

USING AVIRIS IN THE NASA BAA PROJECT TO EVALUATE THE IMPACT OF NATURAL ACID DRAINAGE ON COLORADO WATERSHEDS

Phoebe L. Hauff,¹ David W. Coulter, Douglas C. Peters, Matthew A. Sares,² Eric C. Prosh, Frederick B. Henderson III and David Bird

¹Spectral International, Inc., pusa@rmi.net; ²Colorado Geological Survey, Matt.Sares@state.co.us

1. INTRODUCTION

The Colorado Geological Survey and the co-authors of this paper were awarded one of 15 NASA Broad Agency Announcement (BAA) grants in 2001. The project focuses on the use of hyperspectral remote sensing to map acid-generating minerals that affect water quality within a watershed, and to identify the relative contributions of natural and anthropogenic sources to that drainage. A further objective is to define the most cost-effective remote sensing instrument configuration for this application.

The study area is located in the state of Colorado (Figure 1). Phase I of this project involves the Lake Creek watershed in central Colorado (a major tributary of the upper Arkansas River), which contains extensive, naturally exposed sulfide mineralization that is adversely impacting the water quality of Lake Creek. Phase II will map the upper Arkansas River, which is affected by mine drainage from the Leadville mining district. The two areas will then be compared.

There are two major sources (Red Mountain West and Red Mountain East) for the natural ARD (Acid Rock Drainage) in the study area (Neubert, 2000), and several minor ones, which have been identified through ASTER and AVIRIS imagery. These all lie within the Grizzly Peak Caldera (Oligocene) shown in Figure 1.

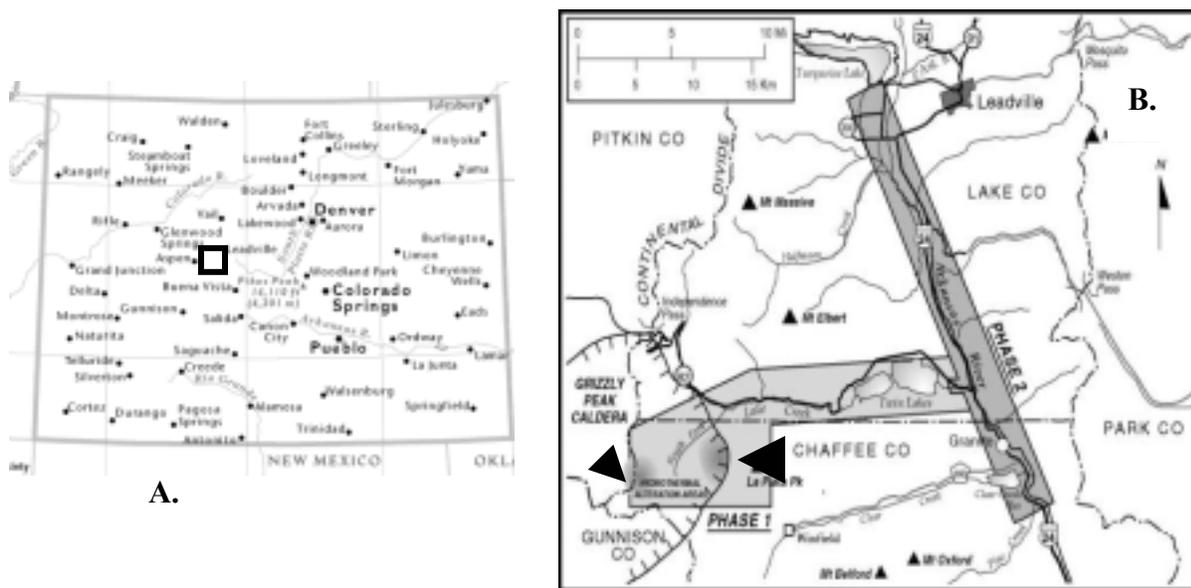


Figure 1 – [A] shows the general location map for the state of Colorado. The study area is located at the base of Mt. Elbert, near Twin Lakes Reservoir, about 20 miles south of the Leadville Mining District. It lies along the Independence Pass road to Aspen (Hwy.82). [B] shows the outlines of the Phase 1 and Phase 2 study areas. Phase 1 follows the Lake Creek watershed, starting with the Peekaboo Gulch drainage from one of the sulfide bodies (large arrow) into South Fork and into Lake Creek. It also includes Sayers Gulch drainage into South Fork from the second hydrothermal source (large arrow). Phase 2 follows the Arkansas River from the Leadville Mining District to south of Granite, and will evaluate mining impacts on water quality of the Arkansas in this area.

