MATERIAL ABSORPTION BAND DEPTH MAPPING OF IMAGING SPECTROMETER DATA USING A COMPLETE BAND SHAPE LEAST-SQUARES FIT WITH LIBRARY REFERENCE SPECTRA

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ABSTRACT

Mapping of mineral and vegetation absorption features in imaging spectrometer data is demonstrated using a least-squares solution of the total band shape of a reference library spectrum to spectra from the imaging data set. The method removes a continuum from the observed and reference spectra and expands and compresses the reference absorption profile to best fit the observed data. The advantage of the method is that it can map complicated band shapes, like a kaolinite doublet, and fits to all data points comprising the feature. The algorithm computes the band depth for a particular absorption feature, a goodness of fit, and the reflectance level of the continuum at the band center. Images of the band depth and goodness of fit are maps of a specific species. The images from this method show species distribution in significantly better detail and with less noise than simpler methods such as band ratios or band-depth images computed from two continuum and one band center channels. Combinations of mineral absorption features may be used to map geologic units.

INTRODUCTION

Imaging spectroscopy instruments such as AVIRIS have narrow bandwidths in many contiguous spectral channels to accurately define absorption features from a variety of materials. However, such data sets must be analyzed in a spectroscopic sense rather than an imaging sense to derive mineralogic information. Spectroscopists generally analyze individual absorption features in a spectrum, not simply ratios at particular wavelengths. In an effort to develop tools to map species, including minerals, vegetation, or environmental materials, we have developed an algorithm to map any complex absorption feature in a spectrum, given a suitable reference spectrum.

The band ratio is a simple analysis of a spectrum that has been common for at least two decades. The band ratio is sensitive to the relative absorption in a spectrum at two wavelengths. In imaging spectrometer data sets, the wavelengths can be chosen close together such that the ratio is particularly sensitive to a given absorption band.

However, it is also sensitive to sloping spectra, so a ratio is not a foolproof indicator of the presence of an absorption band.

BAND-DEPTH ANALYSIS

A band-depth analysis using three spectral channels with imaging spectrometer data was shown by Clark *et al.* (1988). In that case, the absorption band depth, D, was defined relative to its continuum:

$$D = 1 - R_b/R_c \qquad \text{(eqn 1)}$$

where R_c is the reflectance of the continuum at the band center, and R_b is the reflectance at the band center. The definition originates from Clark and Roush, (1984).

The band depth images from Clark *et al.*, 1988 were quite noisy, mostly due to the noisy AVIRIS data during the 1987 flight season. However, the method still is inherently susceptible to noise, because only three channels are used, and only one at (or near) the band center.

In practice most absorption features consist of many spectral channels. For example, the hematite 0.9-μm absorption extends from ~0.75 to ~1.3 μm, or about 56 AVIRIS channels. The kaolinite doublet covers about 13 AVIRIS channels in the 2.2-μm region. Mapping an absorption feature at say 2.2 μm using only three channels (two continuum and one channel at 2.2 μm) is insensitive to either a kaolinite doublet or the singlet montmorillonite feature (and other similar absorptions). Examining all channels comprising the feature for the proper shape would more accurately map the absorption.

In practice, absorption band shapes, such as the kaolinite doublet, are well recognized. The process of absorption band analysis is to first remove a continuum (Figure 1, and see Clark and Roush, 1984; Clark *et al.*, 1988). Once the continuum is removed, a band can be characterized by determining how well the feature matched a reference library spectrum.

A typical spectrum from an imaging spectrometer data set will include other materials in the scene, either in an areal mixture (e.g. vegetation) or in an intimate mixture (e.g. mineral grains in a rock or soil). Commonly, although not always, the pure mineral reference spectrum will have absorption features stronger than observed in flight data. Figure 1 shows a comparison between reference spectra and flight data of kaolinite. Any comparison between the reference and flight data must be able to change the spectral contrast of one of the spectra in order to match the other. The most accurate way to do this would be using a radiative transfer model like that from Hapke (1981), but it is also the most compute intensive.

