HYPERSPECTRAL SENSING OF ACID MINE DRAINAGE – TWO COLORADO CASE STUDIES[1]

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Abstract. The upper Arkansas River basin of central Colorado contains watersheds that are affected by acid rock drainage (ARD) from both natural and mining induced sources, including the Leadville mining district. Hyperspectral, high-resolution remote sensing technology is being used to characterize and map the source mineralogy of ARD, changes in downstream water quality, and the fluvial deposition of mine tailings downstream.

Two case studies are presented. The Lake Creek watershed is affected by natural ARD, emanating from two sources which are sub-economic, sulfide-mineralized, porphyry systems in the headwaters of two tributaries. Extreme metal- and acid-loadings from source areas affect the watershed for 30 km downstream. The main channel of the Arkansas River, primarily downstream of the Leadville District, contains disseminated tailings distributed by fluvial processes. The tailings are a continuing source of metals loading to the river.

The two watershed systems share common mineral coatings, such as jarosite and copiapite for the high-acid sections and goethite for the neutral to alkaline stream rock coatings. However, these are very different systems chemically. Lake Creek contains considerably less sulfur, and therefore, its waters tend to precipitate sulfate, oxide, and hydroxide minerals in a textbook model with changing pH zones with flow down-drainage and as neutral inflows are received. The effluents from the Leadville District wastes are sulfur-enriched, and carbonate-buffered, and consequently produce quite different sulfates such as aluminite (Al sulfate) and amarantite (Fe sulfate). Copiapite and jarosite are restricted to ephemeral backwaters and small tributaries of the main river.

Hyperspectral and multispectral remote sensing data were acquired for these areas using airborne and satellite sensors. 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 time of deposition. Along the Arkansas River, tailings and Leadville wastes deposited within the floodplain are mapped. These techniques assist in baseline characterization, evaluation of impact of ARD on watersheds, and planning and prioritization of remedial activities.

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

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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, identify changes in downstream water quality, and identify mine tailings in fluvial sediments downstream from a mining district. This 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 within the study area (Fig. 1).

Methodology

Remote sensing data were acquired from commercial and government archives for the satellite data and as an original data acquisition request (AVIRIS; flown by Jet Propulsion Laboratory) or commercial contract (HST-1; flown by SpecTIR Corp.) for the airborne data. Only data from the ASTER, AVIRIS, and HST-1 sensors will be discussed in this paper. Hyperspectral data had not previously been collected at low altitude before for our study areas. All image processing, including mineral classification, was performed using the ENVI software package (product of Research Systems Inc., Boulder, Colorado) and proprietary software written by Overhill Imaging and Cartography and SpecTIR Corp. for use during this and other remote sensing projects. Initial results from image classification for mineralogy were field checked through additional sampling and spectral analyses to confirm the classified minerals were present. Classifications then were refined to better reflect field conditions and improve utility of results for the study area.

Water sampling and analyses were performed by the CGS and by Colorado Mountain College under CGS direction. Both flow measurements and water sample compositing were done across the full width of the stream at each sample location. Analyses of the water samples were performed partly in the field for parameters such as pH and dissolved oxygen and by contract laboratory for metals and SO_4^{-2}. Hydrogeochemical modeling was performed by the CGS using PHREEQC (Parkhurst and Appelo, 1999).

Sediment, precipitate, rock, and tailings sampling and analyses were performed by Spectral International, Peters Geosciences, and HENDCO Services. Sediments were sampled such that one sample above recent high-flow water line from each bank was collected (if possible based on flow volume and ability to traverse the entire stream) and one (for very small streams of uniform water flow conditions) to eight samples (for complex flow conditions and larger streams) were collected within the channel or channels at any given location. Analyses by field spectrometer were done for mineralogy on as many samples as possible during field work, with the remainder being analyzed with the same spectrometer under office conditions following field work. Mineral identification was performed by Spectral International using their SPECMIN software package and technical experience. Database compilation, generation of sample maps, and

posting of analytical results was performed by Peters Geosciences using the ArcGIS software package (product of ESRI, Inc., Redlands, California).
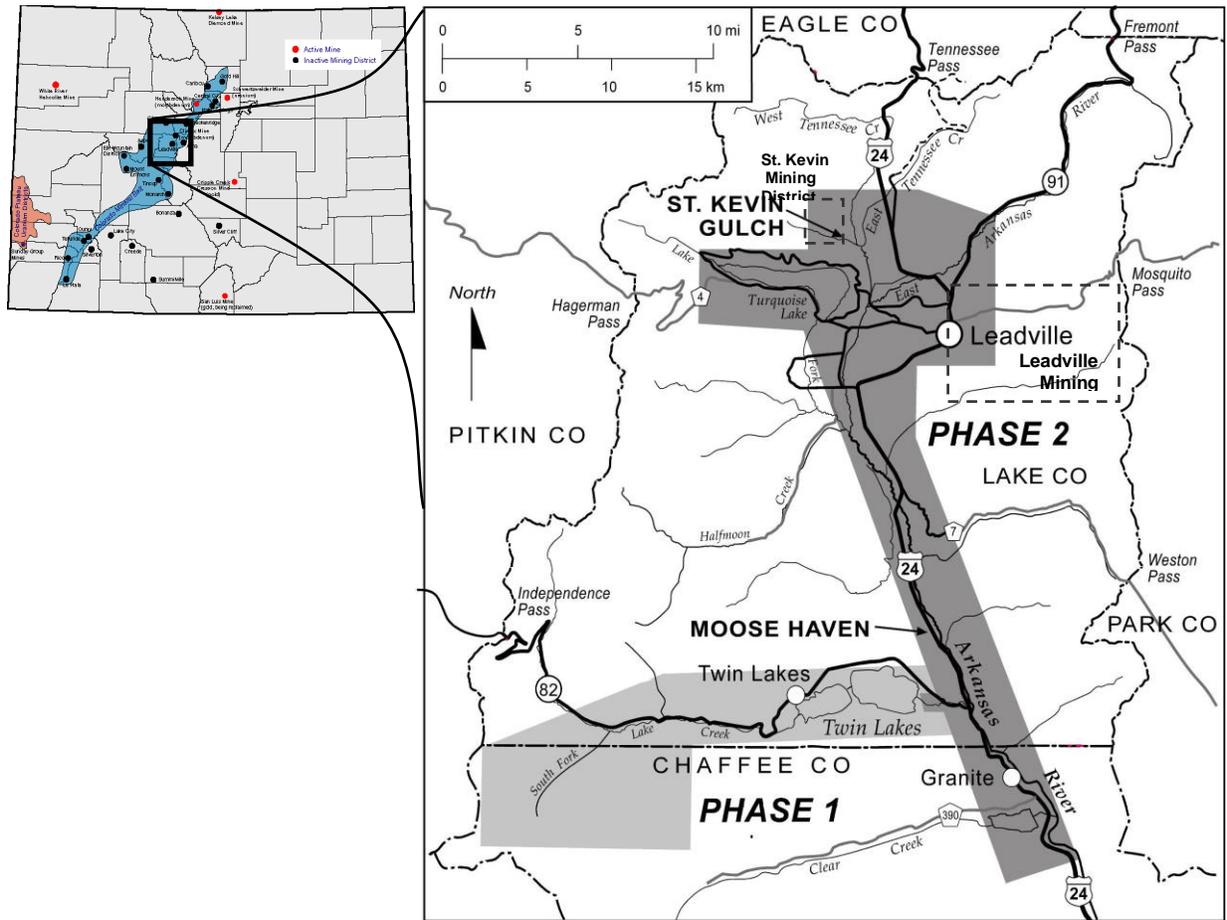

Figure 1. Location map of Phases 1 and 2 of the study area in the upper Arkansas River basin showing the study area's location within the Colorado Mineral Belt (blue).

Case Study 1: Lake Creek Watershed

This part of the project (Phase 1) 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 (Fig. 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 SO_4^{-2}, quartz-sericite, quartz-sericite-pyrite, and argillic assemblages. Disseminated sulfide minerals, primarily pyrite, in these alteration zones are the major source of acidic drainage.

