

Sedimentary Facies Analysis Using AVIRIS Data : A Geophysical Inverse Problem

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Abstract. AVIRIS data can be used to quantitatively analyze and map sedimentary lithofacies. The observed radiance spectra can be reduced to "apparent reflectance" spectra by topographic and reflectance characterization of several field sites within the image. These apparent reflectance spectra correspond to the true reflectance at each pixel, multiplied by an unknown illumination factor (ranging in value from zero to one). The spatial abundance patterns of spectrally defined lithofacies and the unknown illumination factors can be simultaneously derived using constrained linear spectral unmixing methods. Estimates of the minimum uncertainty in the final results (due to noise, instrument resolutions, degree of illumination and mixing systematics) can be made by forward and inverse modeling. Specific facies studies in the Rattlesnake Hills region of Wyoming illustrate the successful application of these methods.

I. Introduction

This study illustrates how AVIRIS data can be used to study sedimentary facies. The problem is cast in the form of a geophysical inversion process. A forward model, describing the relationship between the observed radiance and the surficial composition, is developed and then inverted. The inversion process, employing a modified linear spectral unmixing technique, permits quantitative mapping and analyses of sedimentary lithofacies. However, a lower bound exists on the uncertainty associated with such spectral unmixing results. Noise in the data, the local degree of illumination, finite spectral and radiometric resolutions and the spectral mixing systematics of the particular lithofacies being studied all combine to create some uncertainty in the unmixing results. A method of modeling and deriving this limiting uncertainty is illustrated here. This minimum uncertainty is in general different for each spectrally-defined lithofacies being studied and different for each pixel within the AVIRIS scene. Using geophysical inversion methods to analyze AVIRIS data permits derivation of quantitative geological results, and equally important, estimation of the uncertainty in these results.

The process outlined here demonstrates how AVIRIS data can be used, subsequent to initial field work, to extend the results of that field work over large areas. The process has several steps. First, the observed AVIRIS radiance data are reduced to "apparent reflectance" (modeling true reflectance multiplied by some unknown illumination factor between zero and one at each pixel). Then, the spectral distribution of noise in the data is derived using a new method. Limited field work is conducted to observe and to spectrally characterize the materials present on the surface, including the lithofacies outcrops of interest and all other abundant surface materials. Then, a constrained linear unmixing method is used to derive images of the spatial patterns of abundance of the various surface materials. Next, iterations of simulated forward and inverse modeling of the spectral mixing are performed to derive the minimum systematic uncertainty for each endmember at each individual pixel. This last process creates "uncertainty images" corresponding to the "endmember abundance images" derived by the foregoing spectral unmixing. Finally, sedimentary facies mapping and analyses are performed using the abundance and uncertainty images.

II. Reduction of Radiance to Apparent Reflectance

The observed spectral radiance at the AVIRIS instrument can be modeled as the sum of two terms, path radiance and reflected radiance. If a Lambertian model of the surface is used, diffuse

irradiance is ignored and the atmosphere is assumed to be uniform, then the observed radiance can be modeled as follows.

$$L_o(s,l,\lambda) = L_p(\lambda) + (1/\pi) * E_{sun}(\lambda) * T_{tw}(\lambda) * IF(s,l) * R(s,l,\lambda)$$

Sample, line and spectral channels are denoted by s , l and λ respectively. L_o and L_p are the observed and path radiance values, E_{sun} is the solar irradiance spectrum, T_{tw} is the two-way atmospheric transmission spectrum, IF is the local illumination factor (cosine of the local solar incidence angle) and R is the reflectance spectrum for the surface. Apparent reflectance is defined as $IF * R$. A pixel oriented normal to the solar incidence direction will have an IF of 1.0, so the apparent reflectance and true reflectance will be equal. A pixel receiving little irradiance, shaded by topography or turned away from the sun, will have an IF of near zero and a very low apparent reflectance spectrum.

Five ground sites were spectrally characterized with a field spectrometer and the local slopes and aspects were recorded to permit calculation of offset (L_p) and gain ($(1/\pi) * E_{sun} * T_{tw}$) spectra for reduction to apparent reflectance. Local IF values for these sites were calculated using the field measurements in conjunction with the calculated azimuth and elevation of the sun at the time of AVIRIS overflight (AZ=187.5, EL=37.0, time=10/18/89 19:20 GMT). The observed reflectance, calculated IF values and the 70 extracted AVIRIS radiance spectra (corresponding to the ground sites) were used to solve, on a band-by-band basis, a system of 70 linear equation in two unknowns. The resulting path radiance (offset) and maximum reflected radiance (gain) spectra are shown in Figure 1. The L_p offset spectrum shows the expected low level and the fall-off at longer wavelengths, associated with atmospheric scattering. The $(1/\pi) * E_{sun} * T_{tw}$ gain spectrum shows the combined effects of solar irradiance and atmospheric absorption. The observed radiance spectra can now be reduced to apparent reflectance by subtracting the L_p spectrum and dividing by the $(1/\pi) * E_{sun} * T_{tw}$ spectrum. Three typical reduced spectra are shown in Figure 2.

