THE SEARCH FOR SWELLING CLAYS ALONG THE COLORADO FRONT RANGE: RESULTS FROM FIELD SPECTROMETRY AND HYPERSPECTRAL IMAGERY

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1. INTRODUCTION

Swelling soils are a major geologic hazard, and expansive clays and clay-shales cause extensive damage world-wide every year. Current engineering and geologic practice for characterization of expansive clays involves time-consuming and expensive standard engineering tests for determination of swelling potential, and x-ray diffraction (XRD) analyses for mineralogical identification. Reflectance spectrometry has the potentiality of rapid identification of minerals in soils. Our study investigates the spectral properties of swelling soils and their detectability with an hyperspectral imager. After establishing the spectral properties of swelling soils linked to their swelling potential in the field and laboratory, we investigate the possibilities of hyperspectral remote sensing sensors (AVIRIS, HyMap) in tackling a difficult operational problem of identification and mapping of expansive clays. 35% of all construction in the Front Range swelling soil corridor is affected and the remediation costs are enormous.

2. LABORATORY AND FIELD SPECTROMETRY

The Front Range Urban Corridor in Colorado which is underlain by Cretaceous clay-shales, including the Pierre Shale, is a region severely affected by swelling soil damage to buildings and infrastructure. The sedimentary bedrock strata are generally flat-lying, except near the foothills of the Rocky Mountains where they have been uplifted into steeply-dipping strata. Expansive clays in the Pierre Shale and adjacent formations along the Front Range are responsible for the damage. The hazard is most severe in areas where these units dip steeply because of differential movement of adjacent beds (cm-m) which has been attributed to the abundance and composition of swelling clays (Gill *et al*., 1996). The three most important groups of clay minerals are smectite, illite and kaolinite. Smectite (including montmorillonite, the best-known member of the smectite group) has the greatest swelling potential and is responsible for most swelling soil damage in Colorado.

Figure 1 shows the location of ~180 field samples collected along the 300 km Front Range Urban Corridor. For each sample we determined: (a) categories of swell potential from standard engineering tests; (b) spectroscopic identification with portable spectrometers (ASD FieldSpec™); (c) mineralogical composition from x-ray diffraction and grain size analyses. Olsen *et al.* (2000) showed that the swelling potential indices developed by McKeen (1992) and others correlate reasonably well with the weight percent of total smectite in the samples. The correlation coefficients are on the order of 0.7 to 0.9. Therefore, we can relate the spectroscopy and the swelling potential, if the direct relationship between spectroscopy and mineralogical composition can be proved.

Different types of clays can be identified spectroscopically because of their characteristic absorption bands around 2.2 μm. Near-infrared reflectance spectroscopy of swelling soil field samples has shown that it is possible to discriminate among pure smectite and mixed smectite/illite layers samples (Chabrillat *et al*., 1999, 2000). Smectite has a characteristic single deep absorption band centered at 2.2 μm. An additional absorption band at 2.35 μm provides a measure of the illite content. The higher the amount of smectite (the less illite), the higher the swelling potential. Kaolinite is detected spectrally if above 10% in clay fraction in the sample, with the appearance of a characteristic doublet feature in the 2.2 μm absorption band. A significant amount of kaolinite (>10-15%), and/or a significant amount of illite, is indicative of low swelling potential. In the case of the spectral identification

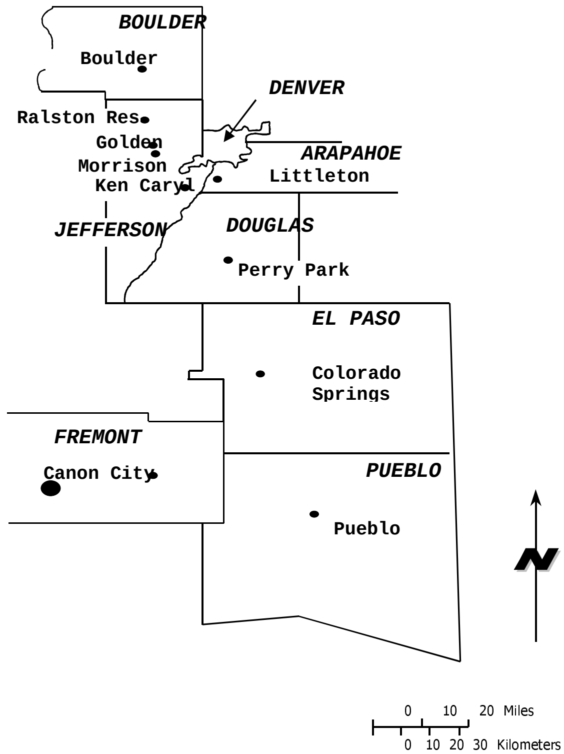

Figure 1. Samples location and geologic setting.

of kaolinite in the sample, but with a high smectite content (deep water absorption band at ~1.9 µm), then the swell potential is not as low as the kaolinite content might suggest, according to the laboratory measurements. Clay spectroscopic identifications are well correlated with mineralogical x-ray diffraction analyses (Chabrillat *et al*., 2000).

