# MAPPING HOT SPRING DEPOSITS WITH AVIRIS AT STEAMBOAT SPRINGS, NEVADA

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## 1.0 INTRODUCTION

Active and fossil hot springs systems occur worldwide, and share many common characteristics that indicate similar genetic histories (White 1955; Waring 1965; Rhinehart 1980; White 1981; Bowen 1989). This research studies the occurrence and characteristics of hot springs at Steamboat Springs, Nevada using Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data. Both high- and low-altitude AVIRIS were used to map and characterize the hot springs system. AVIRIS data identified several alteration minerals, including hydrothermal silica in both active and fossil sinter, and alunite and kaolinite associated with inactive acid-sulfate hot springs. Study of the nature and spatial distribution of specific hydrothermal alteration minerals at this hot springs using hyperspectral remote sensing provides insight into the geochemistry of the system, and to the occurrence and characteristics of hot springs systems in the fossil record, potentially leading to new and/or improved exploration methods for epithermal ore deposits.

## 2.0 HOT SPRINGS CHARACTERISTICS

**2.1 General:** There are thousands of active hot springs around the world occurring predominantly in association with volcanically active areas along spreading mid-oceanic ridges, convergent plate margins (subduction zones) and intraplate melting anomalies (Bowen 1989). Because these areas exhibit high variability in rock permeability, composition, structure, and available surface water, a wide range of surface materials and their related morphologic features occur. Thermal springs may form siliceous sinter, travertine, or other types of deposits at the surface, or they may not form any significant surface deposit at all. Active hot springs systems (and by inference, inactive and fossil systems), can simplistically be genetically divided into three general types based on water chemistry and the types of mineral deposits formed. These are 1) alkaline, siliceous-sinter-dominated systems, 2) travertine carbonate dominated systems, and 3) acid sulfate systems (Breckenridge et al., 1978) (White et al., 1988). Mixed types are also common within individual hot springs systems with both sinter-travertine and alkaline-sulfate transitional types indicating subsurface mixtures of the two types of water. The active hot springs at Steamboat, Nevada, are principally alkaline-type systems.

**2.2 Alkaline Systems:** The siliceous sinters commonly associated with the alkaline systems are purportedly initially deposited as opaline silica and subsequently converted to chalcedony at depth (White, et al., 1988). The alkaline systems are characterized by hot waters (near boiling temperature) carrying chlorides and carbonates as well as large amounts of dissolved silica. Flow rates are typically high and the silica usually forms broad sheets of siliceous sinter (Breckenridge et al., 1978). The sinter deposits are often covered with multi-colored algal mats.

**2.3 Travertine Systems**: The travertine areas are the result of carbon dioxide-rich waters dissolving carbonate rocks at depth and then depositing calcium carbonate as pressure and $CO_2$ decrease at the surface (Breckenridge et al., 1978). The presence of travertine-type deposits depends on spatial relationships to limestones, however, these deposits may also occur in non-limestone areas as calcium is leached from andesites and basalts.

**2.4 Acid Sulfate Systems:** Acid-sulfate systems are dominated by sulfate minerals such as alunite and free sulfuric acid as well as clay minerals like kaolinite and are commonly associated with ridge and slope areas with poor surface water supply (Breckenridge et al., 1978). Only small volumes of siliceous sinter are deposited. These areas are typically barren ground characterized by low flow, abundances of sulfurous gases, and silt/mud-laden waters which often form mudpots and mud volcanoes. Waters from these areas are low in chloride and silica, and high in sulfates. Acid sulfate areas often occur on the fringes of the basins, perhaps representing gas-dominated systems (Breckenridge et al., 1978).

**2.5 Epithermal Ore Deposits:** Epithermal precious metal ore deposits appear to be the fossil equivalents of high-temperature geothermal systems (White 1955; White 1981). Convincing criteria supporting this idea include: 1) ore components (Au, Ag, and other metals) have been found in active hydrothermal systems and these systems are known to transport metals (White et al. 1964, 1992), 2) ore components are often concentrated in unconsolidated Quaternary rocks from which hot springs emerge, 3) there are significant spatial associations between mineralized veins and hot springs, 4) some deposits are related to the present topographic surface, 5) deep alteration of hot springs that have been drilled shows zoning with depth similar to zones observed in epithermal deposits.

