Characterizing Sources of Acid Rock Drainage and Resulting Water Quality Impacts Using Hyperspectral Remote Sensing – Examples from the Upper Arkansas River Basin, Colorado[1]

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

Abstract. The upper Arkansas River basin of central Colorado encompasses watersheds that are affected by acid rock drainage from natural and mining-induced sources. Hyperspectral remote sensing is being used to characterize and map the source mineralogy of acid rock drainage, changes in downstream water quality, and the deposition of mine tailings in fluvial sediments downstream from a mining district.

Lake Creek watershed is affected by *natural* acid rock drainage, emanating from sub-economic metallic sulfide mineralization in its headwaters. Extreme metals and acidity loading from source areas affect the stream for 30 km downstream. St. Kevin Gulch is affected by *mining-induced* acid rock drainage from mine effluent discharging directly to streams and surface waste rock/tailings deposits. The main stem of the Arkansas River downstream of the Leadville mining district contains disseminated tailings material distributed downstream by fluvial processes. The tailings are a continuing source of metals loading to the river.

Hyperspectral and multispectral remote sensing data were acquired for these areas using airborne sensors, such as AVIRIS (Airborne Visible Infrared Imaging Spectrometer) and SpecTIR HST-1, and satellite sensors, such as Hyperion and ASTER. These techniques allowed data assessment utilizing a wide range of spectral (advanced multispectral to hyperspectral) and spatial (1 to 30 meters) resolutions. High spatial resolution hyperspectral data from SpecTIR and AVIRIS allow indirect determination of stream pH through the identification of minerals precipitated on the streambed. Specific iron sulfate, iron hydroxide, iron oxide, and aluminum hydroxide mineral species are only stable within certain pH ranges and are indicative of stream pH at the time of deposition.

Information obtained from this application of hyperspectral remote sensing can be useful in monitoring the impacts of current mining activity, directing and prioritizing the activities of current or planned remedial efforts, and monitoring general water quality improvements over time attributable to remedial activity.

Additional Key Words: ARD, AVIRIS, Leadville, pH, tailings, SpecTIR, watershed

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[2] Matthew A. Sares is a hydrogeologist with the Colorado Geologic Survey, Denver, CO, 80203; Phoebe L. Hauff is a mineralogist and remote sensing specialist with Spectral International Inc, Arvada, CO 80001; Douglas C. Peters is a geologist and remote sensing specialist with Peters Geosciences, Golden, CO, 80401; David W. Coulter is a remote sensing and image processing specialist with Overhill Imaging and Cartography, Golden, CO, 80401; David A. Bird is a hydrogeochemist with the Colorado Geologic Survey; Frederick B. Henderson III is a geologist and remote sensing specialist with HENDCO Services, Nathrop, CO, 81236; Eric C. Prosh is a geologist with Spectral International Inc.

Introduction

The upper Arkansas River basin of central Colorado encompasses watersheds that are affected by acid rock drainage (ARD) from natural and mining-induced sources. The Colorado Geological Survey (CGS) and its partners are using stream water quality, hydrogeochemistry, and hyperspectral remote sensing to characterize and map the source mineralogy producing ARD, changes in downstream water quality, and the deposition of mine tailings in fluvial sediments downstream from a mining district. The project demonstrates the ability of hyperspectral remote sensing to identify specific minerals indicative of acidic and metalliferous environments whether natural or anthropogenic in genesis.

The study area lies within the Colorado Mineral Belt, which is a zone of concentrated economic mineral emplacement trending northeast-southwest through the mountains of Colorado. The Leadville mining district and several smaller mining districts, such as the St. Kevin mining district are located in the study area (Figure 1).

