DEVELOPMENTS IN REMOTE SENSING OF CARBONATITES; AIRBORNE IMAGING SPECTROMETRY AT MOUNTAIN PASS, CALIFORNIA AND IRON HILL, COLORADO.

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Data acquired with the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) over Mountain Pass in California and Iron Hill in Colorado were analyzed to evaluate the use of narrow-band imaging data for carbonatite exploration as well as for regional geologic mapping. The AVIRIS instrument utilizes a linear array of discrete detectors and 4 spectrometers to collect 224 channels of data over the 400 to 2400 nm wavelength region. The spatial resolution is 20 m for swaths 10.5 km wide.

At Mountain Pass, three flightlines of data were collected over the rugged mountain range which encompasses the carbonatite. A block of Precambrian metamorphic rocks, which are the oldest rocks in the region, is exposed in the eastern flank of the mountains; more resistant Paleozoic sedimentary rocks form the higher western half of the range. The metamorphic complex consists primarily of light-colored granite augen gneiss, biotite granite gneiss and garnet gneiss that are intricately interlayered. These rocks are bounded by normal faults on the northeast and by the extensive north-trending Clark Mountain fault on the west. The carbonatite as well as several bodies of potassium-rich igneous rocks intrude the granite augen gneiss. The carbonatite stock which is the major source of light rare-earth elements (REE) in the United States, was selected several years ago as a test site for evaluating AVIRIS capabilities for detecting REE absorption features.

Dolomite is the most widely distributed lithology in the thick sequence of sedimentary rocks exposed west of the Clark Mountain fault. The area is well suited for remote sensing studies because of the sparse nature of Mohave desert-type vegetation, including Joshua and juniper trees, mesquite, grasses and various cacti.

One flight line of AVIRIS data was acquired over the Iron Hill carbonatite, which also was emplaced in Precambrian metamorphic rock, principally granite gneiss. The dolomitic carbonatite (rauhaugite) appears in plan view as a two-lobed stock. Carbonatite dikes radiate outward from the stock, cutting the associated alkalic rocks which surround the rauhaugite core. The alkalic rocks include pyroxenite, uncompahgrite, ijolite and nephelene syenite. A zone of fenitized rocks, formed by metasomatic alteration of the granite and felsite country rocks, surrounds the carbonatite complex.

Vegetation is considerably more dense in southwestern Colorado than at Mountain Pass. In such areas of moderate to heavy vegetation, a special problem exists in interpreting airborne imagery because mineral spectra may be diluted or masked by spectral features associated with chlorophyll and cellulose.

Various methods can be used to enhance high-resolution airborne data as well as to remove atmospheric and solar irradiance effects. Two complementary approaches were used at Mountain Pass: (1) the construction of relative absorption band depth (RBD) images and (2) the use of ground-based spectral measurements to calibrate the AVIRIS radiance data to reflectance.

The initial step was to generate the RBD images directly from the data. The resulting images emphasize diagnostic spectral features of minerals, while minimizing reflectance variations due to topographic slope and albedo differences. The specific wavelengths that define the absorption band shoulders and minimum were determined from laboratory spectral reflectance measurements of samples collected in the field area. The absorption bands initially chosen were those positioned at 2200 nm (Al-OH), 2310 nm (dolomite) and 2330 nm (calcite) wavelengths. To construct an RBD image, two or three channels from each absorption band shoulder are summed and then divided by the channels that define the band minimum. Each RBD image is sensitive to a particular absorption feature. Three RBD images may be displayed as a red-green-blue color composite.

Because there are strong atmospheric features in the visible range near the REE spectral bands, RBD images are unsuccessful in defining the presence of REE-bearing rocks. However, such detailed spectral information may be extracted from the AVIRIS radiance data after it has been calibrated to reflectance. An empirical regression calibration was used to achieve this at Mountain Pass. Spectral reflectance measurements were made in the field during the AVIRIS overflight using several targets of different brightness. These reflectance values were regressed against AVIRIS digital numbers and the calculated gain vs. offset correction applied to AVIRIS data over a wide area having similar surface elevation and sky conditions. AVIRIS "spectra" may then be extracted for individual pixels.