3. HYPERSPECTRAL IMAGERY

3.1 Data sets

Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) scenes were acquired over the Front Range Urban Corridor in Colorado in September and October 1998 (high and low altitude data) and late September 1999 (high altitude data). The comparison between AVIRIS low and high altitude data in 1998 is discussed in Chabrillat and Goetz (1999). Airborne Hyperspectral Scanners (HyMap) scenes were acquired during the AIG/HyVista HyMap campaign in late September 1999, when the vegetation cover was at a near minimum. AVIRIS has 224 spectral channels, 10 nm wide, spanning the 0.37-2.51 µm spectral region. HyMap has 126 spectral channels, 13 to 17 nm wide (17 nm in the SWIR 2), spanning the 0.44-2.47 µm spectral region. AVIRIS high altitude scenes in the area covered provide a pixel size of ~17m x 17m and a swath width of ~10 km. HyMap scenes in the same area provide a pixel size of ~4m x 4m and a swath width of ~2.3 km. The signal-to-noise (SNR) for AVIRIS in 1999 is over 1000:1 in the visible, and ~400:1 in the SWIR 2 spectral region (1.95-2.5 µm). HyMap SNR is ~600:1 in the SWIR 2.

The problem in the identification and mapping of expansive soils in Colorado is that the outcrops are sparse and small, and most of the time more or less covered with vegetation. In addition they are of variable mineralogy at a small scale (<1m). Both AVIRIS (high altitude) and HyMap scenes were obtained over several geological sites of interest in 1999. We will focus here on two examples, Perry Park and the Pueblo area, for the following reasons. Perry Park is representative of the situation in northern Colorado with small sparse outcrop and heavy vegetation cover, and is close to the mountain front with variable mineralogy and many steeply dipping bentonite beds, which are pure smectite. The Pueblo area is representative of the situation in southern Colorado where vegetation is sparse and soils well exposed, and is far from the Front Range with horizontal smectite/illite layers and sometimes kaolinite in the soils. The results from another typical example associated with the Colorado Springs area overflown by AVIRIS in 1997 has been described in Chabrillat *et al*., 1999.

3.2 Pre-processing and processing of the images

Each AVIRIS scene was first radiometrically corrected by the Jet Propulsion Laboratory. The calibration of the data relative to ground reflectance was performed using the following procedure. (a) Atmospheric correction using ATREM 3.1 (Gao *et al*., 1993) to derive reflectance; and (b) ground correction using field spectra acquired on the day and at the time of the overflight on a pure soil calibration target in North Boulder. The HyMap scenes were delivered in apparent reflectance by AIG/HyVista. Their pre-processing methodology includes (a) atmospheric correction using ATREM; and (b) correction of the systematic errors in the calibration with the EFFORT procedure (ENVI 3.2, www.rsinc.com).

The following processing methodology was applied on both AVIRIS and HyMap images, using only the 2-2.45 μm spectral region (43 spectral channels for AVIRIS, 28 for HyMap):

1. A minimum Noise Fraction (MNF) transform was performed,
2. The Pixel Purity Index (PPI) method was used to find the most spectrally pure (extreme) pixels,
3. The extreme pixels were visualized in the data cloud from the ten first MNF bands. One of the clusters was identified as having pixels showing characterictic spectral clay features at 2.2 μm, such as kaolinite, smectite, and possibly illite,
4. Extreme clay pixels (endmembers) were extracted from the "clay" cluster,
5. A Mixture Tuned Matched Filtering (MTMF) method was eventually used to locate and map expansive clays outcrops. This last analysis provides an abundance map for each selected endmember associated with an "infeasibility" image to prevent detecting "false positives" in the original matched filtering algorithm.