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Low pH (pH = 2-5), Fe-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 Fe 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 Fe sulfate and Fe oxide minerals include jarosite $[(K,H_3O,Na)Fe_3(SO_4)_2(OH)_6]$, ferrihydrite $[Fe_5HO_8 \cdot H_2O]$, schwertmannite $[Fe_8O_8(OH)_6(SO_4) \cdot nH_2O]$, copiapite $[Fe^{+2}Fe^{+3}_4(SO_4)_6(OH)_2 \cdot 20H_2O]$, and transitional amorphous phases. In addition, these waters are rich in Al and $Al(OH)_3$ precipitate 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 Fe hydroxide goethite $[FeO(OH)]$, which is stable in near neutral pHs, 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 Al and Fe mineral precipitate coatings on streambed alluvium (Fig. 3).
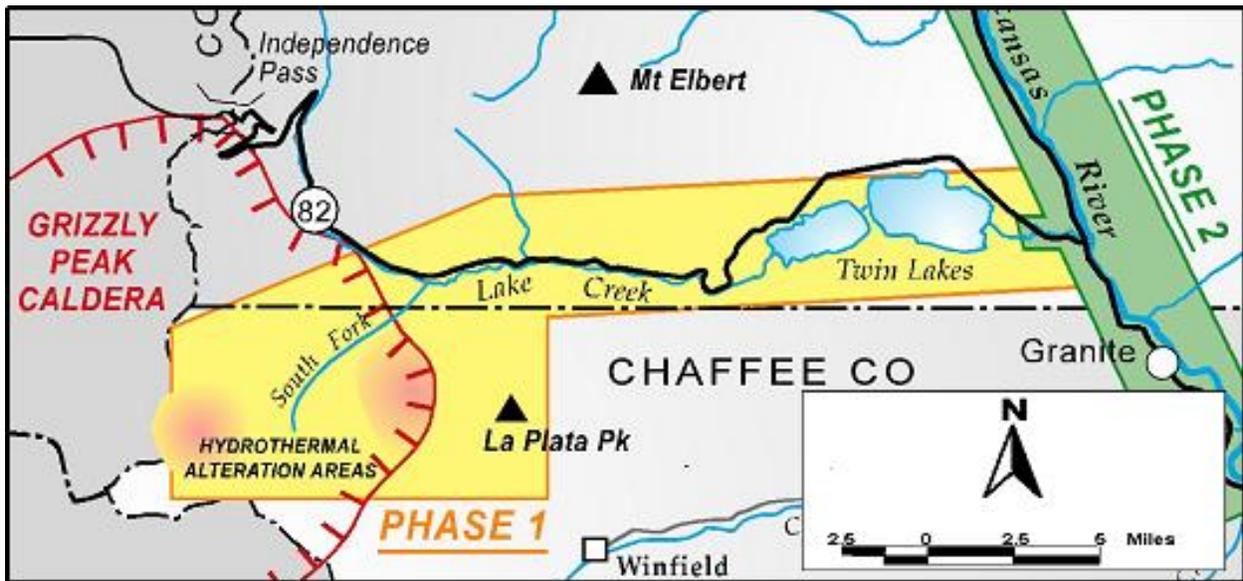

Figure 2. The Phase 1 field area focuses on natural acid rock drainage (ARD) from two hydrothermally altered areas in the headwaters of South Fork Lake Creek and the downstream affects of ARD on the Lake Creek watershed.

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 through near infrared range of the electromagnetic spectrum. A discussion of hyperspectral remote sensing and use for mineralogical identification can be found in van der Meer (2000). The major Fe minerals commonly produced in the Lake Creek watershed are diagrammed in Fig. 4 with attendant pH stability zones. Figure 5 shows the spectra for most of the Fe minerals precipitates found in the Lake Creek drainage to illustrate their spectral differences. It is apparent that these spectral differences can allow for discrimination between the minerals if sufficient spectral resolution is

available with a given sensor. Table 1 lists the general characteristics of the sensors referred to in this paper. Multispectral systems such as ASTER, both airborne and satellite types, do not have sufficient spectral or spatial resolution (depending on the sensor) to discriminate the spectral features necessary to identify all of these key Fe minerals in impacted, narrow, mountain streams. 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 in the stream on a watershed scale. The hydrogeochemistry observed in the Lake Creek watershed was modeled by CGS using PHREEQC (Parkhurst and Appelo, 1999) for key locations below confluence mixing zones. Stream water chemistry was used to predict downstream metal attenuation and the various mineral precipitate species that should be observed on the streambed (Bird, 2003). This modeling corroborated observed mineralogy of Fe and Al precipitates at these locations.
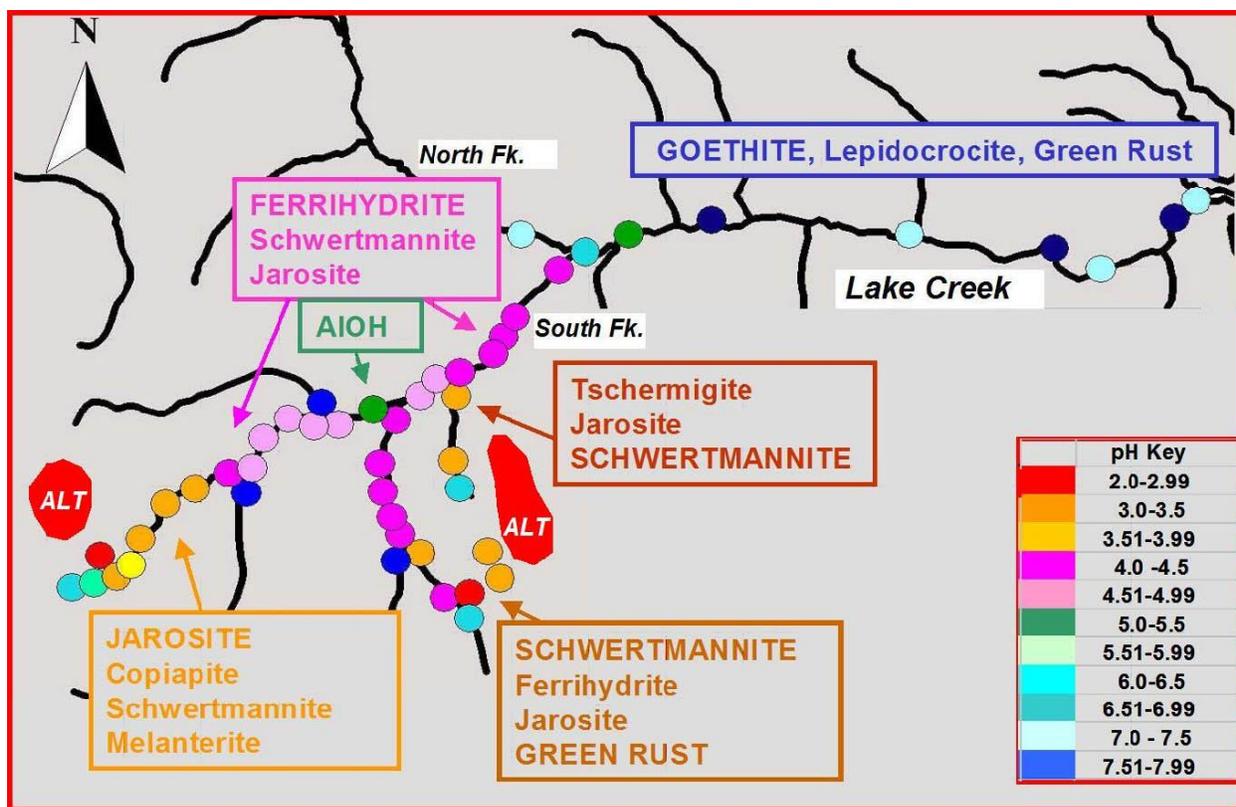

Figure 3. Schematic map of the Lake Creek watershed (Phase 1) correlating general stream pH with streambed precipitate mineral distribution. Hydrothermally altered areas, the sources of acid rock drainage, are labeled "ALT."

Table 1. General characteristics of the sensors referred to in this paper. All three sensors acquiredata for the visible through short-wave infrared (SWIR) portions of the electromagnetic spectrum. The ground resolution of ASTER is 15 m for visible through near-infrared and 30 m for SWIR.

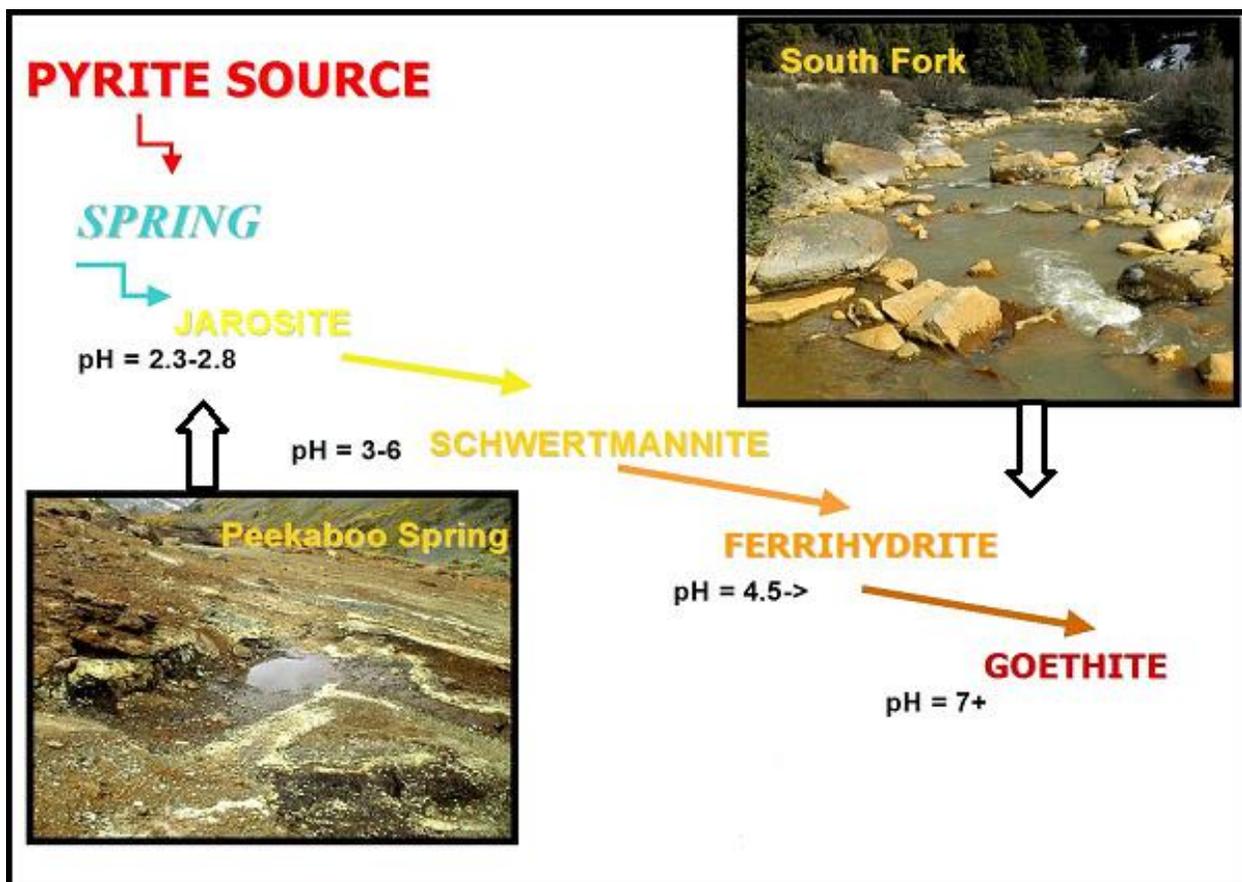| Sensor	ASTER	AVIRIS	HST-1
Ground resolution	15 m & 30 m	4 m (low altitude)	0.5-2.5 m
Spectral resolution	*broad bands*	12-15 nm	10 nm
Number of bands	14 bands	225 bands	240+ bands
Type of platform	Satellite	Airborne	Airborne

