REMOTE MINERAL MAPPING USING AVIRIS DATA AT SUMMITVILLE, COLORADO AND THE ADJACENT SAN JUAN MOUNTAINS

Trude V.V. King, Roger N. Clark, Cathy Ager, and Gregg A. Swayze
U.S. Geological Survey
P.O. Box 25046 MS 964
Denver, CO 80225

INTRODUCTION

From 1985 through 1992, the Summitville open-pit mine produced gold from low-grade ore using cyanide heap-leach techniques, a method to extract gold whereby the ore pile is sprayed with water containing cyanide, which dissolves the minute gold grains. Environmental problems at Summitville include significant increases in acidic and metal-rich drainage from the site, leakage of cyanide-bearing solutions from the heap-leach pad into an underdrain system and several surface leaks of cyanide-bearing solutions into the Wightman Fork of the Alamosa River. The mine's operator had ceased active mining and begun environmental remediation, including treatment of the heap-leach pile and installation of a water-treatment facility, when it declared bankruptcy in December 1992 and abandoned the mine site. The EPA immediately took over the Summitville site under EPA Superfund Emergency Response authority. Summitville was added to the EPA National Priorities List in late May 1994.

Summitville has focused nationwide public attention on the environmental effects of modern mineral-resource development. Soon after the mine was abandoned, Federal, State, and local agencies, along with Alamosa River water users and private companies, began extensive studies at the mine site and surrounding areas. These studies included analysis of water, soil, livestock and vegetation. The role of the U.S. Geological Survey (USGS) was to provide geologic and hydrologic information about the mine and surrounding area and to describe and evaluate the environmental condition of the Summitville mine and the downstream effects of the mine on the San Luis Valley. The environmental condition of the Summitville area is a result of the geologic evolution of this area that culminated in the formation of precious-metal mineral deposits and a result of the mining activity. Understanding the geologic and hydrologic history of this area is a critical piece to understanding the environmental puzzle at Summitville.

IMAGING SPECTROMETER DATA

To address these geologic and hydrologic problems, we analyzed AVIRIS data for the Summitville mining district and the adjacent San Luis Valley, in Colorado. The data were acquired on September 3, 1993. A combined method of radiative transfer modeling and empirical ground calibration site reflectance were used to correct the flight data to surface reflectance (Clark *et al.*, 1994). This method corrects for variable water vapor in the atmosphere and produces smooth spectra with spectral channel to channel noise approaching the signal to noise of the raw data. Thus, the data can be compared to standard laboratory measurements. The calibration site is a plowed field approximately 18 kilometers SW of Alamosa. The calibration site soil samples were obtained on the day of the overflight and measured on the USGS laboratory spectrometer (Clark *et al*, 1990b). The spectra of the calibration field are spectrally bland and serve as an ideal calibration standard.

TRICORDER ANALYSIS

Clark *et al.*, (1990a, 1991) developed a new analysis algorithm that uses a digital spectral library of known

reference materials and a fast, modified-least-squares method of determining if a diagnostic spectral feature for a given material is present in the image. This algorithm is called "tricorder." The tricorder analysis compares continuum-removed spectra (Clark and Roush, 1984) from the remotely sensed data, to a database of continuum-removed spectral features from the reference spectral library (Clark et al., 1993). Multiple features from multiple materials are compared and the material with the closest match is mapped. The algorithm does not force a positive match which makes if different from many other algorithms in use. The tricorder algorithm attempts to map only minerals included in the reference database.

For the present study we mapped minerals based on the presence of absorption features inthe ~0.45 μm to ~1.0 μm, 1.5μm, and 2.2 μm to 2.3 μm wavelength region, which represent the visible and near-infrared portions of the electro magnetic spectrum. In this dataset we looked for 64 different minerals.

