CHARACTERIZATION OF ACTIVE HOT-SPRINGS ENVIRONMENTS USING MULTISPECTRAL AND HYPERSPECTRAL REMOTE SENSING**

F. A. Kruse
Analytical Imaging and Geophysics LLC
4450 Arapahoe Ave, Suite 100
Boulder, Colorado, USA, 80303, kruse@aigllc.com

ABSTRACT

This research studies the occurrence and characteristics of hot springs systems using remote sensing data to provide insights into the origins of hydrothermal systems and precious metal ore deposits. Thermal Infrared Multispectral Scanner (TIMS) data and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data were used to map and characterize both active and fossil hot springs deposits. At Steamboat Springs, Nevada, TIMS delineates the silica sinter associated with active alkaline-type hot springs, while AVIRIS data map alteration minerals including alunite, kaolinite, and hydrothermal silica associated with inactive acid-sulfate hot springs. Sites studied at Yellowstone National Park, Wyoming, include Mammoth Hot Springs, a travertine system, and hot springs in the Firehole River basin, including active hydrothermal areas associated with the Upper, Midway, and Lower geyser basins. At Mammoth, AVIRIS maps several ages of travertine terraces as well as glacially-transported travertine material. At the Firehole River sites, mineralogy characteristic of the both the alkaline and acid-sulfate type hot springs, including alunite, kaolinite, and hydrothermal silica was mapped. Study of the nature and spatial distribution of specific hydrothermal alteration minerals at active hot springs using hyperspectral remote sensing provides insight into the geochemistry of these systems, 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.

1.0 INTRODUCTION

Active and fossil hot springs systems occur worldwide, and share many common characteristics that indicate common genetic histories (White 1955; Waring 1965; White 1981; Bowen 1989). Active hot springs occur as surface expressions of geothermally and volcanically active areas, commonly associated with rhyolite-composition volcanic rocks (Rhinehart 1980). These thermal springs are also common in a variety of rocks in areas of geologically recent folding and faulting (Waring 1965). Fossil hot springs are present as extinct portions of modern, active systems, and also preserved in the geologic record as epithermal mineral deposits (White 1955; White 1981). This research uses multispectral and hyperspectral remote sensing to study the occurrence and characteristics of both active and fossil hot springs, and to provide insights into the origins of various constituents of hydrothermal systems and precious metal ore deposits.

2.0 HOT SPRINGS CHARACTERISTICS

Active hot springs and geysers are dramatic examples of hydrothermal processes at work. There are thousands of active hot springs around the world (over 10,000 in Yellowstone National Park alone (Bryan 1986), 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-

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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 siliceous sinters commonly associated with the alkaline systems are initially deposited as opaline silica and subsequently converted to chalcedony at depth (White, et al., 1988). Other alteration minerals that may form at depth in hot springs systems include kaolinite, alunite, adularia, montmorillonite, illite, sericite, chlorite, pyrite, calcite, zeolites, and sodic plagioclase, as well as Ag, Au, Hg, Mn, W, Sb, Pb, Zn, Cu, As, Sn, and Fe ore minerals (White 1955). Chalcedony, quartz, and calcite are the most common vein minerals.

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. 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. 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. Sulfate areas often occur on the fringes of the basins, perhaps representing gas-dominated systems (Breckenridge et al., 1978). 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 MULTISPECTRAL AND HYPERSPECTRAL REMOTE SENSING

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) 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). Similarly, the Thermal Infrared Multispectral Scanner (TIMS) (Palluconi and Meeks, 1985) is a relatively mature technology, and its utility for geologic mapping is well established. Each of these systems, however, has its advantages and disadvantages. The AVIRIS can map secondary minerals (alteration and weathering), but can’t adequately map the primary rock forming materials (silica, feldspar). TIMS can map silica quite well, but doesn’t provide much information about other minerals and lacks the spectral resolution to fully resolve the restrahlen features. The obvious solution seems to be to use these two sensors in combination, in fact sensors like ASTER and MODIS are designed to provide spectral coverage similar to the combined coverage of these two instruments (albeit at lower spectral and spatial resolution). Yet, only a few studies have been conducted to combine these data at the first level (comparative analysis) (Abrams et al., 1991), and even fewer integrated digital analysis efforts have been undertaken.

