption feature near 730 nm and the reflectance rises again near 800 nm. This supports the hypothesis that these fraction maps reflect the sequential generation of different mineral species.

Spectral Matching: Spectral matching of em10 (oxidized tailings) using both spectral angle and correlation measures revealed that the best matching mineral is goethite, with a spectral angle of 0.075 and a correlation of 0.997. Generally it is considered to be a good match when the spectral angle is smaller than 0.1 or the correlation is greater than 0.9. Goethite is relatively stable and suggests a moderate acid environment. Em5 is also best matched with goethite but with a smaller correlation (0.982) and a larger spectral angle (0.112). The variations between em10 and em5 could occur for three reasons. First, it could imply the emergence of another mineral. Second, it could be caused by different grain sizes in the sediments. When the stream reaches the pond, the velocity of the flow slows down which promotes the deposition of sediments with larger grain size. Third, water attenuation could also play an important role. However, no clear explanation in the existing literature has indicated the effect of water in reflectance of a specific mixture as such. The spectrum of em8 does not match well with any mineral in the spectral library. This could be because em8 is a mixture of two or more minerals with no one mineral occurring in a dominant proportion. Because spectra in the spectral library are derived from pure samples, no match can be found. Overall, this experiment revealed the potential of *casi* to provide information on mine tailing extent and permit separation of tailings with varying composition and oxidation levels.

Ground Measurements: Spectral matching results of the 21 GER spectra of the tailings samples are shown in Table 1. Candidate minerals were accepted if the matching met two criteria: the spectral angle is smaller than 0.1 and the correlation is greater than 0.9. Since the spectra from the USGS spectral library are derived from

pure mineral samples, a good match can only be achieved when a single mineral dominates the sample. If two or more minerals with equal or similar proportions exist in one sample, the spectrum of the sample will be the combined effects of all the contributing minerals. The resulting spectrum may not match with any of the minerals in the library. In the worst case, the mixed spectrum may produce a match with a known spectrum for a mineral that is not relevant to the study area.

Table 1. Candidate Minerals for the Tailings Samples Derived from Spectral Matching with the USGS Spectral Library.

Tailing Sample #	Candidate Minerals	Spectral Angle	Correlation
1	phlogopite	0.078	0.989
2	goethite	0.112	0.989
3	andradite	0.067	0.985
	andisine	0.070	0.967
4	pyrrhotite	0.087	0.960
	andradite	0.089	0.956
5	pyrite	0.037	0.987
6	jarosite	0.133	0.959
7	jarosite	0.072	0.985
8	no match	0.071	0.949
9	andradite	0.085	0.982
	jarosite	0.010	0.979
10	andradite	0.049	0.993
	corrensite	0.085	0.987
11a	jarosite	0.08	0.982
11b	jarosite	0.057	0.986
	pyrrhotite	0.096	0.985
12	jarosite	0.106	0.968
13	phlogopite	0.081	0.970
14	prochlorite	0.049	0.986
	amphibole	0.049	0.984
15	andradite	0.089	0.978
	jarosite	0.092	0.978
16	jarosite	0.051	0.989
17	pyrrhotite	0.063	0.987
18	jarosite	0.056	0.987
	pyrrhotite	0.094	0.985
19	jarosite	0.072	0.980
	andradite	0.093	0.972
20	pyrrhotite	0.054	0.991
	andradite	0.064	0.981
	jarosite	0.072	0.991

Table 1 reveals that the most frequently occurring oxidized minerals in the study site are jarosite $(NaFe^{+3}_3(SO_4)_2(OH)_6,$ $KFe^{+3}_3(SO_4)_2(OH)_6)$ and goethite (alpha-$Fe^+O(OH)$). These mineral matches make sense since the aforementioned minerals are the ones most likely to appear in tailings areas, especially metal mine tailings.