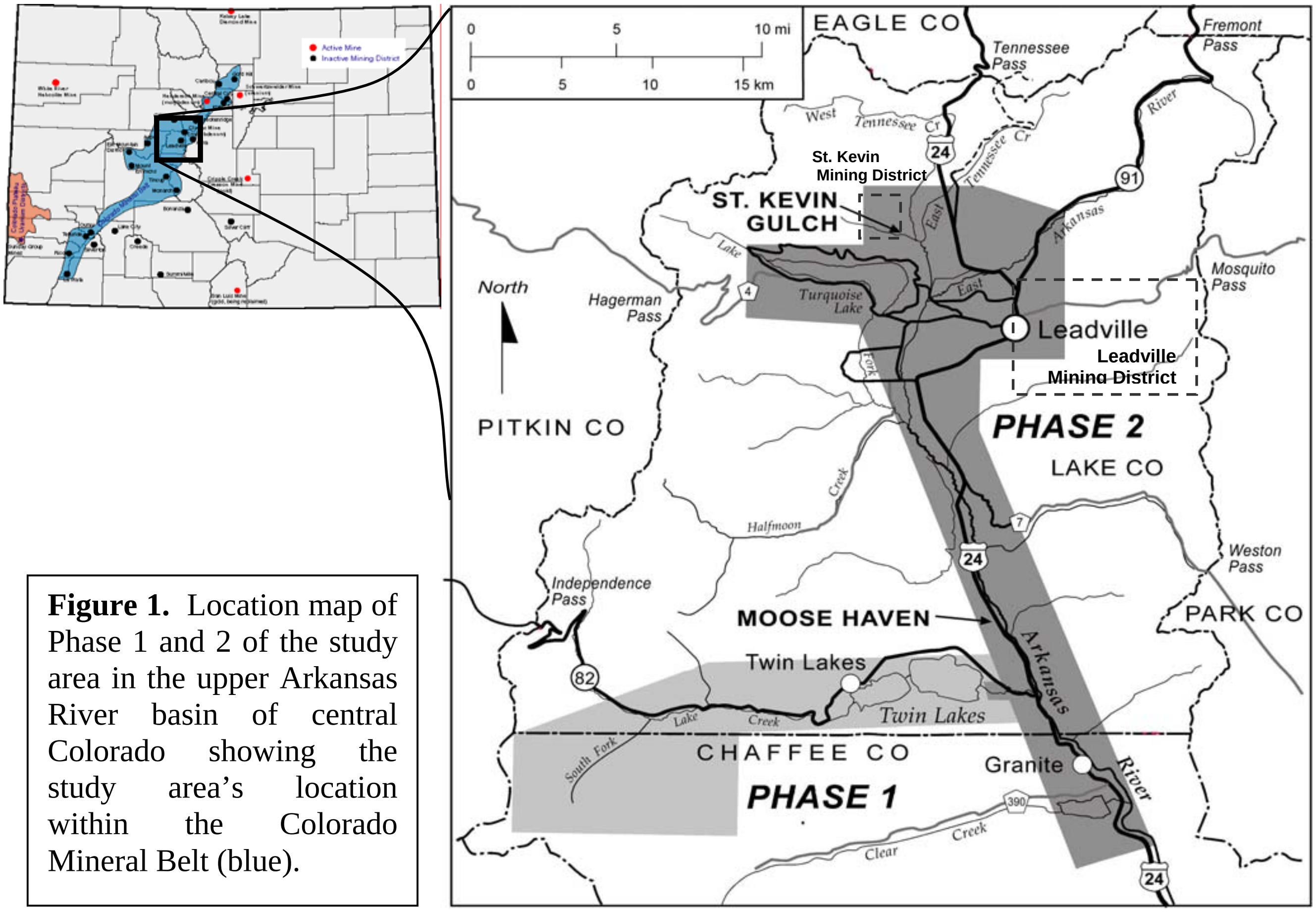

Figure 1. Location map of Phase 1 and 2 of the study area in the upper Arkansas River basin of central Colorado showing the study area's location within the Colorado Mineral Belt (blue).

Lake Creek Watershed (Phase 1)

This part of the project builds upon research and inventory efforts by CGS to identify areas of hydrothermal alteration that are the primary sources of, or contribute to, naturally acidic and metal-rich water in Colorado streams (Neubert, 2000). CGS has observed that the source of ARD to the Lake Creek watershed is primarily natural ARD emanating from two hydrothermally altered areas in the South Fork Lake Creek headwaters (Figure 2). Very little mining activity has occurred in the watershed. A few prospect-type mines were identified, but were essentially dry or seeping water with neutral pH and minimal metal content. The altered rocks are located within the Grizzly Peak Caldera (Oligocene age) and exhibit high-grade alteration including silicic, acid sulfate, quartz-sericite, quartz-sericite-pyrite, and argillic assemblages. Disseminated sulfide minerals, primarily pyrite, in these alteration zones are the major source of acidic drainage.

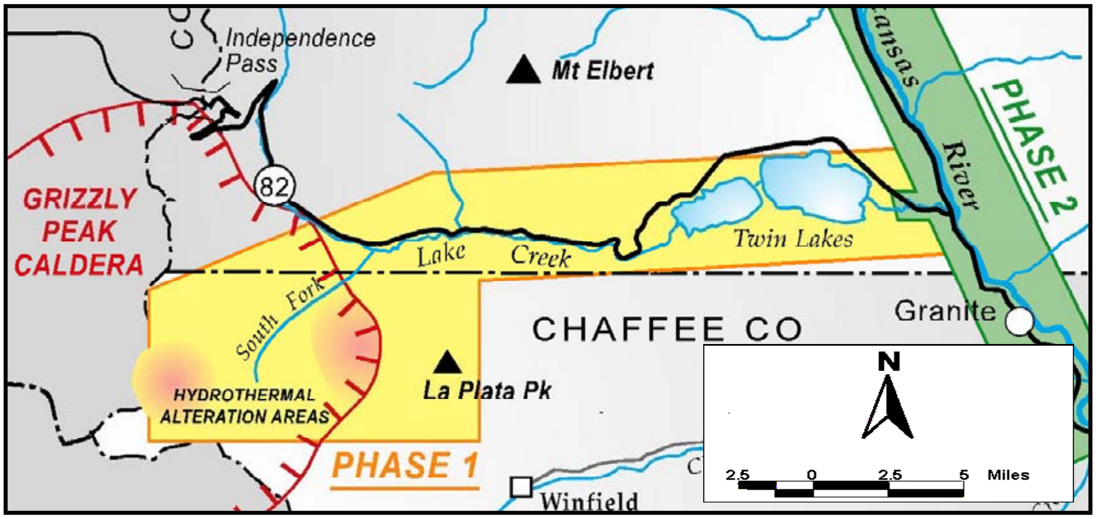

Figure 2. The Phase 1 field area focuses on natural acid rock drainage (ARD) from two hydrothermally altered areas in the headwaters of South Fork Lake Creek and the downstream affects of ARD on the Lake Creek watershed.

Low pH (pH=2-5), iron-rich (up to 498 mg/L dissolved Fe) waters are produced as the rocks in these areas undergo weathering and are exposed to atmospheric oxygen, meteoric water, and circulating ground water. Several iron minerals that are stable in this low pH environment are produced in the slopes, springs, and streams in and downstream from the hydrothermally altered areas. These iron sulfate and iron oxide minerals include jarosite $[(K,H_3O,Na)Fe_3(SO4)_2(OH)_6]$, ferrihydrite $[Fe_5HO_8 \cdot H_2O]$, schwertmannite $[Fe_8O_8(OH)_6(SO_4) \cdot nH_2O]$, copiapite $[Fe2+Fe3+_4(SO_4)_6(OH)_2 \cdot 20H_2O]$, and transitional amorphous phases. In addition, these waters are rich in aluminum and aluminum hydroxide flocculent can be seen in the water column and on the streambed alluvium in streams near a pH of 5 downstream of the ARD sources. As mixing with clean, neutral water from North Fork ameliorates the acidic waters of South Fork, the Lake Creek mainstem approaches and exceeds a pH of 7. The iron hydroxide goethite $[FeO(OH)]$, which is stable in near neutral pH's, is found in abundance as a streambed precipitate in the Lake Creek mainstem. These stream pH and mineral species relationships have been confirmed using extensive high- and low-flow water sampling and field spectrometry of aluminum and iron mineral precipitate coatings on streambed alluvium (Figure 3).