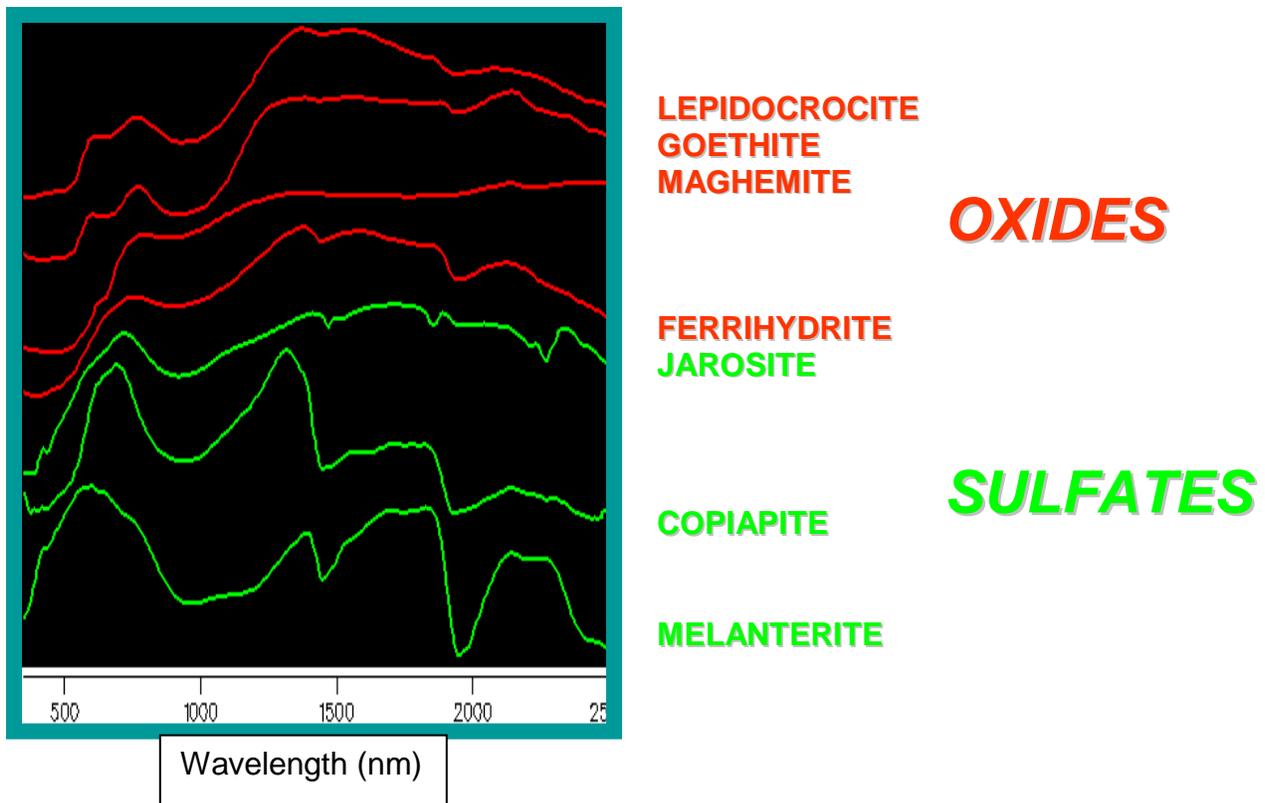Figure 4. Iron minerals observed in the natural-ARD impacted streams of the Lake Creek watershed (Phase 1 study area).

Figure 5. Spectral plot of Fe oxides and sulfates found as precipitates in the Lake Creek watershed.

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 6 is a processed image from ASTER, a satellite-based enhanced multispectral sensor with 15-m resolution in the visible range and 30-m 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 Fe oxide was identified in the wider portions of the Lake Creek streambed.

In comparison, the AVIRIS hyperspectral sensor, flown on the low-altitude airborne platform, was able to obtain 4-m spatial resolution data over the hydrothermally altered area of Red Mountain West (Fig. 7). Compared to the ASTER image in Fig. 6, the AVIRIS data have much greater spatial detail and mineralogical identification ability, which is obtained through more detailed spectral and spatial resolutions. 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.

The SpecTIR Corp. HST-1 hyperspectral sensor, also flown on a low-altitude airborne platform, obtained 1-m to 2.5-m 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 Fe sulfates, Fe oxides, Fe hydroxides, and Al hydroxides with respect to pH, as

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expressed in Fig. 4. These minerals are present on stream alluvium and indirectly indicate the pH of the stream at the time of deposition.
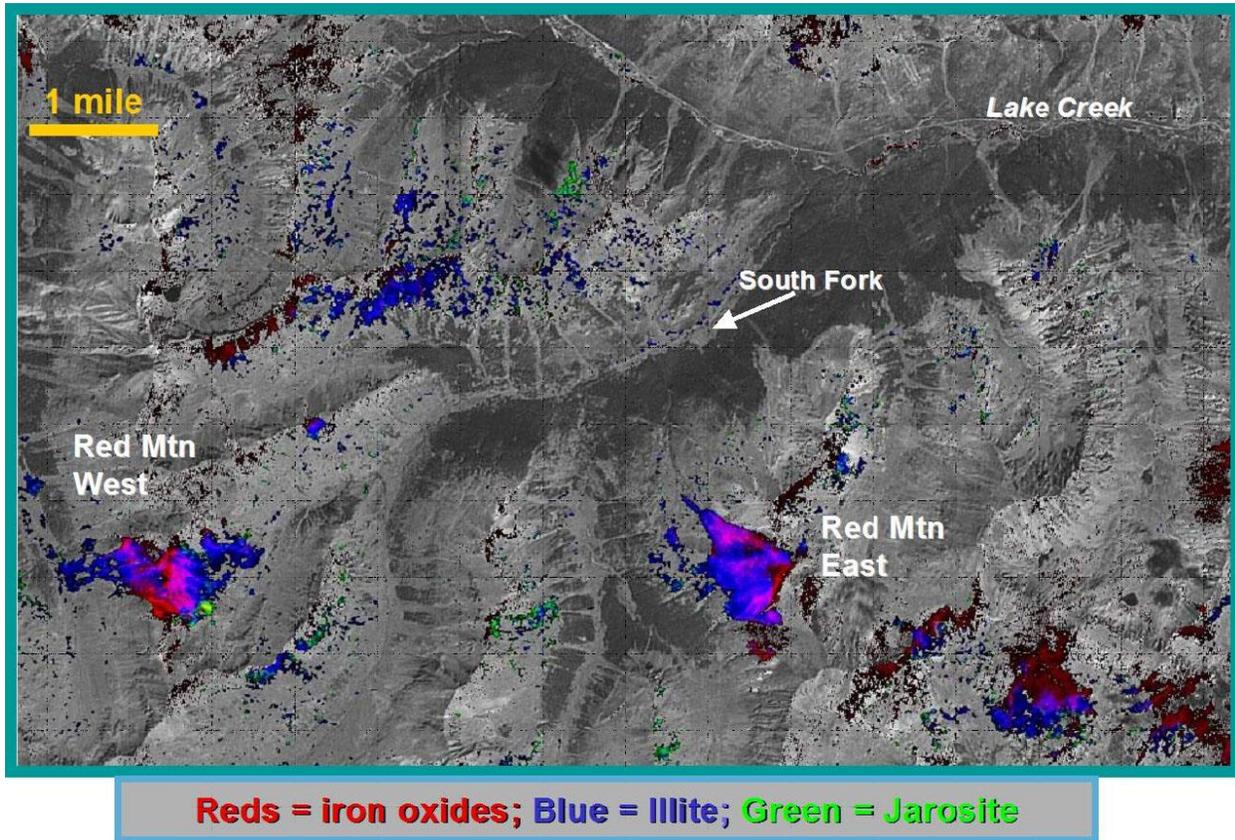

Figure 6. Satellite-based ASTER image of the western portion of the Phase 1 study area processed to show general mineral classes indicative of acid rock drainage.