2. GEOLOGY

The Grizzly Peak Caldera is south of Independence Pass in the headwaters of Lake Creek (Fridrich et al., 1998). At about 39 Ma, prior to formation of the caldera, numerous rhyolitic stocks and dikes were emplaced in an arcuate zone of fractures that encircled and included the site of the future caldera. Circulation of hydrothermal fluids related to this pre-caldera magmatism caused widespread alteration and formed porphyry molybdenum/copper deposits and gold-bearing quartz-pyrite veins (Cruson, 1973; Fridrich and others, 1991; Neubert et al., in prep.).

The Grizzly Peak Caldera resulted from eruption of the rhyolitic Grizzly Peak Tuff between 37 and 32 Ma, into rocks largely Precambrian in age. During subsidence, an inner ring-fracture zone formed. Caldera resurgence caused by emplacement of a granodiorite laccolith resulted in a complexly faulted dome. Post-caldera, intermediate-composition dikes and small stocks later intruded the fault zones in the resurgent dome (Fridrich and others, 1991).

The dominant rock unit within the caldera is the Grizzly Peak tuff, a phenocryst-rich, lithic, lapilli ash-flow tuff that varies in composition from high- to low-silica rhyolite. Caldera collapse breccias (megabreccias), composed largely of Precambrian wall rock clasts, are prominent in the eastern part of the caldera (the "Red Mountain East" area). Numerous intermediate to felsic composition dikes and plutons related to the caldera appear within and on the margins of the caldera. Hydrothermal alteration is prominent in several areas within the caldera, most notably the Red Mountain West and Red Mountain East areas. While prospecting has occurred in those two Red Mountain areas, no significant mining activity has occurred on the eastern side of the Continental Divide (Neubert et al., in prep.).

A small, north-south trending, Tertiary quartz-latitude porphyry stock on the western side of the Continental Divide on the southwestern flank of Red Mountain West (Figure 1B) is strongly hydrothermally altered and weathered. The stock contains quartz-molybdenite-pyrite stockwork veins in a quartz-sericite-pyrite matrix. This intrusive is the likely cause of the extensive alteration of the Red Mountain West area and source for sulfides (Neubert et al, in prep).

Acid-sulfate alteration, composed of the assemblage quartz-sericite-alunite-pyrophyllite, is known from Red Mountain West. Quartz-sericite alteration (QS) and quartz-sericite-pyrite-alteration (QSP) are the dominant alteration types present on the upper east slopes of Red Mountain.

A large area of hydrothermal alteration is exposed to the east of Sayres Gulch on Red Mountain East (Figure 1B), which lies along the eastern ring fracture of the Grizzly Peak caldera. The ring fracture is well marked by megabreccias and a ring dike. Based upon the localization of the hydrothermal alteration and its associated copper and molybdenum anomalies, the altered area probably overlies a shallow, felsic, post-caldera collapse, and porphyry intrusion, which was injected along the ring fracture (Cruson, 1973).

Bedrock in the lower southwestern slope of Red Mountain East, along the two southern tributaries to East Sayres Gulch, is composed of essentially unaltered, Precambrian, banded quartz-biotite gneiss. The gneiss locally contains quartz veins and pegmatites. The principal altered rocks at "Red Mountain East" also appear to be composed of Precambrian gneiss, but the intense alteration makes distinction of rock types difficult. Fragments of Precambrian gneiss form the large clasts in the Tertiary megabreccia. Quartz-sericite alteration (QS) forms the core of the Red Mountain East area. Local areas of quartz stockwork exist within the main quartz-sericite zone. These appear to be composed of nearly pure quartz from a mass of intersecting veinlets. Quartz-sericite-pyrite alteration (QSP) forms a semicircular zone around the north, east, and south sides of the principal quartz-sericite zone, and is also present in a separate zone on the southern end of the altered area. The main minerals are quartz, muscovite, illite, dickite, pyrophyllite and alunite. High kaolinite content, argillic alteration forms both the ridge top and the outermost alteration zone in much of the area. Propylitic alteration is the typical type of alteration present in the megabreccia unit on the northwest side of Red Mountain East. Chlorite is the dominant mineral in the zone of propylitic alteration. Muscovite/illite is the main gangue mineral found through both hydrothermal areas and because of its high albedo will be prominent in the imagery (Neubert et al, in prep) .