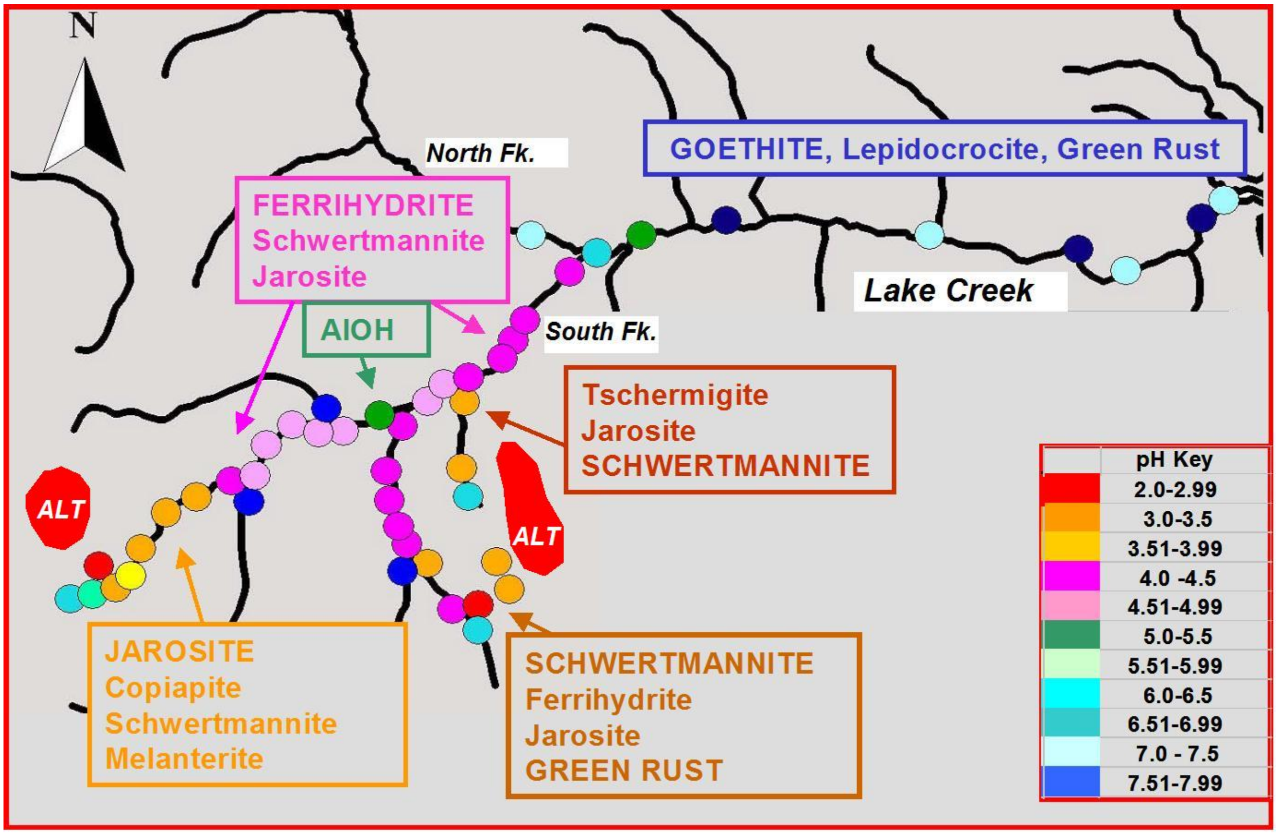

Figure 3. Schematic map of the Lake Creek watershed (Phase 1) correlating general stream pH with streambed precipitate mineral distribution. Hydrothermally altered areas, the sources of acid rock drainage, are labeled "ALT."

Hyperspectral remote sensing can identify these different mineral phases, allowing characterization of both the hydrothermally altered source areas and ARD downstream. The minerals can be spectrally distinguished in the visible-near infrared range. The major minerals commonly produced in the Lake Creek watershed are diagrammed in Figure 4 with attendant pH stability zones. In the Phase 1 area, the natural processes of pyrite decomposition and acid generation are not affected by human interference; therefore, these stability zones can be seen instream on a watershed scale. The hydrogeochemistry observed in the Lake Creek watershed was modeled using PHREEQC (Parkhurst and Appelo, 1999) at key locations below confluence mixing zones. The modeling corroborated observed conditions at these locations, using stream water chemistry to predict downstream metal attenuation and the various mineral precipitate species observed on the streambed (Bird, 2003).