Tailings samples 4 and 5 also make perfect sense. Sample 4 was collected from the known pyrrhotite tailings site in the R4 area and is best matched to pyrrhotite. Sample 5 consists of fresh tailings prior to any oxidation. Therefore, it shows the property of the original ore-rock composition, pyrite. As an example, four spectral matching pairs are depicted in Figure 7. Pyrite and pyrrhotite were chosen to show the original unoxidized tailings. Jarosite and goethite were chosen to show oxidized tailings. According to the study by Swayze *et al.* (1998), with progressive oxidation pyrite weathers first to jarosite, and then to goethite. The spatial distribution of jarosite and goethite therefore provide a means whereby it is possible to identify areas associated with low pH and heavy metal. Jarosite is associated with the initial stage of the oxidation during which a strong-acid environment is present. It usually coexists with more leachable heavy metals. Goethite, a more stable mineral, is formed in a less-acid environment and is associated with lower concentrations of leachable heavy metals.
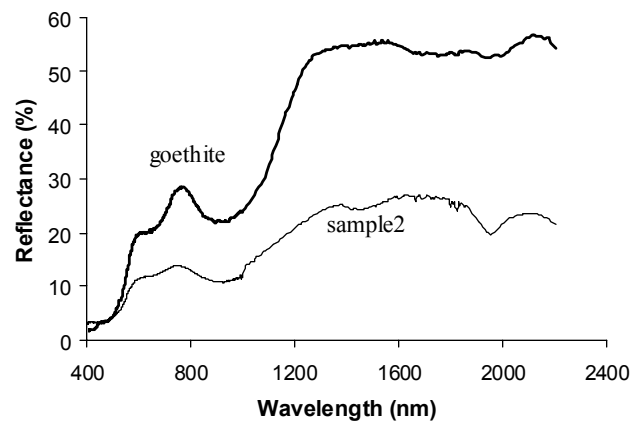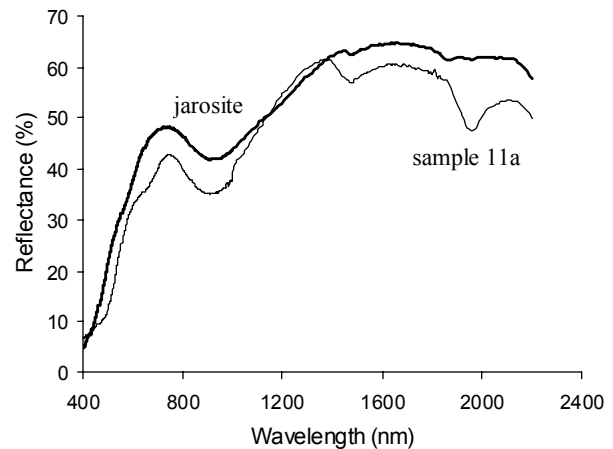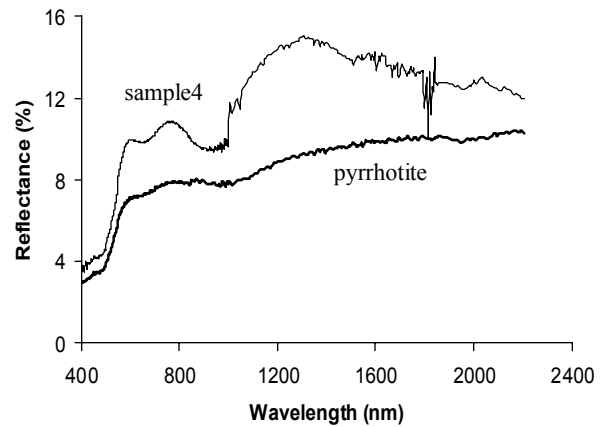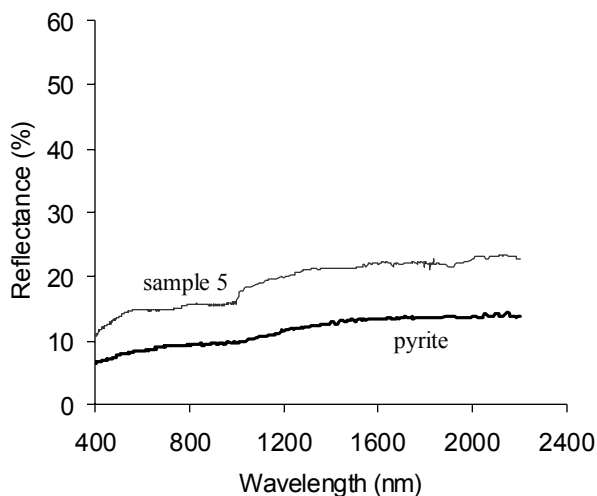
Figure 7. Selected GER spectra and the corresponding matching spectra from the USGS spectral library

