FINAL REPORT - NAGW-1143

EVALUATION OF THE AIRBORNE VISIBLE-INFRARED IMAGING SPECTROMETER FOR MAPPING SUBTLE LITHOLOGICAL VARIATION

PRINCIPAL INVESTIGATOR - F. A. KRUSE

CENTER FOR THE STUDY OF EARTH FROM SPACE (CSES)
COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCE
UNIVERSITY OF COLORADO, BOULDER
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SUMMARY OF THE INVESTIGATION

The primary objective of this work was to evaluate Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data quality and characteristics and the utility of the data in identifying and mapping minerals related to subtle lithological variation. For a site in the N. Grapevine Mtns., NV, the AVIRIS data was compared to seven flightlines of Airborne Imaging Spectrometer (AIS) data, 15 flightlines of Geophysical Environmental Research Spectroradiometer (GERS) data, laboratory and field spectra, and detailed field mapping. For a site at Canon City-Cripple Creek, CO the AVIRIS data was compared to field and laboratory spectra and detailed field mapping.

Two separate acquisitions of AVIRIS data were evaluated; data acquired during the 1987 flight season, and additional data acquired during the 1989 flight season. The suitability of AVIRIS geometric accuracy, spatial resolution, and spectral sampling interval for mapping known mineralogical variation and identifying additional subtle lithological variation was assessed for both sites.

Data acquired for both sites during 1987 was generally low quality. Although spatially, the data looked usable and individual images showed sufficient detail for general geologic mapping, extremely low signal-to-noise (<10/1 in the "D" spectrometer, @2.20 µm) prevented detailed spectral mapping of mineralogy. For the Canon City/Cripple Creek site, all attempts at spectral mapping of known mineralogy failed. All that could be accomplished was simple discrimination between those areas covered by vegetation, and those without vegetation. Mineralogical mapping using the 1987 AVIRIS data was somewhat more successful at the northern Grapevine Mountains site, primarily because of a slightly higher signal-to-noise ratio, arid conditions, and strong mineral absorption bands in well exposed surficial materials. It was not possible, however, to reproduce detailed mineralogical

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maps derived from the AIS and GERS data. Although clays and carbonates could be detected as mineral classes, the minerals sericite (fine grained muscovite), calcite, and dolomite previously identified using the AIS and GERS instruments and verified by field and laboratory work could not be identified using the 1987 AVIRIS data.

Additional AVIRIS data were acquired for the northern Grapevine Mountains site during July 1989. There was a significant improvement in data quality over the 1987 AVIRIS data. Spatially, the data looked very good and detailed photogeologic mapping was possible. The geometry of the images was excellent, requiring only simple scaling and rotation to match a topographic base. Spectrally, the signal-to-noise ratios of the data were much improved (50/1 @ 0.70 μm and 20/1 @ 2.20 μm in the "D" (1.84 - 2.45 μm) spectrometer). This allowed identification and mapping of the minerals sericite, calcite, and dolomite. Results were comparable to those obtained using the AIS instrument, but complete spatial coverage of the site allowed mapping of additional areas not covered by the AIS data. The 1989 AVIRIS data also allowed mapping of the iron oxide minerals hematite and goethite using the "A" and "B" spectrometers (0.41 - 0.70 μm and 0.68 - 1.27 μm respectively).

The AVIRIS data as flown during the 1989 season has been improved to what can be considered an minimal operational state. Geometric characteristics are such that the data can be used as a high-quality image base for geologic mapping. The spatial resolution of approximately 20 m allows mapping of lithologic variation on scales that field geologists find useful. The spectral resolution of the data, although not up to specifications (≤ 10 nm), at 15 nm is sufficient for detailed spectral mapping of mineralogy and permits detection of subtle differences in lithology based on small shifts in absorption band position. Signal-to-noise characteristics of the data are adequate, but performance for geologic applications could be significantly improved by increasing signal-to-noise ratios, particularly in the D spectrometer.

For System

INTRODUCTION

This research was conducted .as part of the AVIRIS data evaluation conducted by NASA during 1987 and 1988. The project was extended for 6 months to December 31 1989 to allow evaluation of AVIRIS data acquired during the 1989 flight season.