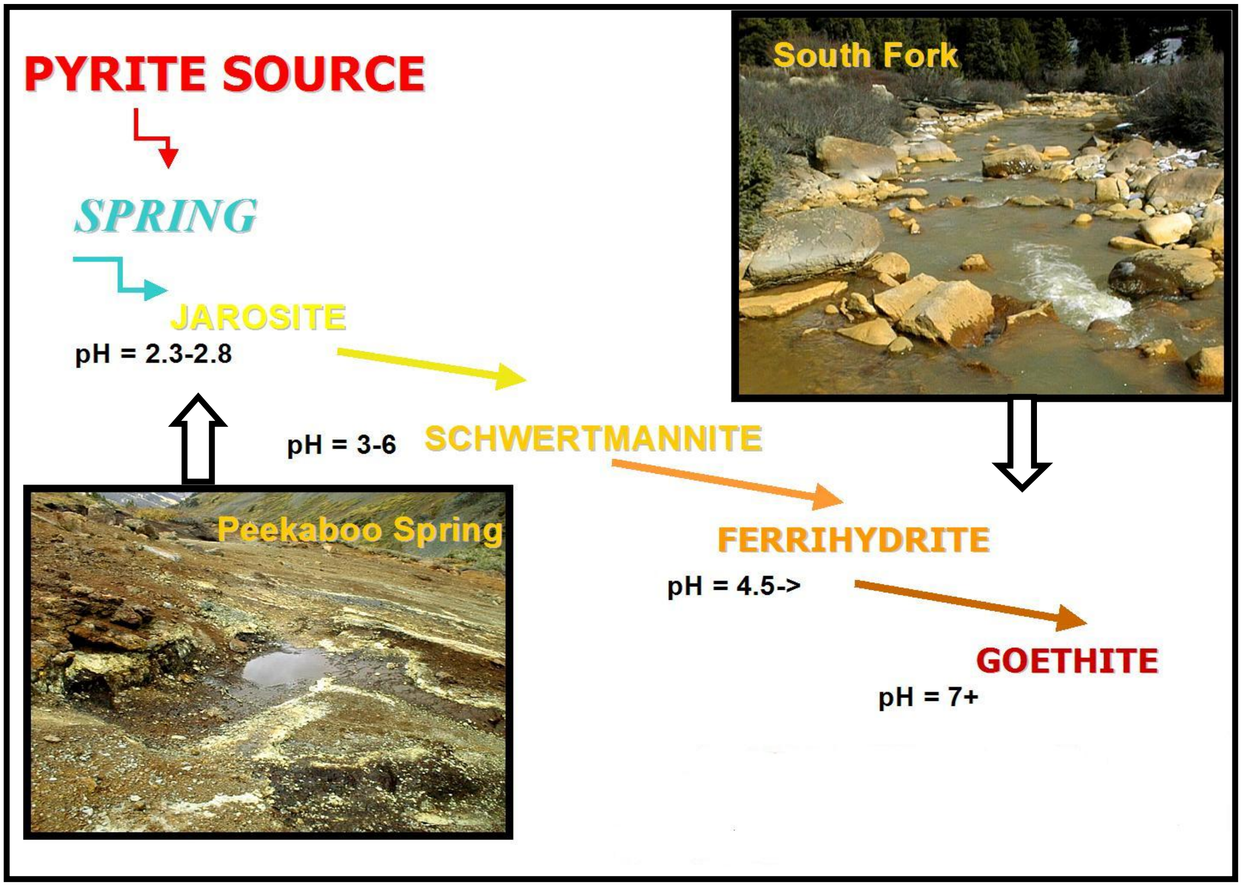

Figure 4. Iron minerals observed in the streams of the Lake Creek watershed that are impacted by natural acid rock drainage (Phase 1 study area).

Multispectral and Hyperspectral Imagery

We have characterized hydrothermally altered source areas for ARD using multispectral and hyperspectral sensors with varying spectral and spatial resolution. Figure 5 is a processed image from ASTER, a satellite-based enhanced multispectral sensor with 15-meter (m) resolution in the visible range and 30m resolution in the infrared range. General classes of minerals indicative of ARD source mineralogy can be identified, but not specific minerals. Also, very little mineralogy can be identified in the receiving streams, although some iron oxide was identified in the wider portions of the Lake Creek streambed.

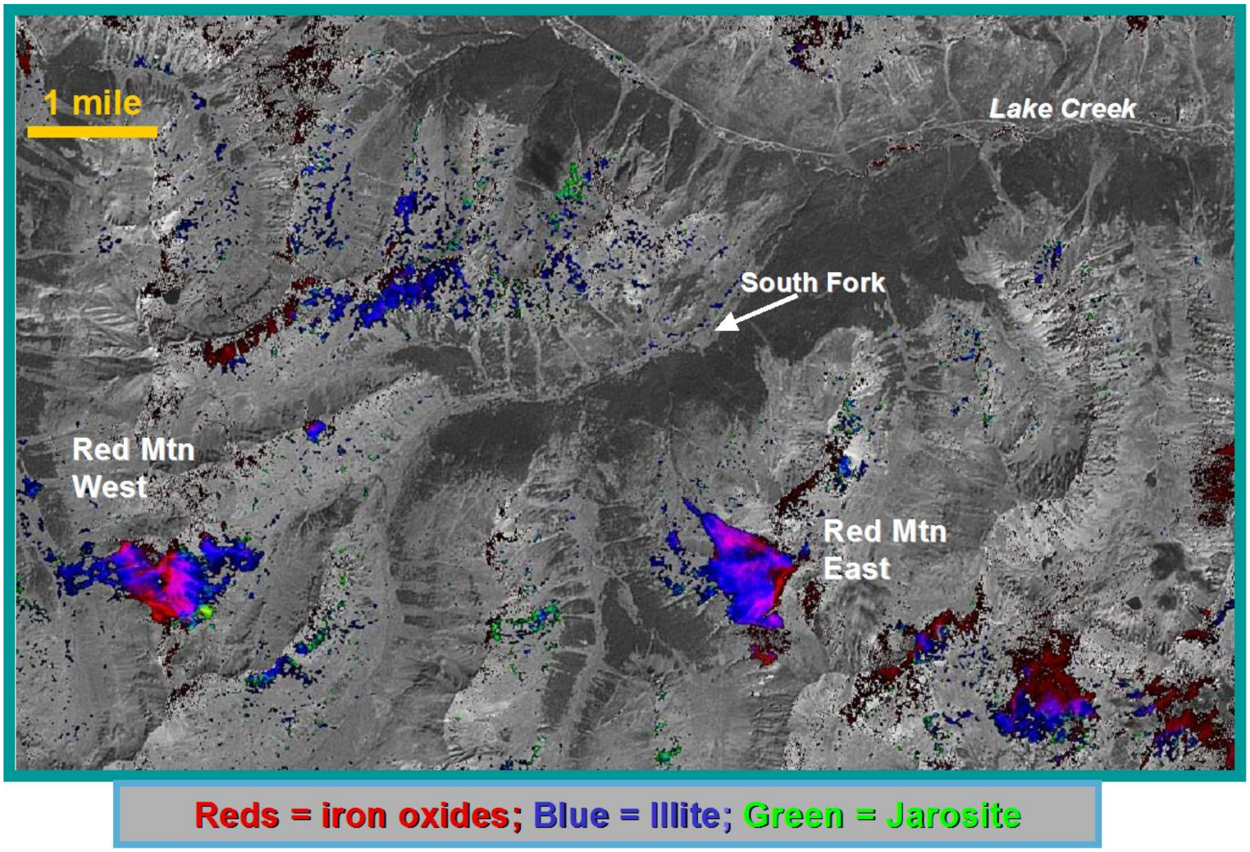

Figure 5. Satellite-based ASTER image of the western portion of the Phase 1 study area classified to show general mineral classes indicative of acid rock drainage.

In comparison, the Jet Propulsion Laboratory's hyperspectral AVIRIS sensor, flown on the low-altitude airborne platform, was able to obtain 4m spatial resolution data over the western hydrothermally altered area of Red Mountain West (Figure 6). Compared to the ASTER image in Figure 5, the AVIRIS data has much greater spatial detail and mineralogical identification ability, which is obtained through greater spectral resolution. With these results, indicator mineralogy for the most acidic ARD sources can be identified; in particular; the mapping of jarosite (light blue) on these slopes indicates very acidic conditions.

