

Iron Oxyhydroxide Minerals as pH Indicators in the Exploration for Precious Metals.

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The main focus of this project is the evaluation of water quality in watersheds that are impacted by acid drainage, when that condition is a function of mining activity or natural, unexploited, mineralized systems.

PRINCIPAL INVESTIGATORS BAA

Colorado Geological Survey, Denver, CO
Spectral International , Arvada, CO
Peters Geosciences, Golden, CO
HENDCO Services, Nathrop, CO

PARTICIPANTS

Colorado Mountain College
State Engineers Office, Colorado Division of Water Resources

U.S. Forest Service US Geological Survey
Lake County Conservation District
Upper Arkansas Water Conservancy District
Arkansas Valley Natural Damage Assessment Impact Response Team
Board of Chaffee County Commissioners



Western Governors Association

The principal investigator is the Geological Survey of the State of Colorado.

Spectral International and Peters Geosciences are providing the technology transfer expertise for spectroscopy and remote sensing, assisted by Overhill Imaging and Cartography, who are doing the actual processing. Hendo Services is providing outreach expertise.

Other listed participants provide different levels of support form sample collection, analyses and outreach.

BACKGROUND
OBJECTIVE
APPROACH
LOCATION
MINERALOGY
ASTER
pH CHEMISTRY Fe MINERALOGY
HYPERSPECTRAL
DECISION

TAKE NOTES!

East Red Mountain, Chaffee Co.

- The talk today will follow the outline shown in this slide. .



LIVING CHEMISTRY

**HOW CAN WE USE
IRON MINERALS TO
DEFINE pH ZONING**

**VECTOR
MINERALIZATION**

**REFLECTANCE
SPECTROSCOPY**

AND

REMOTE SENSING???

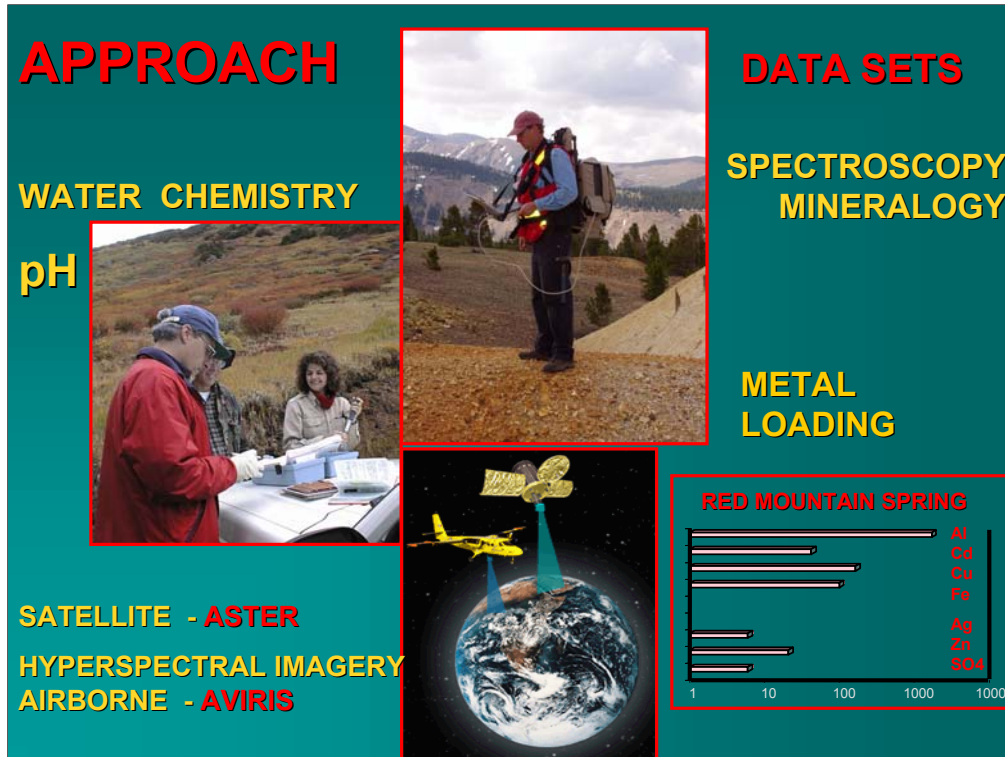
This is a spectacular mixing zone at the confluence of the SBS (Sayers Bowl Stream) and South Fork.

The orange-gold-brown is pH 3 and drains from the East Red Mtn

The white is pH of about 5 and comes from suspended aluminum materials.

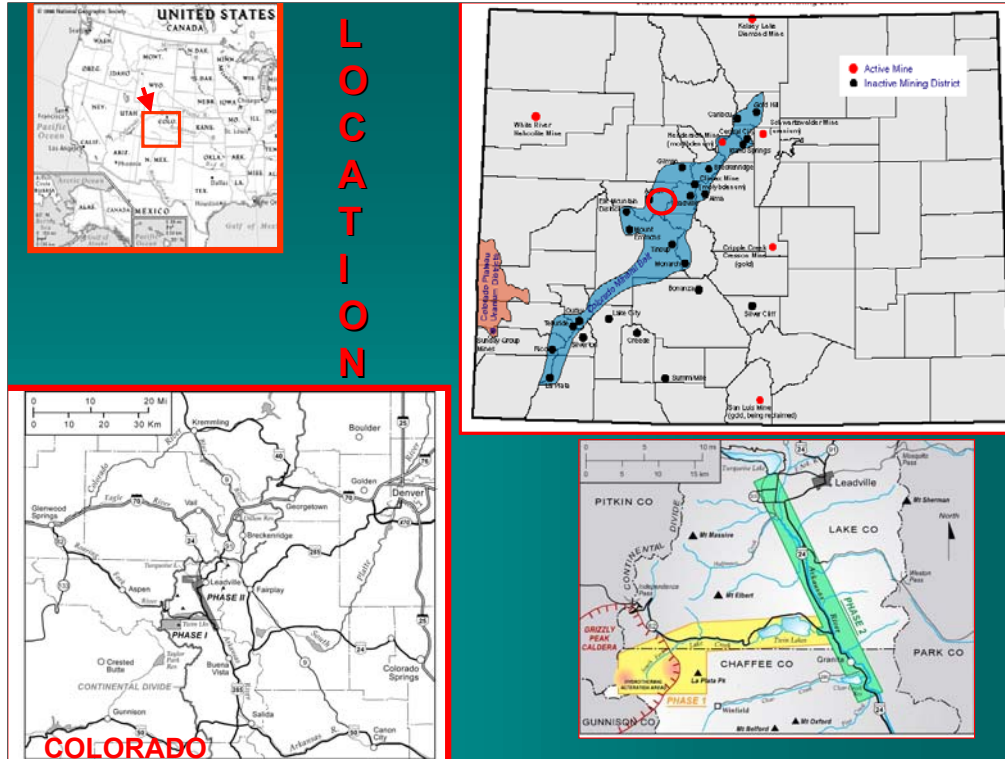
At this point, we need to address one of the objectives of this study, which is HOW CAN WE USE REMOTE SENSING TO CHARACTERIZE AND MAP IRON MINERALS THAT DEFINE pH ZONING ASSOCIATED WITH ACID DRAINAGE.

This translates to the main objective of mapping acid drainage systems and sources using remote sensing - what are the best approaches; what are the best sensors.



APPROACH

The main data sets collected for this study include water chemistry with pH and metal contents; Mineral ground spectroscopy from over 50 sites; XRF of the mineral precipitates; and remote sensing imagery from satellite and airborne platforms.

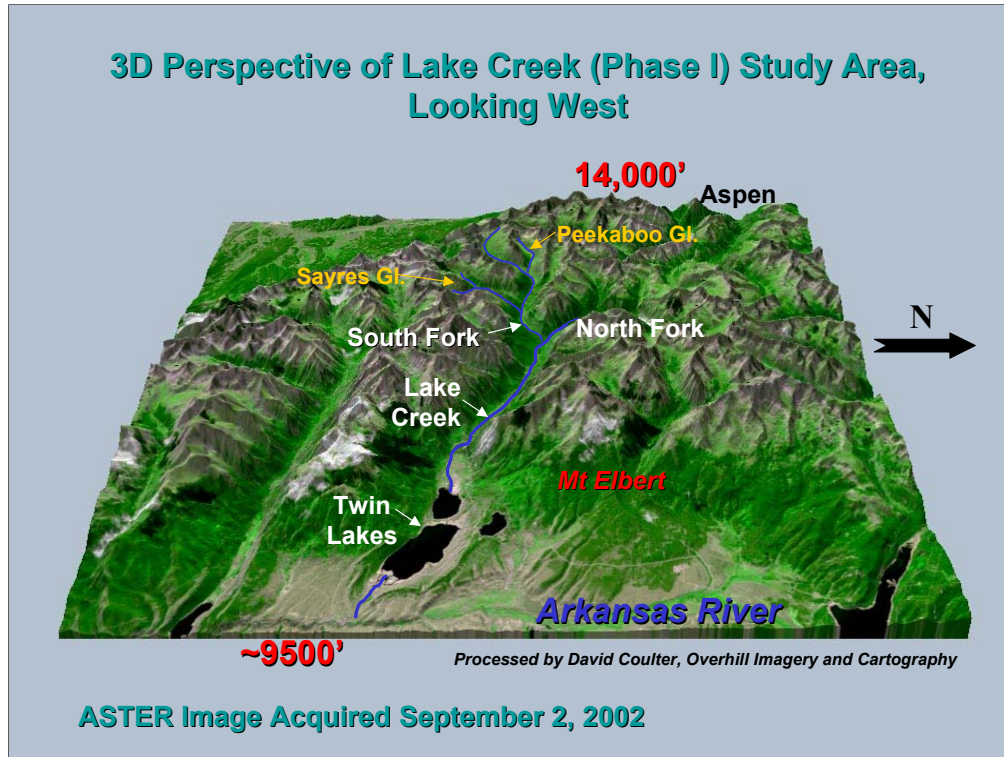


Maps showing location of the project areas relative to the Western United States and Colorado.

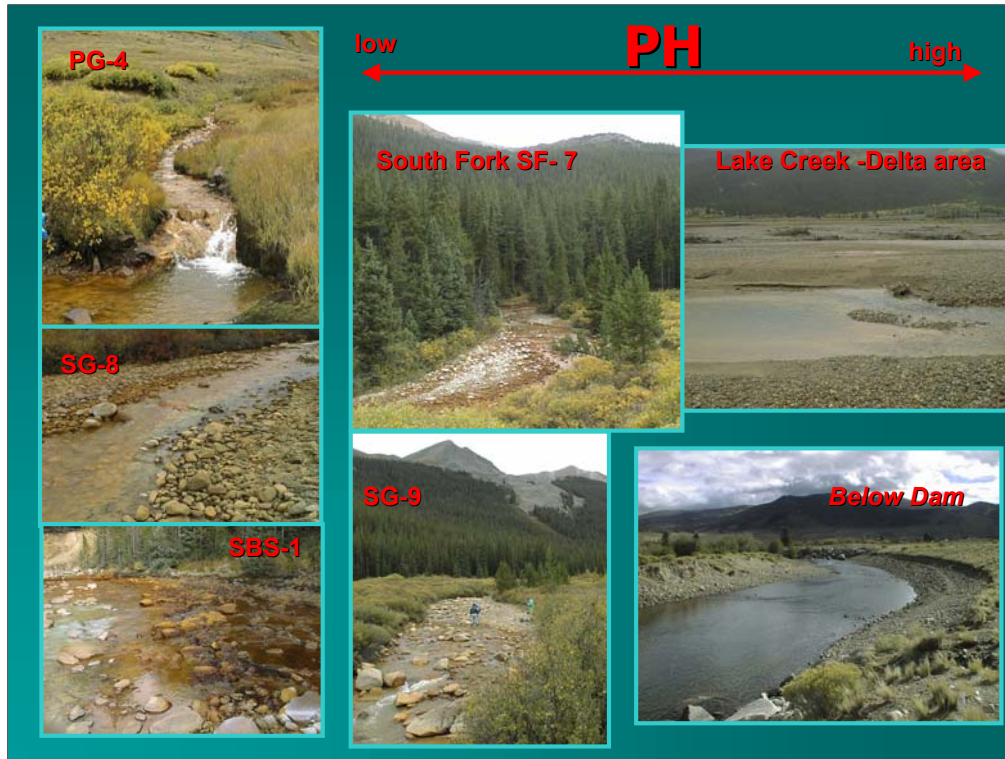
The project area is located in the center of the mineralized belt that runs through the Rocky Mountains in Colorado.

The two phases are shown in yellow and green,

note that there are two source areas for Phase I (yellow area) and that one is located within the Grizzly Caldera and the other is on the edge of the caldera.



- Phase 1 study area is the **Lake Creek watershed**
- This ASTER 3-D perspective illustrates the **topographic relief in the study area**. Continental Divide is on the west.
- Peekaboo Gulch** and **Sayres Gulch** are affected by the **hydrothermally altered areas** in the Grizzly Peak caldera.
- ASTER** is a 14 band **satellite sensor** that collects data in the visible, near infrared and short wave infrared regions of the EMS. It is superior to Landsat in that it allows discrimination of selected mineral species. Its disadvantage for small stream drainages is the 30 meter spatial resolution in the SWIR region. It does have 15m Visible region resolution and may **provide some information on the distribution of iron precipitates**. It was used in this study to identify potential acid generating sources.



- This slide shows a cross section of sample sites. It reflects the changes in the environment as a function of changes in pH, chemistry and mineralogy.
- The high acid, low pH environments are colored oranges, golds and reds; PG-4 = 3.3 SG-8 = 4.16 SBS-1 = 3 SF-7 = 4.07 SG-9 = 4
- LC-9 = 7.75 LC 11 = 7.01 below dam
- the colors reflect progression from the sources - near the sources the colors are intense and coatings are thick as we travel downstream, less is precipitated and the colors become paler.



These are the two source areas for the acid drainage. Although they both have generally the same types of alteration, they are in different host rocks and have been eroded differently and therefore show different parts of alteration systems exposed. They also are contributing in different ways to the drainages. The water sources for RMW are more confined to springs feeding into small drainages. RME, however, also appears to have a major ground water component that puts more metals and acid waters into the water system. It contributes through two streams, what we are calling ESG (East Sayers Gulch) and SBS (Sayers Bowl Stream) as opposed to just the Peek A Boo Gulch drainage off RMW.

The colors reflect the differences in mineralogy. Red Mtn West is dominated by hematite. It appears to be more of a lithocap. It contains a definite advanced argillic component with pyrophyllite and dickite exposed in the upper slopes. It shows distinct zoning of illites and kaolinites.

RME shows more of a phyllic alteration pattern. It can be hypothesized that the advanced argillic component for this source has been eroded away or is an outlier. Advanced argillic mineral have been mapped in the area but not enough locations have been found yet to determine the specific geographical association with the RME source.

SOURCE AREA ROCK TYPES

RED MTN WEST -

INSIDE THE CALDERA

Rhyolitic Grizzly Peak Tuff

Granodiorite Laccolith

Intermediate to Felsic Composition Dikes and Plutons

RED MTN EAST

CALDERA RIM

Precambrian, Banded Quartz-biotite Gneiss Bedrock

Tertiary Volcanic Megabreccia

ALTERATION

Both have advanced argillic and phyllic quartz, sericitic, muscovite, illite, pyrophyllite, dickite, kaolinite, jarosite, hematite, goethite

This slide is fairly explanatory. What makes this area of the Grizzly caldera so interesting is the fact that the two major alteration areas are in different parts of the caldera and in different host rocks

This appears to have had a major effect on how much metal and acid ground water are contributed from each source area.