Absorption bands in the visible portion of the spectrum (~0.4-0.8μm) are caused by electronic processes including crystal field effects, charge transfer, color-centers, and conduction bands. The absorptions resulting in the visible portion of the spectrum involve elements of the first transition series which have an outer unfilled d-shell in their electronic distribution. The energy levels are determined by the valence state of the element, its coordination number and its site symmetry. Differences in these parameters are manifested in individual diagnostic absorption bands. Absorptions in this wavelength region are commonly associated with the presence of iron in the mineral structure.

Near-infrared radiation (1-2.45 μm, in this study) absorbed by a mineral is converted into molecular vibrational energy. The frequency or wavelength of the absorption depends on the relative masses and geometry of the atoms and the force constants of the bonds. There are two main types of molecular vibrations: stretching and bending. A stretching vibration is a movement along the bond axis which either increases or decreases the interatomic distances. Bending vibrations consist of a change in the angle between bonds with a common atom or the movement of a group of atoms with respect to the remainder of the molecule, but without movement of the atoms in the group with respect to one another (Silverstein et al., 1981). Only vibrations that result in a change in the dipole-moment of the molecule will be infrared active.

Absorption features in the 2.2 to 2.3-μm region result from a combination of the OH-stretching fundamental with either the Al-O-H bending mode absorbing at approximately 2.2 μm, or Mg-O-H bending mode absorption at 2.3 μm. At high resolution these bands also appear as characteristic multiple, complex absorption features. Based on previous work (King and Clark,1989, Clark et al., 1990b, Clark et al., 1993), it is known that the strength, position and shape of these features is a function of the mineral chemistry.

In this study we searched for 22 minerals with absorption features at wavelengths near or less than 1.0 μm. We successfully mapped 7 of these 22 potential minerals. The minerals we detected include: amorphous iron-hydroxide, ferrihydrite, goethite, hematite, K-jarosite, Na-jarosite, and an Fe-bearing material that spectrally matches the processed sludge removed from the Reynolds Tunnel. AVIRIS Workshop Slide 7 shows their distribution at, and near, the Summitville mine. Comparison of spectra of these minerals extracted from the remotely sensed data with our laboratory standards shows no differences. We have detected spectral differences that allow us to discriminate between the amorphous iron-hydroxide and ferrihydrite, based on our laboratory standards, however, it is possible that these two materials are chemically similar. It should be noted that the most reliable method of identifying amorphous iron oxides is mossbauer spectroscopy.

Samples of the processed Reynolds Tunnel sludge, collected at the mine site, were used as laboratory standards to identify this material in the remotely sensed data. In AVIRIS Workshop Slide 7, its distribution is depicted in yellow. In this case the algorithm maps solid Fe-bearing material and red-stained water puddles in the mine pit. Several days of rain occurred prior to the day of data acquisition, thus it is likely there was standing water in the pit. Other investigators have reported the occurrence of red-puddles in the pit resulting from precipitation or melting snow.

To detect the presence of minerals that have absorption features in the 2.2-2.3 μm wavelength region we used 48 mineral standards. These 48 standards included phyllosilicates, sulphates, carbonates, and cyanide compounds. Of these 48 standard minerals we detected 8 different phases of significant areal extent. Subtle spectral differences allow for the discrimination between K and Na alunites and poorly-crystalline and highly-crystalline kaolinites. However, because of spectral similarities and limitations of the mapping algorithm, some of the material mapped as Na-montmorillonite may be muscovite or sericite. Recent modifications to the mapping algorithm have eliminated this inconsistency.

Spectral data contained in the AVIRIS pixels are very similar to the spectral standards measured in the laboratory. Figure 1 shows the spectrum of a montmorillonite pixel detected near Alum Creek compared to a

laboratory spectrum of a standard montmorillonite. Breaks in the spectra of the AVIRIS data occur at the wavelengths where absorptions from atmospheric gases occur. The absorption features in the montmorillonite spectrum from the AVIRIS data are identical to the diagnostic absorption features in the laboratory standard at wavelengths near 2.2 µm. The AVIRIS data shows that the montmorillonite is mixed with an Fe-bearing mineral phase because of an absorption near 0.8 µm (this absorption feature would be mapped with the Fe-bearing minerals).