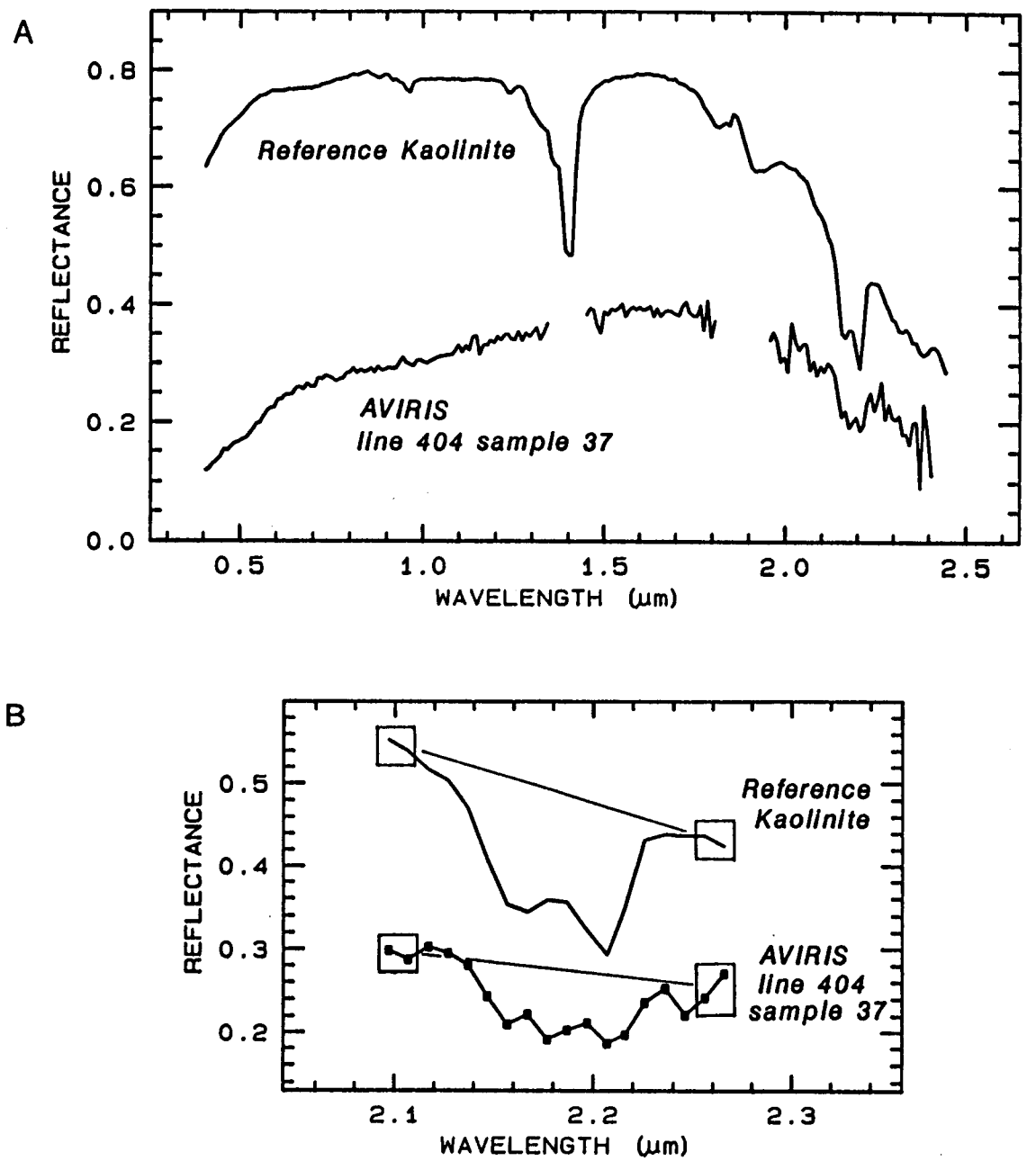

Figure 1. A spectrum from the Canon City AVIRIS flight data is compared to a library reference kaolinite spectrum. The kaolinite spectrum has been convolved to the spectral resolution and sampling interval of the 1989 AVIRIS flight data. A) the full spectrum. B) the isolated kaolinite 2.2-μm doublet is shown with the continua chosen for each spectrum. In this Figure, the absorptions in the reference spectrum are stronger than in the flight data.

A simpler model to change a continuum-removed-absorption feature's contrast is by a constant added to the data at all wavelengths. In this case, the feature would not be represented properly if the band saturation changed significantly, from say a major change in grain size between the reference and observed spectra. The algorithm presented here uses the simple case of an additive component because it is computationally fast compared to a full radiative transfer model. The method can easily be adapted to the full model however, or even a method that examines the band depth and chooses an appropriately saturated absorption feature from a library of materials at several grain sizes.