For instance when the tributary that drains RMW reaches the South Fork of Lake Creek, the Al content, as one example, has gone from 284,000 ug/l to 7500 ug/l and iron has gone from 486,000 ug/l to 2000 ug/l.

The metals, therefore stay in the drainages and do not migrate very far.

**Sediment / Coatings
Sample Collection
and
Mineralogical Analysis
by Spectrometer**



- This slide shows in field sampling and analysis for streambed sediment coatings.
- GPS locations are taken along stream traverses. Sampling is done on traverses because of different chemistry/coatings and different flow regimes--fragile coatings remain in low-flow areas of stream.
- In-field acquisition of spectral signatures for stream coatings is done with the
- Portable spectrometer, which is an ASD Field Spec Pro- Full Range (350-2500 nm)

DOMINATE MINERAL SPECIES

| Mineral | pH | Formulae |
|-----------------------|---------|--|
| Copiapite | 2 - 3 | $(\text{Fe}^{2+}\text{Fe}_3^{+4}(\text{SO}_4)_6(\text{OH})_2 \cdot 20(\text{H}_2\text{O}))$ |
| Jarosite | 2.3-2.8 | $[\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6]$ |
| Melanterite | 3 | $(\text{Fe}^{2+}(\text{SO}_4) \cdot 7(\text{H}_2\text{O}))$ |
| Schwertmannite | 2 - 3 | $\text{Fe}^{3+}16\text{O}16(\text{OH})12(\text{SO}_4)_2$ |
| Ferrihydrite | 4 | $\text{Fe}^{3+}2\text{O}_3 \cdot 0.5(\text{H}_2\text{O})$ |
| Maghemite | 6-7 | $(\text{g-Fe}_2\text{O}_3)$ |
| Goethite | | $\text{Fe}^{3+}\text{O}(\text{OH})$ |
| Lepidocrocite | 6-7 | (g-FeOOH) |
| Green Rust | | $[\text{Fe(II)}_{1-x}\text{Fe(III)}_x(\text{OH})_2]_x[\text{xOH}^-]$ |
| Green Rust | | $(\text{Fe}_4(\text{II})\text{Fe}_2(\text{III})(\text{OH})1\text{SO}_4 \cdot 3\text{H}_2\text{O})$ |

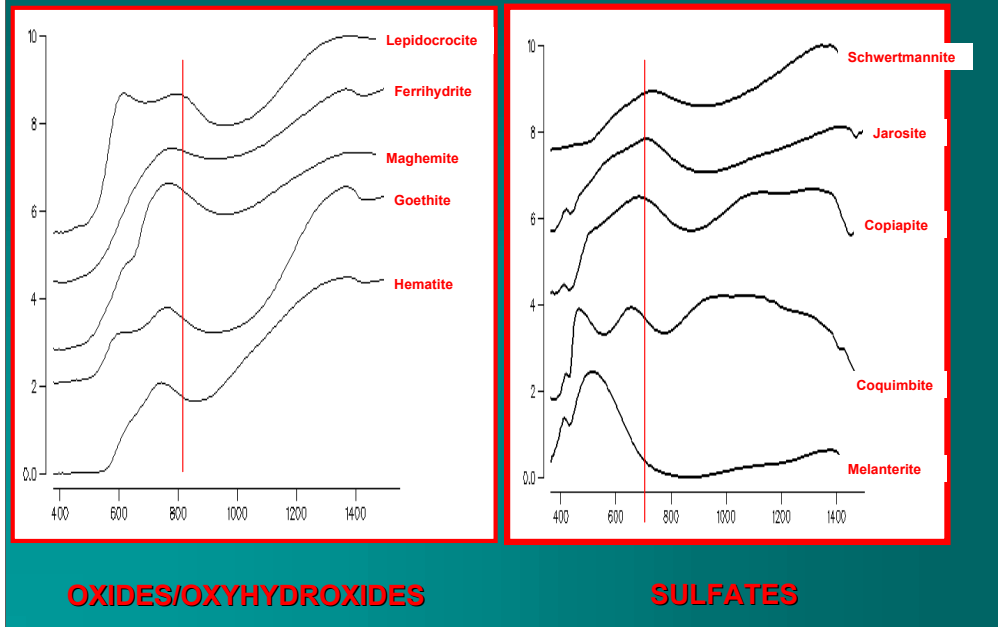
These are the main minerals in the Lake Creek watershed that can be detected with the reflectance spectroscopy method.

The sulfates are found in acid conditions. Species such as copiapite and melanterite are very restricted to the source areas. They are also not stable. Jarosite is more stable and, although also restricted to a small pH range, it is found in more of the confluence areas as an end sulfate product. Schwertmannite appears to be more common than originally thought in the literature. It seems to be a transition phase between jarosite and ferrihydrite. Its spectral signature and structure is similar to jarosite. It appears to be mixed with ferrihydrite along South Fork. Since the pH conditions are constantly changing along the streams as the water flow changes, this is not surprising.

The oxides and oxyhydroxides favor less acid, more neutral conditions. They are mostly found in Lake Creek itself. Goethite, however, can be found through most of the drainages. It can potentially be used to trace flow patterns of the streams as where it exists, oxidizing conditions also exist and it will be found out of the acid waters. Although the stream may initially deposit an acid mineral such as jarosite, schwertmannite or ferrihydrite, these species will oxidize further to goethite with time and stream dilution factors.

An amorphous compound has also been documented from this watershed. It is called "Green Rust". It is created by bacteria and apparently has four possible chemical configurations. We hypothesize that two of them, a sulfate and an oxide, exist in the Lake Creek watershed.

IRON MINERALOGY



These are spectra for the main iron minerals in the study. They are divided into sulfates and oxide/oxyhydroxides. These come from a large iron mineral reference data base that is being constructed for this project. Nothing like this has previously existed. This is an attempt to create definitive, well characterized references that can be used with confidence by future researchers.

It can be observed that the defining features for these minerals are mostly found in the visible region of the EMS. Most have water features and some of those have diagnostic characteristics.

The data base is a dynamic construct and will be constantly upgraded through the project life.




GREEN RUST

$[\text{Fe(II)}_{1-x} \text{Fe(III)}_x (\text{OH})_2]^{+x} [x\text{OH}^-]$

“Fougerite” ----> lepidocrocite, goethite, akaganeite
OR
----> magnetite, maghemite

$(\text{Fe}_x(\text{II})\text{Fe}_2(\text{III})(\text{OH})1\text{SO}_4 \cdot 3\text{H}_2\text{O}$

No Carbonate or Chloride varieties

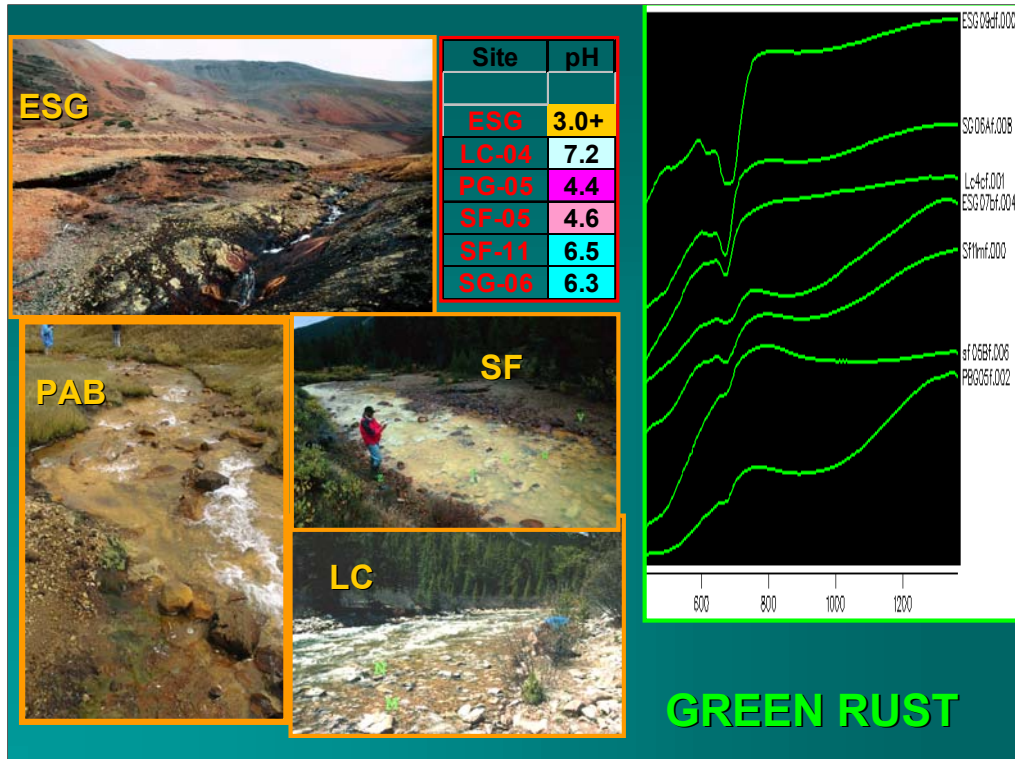
Green Rust has been found throughout the study area under different pH conditions. It is amorphous and occurs in different stoichiometries. It is hypothesized that the oxide and sulfate “species” exist in the Lake Creek watershed. It is bacteria generated.

Analytical work has been done on this compound for us by the Geological Survey of Canada, Jeanne Percival and initial results are included in this document.

“The pH is not as important as the microbial population to reduce the iron or at least keep a mixture of both ferrous and ferric iron around, as we now understand it. If the pH is not sufficiently acidic to affect the microbial population then *the mineral* can easily and readily form as a precursor to other iron minerals. Sulfate is probable because it forms stronger adsorption than hydroxide at pH values below neutral. Chloride is not sufficiently high and carbonate is the weakest adsorber of these species, rare to nonexistent.”

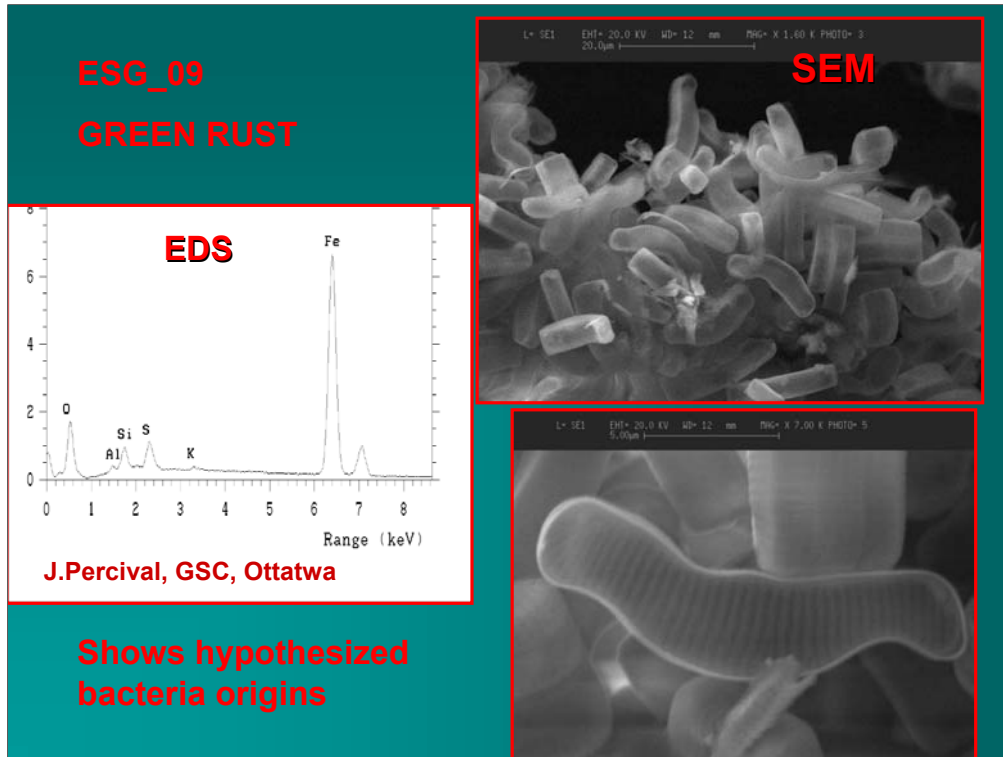
Personal communication - Richard Glanzman

Schwertmann, U. and Fechter, H., 1994, The formation of green rust and its transformation to lepidocrocite: Clay Minerals, Vol. 29, pp. 87-92.



This shows that the green rust is found in all the drainages and under different pH values.

It also compiles representative spectra for this amorphous material. The spectral signature appears to be quite unique in the visible region. This is a little unusual because this material is amorphous.

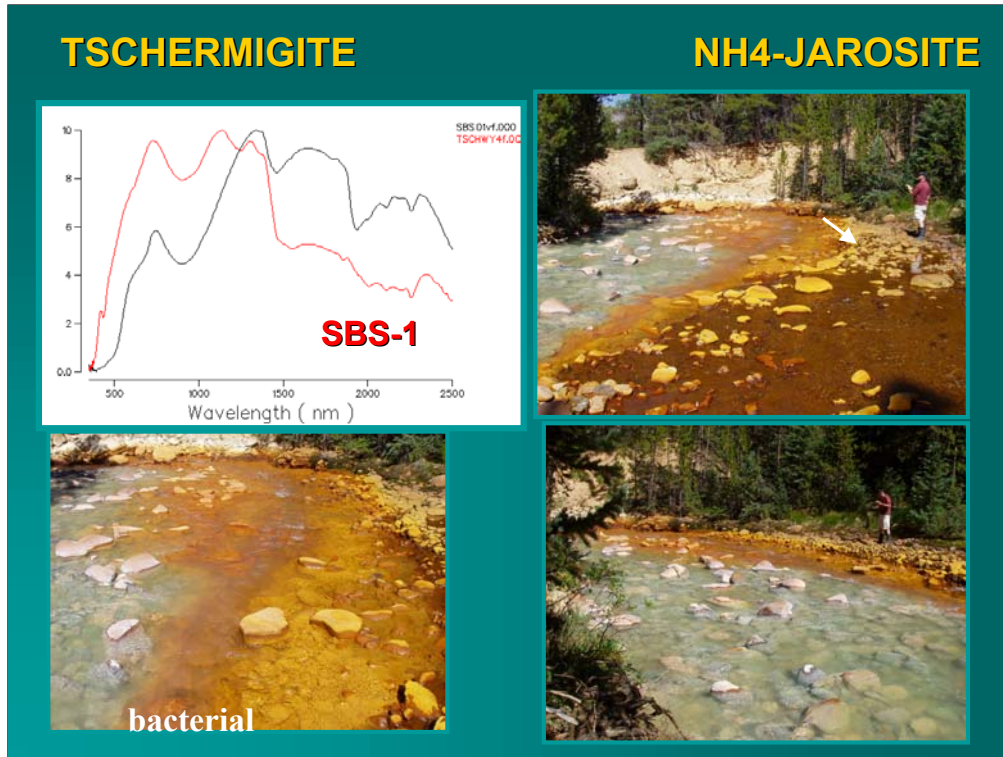


This is a scanning electron micrograph (SEM) collected at the Geological Survey of Canada and shows diatoms (silica) associated with the green rust (Fe and S)

The hypothesized origin is bacterial.

The Energy Dispersive spectrum (EDS) shows the presence of iron, sulfur, silica, oxygen and minor aluminum and potassium.

