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# SPECTROSCOPY OF MOSES ROCK KIMBERLITE DIATREME

**CARLE M. PIETERS and JOHN F. MUSTARD,** Department of Geological Sciences, Brown University, Providence RI 02912

**ABSTRACT:** Three types of remote sensing data (AIS, NS001, Zeiss IR-photographs) were obtained for the Moses Rock kimberlite dike in southern Utah. Our goal is to identify and characterize the mantle derived mafic component in such volcanic features. The Zeiss and NS001 images provide information on the regional setting and allow units of the dike to be distinguished from surrounding material. A potential unmapped satellite dike was identified. The AIS data provide characterizing information on the surface composition of the dike. Serpentized olivine-bearing soils are (tentatively) identified from the AIS spectra for a few areas within the dike.

## Introduction

A number of small kimberlite-bearing diatremes of Tertiary age occur on the Colorado Plateau. The origin of these unusual volcanic features is not well understood, but is believed to be associated with mantle processes that result in a rapid rise of material from the mantle through the continental crust. Although such an event (presumably explosive) has never been directly observed, kimberlite-bearing volcanic features are a valuable source of otherwise inaccessible mantle and crustal rocks of great interest to the geochemist (and sometimes a source of diamonds for the investor). Kimberlite-bearing features have not been explored extensively with remote sensing techniques primarily because of their small size and because their identifying characteristics have not been well documented.

The Moses Rock dike in southern Utah was chosen for analysis with the Airborne Imaging Spectrometer (AIS). Rocks, breccias, and deposits of the dike have been mapped in detail (1:12000) by McGetchin (1968, unpublished). A schematic geologic map of Moses Rock dike and observed rock types were presented by McGetchin and Silver (1970, 1972) with a discussion of the mineralogy, petrology and geochemistry of the mantle-derived materials (summarized in Geology section below).

Our goal in studying Moses Rock Dike with AIS data is to identify and characterize the mantle-derived mafic and ultramafic material. These types of rocks and minerals are known to exhibit characteristic absorption bands near 1 µm as well as bands between 1.6 and 2.5 µm due largely to iron and other transition metals in their crystal structure (eg. Adams 1974, 1975; Hunt and Salisbury, 1970). If successful, this type of data will provide a significant exploration tool to be used not only in identifying these unusual volcanic structures, but also for unraveling the normally complex distribution of material within them.

The flight over the Moses Rock target area in Monument Valley was flown July 20, 1984. Data collected included Zeiss color infrared photographs, NS001 (TM simulator) multispectral images, and AIS data. The day was clear and cloudless. Analysis of these data commenced January 1985, and a preliminary discussion of results is presented below. A few system problems occurred on our flight: the navigation system (INS) was not functioning properly and could not provide accurate positioning of the aircraft, the Nikon camera was inoperative, and the clocks on the Zeiss and NS001 were either inoperative or inaccurate.

## Geology of the Moses Rock Dike

(from McGetchin, 1968; McGetchin and Silver 1970, 1972)

Moses Rock dike is a breccia-filled, kimberlite-bearing diatreme located in the Colorado Plateau of south-eastern Utah. It is hooked-shaped in plan and about 6 km in length. It intrudes the undeformed and unmetamorphosed sandstone, siltstone and limestone of the Permian Cutler formation. The dike contact is sharp and the walls are steep. A system of joints extends out into the host rocks parallel to the dike contact. Moses Rock dike occurs in a cluster of diatremes southeast of the Monument uplift (a large regional anticline) and along the axis of the Comb Ridge monocline. Superimposed on the regional structure are a series of north-south trending anticlines and synclines. Total structural relief does not exceed 1500 meters and is concentrated along the Comb Ridge monocline.

The majority of the dike consists of large blocks up to several hundred meters across derived from the Cutler formation of sandstones exposed in the vent walls. The interstices between the large blocks are filled with a matrix of unconsolidated breccia. This matrix is composed of fragments from the large blocks, limestone fragments, crystalline rock fragments, and mafic and ultramafic constituents.

Kimberlite, which constitutes about 1% of the dike, occurs as small bodies not larger than 10 meters in diameter. It is a highly serpentinized, ultramafic microbreccia containing olivine, pyroxene, garnet, phlogopite and spinel. Most of the primary mineralogy is relict after serpentine and chlorite. These mineral constituents and alteration products are found dispersed throughout the breccia matrix. Material derived from kimberlite constitutes about 12% of the breccias. About 3% of the breccia consists of igneous, altered igneous, and foliated metamorphic rocks derived from the basement. Dense ultramafic mantle-derived fragments, which include eclogite, lherzolite, websterite, and jadeite-pyroxenite, are rare. The distinctly comminuted texture, the absence of silicate melt, and the dispersion of kimberlite material throughout the breccia indicates that the dike was emplaced as a fluidized volatile and solid particle system driven by $H_2O$ and $CO_2$. The source of the kimberlite magma has been estimated to have been at a depth in excess of 100 km.