Figure 8 shows processed imagery for both AVIRIS and HST-1 in the vicinity of the confluence of South Fork (SF) and Sayres Bowl Stream (SBS). SBS drains the north end of the eastern hydrothermally altered area (referred to as Red Mountain East). The AVIRIS sensor (with 4-m 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 1-m spatial resolution) can do this and, in addition, HST-1 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 1 m resolution of the HST-1 sensor introduces the ability to see not only two spatial dimensions, but also a third dimension of time.
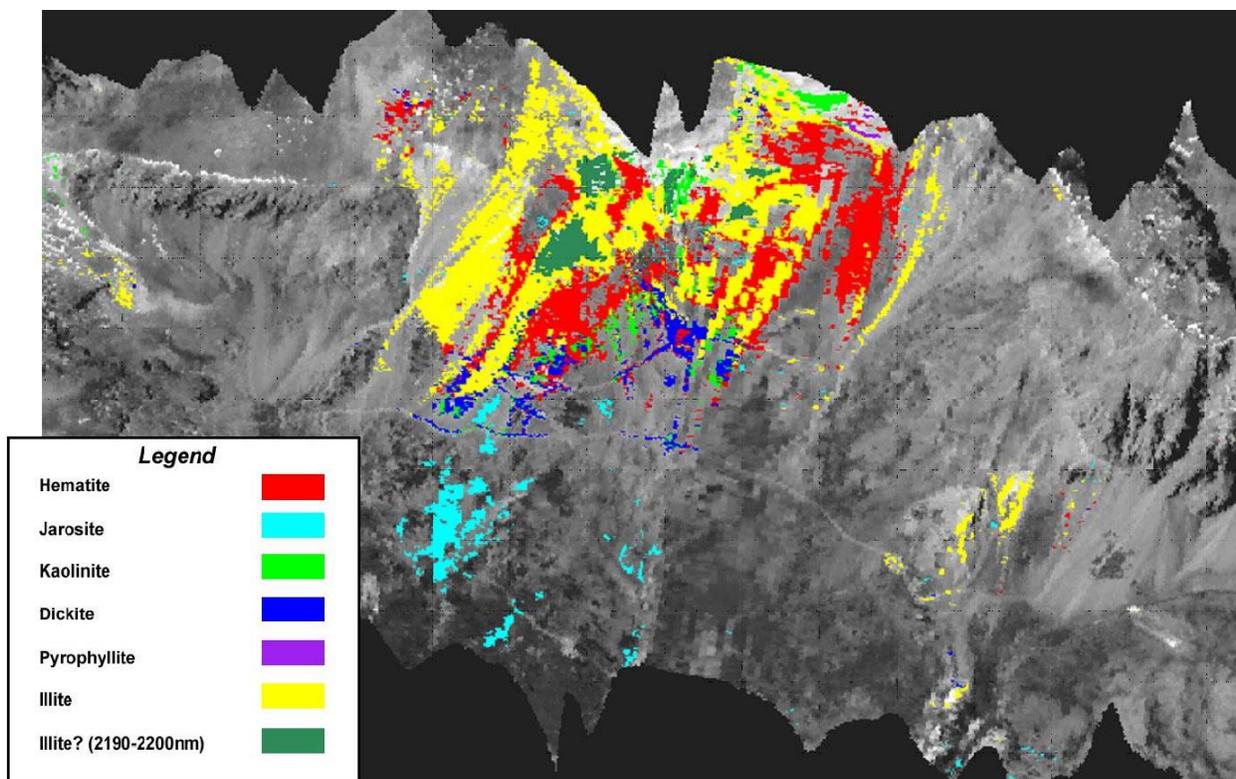
Figure 7. Low-altitude, airborne-platform AVIRIS imagery (4 m spatial resolution) over Red Mountain West processed for specific minerals found in areas of hydrothermal alteration and acid rock drainage.

Case Study 2: Upper Arkansas River Watershed

The Phase 2 study area is within the upper Arkansas River basin (Figs. 1 and 9) and has mine wastes as disseminated tailings both along the main river and within some tributary drainage systems. This is the same general application of hyperspectral technology as in Phase 1, but from the perspective of a different source. In the upper Arkansas basin, the acid source is mining-related enhancement of oxidation and drainage rather than from natural, unexploited, sulfide mineralization.

The tributaries and sample areas investigated in Phase 2 are, for the most part, farther from the source hydrothermal alteration systems than in the Phase 1 study area. ARD and heavy metals are a product of mining and beneficiation, with waste materials (mainly tailings) released into the river environment from the exploited, mineralized systems in the upstream mining districts.

Tailings deposited along the upper Arkansas River are of concern for environmental purposes not only due to siltation effects, but also because of contained metals that can leach into the wetlands and river and subsequently be carried downstream. Sulfate mineral "blooms" (white to light colored) are seen in many places along the stream floodplain during drier weather, indicating that metals have been mobilized from the tailings by evaporation and ground water.