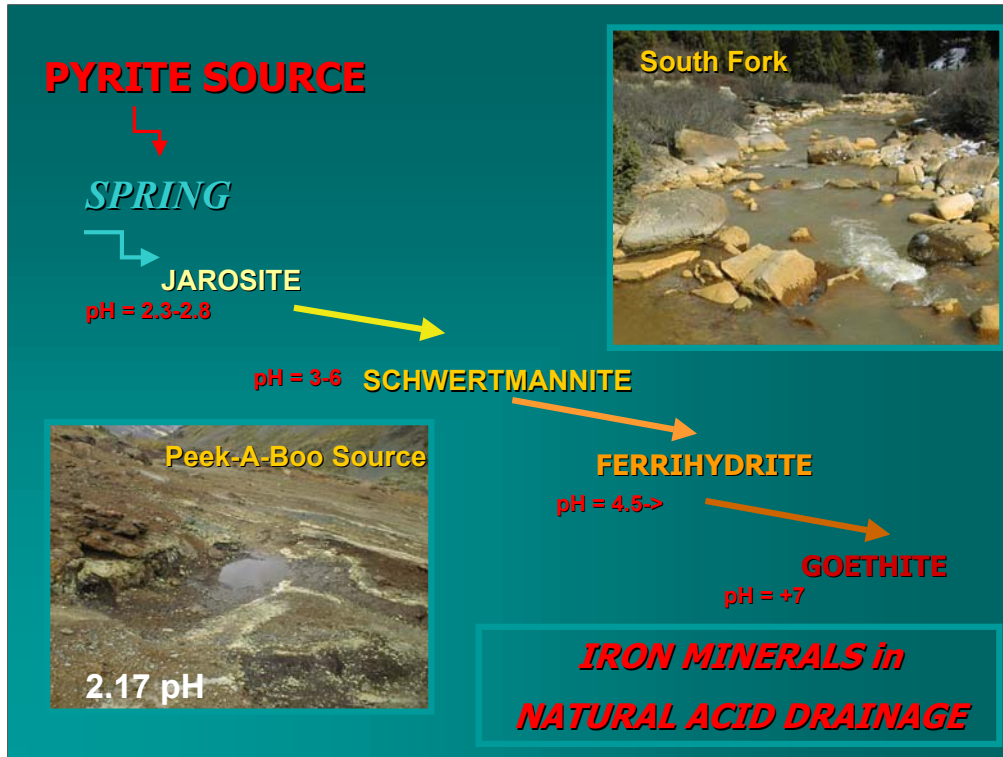
This sample comes from an acid environment. It is most likely the sulfate variety.



Tschermigite is an ammonia bearing jarosite found at the SBS South Fork confluence.

The pH here is 3, where the sample was collected. The white arrow shows where the sample was found.

This is a mixing zone with high bacterial contents. The SBS stream has a pH of 3 while the pH of South Fork with the white ppt has a pH of just under 5



- Precipitate coatings on rocks exhibit a **sequential zonation of iron minerals** (sulfates and oxy-hydroxides), from springs in the hydrothermal alteration areas and downstream in the Lake Ck watershed.
- These minerals have a **specific pH range of stability** and are found in natural ARD systems.
- Jarosite** is one of the **most common acid-generating oxidation products of pyrite** and more stable sulfate phases. (Although there are multiple pathways for the breakdown of pyrite and ultimate oxidation to goethite and hematite)
- Therefore, jarosite is the **most likely intermediate sulfate that is detectable through remote sensing**. methods.
- It is important for **exploration or environmental purposes**, because it is a **pathfinder mineral indicating the presence of sulfides**.
- For acid rock drainage and mine waste applications, it is an **indicator of potential or actual acid generation**.

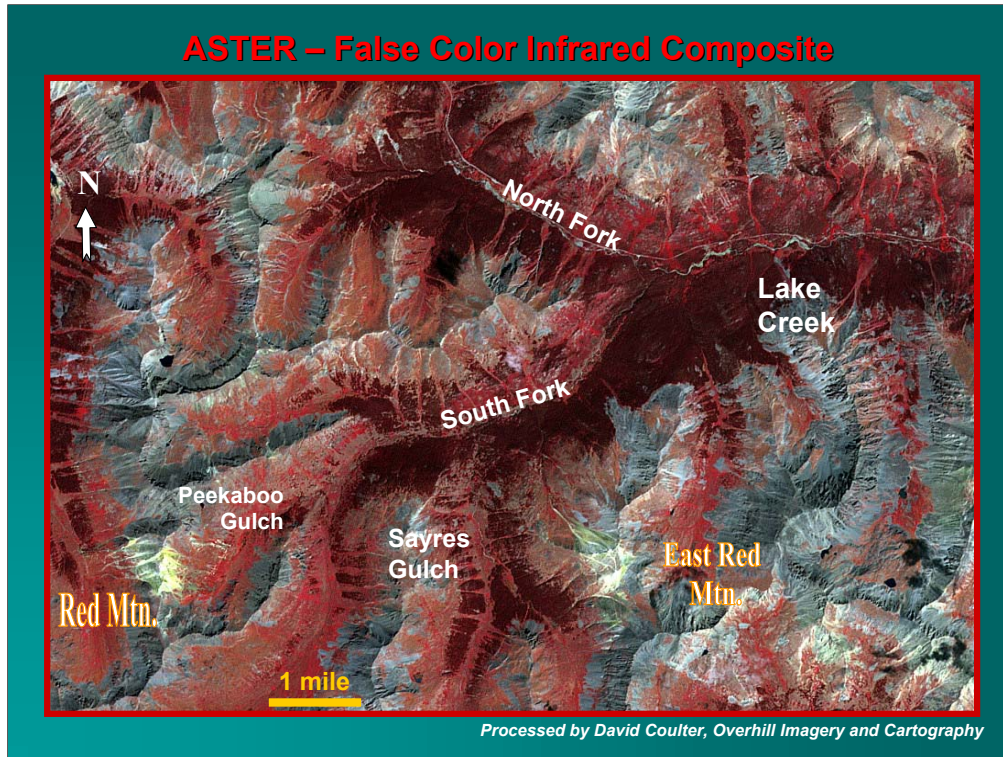
ASTER SATELLITE IMAGERY Reconnaissance

| <i>Resolution</i> | <i>Detector</i> | <i>Mineral Groups</i> |
|-------------------|-----------------|--|
| 15 M | VIS | Iron Oxides, Hydroxides, Sulfates |
| 30 M | SWIR | Illite/Muscovite, Mafics, Kaolinite/Dickite, Alunite/Pyrophyllite |
| 90 M | THERMAL | Silica |

This chart shows the configurations for the ASTER satellite for the different detectors.

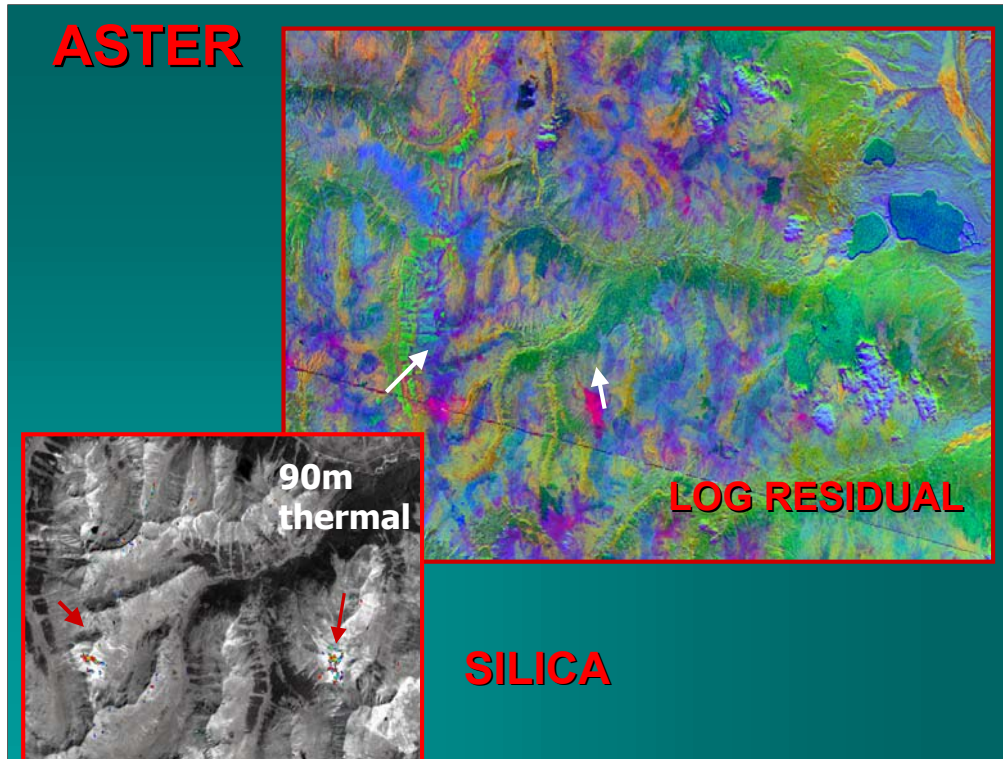
It also details what minerals can be detected by the different detectors.

Because of the spatial resolution, ASTER is best for reconnaissance. It would be almost ideal if the pixel size was smaller.



- This is a false color visible range ASTER image. It shows the drainages in the Lake Creek watershed.
- Red is vegetation. **Hydrothermally altered areas** appear **yellow** in the false-color infrared composite.
- Source (mineralized) areas for natural acid rock drainage: **Red Mtn and East Red Mtn.**

- Natural acid rock drainage severely **affects Peekaboo and Sayres Gulches**. **Affects water quality far downstream** into South Fork and Lake Creek



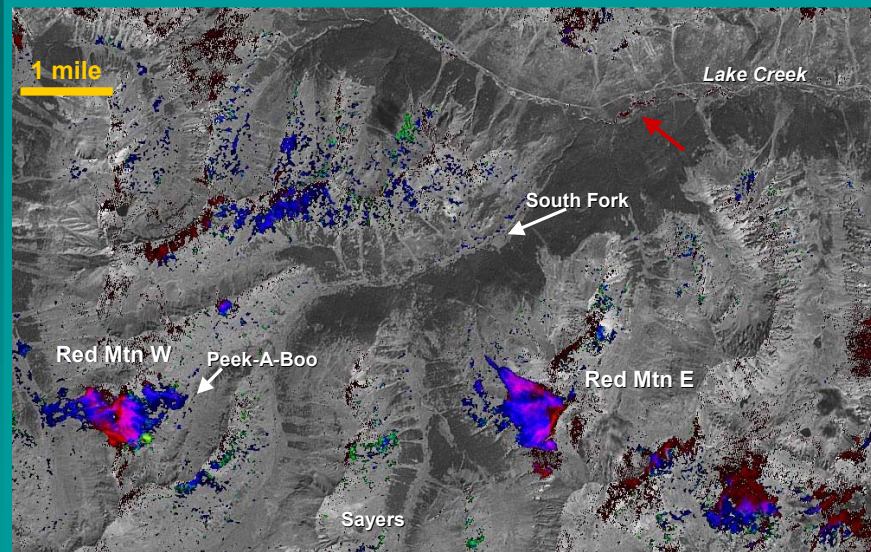
These are 2 other types of ASTER images

The Log Residual is used to very generally map alteration (pinks) and vegetation (green and yellow). It uses SWIR 30m data and can very generally be equated to Landsat

The other image shows where silica is present in the two source areas. This has been tightly processed. The 90m spatial resolution will show large broad distributions.

ASTER - Preliminary Mineral Classifications

Reds = iron oxides; Blue = Illite; Green = Jarosite



Processed by David Coulter, Overhill Imagery and Cartography

This slide is a preliminary ASTER image of the hydrothermal alteration present in the study area.

Reds = iron oxides; Blue = Illite; Green = Jarosite

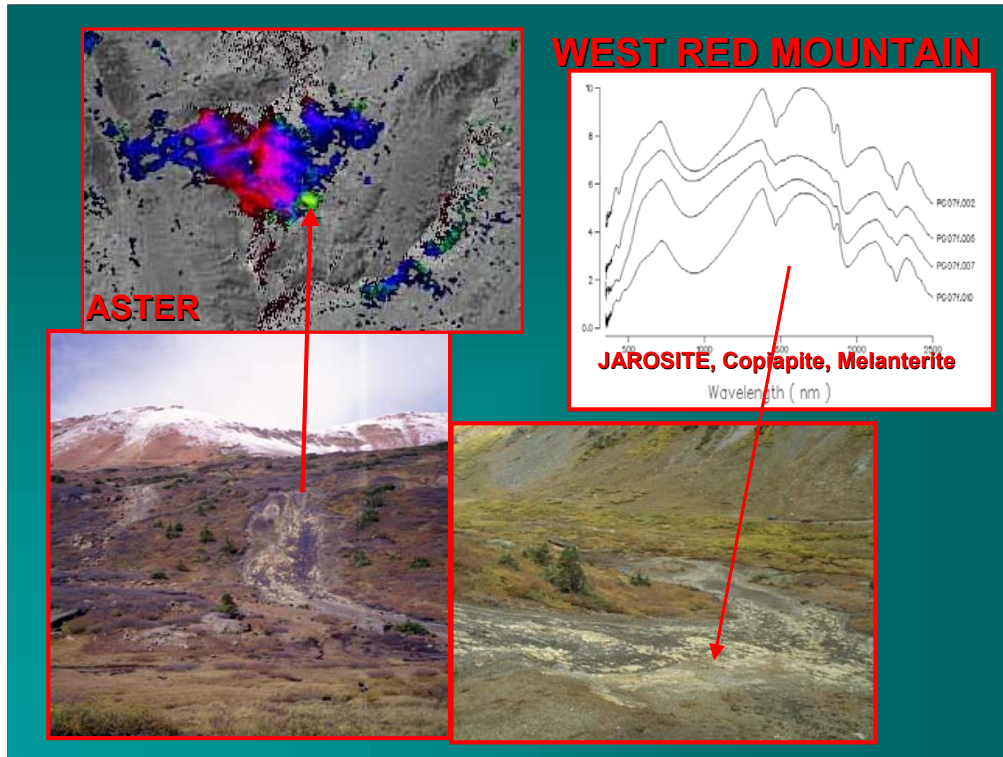
It very clearly shows the sources of the natural acid drainage in blues, reds and pinks at Red Mtn west, which drains into Peek-a-Boo into South Fork and Red Mtn East which drains into Sayers into South Fork into Lake Creek

these are large porphyry systems with high volumes of sulfides; the main alteration clay mineral is illite/muscovite. The reds and pinks vector to the altering sulfides, which are actively creating the natural acid drainage.

the green jarosite area lies immediately to the east of the white aluminum bearing stream and has been field verified to contain jarosite and schertmannite

note the linear relationship between the two major alteration areas with smaller areas exposed between them. This pattern is repeated elsewhere on the image

there are numerous areas of dark red denoting additional iron oxides in lower concentrations than the major altered areas.



This shows an expanded view of the ASTER alteration image of the area on Red Mtn where the sulfate mineral jarosite (green on the image) occurs.

This is a source for acid waters. It is actually a spring and has a pH of 2.17 at low flow. The sulfate minerals (jarosite, copiapite and melanterite) form as the acid water flows downstream and the sulfides oxidize.