III. Derivation of Noise Levels

The spectra shown in Figure 2 obviously are contaminated with considerable noise. A measure of this noise is essential in any attempt to use these data quantitatively. An improved method for noise derivation, more widely applicable than past methods, is outlined here. Past methods have required a large and spectrally uniform target, such as a playa or runway, for noise derivation. Such targets are not found in most AVIRIS scenes. The method presented here allows for some natural variance in the area chosen for noise derivation. The observed variance is modeled as the sum of the natural and noise variances.

The most nearly uniform large area of the scene is selected and the associated spectra are extracted from the AVIRIS radiance data. The standard deviation of these pixels, band-by-band, is calculated to form a "standard deviation spectrum". Then the spectra are averaged together in groups of two and another standard deviation spectrum is calculated. This process is repeated, averaging the pixels in groups of 4, 5, 8, 10, 16, 20 and 25. For each band, nine standard deviations are calculated, each corresponding to a different degree of spatial averaging. The noise level in a band can be estimated by fitting a line to these calculated points after they are plotted versus the reciprocal of the square root of the number of pixels averaged. The noise portion of the variance should drop predictably. The natural variance should remain nearly constant until the spatial averaging crosses a natural "texture scale" of the area being used. By examining the linearity of these plots, the validity of the underlying assumptions can be assessed. Application to a typical AVIRIS band is shown in Figure 3.

The derived noise level represents an estimate of the standard deviation of the noise at each spectral band, in terms of apparent reflectance. This spectrum is shown in Figure 4. Since the apparent reflectance signal varies both spatially and spectrally, so does the signal-to-noise-ratio. Poorly illuminated and/or low reflectance pixels have lower signal-to-noise ratios than fully illuminated

and/or high reflectance pixels. Figure 5 shows the mean signal-to-noise spectrum for the three AVIRIS segments studied. The low signal-to-noise levels are a result of the low signal levels, in turn caused by the low sun angle at the time of the mid-October acquisition. The derived noise level spectrum (Figure 4) plays a key role in modeling the uncertainty in the results of the spectral unmixing procedure.

IV. Modified Linear Spectral Unmixing and Uncertainty Modeling

A modified linear spectral unmixing method is used to map the spatial distributions of, and thus the stratigraphic relationships among, the lithofacies being studied. Field spectral measurements and laboratory measurements of field samples are used to form a mixing library for the specific region being studied. The AVIRIS apparent reflectance spectra are modeled as linear combinations of these endmember spectra. A system of simultaneous equations can be developed at each pixel and solved in a least-squares sense to estimate the abundance of each endmember material within each pixel.

Several modifications are made to this least-squares procedure, compared to similar applications previously reported by other workers (Adams and others, 1986; Gillespie and others, 1990). The apparent reflectance spectra, reduced from the observed AVIRIS radiance spectra, are unmixed using absolute reflectance spectral endmembers. The derived abundances are constrained to be non-negative and to sum to one or less, using the numerical methods described by Lawson and Hanson (1974). The effect of these two modifications is to allow a simultaneous derivation of estimates for the unknown endmember abundances and the unknown local illumination factor, IF, at each individual pixel. This method treats illumination and shadowing effects as an unknown gain factor, IF, rather than including shade as a mixing endmember as done by others (Gillespie and others, 1990). The gain factor method is numerically more stable since the shade endmember, by definition a very dark spectrum, makes the mixing library more ill-conditioned (Menke, 1984; Press and others, 1986) since it is nearly linearly dependent with all spectra in the library and their linear combinations.

Noise, finite resolutions, variable illumination and the mixing systematics of the particular library combine to limit the certainty in unmixing results. Forward modeling, simulations of observed data, can be used to derive this lower limit on uncertainty. The mixing library is modified to match the spectral and radiometric resolutions of the AVIRIS instrument. Then the spectra are mixed, in known proportions, and degraded by the addition of a proper noise spectrum. Unmixing of many of these simulated spectra provides estimates of the minimum uncertainty for each endmember as a function of abundance of every endmember and the degree of illumination.

V. Facies Study Example

An example study is illustrated here of the Cretaceous Frontier and Mowry Formations, which crop out in the Rattlesnake Hills region of central Wyoming. The Rattlesnake Hills area has been previously mapped and studied, using conventional field methods (Boggett, 1951; Pekarek, 1974). The Mowry Formation is a siliceous ridge-forming shale and the Frontier is a thick sequence of interbedded and discontinuous sandstone and black shale facies. A bentonite bed also occurs near the contact between the two formations. This example illustrates how spectral unmixing of AVIRIS data, applied after initial field work, can successfully create detailed lithofacies maps for these clastic formations.