The hot springs/epithermal mineral deposit association described above provides the perfect opportunity to develop integrated analysis methods for these data as well as to provide basic scientific results that will allow geologists to better understand these systems and to exploit their economic potential. AVIRIS data are well suited to map the suite of minerals associated with hot springs deposits including alunite, montmorillonite, sericite/illite, calcite, ammonium minerals, and surprisingly - hydrothermal silica (Podwysocki et al., 1985). Additionally, minerals like hematite, goethite, and jarosite, commonly deposited in hot springs deposits by thermophilic bacteria and algae are also easily detected using imaging spectrometer data. In the thermal IR, emission spectra of typical rocks indicate that this region is best suited for determining rock types based on shifts of the emissivity minimum from around 8.5 µm for framework silicates (quartz and feldspars) to progressively longer wavelengths for sheet and chain silicates, and isolated SiO_4 (Hunt 1980; Hook et. al., 1994). Despite their relatively low spectral resolution, the TIMS data are well suited to mapping the extensive sinter deposits associated with some hot springs because of their sensitivity to the silica restrahlen feature near 8.5 µm (Kahle and Goetz 1983; Hook et. al., 1994).

4.0 FEASIBILITY STUDIES AND PRELIMINARY RESULTS

The following examples are provided of preliminary work conducted with AVIRIS and TIMS data for the study areas described below to demonstrate the viability of the individual sensors for mapping hot springs systems, and to illustrate the need for combined and integrated analysis.

4.1 Steamboat Springs, Nevada (Alkaline/Siliceous Sinter)

The Steamboat Springs hydrothermal system is described as a present-day equivalent of epithermal gold-silver deposits (White 1955; White 1967). The hydrothermal system, located just south of Reno, Nevada 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 at Steamboat consists of chalcedonic sinter deposits. 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 (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.

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). AVIRIS data 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 and preliminary mineral abundance maps were created using matched filtering methods (Kruse et al., 1996). Figure 1 shows endmember spectra and the preliminary mineral maps. Bright areas represent high abundances. 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.

Both day and night TIMS data were acquired for AIG on a reimbursable basis by NASA Ames Research Center during September 1996. Two flightlines of TIMS data were processed using standard Decorrelation Stretch procedures (Gillespie et al., 1986) to segregate most temperature effects in the image intensity while enhancing emissivity differences by displaying most of this information in the image color variation. These two flightlines were roughly geometrically corrected to match the AVIRIS image above. Figure 2 shows band 3 of the TIMS decorrelated image. Areas with high concentrations of silica appear dark. The TIMS data allow more definitive mapping of silica alteration than the AVIRIS data, however, results are qualitative and limited to interpretation of the images. The characteristics of the TIMS and AVIRIS data are very complementary, providing a more complete picture of the alteration assemblages present around the active hot spring system.

