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# Environmental study of the Bonanza Mining District, Colorado using AVIRIS, aircraft, satellite, and terrain data

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## INTRODUCTION

The objective of this study was to describe the mineralization, altered rock, and mining impacts on the environment of the Kerber Creek drainage within the Bonanza Mining District, Colorado, using several types of remotely sensed data. Several types of data set were analyzed, including imagery, map data, and point data. These data were assembled into a coregistered database where features were correlated between layers visually and/or combined through masking.

## BONANZA MINING DISTRICT

The Bonanza Mining District is located at the headwaters of Kerber Creek, within the San Juan Mountains 120 miles southwest of Denver, Colorado. It is situated within the Bonanza caldera with mountains forming three sides of the drainage basin. Kerber Creek water is used for crop irrigation and drinking water 15 miles downstream in the San Luis Valley.

## DATA SETS

Data sets used were a digitally scanned reconnaissance geologic map, Digital Elevation Model (DEM), Thematic Mapper Simulator (TMS), National Uranium Resource Evaluation (NURE), and Airborne Visual and Infra-Red Imaging Spectrometer (AVIRIS). All data were georeferenced to a Systeme Probatoire d'Observation del la Terre (SPOT) image. Lithology and structure as mapped and compiled by Knepper (1974) after Burbank (1932) and information from a literature review were used as ground truth as well as local checking of several spectral anomalies with an Analytical Spectral Devices (ASD) field spectrometer and by hand-sample examination.

The airborne TMS sensor covers 12 broad-band channels with reflectance coverage from 0.42 to 2.35$\mu$m and thermal coverage from 8.5 to 14$\mu$m. These data were acquired on August 28, 1992 under cloud-free conditions from a NASA ER-2 simultaneously with the 1992 AVIRIS data. DEM point-elevation data and gridded NURE radiometric data were acquired from the U.S. Geological Survey. The NURE gamma-ray spectrometry data were flown on a one-quarter-mile spacing in the mid 1970's with radioactive uranium, thorium, and potassium counts recorded. AVIRIS data were acquired in 1992 (west north-south line) and on October 11, 1994 (east north-south line) with 70% overlap. The two flightlines were processed separately; the 1992 mineral mapped coverage which fell outside the 1994 flightline was added to the 1994 mineral maps. These reflectance data were measured in 224 channels from .45 to 2.45$\mu$m.

## GEOLOGY

The pre-volcanic basement upon which the middle Tertiary volcanic rocks of the Kerber Creek area (Bonanza volcanic field) were deposited, consist of Precambrian crystalline rocks and

Paleozoic sedimentary strata containing sandstone, shale, and carbonate units. Rocks of Mesozoic age that are presumed to have once covered the area were completely eroded (Burbank, 1932) following the uplift of the region during the late Cretaceous-Eocene Laramide orogeny (Knepper and Marrs, 1971).

Oligocene volcanic rocks (Bonanza volcanic sequence) are exposed over a large portion of the Kerber Creek drainage basin. These rocks consist of flows, intrusives, and lava domes varying from mafic to silicic in composition. The alteration and mineralization in the Kerber Creek drainage basin are associated with this period of volcanic activity and are mostly hosted by rocks of this volcanic sequence. After the eruption of the ash-flows and during and after eruption of younger andesites and latites, the central portion of the Bonanza volcanic center collapsed forming the asymmetric Bonanza caldera (Burbank, 1932; Marrs, 1973). The caldera is the dominant structural feature of the Kerber Creek drainage basin and is directly responsible for most of the present-day topographic configuration of the area.

Following the eruption of the andesites and latites, small plutons and lava domes were emplaced in the Bonanza volcanic sequence. Post-volcanic deposits in the Kerber Creek drainage basin are limited to Pleistocene and Holocene alluvial fans, terraces, and channel deposits.

## MINERALIZATION/ALTERATION

Mineralization and hydrothermal alteration of rock at Bonanza is considered a Creede type epithermal vein deposit (figure 1). The Bonanza District has quartz-adularia alkali-chlorite polymetallic vein deposits with silver-lead-zinc-copper ore (Burbank, 1932; Mosier and others, 1986). The ore occurs in sub-vertical quartz-pyrite-base metal sulfide veins hosted in felsic to intermediate volcanics (rhyolite-latite-andesite). The veins are structurally controlled within the caldera's concentric and radial faults which localize the ore shoots and grade of altered minerals.