Reconnaissance water quality data was collected in the area in 1994 (Sares, 1996 and 1999; Neubert, 2000) by the Colorado Geological Survey. During these investigations several springs on the east side of Red Mountain West exhibited extreme acidity with pH values ranging between 2.17 to 3.12. The pH of Peekaboo Gulch, the

receiving stream for these springs varied from 3.82, below the springs, to 4.40, approximately 1.5 miles downstream at its mouth with South Fork Lake Creek. The reconnaissance evaluations of spring water in the Red Mountain area confirmed the detrimental effect the hydrothermally altered rocks had on water quality in this area.

3. PROJECT DESCRIPTION

Phase 1 of the project focuses on areas that exhibit natural acid rock drainage, specifically, the South Fork of Lake Creek and its watershed, and Lake Creek downstream of the confluence with South Fork. The South Fork watershed contains two areas of hydrothermal alteration, Red Mountain West (Fig. 2) and Red Mountain East, which drain acidic, metal-laden water into Peekaboo Gulch, Sayres Gulch and smaller, unnamed tributaries. Metals and acidity derived from these areas affect water quality far downstream in Lake Creek. Before discharging to the Arkansas River, Lake Creek water moves through the Twin Lakes Reservoir, which stores trans-basin diversion water for the water supply of Colorado Springs. Water sampling will correlate stream water quality to mineral types identified in the alteration areas and downstream. Mineral types will be identified through hyperspectral remote sensing data and “ground-truth” spectral data collected in the field using hand-held spectrometers.



Figure 2 - Hydrothermally altered rocks of Red Mountain West in the heart of the Grizzly Peak Caldera. Springs here discharge very acidic (pH~2-5), metal-rich water. There are two types of activity. The iron sulfides are altering directly to iron sulfate minerals such as jarosite, schwertmannite, copiapite and melanterite. This is occurring at the spring sources (black arrows). Sulfur deficient, acid groundwater is also leaching the feldspars in the volcanic host rocks and creating a pH 5 effluent, highly aluminum enriched, that is discharged from a spring indicated by the white arrow. This results in major aluminum loading in the watershed.

Phase 2 will compare Lake Creek, primarily affected by natural acid rock drainage, with the upper Arkansas River, primarily affected by impacts from historic mining districts in the Leadville area. Much work has been done in identifying, characterizing, and remediating mining-induced contaminants in the Leadville area (USEPA, 2002). Phase 2 of the project will attempt to use hyperspectral remote sensing to identify sources of metals downstream from Leadville, such as mill tailings transported downstream and deposited in flood plains and point bars of the Arkansas River. Water quality will be analyzed and related to these types of metal sources along the main stem of the upper Arkansas River.

4. PROBLEMS & OBJECTIVES

A number of streams in eleven different headwater areas of Colorado have naturally high concentrations of metals and/or acidity, upstream of any significant human impacts. Rocks in these areas have been affected by intense hydrothermal alteration in the geologic past. It is hypothesized that by characterizing the iron and aluminum bearing minerals, through reflectance spectroscopy, that these areas can be mapped using hyperspectral remote sensing to identify the minerals and therefore delineate pH zones and transported metals.

The objectives are therefore to:

- Identify the spectrally active minerals in the watershed
- To correlate those minerals to stream pH water quality, source area and streambed precipitates
- Identify cost-efficient remote sensing technologies for identification of mineralogy
- Geochemically model controls of metal solubility and mobility
- Assess the ability of remote sensing to identify and discriminate natural vs. anthropogenic sources of contamination

The NASA grant will allow us to look at this area in greater detail and test the usefulness of current remote sensing technology for identification of natural and anthropogenic influences on the environment

5. APPROACH

The approach used in this project is similar to those developed in previous NASA funded investigations (Hauff et al., 1999a,b, 2000; Peters et al., 2000, 2001). Background information on the area is first collected. Field sample sites are chosen, GPS coordinates taken for each and surface samples collected from each site. These are analyzed with a field spectrometer for infrared active mineral signatures and portable XRF for metals content. For this project the iron and aluminum coatings on the rocks in the stream beds are of major interest. A special purpose, site specific database of spectral signatures and metal chemistry is compiled for the project.

Because the assessment and monitoring of water quality is the focus of this application, water quality data were collected at both high- and low-flow periods in the Lake Creek watershed. Data elements include dissolved and total recoverable metals, pH, conductivity, alkalinity, total mineral acidity, total acidity, sulfate, chloride, fluoride, nitrate/nitrite, and total suspended solids. A geochemical model of the entire watershed will be produced to predict seasonal flow and changes in pH, metal loading and mineralogy. It is anticipated that it will be possible to apply such a model to other similarly impacted watersheds, without the intense field work employed to develop the Lake Creek model.