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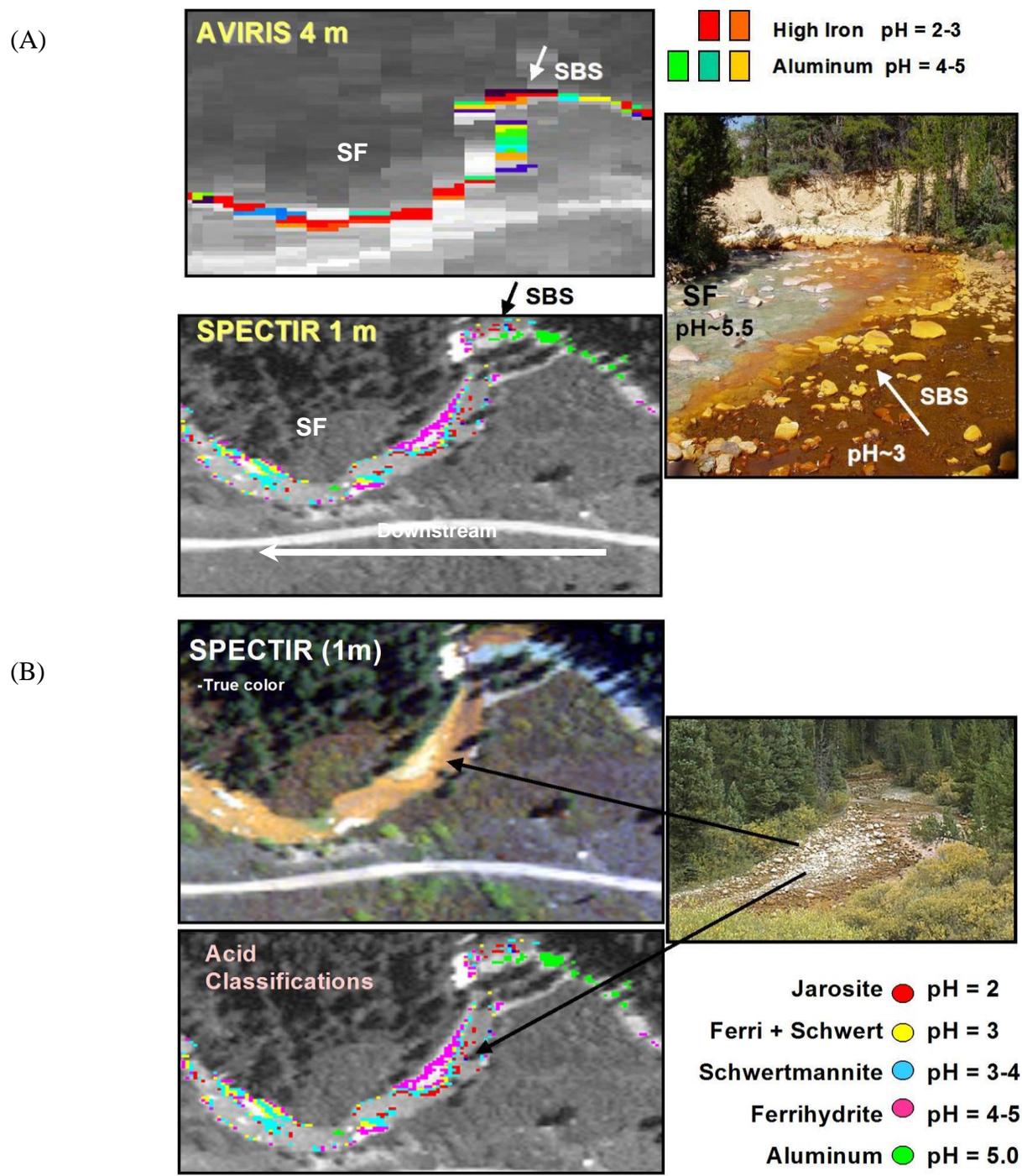
Figure 8. (A) Comparison of AVIRIS (4-m resolution) and SpecTIR HST-1 (1-m resolution) imagery at the confluence of South Fork (SF) and Sayres Bowl Stream (SBS). Changes in precipitate mineralogy on the streambed alluvium are indicative of stream pH. (B) The better spatial resolution of the HST-1 imagery allows mineralogical zoning to be observed on the gravel bar, indicating changing stream pH conditions from high-flow to low-flow stream stages.
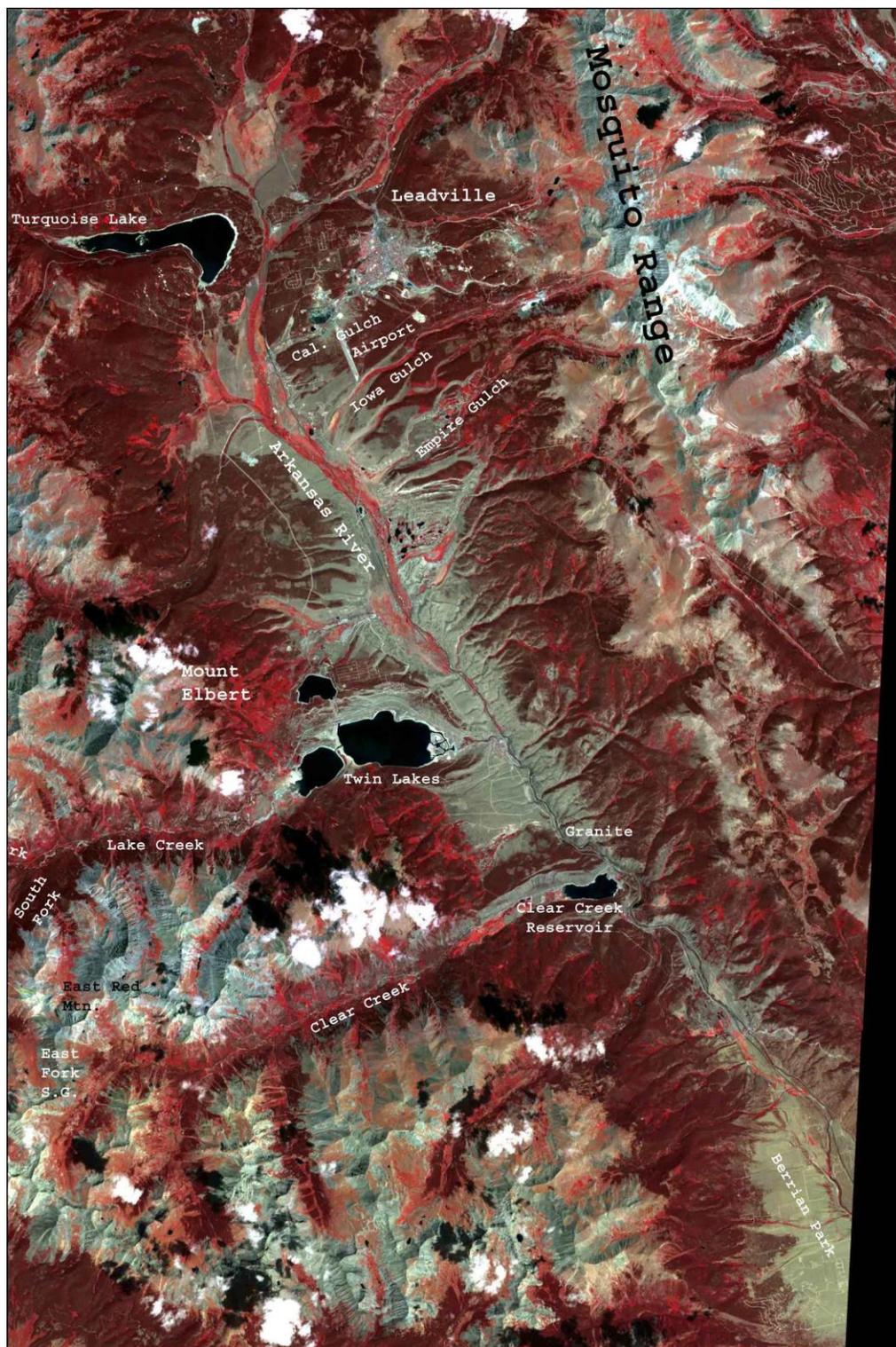
Figure 9. ASTER false-color image of the Phase 2 study area, along the Arkansas River from northwest of Leadville to the north end of Berrian Park. Part of the Phase 1 study area (Lake Creek) also is shown.

Such salts then are easily flushed into surface waters during wet periods probably resulting in metal-laden pulses of drainage. Subsequently, there is more oxidation and precipitation of metal-containing and acid-generating mineral species during dry cycles.

Table 2 shows pH values (measured in the field with a portable pH meter and calibration buffers) that indicate the overall more neutral pH environment of the Phase 2 study sites. In this table, only St. Kevin Gulch (SKG-W1) shows highly acidic conditions, with a pH of 3.7 (low stream flow) to 4.2 (high stream flow). California Gulch (CG-W-3), just above the confluence with the Arkansas River, which drains the main Leadville mining district, shows moderately acidic waters with a narrow pH range of 5.5 (low flow) to 5.7 (high flow). This is a reflection of 1) remediation of mine wastes that has occurred in the Leadville mining-impacted watershed and 2) dilution from the Leadville wastewater treatment plant upstream from this sample site.

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 Fe minerals (Table 2 and Fig. 10). 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 River, indicating moderately acidic (pH = 4-5) to neutral conditions. St. Kevin Gulch, however, still contains sulfide minerals in dumps, which are generating acidic and metal-rich waters. This causes pH values in the 3-4 range in the Gulch drainage.

St. Kevin Gulch

The first Phase 2 subarea study that we discuss for the Upper Arkansas River Basin is the tailings and mill wastes in St. Kevin Gulch and southwestern Tennessee Park. These locations can be seen on the ASTER image in Fig. 11.

The mines in the St. Kevin District were discovered in the 1880s and were intermittent producers until the 1930s, with most activity in the 1880s-1893 and from 1915-1924. The following discussion is derived from information in Neubert and Wood (2001) and Singewald, (1955). Sulfide mineralization is concentrated within fault zones hosted by Precambrian granites. Associated alteration is sericitization and locally silicification. Alteration minerals that could be determined from the dumps and tailings include muscovite, illite, dickite, and quartz. Pyrite was abundant with localized galena and sphalerite. Jarosite, an acidic weathering product of pyrite, also was found in the dumps and tailings. Silver sulfides also were present in streaks in the veins. Shipped ore included oxidized, siliceous Fe-sulfide with Ag, sulfide ore with Ag and Au, and Ag-Pb-Zn sulfide ore. Production concentrated on the extraction of Au, Zn, and Ag, with primarily Ag being produced. There was minor Pb and Cu. Minerals precipitated by the acid drainage include Fe sulfates, oxides, and oxyhydroxides. Significant metals in the present drainage include Al, Fe, Cd, Mn, Zn, Cu, and Pb. Detailed information on ore processing was not available (Neubert and Wood, 2001; Singewald, 1955).

Table 2. Summary of the pH at selected sites on the Arkansas River and some of its tributaries.