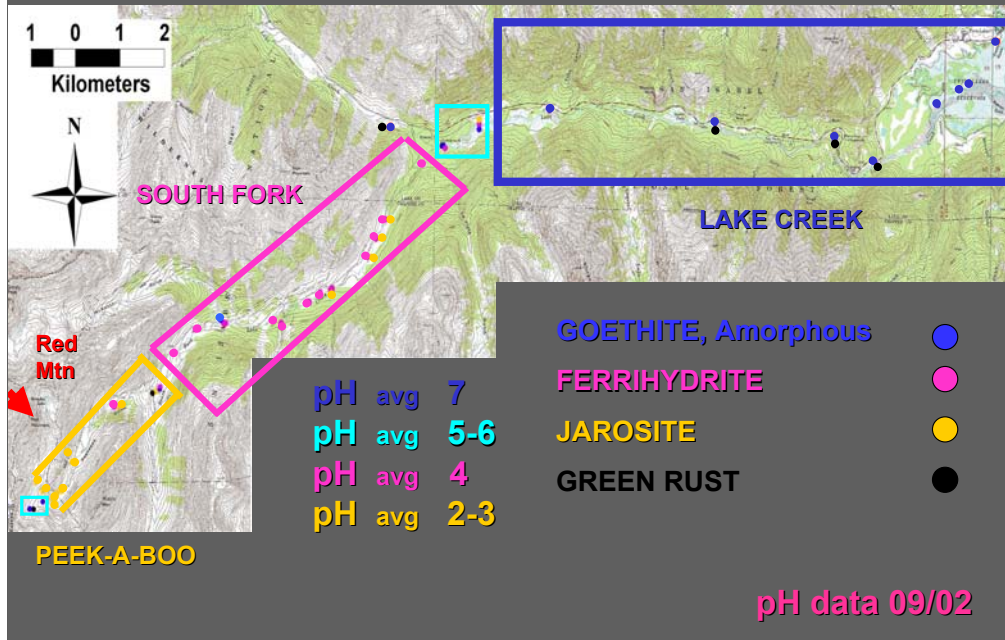
Spectra shown were collected from the yellow crusts shown in the ground pictures.

- **pH DISTRIBUTION IN STREAMS**
- **VS MINERALOGY**
- **INTEGRATE WITH IMAGERY**

This section will look at the distribution of the pH values throughout the watershed and how they correlate with the mineralogy

the next section will integrate this ground information with the imagery

pH vs IRON MINERAL SPECIES



An original hypothesis for this project is that there would be definite pH zones down the drainages from the source sulfide bodies and that these zones would have specific minerals associated with each, as a function of the pH. This slide demonstrates the validity of the hypothesis.

Colored dots are sample locations

Color is a function of minerals found at each site correlated with mineralogy

This is **HIGHLY** generalized as there are other minerals present. The minerals chosen have the best chance at being identified from the air. The iron minerals have been chosen for this example.

In the jarosite zone, other low pH sulfates such as melanterite and copiapite have been tentatively identified, with schwertmannite hypothesized. The other issue is what can be identified from the air.

The undetermined mineral is an iron mineral that we hypothesize is green rust, but we do not have verification of this as we do not yet have a reliable reference for this mineral. It has a very diagnostic feature in the visible that should be identifiable with AVIRIS and SPECTIR data.

The **colored boxes** outline zones along the three drainages in which the average pH is as designated. The colored dots show there is only selected variation from this. The source of the oxidizing sulfides is Red Mountain.

Of interest is that the 3 different drainages have nearly consistent pH values throughout the drainage.

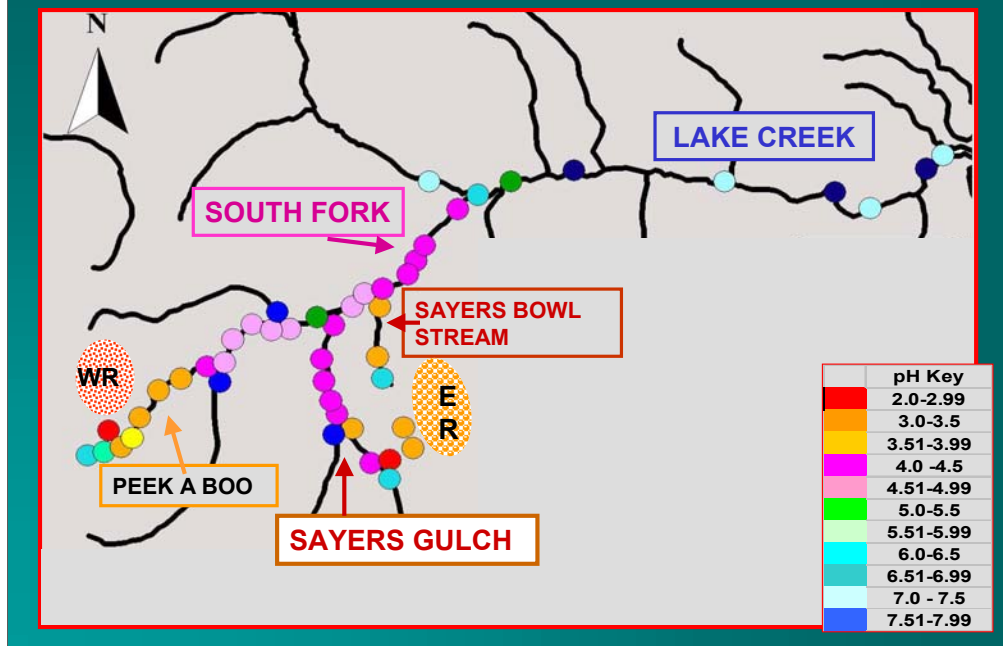
This implies that a fairly significant volume of water is required to provide the dilution required to modify the pH.

Exceptions, which are not shown in detail in this slide, occur when tributary drainages enter the main stream. This happens where South Fork enters Lake Creek and where La Plata Creek enters Lake Creek (Cyan Box). When the pH goes from the background average of ~7 to a 5, it indicates acid waters are entering the main stream. The presence of ferrihydrite and/or jarosite at these locations indicate that the tributary is probably draining from or through a sulfide source. In the ASTER alteration image of the area, there are indications of jarosite up the La Plata Creek tributary, which substantiates this. South Fork has an average pH through 4, so where it enters a stream with a neutral pH, there will be dilution effects and this is seen at LC-10.

This also occurs where the nearly neutral waters of McNasser Gulch enter South Fork and is represented by a blue dot.

It also occurs where Peek-A-Boo Gulch enters South Fork and all mineral variations from highly acidic jarosite to neutral goethite are seen in this mixing zone. The use of iron minerals to mirror pH has a dual application. This can be used to obtain a first pass estimate on water quality and possible presence of heavy metals in the drainage. It can also be used as an exploration tool for precious metals by vectoring tributary streams that require further investigation.

pH DISTRIBUTION LAKE CREEK WATERSHED



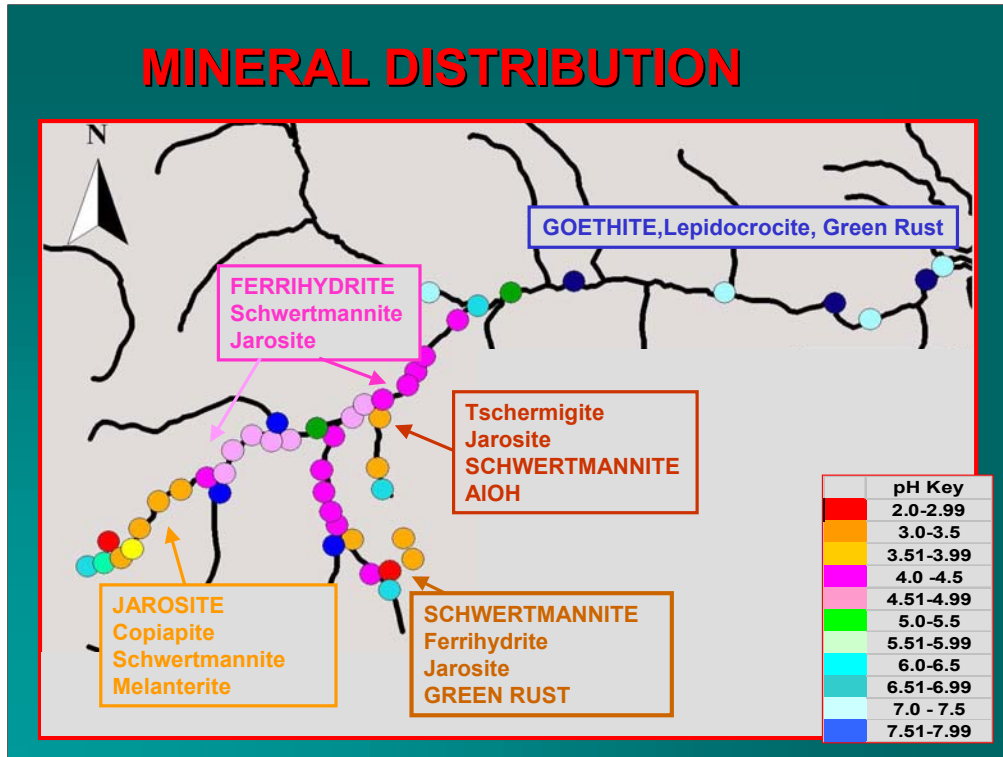
This graphic diagrammatically depicts the part of the Lake Creek watershed under investigation. The objective of the NASA study is to map water quality using acid and neutral minerals, which can be detected from the satellite and airborne sensors.

There are two source areas for acid drainage, Red Mountain (designated WR) and the Sayers Bowls/East Red Mountain (Designated ER). These are rocks that have been changed by heat and then mineralized with sulfides and metals. As the sulfides are exposed to air and ground water, they oxidize or rust. It is the iron and aluminum products of this rusting that cause the orange, gold and white coatings on the rocks in the streams. These coatings contain minerals that exist at different and distinct pH values. Very acid pH minerals are found in Peek A Boo, Sayers Gulch and Sayers Bowl stream and are color coded red and gold. These waters will cause your fingers to tingle. Moderate acid pH minerals are found in South Fork and parts of Sayers Gulch. They are coded lite and dark pink. The green codes indicate where the aluminum coatings are found. Aluminum is very toxic to fish. There are no fish in South Fork.

The neutral waters, which are safe drinking waters, are coded in blues.

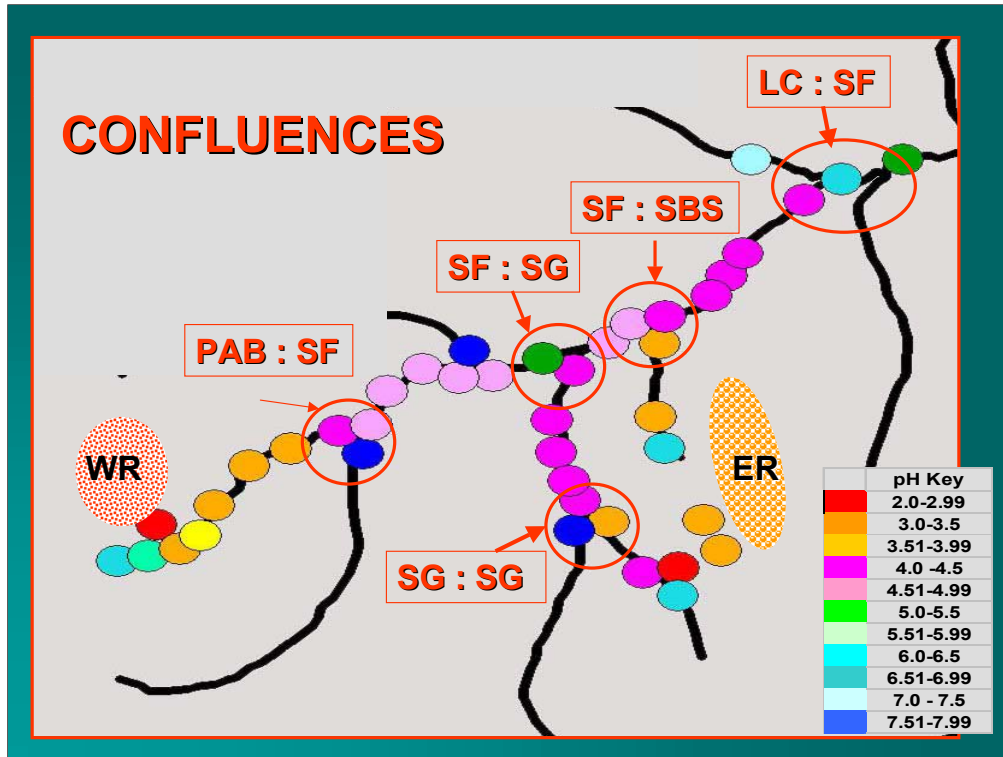
It is therefore possible to map the acid zones and also the degree of acid present by analyzing the coatings on the rocks. This can be done using satellites and also airplane surveys.

MINERAL DISTRIBUTION



Again the drainages are shown with pH values at the different sample locations.

In this slide the minerals found in each drainage are listed. As seen and discussed in previous slides, there is an excellent correlation between the minerals predicted and those that occur which correlates to the pH zones.



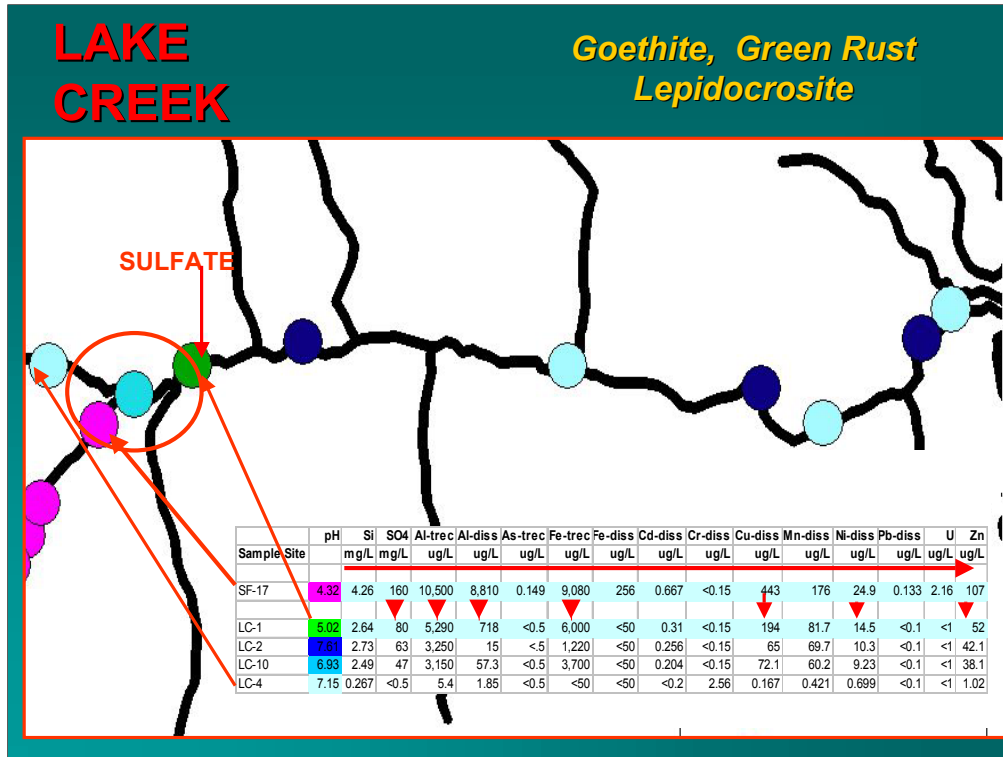
Confluences of different tributaries are very important in the watershed. It is at the confluences where the mixing of acid and neutral waters occur.

This is a diagrammatic representation of the drainages with pH values and confluences of the different streams circled. The two source areas are labeled as WR (West Red) and ER (East Red)

- LC Lake Creek
- SF South Fork
- SBS Sayers Bowls Stream
- SG Sayers Gulch
- PAB Peek A Boo Gulch

The pH values are shown in the key.