## 3.0 STEAMBOAT SPRINGS, NEVADA

**3.1 Location and Geology:** The Steamboat Springs hydrothermal system is described as a present-day equivalent of epithermal gold-silver deposits (White 1955; White 1967). This hydrothermal system, located just south of Reno, Nevada (Figure 1) is associated with four rhyolite domes, and thermal activity has probably been continuous for at least the past 0.1 m.y (Silberman et al., 1979). Numerous wells have been drilled at Steamboat for geothermal energy and to obtain hot water for local resort facilities. Wells range from 218 - 558 m with maximum measured temperature of 186 degrees C (White 1968; White 1981). The principal surface mineralogy reported at Steamboat consists of chalcedonic sinter deposits (Figures 1 and 2). Dark siliceous muds are also being deposited in the active springs and acid-leached opaline residues, kaolinite, and alunite occur in solfatarically altered granodiorite and basaltic andesite in the western part of the area (Figures 1 and 2) (Sigvaldason and White et al., 1962; White et al., 1964; Schoen and White 1967; Schoen et al., 1974). Significant concentrations of precious metals and related pathfinder elements occur in the Steamboat Springs sinter deposits, as chemical sediments in spring vents, and as veins at depth (White 1981). Gold was detected at the 1-2 ppm level along with anomalous Ag and As concentrations in analysis of samples from several drill holes, and small amounts of Hg has been mined from the Mercury mine at Steamboat (White et al., 1992). Deep drilling at Steamboat shows vein and alteration patterns that are indistinguishable from those of many epithermal ore deposits, containing adularia, illite, montmorillonite, and chlorite-group minerals as well as kaolinite, chalcedony, calcite, and quartz. Both stibnite and cinnabar are present near the surface, however, ore-grade concentrations of metals appear to be absent both in the near surface deposits and in the veins at depth.

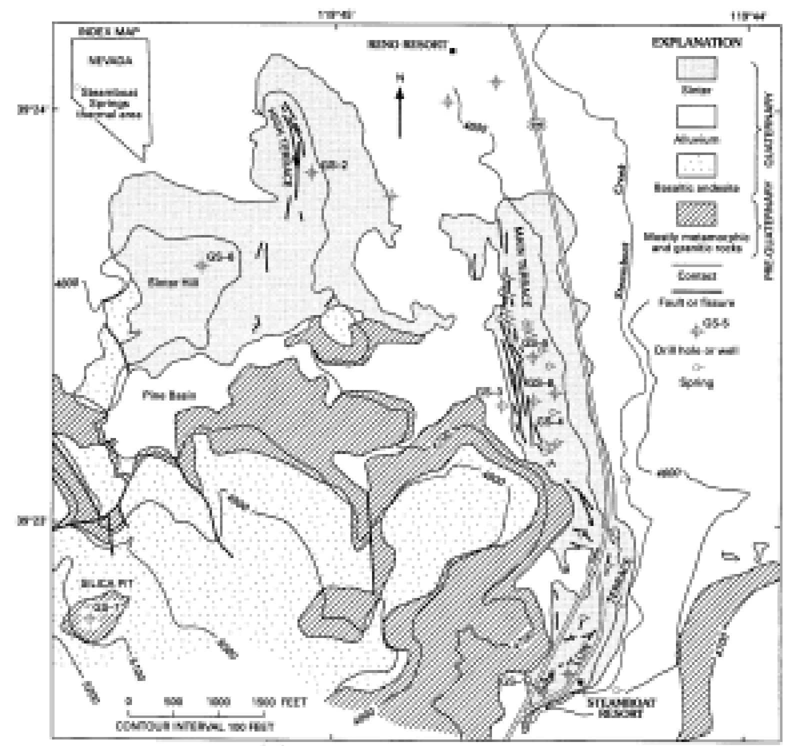


Figure 1: Location and Geology of Steamboat Springs, Nevada (from White et al., 1992)

Figure 2. Ground-level photographs at Steamboat Springs, Nevada.
Left photo shows silica sinter surface. Right photo shows acid-sulfate area.

**3.2 AVIRIS Data Analysis:** Remote sensing technology for geology has advanced tremendously over the last few years, particularly as regards the use of imaging spectrometers (hyperspectral sensors) for operational use. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Porter and Enmark, 1987; Green et al., 1999) has reached a level of excellence where it can be used for quantitative mineral mapping for a variety of geology subdisciplines (Kruse 1993). Atmospheric calibration is routinely done without ground measurements (Gao and Goetz 1990), and analytical methods now exist to go from raw radiance data to mineral maps on a relatively routine basis (Kruse et al., 1996).