The first step in the process is the spectral characterization of the common materials found on the surface in the study area. The surface materials were divided into seven mixing endmembers, four lithofacies (Mowry shale, Frontier sandstone, Frontier black shale and the bentonite unit) and three unrelated but abundant surface materials (green vegetation, dry vegetation and soil A horizon). The reflectance properties of these "pure" endmember materials were measured using a field spectrometer in a laboratory setting. Composite average spectra, convolved with the AVIRIS spectral bandpasses, are shown in Figure 6. These seven spectra form the mixing library.

The spatial patterns of abundance of each of the seven endmembers were determined using modified linear spectral unmixing. The AVIRIS data, reduced to apparent reflectance spectra, were unmixed using the seven-member library of absolute reflectance spectra. The sum of the seven derived abundances, each constrained to be positive, is an estimate of the local illumination factor, IF . At each pixel the derived abundances were normalized by this sum to form abundance images relatively uninfluenced by illumination variation. These normalized abundance images and the corresponding IF image are shown in Figure 7. Also shown is the root-mean-square error image illustrating the goodness of fit between the modeled and observed spectra. These nine images illustrate how the geologic information in AVIRIS data can be extracted and quantified using spectral unmixing methods. The stratigraphic relationships among the various lithofacies can be mapped and analyzed using these results and an image processing workstation. Figure 8 shows the unmixing results for a single pixel found to be rich in bentonite. This figure illustrates the advantage of using the full spectral range for curve-fitting, as opposed to analysis of discrete spectral absorption features such as the clay band at $2.2\ \mu\text{m}$. The noise in the data prevents a direct visual identification of the spectral feature but the unmixing method, using all but the 60 noisiest channels, was able to correctly identify the surface composition.

Minimum unmixing uncertainties in the unmixing results were modeled using the methods outlined above. Figure 9 shows images of the uncertainties for the abundance images of Figure 7. Each endmember has a unique sensitivity to noise and instrument resolutions in the context of the particular mixing library. The black shale endmember, devoid of spectral features and low in albedo, has the least distinct spectrum and accordingly the highest uncertainty. Conversely, the vegetation endmembers, being more linearly independent, have the lowest uncertainties. For a single endmember, the uncertainty varies spatially due to illumination variation and changes in abundance of the other mixing endmembers.

VI. Conclusions

Geophysical inversion methods can be applied to AVIRIS data to quantitatively map and analyze sedimentary lithofacies. The modified linear spectral unmixing approach, outlined here, provides a numerically stable method for the simultaneous derivation of endmember abundance and illumination patterns. Using forward modeling methods and an accurate noise level spectrum, the minimum uncertainty for each endmember at each pixel can be determined. This application of geophysical methods to AVIRIS data analysis illustrates the usefulness of the data. Even in the presence of significant noise, lithofacies information and associated uncertainties can be derived.

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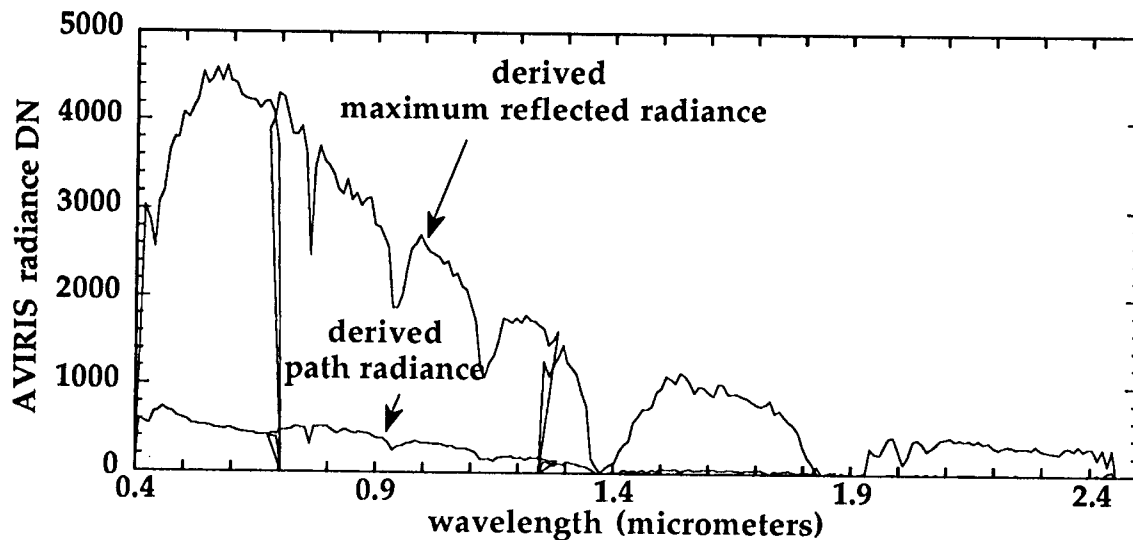


Figure 1. Derived gain and offset spectra.