The field data is then integrated with remotely sensed imagery. Several kinds of sensor data will be used during the project, as one of the objectives is to determine the optimum sensor configuration for the narrow, high mountain drainages. The NASA Stennis ART Toolkit (Zanoni, 2002), with AVIRIS and SPECTIR high-resolution data sets will be used to simulate sensor configurations that are optimum for this application in other parts of Colorado and other mineralized and mined areas. The sensors used to collect the data vary in spatial resolution, spectral resolution, and operating cost. Obtaining data from a sensor on a satellite platform is less expensive than from an airborne platform, however, the spatial resolution is usually poorer. Table 1 summarizes the different sensors for this project.

Table 1 - SENSOR TYPES

Name	Description	Spectrum	Platform	Strengths
LANDSAT	Earth resources satellite	VNIR	Satellite	Regional view; low-cost
ASTER	<u>A</u> dvanced <u>S</u> paceborne <u>T</u> hermal <u>E</u> mission and <u>R</u> eflection Radiometer	VNIR & SWIR	Satellite	Monitoring potential; low-cost
IKONOS	Private-sector satellite	VNIR	Satellite	Spatial detail; low-cost
HYPERION	<u>H</u> yperspectral <u>I</u> mager	VNIR & SWIR	Satellite	Spectral detail; moderate cost
AVIRIS (low-altitude)	<u>A</u> irborne <u>V</u> isible- <u>I</u> nfrared <u>I</u> maging <u>S</u> pectrometer	VNIR & SWIR	Airborne	Spatial & spectral detail
SPECTIR	Full range Hyperspectral imaging spectrometer	VNIR - SWIR	Airborne	High resolution spatial and spectral

6. WATER CHEMISTRY AND MINEROLOGY

6.1 IRON & ALUMINUM METALS DISTRIBUTION

The type and quantity of metals in the stream and within the precipitates coating the rocks is of major importance in determining water quality factors. Table 2 compiles an example of metal content from a very low (2.17) pH spring at the base of Red Mountain West.

Table 2 – Red Mountain West (from Sares, 1996).

Analyte	Multiple above aquatic life standards
Al	1,724x
Cd	42x
Cu	164x
Fe	100x
Mn	within standard
Pb	within standard
Ag	6x
Zn	21x
SO4	6x

The values in the table show the presence of the listed elements in the spring, not in concentration, but in the multiple above the statewide water quality standards for aquatic life. For example, the concentration of aluminum is 1,724 times the aquatic life standard of 87 micrograms per liter. This spring is draining from the mineralized and altered areas on Red Mountain West. These rocks contain high volumes of aluminum bearing minerals such as feldspars, muscovite and illite. Aluminum poses a great danger to aquatic life. It can coat the gills of fish and suffocate them. New research is also showing that aluminum can be chemically toxic to fish in both acidic and neutral waters (Soucek et al., 2002). No fish live in the upper parts of the watershed affected by natural acid rock drainage.

6.2 IRON MINERALS & pH CORRELATION

Over 80 ground truth data sets, which include seasonal water pH, water chemistry, mineral reflectance spectroscopy, and mineral XRF(X-ray Fluorescence), have been collected for correlation to the airborne and satellite sensor data. The main environmental remote sensing issues involve iron and aluminum oxyhydroxide phases that are created when the iron sulfides oxidize and generate acidic drainage, and the in-situ aluminum silicates that are chemically weathered by acidic ground waters. Iron and aluminum precipitates concentrate at the sources, collect metals, and are deposited throughout the drainages all the way down to Twin Lakes Reservoir.

The infrared-active iron minerals currently detected include: 1) the sulfates jarosite, schwertmannite, copiapite, and melanterite; 2) oxyhydroxides, maghemite, lepidocrocite, ferrihydrite, and goethite. The diagram below shows the pH zones at which the commonest of these minerals form. This model will be used to predict the minerals most likely to occur through the drainages within the changing pH zones.