Many of the lithologic units were discriminated on the RBD composite images. At Mountain Pass, granite gneiss, dolomite outcrop and the surrounding calcitic alluvial material are clearly separated on a 2200-nm, 2310-nm and 2330-nm RBD color composite image. Granite and quartzite could be separated because the intensity of the 2200-nm absorption feature due to muscovite is directly related to the proportion of that mineral in each rock type. The Clark Mountain fault is delineated on the image both in areas of bedrock and alluvium. Skarn deposits were revealed west of Mountain Pass.

The REE spectral reflectance features of interest to remote sensing are the narrow, sharp absorption bands due to Nd which occur near 580, 740, 800, and 860 nm. It is possible to detect these narrow Nd features only because of the high spectral resolution (AVIRIS channels are only 10 nm apart). At Mountain Pass, spectra which displayed the Nd features were observed in pixels extracted from the mine area. Spectra were extracted which displayed the calcite features at 2330 nm and the 2200 nm feature due to Al-OH-bearing minerals in the granite country rock. Spectra were also extracted from major lithologic units, alluvial fans and areas of hydrothermal alteration and compared with a library of laboratory spectra for mineral identification.

Processing the data at Iron Hill was complicated by the moderately heavy vegetation cover. Various RBD images were generated but vegetation obscured much of the mineralogical information. The characteristic carbonate feature for rauhaugite, near 2310 nm, coincides with the wavelength region for cellulose absorption. However, vegetation is not so dense at lower elevations, and rauhaugite dikes were located crosscutting the alkalic rocks. The most successful RBD image for spatial definition of the rauhaugite stock represented a broad, but sometimes intense band centered near 1100 nm. This distinct feature, which may occur as a doublet in laboratory spectra, is assigned to ferrous iron that substitutes for magnesium in the dolomite lattice. Results of laboratory spectral measurements of carbonatite samples collected world wide indicate that this absorption feature is common in rauhaugite samples although it is rare in sedimentary or metamorphic dolomites. The distribution of alkalic rocks could also be mapped by the ferrous iron RBD image. The spectral response displayed by rauhaugite is more intense, enabling the separation of the stock and dikes from the alkalic rocks.

A distributed flat field correction was used to remove atmosphere effects from the Iron Hill AVIRIS data so that spectra could be extracted. This technique is an alternativ to the empirical regression process used at Mountain Pass and is useful when in situ spectral measurements have not been made. For this calibration, RBD images were first examined to identify pixels having weak or absent mineral and vegetation absorption bands. The average radiance spectrum of these scattered, spectrally flat pixels was then divided through the data set.

Dolomite spectra were extracted from the calibrated Iron Hill data, but there has been limited success in extracting Nd absorption bands. The REE content of Iron Hill carbonatite rocks is low and Nd bands are weak or nonexistent in laboratory and field spectral measurements of these rocks. Also, a chlorophyll absorption band occurs near the Nd feature at 680-nm which will conceal weak Nd features. The next step in future processing of these data is to "unmix" the vegetation, so that the spectral response of underlying rocks and soils may be detected.

High-resolution multispectral imagery is potentially a very effective tool for geologic mapping, both because certain surface minerals can be identified by their spectral-reflectance characteristics and because remote sensing provides a synoptic view of landforms. Imaging spectrometers such as AVIRIS provide sufficient spectral sampling to define diagnostic spectral signatures on a per-pixel basis.

A useful approach to the processing of AVIRIS data is to first construct RBD images, so that the major lithological units may be separated. These images also quickly provide information on the provenance of alluvial material and may show structural details in areas of limited bedrock exposure. For detailed mineralogical characterization, calibration to reflectance units is necessary, so that spectral curves may be extracted and interpreted for selected areas. Because carbonatites display a unique combination of spectral characteristics, including carbonate, Nd, and often ferrous iron absorption features, these methods are useful not only for exploration of carbonatites, but also for the delineation of the surface extent of the carbonatite core, dikes and related alkalic rocks.