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## **QUANTITATIVE REMOTE SENSING OF AMMONIUM MINERALS, CEDAR MOUNTAINS, ESMERALDA COUNTY, NEVADA**

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### **1. INTRODUCTION**

Mineral-bound ammonium ( $\text{NH}_4^+$ ) was discovered by the U.S. Geological Survey in the southern Cedar Mountains of Esmeralda County, Nevada in 1989. At 10 km in length, this site is 100 times larger than any previously known occurrence in volcanic rocks (Krohn, 1989). The ammonium occurs in two hydrothermally altered, crystal-rich rhyolitic tuff units of Oligocene age, and is both structurally and stratigraphically controlled. This research uses Advanced Visible/Infrared Imaging Spectrometer (AVIRIS) data to quantitatively map the mineral-bound ammonium (buddingtonite) concentration in the altered volcanic rocks.

Naturally occurring mineral-bound ammonium is fairly rare; however, it has been found to occur in gold-bearing hydrothermal deposits (Krohn et al., 1988). Because of this association, it is thought that ammonium may be a useful tool in exploration for gold and other metal deposits.

Mineral-bound ammonium is produced when an ammonium ion ( $\text{NH}_4^+$ ) replaces the alkali cation site (usually  $\text{K}^+$ ) in the crystal structure of silicate minerals such as feldspars, micas and clays (Krohn et al, 1988). Buddingtonite is an ammonium feldspar. The ammonium originates in buried organic plant matter and is transported to the host rock by hydrothermal fluids (Hallam and Eugster, 1976). Ammonium alteration does not produce visible changes in the rock, and it is barely detectable with standard x-ray diffraction methods. It is clearly identified, however, by absorption features in short wave-infrared (SWIR) wavelengths (2.0 - 2.5  $\mu\text{m}$ ). The ammonium absorption features are believed to be caused by N-H vibrational modes and are analogous to hydroxyl (O-H) vibrational modes, only shifted slightly in wavelength (Krohn et al., 1988). Buddingtonite absorption features in the near- and SWIR lie at 1.56, 2.02 and 2.12  $\mu\text{m}$ . The feature at 2.12  $\mu\text{m}$  is the strongest of the three and is the only one used in this study. The southern Cedar Mountains are sparsely vegetated and are an ideal site for a remote sensing study.

### **2. LABORATORY MEASUREMENTS**

Nitrogen content of 54 samples was determined by a combustion (Dumas) technique (Tabatabai and Bremner, 1991). The weight percent nitrogen is converted to percent ammonium by multiplying it by 1.286 (Kydd and Levinson, 1986). This method assumes that there is no other source for nitrogen in the rock.

The depth of the 2.12  $\mu\text{m}$  ammonium absorption feature was measured on continuum-removed PIMA spectra for the same 54 samples. The PIMA is a hand-held field spectrometer that covers the range from 1.3 to 2.5  $\mu\text{m}$ . It uses an internal light source so spectra may be acquired under cloud cover or even at night. An internal reflectance standard is scanned after each spectrum is taken to provide calibration.

The 2.12  $\mu\text{m}$ , continuum-removed band depths and corresponding ammonium concentrations were plotted, and a linear relationship was observed. The equation of this linear relationship was used as a quantitative calibration for the remotely-sensed

spectra. With it, appropriate continuum-removed band depths can be converted to ammonium concentrations (Felzer, 1990).

### 3. DATA PROCESSING

AVIRIS data acquired during July 1990 were processed to create quantitative ammonium concentration maps. Field spectra of light and dark ground-targets were used to calibrate the data to reflectance with the empirical line method (Roberts et al., 1985). Buddingtonite occurrences and relative concentrations were established using a spectral matching program called the Spectral Angle Mapper (SAM) (Kruse et al., 1993a). The program determines the similarity of a test spectrum (from an AVIRIS pixel) to a reference spectrum (laboratory spectrum). The spectra are treated as vectors and a small angle between the spectral vectors indicates a better match. Output from the SAM consists of a gray scale image where higher values denote a better match with buddingtonite spectra.

To make quantitative measurements of buddingtonite concentration, band depth values from continuum-removed AVIRIS spectra had to be found. Continuum removal was achieved with a prototype expert system called the General Use Expert System for Spectra (GUESS) (Kruse et al., 1993b). Depth of the buddingtonite absorption feature was measured at band 190 (2.119  $\mu\text{m}$ ) on the continuum-removed AVIRIS data and an image consisting of band depth values was produced.

To create an image showing ammonium concentration, the linear calibration was applied to the band depth image. The equation is:

$$Y = 13865X - 347.93$$

where  $X$  is the input band depth "DN" value and  $Y$  is the output ammonium concentration in ppm. After applying this equation to the AVIRIS data, each pixel is converted to an ammonium concentration in ppm. The ammonium concentration image was contoured to produce quantitative ammonium concentration maps (Figure 1).

On the concentration map, a few anomalously high ammonium values were indicated in a region that was known from field work to be barren. Inspection of several AVIRIS spectra from this region showed no buddingtonite features. The SAM results were used to construct a filter that masked these false high-ammonium values.