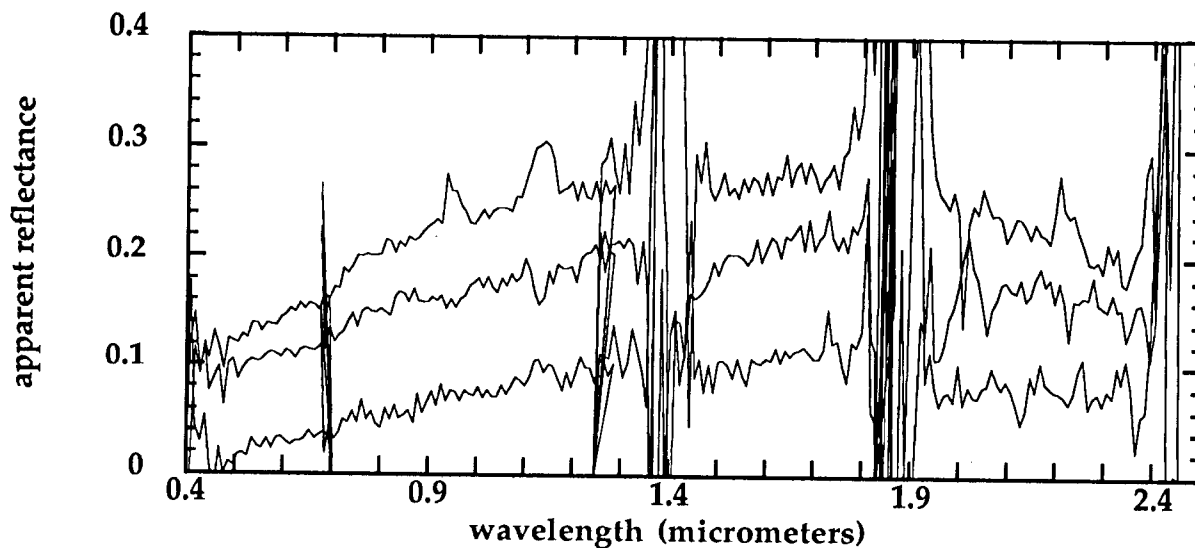


Figure 2. Three typical apparent reflectance spectra:

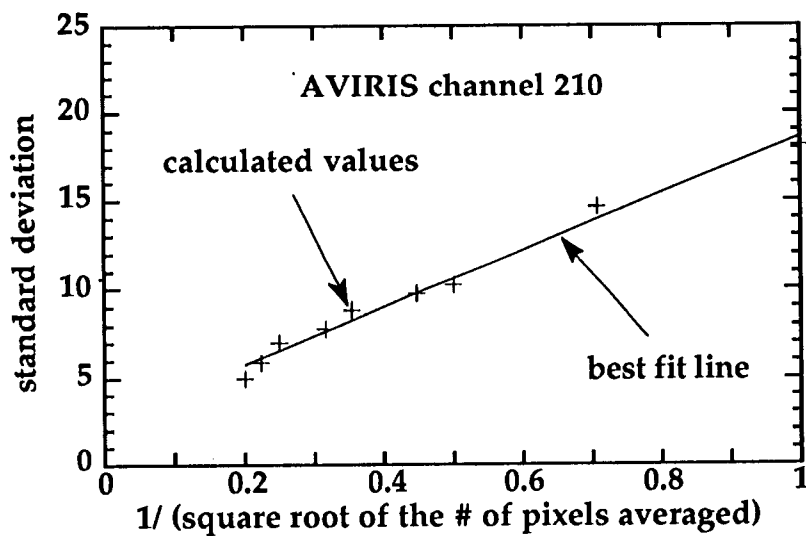


Figure 3. Application of the new noise derivation to AVIRIS band 210.