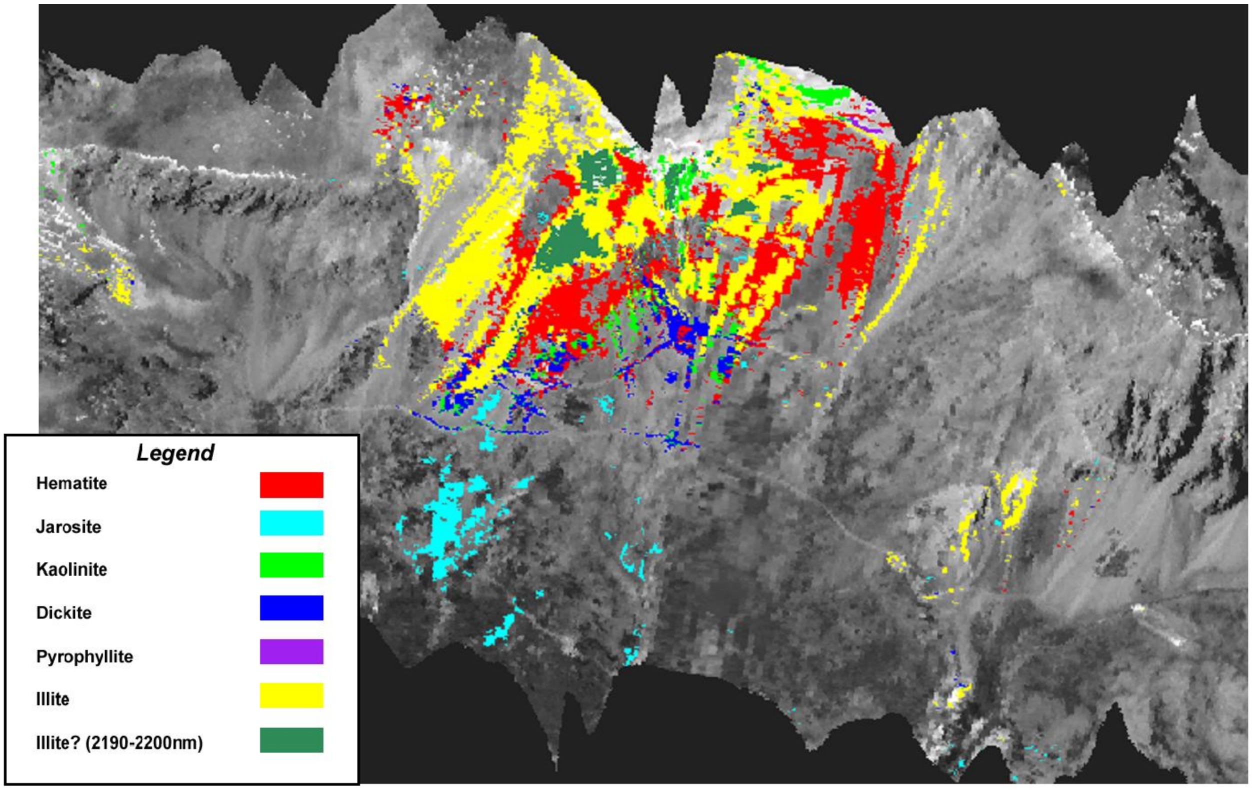

Figure 6. Low-altitude, airborne-platform AVIRIS imagery (4m spatial resolution) over Red Mountain West processed for specific minerals found in areas of hydrothermal alteration and acid rock drainage.

The SpecTIR Corp. HST-1 hyperspectral sensor, also flown on a low-altitude airborne platform, obtained 1 to 2.5m spatial resolution throughout the study area. This sensor was compared to the AVIRIS sensor for the ability to qualitatively assess water quality in South Fork and Lake Creek. Qualitative assessment of water quality is possible because of the mineralogical zoning of iron sulfates, iron oxides, iron hydroxides, and aluminum hydroxides with respect to pH, as expressed in Figure 4. These minerals are present on stream alluvium and indirectly indicate the pH of the stream at the time of deposition. Figure 7 shows processed imagery for both AVIRIS and HST-1 in the vicinity of the confluence of South Fork (SF) and Sayres Bowl Stream (SBS), which drains the north end of the eastern hydrothermally altered area. The

AVIRIS sensor with 4m spatial resolution is able to discern changes in precipitate mineralogy on the South Fork alluvium and the changes that occur in the mixing zone downstream of Sayres Bowl Stream. The HST-1 sensor with 1m spatial resolution can do this and in addition, its imagery shows detailed variation in mineralogy, hence pH, within the exposed alluvium. Zoning of mineralogy occurs on the gravel bar and characterizes the changes in precipitate mineralogy as stream flow drops from high-flow to low-flow conditions. Higher flow conditions are indicated as higher pH zones on the interior, topographically higher, portion of the gravel bar and low-flow conditions are indicated as the lower pH zones adjacent to the stream. In essence, the 1m resolution of the HST-1 sensor introduces the ability to see not only the two spatial dimensions, but also the third dimension of time.