Each of these will be discussed separately

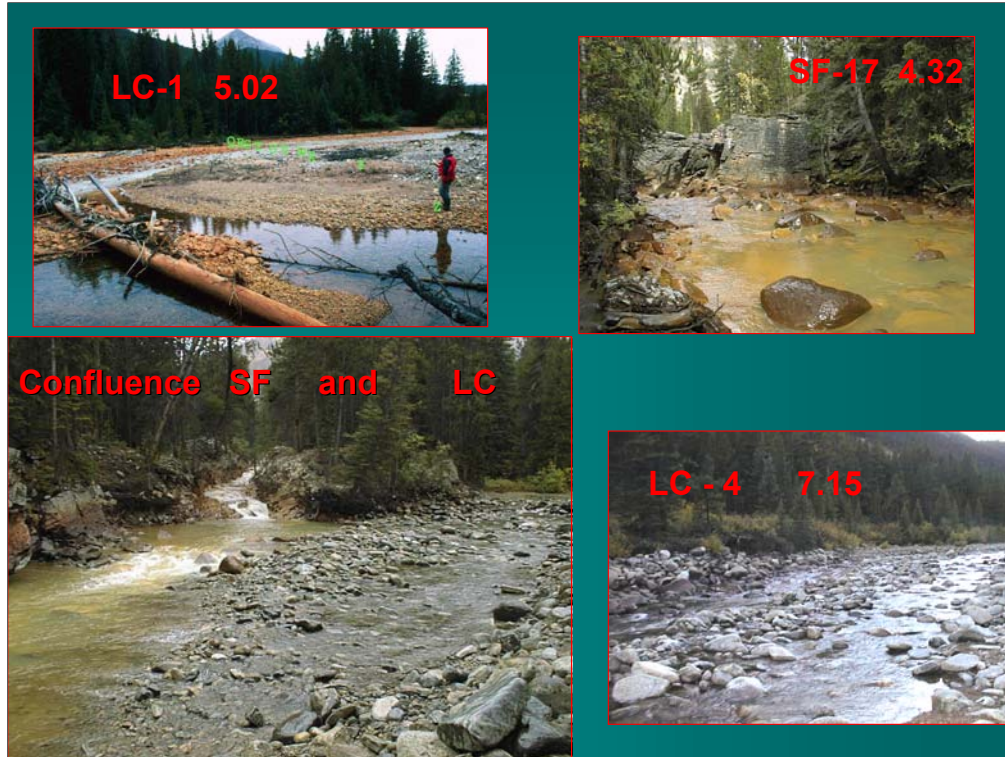


This shows the pH values and chemistry at the confluence of Lake Creek and its south fork.

Lake creek has a high volume of water, greater than South Fork and it is neutral - 7.15. The input from South Fork is 4.32, so very acid. Unfortunately the sample in the mixing zone was not well chosen and therefore LC-10 is not representative of this mixing zone.

LC-1 does show the effect of neutral and high acid mixing with a resulting pH there of 5.02

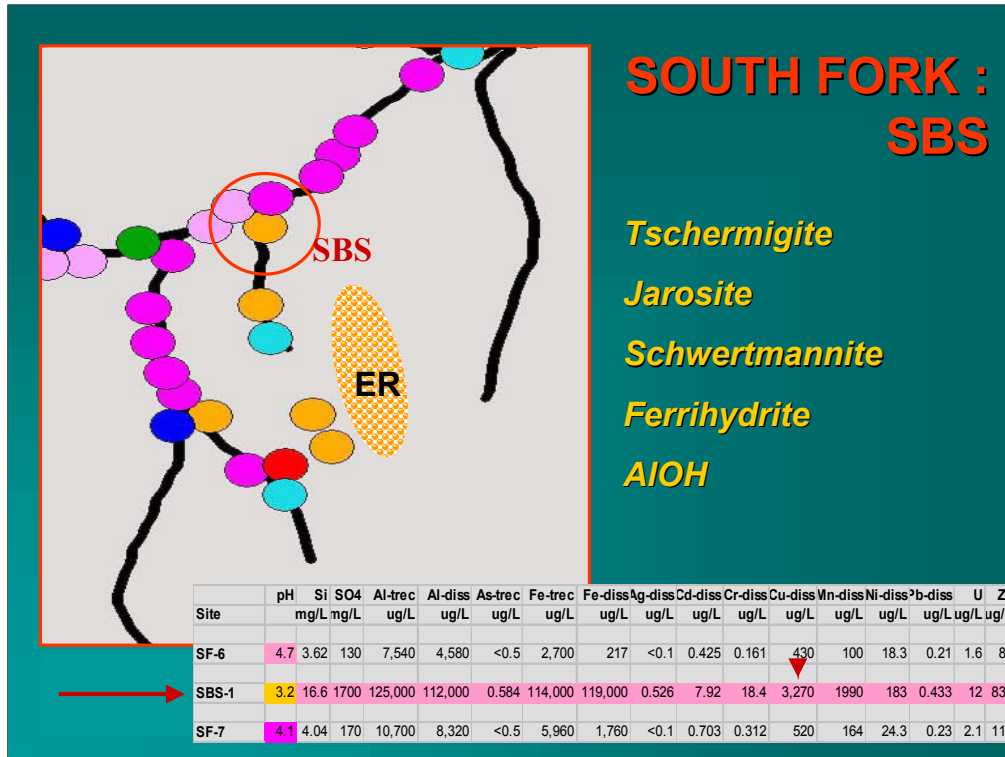
Note the metal contents in the above chart and how they decrease from the mixing zone downstream. There is a 50% drop in the Al and many of the other elements between SF-17, which carries high metals and LC-1 below the mixing zone. The hypothesis is that most of the metals are precipitated from solution within a short distance of mixing with neutral waters.



These are pictures of the confluence of the North Fork of Lake Creek and the South Fork of Lake creek.

High iron and high ppt in suspension is seen at SF-17.

The actual confluence is a great picture as it shows the iron/Aluminum bearing waters of South Fork, cloudy and orange red in color melding with the very clear water of Lake Creek - North Fork.



This shows the pH values and chemistry at the confluence of south fork and the Sayers Bowl Stream (SBS-1).

This is the most active confluence. The metal values feeding in from SBS are incredible. SBS is a small stream, yet it is loaded with metal, orders of magnitude higher than that observed in Peek A Boo.

At the confluence, Al is 125,000, yet 50-60 meters downstream, the values drop to 10,700 ug/l; iron 114,000 and at SF-7, 6000. These values are fairly consistent through SF-8, 9 and SF-10.

Apparently there is a lot of metal dropped in the mixing zone. The water is extremely turbid and cloudy

RME appears to be contributing much greater volumes of metals than RMW



Pictures at the confluence of SBS and South Fork.

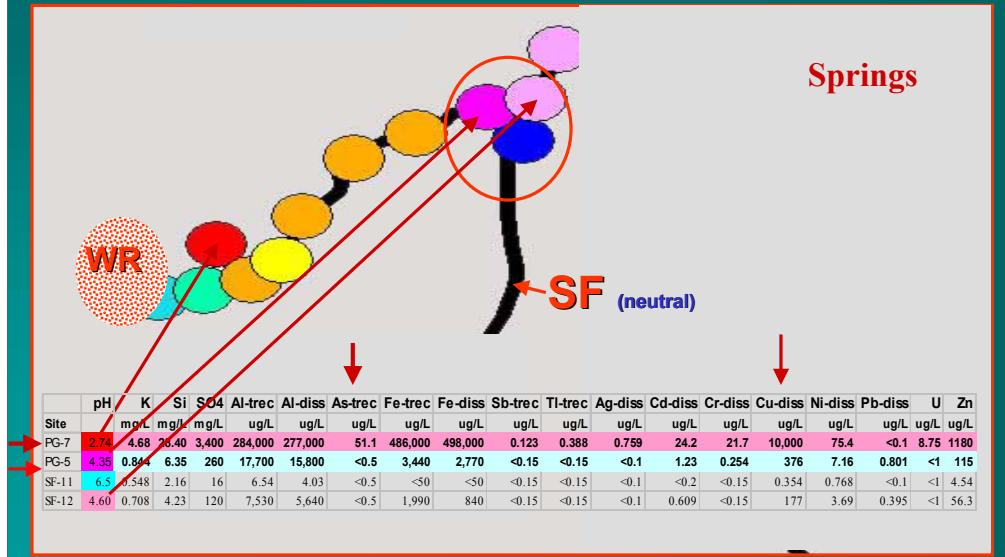
This is an amazing mixing zone. The colors show the different components of iron - orange and gold and aluminum milky white. The zones remain separate until they flow around the small bend

at that point they start to mix and within 50', they are mixed.

There is an incredibly high volume of metal within this short distance from the entry of SBS into South Fork to SF-7.

PEEK-A-BOO SOUTH FORK

Jarosite
Copiapite,
Melanterite,
Schwertmannite



This shows the pH values and chemistry at the confluence of south fork and Peek A Boo Gulch. Peek A Boo carries the metals from the RMW source.

Contrast what is coming out at the source spring (PG-7)-pH of 2.74 with Al at 284,000, iron at 486,000 and copper at 10,000 ug/l with what is ending up in the South Fork drainage (PG_5_-pH of 4.35; Al 18,000, Fe 3400, and Cu 376 ug/l.

It appears that most of the metals and the aluminum remain in the PAB drainage. The drainage maintains a low pH until it starts to mix with south fork. The interesting thing is that the water through PAB is fairly cloudy and red orange. It carries only a small fraction of the suspended metals. Most of the metals appear to drop out close to the source



This slide shows a close up of a section of the watershed from the high acid drainage(Peek-a-Boo) into the mid-acid drainage (South Fork)

Selected locations are shown in the pictures

pH values are for low flow in September

Start at PG-7 – the high acid spring which is seeping through a massive pyrite concentration

On the edge of the alteration is PG-6 draining through host volcanics or metamorphics with a neutral pH

At PG-10, the pH is 5 from an aluminum bearing spring

At the confluence with PG-7= PG-1, they are mixing to a pH of 3.88

At PG-4, this has dropped slightly to pH 3.33

This drains through a meadow to PG-8 and keeps about the same level at 3.43

At PG-5, there is a mixing zone – South Fork is neutral at this point draining from volcanics and metamorphics to the west as shown by SF-11

With a pH of 6.5

Initially the value is a low 4.35 at PG-5 but with the higher volume of neutral water from upper South Fork, it starts to increase and is pH 4.6 at SF-12

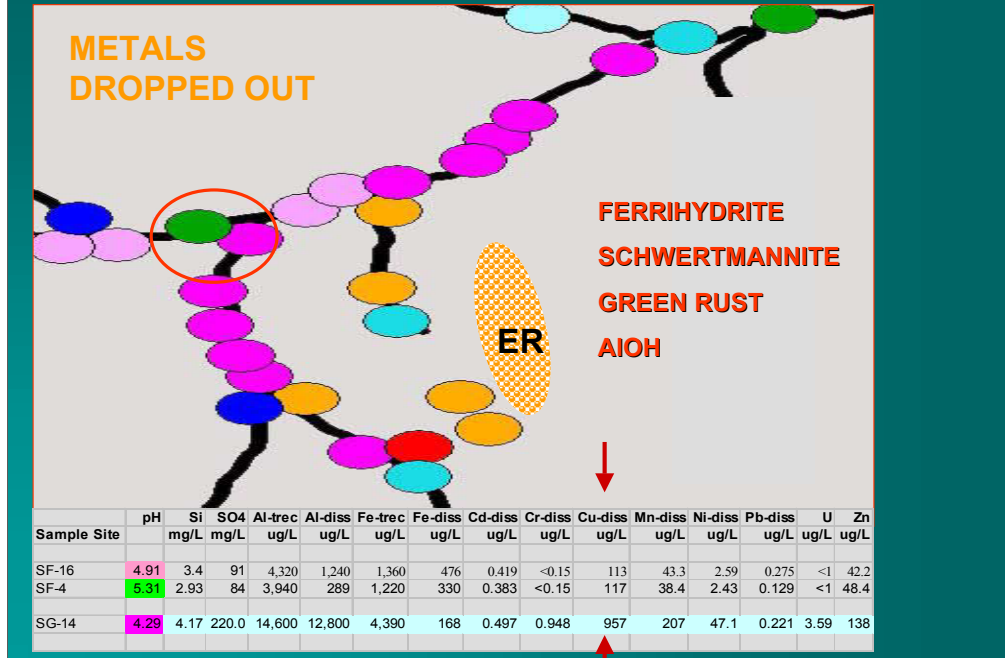
It continues to rise in pH through SF-13 (4.68) and SF-14 (4.72)

What is not shown on this slide are continuing reactions as another neutral tributary enters South Fork and then an acid trib of pH 3 from the second sulfide source, which drops the pH again. It then continues to rise towards 5 along South Fork and with major dilution from the North Fork goes onto pH's of 7 on its way to the lakes.

SAYERS GULCH



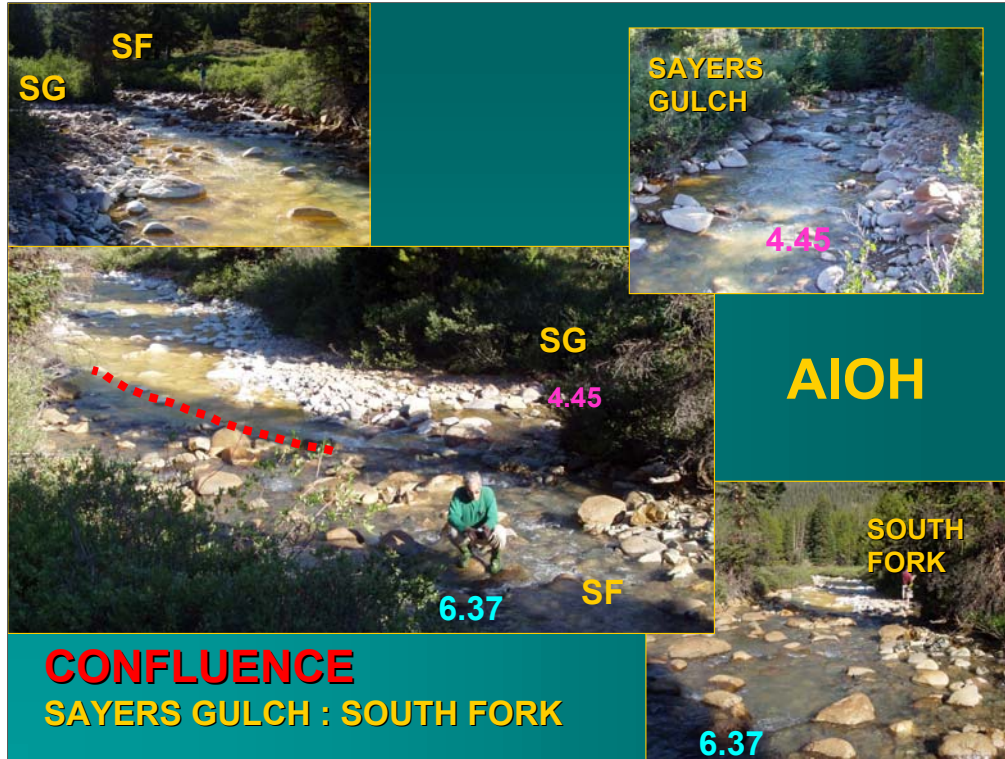
SAYERS GULCH : SOUTH FORK



This shows the pH values and chemistry at the confluence of Sayers Gulch and south fork.