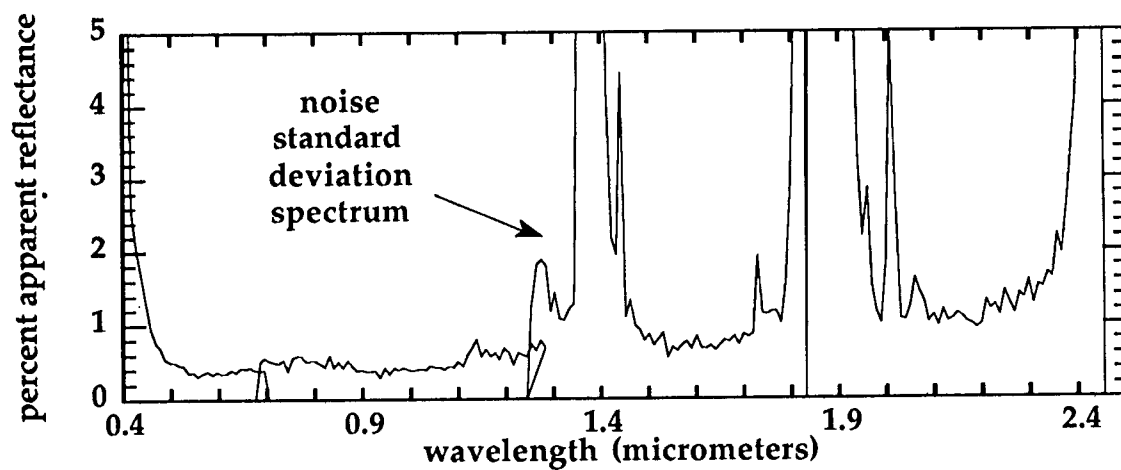


Figure 4. Noise standard deviation spectrum.

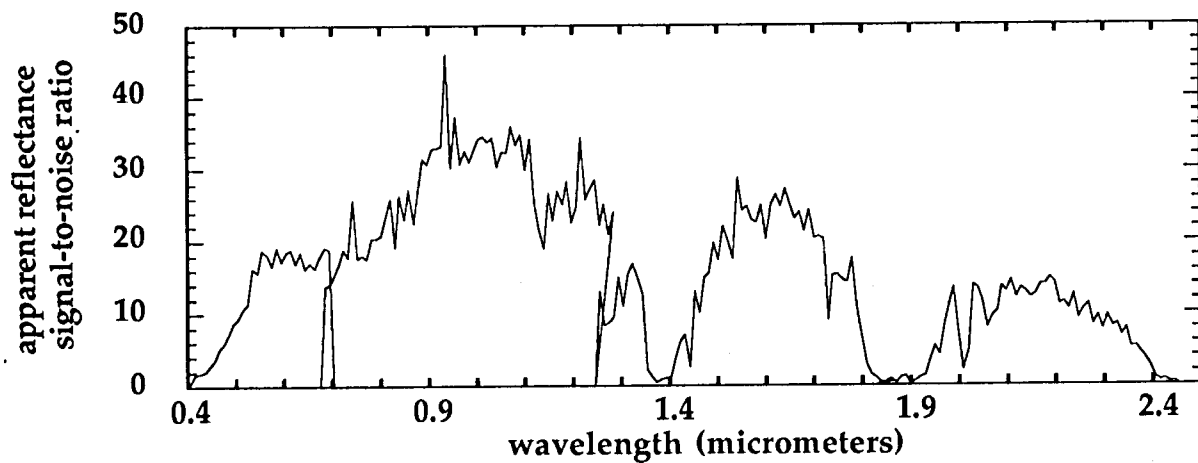


Figure 5. Mean signal-to-noise ratio spectrum.

