URANIUM MINE DETECTION USING AN AIRBORNE IMAGING SPECTROMETER*

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ABSTRACT

As part of a project to explore methods for identifying uranium mining and related activities from a satellite platform, imagery of a uranium mine site in Northern Saskatchewan was acquired in August 2000 with an airborne Short Wave Infra Red imaging spectrometer. Radiance data converted to reflectances using MODTRAN4 radiative transfer code, were analysed via a constrained linear unmixing technique, using end members extracted from the scene in an automated process. Selected end member spectra and their corresponding fraction images are presented. A vicarious calibration procedure used to calibrate the airborne imaging spectrometer is described.

1.0 INTRODUCTION

The Canada Centre for Remote Sensing and the Canadian Nuclear Safety Commission have undertaken, in support of the Safeguards and Verification Program of the International Atomic Energy Agency, to explore the possibilities provided by imaging spectrometry in the detection, from a satellite platform, of uranium mines and associated milling and refining facilities.

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In this paper we examine the results of analysis of Short Wave Infra Red (SWIR) hyperspectral data acquired over a uranium mine site located at Key Lake in northern Saskatchewan, Canada.. Although uranium is no longer being mined at this site, many of the activities normally associated with the mining and milling of uranium are represented here. Milling operations continue with ore that is being transported from another mine and tailings from these operations are being deposited in a tailings management facility at the Key Lake site.

The data processing chain includes the conversion from radiance to surface reflectance, the extraction of end member spectra using the IEA (Iterative Error Analysis) method (Neville, 1999; Szeredi, 2001), and the spectral unmixing of the image data using these end member spectra. The resulting abundance images and their corresponding spectra are discussed in the context of the mining operations engaged in at the site. Also as part of this mission, a reflectance based vicarious calibration (Secker, 2000) of the airborne imaging spectrometer was performed.

2.0 SITE

The uranium mine site located at Key Lake in northern Saskatchewan is one of several in the Athabasca sandstone formation. While Key Lake is no longer functioning as a mine, high grade ore is being trucked in from the mine at McArthur River, a distance of 80 km, for processing in the facilities at Key Lake. This high grade ore, with an average uranium concentration of 12%, must, prior to processing, be diluted by mixing with waste rock remaining at the Key Lake site from previous mining operations. The data set presented in this paper includes the ore receiving facility and the neighbouring area where the waste rock is stockpiled prior to mixing with the high grade ore.

The Key Lake site also contains both an underwater tailings management facility and an above ground tailings facility. In the former operation, the tailings are piped as a slurry to the tailings facility and deposited under water in Deilmann Pit, one of the former open pit mines at Key Lake. The water level in the pit is kept below that of the surrounding water table. The water pumped from this facility undergoes extensive treatment including a reverse osmosis process to remove contaminants before releasing the water to the environment.

3.0 DATA ACQUISITION

Image data were acquired by the SWIR Full Spectrum Imager (SFSI-2) (Neville, 1995) which operates in the SWIR spectral range of 1224.2 nm to 2426.9 nm. The relevant sensor parameters are listed in Table 1. The airborne data acquisition flights were made on 6 August, 2000, between approximately 9 and 11 am MDT. While this gave a rather low (~29°) solar elevation for the initial flight lines, it was essential to begin the acquisition at this early hour in order to complete mapping of the whole mine site before cumulus clouds had begun to form at 11 am.

Approximately 10 Gb of SWIR data were acquired over the Key Lake site, covering 35 to 40 km^2 . The SFSI-2 data consist of 231 spectral bands with spectral sampling on 5.2 nm centres, and spatial sampling on 3.12 ± 0.05 m centres across track, depending on the aircraft altitude, and 3.31 ± 0.64 m along track depending on ground speed for the individual flight lines. The flight line parameters for the data cube analysed for this paper are displayed in Table 2.