AVIRIS data were acquired during July 1995 for the Steamboat Springs area as part of a reimbursable flight coordinated by AIG (Kruse et al., 1996) and during October 1998 as part of the JPL AVIRIS low altitude test program (Chrien et al, 1999). AVIRIS data from both flights were calibrated to apparent reflectance using the ATREM method (Gao. and Goetz 1990; CSES, 1992). Data were then analyzed using standardized procedures developed by AIG (Kruse et al., 1996). Figure 3 shows endmember spectra and mineral maps for the 1995 data (~20 meter pixels).

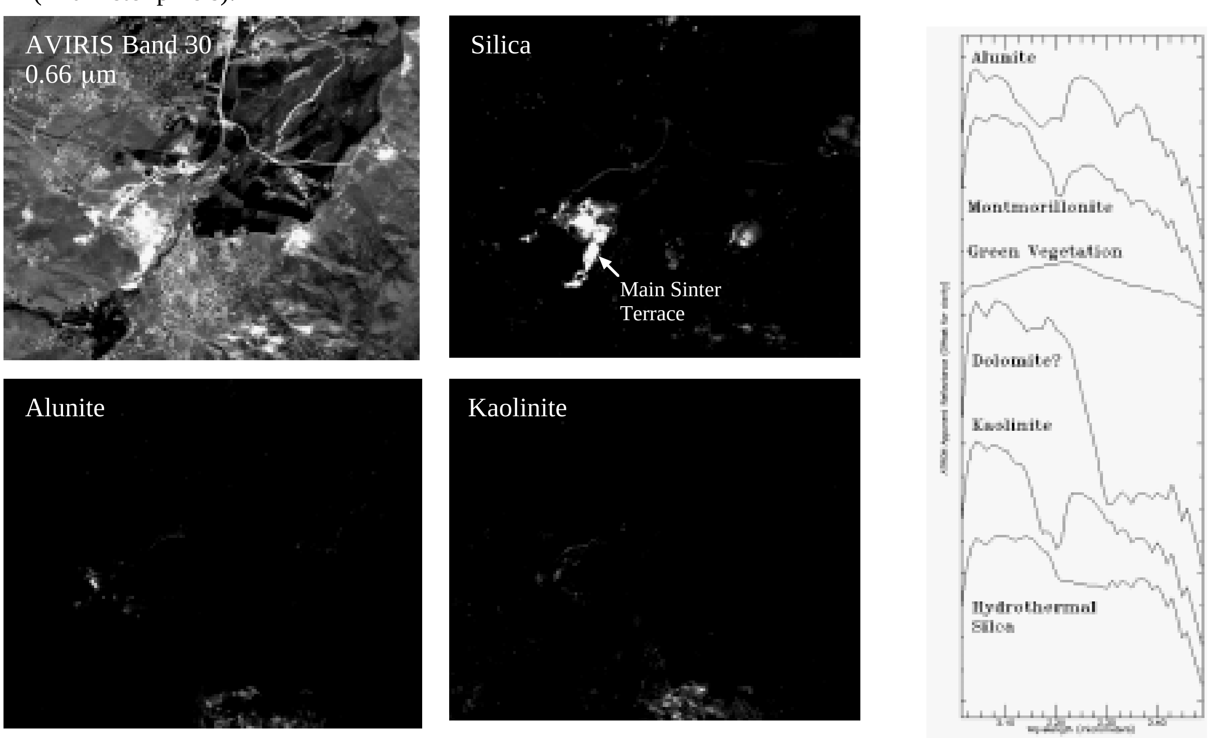


Figure 3: Steamboat, Nevada, 1995 AVIRIS results. Spectral plot shows AVIRIS image endmember spectra.

Bright areas on the images in Figure 3 represent high abundances. Figure 4 shows the endmember spectra extracted from the 1998 AVIRIS data (~2.4 meter pixels).

Standard methods used in this analysis are implemented in the ENVI software package, including spectral data reduction using the Minimum Noise Fraction (MNF) transformation, spatial data reduction using the Pixel Purity Index™ (PPI), endmember extraction using n-Dimensional Visualization™, and spectral identification using the Spectral Analyst™. Mineral abundance maps were created using matched filtering and Mixture-Tuned-Matched-Filtering™ methods (Kruse et al., 1996; Boardman, unpublished data).