| | NASA - Lake Creek Project | | | | | NASA - Lake Creek Project | | | |
	Spring 2003 - High Flow Sampling Event					Fall 2003 - Low Flow Sampling Event			
	Arkansas River					Arkansas River			
	Water Sample ID	Sed Sample ID	pH			Water Sample ID	Sed Sample ID	pH	
Pine Creek	PC-W-1	PC1	7.8			PC-W-1	PC1	7.1	
Clear Creek	CC-W-1	CC1	6.86			CC-W-1	CC1	6.99	
	CC-W-11		6.89	Dup AR-CC-W-1		CC-W-11			Dup AR-CC-W-1
Lake Creek confluence Ark River	LC-W-12	LC12	6.63			LC-W-12	LC12	7.5	
Box Creek	BC-W-1	BC1	8.58			BC-W-1	BC1	8.9	
	EG-W-1	EG1				EG-W-1	EG1		No water sample -
Empire Gulch	EG-W-2		8.22			EG-W-2			No water sample -
						EG-W-3			
Iowa Gulch	IG-W-1	IG1	8.19			IG-W-1	IG1	7.9	
	HMC-W-1	HMC1	8.13			HMC-W-1	HMC1	6.8	
	HMC-W-2					HMC-W-2			
Lake fork	LF-W-1	LF1	7.74			LF-W-1	LF1	7.4	
	EF-W-1	EF1	8.07			EF-W-1	EF1	7.95	
St Kevins Gulch	SKG-W-1	SKG1	4.15			SKG-W-1	SKG1	3.7	
California Gulch	CG-W-1	CG6?	7.5			CG-W-1	CG6?	6.7	
	CG-W-2	CG5?	6.33			CG-W-2	CG5?	5.4	
confluence Ark river	CG-W-3	CG4?	5.75			CG-W-3	CG4?	5.47	
	CG-W-4	CG3?				CG-W-4	CG3?		
	TC-W-1	TC1	7.88			TC-W-1	TC1	6.8	
Tennesee Creek conflu St Kevins?	TC-W-2	TC0	7.1			TC-W-2	TC0	7.38	
Valentine	VS-W-1	VS1 & VS2	7.14			VS-W-1	VS1 & VS2	7.23	
Arkansas River - southernmost point	AR-W-1	AR5	7.29			AR-W-1	AR5	7.8	
	AR-W-2					AR-W-2			Trip Blank
	AR-W-3		6.68			AR-W-3		8.06	
	AR-W-4		8.1			AR-W-4		7.8	
Ark River ……..	AR-W-5		7.5			AR-W-5		8.0	
Ark River - east of Clear Ck Reservoir	AR-W-6	AR6	7.9			AR-W-6	AR6	8.19	
Granite	AR-W-7	AR7	7.92			AR-W-7	AR7	7.99	
Ark River -NE of Hwy-opposite Lake Ck	AR-W-8	AR8		dup ARW7		AR-W-8	AR8		Dup AR-W-7
Arkansas River confluence - upstream	AR-W-9	AR9	8.02			AR-W-9	AR9	6.96	
Arkansas River confluence - downstream	AR-W-10	AR10	7.88			AR-W-10	AR10	7.9	
Doc Smith Ranch	11	AR11					AR11		
above US24 bridge	12	AR12					AR12		
Moose Haven/Kobe	13	AR13					AR13		
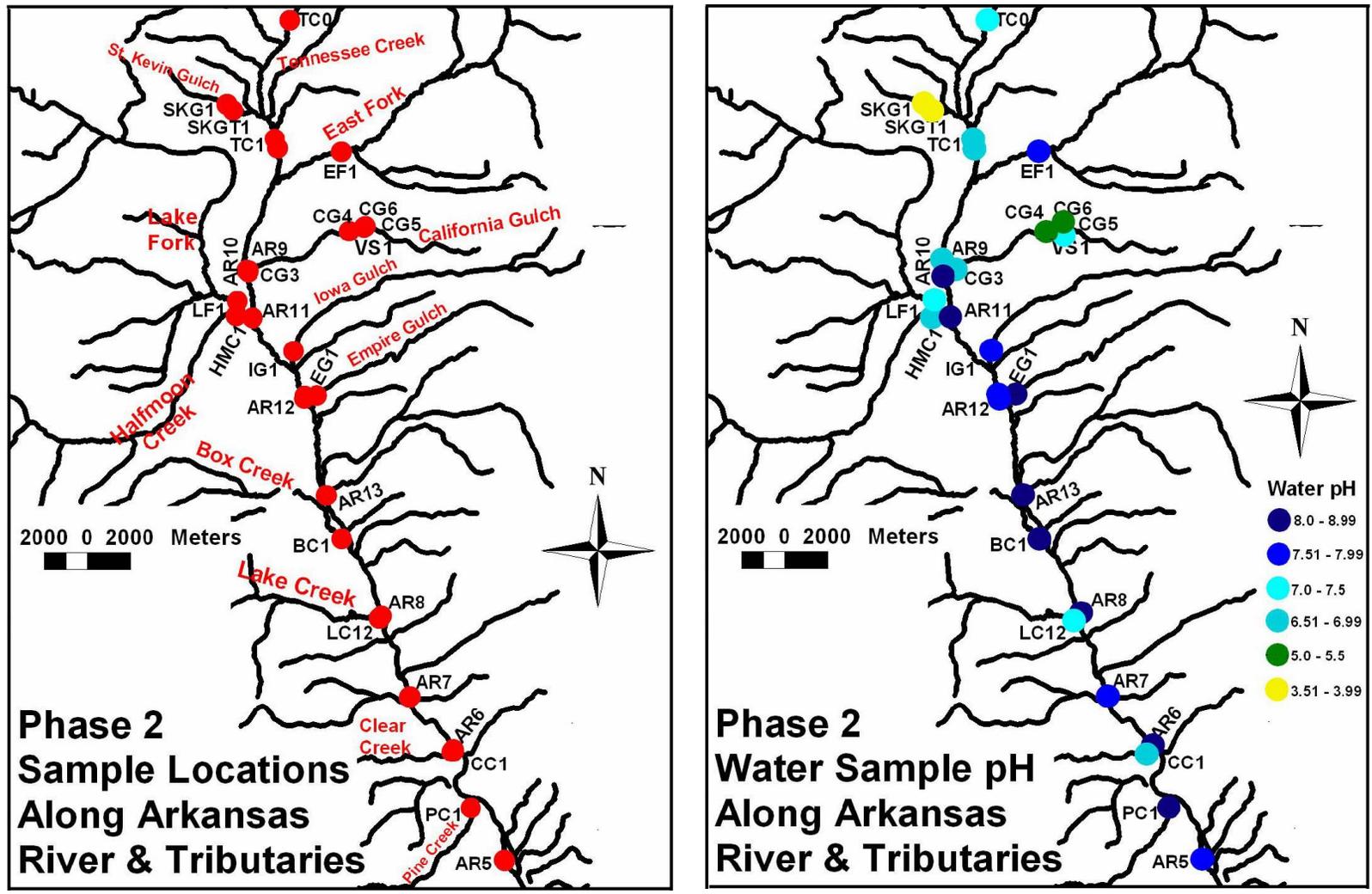
Figure 10. Phase 2 Sample locations and pH values of water samples collected along the Arkansas River and tributaries within the Upper Arkansas River Basin. Please note the more neutral to slightly alkaline values. Only St. Kevin Gulch (SKG) and California Gulch (CG; draining from the Leadville District) contain acid pH range values.
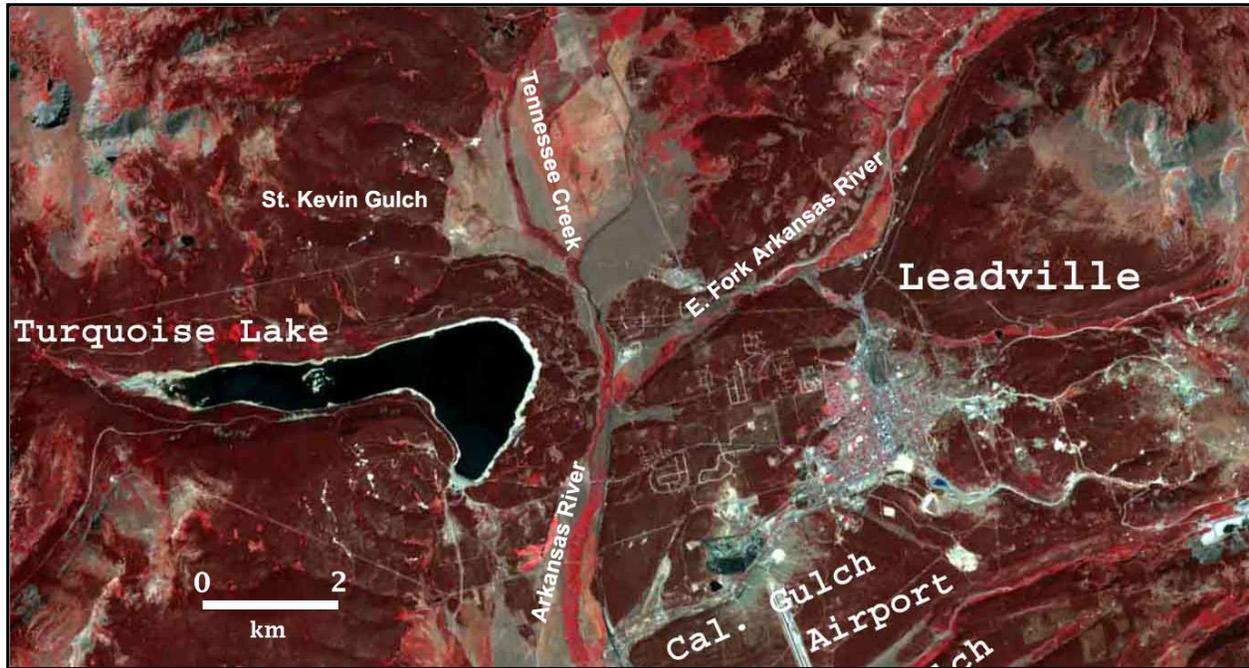
Figure 11. ASTER false color image of the Arkansas River headwaters area showing St. Kevin Gulch, Tennessee Park, Turquoise Lake, California Gulch from the Leadville mining district, and the town of Leadville. The white dots in and above St. Kevin Gulch, are mine dumps.

Abandoned mines in St. Kevin Gulch (such as shown in Fig. 12), which is northwest of Leadville (Fig. 11), continue to produce acid drainage that can be compared with the Phase 1 results. These are restricted in areal extent. The green dotted line in Fig. 12 outlines mill tailings that probably were produced from the old mill labeled in the figure. The very fine grained white and black material in the middle ground of Fig. 12 washed into the stream and out onto the flats of Tennessee Park, which is less than 2 km downstream. It has a very diagnostic spectral signature of the mineral dickite, which is directly associated with the hydrothermal mineralization in the mine. The signature was used to classify for dickite (red pixels) in the hyperspectral image in Fig. 13.

The mill waste, which contains dickite, a hydrothermal clay mineral, has eroded into the stream. This waste is found in the streambed in places below the Griffin Mine and in the materials which have washed from St. Kevin Gulch into Tennessee Park. Illites from the dumps also have migrated downstream into Tennessee Park. Where found in the tailings outwash in Tennessee Park, these minerals provide evidence of sources for the mine and mill wastes that flowed from the Gulch into the southwestern fields of Tennessee Park. Please also note the heavily impacted Fe-rich stream in Fig. 12. This is quite acidic (pH = 3-4), which is a product of the weathering sulfides (mostly pyrite) in the dumps. This also can be traced down the Gulch to Tennessee Park.