4. RESULTS

4.1 Perry Park

Figure 2 presents the spectra associated with the endmembers selected in the clay cluster, for the HyMap and the AVIRIS scene. Although the HyMap scanner has less spectral resolution than AVIRIS, the characteristic clay spectral features were detected. There is no illite/smectite endmember in the AVIRIS data (see below). Figure 3 shows the abundance maps obtained with the MTMF algorithm for the HyMap data for the three endmembers, smectite (fig. 3b), illite/smectite (fig. 3c) and kaolinite (fig. 3d). The greyscale coding ranges from black (abundance=0%) to white (abundance=100%) meaning a perfect match between the spectra of the pixel and the endmember. Figure 3a shows for reference the part of the HyMap image associated with the area shown in the abundance maps. By zooming on a very small area, ~1 km in extent, we can see in the abundance maps that clay materials exposed in this area are very sparse and small in size. This agrees with our field knowledge. Also, many areas rich in smectite were detected. This also agrees with the fact that Perry Park is known for its smectite-rich claystone exposures, along with the occurrence in the mixed smectite/illite layers of several thin bentonite beds.

Several points of interest are located in fig. 3 with the labels 1, 2 and 3. The label 1 is associated with the location of the smectite endmember. This area in the field was associated with soils exposed around a house under construction (circular shape). The field samples collected around this house showed a pure smectite feature in their spectra, confirming the remote sensing identification. The same analysis on the Perry Park AVIRIS scene showed

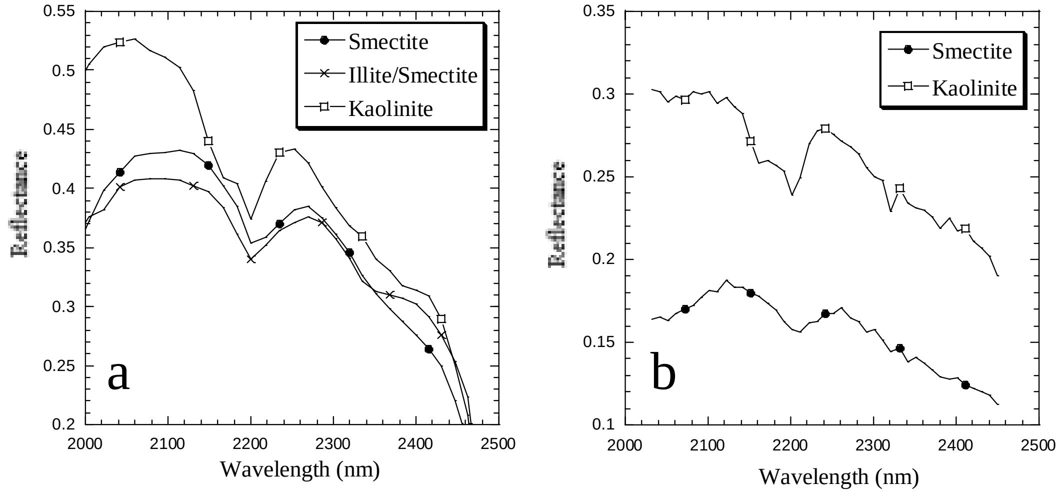

Figure 2. Spectra of the clay endmembers (SWIR 2), Perry Park area.
a- HyMap, b- AVIRIS.