**3.3 AVIRIS Results:** Both the 1995 and 1998 AVIRIS data show similar endmember mineralogies and spatial distributions. Most differences appear to be caused by the differences in spatial coverage caused by different pixel sizes. The predominant mineralogy at Steamboat Springs is the hydrothermal silica, exposed in silicious sinters. Peripheral to this are exposures of alunite and kaolinite. Montmorillonite is present, though not abundant. Both green and dry vegetation dominate outside the hot springs areas.

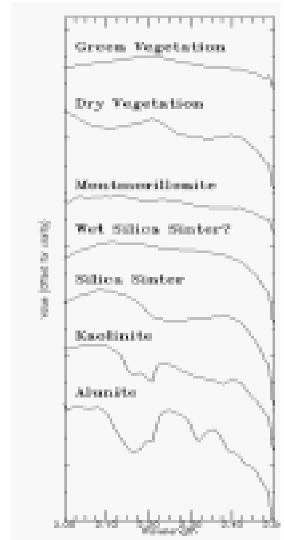


Figure 4. Steamboat, Nevada, 1998 AVIRIS Endmembers

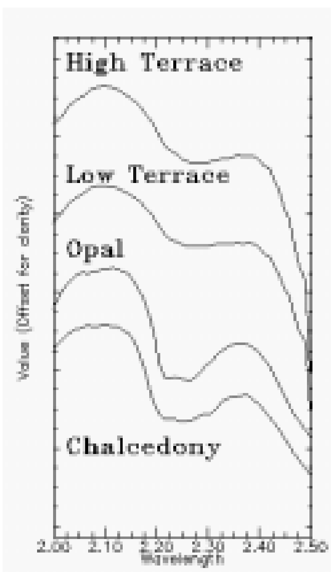


Figure 5: Comparison of active (low terrace) and inactive (high terrace) sinter spectra to library spectra of opal and chalcedony.

Active and inactive sinters at Steamboat Springs have been described as opal and chalcedony respectively (White et al., 1992). Spectral matching using Spectral Feature Fitting™, a least-squares band matching method (Kruse, unpublished data), however, indicates that AVIRIS spectra from both locations appear to best match an opal library spectrum. Figure 5 shows a comparison of 1998 AVIRIS spectra from the active terraces (Low Terrace) and the inactive terraces (High Terrace), compared to laboratory reflectance spectra of opal and chalcedony from the USGS Denver Spectral Library (Clark et al., 1993). At first glance, the opal and chalcedony spectra appear very similar, however, slight shape differences exist between the two species. When compared with the AVIRIS spectra, these cause preferred RMS fits to the opal laboratory spectrum.

AVIRIS results images were georeferenced to the 7 _" USGS topographic maps to allow direct comparison of the 1995 and 1998 mapping results. Figures 6 and 7 show silica, alunite, and kaolinite pixels overlain in various shades on a subset of the topographic map. Note the association of the mapped silica distributions with the low-lying areas, the "basin" and the apparent association of the mapped acid-sulfate areas with the fringing hills and ridges. This seems to support the idea that the distribution of mineralogy at Steamboat Springs was (and still is) controlled by the current topography. Also note that image coverage of the 1998 data was limited to the area outlined by the dashed lines in Figure 7.

