Preliminary Results of Hydrothermal Alteration Assemblage Classification in Aurora and Bodie Mining Districts, Nevada and California, with Airborne Hyperspectral Data

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ABSTRACT

The Aurora and Bodie mining districts are located in Bodie Hills, north of Mono Lake, on opposite sides of the Nevada-California state line. From the standpoint of economic geology, both deposits are structurally controlled, low-sulfidation, adularia-sericite precious metal vein deposits with an extensive alteration halo. The area was exploited from the late 1870's until 1988 by both underground and minor open pit operations (Aurora), exposing portions of ore-hosting altered andesites, devitrified rhyolites as well as quartz-adularia-sericite veins. Much of the geologic mapping and explanation was ad-hoc and primarily in support of the mining operations, without particular interest paid to the system as a whole. The University of Nevada, Reno has acquired both high- and low-altitude AVIRIS data of the region. Low-altitude data was acquired in July 2000, followed by high-altitude collection in October 2000. The AVIRIS coverage was targeted on the main vein system in Aurora (Prospectus and Humboldt Vein), East Brawley Peak prospect (midpoint between Aurora and Bodie) and "Bonanza Zone" (Bodie Bluff and Standard Hill) in Bodie, where the hydrothermal alteration zones appear to be the most pervasive. The ground-observations and mining/prospecting reports suggest propylitic alteration throughout the Bodie Hills, argillic and potassic alteration in Aurora and Bodie, (low-sulfidation system) and alunitic alteration (high-sulfidation system) on East Brawley Peak.

The AVIRIS data allows identification of alteration zones containing dominant kaolinite, sericite (Aurora), alunite (E. Brawley Peak) and Na and Ca-montmorillonite (Bodie), which have been verified with ASD spectrometer and XRD analysis on field collected samples. Spectral mapping is somewhat hindered by anthropogenic factors (mine dumps and reclamation efforts) and coatings (heavy varnish and pyroclastic "sand" from Inyo Craters). We will present the mapping results from the high-altitude data set and an initial comparison to the low-altitude scene.

AREA and GEOLOGY

Aurora:

The Aurora district, formerly known as the Esmeralda Mining District, was discovered in 1860 by J. M. Braly, E. R. Hicks and J. M. Cory. Most of the estimated 1.6 million ounces of gold and 2.4 million ounces of silver was produced in the heyday of the district between 1862 and 1865 with sporadic production up to 1988. The district is located in the Bodie Hills, south of Hawthorne, Nevada (via Lucky Boy Pass) and northeast od Bridgeport, California (via Bodie Road) (Figure 1). The area is mountainous with elevations ranging from 1,716 m (5,150 ft) at Fletcher Valley to (3,675) 11,015 on Potato Peak and characterized by semi-arid climate and vegetation characteristic for Great Basin (Sagebrush, Rabbitbrush, Mormon tea, Cacti, Pinon pine, Jeffrey pine and Juniper).

The oldest rocks in the district are metavolcanics of the Mid-Triassic Excelsior Formation, intruded by Cretaceous Sierra Nevada Granites. Tuffs (15 Ma?) and andesitic lava flows and breccias (14.8 Ma) of East Brawley Peak are resting unconformably upon the granitic and metavolcanic basement. The East Brawley Andesites (Aurora Andesites 13 Ma) are the main body of mineralized andesites found in the Aurora district. Del Monte shaft, sank to a depth of 700 m (2200 ft), had not reached the lower contact of the Aurora Anesdite sequence. An episode of rhyolitic volcanism occurred at about 11.2 Ma intruding the andesites and tuffs, followed by hydrothermal activity, alteration and most likely precious metal mineralization in the Aurora area (at 10.2 Ma). Approximately 3 Ma ago, the style of volcanism shifted from Calc-alkaline to alkalic-calcic. Another episode of rhyolitic volcanism occurred around 2.5 Ma with emplacement of Aurora Peak and Martinez Hill. The volcanism in the district ceased with emplacement of Aurora Crater basalts (25 Ka) (Breit, 2000; Al-Rawi, 1970). The district mineralization itself, appears to be structurally controlled and related to N20E trending right-lateral strike slip faults (Osborne, 1986). The most significant alteration assemblages (sericitic, argillic) appear to be closely associated with the fault-contact between 13 Ma Andesite and 11 Ma rhyolite, although almost all of the Aurora Andesite in the district appears to be altered to a degree (Field observations, Larson, L.T. Pers. Comm). The mineralized veins in the district appear to follow zones of earlier structural weaknesses and most likely have been deposited from meteoric hydrothermal waters, contemporaneous with the emplacement of Rhyolite flow dome, which may have provided the heat to drive the hydrothermal system. The system at Aurora is classified as a Quartz - Sericite - Adularia type gold deposit. Thin sections reveal that the veins are dominantly Quartz with a few percent or less of Sericite and a fraction of a percent or less of adularia (K-feldspar). Adularia appears to be replacing earlier bladed, hydrothermal calcite. The dominant ore mineral in the veins is electrum with associated trace amounts of the silver sulfides: acanthite, aguilarite, proustite, pyragyrite, and pearcite. Gangue minerals include pyrite, goethite, and in some veins trace amounts of arsenopyrite and sphalerite. The type of ore found in the veins varies: disseminated electrum in a coarse grained quartz, electrum deposited along the boundaries of well defined bands or ribbons of quartz and occasionally, electrum encapsulated in pyrite and/or goethite (Nevada Goldfields Internal Report, 1988).