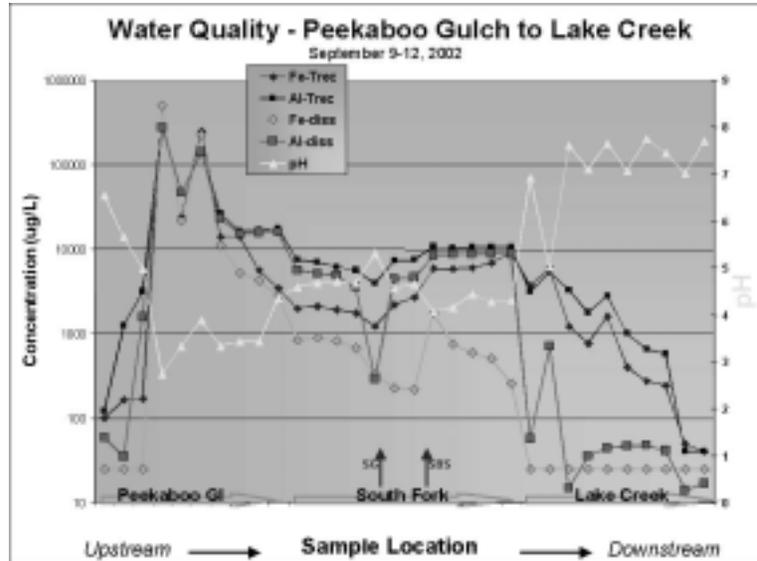


Figure 3-Graph showing water quality changes downstream of the Red Mountain West hydrothermally altered area. Extreme concentrations of iron and aluminum are shown in upper Peekaboo Gulch near the acid generating source rock. Metal concentrations generally decline downstream due to metals precipitating out of the water column onto the streambed and due to inflow of higher pH diluting water. Separation between the dissolved (diss) and total recoverable (trec) concentrations occurs as the Fe and Al ions moved out of the dissolved form into a suspended solid form. Acidic inflows from Sayres Gulch (SG) and Sayres Bowl Stream (SBS) show a temporary reversal in these downstream trends.

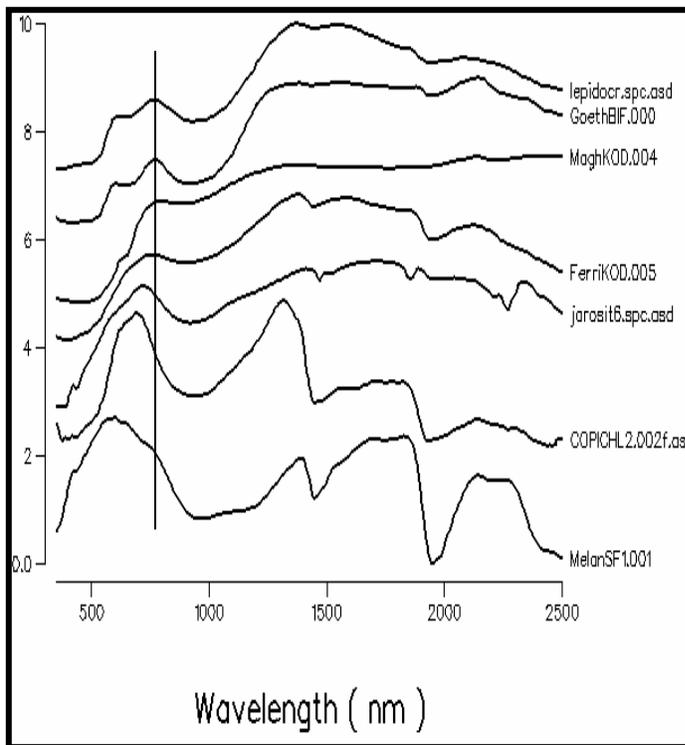
PYRITE SOURCE

JAROSITE pH = 2.3-2.8

SCHWERTMANNITE pH = 3-6

FERRIHYDRITE pH = 4.5->

GOETHITE pH = +7



A
B
C
D
E
F
G

Figure 4 – This figure plots the iron oxyhydroxide and sulfate minerals observed to date in the Lake Creek drainage, and includes [A] lepidocrocite (γ -FeOOH), [B] goethite $\text{Fe}^{3+}\text{O}(\text{OH})$, [C] maghemite (γ - Fe_2O_3), [D] ferrihydrite $\text{Fe}^{3+}_2\text{O}_3 \cdot 0.5(\text{H}_2\text{O})$, [E] jarosite $[\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6]$, [F] copiapite ($\text{Fe}^{2+}\text{Fe}^{3+}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20(\text{H}_2\text{O})$), and [G] melanterite ($\text{Fe}^{2+}(\text{SO}_4) \cdot 7(\text{H}_2\text{O})$).

Please note that each of these minerals have diagnostic spectral profiles, especially in the visible through Near Infrared region (400-1000 nm). Although copiapite and melanterite have been identified in Peekaboo Gulch, they are not present in large enough amounts to be detectable from the air. The other issue is that nearly all of the spectra collected from the precipitates are mixtures of iron phases. Because the pH will change with stream flow, stability fields are constantly shifting as water levels fluctuate.