It can be seen that differences exist between the sample spectra and the library spectra, even for the best-matched spectral pairs shown in Figure 7. This could be caused by the real difference between the samples and the library minerals. As mentioned earlier, the library spectra were derived from pure mineral samples. In contrast, the tailing samples are more likely mixtures of a variety of minerals. When the proportions of the minor minerals reach a certain level, the spectral shape of the sample will alter and start to resemble the absorption features of the minor minerals.

Spectral matching of the *casi* image spectra revealed mineral results similar to the laboratory-acquired GER spectra. Sample 4 is also best matched with pyrrhotite. Samples 7, 11a, 11b, and 20 also show the same results as the GER. This suggests that *casi* data have the potential for providing information on variations of the oxidation of tailings. As an example, two spectral matching pairs of *casi* spectra are shown in Figure 8.
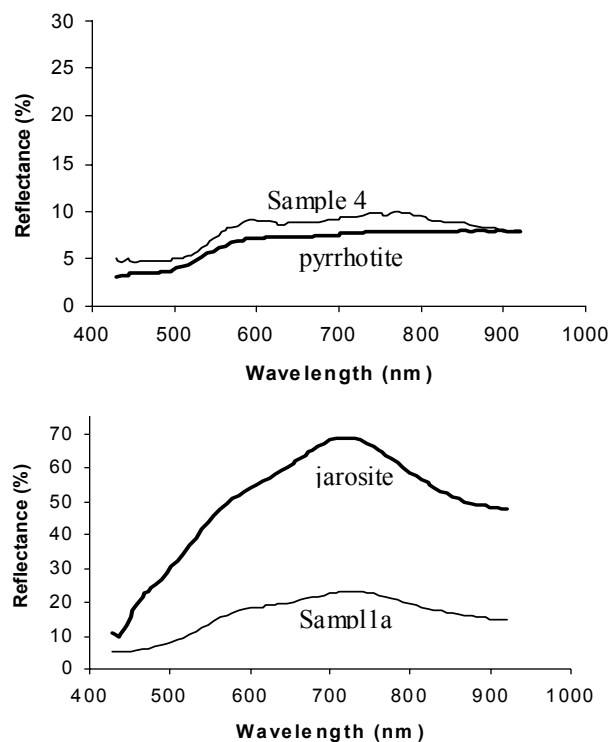

Figure 8. Selected casi spectra and the corresponding matching spectra from the USGS spectral library.

Given the fairly good alignment between the spectral matching results of the same tailing samples from the GER and *casi*, there are some disagreements. This is due to three causes. First, some subtle yet vital absorption features may exist only in the shortwave infrared region of the spectrum which *casi* does not cover. Second, the spectrum of a single pixel represents the averaged information of a broad area, approximately 4 m x 4 m. However, the GER samples very small areas, for this study 20 cm^2. Therefore inherent differences may exist between the tailings being measured. Third, co-location of the sample sites can also contribute to the disagreement. Even though the image spectra were picked visually from the *casi* imagery at the same locations as where the tailing samples, the visual judgement could be off by several pixels.

Conclusions

This study has demonstrated that *casi* data can be used to provide information on separating the oxidation zonations of the tailings. Spectral matching revealed that the most likely existing minerals on this tailings site are pyrite pyrrhotite, jarosite, and goethite. Despite of *casi*'s limited spectral coverage, similar results were found as from the GER spectral matching. Unfortunately, no direct relationships were found between the oxidation phases and the age of the tailings. A more detailed study will be performed in the future on the entire tailings site. Hopefully, it will reveal information on the spatial distribution of oxidized minerals at various phases to provide a better understanding of the evolution of tailings over time.

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