Table 1.SFSI-2 Sensor Characteristics

Sensor Parameter		Value
Number of Bands		231
Number of Pixels Across Swath		496
Field-of-View	[deg]	33.1
Spectral Range	[nm]	1224.17 - 2426.90
Band Centre Spacing	[nm]	5.2
Band Width (FWHM)	[nm]	13.5
Integration Period	[s]	0.0667

4.0 DATA PROCESSING

The opportunity, provided by the availability of a gravel airstrip at Key Lake, was taken to update the sensor calibration via a reflectance based vicarious calibration procedure (Secker, 2000). A ground-based, vehicle-mounted field spectroradiometer was used to make spectral reflectance measurements distributed over approximately 60% of the surface of the relatively uniform airstrip. These measurements, combined with MODTRAN4 radiative transfer (Berk, 1998) calculations, were used as a reference against which to compare the radiance measurements made by the airborne imaging spectrometer. Any variances were assumed to be the result of errors in the sensor signal-to-radiance conversion coefficients; these were corrected simply by factoring in the ratio of the computed to the measured radiance.

The data processing was performed by ISDAS, the CCRS Imaging Spectrometer Data Analysis System (Staenz, 1997). After the vicarious calibration coefficients had been applied to correct the spectral radiance values provided by the sensor, these radiances were converted to reflectances by correcting for the atmospheric effects. As in the vicarious calibration procedure, MODTRAN4 radiative transfer code was employed using a subarctic summer atmosphere model, a rural continental haze model, a water vapour value of 1.5 g cm^{-2}, a visibility of 50 km, and the model's default values for ozone and CO_2. The relevant time and location parameters are listed in Table 2.

The first step was to create a three dimensional look-up-table (LUT), one dimension of which was wavelength, a second the pixel view direction, and the third the scene reflectance. Radiances were calculated for the spectral range corresponding to the SFSI-2 bands, five values of the pixel view direction, one for the centre pixel, one for each of the extreme edge pixels, and two intermediate ones. Two values of reflectance were used: 5% and 60%. In the implementation stage, the scene surface reflectance values are calculated by linear interpolation between the LUT values for the relevant pixel view directions.

In the next step, the end member spectra are extracted from the scene data by the IEA method (Neville, 1999; Szeredi, 2001). In the present case 30 end members were requested. The scene was unmixed using these in a constrained linear unmixing process.

Table 2.Data Acquisition Parameters

Parameter	Value
Date	6 August 2000
Time (GMT) [h:m:s]	16:29:41.4
Latitude (N) [d:m]	57:12.14
Longitude (W) [d:m]	105:38.84
Solar Elevation Angle [deg]	39.8096
Solar Azimuth Angle [deg]	127.2056
Aircraft Altitude (AGL) [m]	2559
Ground Elevation (ASL) [m]	510
Ground Speed $[\mathrm{m\ s^{-1}}]$	47.8
Aircraft Heading [deg]	180
Pixel Centre Spacing Along Track [m]	3.19
Pixel Centre Spacing Across Track [m]	3.13

Upon visual inspection of the spectra and of the fraction or abundance maps, it was determined that the differences between some of the end member spectra were not sufficiently significant to warrant the separate display of their fraction maps. In these cases the relevant fraction maps were summed and the corresponding spectra were averaged.

5.0 DISCUSSION OF RESULTS

The scene imaged in Figure 1, where a spectral band centred on 1272.3 nm is printed as red, 1717.3 nm as green, and 2216.6 nm as blue, was processed as described above. Beside the RGB image in Figure 1 is a site map of the imaged area on which the functions of the different areas and buildings are labelled. Contained in this scene is the ore receiving facility where the high grade uranium ore is offloaded from the trucks which transport it to the site. The area to the north of this building and the ore crushing facility is where the waste rock is stockpiled prior to mixing with the ore. Deilmann Pit, the end of which appears on the east side of the image is one of the former open pit mines at Key Lake, and is currently the active underwater tailings management facility.