The algorithm, which we call the Band Mapping Algorithm, Version 1 (BMA1) first removes a straight line continuum from the library reference spectrum using channels on each side of the absorption feature that is to be mapped (e.g. Figure 1b). The continuum is removed from the observed spectrum in the flight image using the same method and spectral channels. The user may select several channels on each side of the band so that noise in the continuum is averaged. The continuum is removed by division:

$$L_c(\lambda) = \frac{L(\lambda)}{C_l(\lambda)} \quad \text{and} \quad O_c(\lambda) = \frac{O(\lambda)}{C_o(\lambda)}, \qquad \text{(eqn 2 a and b)}$$

where $L(\lambda)$ is the library spectrum as a function of wavelength, λ, O is the observed spectrum, C_l is the continuum for the library spectrum, C_o is the continuum for the observed spectrum, L_c is the continuum removed library spectrum, and O_c is the continuum removed observed spectrum.

The contrast in the reference library spectrum absorption feature is modified by a simple additive constant, k:

$$L_c' = \frac{L_c + k}{1.0 + k}, \qquad \text{(eqn 3)}$$

where L_c' is the modified continuum removed spectrum that best matches the observed spectrum. This equation can be rewritten in the form:

$$L_c' = a + bL_c, \qquad \text{(eqn 4)}$$

where

$$a = k/(1.0 + k), \text{ and}$$

$$b = 1.0/(1.0 + k). \qquad \text{(eqn 5)}$$

In Equation 4 we want to find the a and b that gives a best fit to the observed spectrum O_c. The solution is done using standard least squares:

$$a = (\Sigma\, O_c - b\Sigma\, L_c)/n,$$

$$b = \frac{\Sigma\, O_c L_c - \Sigma\, O_c \Sigma\, L_c/n}{\Sigma\, L_c^{\,2} - (\Sigma\, L_c)^2/n},$$

and

$$k = (1-b)/b, \qquad \text{(eqn 6)}$$

where n is the number of spectral channels in the fit.

Figure 2 shows an example reference kaolinite spectrum and the observed spectrum from Figure 1, where the continua have been removed and the library spectrum fitted to the observed spectrum by the above method. By fitting a library reference spectrum to each spectrum in an imaging spectrometer data set, a map of the material can be produced. The algorithm produces a band depth, indicating its spectral abundance in the image, and a goodness of fit which gives a measure of confidence of the accuracy of the resulting map.

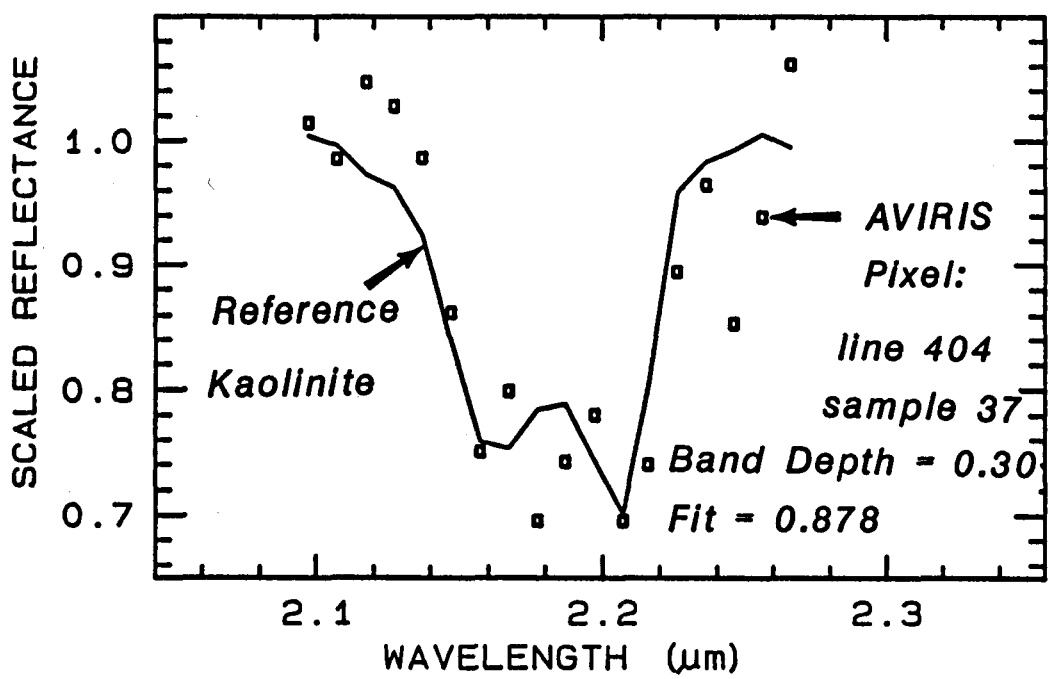

Figure 2: The kaolinite spectra from Figure 1b have had continuum removed and the library spectrum fitted to the observed AVIRIS spectrum. While a single spectrum may not show the kaolinite doublet structure well, an average of several pixels from this region does.