Figure 12. View of the Griffin Mine dump in St. Kevin Gulch.

    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). The pH of the stream at the mouth of St. Kevin Gulch is between 3 and 4. At its confluence with Tennessee Creek, the pH during low water is just below 7. The pH rises to above 7 in the combined Tennessee Creek waters. This shows that the acid drainage from St. Kevin does not travel far, unless it goes into the groundwater system as it leaves the Gulch area. Dilution from other ground water in the Park also is possible.

Hyperspectral Imagery. The St. Kevin Gulch and Tennessee Park area were flown with the commercial SpecTIR HST-1 hyperspectral sensor in September of 2003, with a ground resolution of 2.5 m. Figure 13 is a mineral classification image produced from this data set.

    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 2.5 m 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 stream and among the in-place and transported wastes. Subsequent image processing then can be done to show a wider distribution of mixed materials.

The objective of the hyperspectral survey was to be able to coordinate source (e.g., wastes) and output (e.g., ARD and alluvial tailings) so this type of information can be used for future remediation and characterization efforts. In this case, the source was, at minimum, the Griffin Mine dump and Griffin-Wilkes Barre Mill tailings in St. Kevin Gulch.

The Griffin dump contains the same illite as is seen in an outflow pattern onto the Tennessee Park fields. This material is a bright green in the image. This is a hydrothermal illite extracted as ore host from the Griffin veins. It has migrated downstream from the dumps as surface runoff, probably mostly during storms and flash flood events.

The red pixels in the image indicate a hydrothermal dickite that is hypothesized to have been associated with one ore type in at least the Griffin mine. It was discovered as mill wastes/tailings at the south end of the Griffin dump (Fig. 12). It was next observed in the St. Kevin Gulch streambed east of the mill. Here it covers areas that are too small and under too dense vegetation cover or shadow to be detected by the sensor. This material finally was noted as small white and gray patches of very fine-grained material scattered across the Tennessee Park outwash area.

Because the illite and dickite can be directly linked to the mineralization at the Griffin Mine, their appearance downstream reasonably can be attributed to that source. This demonstrates the effectiveness of hyperspectral remote sensing to track the migration of the mine and mill wastes.

Based on our experience with acidic waste materials and extensive experience with clay minerals, the smectite (cyan pixels) is a weathering product of the illite and is fine grained. It most likely was created *in-situ* in the Tennessee Park fields, particularly given that it is not widely identified in the eroding source wastes.

Arkansas River Alluvial Tailings

Tailings deposits from the Leadville mining district have been identified in the banks of the Arkansas River as far south as the north end of Berrian Park (Fig. 9), more than 30 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 of the tailings. Sulfate mineral blooms are sufficiently ephemeral that the ability to track them with the 2.5-m resolution 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.
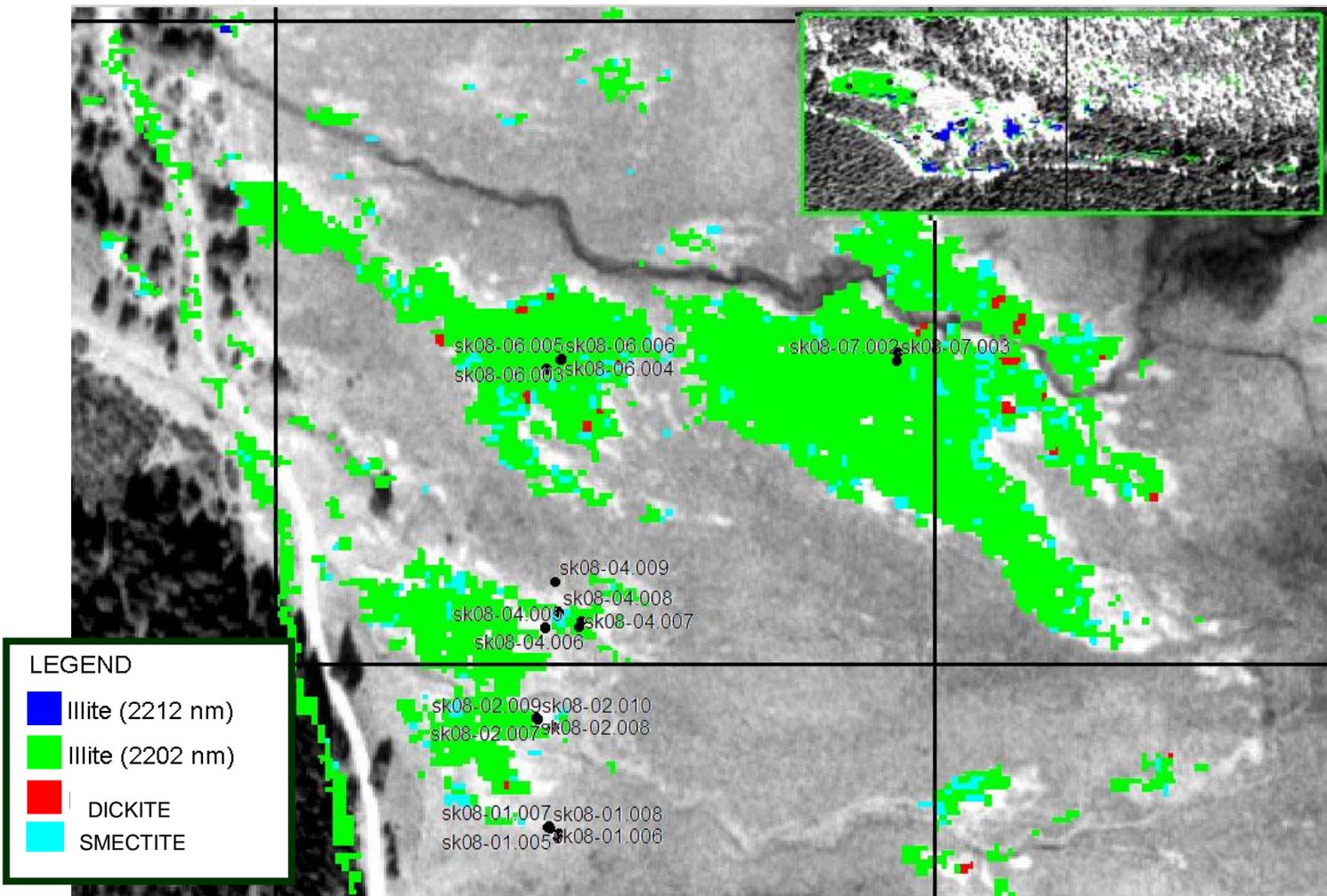
Figure 13. SpecTIR hyperspectral mineral classification image of the Tennessee Park tailings outwash with inset image at top for the Griffin Mine dump Griffin-Wilkes Barre Mill area (sample locations shown as red dots in inset image). The images are slightly out of registration as a function of differential terrain changes within the background orthophotograph image. It is most noticeable along the road on the left side of the image.

Leadville Mining District. Mineral types present in the Leadville mining district ores, and expected to occur in tailings and mine wastes, 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 voluminous waste rock piles and tailings, rich in pyrite, other sulfides, and carbonates, which now cover approximately 30 km^2 east and south of the town of Leadville as well as in alluvial deposits along the Arkansas River.

Given the ore and gangue mineralogy, carbonates and clays will dominate the tailings; the waste rock dumps still will contain sulfides. Gravity and fluvial processes moved some of this material into the drainages and down to the river. As the sulfides weather, acidic ground waters are created. The carbonate minerals can 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 also can 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 anastomosing channels forming the Arkansas River active channels and floodplain. In this area, the river system has deposited tailings in the floodplain over more than 120 years in bars and channels that are within the historical high-water and flood limits and which now frequently can be seen exposed in the river banks and as areas impacted by acidic ground waters (Fig. 14). Eroded and remobilized tailings still are being transported by the river and redeposited in sand bars or along high-water channels. The tailings contain sufficient sulfides (pyrite contents up to 2% have been observed) to actively create zones of acidic surface and ground water drainage, evidenced by SO_4^{-2} blooms (Fig. 14A) and ephemeral high-Fe puddles that have been observed during field work.

The tailings are concentrated and exposed at the surface in the smaller seasonal channels that anastomose with the river (Fig. 14A). 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 tailings mixed on the sides of the streambed. In this area, the secondary minerals copiapite, jarosite, and schwertmannite are forming (identified with a portable spectrometer), indicating pH values in the range of 2 to 4. On the low banks and into the vegetation zone, there is an Al 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 precipitating anew as the weather and water flow fluctuates. Normal tailings 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 SO_4^{-2} levels in the river

and groundwater. The source of the SO_4^{-2} is most logically from weathering of sulfide minerals from the Leadville District's wastes.

Figure 14. (A) One of the small seasonal channels that contain tailings. Note the dark material concentrated in the center of the bed. This is a manganese-coated hardpan where more acidic minerals form as water wicks upward through the soils. The white material is an Al sulfate mineral called aluminite. (B) Arkansas River main channel showing tailings in the bank (arrow).

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 (Fig. 14B). 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 2.5-m 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, and water) on the Earth's surface. Figure 15 is a mineral classification image from that survey, which also shows the sample locations for the ground truth survey.