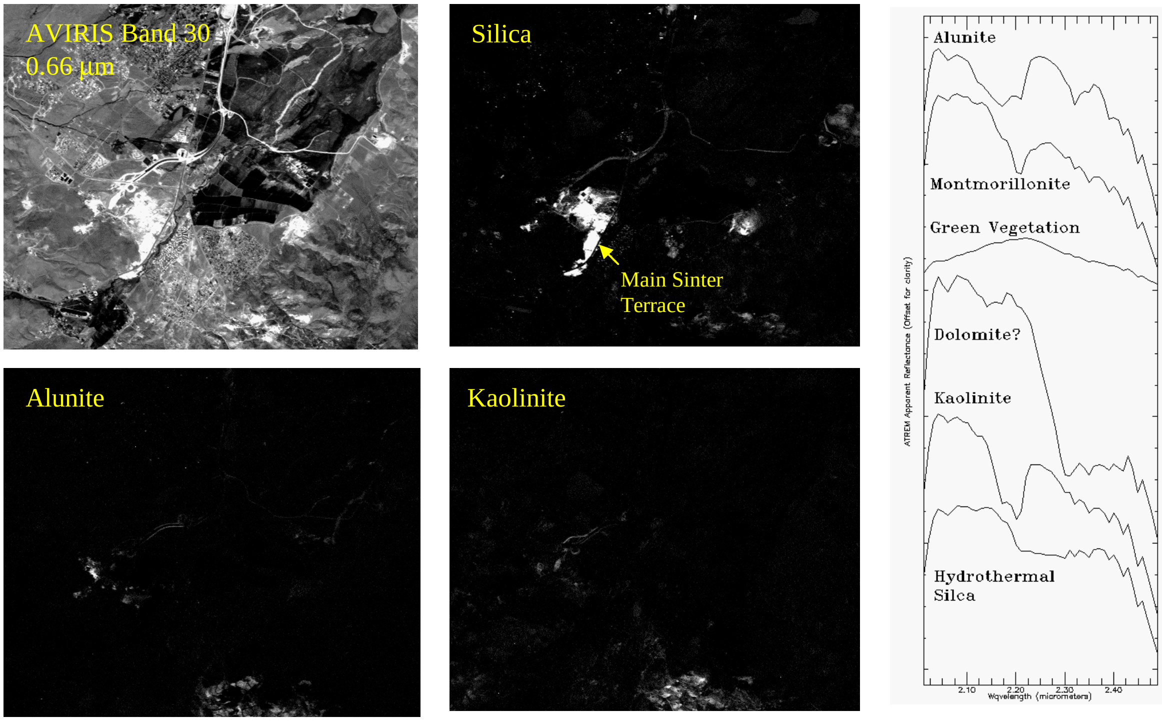


Figure 1: Steamboat, Nevada, 1995 AVIRIS results. Spectral plot shows AVIRIS image endmember spectra.

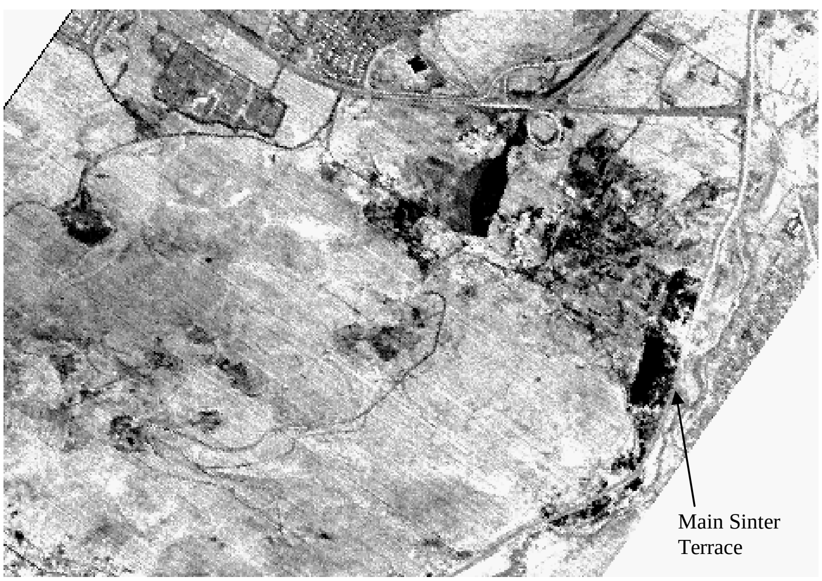


Figure 2: Steamboat, Nevada, 1996 TIMS results. Dark areas represent high silica concentrations