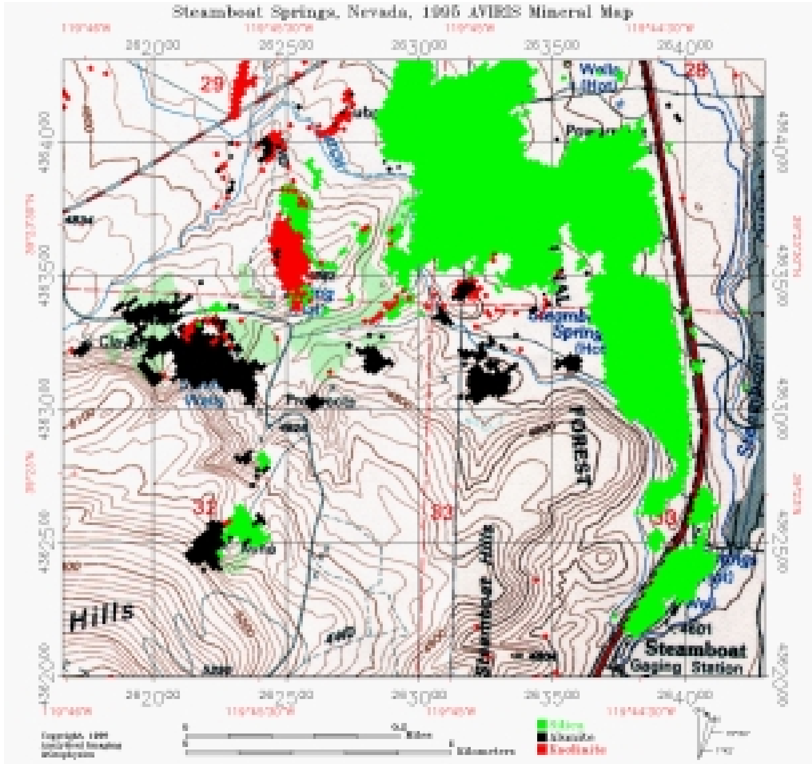


Figure 6:  Steamboat, Nevada, 1995 AVIRIS mineral mapping results

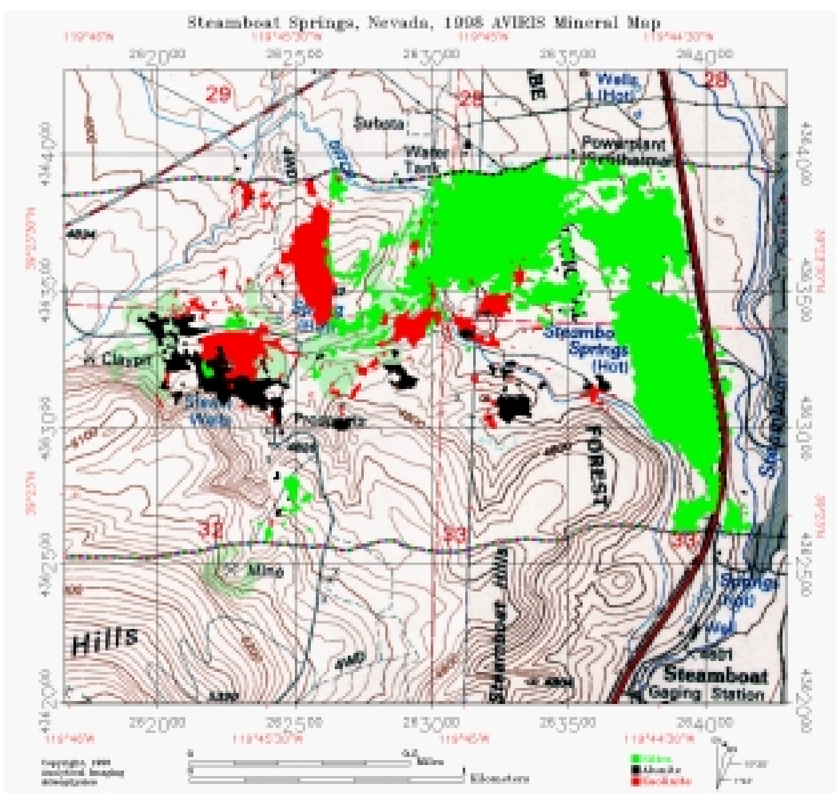


Figure 7.  1998 AVIRIS Low-Altitude mapping results.  Results have been generalized by clumping and sieving pixels. Dashed lines show extent of geocorrected 1998 AVIRIS coverage.

N-Dimensional scatterplotting of only the silica endmember spectra from the 1998 AVIRIS data was used in an attempt to break the silica sinter down into finer mineralogical detail.  Several similar hydrothermal silica spectra were extracted from the data (Figure 8).  Mixture-Tuned-Matched-Filtering was used to map the spatial distributions of materials having these subtle spectral differences.  At least three of these have unique spatial distributions, as shown in Figure 8.

Further field mapping and spectral measurements are required before the nature of these differences can be confirmed.