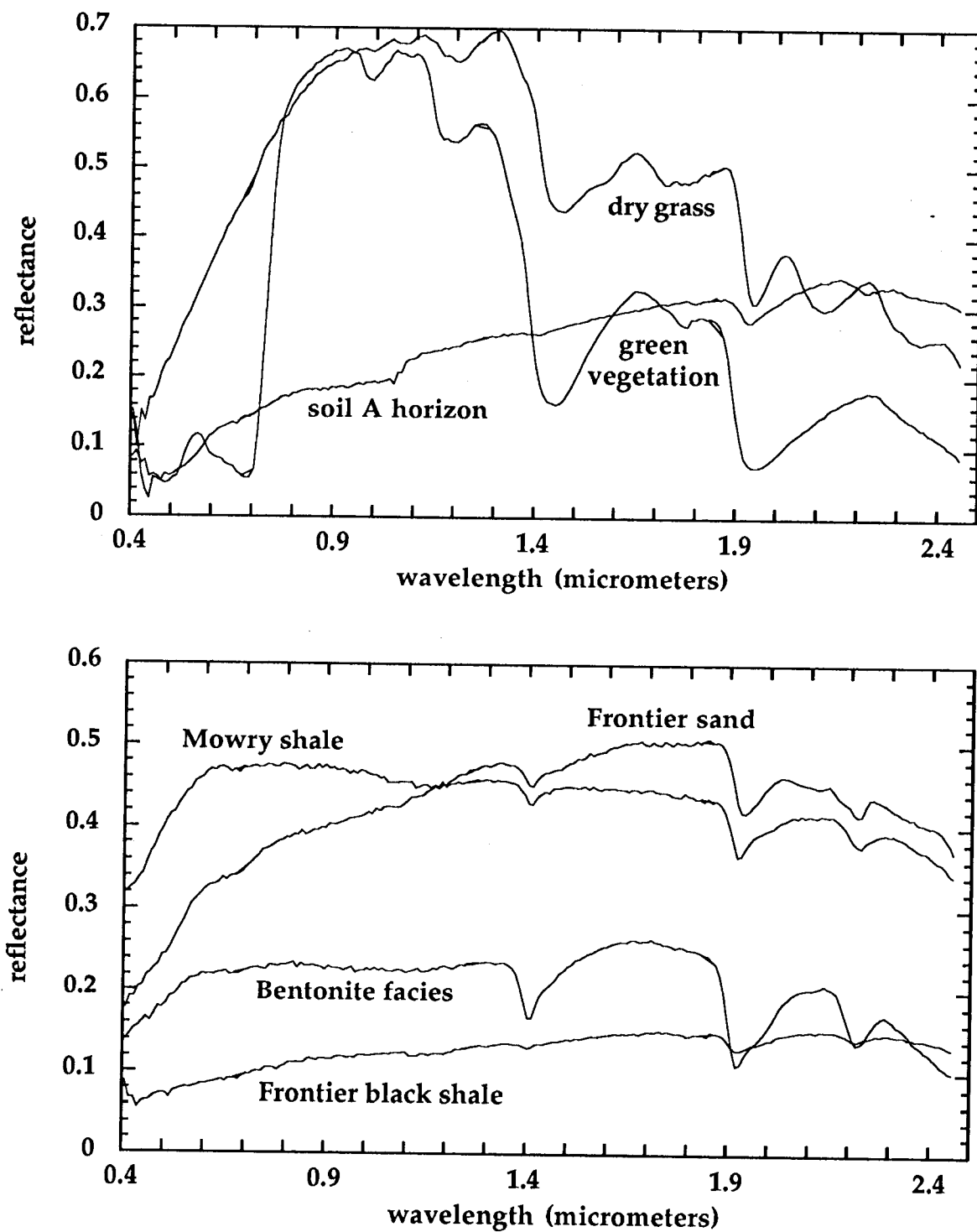


Figure 6. Frontier/Mowry mixing library endmembers.