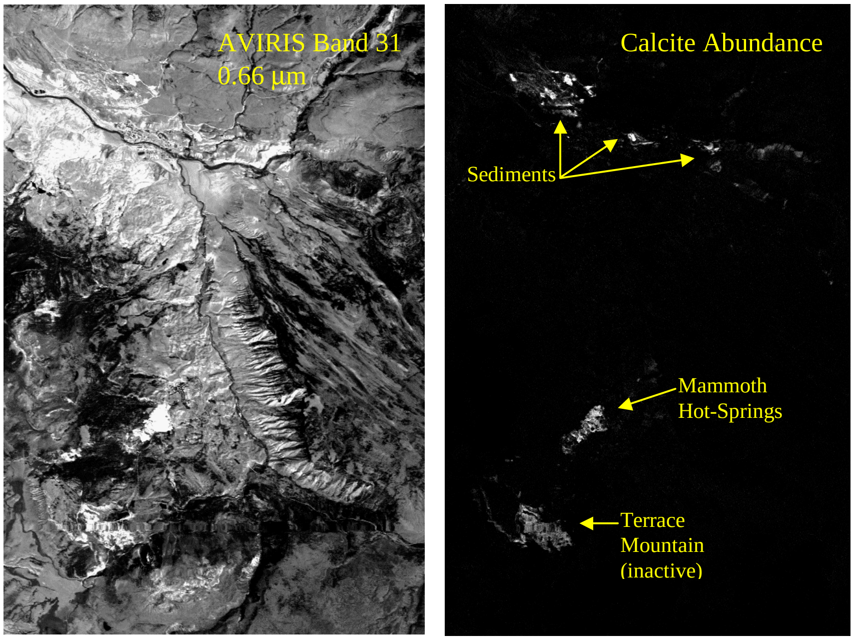
4.2 Yellowstone National Park (Alkaline/Siliceous Sinter, Acid-Sulfate, Travertine)

Yellowstone National Park covers nearly 3500 square miles in the northwest corner of Wyoming and contains the largest concentration of geothermal features in the world (Rhinehart 1980). The park contains around 100 hot springs groups, totaling over 10,000 individual thermal features (Bryan 1986). Yellowstone has been the site of extensive volcanism throughout the Cenozoic (Ruppel 1972), with the geyser basins underlain entirely by Quaternary-age rhyolitic rocks (Breckenridge et al., 1978). Regional fault systems and the Yellowstone Caldera control the distribution of thermal features (Eaton et al., 1975; White et al., 1988). The entire area has been extensively glaciated, and many of the springs and geysers issue from stream and glacial sediments derived from the rhyolites (Pierce 1979).

Yellowstone contains numerous examples of all three types of hot springs described above as well as mixed types (Breckenridge et al., 1978; Bryan 1986; White, et al., 1988). Specific examples from the alkaline-type (Upper, Midway, and Lower Geyser Basins) and travertine-type (Mammoth Hot Springs) are briefly described below. Acidic types (Mud Volcano area) and mixed types (Norris Geyser Basin) are also being studied, but not reported here.

The Upper, Midway, and Lower Geyser Basins of Yellowstone National Park occur along the Firehole River in the west central part of the park. The Upper Basin, containing over 150 hot springs and geysers, extends approximately 5 km northwest from Old Faithful along both sides of the river (Breckenridge et al., 1978). The large majority of thermal features have high flow, alkaline-composition waters, many of which commonly discharge directly into the river. Some acid-dominated systems occur along the fringes of the basin, characterized by low flow and minimal deposition of sinter and sulfur. Midway Basin occurs downstream along the Firehole River and contains approximately 30 springs with predominantly alkaline chemistry, including the largest single hot spring in the world, the Grand Prismatic Spring, which is more than 100 m across. The Lower Geyser Basin is the largest of all of the Yellowstone geyser areas, characterized by large, deep hot springs and alkaline geysers covering an area of approximately 40 square km. As in the Upper Geyser Basin, surrounding slopes and ridges characteristically have acid springs, mud pots, and fumeroles; some of the acid features, however, occur in close proximity to alkaline hot springs (Bryan 1986). Mammoth Hot Springs, at the north end of the park is a well defined example of the travertine hot spring type, consisting of over 100 hot springs scattered over a number of travertine terraces (Bargar et al., 1975). Many of the active terraces are colored by algae and bacteria in the hot springs and runoff areas (Bargar 1978). There are also many inactive and abandoned travertine terraces in the Mammoth area, including Terrace Mountain, and old travertine terrace blocks which occur in landslides near Silvergate. Other inactive travertine terraces are located at Soda Butte near the Park's northeast entrance (Breckenridge et al., 1978). The Mud Volcano area west of the Yellowstone river north of Lake contains primarily sulfate/acid waters (Breckenridge et al., 1978). The nearby Crater Hills have surface deposits of free sulfur. Norris Geyser Basin contains a wide variety of alkaline and acid features along with transitional thermal features indicating subsurface mixtures of the two different water types (White et al., 1988). Norris is characterized by an assortment of clear deep springs, geysers, sandy gas emitting areas, muddy springs and mudpots and widespread sinter and loose sulfur areas (Breckenridge et al., 1978). The basin displays a wide variety of chemical types of waters, precipitates and altered rocks which span nearly the entire range found elsewhere in the park (White et al., 1988).