MINERAL MAPPING

Absorption Band Mapping was applied to the AVIRIS image taken over Canon City, Colorado using the U. S. Geological Survey digital spectral library. The AVIRIS data were obtained on September 24, 1989 at 1 p.m. MDT, so the sun angle was relatively high. The radiance data were corrected to ground reflectance using large uniform areas on the ground as calibration targets. The ground sites were calibrated using hand samples and the same spectrometer that was used to measure the spectral library samples.

To properly fit a reference spectrum to the flight data, the data sets must be sampled at the same wavelengths and resolution. The USGS spectral library was spectrally convolved to the resolution of the flight data and sampling values as supplied by the JPL AVIRIS investigators (Green, private communication).

The images processed cover an area of 11 km wide by about 14 km long (Figure 3a and Slide 14; in the images, north is to the upper left). In the lower portion of the image, Phanerozoic dolomite, limestone, arkose, sandstone and shale rock units form gently southwest dipping hogbacks on the east limb of a broad syncline. These rock units are truncated by northwest trending faults which juxtapose them against Proterozoic meta-igneous and gneiss rock units in the upper right part of the image.

Example mineral maps using three different techniques are shown in Figure 3. The fastest method, a ratio of 2 channels, used to map kaolinite, appears rather noisy (Figure 3b), as does the 3-channel band-depth computation (Figure 3c). The least-squares method shows less noise and more detail (Figure 3d).

DISCUSSION

Many materials can be mapped with the algorithm. For example, Figure 4 shows maps of dolomite, calcite, green vegetation and goethite. Maps of three materials can easily be combined to produce color images. Clark *et al.* (1988) called such images Color-Composite-Band-Depth Images (CCBDI). Slides 15 through 18 illustrate such maps. The mapped minerals correlate very well with geologic maps of the region.

For example, this method is so sensitive to absorption band position and geometry, that it can distinguish between dolomite and calcite which have nearly identical absorption bands shifted from each other by only 20 nanometers at AVIRIS spectral resolution. Figure 5 shows an averaged AVIRIS spectrum of the dolomite unit compared to laboratory spectra for dolomite and a field sample of the dolomite unit. Note the presence of a strong 2.3-μm region absorption in the AVIRIS data that matches well with the laboratory spectra. Figure 4a and red in Slide 15 highlight flatirons and erosional outliers of dolomite overlying basement in the upper right portion of the image. Figure 4b and green in Slide 15 show a thin sinuous outcrop of limestone trending across the lower central portion of the image. Although the dolomite image also