Bodie:

The Bodie Mining District was incorporated in 1860, and several reports were written in the years that followed, most notably by Joseph Watson, who had prepared a preliminary report for members of the New York Bullion Club and H.A. Whiting's report to the USGS and Bodie Consolidated Mining Company in 1888 (State Mineralogist Report, 1888). Empire Mill and Mining Co. of New York, NY incorporated and consolidated earlier claims and invested large sums of money in the district in 1863. By 1865, no substantial ore was found. Empire abandoned the operation and the district was held in very low regard until 1872 when rich ore was struck. In 1876, San Francisco venture capitalists bought the mines and ran the operation until 1883. The mining in the district ceased in 1947. Bodie is now a part of the California State Park system.

The rock units found around Bodie are mainly composed of tuff breccias, dacite flows and some intrusive dacite. Volcanism commenced in Bodie Hills and eastward, approximately ~17 Ma ago with eruptions of calc-alkaline andesite, dacite and rhyodacite onto topographically flat surface (presumably of sedimentary origin) (Kleinhampl et al., 1975). Initial geothermal activity began at Masonic District (northern Bodie Hills, ~20km NE of Bodie). Two distinct episodes of geothermal activity at ~7.8 Ma and ~7.2 Ma (Silberman, et al., 1972), produced economic mineralization in Bodie District, although some hydrothermally altered areas at Bodie may be related to an earlier, non-economic, hydrothermal activity of 8.4 Ma (Chesterman et al., 1986). The mineralizing events in Bodie are geochemically and minerologically distinct (Brown, 1907; Silberman, 1995) and are localized on the southeast flank of the alkali-calcic Bodie Mountain – Potato Peak stratovolcanoes (Chesterman et al., 1986). The hydrothermal alteration in Bodie is widespread and appears to have had four major episodes, beginning with propylitic and following, in succession, by argillic, potassic and silicic. Propylitic alteration is widespread over 9 square mile radius and appears to have affected all rock types regardless of composition or structure. Argillic alteration is characterized by montmorillonite, kaolinite and minor sericite and appears to be concetrated along joints and fractures. Potassic alteration appears to be confined to the rocks in and surrounding the Bodie Bluff-Standard Hill. Silicic alteration is, most likely, the last stage of the hydrothermal activity and perhaps a factor in the formation of quartz veins. Similar to Aurora, Bodie is classified as a low-sulfidation epithermal vein depost.

AVIRIS FLIGHTS and PREVIOUS WORK

Bodie was targeted for 1992 AVIRIS overflight and the data have been processed by Crosta, Sabine and Taranik (1998) and USGS (Trude King, unpublished report). Both parties were successful in extracting Ca and Na-montmorillonite spectra from the 1992 imagery as well as spectra of Fe-oxides and hydroxides. The goal of the project was to compare the alteration systems at Bodie and Paramount (a small mercury mine west of Bodie) and methods of spectrally classifying the deposits (using SAM and Tricorder). The zones of iron and clay enrichment were corresponding with the mineralized areas in Bodie. The University of Nevada Reno proposed both high altitude and low altitude flights over Bodie and Aurora for the 2000 flight season. The low altitude data were acquired on July 9, 2000 and high altitude on September 19, 2000. The AVIRIS data are to be used in conjunction with other data sets and extensive field observations in understanding the structural and lithologic constraints to mineralization in the districts.