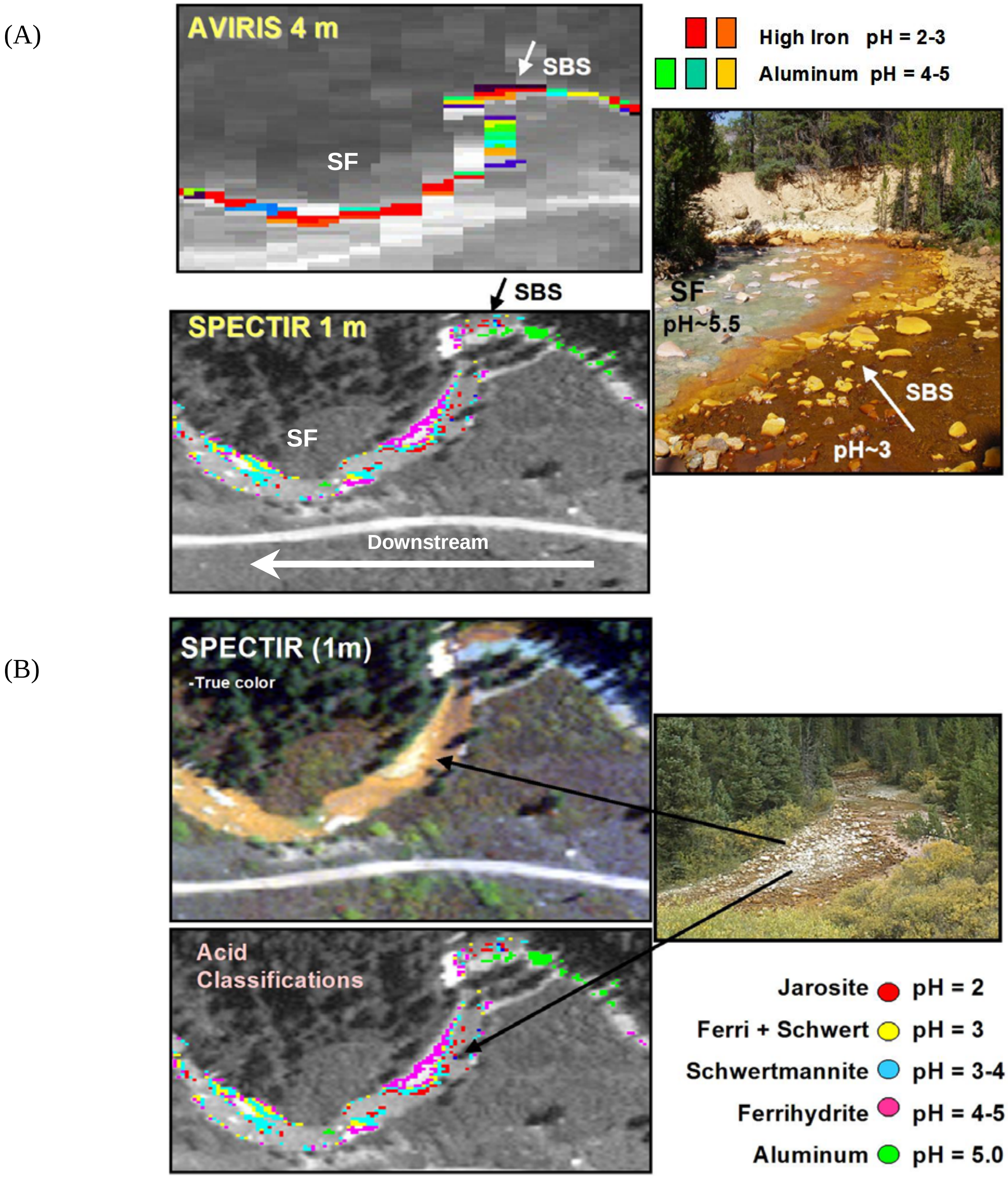

Figure 7. (A) Comparison of AVIRIS (4m resolution) and SpecTIR HST-1 (1m resolution) imagery at the confluence of South Fork (SF) and Sayres Bowl Stream (SBS). Changes in precipitate mineralogy on the streambed alluvium are indicative of stream pH. (B) The better spatial resolution of the HST-1 imagery allows mineralogical zoning to be observed on the gravel bar, indicating changing stream pH conditions from high-flow to low-flow stream stages.

Upper Arkansas River Watershed (Phase 2)

The Phase 2 study area is within the upper Arkansas River basin (Figure 1) and exhibits the presence of mine wastes as disseminated tailings either along the river or within tributary systems. This is the same general application of hyperspectral technology as in Phase 1, but with a different perspective.

The tributaries and sample areas investigated in Phase 2 are, for the most part, farther from the source alteration systems than in the Phase 1 study area. They are a product of man's interaction with the landscape and the subsequent materials released into the environment from exploited mineralized systems.

Tailings deposited along the upper Arkansas River are of concern for environmental purposes not only for siltation effects, but also for contained metals that can leach into the wetlands and river and subsequently be carried downstream. Sulfate mineral “blooms” are seen in many places along the stream floodplain during drier weather, indicating that metals have been mobilized from the tailings and flushed downstream during wet periods, with subsequent oxidation and re-precipitation of acid generating species.

Most of the tributaries to the upper Arkansas River appear to contribute very minor, if any acidic mineral products to the main drainage and do not have identifiable iron minerals. California Gulch, draining from the Leadville mining district, has been remediated to the point that there is only goethite and possibly ferrihydrite remaining at the confluence with the Arkansas, indicating moderately acid (pH 4-5) to neutral conditions.

Abandoned mines in St. Kevin Gulch, which is northwest of Leadville, continue to produce acid drainage that can be compared with the Phase 1 results. These are restricted in areal extent. The metals and acid contribution of this area are not considered by the USGS to significantly impact the watershed above Leadville (Redente et al, 2002).

Tailings deposits from the Leadville mining district have been identified in the banks of the Arkansas River as far south as the town of Granite, 26 km downstream from Leadville. Tailings deposited along the upper Arkansas River, as outflow from St. Kevin Gulch and California Gulch were a focus of work in Phase 2. Image processing of the hyperspectral data for the upper Arkansas River shows depositional patterns. Sulfate mineral blooms are sufficiently ephemeral that the ability to track them with the 2.5m hyperspectral data is marginal. One area, Moose

Haven, is discussed here with imagery and supporting ground reflectance spectroscopy data. Moose Haven, is 17 kilometers downstream of Leadville along the mainstem of the Arkansas River.

Leadville Mining District

Mineral types present in the Leadville mining district ores and expected to occur in the tailings and mine waste include various metal carbonates and metal sulfides. Specific minerals found in the district include argentiferous cerussite, smithsonite, pyrite, marcasite, chalcopyrite, sphalerite, galena, tetrahedrite, pyrrhotite, electrum, magnetite, specularite, chalcocite, bornite, and covellite (Tweto, 1968; Thompson and Arehart, 1990; Thompson and Beaty, 1990; Emmons et al, 1927). Common gangue minerals expected in the tailings and mine waste, include silica (quartz or jasperoid), siderite, mangano-siderite, dolomite, and barite (Thompson and Beaty, 1990).

Total production from Leadville between 1859 and 1963 was 92 tons (t) Au, 7466 t Ag, 0.049 Mt Cu, 1.01 Mt Pb, 0.73 Mt Zn (Tweto, 1968). Additional production between 1965 and 1998, from the Irene Mine and Black Cloud Mine, has occurred since these statistics were compiled. This prolific history resulted in waste rock and tailings, rich in pyrite, other sulfides, and carbonates, which now cover approximately 30km^2 east and south of the town of Leadville.

Given the ore and gangue mineralogy, carbonates and clays will dominate the tailings; the waste rock dumps will still contain sulfides. Gravity and fluvial processes will move all of this material into the drainages and down to the river. As the sulfides weather, acidic ground waters will be created. The carbonate minerals will buffer some of this acid production. However, as this material moves into the watersheds, the carbonate will be diluted and zones of acidic water and acidic tailings will form along the drainages. Enrichment in manganese can also be expected in the tailings and waste rock.

Moose Haven

Moose Haven was chosen for this investigation as it is distal from the Leadville mine workings and is an area of imbricating, braided small streams intertwined with the Arkansas River. In this area the river has deposited tailings in the banks and sand bars. The tailings contain sufficient sulfides to actively create zones of acid drainage (Figure 8).

Figure 8. (A) One of the small seasonal streams that contain tailings. Note the dark material concentrated in the center of the bed. This is a manganese-coated hardpan where the more acidic minerals will form as water wicks upward through the soils. The white material is the aluminum sulfate mineral, aluminite.