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is the first of a second generation of imaging spectrometers measuring near-laboratory quality spectra in 224 10 nm-wide channels in the spectral range 0.41 to 2.45 µm (Porter and Enmark, 1987). The AVIRIS is flown aboard the NASA ER-2 aircraft at an altitude of 20 km, with an instantaneous field of view of 20 m and a swath width of about 10 km. It utilizes four linear arrays and four individual spectrometers to collect data simultaneously for the 224 bands in a scanned 614 pixel-wide swath perpendicular to the the aircraft direction. The second dimension of the images is provided by the forward motion of the aircraft, which moves the ground field of view along the terrain.

The research had dual goals: 1) to evaluate the AVIRIS data, and 2) to look at subtle lithological variation at the two test sites to develop a better understanding of the regional geology and surficial processes. The primary characteristics of the AVIRIS data to be evaluated were the geometric characteristics of the data, adequacy of the spatial resolution, and adequacy of the spectral sampling interval. The geologic differences to be mapped at the test sites included lithological variation caused by primary sedimentary layering, facies variation, and weathering; and subtle mineralogical differences caused by hydrothermal alteration of igneous and sedimentary rocks.

The investigation utilized laboratory, field, and aircraft spectral measurements; known properties of geologic materials; digital image processing and spectrum processing techniques; and field geologic data to evaluate the selected characteristics of the AVIRIS data. AVIRIS data were calibrated to reflectance and the capability of the data to detect the subtle mineralogical variations in the rocks and soils of both test sites was evaluated.

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TEST SITES

The northern Grapevine Mountains test site, California and Nevada (Figure 1), has been the focus of a detailed multisensor remote sensing study, designed to test and evaluate multispectral remote sensing data for the detection and mapping of hydrothermally altered rocks (Kruse et al., 1985a, 1985b, 1985c, 1986; Kruse, 1986, 1987a, 1987b, 1987c, 1988). In addition, the test site has been mapped in detail using conventional geologic mapping techniques and the rocks have been well characterized through petrologic, X-ray diffraction, and field and laboratory spectral analysis (Wrucke et al., 1974; Kruse, 1987c). Previous acquisition and analysis 7 flightlines of 128 channel AIS imagery (Kruse et al., 1985a, 1986; Kruse, 1987a, 1987b, 1987c) made this site ideal for evaluation of the spectral and spatial quality of the AVIRIS system and for developing strategies for mapping subtle lithological variation with imaging spectrometers.
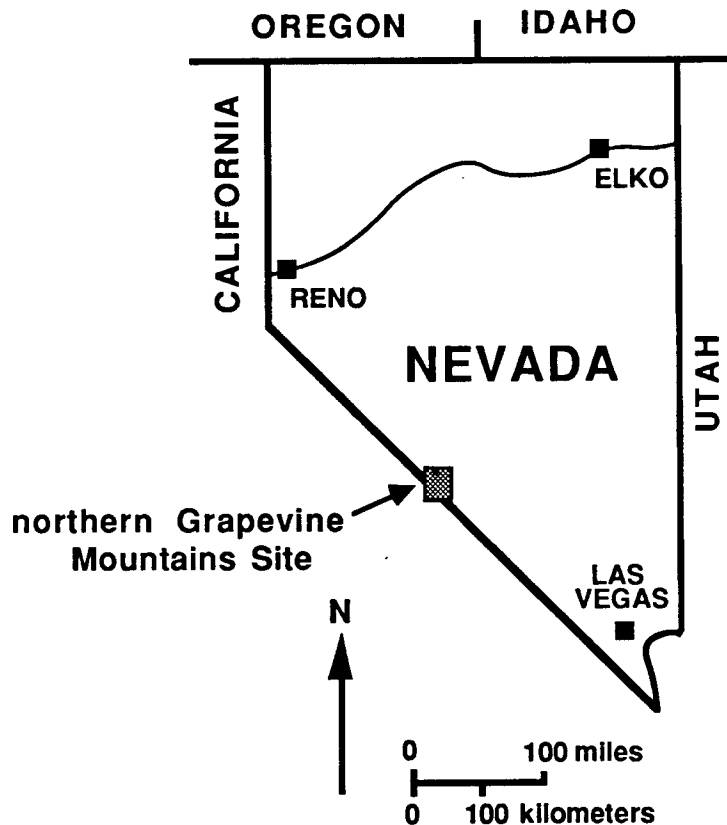
Figure 1. Sketch map showing the location of the northern Grapevine Mountains, Nevada, test site.