AVIRIS data were acquired during August 1996 as part of U.S. Geological Survey efforts to map the national parks using AVIRIS data. These data were obtained from the U.S.G.S, and 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), individual reflectance spectra were extracted from the data, and preliminary image maps were created to show the varying hot springs characteristics. Study of two different areas within the park is in progress; the Mammoth Hot Springs area (a $CaCO_3$-dominated hot springs area as described above) and the Upper, Midway, and Lower Geyser Basins (alkaline-dominated with some acid springs). Figure 3 shows apparent reflectance spectra and a mineral abundance map for Calcite (Travertine) for the Mammoth Hot Springs area. Based on comparison to published geologic maps, AVIRIS successfully maps both active and inactive travertine terraces. Figure 4 shows apparent reflectance spectra and selected endmember abundance images for the Upper, Midway, and Lower Geyser Basins. Bright areas on the mineral maps represent high abundances. The AVIRIS data serve to illustrate differences in mineralogy between the basins and the ability of AVIRIS to map hydrothermal silica in siliceous sinter materials.



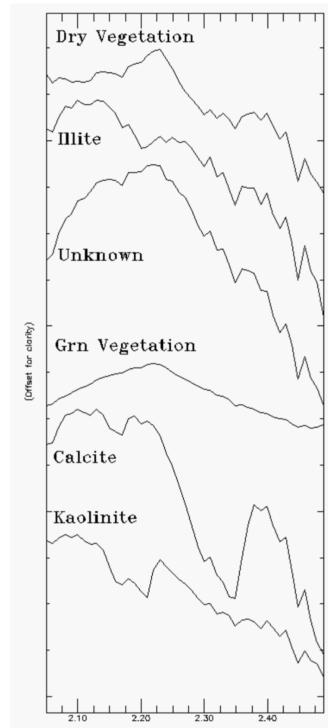


Figure 3: Mammoth Hot-Springs 1996 AVIRIS Results.