(B) Main Arkansas River channel showing tailings in the bank (arrow).

The tailings are concentrated and exposed at the surface in the smaller seasonal channels that splay off the river (Figure 8A). There is a pH zoning reflected in the mineralogy. The center of the dry, ephemeral channel contains a highly manganiferous black hardpan that grades into sand and tails mixed on the sides of the streambed. In this area, the secondary minerals copiapite, jarosite, and schwertmannite are forming, indicating pH values in the range of 2 to 4. On the low banks and into the vegetation zone, there is an aluminum sulfate precipitate, aluminite $\{[Al_2(OH)_4(H_2O)_3](SO_4)(H_2O)_4\}$, which occurs in a pH range near 5. These minerals are very ephemeral. Most are water soluble, dissolving and re-precipitating as the weather and water flow fluctuates. Base minerals include smectite, some illite and carbonates, one of which is smithsonite [$ZnCO_3$], which is diagnostic for tailings from the Leadville mining district (Tweto, 1968). Gypsum [$CaSO_4 \cdot nH_2O$] is ubiquitous, found at almost every site and is a secondary product of high sulfate levels in the river and groundwater. The source of the sulfate is most logically weathering of sulfide minerals from the Leadville district.

Through the over 100 years of Leadville district mine and mill production, tailings have also been deposited in the banks of the higher energy Arkansas River main channel (Figure 8B). These are also constantly re-worked and pushed farther and farther downstream, carrying with them residual sulfides and metals.

Hyperspectral Imagery

The upper Arkansas River valley was flown with the SpecTIR hyperspectral sensor at a 2.5m pixel size for ground resolution. This airborne sensor consists of a series of detectors that collect spectral signatures reflected from materials (e.g. minerals, rocks, vegetation, water) on the Earth's surface. Figure 9 is a mineral classification image from that survey which also shows the sample locations for the ground truth survey.

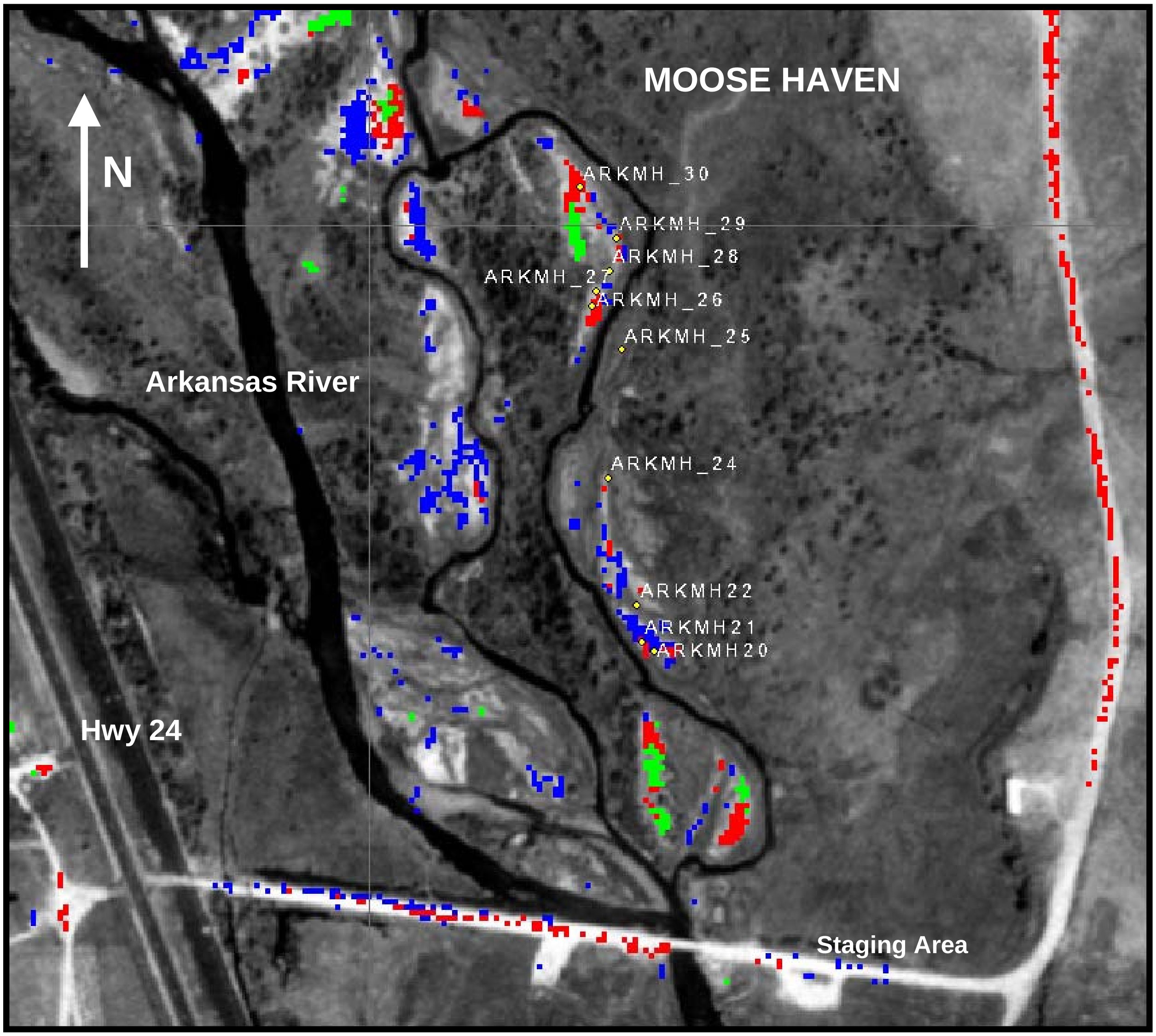

Figure 9. SpecTIR hyperspectral mineral classification image of the Moose Haven area on the upper Arkansas River. Pixel classifications: red = iron minerals and tailings; blue = tailings; green = river clays. The area is located approximately 15 km downstream (south) from Leadville. Sample sites lie on the east side of the river to ease access for the field spectrometer.

A classification image is created to show the different materials whose spectral signatures can be detected with the hyperspectral data and classification process. Each classification is then color-coded. Pixels or picture elements in the image, which are the 2.5m spatial units on the ground, then are assigned different colors relative to materials the computer is trained to recognize. Training of the computer recognition process is done with "ground truth" spectral data obtained by taking a field spectrometer out to the field location, collecting data or spectra from specific, GPS-documented sites, and integrating those spectral signatures into the image processing program as references.