IMAGE PROCESSING

Both high and low altitude data sets were ATREM corrected, but only the high altitude set was EFFORT polished; the procedure has created significant artifacts in the low altitude set. For the preliminary analysis, both sets were subsetted to SWIR range and individual scenes mosaicked. A Minimum Noise Fraction (MNF) transformation was used to produce spectral bands free of instrumental and/or atmospheric noise. A Pixel Purity Index (PPI) routine was then used to select all of the pixels in the image that are above the noise floor and appear to contain unique spectra that can be further used to determine spectral “end members.” The term “end member” is used to denote a pixel that contains unique spectra that is representative and characteristic of a dominant mineral, or intimate mixtures of minerals. The improved signal to noise of AVIRIS allowed 11 characteristic end members to be selected from the high altitude and 16 from the low altitude data. These end members were used to further process the image using the Mixture Tuned Matched Filtering (MTMF) and Spectral Angle Mapper (SAM) algorithms. The results from the application of these algorithms, and comparison with the USGS spectral library produced relative mineral abundance thematic displays for the main mineral constituents, including alunite, kaolinite, illite, muscovite (sericite), and na, ca-montmorillonite. Additionally, the low-altitude data have the inherent geometric distortions and under sampling in the down-track direction because of aircraft pitch, yaw and roll and instrument constraints. The low-altitude scene was co-registered to a special reference file compiled by AIG for NASA. This file contains information on actual and “artificial” pixels used to georectify the flight line. The reference file was used to create an image mask to drape over the image thus highlighting only actual spectral measurements for classification.

RESULTS

The analysis of high altitude data allowed indentification of alunite, kaolinite and sericite in the Aurora-Bodie transect (Figure 2). The main body of hydrothermal alteration in Aurora, is associated with the main vein system.The mineral classes include sericite (in proximity to the veins), illite and kaolinite associated with the vein alteration halo, kaolinite distributed throughout the district, but particularly evident in the section of altered rhyolites, immediately west of the main mine works. It was also possible to distinguish some exposed quartz-veins by their lack of spectral features in SWIR. Similarly, in Bodie it is possible to distinguish the zones of Ca-Na montmorillonite and Kaolinite with minor sericite. The main body of alteration is constrained in the so-called “Bonanza Zone;” an extensional graben including the Bodie Bluff and Standard Hill with a minor splay on Queen Bee Hill (south of the Bonanza Zone and delineated by the Red Cloud fault). Aside from the mining district, it is also possible to distinguish alunite associated with the high-sulfidation hydrothermal system on East Brawley Peak, illite and kaolinite associated with sections of altered granites near Spring Peak and rhyolites near Rough Creek.

The low altitude data, centered at the districts themselves allow better spectral classification with the improved spatial resolution. In Aurora, it is possible to distinguish the areas of sericitic alteration and display them in the more field-observable context. Furthermore, it is possible to trace the argillic alteration (kaolinite, illite) along the length of Prospectus fault (which may be the primary structure responsible for the mineralization in the district) and trace it in the areas where it may not be well exposed (the actual extent of the fault is a point of violent dispute among the mine geologists in Aurora). The low-altitude data also allows identification of, what appears to be supergene, clay in the tuffaceous sediments ringing the Martinez Hill. In Bodie, it is possible to map the distribution of kaolinite on Bodie Bluff and Ca-Na montmorillonite on Standard Hill with a sericitic zone in between. Relatively sharp contact between the mineralogic units appears to be congruent with the normal faults defining the “Bonanza Zone.” In particular the distribution of sericite corresponds with the approximate location of mineralized veins at depth.

The AVIRIS spectral measurements were checked with field-measured spectra and XRD diffraction on select samples (Figure 3). Both XRD spectra and ASD field-spectra support the results obtained from AVIRIS.

DISCUSSION AND CONCLUSIONS

Most of the mining in Aurora and Bodie was concentrated on “chasing the veins” through the district where the miniscule structural features or surficial expressions of the vein at depth (alteration) made the difference in choosing the mineralized versus barren vein. The high altitude AVIRIS data gives an excellent overview of the terrain, with predominat alteration types on the district level. However, the integration with the low-altitude data sets allows interpretation and characterization at the sub-district level, which was the historic way of exploring the district. The high altitude data tends to clump the spectral measurements and masks them with the robust spectral signature of the dominant material (the mixed pixel problem). In Aurora and Bodie it is very difficult to hone in on sericite – its features are often masked by much more dominant clay absorption features. However, the increased spatial resolution of the low altitude data set allows for the effective mapping of sericite and interpretation of how it fits within the vein system. Further, it is possible to observe the zones that may be associated with the fault system in the district, most notably the extent of the Prospectus Fault (through argillized fault breccia) and its relation to the mineralization in the district.