The ground data collected show a distinct zoning of iron minerals that correlates to pH. The iron sulfates jarosite, schwertmannite, melanterite and copiapite occur in Peekaboo Gulch, and all are low (2-4) pH. These mineral assemblages change, as the pH increases to the 4.0-4.99 range along the South Fork Drainage, to iron oxides, dominant of which is ferrihydrite. In the Lake Creek drainage, the water is diluted by neutral North Fork water and the pH values range from 6.93 to 7.75, with goethite and lepidocrocite the main iron minerals.

Table 3 summarizes the generalized mineralogy through the three drainages (Peekaboo – PG; South Fork-SF and Lake Creek-LC) under discussion. It can be seen how consistent the correlation of mineralogy to pH is. Location LC-1 has higher acidity as a function of inflow of lower pH waters from La Plata Creek and South Fork. Jarosite occurs along South Fork in selected areas below Site SF-7. At SF-7, a highly acid (pH=3) tributary drains into South Fork from the Red Mountain East sulfide source, causing jarosite precipitation within and below the mixing zones.

Table 3 – Comparison of Minerals against pH

Sample Site	Date	pH	Total Acid	Minerals
LC-01	9.10.02	5.02	23	goethite, maghemite, jarosite
LC-02	9.9.02	7.61	8	maghemite, goethite, lepidocrocite
LC-03	9.9.02	7.11	8.3	maghemite, goethite
LC-04	9.10.02	7.15	7	maghemite, goethite, lepidocrocite
LC-05	9.9.02	7.66	6	maghemite, goethite, lepidocrocite
LC-06	9.9.02	7.06	6.8	maghemite, goethite, lepidocrocite
LC-07	9.9.02	7.44	9	maghemite, goethite, lepidocrocite
LC_08				lepidocrocite, goethite
LC-09	9.9.02	7.75	9	lepidocrocite, goethite
LC-10	9.10.02	6.93	25.6	goethite
LC-11	9.9.02	7.01	1.11	lepidocrocite, goethite
SF-04	9.10.02	5.31	25	ferrhydrite
SF-05	9.10.02	4.57	40	ferrhydrite
SF-06	9.10.02	4.66	74	ferrhydrite
SF-07	9.10.02	4.07	73	ferrhydrite, jarosite
SF-08	9.10.02	4.16	72	ferrhydrite, jarosite
SF-09	9.10.02	4.45	*	ferrhydrite, jarosite
SF-10	9.10.02	4.28	65	ferrhydrite, jarosite
SF-11	9.10.02	6.5	16	maghemite, lepidocrocite, goethite
SF-12D	9.10.02	4.6	49	ferrhydrite, AlOH
SF-13	9.10.02	4.68	40	ferrhydrite, jarosite
SF-14	9.10.02	4.72	39	ferrhydrite
SF-15	9.10.02	4.68	33	ferrhydrite
SF-16	9.10.02	4.91	22	ferrhydrite
SF-17	9.10.02	4.32	69.1	ferrhydrite
PG-01	9.11.02	3.88	1050	melanterite, jarosite, copiapite
PG-02				copiapite, jarosite
PG-04	9.11.02	3.33	171.2	jarosite
PG-05	9.11.02	4.35	140.8	copiapite
PG-06	9.11.02	6.55	18	maghemite
PG-07	9.11.02	2.74	2300	jarosite, schwertmannite
PG-08	9.11.02	3.43	122	jarosite

pH values in Peekaboo Gulch change as a function of more neutral water sources (PG-6) above the main acid springs (PG-7, PG-1, PG-2).

7. HYPERSPECTRAL REMOTE SENSING

7.1 INTEGRATION with ASTER and AVIRIS

ASTER satellite data are being evaluated in this project as a potential reconnaissance tool. The 30 meter SWIR range ASTER will have limitations in the narrow (3-5 meters), high mountain valleys. However, ASTER defines aluminum-bearing alteration minerals well. It can be used to outline areas of hydrothermal alteration and

can locate large concentrations of iron oxides (Figure 5, white arrow). It appears that ASTER can be used to vector towards drainages that potentially contain iron oxides and sulfates.