Deposits within the district have their mineralogy vertically and laterally zoned (from top to bottom or center outward). Deposit tops contain a massive silicification and acid-sulfate cap (kaolinite and/or alunite), followed by quartz+/-kaolinite+montmorillonite+/-zeolites+/-barite+/-calcite, at mid-level with quartz+sericite+pyrite (QSP), and at depth with quartz+chlorite+adularia (potassic alteration). A distal propylitic assemblage of chlorite+epidote+calcite+pyrite is pervasive throughout the district.

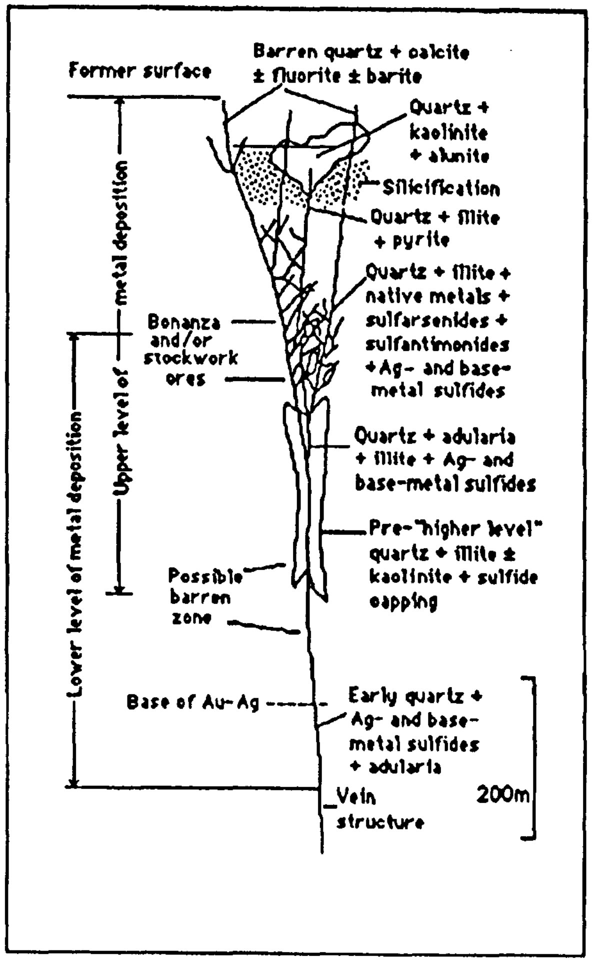


Figure 1. Schematic cross section of mineral deposit model 25b (Mosier and others, 1986).

## RESULTS

### TMS Image of Inferred Iron Oxides and Clay

An iron oxide and clay image was formed through the selection of a specific Digital Number (DN) interval for iron oxide (band ratio 9/10 gray-scale image) and a DN interval for clay (band ratio 5/2 gray-scale image) after visually analyzing color hue ranges from a color-ratio-composite (CRC) image. The band ratios for the CRC were bands 9/10, 5/2, and 5/7, which are equivalent to the Landsat TM ratios 5/7, 3/1, and 3/4. A CRC hue range was visually selected which represents the dominate color range for iron oxide and for clay (Knepper and Simpson, 1992), then the gray-scale image DN intervals were measured for the same spatial regions. The iron oxide and clay theme image was also masked for vegetation generated from an vegetative index theme image. Clays, micas, carbonates, and sulfates form one group of altered minerals while iron oxides and hydroxides form the other.

### DEM Image of Ground Slope

The DEM data were used to generate a ground slope image. Relative steepness was assessed and a minimum steepness threshold DN measured. Slope steepness, combined with bare areas rich in clay were used to characterize areas susceptible to ground failure and potential release of heavy metals.

### Radiometric Image

A radiometric image of uranium and thorium was formed similarly to the TMS image. A color-composite image of uranium, thorium, and potassium was generated to visually aid in selecting regions anomalously radioactive, with DN intervals measured from the uranium and potassium gray-scale images. Thorium within the Bonanza District is highly correlated with uranium and was not utilized further. Uranium was found to be associated with thick regions of the Bonanza Tuff while potassium is associated with the younger latite volcanic flows. Sedimentary rocks are low in radioactive potassium. A zonation was also found between uranium and potassium where potassium anomalies trend further from the caldera than the uranium anomalies.