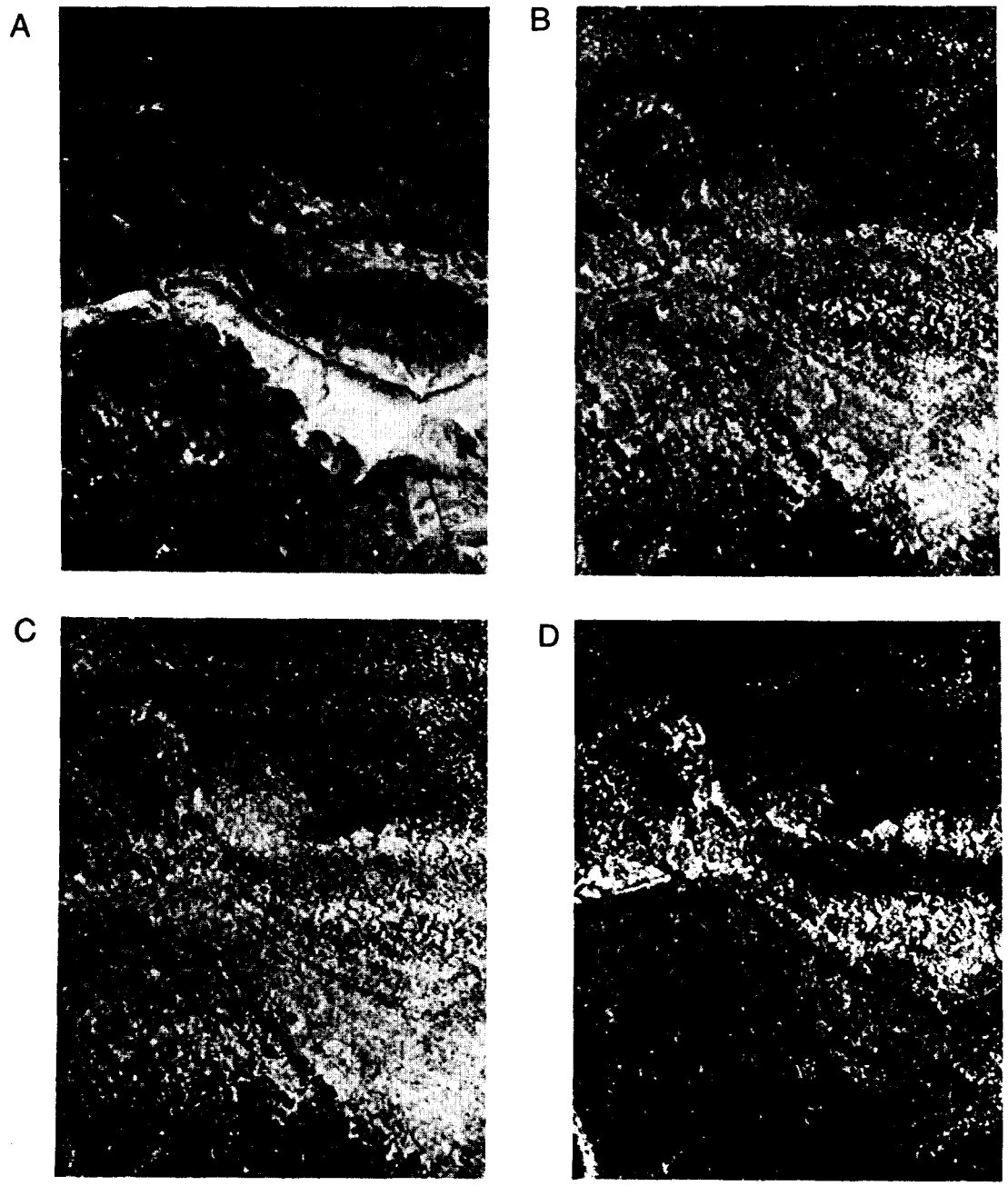

Figure 3: A) A single band image of the Canon City scene. Canon City is at the lower part of the image. North is to the upper left. B) A simple band ratio image (2.25/2.205 μm) shows some detail related to kaolinite occurrence. C) A simple three-point band-depth image (continuum points at 2.12 and 2.25 μm and band center at 2.205 μm) shows detail similar to the ratio method. D) The least-squares band map image method is shown. The image is the band-depth times the goodness of fit. The least-squares method isolates very well the kaolinite exposures. In B, C and D, white corresponds to stronger kaolinite signature.