The Canon City-Cripple Creek, Colorado test site (Figure 2) has a long history as a test site for NASA-supported remote sensing investigations (Taranik and Kruse, 1989; Kruse et al., 1988; Clark et al., 1988; Lee, 1972, 1973, 1974; Lee et al., 1974; Knepper, 1975) because of its exceptional range of dramatically exposed lithologies and structures and its geography and climate. Numerous NASA aircraft missions have provided complete large- and small-scale color and color-infrared photographic coverage of the area, as well as abundant day and night thermal infrared imagery and SLAR imagery. Field and laboratory spectral measurements have been acquired for representative rock types in the study area (Taranik and Kruse, 1989; Clark et al., 1988; Lee, 1984, 1985; Raines and Lee, 1974a, 1974b, 1975).
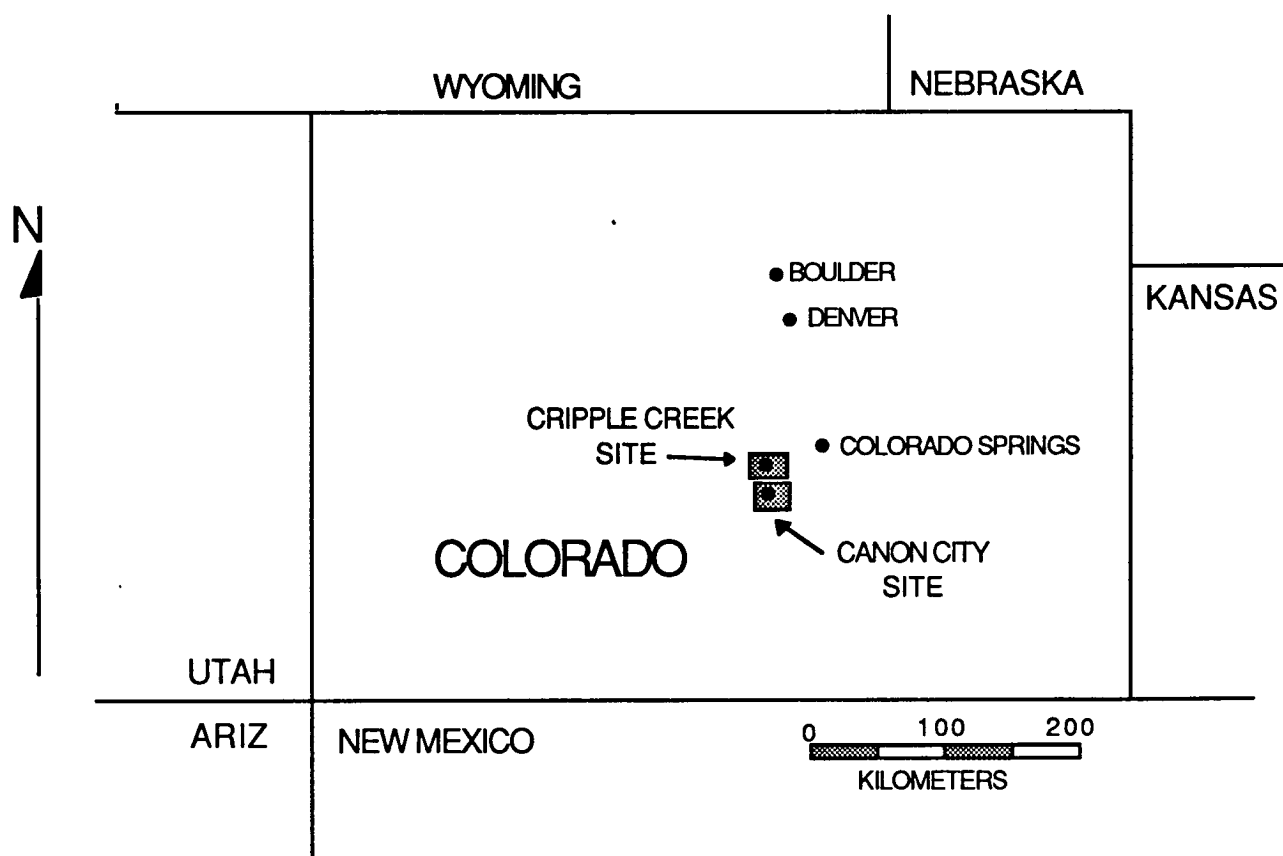
Figure 2. Sketch map showing the Cripple Creek/Canon City study site location.