### AVIRIS Mineral Suite Images

Mineral maps were formed which identify iron bearing minerals and clay, mica, and carbonate minerals. The data were corrected for atmospheric path radiance using the program ATmosphere REMoval (ATREM) version 1.1 from the Center for the Study of Earth From Space (CSES), University of Colorado (Gao and others, 1992), then further calibrated to relative ground reflectance using field spectra acquired from a ground calibration site with an ASD field spectrometer. Several dozen identified mineral images were generated from these data using the U.S.G.S. goodness-of-fit program (Clark and others, 1990; Swayze, 1997), which correlates the fit of diagnostic absorption bands of pixel spectra (continuum removed) to mineral spectra from the U.S.G.S. library database (Clark and others, 1993). Mineral maps were assembled from selected mineral images which had visible mineral anomalies, pixels with high goodness-of-fit numbers, and moderate to strong absorption band depths. Pixels which did not meet these criteria were not mapped. Vegetation obscured a significant portion of the area, which also was not mineralogically mapped. Mineral identification was confirmed by visual examination of mapped pixel spectra within the AVIRIS image cube, by field examination of hand specimens, and for a few mineral anomalies, by measurement with an ASD field spectrometer. Iron-bearing minerals individually identified and mapped using AVIRIS data were goethite, hematite, jarosite, and two varieties of ferrous iron minerals. The mapped Clay- and carbonate minerals were kaolinite, montmorillonite, several spectrally distinct varieties of muscovite/sericite/illite, paragonite, calcite, and dolomite. Maghemite has been spectrally identified, but is most likely the mineral hematite.

Eight types of altered mineral suites and a carbonate suite (table 1) have been characterized using the AVIRIS mineral maps.

**Table 1**: Altered mineral suites (1-8) and carbonate suite (9)

| Suite | Primary minerals | Location |
|---|---|---|
| 1 | montmorillonite-goethite-$Fe^{+2}$ bearing minerals | Superior and Rawley Mills, Kerber Creek tailings ponds south of Bonanza; fluvial sediments downstream from Greenback Gulch, which also contain maghemite and hematite. |
| 2A | sericite-montmorillonite +/- kaolinite-jarosite-goethite +/- hematite | Cocomongo-Bonanza, Minnie Lynch, and Rawley Mines dumps, and Hayden Peak - Elkhorn Peak. The latter area also contains goethite, but lacks jarosite. |
| 2B | montmorillonite-sericite +/- kaolinite-iron oxides | Sheep Mountain (with jarosite-goethite-hematite), Antora Meadows (with maghemite and/or hematite), and Flagstaff Mountain ($Fe^{+2}$-goethite surrounded by maghemite). |
| 3 | sericite-kaolinite-hematite-goethite | Greenback Gulch - Express Gulch |
| 4 | sericite-$Fe^{+2}$ bearing minerals | On ridge southwest from Hayden Peak |
| 5 | maghemite ? | Kerber Creek - Little Kerber Creek intersection and Eagle Gulch-Chloride Gulch |
| 6 | sericite-hematite | Kerber Creek - southern part of district |
| 7 | kaolinite-$Fe^{+2}$ bearing minerals | Kerber Creek - southeastern part of district |
| 8 | kaolinite-$Fe^{+2}$ bearing minerals with lesser goethite-jarosite | Section 11, southwest of Porphyry Peak |
| 9 | dolomite and calcite (lithologic, no mineral alteration). | Kerber Creek - southern and southeastern part of district |

## CONCLUSIONS

Areas within the Kerber Creek drainage that can have significant impact on environmental factors locally or more distant include mined and mineralized but unmined ground, flood plains, creek bottoms, and regions with natural alkali conditions. The impact of areas may be detrimental, or in the case of country rock that can neutralize acid waters, beneficial.

Mine dumps and mill tailings occur throughout the district, but are concentrated near the town of Bonanza. Several mills dumped tailings into ponds along Kerber Creek, which have since been breached, spreading clay, powdered rock, and heavy metals throughout the flood plain. Clay and silt erosion 'trains' are seen in the AVIRIS mineral maps of Kerber Creek.

Heavy metals (Pb-Zn-Cu), acid waters, and iron are derived from oxidation of sulfide rich rock that occur as mined material discarded on surface, mineralized rock exposed within mined workings, or mineralized rock exposed through erosion. This material is introduced into Kerber Creek where natural buffering capacity of the country rock (limestone and propylized volcanic rock) begin to neutralize the acidity of the transported material, and thus precipitate the iron and heavy metals. The clays, which carry these precipitates, are deposited along the stream banks and flood plains. Moran and Wentz (1974) have found that the combination of high iron content, low pH, and toxicity effect of high metal concentrations (Pb, Zn, Cu) eliminate all occurrences of aquatic macroinvertebrates and fish. Dissolved metals within the water exceed drinking water quality standards for 20 miles downstream.