Eight of the end member spectra, some a composite of more than one of the original 30 end members, are plotted in Figure 2 for the limited, but information rich, spectral region 2050 nm to 2390 nm. These spectra have been identified by their spectral shape or by the ground truth pertaining to the end member's source location and have been labelled accordingly. The corresponding fraction images are displayed in Figure 3, with dark red representing high fraction values and dark blue, low values.

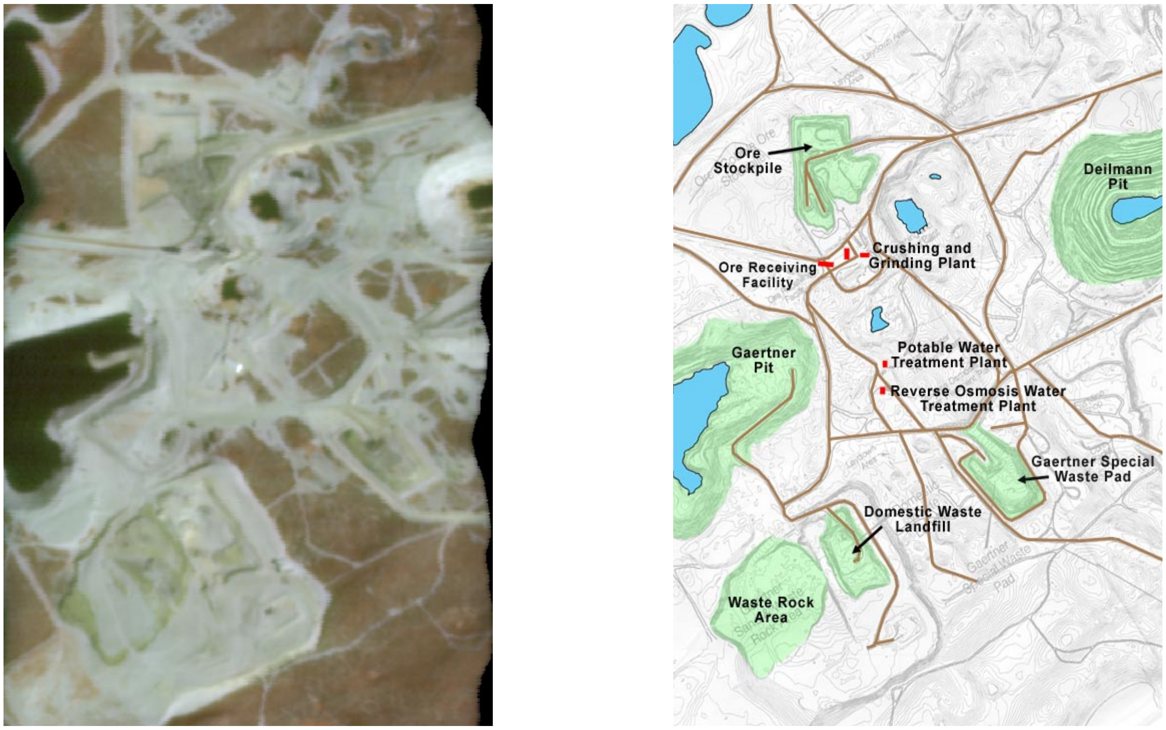

Figure 1. Ore receiving site at Key Lake. At left: RGB image; R = 1272.3 nm, G = 1717.3 nm. B = 2216.6 nm; and at right: site map.

The ‘sandstone’ end member was identified on the basis of its location in the image. Its spectrum indicates unrealistically high reflectance values near 100%. The reason is that this spectrum has come from pixels located on a southward-facing pit wall. Because of this the solar irradiance on this pit wall is significantly higher than has been calculated by the atmospheric correction process, wherein it has been assumed that all surfaces are horizontal. While this will induce a corresponding error in the calculated fraction values, it will not influence the qualitative results regarding the composition of the pixels. The fraction image indicates that this material is, not surprisingly, ubiquitous at this site, given that the Key Lake mine is located in the Athabasca sandstone formation. The spectral absorption feature at 2200 nm indicates that clay is present in the sandstone.