## Zeiss Infrared Photographs

The Zeiss camera used color infra-red film with a spectral range of 510-900 nm. The field of view is approximately 7 kilometers with a ground resolution of about 1-2 meters. These high-quality stereo images provide a regional perspective of the flight lines and facilitate mapping of fine structural features. These images were our primary data for locating the ground tracks of both the NS001 and AIS data. The high-resolution and stereo viewing allow the influences of topography and texture to be assessed.

East and South of Moses Rock the Permian beds dip moderately away from the dike towards an area of flat-lying Triassic and Jurassic sandstones. Where the Navajo sandstone is exposed a prominent set of parallel joints is visible. They are oriented approximately ESE/WNW and are regularly spaced at 50 to 100 meter intervals with no apparent offset along the joints. The orientation of the joints is orthogonal to the axis of the Monument uplift and Comb Ridge which implies the joints are a result of the regional stresses that existed during the formation of the uplift and monocline. There are also scattered lineations oriented about 60 degrees to the joints and localized circular and curvi-linear fracture patterns in the same formation. These are attributed to local structural response due to stratigraphic irregularities in the regional stress environment.

On the basis of texture and color in the Zeiss images, Moses Rock dike is divided into three units; the head, the body, and the tail. The apparent color of each unit is distinctive in the IR photographs: pale blue, green, and grey to blue-grey. The head is complex and coarsely textured. On the east margin of the head a long linear feeler dike intersects two elliptical mounds of uniform debris. In the body, large locally derived breccia blocks are surrounded by a mottled, bright matrix. The tail is characterized by a uniform fine-grained texture and an absence of breccia blocks. 900 meters east of the tail is a small elliptical zone about 300 meters in length with the long axis oriented parallel to the bedding. It is similar in texture and apparent color to the tail, and may be a previously undetected satellite dike.

## NS001 (TM Simulator)

Airborne simulated thematic mapper (NS001) digital data were examined to quantify the qualitative observations from the Zeiss images. Ratio images were prepared and principal component analysis (PCA) images were studied in this preliminary examination to better define the general nature of Moses Rock dike as well as potential satellite dikes.

It is apparent by visual inspection that the units of the dike show the greatest spectral variation in the first five TM bands. Many ratios were examined and it was found that the ratios of bands 2 (0.53-0.60 µm) to 5 (1.00-1.35 µm) and bands 3 (0.63-0.69 µm) to 5 (1.00-1.35 µm) best differentiate the dike units. In both images the tail has a uniformly high ratio while the head and body show an irregular distribution of regions with a high ratio. Comparisons of these regions to the Zeiss images show that they occur in the interstices between breccia blocks. Kimberlitic mineral components and alteration products are found dispersed throughout the matrix (see Geology section), and may account for the observed distinction in the ratio images. Further comparison with the geologic map of Moses Rock (McGetchin, 1968) shows that the regions with the highest ratios correspond very well with the units mapped as containing the most serpentine in the matrix. Some beds within the Cutler formation, however, exhibit comparable ratio values and may also be a significant component of the matrix. The potential satellite dike unfortunately lies along one of these beds and was unresolvable in the ratio images.

PCA of the first six thematic mapper bands was done to further classify the dike. The program used accepts up to six input images and by a linear transformation of the variables produces images of the first three principle components. Although the results of the PCA are at the moment preliminary and qualitative, the third principle component image clearly shows that the "satellite dike" is similar in nature to the tail and different than the sedimentary units surrounding it. With further analysis of the principal component images in conjunction with the ratio images, we expect to obtain a better understanding of unit distinctions within the Moses Rock area.

## Airborne Imaging Spectrometer (AIS)

Six of seven short AIS swaths did cross the Moses Rock dike target. Five of these were in the 'rock' mode (about 1.15 to 2.35µm); one was in the 'tree' mode (about 0.86 to 2.04µm). Data processing was performed at JPL using the specialized, but versatile, software package 'SPAM' developed by J. Solomon. When this useful package is incorporated into the VAX-based VICAR2 package, we will continue AIS analysis using our facilities at Brown.

### AIS Data Assessment.

Although the data from this flight were adequate to determine that useful spectroscopic information is indeed obtainable for kimberlite-bearing surfaces (see below), there were a number of undetermined instrumental or calibration problems that made the precision, and possibly accuracy, of the data lower than it should be. Serious line-to-line (spatial) banding was observed for about half the spectral channels. Banding in one channel was correlated with banding in neighboring channels. For a few channels along-track stripping was also present. These effects added considerable noise to the spectroscopic measurements of pixel groups and could not be removed without destroying most spatial information.