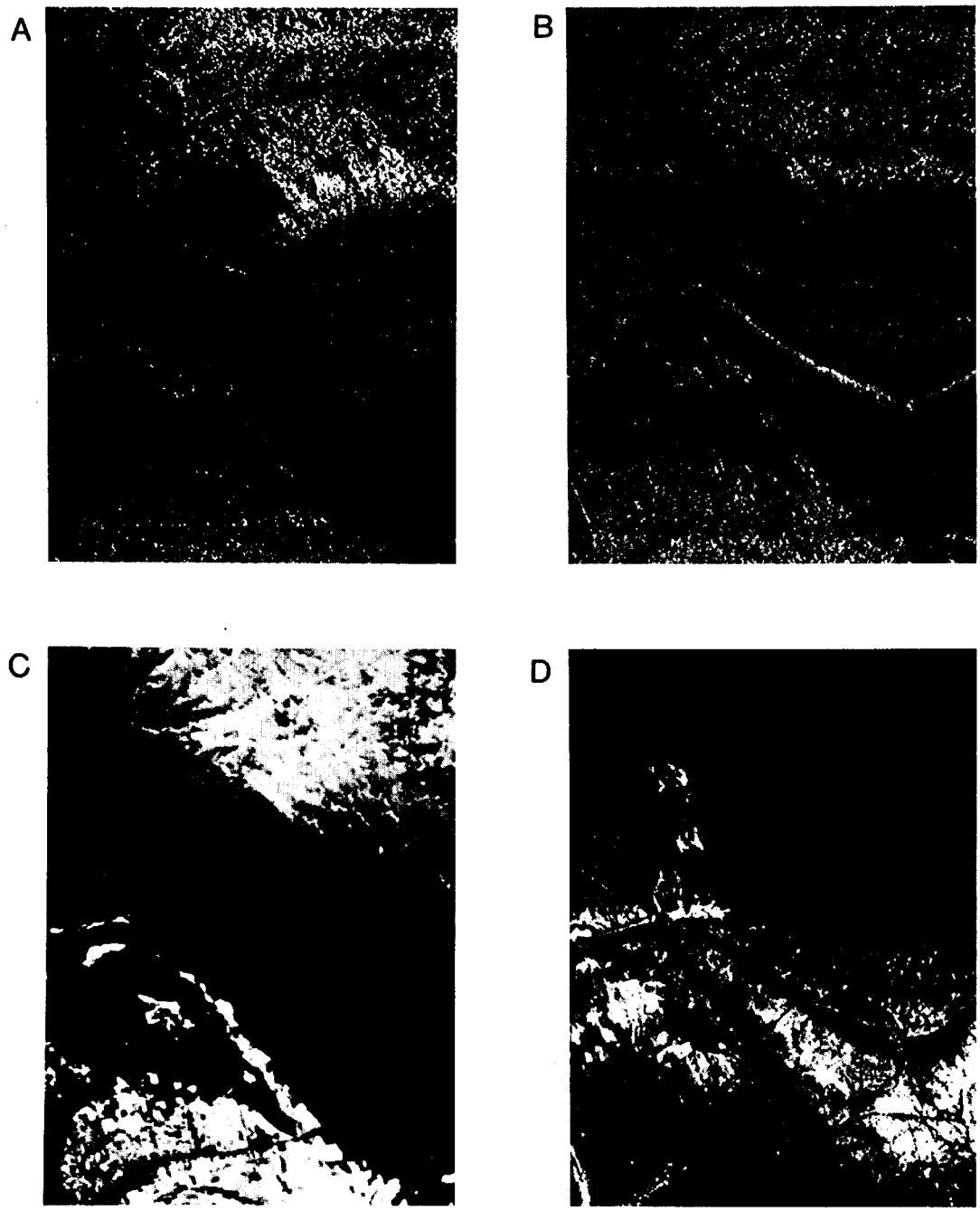

Figure 4: Band maps for 4 materials are shown. Each image is the band-depth times the goodness of fit, and white corresponds to greater signature. A) Dolomite. B) Calcite. C) Green vegetation. D) Goethite. Note that the band-depth maps separated dolomite (upper right of center) from calcite (thin line below center from left to right). In addition, note that the region of dolomite exposure shows no kaolinite (compare to Figure 3d). Also see the color slides.