### 4. FIELD VERIFICATION

To test the accuracy of the AVIRIS concentration map, spectra were taken in the field with the PIMA spectrometer and a ground-truth concentration map was produced. An area covering about 620 AVIRIS pixels that showed the greatest ammonium concentration was chosen. In the field, spectra were measured on fresh and weathered surfaces on a regular grid of 40 m. Ammonium concentrations were derived using the linear calibration; and the ground-truth concentration map was contoured for comparison with the AVIRIS concentration map of the same area (Figure 1).

### 5. DISCUSSION

Comparison of the ground-truth concentration map and the AVIRIS concentration map demonstrates that ammonium can be quantitatively mapped with AVIRIS data (Figure 1). While the two maps are not identical, they do match in both magnitude and pattern. The AVIRIS map indicates that the region is dominantly greater than 4000 ppm and increases to 5500 ppm in the center. The ground-truth map shows less of the highest concentrations, yet it confirms that the region is dominantly greater than 4000 ppm and increases to 5500 ppm in the center. It must be remembered

that the ground truth map was sampled at points every 40 m while AVIRIS sampled every 20 m and averaged spectra from an approximately 400 m<sup>2</sup> area. We therefore may expect AVIRIS to give a more accurate representation of the buddingtonite concentration in this zone because it is not affected by the very small-scale variations that could deceive the pin-point ground sampling.

An interesting feature that appears on both maps is a small zone of no buddingtonite. It was masked by the SAM filter on the AVIRIS image and showed no ammonium on the ground survey. Inspection of the area revealed a 20 m by 5 m piece of ammonium-free rock that was faulted in place.

On a larger scale, AVIRIS showed that the buddingtonite occurs in two of four exposed volcanic tuff units, and forms isolated zones along the western mountain front. Within the ammonium zones, areas of high and low concentration are generally linear and are believed to correspond to fracture patterns. It is thought that these fractures were the passages along which ammonium-bearing hydrothermal fluids once flowed.

Field mapping indicates a relationship between buddingtonite and northeast-striking, high angle, dip-slip basin and range(?) faults. All of the high-ammonium zones inspected were on the northern, down-dropped side of these dip-slip faults. Within the buddingtonite zones the rock is broken by closely spaced fractures that are sub-parallel to the northeast striking faults.

### Ammonium Ridge Area

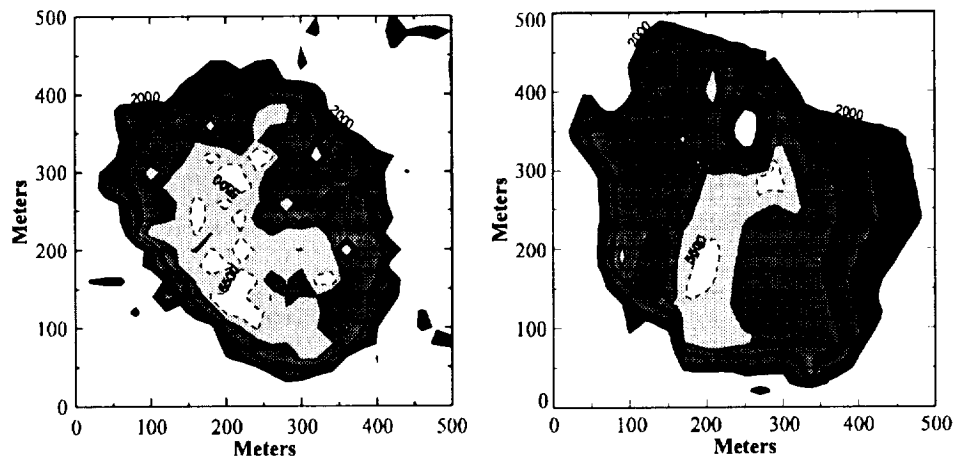


Figure 1. AVIRIS (left) and ground-truth (right) NH<sub>4</sub> concentration maps: Contour interval is 1000 ppm, dashed contours are 5500 ppm

## 6. CONCLUSIONS

AVIRIS is capable of quantitatively mapping buddingtonite concentration in the southern Cedar Mountains, Nevada. This is accomplished by producing a calibration equation based on laboratory analysis and applying it to appropriately processed AVIRIS data. Buddingtonite is both stratigraphically and structurally controlled at this site, and is found commonly in concentrations up to 6000 ppm.

This method may be applicable to other hydroxyl minerals, found in hydrothermally altered rocks, that contain absorption features in the SWIR. Besides buddingtonite, other examples include alunite, kaolinite and jarosite. If these can be quantitatively mapped, not only can we determine the geometry of a fossil hot spring system, but we can infer much about the chemistry of the hydrothermal fluids that affected different parts of the system. Alunite would indicate low pH and more

oxidizing fluids, while buddingtonite denotes high pH and more reducing fluids. Kaolinite is formed by oxidizing fluids of an intermediate pH (Krohn, et al, 1988). Knowledge of fluid chemistry in fossil hot springs can aid in their study and be valuable in choosing prospecting sites.

## 7. REFERENCES

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