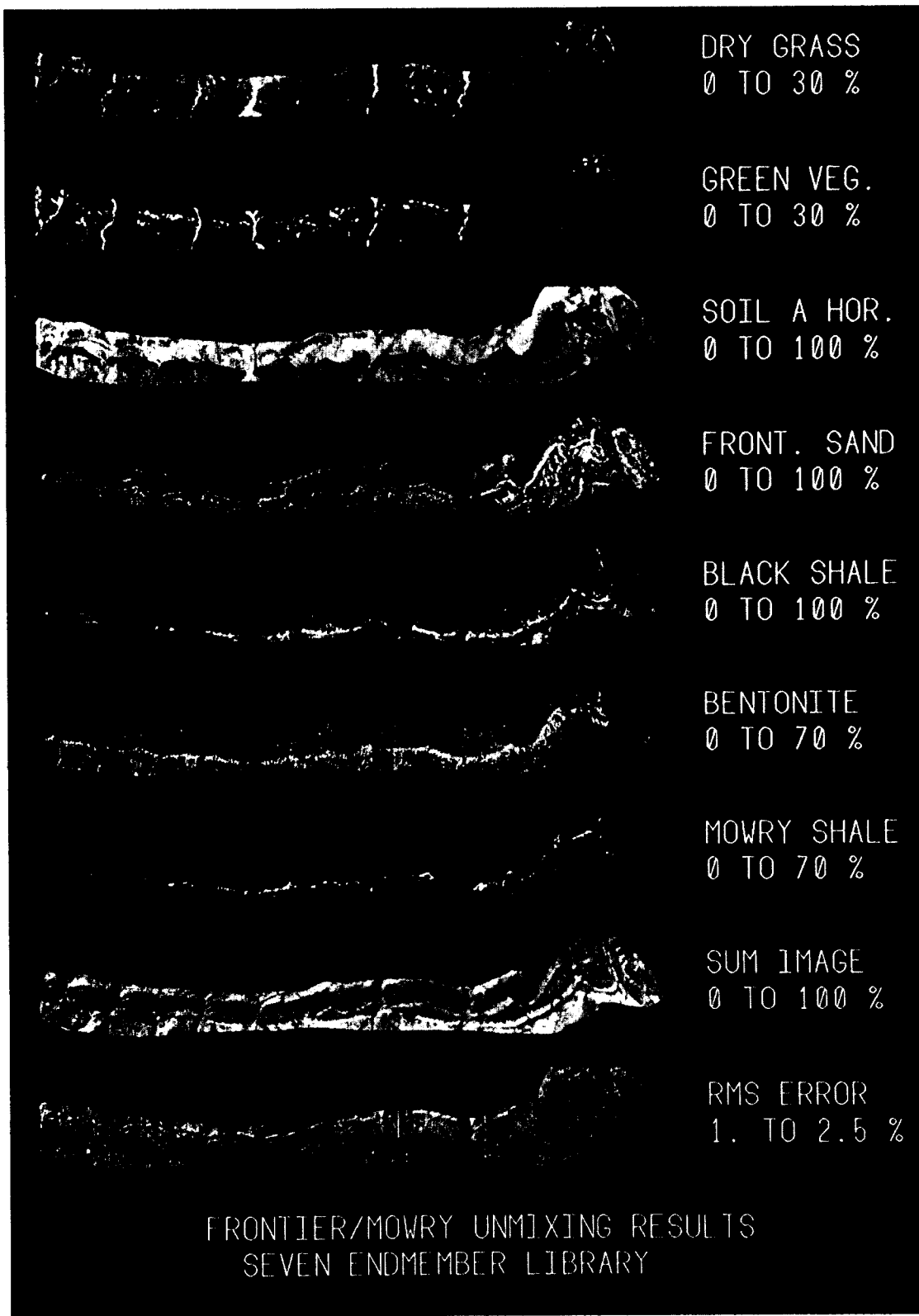


Figure 7. Endmember abundance images.