## AIS Data Processing.

Data analysis dealt largely with 'relative reflectance spectra' produced by ratioing the spectrum of an area of interest to the spectrum of a standard area (chosen as representative of local soil around the dike). This process has the advantage of allowing instrumental and atmospheric effects to be cancelled (except in saturated water bands). To obtain true reflectance spectra, the standard area needs to be calibrated independently. For these preliminary analyses we have assumed that the spectral character of the standard soil is relatively featureless. (Anticipated field work this summer will check this.)

Once distinctive spectroscopic areas were identified (see below), the SPAM 'find' function was employed on the type spectrum (original, not ratioed) to estimate areal extent of a unit within ths AIS swath.

## AIS Data Analysis.

Within the limits of this flight of data, two distinct units with well-defined spectroscopic features were identified in addition to the more spatially extensive local standard. The vast majority of surface material covered in the AIS swath is not greatly different from our chosen standard.

The first of the spectroscopic units is in the dike and is what we have tentatively called Moses Rock 'kimberlite'. The type area was chosen based on the unpublished map of McGetchin (1968). This type area was crossed by AIS swaths of both spectroscopic modes allowing its spectral character to be examined from 0.86 to 2.35 µm. The 'kimberlite' area exhibits two spectral features: 1) a band that begins relatively sharply at about 2.25 µm and increases in absorption (up to about 25%) toward 2.35µm; and 2) a broad band of similiar strength between 0.86 and 1.50µm with an apparent center near 1.15µm. These features are consistent with serpentized olivine-bearing rocks or soil, currently our preferred interpretation. For comparison our "kimberlite" relative spectrum is presented in Figure 1, and a serpentized olivine reflectance spectrum from Hunt and Salisbury (1970) is presented in Figure 2.

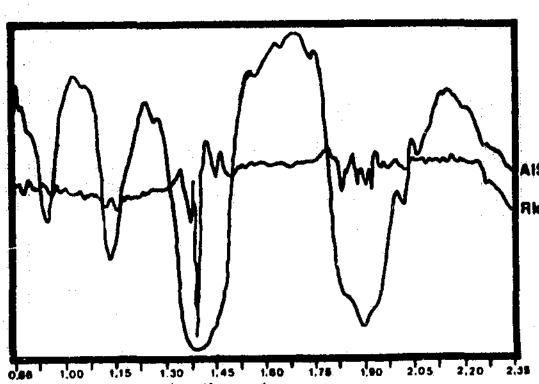


Figure 1. AIS spectra from combined 'rock' and 'tree' modes for our standard area (AIS, raw calibrated spectrum) and the 'kimberlite' area (Rkimb, reflectance spectrum relative to the standard area spectrum).

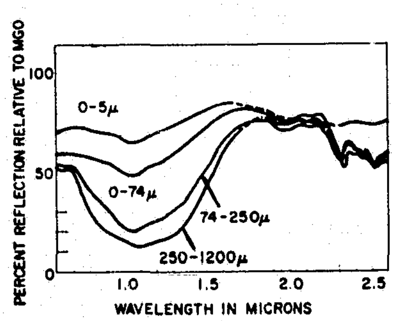


Figure 2. Reflectance spectra of serpentized olivine (from Hunt and Salisbury, 1970)

The second spectroscopic unit occurs as a local soil type east of the dike that exhibits a weak band (about 7%) between 2.1 and 2.35µm, centered near 2.2µm [and perhaps another feature hidden by the 1.9µm atmospheric water band]. We interprete this as soil containing an abundance of a hydrated mineral (currently undefined).

## Summary of Results

Although we have not yet thoroughly analyzed the interrelation between the AIS, NS001, and Zeiss data, it is clearly important to have coordinated data: one type of data is needed that is optimized for *mapping* surfaces (such as the NS001 and Zeiss) and allows material of generally similar characteristics to be identified and mapped over large areas; and another type of data is needed that is optimized for *characterization* of surface material (such as AIS) and allows specific compositional information to be determined. The AIS data has produced spectra that can be interpreted directly in terms of mineral components. Mafic material at Moses Rock dike has tentatively been identified and interpreted as serpentized olivine-bearing soils (confirmation awaiting field work). The NS001 images have not only allowed the necessary regional overview, but have also identified additional areas in the region that may be associated with the dike. Additional AIS flights and/or field work for these areas will clarify the association.

## Recommendations

High-spectral resolution mapping spectrometers provide important information about the composition of surface materials. The AIS is a good, if not excellent, prototype of such instruments. Major areas of improvement that would strongly enhance and enable science applications include: 1) more complete spectral coverage [eg. 0.5 to 2.5µm], 2) higher accuracy and precision [largely a function of instrument calibration and noise control], 3) wider swath width [or at least continuation of coordinated multispectral imaging over a wider area].

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