1987 DATA EVALUATION

SUMMARY

The 1987 AVIRIS data was evaluated for its utility in mapping minerals at both the Cripple Creek/Canon City, Colorado, and the northern Grapevine Mountains, Nevada sites. AVIRIS data for these two sites were acquired on 10/19/87 and 7/30/87 respectively. The geometric characteristics of the data were evaluated by visual comparison to base maps and by geometrically correcting the AVIRIS images using the base maps and other corrected images. Signal-to-noise ratios were calculated for each AVIRIS channel. The spectral resolution was calculated by fitting an atmospheric water absorption band at 1.14 μm using an atmospheric model (Gao and Goetz, 1989). Spatial resolution was calculated by measuring known distances in both the line and pixel directions. The data were calibrated to Internal Average Relative Reflectance [IARR] using techniques described in Kruse (1988), spectra were extracted from the data for areas of known mineralogy, and these spectra were compared to both laboratory spectra and spectra from other aircraft systems (AIS and GER line spectrometer data) to determine the suitability for detecting subtle lithological variation.

GENERAL QUALITY OF THE DATA

The data quality of the 1987 AVIRIS data for both test sites was poor. Numerous dropped data lines were present in the data. Additionally both data-sets exhibited large amounts of horizontal striping (probably caused by inadequate dark corrections) as well as large gain changes along the flightlines. The overall Cripple Creek/Canon City data quality was so low as to be unusable for spectral geologic mapping. The principal problem with both data sets was the excessively low signal-to-noise ratios of the data.

SIGNAL-TO-NOISE

Signal-to-noise was calculated for the entire AVIRIS scene using techniques developed by Gao (1990). This procedure is based on the observation that high spatial resolution images contain a large number of small homogeneous areas (Lee and Hoppel, 1988).

The average signal for each band of the image (global average) is calculated using a simple average for all lines and pixels (Figure 3). The noise is calculated by segmenting the image into 4 x 4 (line x pixel) blocks and calculating the local average and standard deviation (Gao, 1990). Image blocks that on the Earth's surface consist of homogeneous surface materials have small local standard deviations and provide information on the noise in the image. Image blocks with high local standard deviations correspond to mixed pixels, edges, and textural features. A histogram is compiled counting the number of occurrences of various standard deviations and the bin with the largest number of blocks corresponds to the mean noise of the image (Figure 4). Noise is approximately independent of signal and for the AVIRIS data is mostly additive (Gao, 1990). The signal-to-noise is calculated by dividing the mean signal for each band by the mean noise for each band as calculated above (Figure 5).

The calculated signal-to-noise for the northern Grapevine Mountains, Nevada, site (Figure 5) was 46/1 at 0.70 (vs desired specification of 100/1 at 0.70) and 12/1 at 2.20 (vs desired specification of 50/1 at 2.20). The calculated signal-to-noise for the Cripple Creek/Canon City site (Figure 6) was 14/1 at 0.70 (vs desired specification of 100/1 at 0.70) and 6/1 at 2.20 (vs desired specification of 50/1 at 2.20). Neither flight met the AVIRIS design specifications, and it can be seen that the signal-to-noise performance was seriously degraded over time from July 1987 to October 1987.