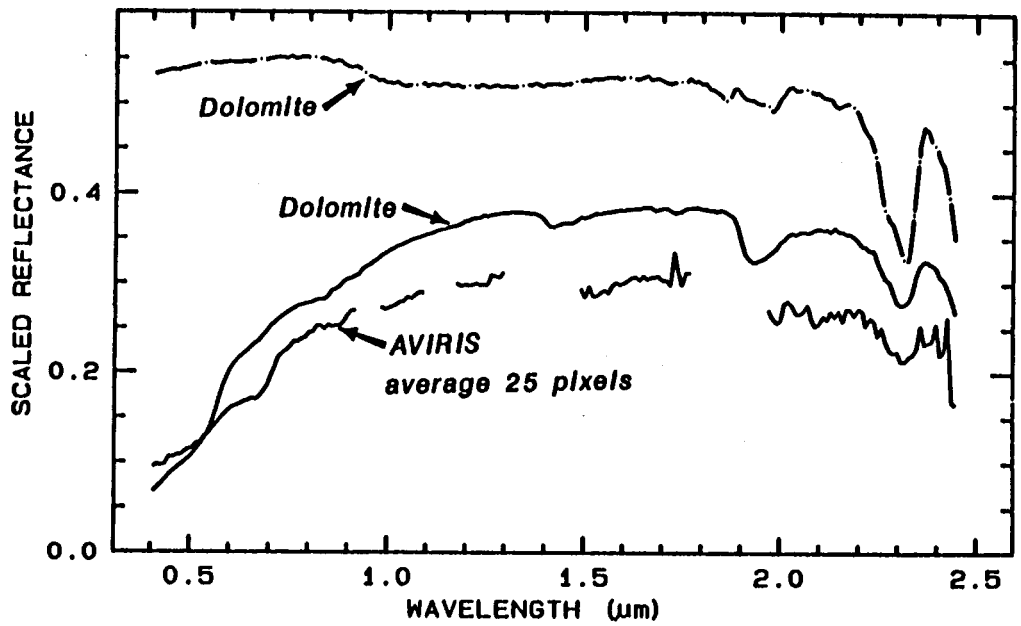

Figure 5: An average spectrum of 25 pixels from the Canon City AVIRIS image (bottom curve) compared to a reference library spectrum of dolomite (dashed-dotted curve, top) and a spectrum of a rock sample from the dolomite rock unit seen in Figure 4a. Spectral regions of atmospheric absorption have been deleted for clarity in the averaged AVIRIS spectrum. The rock unit and AVIRIS spectra both show a dolomite absorption band at 2.3 μm.

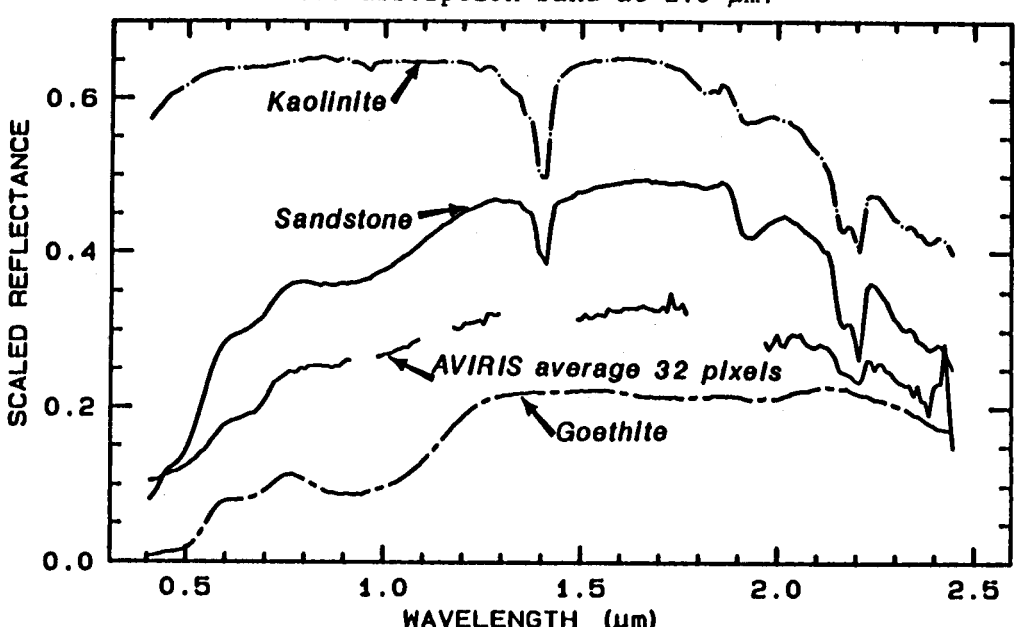

Figure 6: An average spectrum of 32 pixels from the Canon City AVIRIS image compared to reference library spectra of kaolinite and goethite (dashed-dotted curves) and a spectrum of a rock sample from the sandstone unit seen in Figure 3d. Spectral regions of atmospheric absorption have been deleted for clarity in the averaged AVIRIS spectrum.

shows this limestone unit because of noise in the signal, it does so with less intensity and can be adequately differentiated by the goodness of fit.

Because the program can fit complex absorption bands like the kaolinite doublet, it can differentiate this mineral from montmorillonite, illite, and other clay minerals having single absorptions in the 2.2-μm region. Figure 6 shows an averaged AVIRIS spectrum of the sandstone unit compared to laboratory spectra of kaolinite, goethite, and a field sample of the sandstone unit. Figure 3d and the blue in Slides 15, 16, and 18 show the presence of kaolinite in the sandstone and arkose units where feldspars have been altered. In Slide 18, montmorillonite (red) and illite (green) highlight and differentiate several shale units. This suggests the possibility of mapping subtle compositional variations within individual rock units.