Sayers Gulch receives metals and acid waters from RME through the ESG stream. By the time it reaches South Fork, most of the metals appear to have dropped out. Sayers is visibly milky with suspended AIOH. The iron however, is fairly low here compared to the Al.

Again we see the metals being precipitated out fairly close to the source and at the confluences.



These pictures show both Sayers Gulch and South Fork separately and at their confluence.

Note that South Fork has some minor iron staining. The pH here is 6.37. From its confluence with Peek A Boo, it has lost most of the metals and been diluted by the inflow from McNaser Gulch.

Sayers, however, has a pH of 4.45 and is contaminated with suspended AIOH which is visible as a milky white to gold suspension.

The mixing zone is similar to what has been observed at other confluences - the two streams maintain their integrity of pH and suspended materials for some distance below the confluence.

A speculation is that the aluminum remains in suspension longer than most of the metals, which appear to drop out before the pH reaches 5.

SUMMARY

SULFATES

Acidic Conditions

GREEN RUST

*Seems pH Independent
- High Mobile Iron*

FERRIHYDRITE

Moderate Acid Conditions

GOETHITE

Neutral pH

This slide is fairly self explanatory

it shows what materials exist under what conditions

Hyperspectral AVIRIS

JPL/NASA Sensor

4 Meter Spatial

12-15 nm Spectral

Sees individual Mineral Species



The NASA sensor called AVIRIS was used to collect data over the study area.

This is a hyperspectral sensor flown on the ER-2 airforce plane at 65,000', and shown in this picture; or on the Twin Otter, flown at 12-15,000' for smaller pixels.

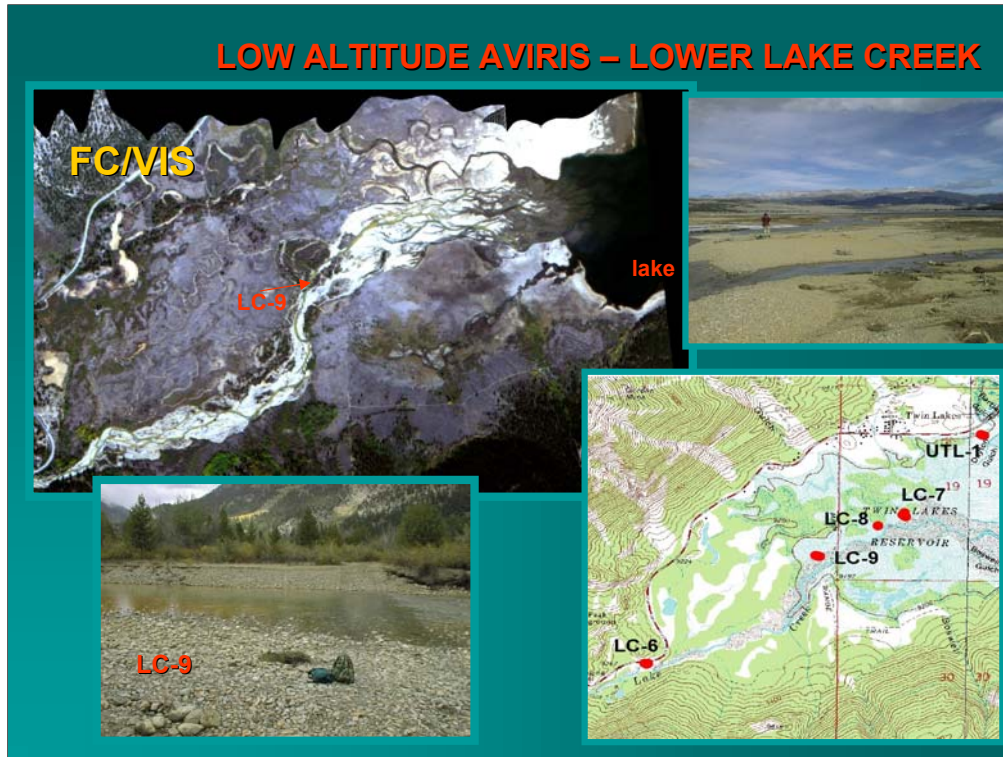
AVIRIS is the benchmark sensor for hyperspectral work. It is managed by the Jet Propulsion Laboratory in Pasadena, for NASA.

This sensor collects data in narrow bands 12-15nm wide from 400 - 2500nm.

It can be processed for mineral species.

LAKE CREEK



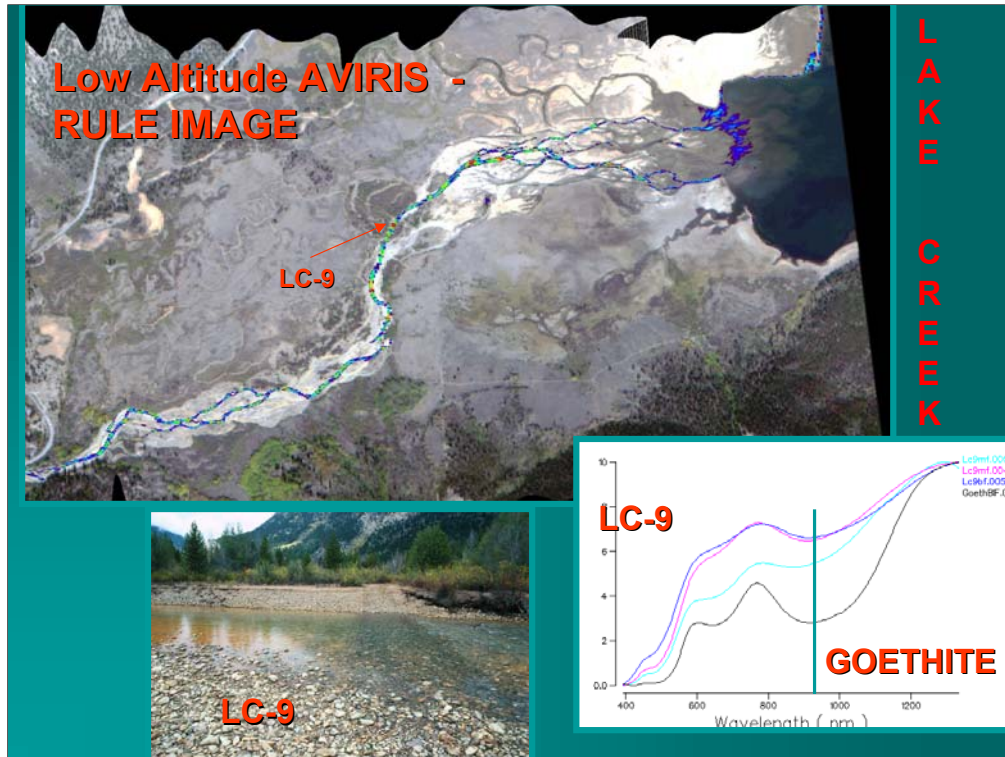


This is an AVIRIS image – processed using bands for pseudo-true color.

Sample Site LC-9 shown on the topo map and in the picture, was used as the training site for this image. This image is of the delta area just before the lake.

The objective was to extract the mineral goethite from the image and map its occurrence within and along the stream. The spatial resolution is 4 meters.

In the visible image, the iron minerals show as gold within the imbricating main stream channel.



A spectrum representing goethite was extracted from a pixel at site LC-9. It was compared to ground truth data collected with an ASD Field Spec Pro spectrometer. It was then imported into the image processing program and the program was instructed to match that spectrum to the image and extract any matching spectra. The result is a rule image. The colors represent matches to the training spectrum. Red is highest confidence, then yellow, green and blue.

Note what happens when the Lake Creek waters enter Upper Twin Lakes. There is enough difference in pH - the lake being more alkaline, that goethite is precipitated at the mixing interface. It shows up as blue in the confidence schema because it is viewed through the water.

Goethite:

- SAM classification was used

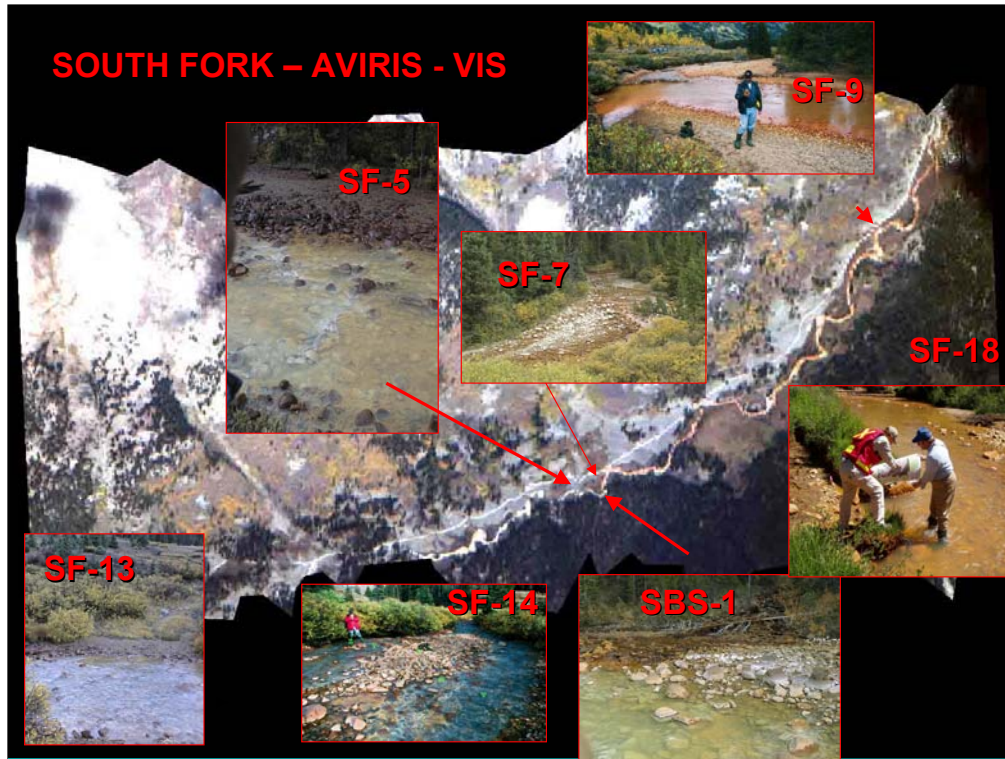
- Training pixel was selected from AVIRIS at the field measurement location

- Inverted rule image was thresholded and color sliced (purple = low red = high)

Redness:

- Simple band difference (red - blue)

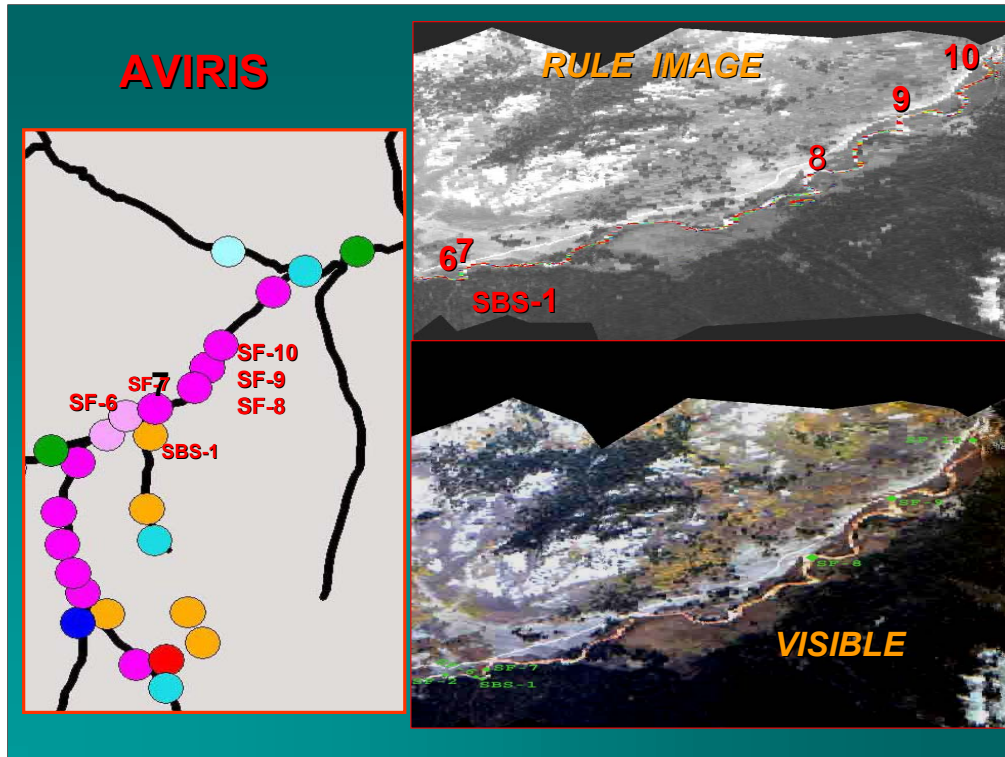
SOUTH FORK AVIRIS



This is also AVIRIS – pseudo-true color using visible range information.
It shows the oranges, reds, golds and whites along the stream

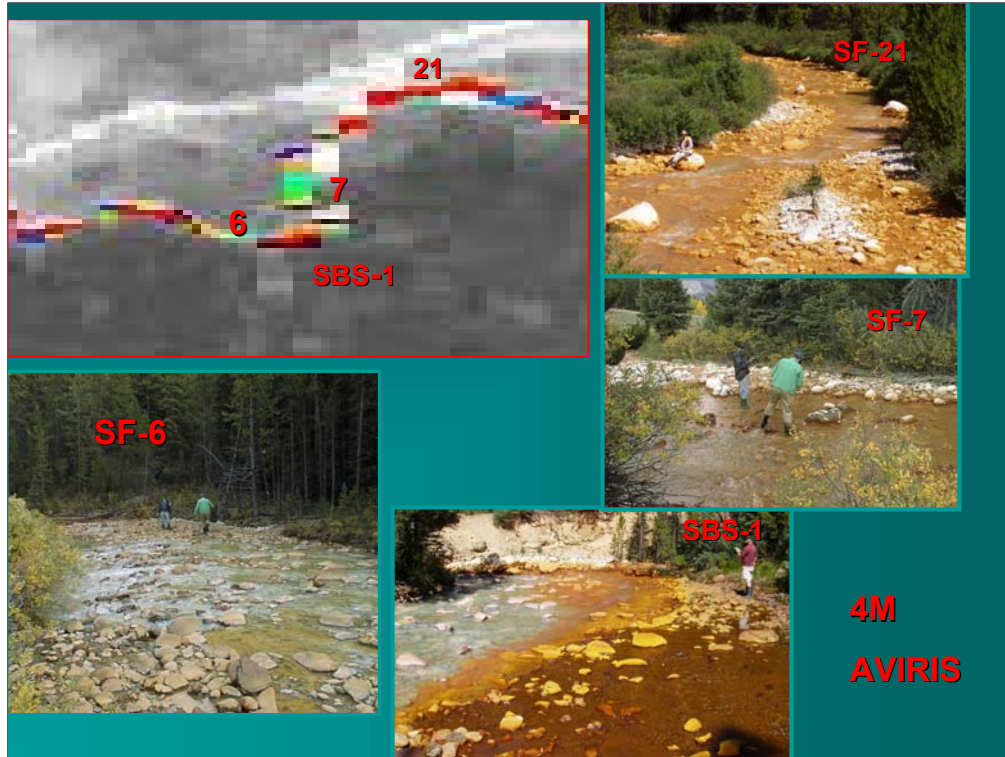
the pictures from different sample locations show how the ground corresponds to the imagery.

Note that above SBS-1 confluence with South Fork, the stream is white and below that confluence which is introducing volumes of iron into the stream, the colors change to oranges and golds as seen in the pictures.



