

MAPPING OF ACID-GENERATING AND ACID-BUFFERING MINERALS IN THE ANIMAS WATERSHED BY AVIRIS SPECTROSCOPY

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1. INTRODUCTION

The Animas River Watershed is the site of a coordinated effort to characterize the extent and severity of environmental effects from acid water drainage. This water originates both from numerous abandoned mine sites that date as far back as the late 1800s, and from extensive areas of natural altered and mineralized outcrops. The headwaters of the Animas River are within the San Juan and Silverton calderas, which were responsible for creating large fractures and faults suitable for later mineralization. As part of the Abandoned Mine Lands (AML) Project of the United States Geological Survey (USGS), data were obtained over the San Juan Mountains and Animas Watershed using the Jet Propulsion Laboratory's Airborne Visible and InfraRed Imaging Spectrometer (AVIRIS) and are being used in conjunction with field geologic mapping, geochemistry and geophysics to determine the relative extent of natural and anthropogenic sources of acid water runoff, and its effect on water quality in the drainage.

2. THE AVIRIS DATASET

The Animas Basin AVIRIS data set is comprised of 14 AVIRIS scenes, approximately 10.5 km x 8 km apiece, extending from Hermosa Colorado to the headwaters of the Animas River north of Silverton, near the ghost town of Animas Forks. The 224 spectral channels cover a range from .37 to 2.51 μm , encompassing visible and near-infrared wavelengths suitable for mapping a wide variety of vegetation and minerals, including but not limited to the hydrothermally altered rocks of particular relevance to the San Juan Mountains. The 14 scenes are arranged in two overlapping lines parallel to and bounding the Animas river as it flows from its headwaters toward Durango, Colorado, including most of the Silverton caldera situated within the watershed. The data were acquired under cloud-free late morning conditions on June 18, 1996 in a 17-minute pass over the two lines. While yearly precipitation is normally quite high in the San Juan Mountains, the resulting thick vegetation still leaves significant large outcrops of exposed rock available for mapping analysis; in addition, at the time of acquisition of this dataset, the snowpack was greatly reduced due to melting.

3. REGIONAL GEOLOGY AND MINING ACTIVITY

The Animas watershed is located in the western part of the mid-late Tertiary age San Juan volcanic field (Lipman *et al.*, 1976). Here the local geology is largely comprised of lavas and related volcanic rocks associated with the San Juan caldera and the younger Silverton caldera (Steven and Lipman, 1976). Episodes of intense hydrothermal alteration and mineralization associated with dacitic to rhyolitic intrusion followed caldera formation by several million years (Casadevall and Ohmoto, 1977; Lipman *et al.*, 1976). More recent geologic activity has been dominated by uplifts during the Neogene (Steven *et al.*, 1995), followed by down-cutting and the formation of the Animas River and its tributaries, with brief episodes of deposition.

Gold was discovered in the San Juan Mountains in 1871 and upwards of a thousand mining claims were staked in the upper Animas River above Silverton within the next two decades. The Denver and Rio Grande railroad was extended from Durango to Silverton in 1882 and ore production continued at various levels until 1991 when the Sunnyside Mine directly upstream from Silverton was closed (Church, *et al.*, 1997). Remediation of private holdings in the region continues today, and the AML project is concerned in large part with evaluating remediation needs of the area, including the thousands of abandoned prospects and mines on both federal and private properties.

4. PRELIMINARY MINERAL MAPPING RESULTS

The AVIRIS data for the Animas Watershed were converted to apparent surface reflectance using the radiative transfer methods of ATREM (Gao *et al.*, 1993; Gao *et al.*, 1997) followed by calibration to ground reflectance using a path radiance correction (Clark *et al.*, 1993a). The reflectance data were then analyzed using Tricorder (Clark *et al.*, 1990, 1991, 1993b, 1995), testing for the presence of over 250 minerals, mineral mixtures, water, vegetation, and other materials of interest. The most significant materials detected were then assembled into color-coded mineral maps. For this investigation we focused our attention on the pyrite weathering sequence, wherein pyrite (Fe_2S) weathers to jarosite, which in turn weathers to goethite, and then hematite. Pyrite oxidation is the primary source of mining-related acidic runoff because sulfuric acid (H_2SO_4) is a product of this weathering reaction (Swayze *et al.*, 1996). Pyrite itself is difficult to detect directly using AVIRIS because of its extremely low reflectance; however its oxidation products are quite bright and have strong 1- μm absorptions due to Fe^{3+} in the matrix, making them easy to identify. These minerals are abundant in intensely mineralized regions such as in the Red Mountain area north of the Silverton mining district, and elsewhere throughout the watershed. Mine tailings in the San Juan Mountains are typically weathered to jarosite and goethite, and these surface expressions readily pinpoint mines and prospects in the AVIRIS scenes. Creeks carrying runoff from tailings piles and mineralized outcrops often have pH values as low as 1.8, and this high level acidity enables these streams to carry high concentrations of heavy metals such as zinc, copper, cadmium, arsenic, and mercury. Stream beds and edges typically display thick rinds of precipitated iron oxide materials, which also are quite evident in the Tricorder-processed AVIRIS mineral maps.