Radioactive uranium and potassium occur throughout the district, but are most commonly associated with the caldera rim. Uranium also occurs within thicker parts of the Bonanza Tuff and at a local volcanic complex (Greenback Gulch).

Regions with potential impact on environmental factors are mineralized areas which are susceptible to slope failure. These are areas of steep, bare, mineralogically altered (clay rich) ground which may contain Pb-Zn-Cu and possibly uranium mineralization. A location map of these areas (figure 2) was generated using the DEM slope map, the TMS vegetation mask, the AVIRIS mineral maps, and the Uranium theme image.

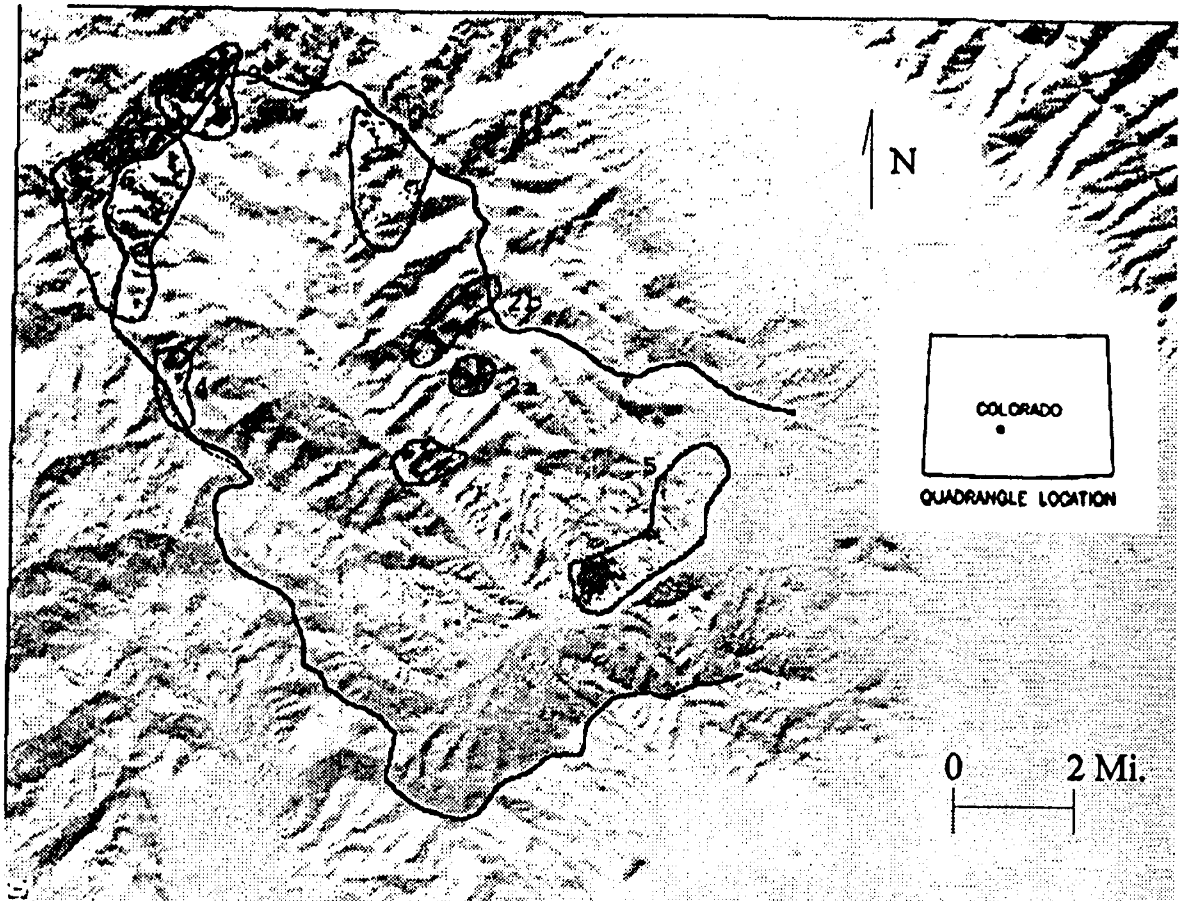


Figure 2. Outline of the Kerber Creek Drainage showing 8 regions of detected altered ground. Dark gray zones within the mineralized areas are classified as steep, bare, clay-rich areas that may be susceptible to slope failure.

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