This method of mapping mineral absorptions is much less sensitive to noise in individual channels. For instance, the kaolinite spectrum in Figure 2 has the strongest feature in the Canon City image, yet the noise in the spectrum is quite high. In general, the Canon City AVIRIS data have a signal to noise of about 30 for a reference reflectance of 0.5 in the 2.2-μm region (Figure 7). The typical albedo in the image is about 0.25 or less, so the signal to noise to map the kaolinite doublet is only about 15. Examining regions of the image where significant kaolinite is mapped, the band-depth of about 4% is mapped. A signal to noise of only 15 in the spectrum corresponds to mapping the absorption band when the feature strength is about one-half the signal to noise of a single channel. The method is able to map the feature because many channels are used, effectively increasing the signal to noise for feature detection.

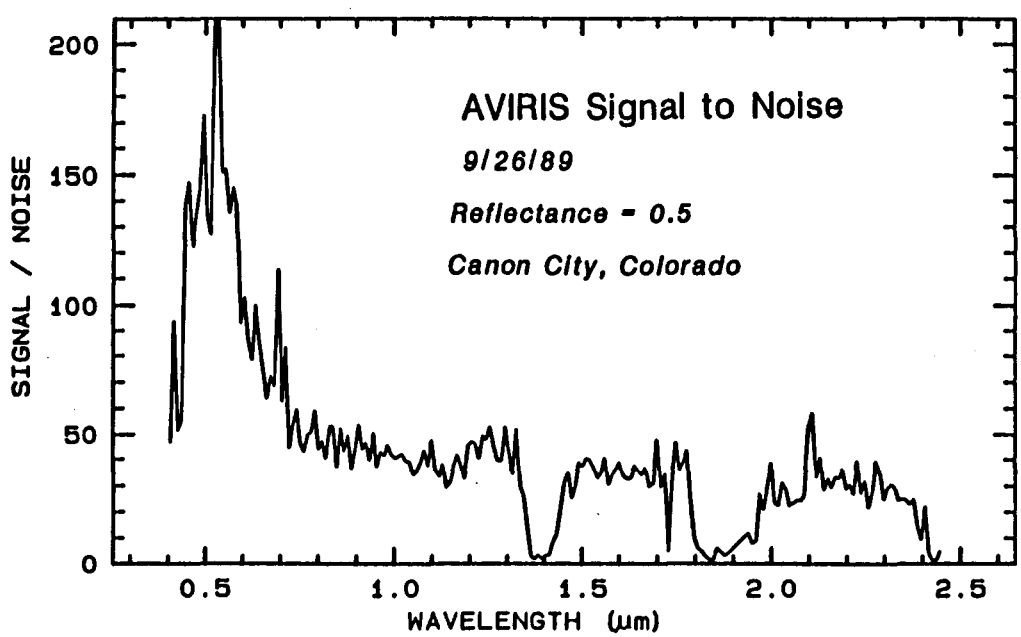

Figure 7: The signal to noise of AVIRIS on September 26, 1989 for a reference reflectance of 0.5.

The method is sensitive enough to map different regions as a kaolinite versus a halloysite-like feature. Although such subtle spectral differences have yet to be confirmed by field work, it illustrates the power of fitting to an entire spectral feature compared to more simple band minima and width methods.

CONCLUSIONS

We have developed a new method of image processing which can map absorbing materials using a least-squares linear regression between imaging data and a reference spectrum. This method requires a reference spectrum of the material that is accurately convolved to the spectral resolution and sampling of the flight instrument. Our analyses have shown that this method gives substantially improved results over simpler techniques like band ratios or 3-point band-depths. It should be pointed out that this technique can be used to map any material, not just minerals, as long as there are diagnostic absorption bands in the spectral region covered by the imaging instrument.

REFERENCES

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SLIDE CAPTIONS

Slide No. 14. A false-color-infrared composite of the Canon City AVIRIS scene.

Slide No. 15. A Color-Composite-Band-Depth Image (CCBDI) for Canon City: blue is kaolinite, green is calcite, and red is dolomite.

Slide No. 16. A Color-Composite-Band-Depth Image (CCBDI) for Canon City: blue is kaolinite, green is montmorillonite, and red is goethite.

Slide No. 17. A Color-Composite-Band-Depth Image (CCBDI) for Canon City: blue is montmorillonite, green is goethite, and red is hematite.

Slide No. 18. A Color-Composite-Band-Depth Image (CCBDI) for Canon City: blue is kaolinite, green is illite, and red is montmorillonite.