The mapping of the halloysite or kaolinite-smectite mixtures from the AVIRIS data has been less certain because of inconsistencies in both the spectral data and supporting x-ray analysis. Initially, the halloysite was mapped based on laboratory standards. However, X-ray data indicated that the material contained kaolinite and other unidentified phases, but did not contain either halloysite or illite (Stephen Huebner, USGS, personal communication, 1994). The spectral data of the material (collected in the field) clearly indicates that crystalline kaolinite is not present and that absorption features very similar to illite and halloysite are present. Thus, we believe that the material is likely to be a supergene weathering product, a mineral for which we do not have either spectral or X-ray standards, or a new mineral. Therefore, caution should be applied in interpretating the presently-mapped areal distribution of this phase.

DISCUSSION

Imaging spectroscopy data of the Summitville mine and the Iron, Alum and Bitter Creek basins were used to identify minerals associated with alteration. Hydroxyl-bearing materials, including clays, show discrete distribution patterns at both the mine site and within the Iron, Alum and Bitter Creek basins. Mineralogic differences between the open pit and the heap leach pile at the mine site can be distinguished and discrete mineralogical boundaries in the Iron, Alum and Bitter Creek basins can also be detected.

Perhaps the most interesting observation is that the Summitville mine apparently does not contribute OH-bearing minerals via the Wightman Fork to the Alamosa River. In contrast the mineralized area in Iron, Alum and Bitter Creek basins do contribute OH-bearing minerals to the Alamosa River. This observation is based on the spectral characteristics of the exposed fluvial sediments along Alum Creek and Bitter Creek and lack of OH-bearing fluvial sediment along the Wightman Fork. The unmined mineralized areas are believed to contribute OH-bearing materials to the Alamosa River due to the porous character of the well-exposed rock, which allows altered materials to be eroded easily and deposited along the stream banks. If hydroxyl-bearing materials, and associated contaminants, are being supplied to the Wightman Fork by the Summitville mine, the material must be carried as a very fine-grained aqueous suspension which cannot settle onto the creek banks.

Images show that both the Summitville mine and Iron, Alum and Bitter Creek basins are sources of iron-bearing sediments to the Alamosa River (AVIRIS Workshop Slide 7). These sediments give a reddish-brown color to stream banks, a characteristic typically associated with acid drainage, and are potential carriers of heavy metals to locations downstream. Consequently, in assessing the environmental impact of mining at Summitville, it is important to recognize that both the Summitville mine site and the Iron, Alum and Bitter Creek basins contribute this type of sediment to the Alamosa River.