Recent work has shown that carbonate minerals in the San Juan Mountains may play an important role in the buffering of stream waters, reducing metal concentrations and carrying capacities (Church *et al.*, 1997). Calcite occurs in the San Juan Mountains both as sedimentary limestone, and as alteration products of primary minerals within volcanic rocks. While calcite within propylitically altered rocks may play a reduced role due to limited availability for buffering reactions, the importance of calcite in buffering reactions has been established in studies of limestones (Runnels and Rampe, 1989). Magnesium-bearing chlorites such as clinocllore may also provide some level of buffering of acidic stream reaches, however this has not yet been quantified (G. Desborough, private communication, 1997). Calcite has been identified in the Animas River watershed using imaging spectroscopy, and the presence of mapped calcite in particular stream reaches correlates with increased pH levels and attendant lowered heavy metal concentrations (Church *et al.*, 1997). Clear identification of calcite in the AVIRIS data is complicated by the spectral absorption bands of epidote and chlorite which overlap the 2.3- μm diagnostic calcite absorption. Epidote-chlorite-calcite-bearing lavas are widely distributed in the western San Juan Mountains. Samples of these have been obtained and work is underway to incorporate the complex spectral character of these mixtures into the Tricorder analytical database. As the comparative concentrations of epidote, chlorite and calcite vary in the lavas, the behavior of the 2.3- μm absorption band changes in ways that lend themselves well to mapping via spectral feature analysis. The possible revision of pixels previously mapped as calcite to primarily chlorite-epidote would still imply that they present some level of acid-buffering potential. The extent of this buffering capability, however, and improved mapping of these lavas, is an ongoing aspect of our current work.

5. UTILITY OF AVIRIS MAPPING

The distributions of major iron-bearing minerals, phyllosilicates, clays, carbonates, and acid-generating and acid-buffering materials, as determined by Tricorder analysis, have already been used to assist multi-disciplinary field investigations. During the 1997 field season, Tricorder maps of minerals were used to direct field geologists to outcrops of interest, assess the levels of acid generating potential of individual regions, and to locate mine tailings and associated abandoned mine sites. Biologists investigating heavy metal contamination of local waterfowl used Tricorder maps of acid-generating mineralogy to locate potentially compromised ptarmigan habitat, and EPA-mandated mine remediation sites were clearly identified on the Tricorder maps. The extent of naturally-occurring deposits of pyrite, jarosite and goethite within unmined areas suggests that acidity in the upper Animas River may have a sizable natural component. However the presence of potentially acid-buffering minerals within the watershed may play an important role in reducing acidity and metal concentrations as measured by field geochemical analyses (Church *et al.*, 1997). The AVIRIS maps also delineate regions where the river has deposited its sediment load containing iron-bearing precipitates and pyrite weathering products; curiously several of these sites correlate with influxes of potentially buffered water from tributaries that flow through the chlorite- and calcite-bearing structures. Though incomplete, Tricorder analysis of the Animas AVIRIS dataset has already demonstrated its usefulness and cost-saving capabilities, providing a unique regional coverage unavailable by other methods.

6. SUMMARY

Mapping of the 1996 Animas River Watershed using AVIRIS data and the USGS Tricorder algorithm continues to provide a wealth of important and cost-saving information. Improved field planning and insights into laboratory investigations of geochemical data are having direct impacts on interpretations of data collected to support the AML initiative. Synoptic mapping of the primary acid-generating minerals has been accomplished and extensively field-checked. Mapping of acid-buffering minerals, while incomplete, has been found to correlate with the findings of field geochemistry efforts from the 1997 field season. Efforts to further refine the mapping of these complex acid-buffering lithologies will continue in the 1998 field season.

This preliminary study, appropriate images, follow-on studies and related research can be found at our web site: <http://speclab.cr.usgs.gov>.

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