This pair of AVIRIS images shows the visible, described in the previous slide, and an iron mineral rule image showing best matches. Again the color scheme is red for best match - highest confidence, through yellow, green and blue.

The sample locations and corresponding pH values are shown in the cartoon to the left. Please note that the darker oranges in the Visible image correspond to the higher confidence levels in the Rule Image.



This slide shows how well the 4m AVIRIS data matches the ground and how well the methodology works overall.

South Fork is shown subset at the confluence with SBS. At this scale, the pixels are elongated. Sample locations are marked on the image and ground pictures arranged around the image.

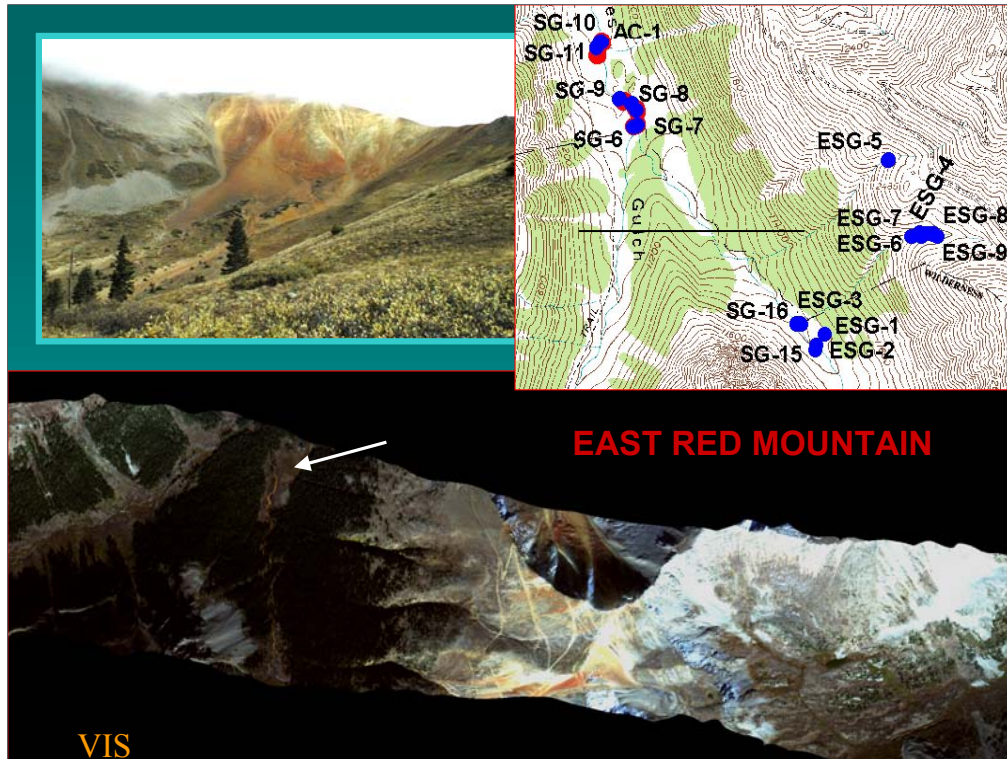
This is quite compelling This is a classification image and it shows iron oxides/sulfates as a single class. The geophysics color key applies here. The best matches to the iron minerals are red, then yellow, green, blue.

| Loc | pH | ground | AVIRIS |
|-------|------|------------------------------|-------------------|
| SF-6, | 4.66 | white ppt mixed with iron | blue |
| SBS-1 | 3.17 | dark orange red high iron | red |
| SF-7, | 4.07 | mixing zone white and orange | gold->green->blue |
| SF-21 | 4.45 | orange ppt - high iron | red |
| | | white gravel bar | blue |

where there is high iron and the lower pH values, the pixels are red
 the Aluminum coated white rocks show blue and green pixels.

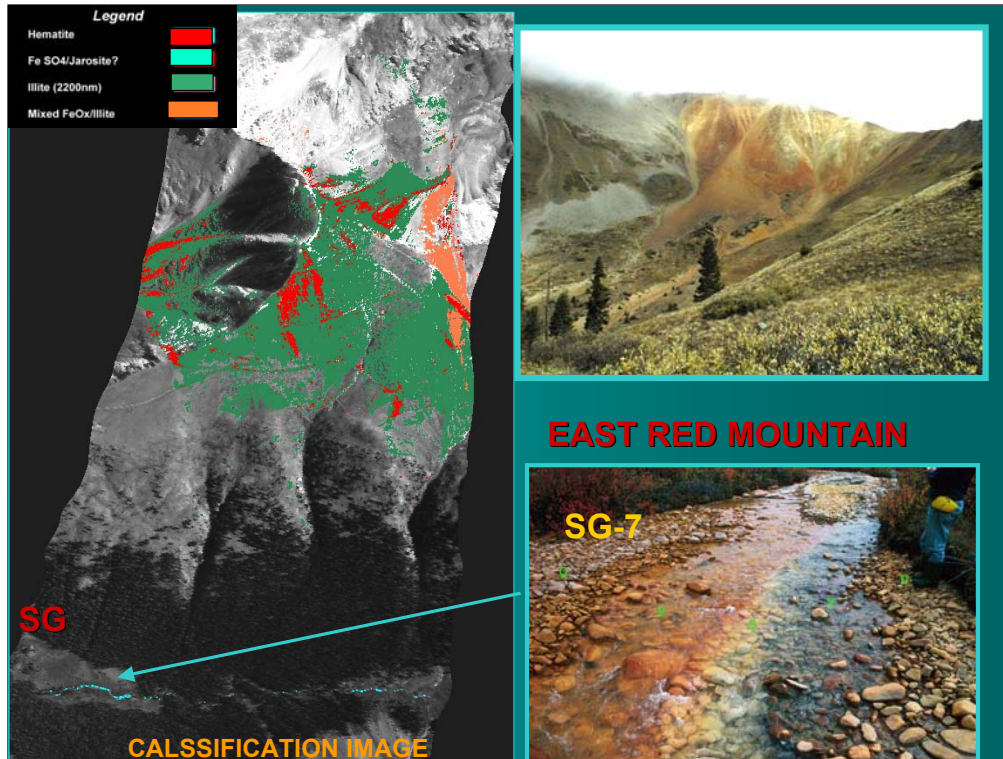
SOURCE AREAS AVIRIS





This is an AVIRIS pseudo-true color image of East Red Mountain and Sayers Gulch (arrow).

The ground picture can be matched to the image. This is a complicated area with two back to back bowls that are both contributing acidic water and ground water to two tributaries, ESG and SBS that both ultimately drain into South Fork.



In this image the minerals have been mapped on East Red Mtn

Green = muscovite/illite

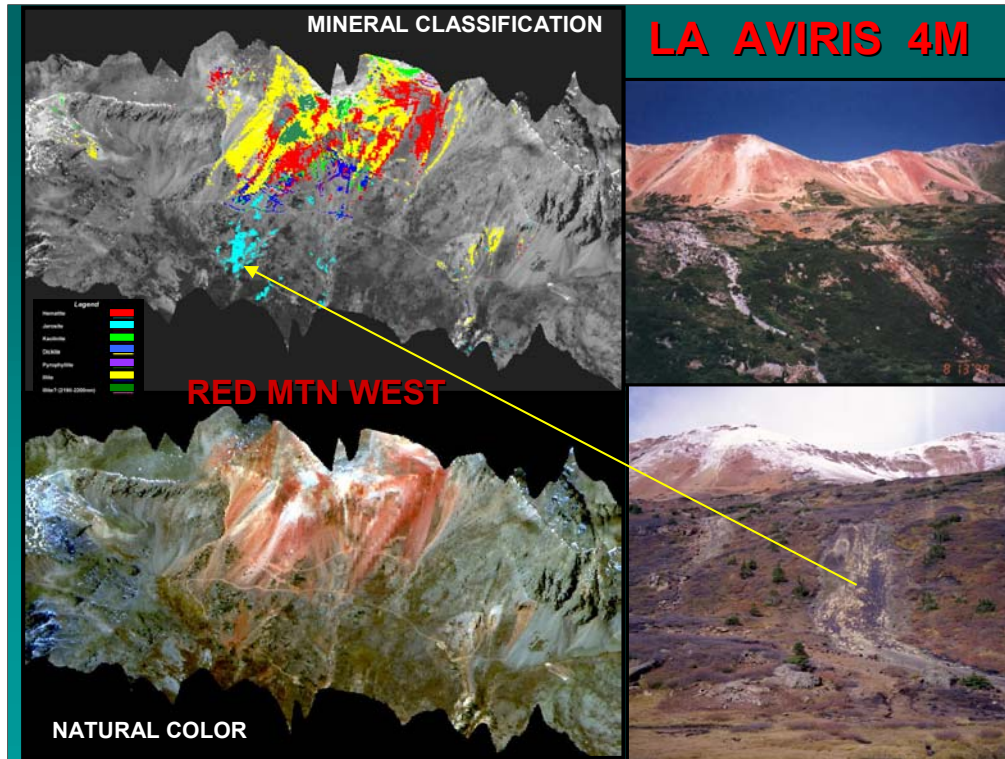
Red = hematite

orange = other iron oxides

Blue/cyan - sulfates

this appears to be primarily a phyllic alteration systems which can also be called QSP - quartz-sericite-pyrite.

This image is particularly striking in the Sayers Gulch part (SG-7) as it shows the sulfates within the stream. Again this is 4 meter pixels and to be able to define that narrow stream with the hyperspectral data is excellent.



There are 2 AVIRIS images; The pseudo true color and the classification image.
The ground pictures make it easier to match to the images

Hematite = red

Illite = yellow

Cyan = jarosite








Dk green high temperature illite

Lite green kaolinite

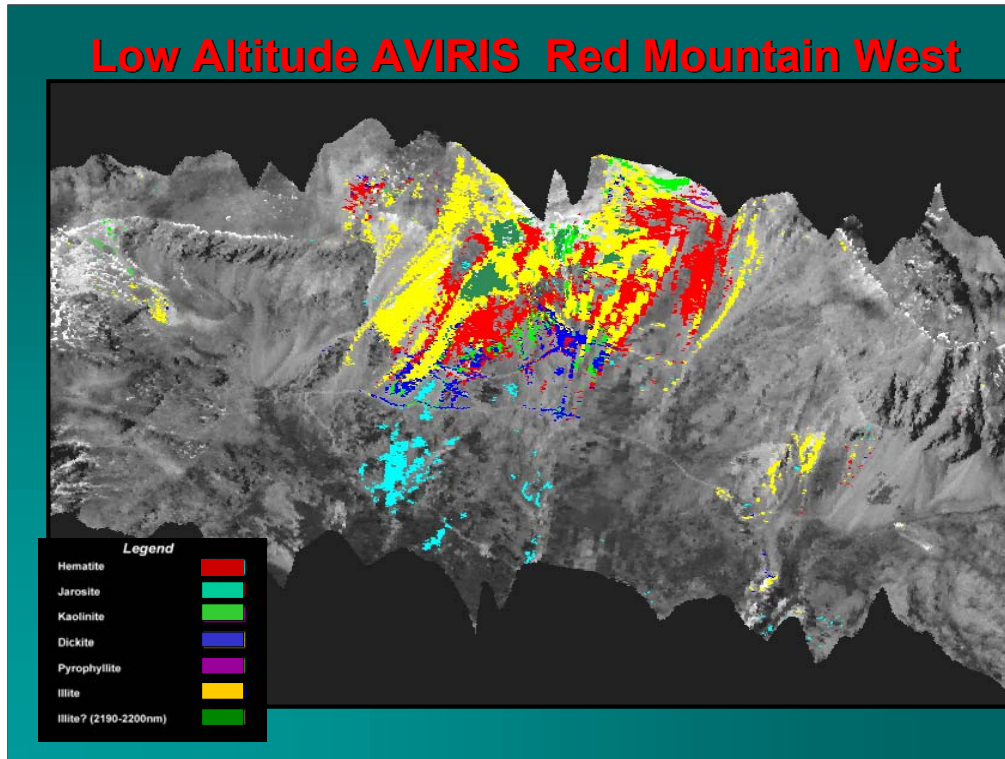
Dk blue = dickite

Purple = pyrophyllite

Legend

| | |
|------------------------------|---|
| Hematite |  |
| Jarosite |  |
| Kaolinite |  |
| Dickite |  |
| Pyrophyllite |  |
| Illite |  |
| Illite? (2190-2200nm) |  |

Note the very striking zoning in this image. The hydrothermal illites are zoned within the weathered illites. The kaolinite is peripheral to this forming a more argillic alteration pattern. What is particularly striking is the structural feature containing the pyrophyllite. This mineral is particularly difficult to identify in imagery. Jarosite is concentrated in the area where the spring is feeding acid waters from oxidized sulfides into the Peek A Boo drainage.



This is an expanded view of the mineral classification image in the previous slide

🌐 **WEST RED**

- 🌐 *Advanced Argillic*
- 🌐 *chemistry less interesting*
- 🌐 *streams spring fed*
- 🌐 *Mineralogy more compelling*
- 🌐 *Low flow-metals remain above*

🌐 **EAST RED**

- 🌐 *More AL⁺ illite/muscovite*
- 🌐 *Less argillic on Mtn*
- 🌐 *Advanced Argillic in streams*
- 🌐 *Better chemistry*
 - Ground water leaching*
- 🌐 *Lower in System?*



EXPLORE MORE WHERE???

•AVIRIS data acquired in late September. Processing will be done in early 2003. Airborne hyperspectral will have 1-4 meter resolution allowing detailed view of streambed metal precipitate coatings.

•This application of hyperspectral remote sensing may be used to indirectly assess water quality in other areas affected by natural or anthropogenic acid rock drainage.

END OF SLIDES IN TALK
FOLLOWING ARE FROM OTHER TALKS

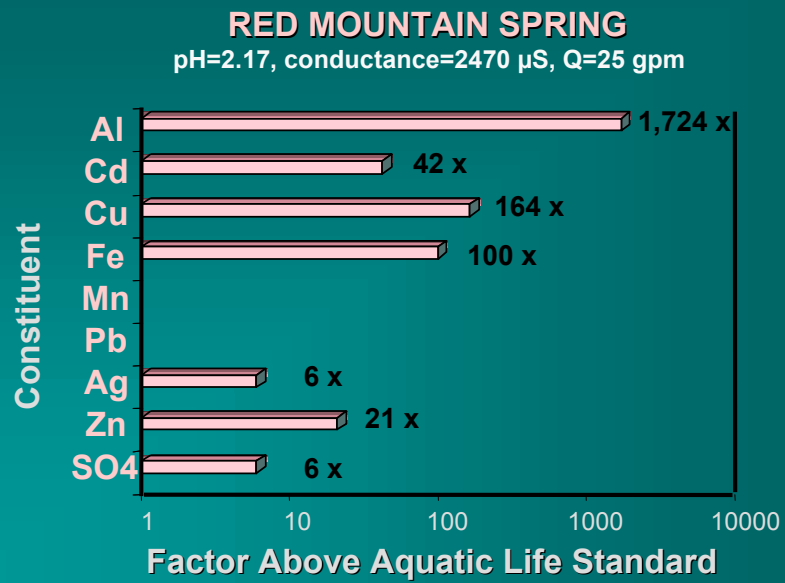




RED MOUNTAIN EAST



Natural acid rock drainage dissolves metals present in the rock, affecting downstream water quality.



8/94

- Water sampled in 1994 from this Peekaboo Gulch spring **greatly** exceeded state standards in
- aluminum,
- cadmium,
- copper,
- iron,
- zinc
- Silver and sulfate concentrations also exceeded standards.