SUMMARY

In summary, we have demonstrated the unique utility of imaging spectroscopy in mapping mineral distribution. In the Summitville mining region we have shown that the mine site does not contribute clay minerals to the Alamosa River, but does contribute Fe-bearing minerals. Such minerals have the potential to carry heavy metals. This application illustrates only one specific environmental application of imaging spectroscopy data. For instance, the types of minerals we can map with confidence are those frequently associated with environmental problems related to active and abandoned mine lands. Thus, the potential utility of this technology to the field of environmental science has yet to be fully explored.
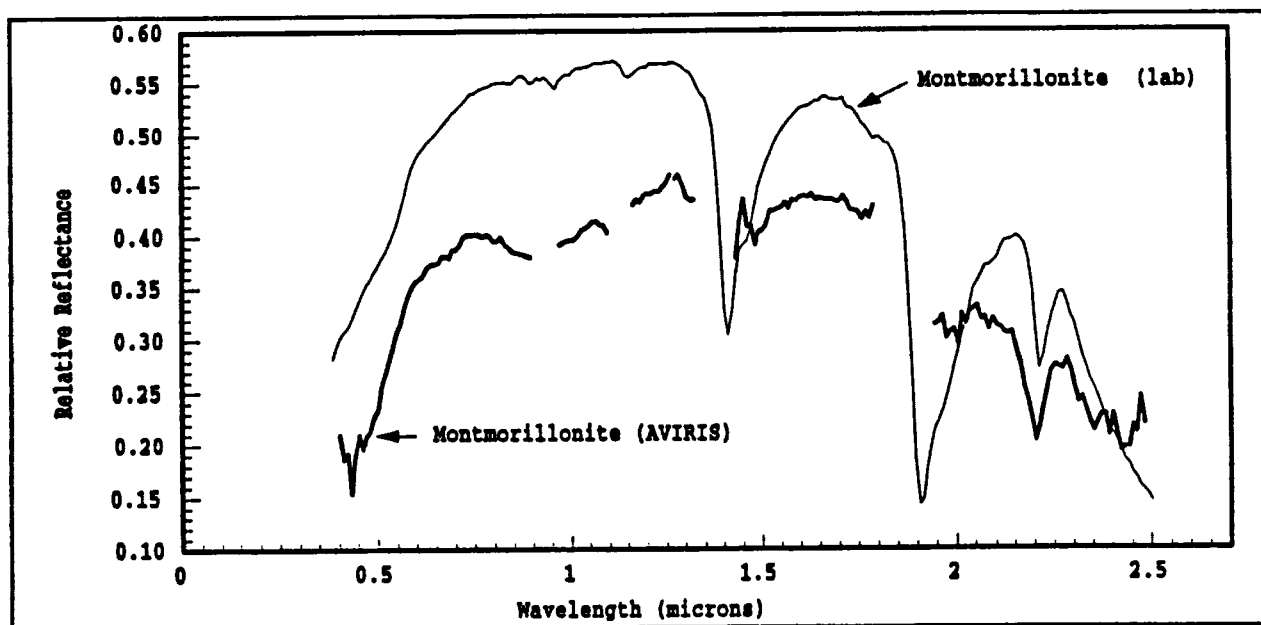
Figure 1. Spectra of montmorillonite measured in the laboratory and montmorillonite detected by AVIRIS near Alum Creek.

REFERENCES

Clark, R.N. and T.L. Roush, Reflectance Spectroscopy: Quantitative Analysis Techniques for Remote Sensing Applications, *J. Geophys. Res.,* 89, 6329-6340, 1984.

Clark, R.N., A.J. Gallagher, and G.A. Swayze, Material absorption band depth mapping of imaging spectrometer data using a complete band shape least-squares fit with library reference spectra: *Proceedings of the Second Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop,* JPL Publication 90-54, p. 176-186, 1990a.

Clark, R.N., T.V.V. King, M. Klejwa, G. Swayze, and N. Vergo, High Spectral Resolution Reflectance Spectroscopy of Minerals: *J. Geophys Res.* 95, 12653-12680, 1990b.

Clark, R.N., G.A. Swayze, A. Gallagher, N. Gorelick, and F. Kruse, Mapping with Imaging Spectrometer Data Using the Complete Band Shape Least-Squares Algorithm Simultaneously Fit to Multiple Spectral Features from Multiple Materials, *Proceedings of the Third Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop,* JPL Publication 91-28, 2-3, 1991.

Clark, R.N., G.A. Swayze, A. Gallagher, T.V.V. King, and W.M. Calvin, The U. S. Geological Survey, Digital Spectral Library: Version 1: 0.2 to 3.0 μm, *U.S. Geological Survey, Open File Report 93-592,* 1340 pages, 1993b. (Also being published as a USGS Bulletin, 1300+ pages, 1994 *in* press.)

Clark, R.N., G.A. Swayze, K. Heidebrecht, R.O. G.A.F.H. Goetz: Calibration to Surface Reflectance of Terrestrial Imaging Spectrometry Data: Comparison of Methods, *Applied Optics in* review, 1994a.

King, T.V.V. and R.N. Clark, Spectral Characteristics of Chlorites and Mg-Serpentines Using High-Resolution Reflectance Spectroscopy. *J. Geophys. Res.,* 94, 13,997-14,008, 1989.

Silverstein, R.M., G.C. Bassler, and T.C. Morrill, Spectrometric Identification of Organic Compounds. John Wiley, New York, New York, 442p., 1981.