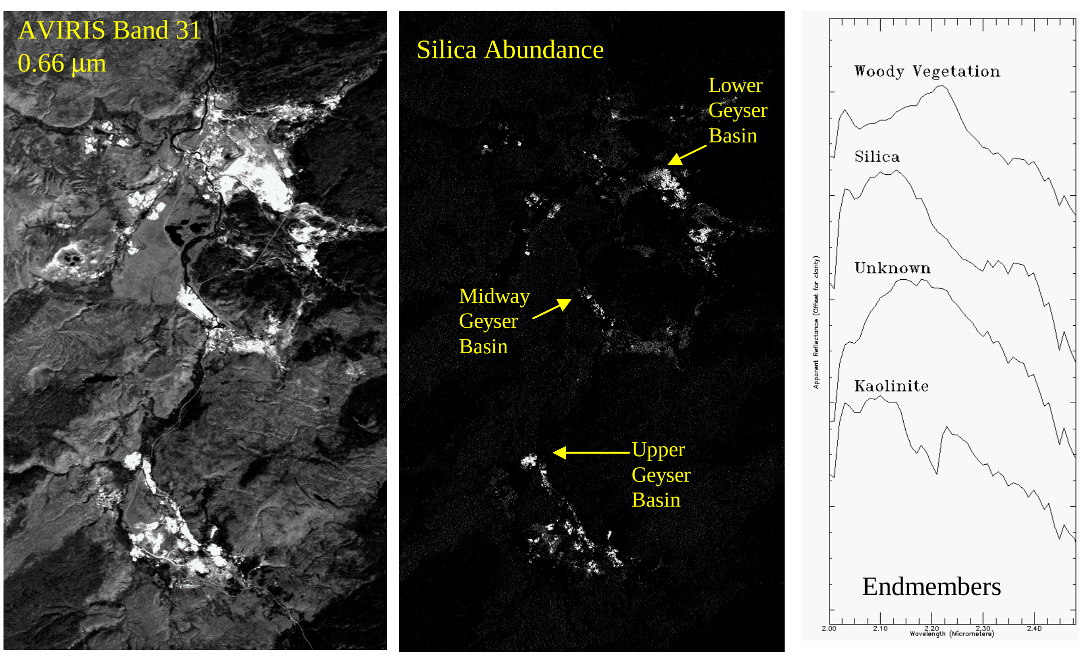


Figure 4: Firehole River 1996 AVIRIS Results

5.0 SUMMARY

This research is using the combination of multispectral thermal infrared and 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 these technologies, and methods for integrated study are under development. We expect that the results will reaffirm the link between the active hot springs and fossil hot springs in the geologic record, resulting in improved understanding of specific systems and an operational exploration strategy utilizing integrated remote sensing for discovery and characterization of epithermal mineral deposits.

6.0 REFERENCES CITED

Abrams, M., Abbot, E., and Kahle, A. B. (1991). "Combined use of visible, reflected infrared, and thermal infrared images for mapping Hawaiian lava flows." Journal of Geophysical Research **96** (B1): p. 475-484.

Bargar, K. E. (1978). "Geology and thermal history of Mammoth Hot Springs, Yellowstone National Park, Wyoming." U. S. Geological Survey Bulletin 1444: 55 p.

Bargar, M. L., and Muffler, L.J.P. (1975). "Geologic map of the travertine deposits, Mammoth Hot Springs, Yellowstone national Park, Wyoming." U.S. Geological Survey Miscellaneous Field Studies Map MF-659 1:4,8000 and 1:2,400 scale.

Bowen, R. (1989). Geothermal Resources. New York, Elsevier.

Breckenridge, R. M., and Hinckley, B. S. (1978). "Thermal springs of Wyoming." Geological Survey of Wyoming Bulletin 60: 104 p.

Bryan, T. S. (1986). The Geysers of Yellowstone. Boulder, Colorado, Colorado Associated University Press, 299 p.

Center for the Study of Earth from Space (CSES) (1992). "ATmosphere REMoval Program (ATREM), Version 1.1." Internal Report, University of Colorado, Boulder: 24 p

Eaton, G. P., Christiansen, r. L., Iyer, H. M., Pitt, A. M., Mabey, D. R., Blank, H. R. Jr., Zietz, I., and Gettings, M. E. (1975). "Magma beneath Yellowstone National Park." Science **188**: pg 787-796.

Gao B. and Goetz, A. F. H. (1990). "Column atmospheric water vapor and vegetation liquid water retrievals from airborne imaging spectrometer data." Journal of Geophysical Research **95**(D-4): p. 3549-3564.

Gillespie, A. R., Kahle, A. B., and Walker, R. E (1986). "Color enhancement of highly correlated images I." Remote Sensing of Environment **20**: p. 209 - 235.

Hook, S. J., Karlstrom, K. E., Miller, C. F., and McCaffrey, K. J. W. (1994). "Mapping the Piute Mountains, California, with thermal infrared multispectral scanner (TIMS) images." Journal of Geophysical Research **99**(B8): p. 15605 - 15622.

Hunt, G. R., Ed. (1980). Electromagnetic Radiation: The communication link in remote sensing. Remote Sensing in Geology. New York, John Wiley.

Kahle, A. B., and Goetz, A. F. H. (1983). "Mineralogic information from a new airborne thermal infrared multispectral scanner." Science **222**(4619): 24 - 27.

Kruse, F. A. (1993). Imaging Spectroscopy: New directions for terrestrial geology. Remote Geochemical Analysis: Elemental and Mineralogical Composition. C. M. in Pieters, and Englert, A. J. New York, Cambridge University Press**:** 283-307.