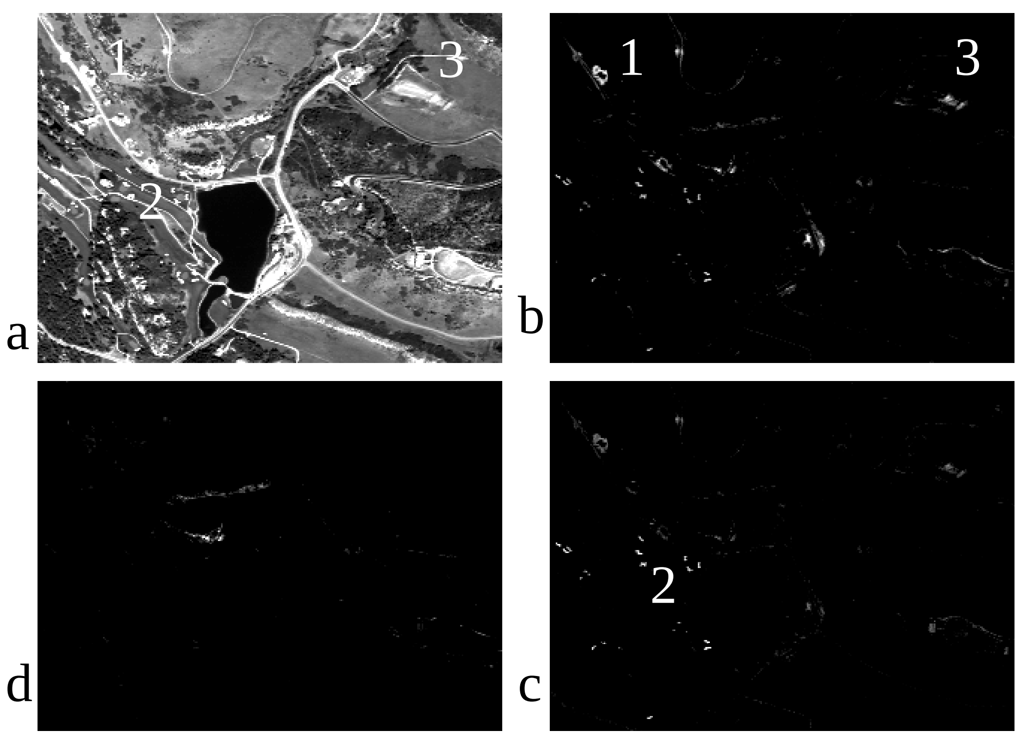

Figure 3. Abundance maps obtained with the mixture tuned matched filtering algorithm for the three endmembers shown in figure 2a, Perry Park area, HyMap data.
a- image at 0.6 μm, b- smectite, c- illite/smectite, d- kaolinite.
The points of interest are located with the labels 1, 2 and 3.

the same results, and the same location for the smectite endmember. The label 2 is associated with the location of the illite/smectite endmember in the HyMap data. This area in the field was associated with golf holes a few meters in extent, surrounded by green grass. These golf holes, and also the illite/smectite endmember, were not detected in the AVIRIS data because of the larger pixel size. They are already at a sub-pixel size for the HyMap data. The label 3 is associated with three Gronero shale outcrops. Those outcrops are well exposed with almost no grass, but are small in size (10-30 m) and have a very dark grey color (low in reflectance, <10% in the SWIR 2 region). AVIRIS results are similar to HyMap results. They both detected one of those outcrops, brighter than the two others, but the two darker ones were only partially detected. In this case, the detection limits in terms of SNR have been reached. This problem was already identified in Chabrillat and Goetz, 1999, with AVIRIS 1998 low and high altitude data.

4.2 Pueblo

Figure 4 presents the extreme clay spectra extracted from the clay cluster for the HyMap and the AVIRIS scenes. We notice that the clay features in those extreme spectra are not as deep as, for example, the ones that could be extracted from an area more mineralogically heterogeneous like Perry Park. Indeed, the Pueblo clay endmembers are not as extreme (less “pure”) than in others areas, and this is not the result of a spatial resolution effect. This is consistent with the known geological setting around Pueblo. The soils exposed contain illite/smectite layers with few bentonite beds and, in general, they are less smectite-rich than in areas against the Front Range, and less variable in mineralogy. The reduced compositional variability comes from the fact that the beds are more or less horizontal (<30°) as opposed to the near-vertical beds along the Front Range that expose different compositions. Figure 5 shows the abundance maps obtained with the MTMF algorithm for the HyMap data for the three extreme clay spectra shown in fig. 4a. The greyscale coding is the same as in fig. 3. The mapping shows that well-exposed illite/smectite layers, and kaolinite-rich soils are found in an area associated with the top of a large Mesa North-East of Pueblo city. This is consistent with our field observations, i.e. laboratory spectra and analyses of field samples and field spectra from the Baculite Mesa outcrop, directly below the large Mesa. All those samples showed a mixed content in smectite and illite, with some kaolinite content. The processing of the AVIRIS scenes over the same area showed roughly the same results, with small differences associated with the larger pixel size.

5. SUMMARY

Near-infrared (NIR) reflectance spectroscopy of swelling soil field samples shows that it is possible to discriminate among pure smectite and mixed smectite/illite layers samples. The absorption band at 2.35 μm provides a measure of the illite content. The higher the amount of smectite (the less illite), the higher the swelling potential. Spectroscopic identifications are well correlated with mineralogical x-ray diffraction analyses and geotechnical engineering tests. We have identified kaolinite in samples rich in smectite. In this case, the smectite feature at 1.9 μm is key to its identification. The swelling potential as measured by engineering standards correlates reasonably well with the smectite content that can be measured by spectroscopy.

The analysis of the hyperspectral images shows that, using a matched filtering algorithm, exposures of expansive clays can be detected among the other components in the images, and in the presence of significant vegetation cover. A map of exposed clay material is produced and among those exposures, spectral discrimination, and identification of variable clay mineralogy (kaolinite, smectite/ illite, smectite) related to variable swelling potential is possible. Field checks have shown that the maps of clay type derived from the imagery are accurate.