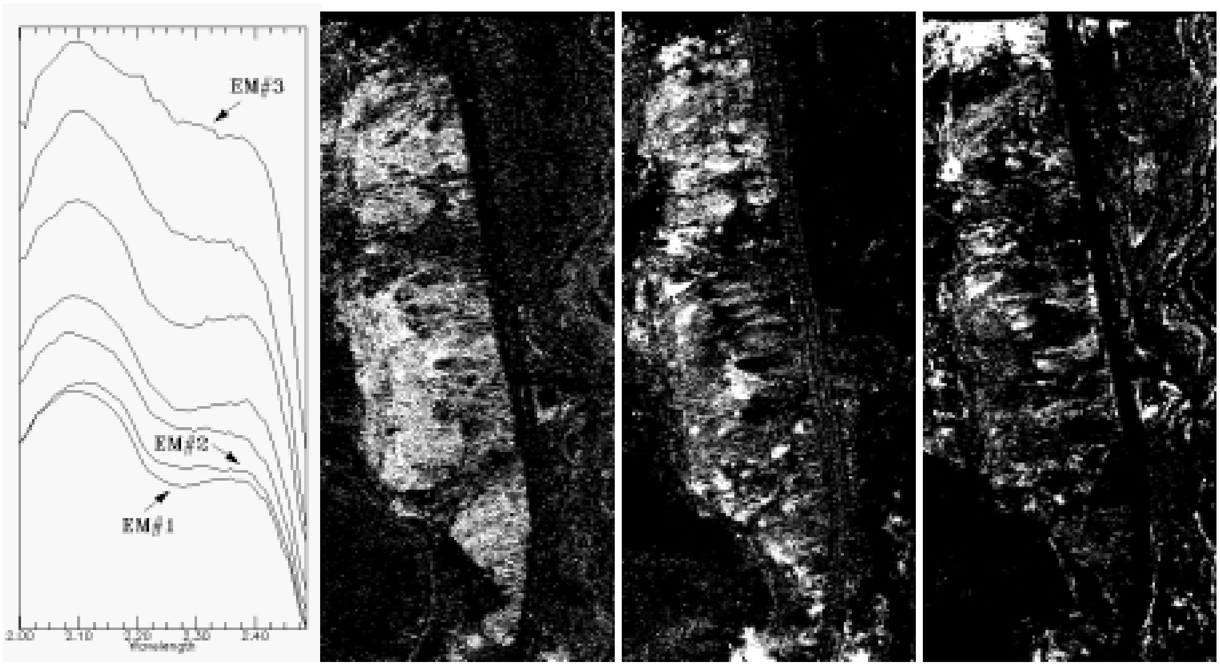


Figure 8: Spectral plots and Matched Filter images showing subtle spectral differences in 1998 AVIRIS data of the silica sinter at Steamboat Springs, Nevada. Plot shows endmember spectra. Three MF images show best matches to three distinct spatial occurrences, EM#1 (left), EM#2 (center), and EM#3 (right). Bright pixels in MF images represent best matches.

## 4.0 SUMMARY AND CONCLUSIONS

This research is using hyperspectral remote sensing to lead to a better understanding of the distribution of minerals related to hot springs and epithermal mineral deposits. Selected hot springs are being mapped and characterized using advanced hyperspectral analysis techniques, and methods for integrated study using LWIR data are under development.

Steamboat Springs provides an example of the hyperspectral mapping methodology and preliminary results. At the reconnaissance level, 1995 and 1998 AVIRIS produced similar results. The major minerals were detected and mapped. Radiometrically, the low-altitude data are excellent, producing similar quality to previous AVIRIS collects, but with much larger pixels. The geometric correction based on navigation data and GPS is internally consistent, however, it lacks absolute accuracy (RST using GCPs is required to match map/DEM) and positional errors are on the order of 100m in X and 500m in Y). Replicated pixels in the geo-corrected Low Altitude data present processing problems - both the data volume, and difficulty caused for algorithms by duplicate data

The AVIRIS data allow detailed mapping of the hot-springs-associated alteration mineralogy, including the distribution of the siliceous sinter based on an absorption feature near 2.25 μm. At Steamboat Springs, silica was mapped in terrace-like spatial patterns associated with known hydrothermal activity as well as on inactive terraces. AVIRIS data confirms Steamboat Springs as principally an alkaline hot-springs environment. Reported distributions of opal on active terraces, and chalcedony on inactive terraces, however, was not confirmed. The AVIRIS data indicate that all of the exposed silica is opaline. The 1998 low-altitude AVIRIS, with 2.4 meter spatial resolution, not surprisingly allows mapping of greater detail at the “deposit” level - “improved photo-interpretation” of spectral results. Spectral variability was observed and mapped within the active sinter terraces utilizing the 1998 AVIRIS data, however, the physical nature/cause is presently not known. An association was noted at Steamboat Springs between the hot-springs mineralogy and the topography, with the silica sinters located principally in the basins, and the acid-sulfate minerals along positive topographic features (ridges and hilltops) along the periphery of the basin.

Continued studies of a variety of hot springs will allow improved understanding of the link between active hot springs and the expression of fossil hot springs in the geologic record. Selected systems will be used to develop an operational exploration strategy utilizing integrated remote sensing for discovery and characterization of epithermal mineral deposits.

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