Peek-A-Boo



SPRING
pH =

Peek-A-Boo



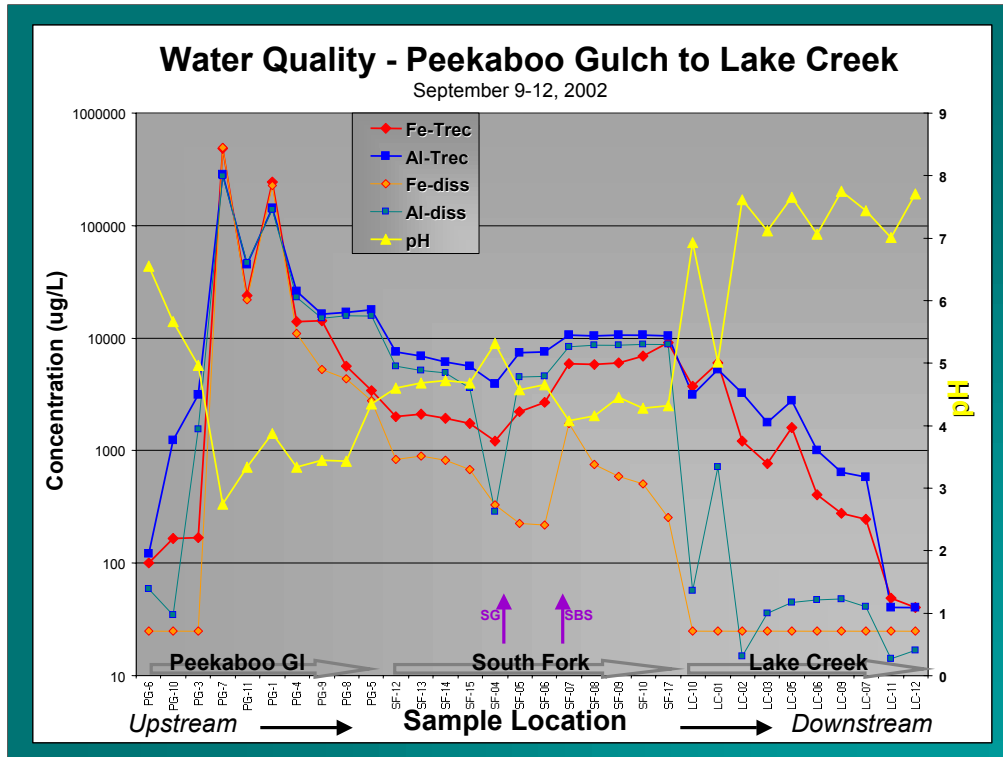
DRAINAGE
pH =

**Low pH
ENVIRONMENTS**

South Fork SF-7

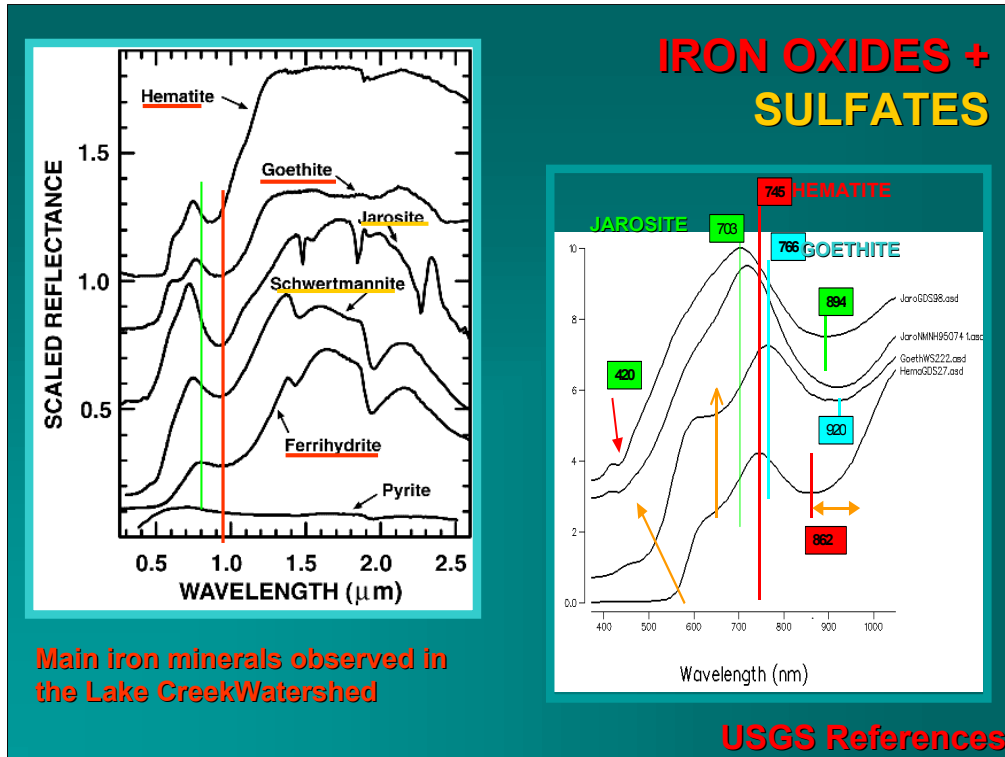


CONFLUENCE
MIXING ZONE
Ph = 4.07



Note:

- 1) Extremely **high Fe and Al** content in Peekaboo GI headwaters
-
- 2) Inverse relationship of pH and metal concentrations
- 3) **Sensitivity of dissolved Al** concentration to pH. Whenever pH > 5.0 get separation of the dissolved and total recoverable Al concentrations.
- 4) Fe drops out of solution onto streambed at different pHs.
- 5) **Fe and Al** concentration **do not exceed statewide aquatic life standards** in mid-Lake Creek and downstream.

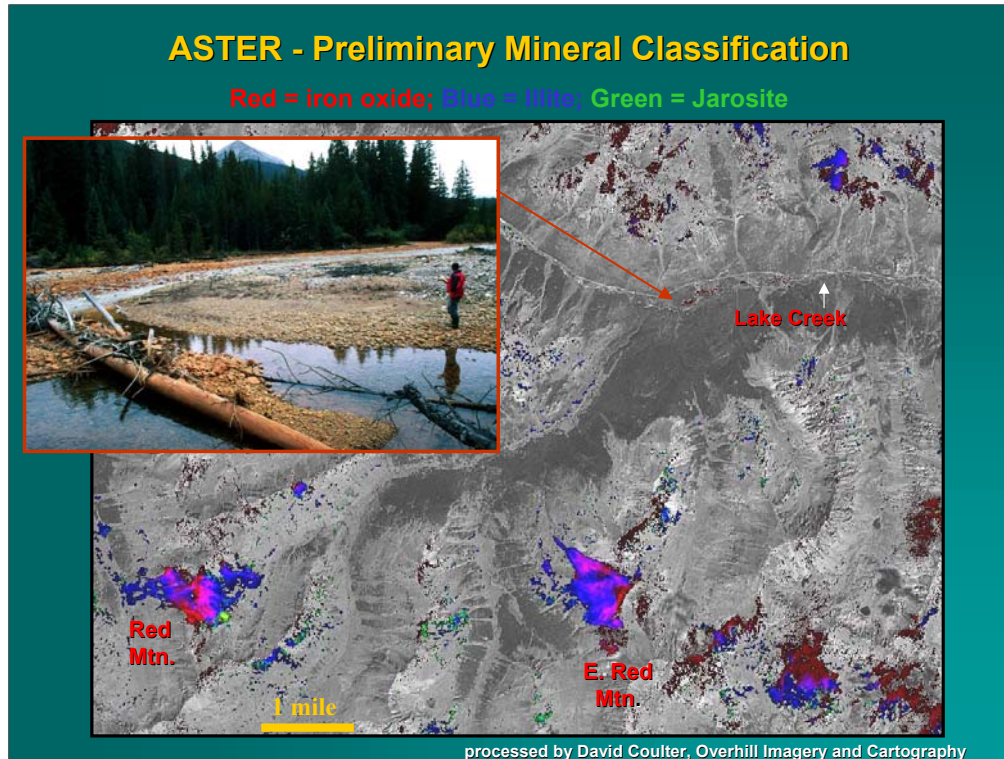


- These are examples of the **spectra of the primary iron oxides and sulfates** identified to date in the Lake Creek watershed. (Maghemite is also present)

- These minerals have **similar spectral features**. They can be identified with the field spectrometer, but pose some challenges in the remotely sensed data sets. However, we have some confidence that acid generators such as jarosite, schwertmannite and ferrihydrite can be differentiated from the more neutral goethite and hematite phases

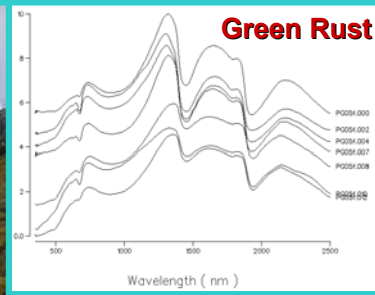
- The graph on the right indicates the **spectral features** commonly used to **discriminate jarosite from iron oxides** (goethite and hematite). Presence of a **reflectance high near 700 nm** and a small **peak near 420 nm** appears to be diagnostic for jarosite.

- Also, Jarosite is **rarely found in the pure end member state** and is usually mixed with goethite, as they are both products of the same supergene cycles. A specialized computer identification algorithm is under development to discriminate the species and mixtures.



- Using ASTER data this preliminary classification was done for iron oxide, illite, and jarosite.
- The iron-oxides were classified using the 15-meter resolution VIS-NIR bands
- Illite and Jarosite were classified using 30-meter resolution SWIR bands.
- Red Mtn and East Red Mtn appear as large, solid areas of iron oxide and illite associated with hydrothermal alteration
- Red Mountain exhibits the low pH mineral jarosite, probably related to acid-spring ferricrete deposits on its slopes.
- Iron oxide associated with the upper Lake Creek drainage just downstream of South Fork is also evident in this classification. Identification of exposed iron-oxide streambed coatings can be inferred to be from natural acid-rock drainage downstream of the altered areas.
- Much more detailed results, both spatially and in mineral identification are expected from airborne 1-4 meter resolution AVIRIS data, acquired in late September.

NATURAL ACID DRAINAGE SYSTEMS



IRON OXIDE SPECIES

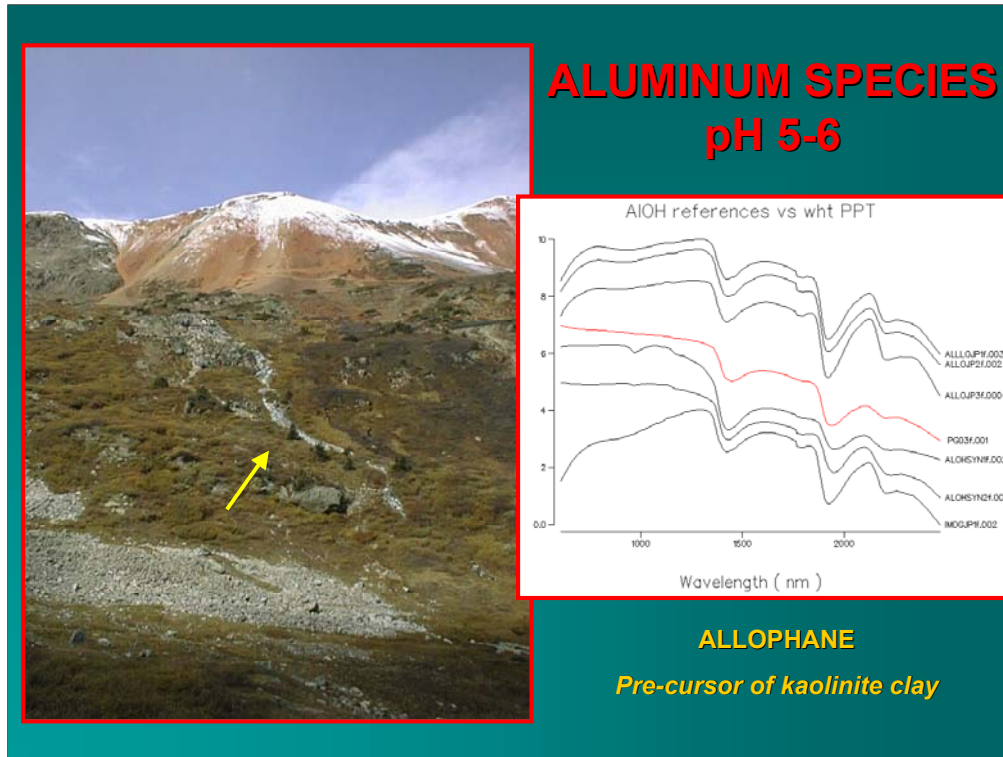
pH 1-4

- Iron precipitates in the streambed characterize the affected watersheds
- These precipitates have characteristic spectral reflectance data

pH vs SAMPLE SITES

| Drainages | Sites | pH 2 | pH 3 | pH 4 | pH 5 | pH 6 | pH 7 |
|---------------------|-------|------|------|------|------|------|------|
| Lake Creek | 11 | | | | 1 | 1 | 9 |
| South Fork | 16 | | | 14 | 1 | 1 | |
| McNasser Gulch | 1 | | | | | 1 | |
| Sayers Gulch | 12 | | 1 | 9 | | 2 | |
| Sayers Gulch-Upper | 3 | 1 | 2 | | | | |
| Sayers Bowls Stream | 3 | | 2 | | | 1 | |
| Peek-A-Boo Gulch | 10 | 1 | 5 | 2 | 1 | 1 | |

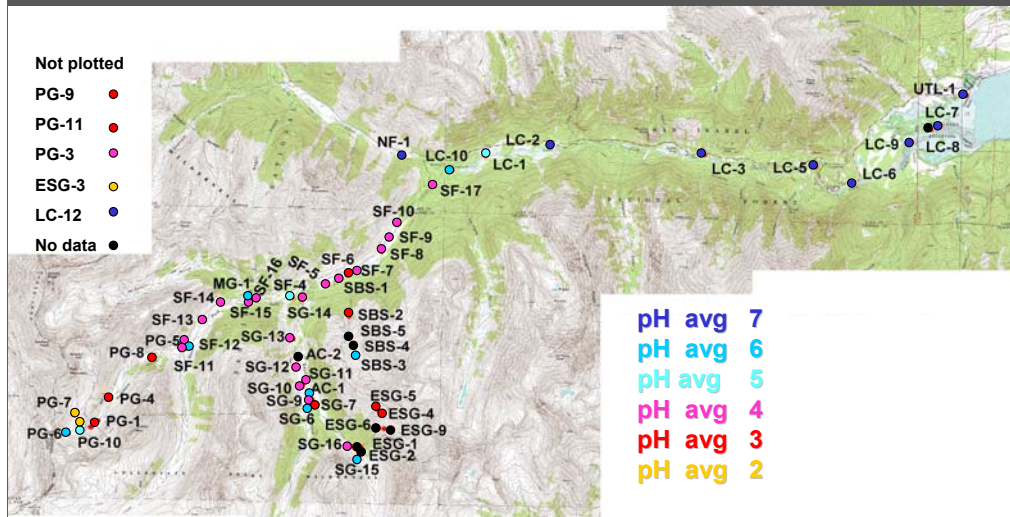




Red Mountain-Peekaboo Gulch

- The stream here contains an amorphous Al-OH mineral that exists in an acidic environment.
- It is allophane, a precursor of kaolinite

GENERALIZED pH VALUES FOR STUDY AREA



pH collected 09/02