When compared to the 1992 data over Bodie, the 2000 data set presents a dramatic improvement in both spectral and spatial domains . The addition of the low-altitude data enhances the mapping potential and allows an easy integration with the field orientation and mapping. Mineralogic assignments corresponding to structural boundaries are a tremendous asset in use and application of the data and may help resolve differing interpretation of fault location and extent.

ACKNOWLEDGMENTS

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FIGURES:

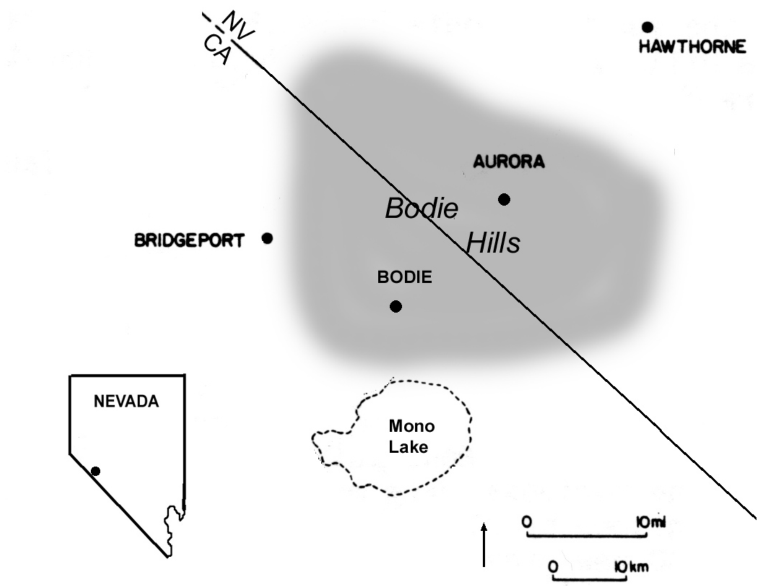

Figure 1 – Area Location

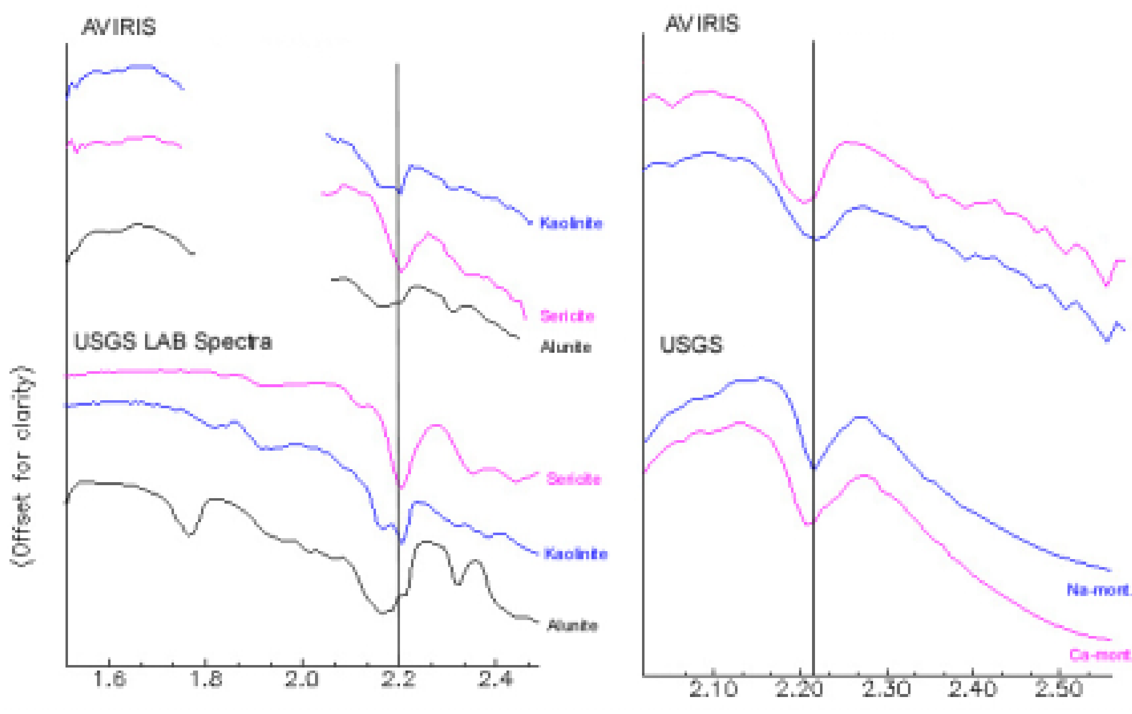

Figure 2 – AVIRIS and LAB Spectra

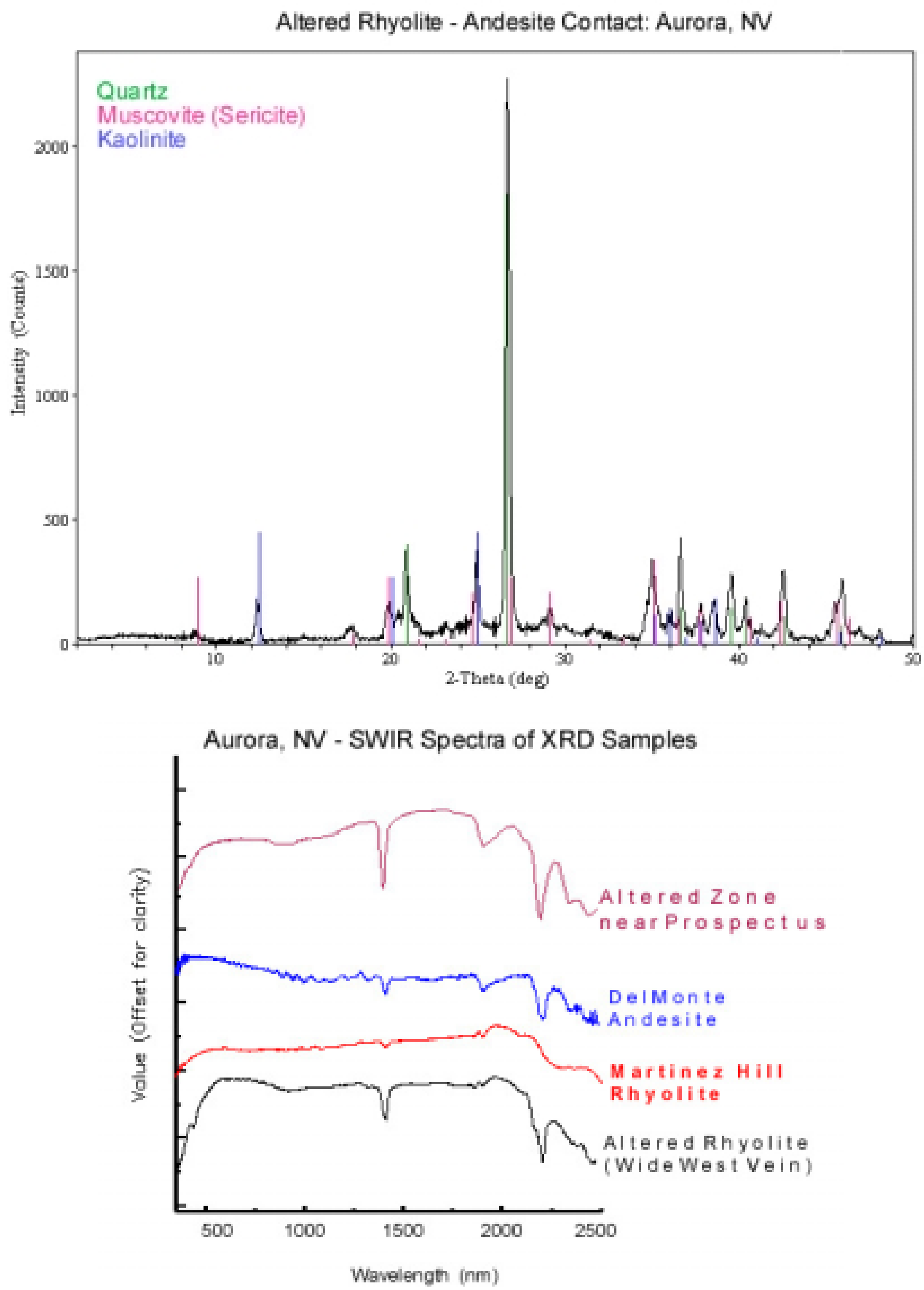

Figure 3 – XRD Spectra and ASD Field Spectra on XRD samples.

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