Table 3 summarizes the mineralogy for the ground truth sample sites. The acid-generating minerals have been grouped together as $FeSO_4$ for simplicity and include copiapite, jarosite, and schwertmannite. The $AlSO_4$ group includes aluminite and amorphous Al sulfate compounds. The "classification" column in Table 3 refers to the classification colors in Fig. 15, where the image shows tailings in blue, Fe compounds associated with tailings in red, and indigenous river clays (non-tailings sediments) in green.
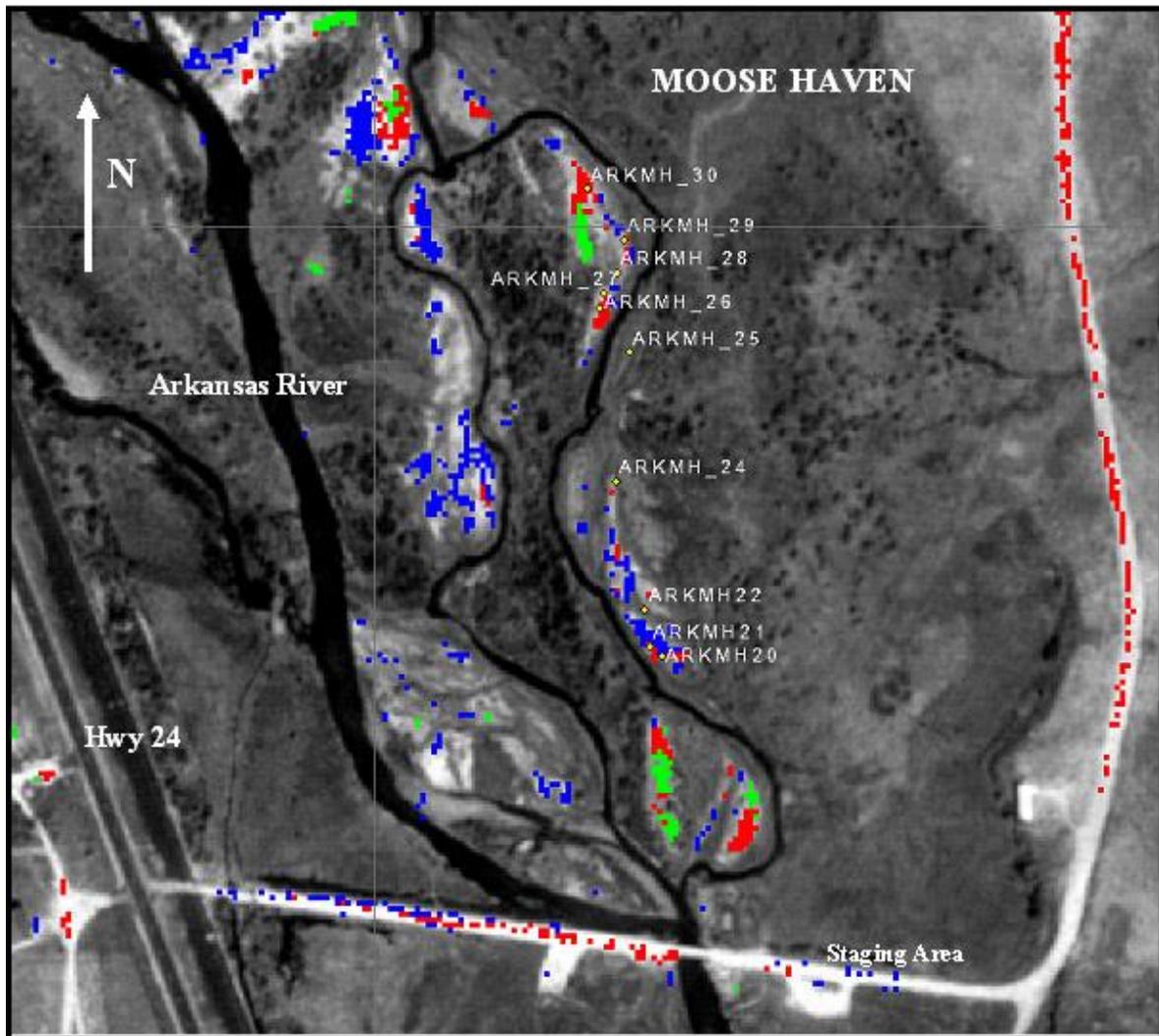
Figure 15. SpecTIR hyperspectral mineral classification image of the Moose Haven area on the upper Arkansas River. Pixel classifications: red = Fe minerals and tailings; blue = tailings; green = river clays. This area is located approximately 15 km downstream (south) from Leadville. Sample sites lie on the east side of the river to ease access for the field spectrometer.

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 (Fig. 16). It is usually, but not always, near sites of Fe sulfate- or oxide-coated pebbles. Aluminite is very diagnostic of the presence of tailings and tailings-impacted sediments in the Arkansas River floodplain. It is also ephemeral and tied to wet and dry cycles. Image processing for this mineral 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.

Table 3. 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 mineral abbreviations are Kao = kaolinite, Smc = smectite, ill = illite, FeSO$_4$ = Iron sulfates, CO$_3$ = carbonates, AlSO$_4$ = aluminum sulfates, goe = goethite, and Gyp = gypsum.

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)

In general, the tailings contain all or selected mixtures of Fe sulfates (such as copiapite, schwertmannite, and jarosite), Fe oxides, illite, plus or minus kaolinite, plus or minus aluminite, and 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 an 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 background river clays. It is also present within degraded illites (i.e., illites that have started converting to smectite) and has been included with such illites in Table 3.

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 Fig. 15 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 and mineralogical changes with wet and dry weather. However, there are sufficient low-vegetation and bare-ground exposures to produce a viable image of the distribution of the tailings along the river system.

Figure 16. The mineral aluminite is shown here as sulfate "blooms" (white arrows) associated with Fe-stained gravel and cobbles within the seasonal riverbed. This is a diagnostic indicator of the presence of sulfate-enriched ground waters. The SO_4^{-2} originates from acidic ground water created by sulfide decomposition and permeates the tailings-impacted portion of the river floodplain.

Discussion

The contrast between the ARD-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 Al minerals in high abundance. In the Lake Creek watershed, sulfur is present, but appears to be associated with the Fe precipitates. The main Al precipitate is an amorphous Al(OH) compound. In the Arkansas River floodplain, south of Leadville, two different conditions exist: 1) there is more buffering from the carbonate mineralization host and gangue minerals such as illite and ore carbonates, and 2) there is more sulfur available in the ground water. This leads to an Al sulfate mineral, aluminite, precipitating along the banks and in and around tailings-impacted seasonal channels and sand and gravel bars.

However, there are still sufficient concentrations of sulfides within the alluvial tailings to actively produce Fe 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 many major sources of acidity and metals in the Leadville district have been remediated, and ARD flow to the river is much more restricted, the remote sensing

data for the upper Arkansas River show a much more benign landscape with more restricted, localized acidic zones.

Conclusions

High spatial resolution (1-4 m) hyperspectral remote sensing can be used to characterize natural and mining-induced acid rock drainage (ARD) environments. This technology 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 Fe sulfate, Fe hydroxide, Fe oxide, and $Al(OH)_3$ mineral species, present as precipitates on streambed alluvium, and relating them to each mineral's pH stability range. Hyperspectral remote sensing also was used successfully to map tailings deposits in the Arkansas River seasonal floodplain more than 15 km downstream of the Leadville mining district, the source of the tailings. Because fine spectral and spatial details are needed to correctly identify indicator precipitates and minerals, multispectral sensors and satellite sensors (whether hyperspectral or multispectral) with inadequate spatial resolutions are not generally useful for water and waste characterization.

The usefulness of the technology for remedial investigations of active and abandoned mine sites and mining districts 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 and true extent of these 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 changes in water quality such as the effectiveness of cleanup efforts on stream water quality in and downstream of natural and mining sources of ARD. However, use of hyperspectral data requires more rigorous image processing techniques and understanding of spectra of materials, as well as computers capable of handling the very large data sets involved. Ground truthing is necessary to both understand the materials present in a study area and to verify and refine the spectral classifications produced by image processing. Once a basic spectral database of study materials is compiled, ground truthing can be reduced, compared to this study's sample collection, to spot checking and investigation of anomalies.

For water quality identification and monitoring, the Lake Creek test case shows that pH and Fe and Al precipitates can be identified, and changes in the streams can be tracked over time (at least seasonally). For routine applications, such as State or Federal monitoring of water quality, once an impacted stream is identified and a baseline characterization performed, it can be seen that hyperspectral remote sensing can provide an understanding of key quality indicators (e.g., precipitates) for repeated remote measurements and prioritization of streams or reaches for more detailed field investigation and/or monitoring.

For tailings identification, the hyperspectral technology has demonstrated the capability to both identify deposits and their mineralogy as an aid to mapping the true extent of deposits along a river and impacted tributaries. The source of tailings also can be identified through mineralogy where the source remains unreclaimed. Investigation of tailings using hyperspectral remote sensing would not be a repeated, routine operation unless large volumes were being remobilized

by a river and tracking of new deposits was an important point for a state or federal agency or where reclamation and remediation activities are in progress and an agency wishes to track progress and short- or long-term success of these efforts.

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