The comparison of the HyMap data (126 channels, 13-17 nm wide, 4m pixel size), with the AVIRIS high altitude data (224 channels, 10 nm wide, ~17m pixel size) has been instructive. The loss of HyMap spectral resolution in the SWIR 2 (17 nm vs. 10 nm sampling) does degrade our ability to detect mixing with kaolinite, as the doublet feature is somewhat degraded, but does not impair our ability to identify smectites or illites. The gain in spatial resolution of HyMap vs. AVIRIS allows for a more precise mapping and more extreme endmembers, although no new natural outcrops were detected. However, smaller pixel size does *not* compensate for the SNR detection limits of either instrument.

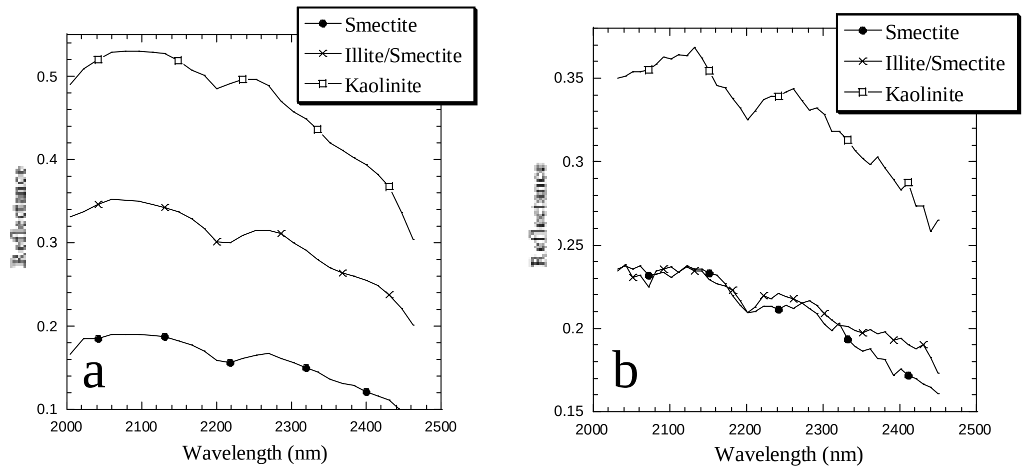

Figure 4. Spectra of the clay endmembers (SWIR 2), Pueblo area.
a- HyMap, b- AVIRIS.

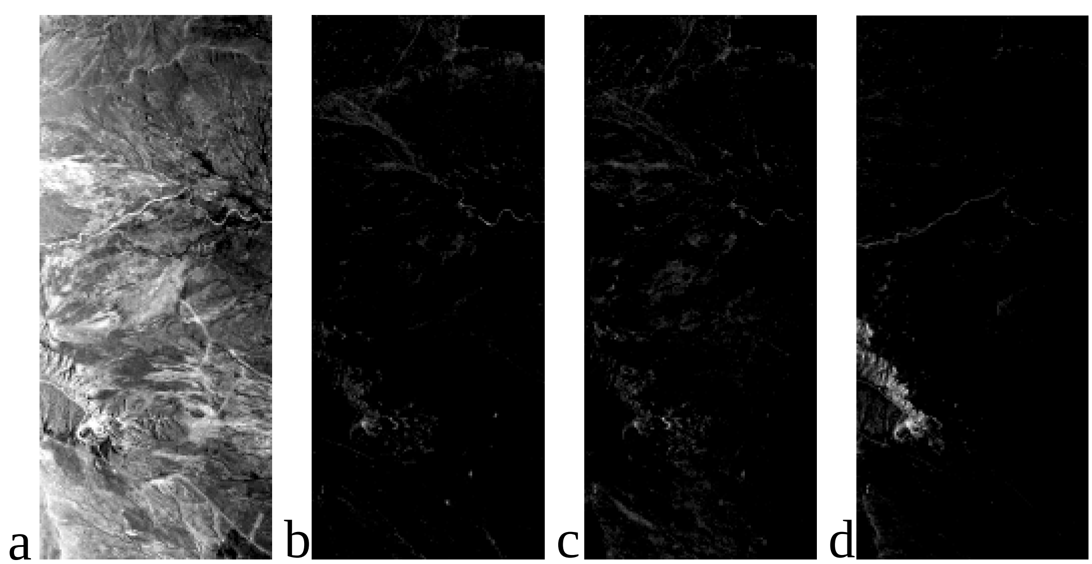

Figure 5. Abundance maps obtained with the mixture tuned matched filtering algorithm
for the three endmembers shown in figure 4a, Pueblo area, HyMap data.
a- image at 0.6 μm, b- smectite, c- illite/smectite, d- kaolinite.

6. ACKNOWLEDGMENTS

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