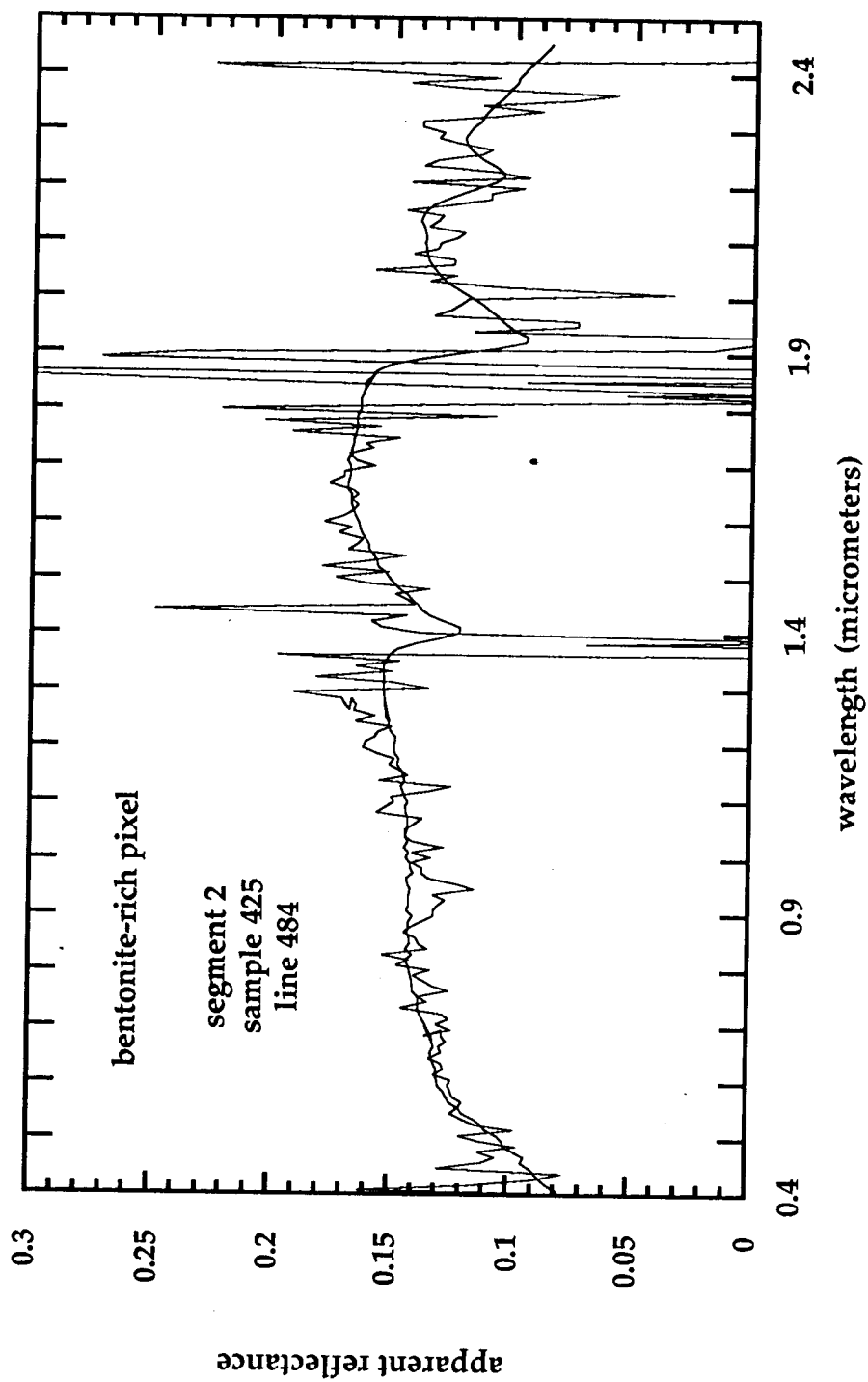


Figure 8. Single pixel observed spectrum and best fit model.

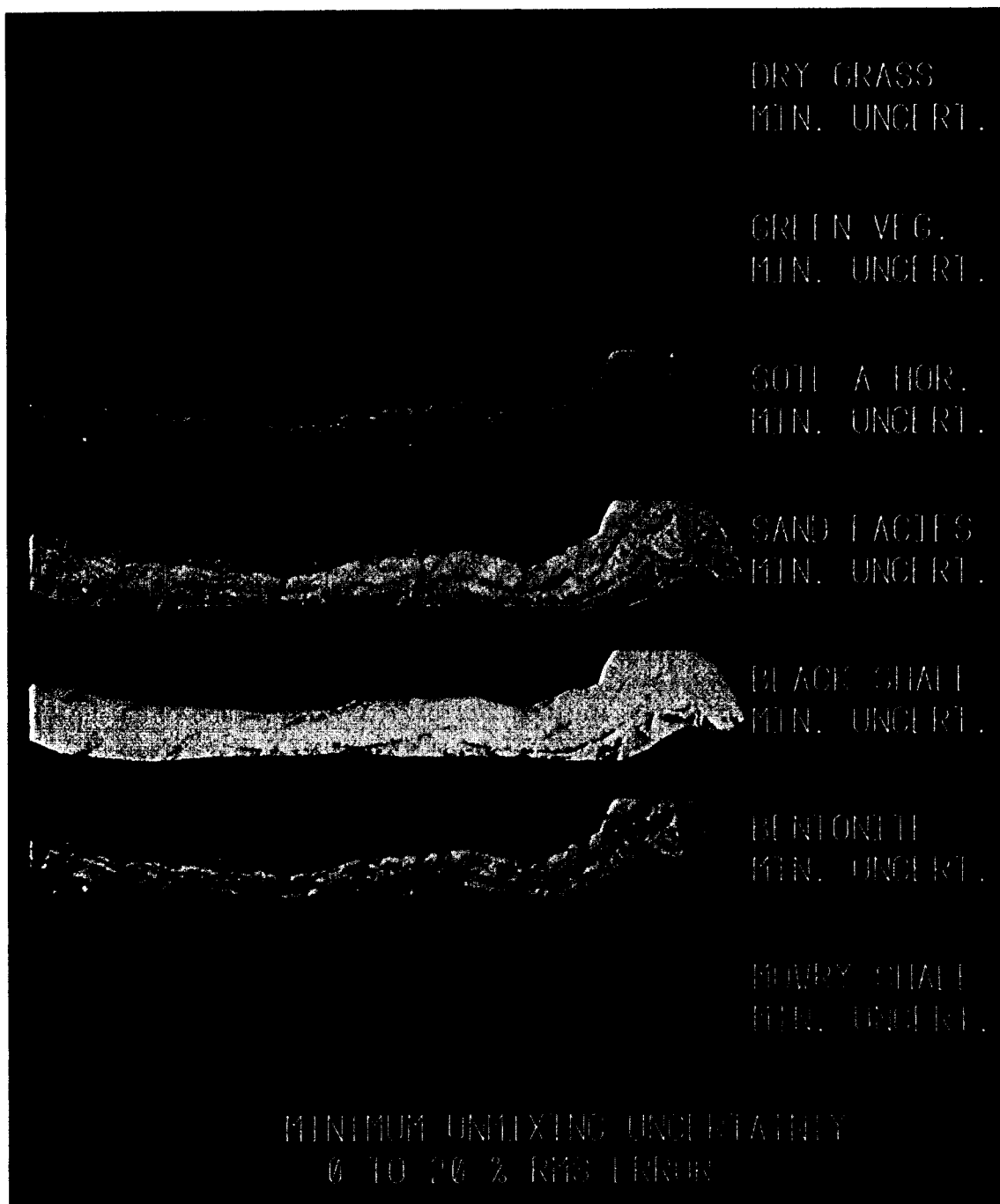


Figure 9. Minimum uncertainty images corresponding to Figure 7.