Classifications are created using different matching statistics. Those with a tight statistical window indicate high levels of confidence that the material identified in the image actually exists at that place on the ground. These statistical windows can be opened up to include lower levels of confidence where mixtures with other materials dominate. In this image, however, the statistical window was limited to only the best matches or highest levels of confidence. This was done as a first pass to assure that the processing picks the dominant material types along the river. Subsequent processing then can be done to show a wider distribution of mixed materials.

Table 1 summarizes the mineralogy for the ground truth sample sites. The image in Figure 9 shows tailings in blue, iron compounds associated with tailings in red, and indigenous river clays in green.

Table 1 Summary of minerals identified from the ground truth survey. The sample sites are listed with the minerals identified by field spectrometer at each site. The minerals include: Kao = kaolinite, Smc = smectite, ill = illite, FeSO4 = Iron sulfates, CO3 = carbonates, AlSO4 = aluminum sulfates, goe = goethite, and Gyp = gypsum. The acid-generating minerals have been grouped together as FeSO4 for simplicity and include copiapite, jarosite and schwertmannite. AlSO4 classification includes aluminite and amorphous aluminum sulfate compounds.

Sample	**classification**	**Kao**	**Smc**	**ill**	**FeSO4**	**CO3**	**AlSO4**	**goe**	**Gyp**
ARKMH20	blue	tr		x	x	??			x
ARKMH21	red	tr	x	x	x		mix		x
ARKMH22	not class		x		??		x		
ARKMH23	no spl								
ARKMH_24	not class		x	2204			x		x
ARKMH_25	not class						x		x
ARKMH_26	red	poor		2201	??	??		x	x
ARKMH_27	not class		2204	2206					X
ARKMH_28	not class	x	x	2205		??		x	x
ARKMH_29	red	tr	x	x				x	x
ARKMH_30	red	tr	x					x	x

Symbol Key: x = present; tr = trace; ?? = possible; poor = poor response; mix = mixture of minerals; number = illite peak response value (nm)

All the samples in this table are tailings or tailings-impacted materials. Aluminite is very difficult to identify from the air, but very easy to identify on the ground (Figure 10). It is usually, but not always, near sites of iron oxide-coated pebbles. It is very diagnostic of the presence of tailings. It is also ephemeral and tied to wet and dry cycles. Image processing for it still must be refined. The river clays were not included in this particular ground truth survey, but were included in a previous one that showed only smectite associated with the green pixels.

Figure 10. The mineral aluminite is shown here as sulfate "blooms" (white arrows) associated with iron-stained cobbles within the riverbed. This is a diagnostic indicator of the presence of sulfate-saturated ground waters. The sulfate originates from acidic ground water created by sulfide decomposition and it permeates the tailings-impacted portion of the river floodplain.

In general, the tailings contain all or selected mixtures of iron sulfates (copiapite, schwertmannite, jarosite), iron oxides, illite, plus or minus kaolinite, plus or minus aluminite, plus or minus carbonates (especially smithsonite). Most samples collected contain gypsum, an indicator of sulfur enrichment, and probably an indicator of the presence of tailings. However, gypsum is a ubiquitous mineral in sulfur-rich materials, especially in semi-arid climates and therefore must be used carefully as an indicator. Smectite is also ubiquitous. When present by itself, it is an indicator of river clays. It is also present within degraded illites and as such has been classified in Table 1.

The mineralogical agreements between the ground samples and the image classifications generally are acceptable. The agreement is further substantiated by visual observation. All the red and blue areas in Figure 9 contain some type of tailings or tailings-impacted materials. Statistically, additional ground samples should be collected for a viable accuracy assessment. This is a difficult ground environment to process because of the extensive and varied vegetation present. However, there is sufficient ground exposure to produce a viable image of the distribution of the tailings along the river system.

Discussion

The contrast between the impacted Lake Creek watershed, where it is possible to track pH zoning from pH = 2.0 to pH > 7, and the upper Arkansas River basin, is dramatic. Both systems contain aluminum minerals in high abundance. In the Lake Creek watershed, sulfur is present, but appears to be taken up by the iron, and the aluminum mineral is an amorphous AlOH compound. In the Arkansas River, south of Leadville, two different conditions exist. There is more buffering from the carbonate mineralization host and gangue minerals such as illite and ore carbonates, plus there is more sulfur available in the ground water. This leads to an aluminum sulfate mineral, aluminite, precipitating along the banks, and in and around gravel bars.

However, there are still sufficient concentrations of sulfides within the alluvial tailings to actively produce iron sulfates such as copiapite, schwertmannite, and jarosite, indicating very low pH ranges. These minerals and compounds come and go, almost on a daily basis, in the low flow to ephemeral backwaters of the river. This is not seen in the Lake Creek watershed where the lowest pH species (i.e., copiapite and melanterite) are only found at the sources, with jarosite, schwertmannite, and ferrihydrite defining pH zones along the drainages.

Additionally, now that major sources of acidity and metals in the Leadville district have been remediated, the remote sensing data for the upper Arkansas River show a rather benign landscape with more restricted, localized acidic zones.

Conclusion

High spatial resolution (1-4m) hyperspectral remote sensing can be used to characterize natural and mining-induced acid rock drainage (ARD) environments. This demonstration project in the upper Arkansas River basin of Colorado has used hyperspectral remote sensing to characterize the surface mineralogy of the hydrothermally altered areas that are the source for natural ARD in the Lake Creek watershed. Stream pH downstream from the altered areas can be indirectly characterized through remote sensing by identifying specific iron sulfate, iron hydroxide, iron oxide, and aluminum hydroxide mineral species present as precipitates on streambed alluvium and relating them to each mineral’s pH stability range. Hyperspectral remote sensing was also used successfully to map tailings deposition along the Arkansas River mainstem more than 15 km downstream of the Leadville mining district, the source of the tailings.

The usefulness of the technology for remedial investigations at active and abandoned mine sites is readily apparent. The spatial richness of remote sensing data, as compared to field point-sample data, can help the remedial specialist identify more precisely the highest priority areas for cleanup. In addition, the ability of hyperspectral remote sensing to indirectly identify stream pH in watersheds affected by ARD could be used as a periodic monitoring tool to assess the effectiveness of cleanup efforts on stream water quality.

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