The ‘silica’ end member is identified as such based upon the marked opal-like roll off of the reflectance between 2150 nm and 2200 nm. The distribution of this material is concentrated primarily in the banks of a pit which has been excavated into a hillside, indicating that

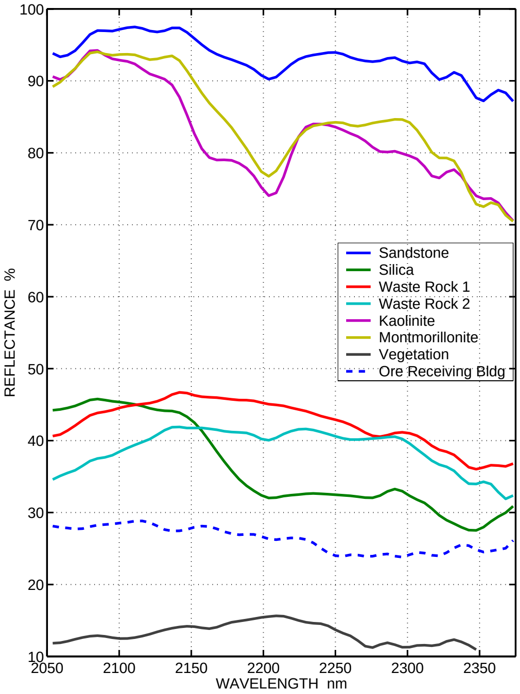

Figure 2. End member spectra extracted from hyperspectral data for the image in Figure1.