Kruse, F. A., Huntington, J. H., and Green, R. O (1996). "Results from the 1995 AVIRIS Geology Group Shoot." Proceedings, 2nd International Airborne Remote Sensing Conference and Exhibition **I**: p. I-211 - I-220.

Palluconi F. D, and Meeks, G. R. (1985). "Thermal Infrared Multispectral Scanner (TIMS): An investigator's guide to TIMS data." JPL Publication 85-32: 14 p.

Pierce, K. L. (1979). "History and dynamics of glaciation in the northern Yellowstone Park area." U.S. Geological Survey Professional Paper 729-F: 90 p.

Podwysocki, M. H., Salisbury, J. W., and Vergo, N. (1985). "Use of near-infrared spectra to distinguish between sedimentary cherts and hydrothermal silica associated with disseminated gold deposits (Abst.)." Geological Society of America Abstracts with Programs 1**7**: 691.

Porter, W. M., and Enmark, H. E. (1987). "System overview of the Airborne Visible/Infrared Imaging

Spectrometer (AVIRIS)." in Proceedings, Society of Photo-Optical Instrumentation Engineers (SPIE) 834: p. 22-31.

Rhinehart, J. S. (1980). Geysers and Geothermal Energy. New York, Springer-Verlag.

Ruppel, e. T. (1972). "Geology of pre-Tertiary rocks in the northern part of Yellowstone National Park, Wyoming." U.S. Geological Survey Professional Paper 729-A: 66 p.

Schoen, R., and White, D. E., (1967). "Hydrothermal alteration of basaltic andesite and other rocks in drill hole GS-6, Steamboat Springs, Nevada." U.S. Geological Survey Professional Paper 575-B: p. 110-119.

Schoen, R., White, D. E., and Hemley, J.J. (1974). "Argillization by descending acid at Steamboat Springs, Nevada." Clays and Clay Minerals 22: p. 1-22.

Sigvaldason, G. E., and White, D. E. (1962). "Hydrothermal alteration in drill holes GS-5 and GS-7, Steamboat Springs, Nevada." U.S. Geological Survey Professional Paper 450-D: D113-D117.

Silberman, M. L., White, D. E., Keith, T. E. C., and docktor, R. D. (1979). "Duration of hydrothermal activity at Steamboat Springs, Nevada , from ages of the spacially associated volcanic rock." U. S. Geological Suvey Professional Paper 458-D: 14 p.

Waring, G. A. (1965). "Thermal springs of the United States and other countries of the world -- A Summary." U.S. Geological Survey Professional Paper 492: 383 p.

White, D. E. (1955). "Thermal springs and epithermal ore deposits." Economic Geology Fiftieth Anniversary Volume: p. 99-154.

White, D. E., Anderson, E. T., and Grubbs, D. K.. (1963). "Geothermal brine well/mile-deep drill hole may tap ore-bearing magmatic water and rocks undergoing metamorphism." Science 139(p. 919-922).

White, D. E., Thompson, G. A., and Sanberg, C. S. (1964). "Rocks, structure, and geologic history of Steamboat Springs thermal area, Washoe County, Nevada." U. S. Geological Survey Professional Paper 458-B: 63 p.

White, D. E. (1967). "Some principles of geyser activity, mainly from Steamboat Springs, Nevada." American Journal of Science 265(8): p. 641-684.

White, D. E. (1968). "Hydrology, activity, and heat flow of the Steamboat Springs thermal systems, Washoe County, Nevada." U. S. Geological Survey Professional Paper 458-C: 109 p.

White, D. E. (1981). "Active Geothermal Systems and Hydrothermal Ore Deposits." Economic Geology 75th Anniversary Volume: p. 392-423.

White, d. E., Hutchinson, R. A., and Keith, T.E.C. (1988). "The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming." U.S. Geological Survey Professional Paper 1456: 84 p.

White, D. E., Heropoulos, C., and Fournier, R. O. (1992). "Gold and other minor elements associated with the hot springs and geysers of Yellowstone National Park, Wyoming, supplemented with data from Steamboat Springs, Nevada." U.S. Geological Survey Bulletin 2001: 19 p.