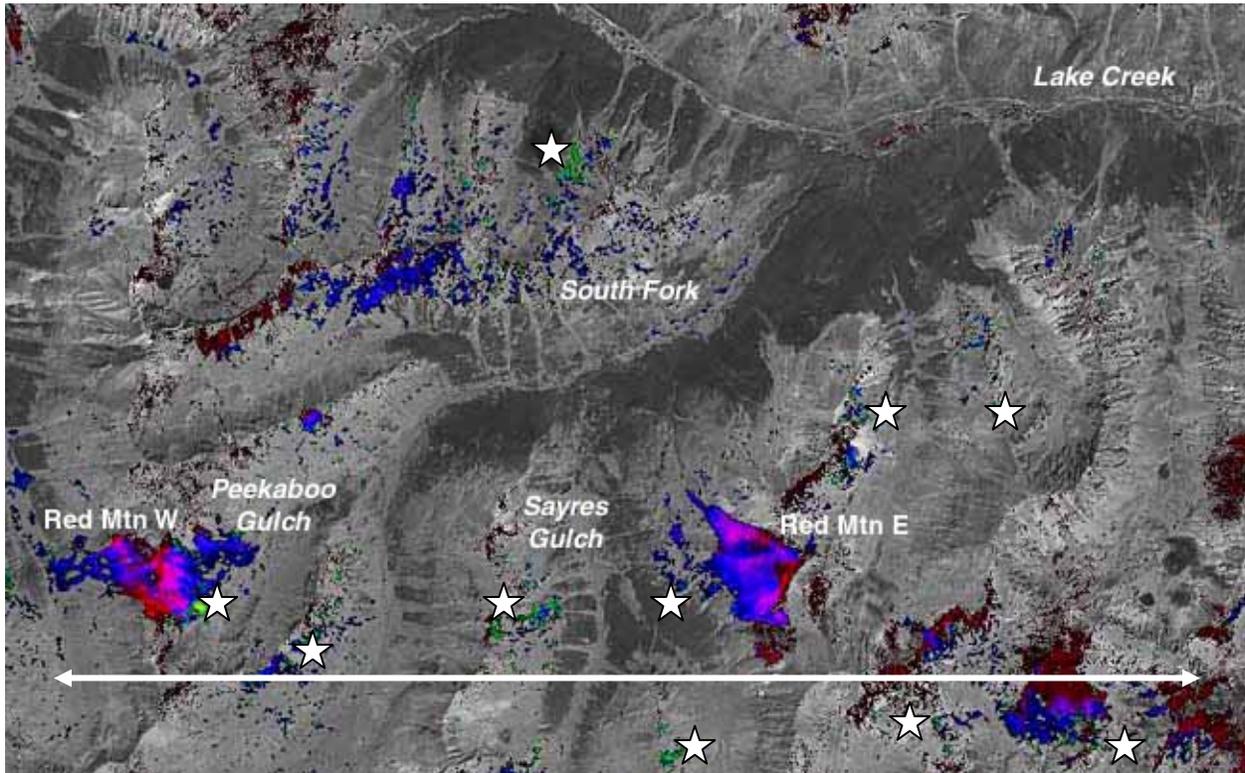


Figure 5 – Pixels from ASTER SWIR 30 meter alteration image are overlain on the 15 meter visible image. The white double arrow runs through the two main alteration systems at Red Mountain West and Red Mountain East. This image was processed for iron oxides, jarosite and muscovite/illite. Selected jarosite locations are marked with white stars. Some have been field verified. The image demonstrates that ASTER can be used as a first pass over an area to determine the presence of hydrothermal alteration and some secondary products. *This image was processed by David Coulter, Overhill Imaging and Cartography.*

7.2 AVIRIS IMAGE OF LAKE CREEK DELTA

7.2.1 CALIBRATION

Empirical line calibration spectra were collected from the broad, fairly homogeneous quartz-illite beach between the two reservoirs (Fig.6). The spectra were taken with an ASD FieldSpec Pro spectrometer. The calibration was checked with a pixel from the lake water.

The beach was considered a uniform flat field. A cross check was made using a deeper part of the lake where the spectrum should be flat. This calibration was used for the AVIRIS images

Low-altitude AVIRIS was flown in September, 2002, over both Phase 1 and Phase 2 areas. The data are now in the initial stages of calibration and processing. A segment of Flight Line LC-3 (Fig. 7B) is shown, covering the Twin Lakes Reservoir, lower Lake Creek, and the Lake Creek delta (Fig. 7A). The image was processed for the iron mineral goethite, which was identified at several sample sites (LC-7, 8, 9).