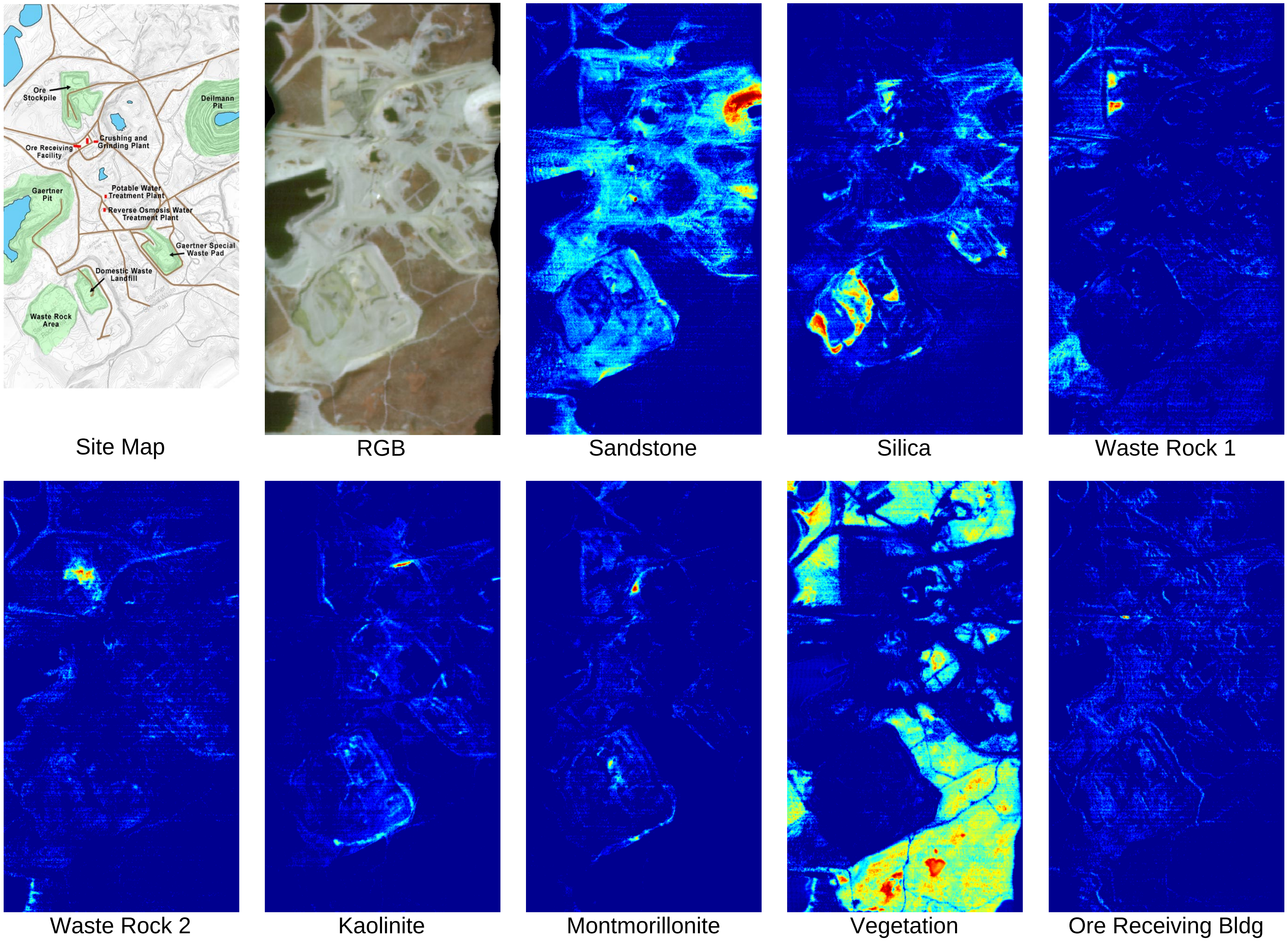

Figure 3. Fraction images corresponding to end member spectra extracted from the scene and plotted in Fig.2. Dark red = 100%; Dark blue = 0%.

this material is present in a particular stratum remaining at this location.

The fraction images corresponding to the montmorillonite and kaolinite end member spectra indicate quite discrete localisations. It has been suggested that these materials may be residual ‘mud’ used in prior drilling operations at the site. The absolutely classic shape of the extracted kaolinite spectrum provides a measure of quality assurance with respect to the spectral signatures derived from this data set.

There are two end members which map stockpiled materials awaiting mixing with the high-grade uranium ore. One has a relatively nondescript spectrum, while the other has a couple of minor features, one of which is common to clay. When more of the data has been processed it is expected that it will be possible to identify the source of these waste rock materials.

Included in addition to these mineral end members, is the fraction image an unknown vegetation type, with characteristically low reflectance values in this spectral region, and the fraction image for the ore receiving building itself.

6.0 SUMMARY AND FUTURE WORK

Imaging spectrometer data acquired at a uranium mine site at Key Lake located in northern Saskatchewan has been processed to reflectance and has been unmixed using end member spectra extracted from the scene by means of an automatic process. The images presented in this paper represent a small fraction of the whole data set which covers the complete mine site area. In addition, the interpretation of the results must be considered preliminary. While a number of the end member spectra have been identified, many more remain unidentified, indicating the need for ground sampling and mineralogic analysis. It is expected that the processing of the remaining data from this site will provide many additional unidentified end member spectra which will require ground truth verification.

While the objective of the project remains the identification of uranium mines and the ancillary milling, processing, and tailings facilities, it has to be noted that no uranium compounds have as yet been identified from the remote imagery of the Key Lake site. Indeed it may prove to be impossible to do so, given that no exposed ore or tailings at this site have uranium concentrations exceeding 1%. It would require an exceedingly strong, unique, and sharply defined absorption feature for any uranium compounds to be detectable at such low concentrations.

In the more general situation in which hyperspectral imagery is acquired by a satellite-borne sensor over a potential uranium mine site, at which procedures are in place to prevent the open exposure of high grade uranium ore or its concentrated or refined products, then it is unlikely that the true identity of the mine type can be ascertained on the basis of these data alone. Nevertheless, these hyperspectral data provide information which give the context within which other remotely acquired data, such as high spatial resolution imagery, can be interpreted. If in addition, these composite and complementary data sets are acquired on a multi-temporal basis, then the probability of successful identification of the mine type by mining operations experts is greatly enhanced.

7.0 REFERENCES

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