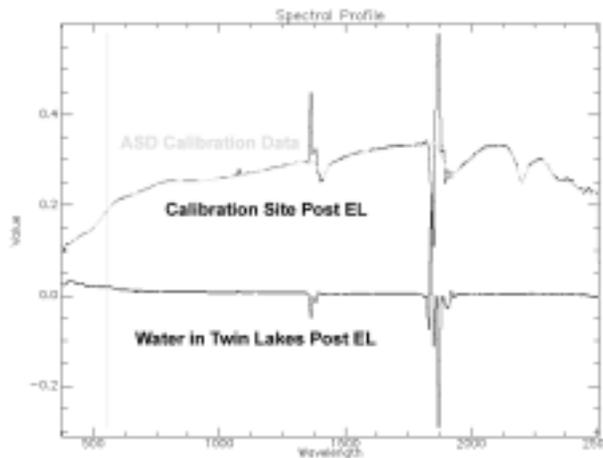


Figure 6 – Atmospheric calibration data.



Figure 7A – Topographic map of AVIRIS image (below).

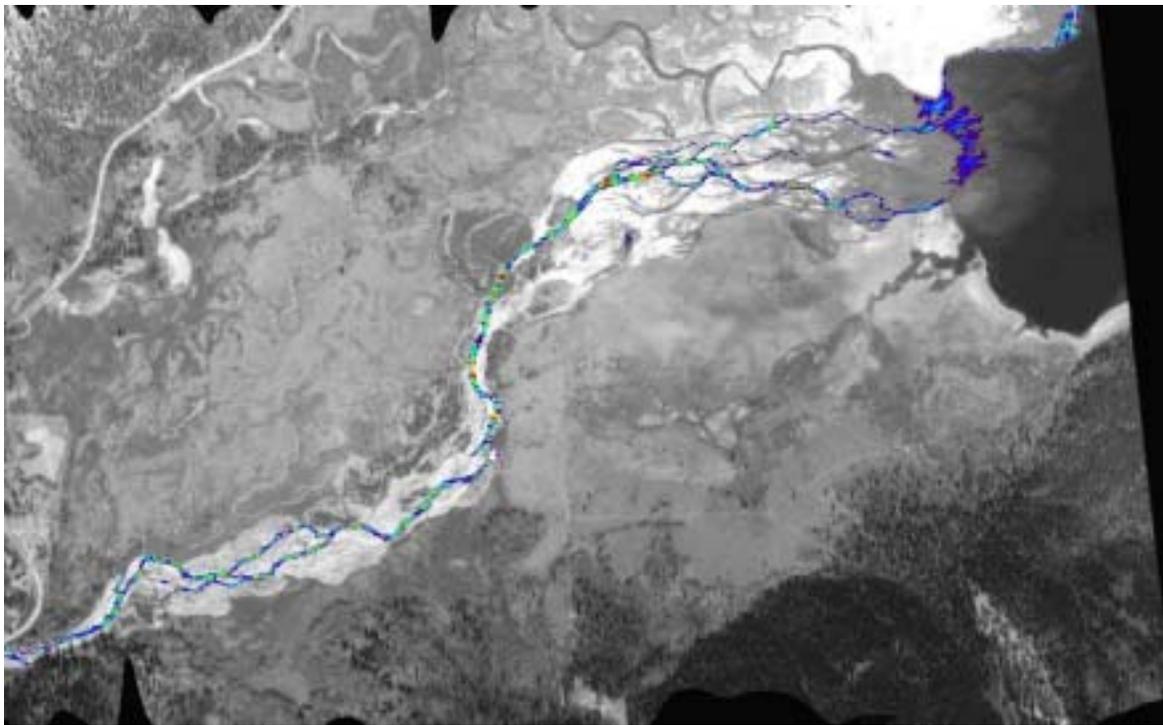


Figure 7B – Low-altitude AVIRIS classification image of the iron oxide mineral goethite. Distribution of goethite is directly along the banks of the main channel. Goethite indicates a neutral pH. Spatial resolution on the images is about 3 m. Image processed using SAM (Spectral Angle Mapper) algorithm. Displayed image is a rule image, with color progression of red-yellow-green-blue, with red = spectral angle of zero, or a perfect match of the image pixel to the reference.

8. DISCUSSION

Although this data contains the first stage results of the project, the correlations between the ground mineralogy and the pH zones are compelling and demonstrate the usefulness of reflectance spectroscopy to characterizing and monitoring this type of ARD. Initial imagery demonstrates that ASTER has the potential to be used in a reconnaissance mode over a watershed, indicating areas of iron oxide/sulfate minerals. AVIRIS low-altitude images with 1-3m pixel size will further target specific iron minerals and their distribution along stream banks, and even within the water itself.

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