GEOMETRIC CHARACTERISTICS

The geometry of the 1987 AVIRIS images was excellent. Visual comparison to topographic maps indicated that no obvious distortions exist in the data. The data were also geometrically corrected to a digital topographic base using simple linear rescaling and rotation. This is in contrast to the AIS data for the northern Grapevine Mtns., NV site which required selection of a high number of ground control points (on the order of 100 per

Figure 3.   Average Signal for 1987 AVIRIS for northern Grapevine
            Mtns. site
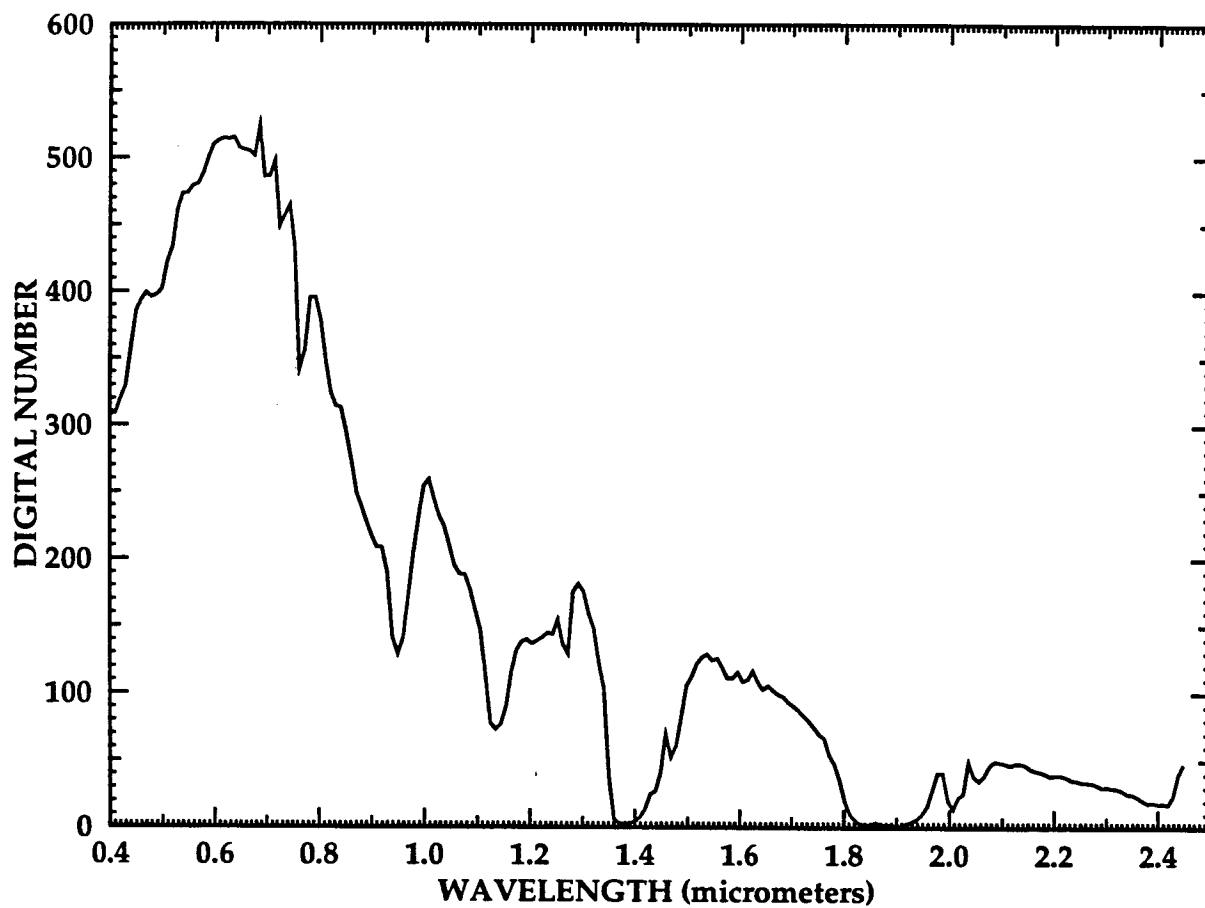
Figure 4.   Average Noise for 1987 AVIRIS for northern   Grapevine
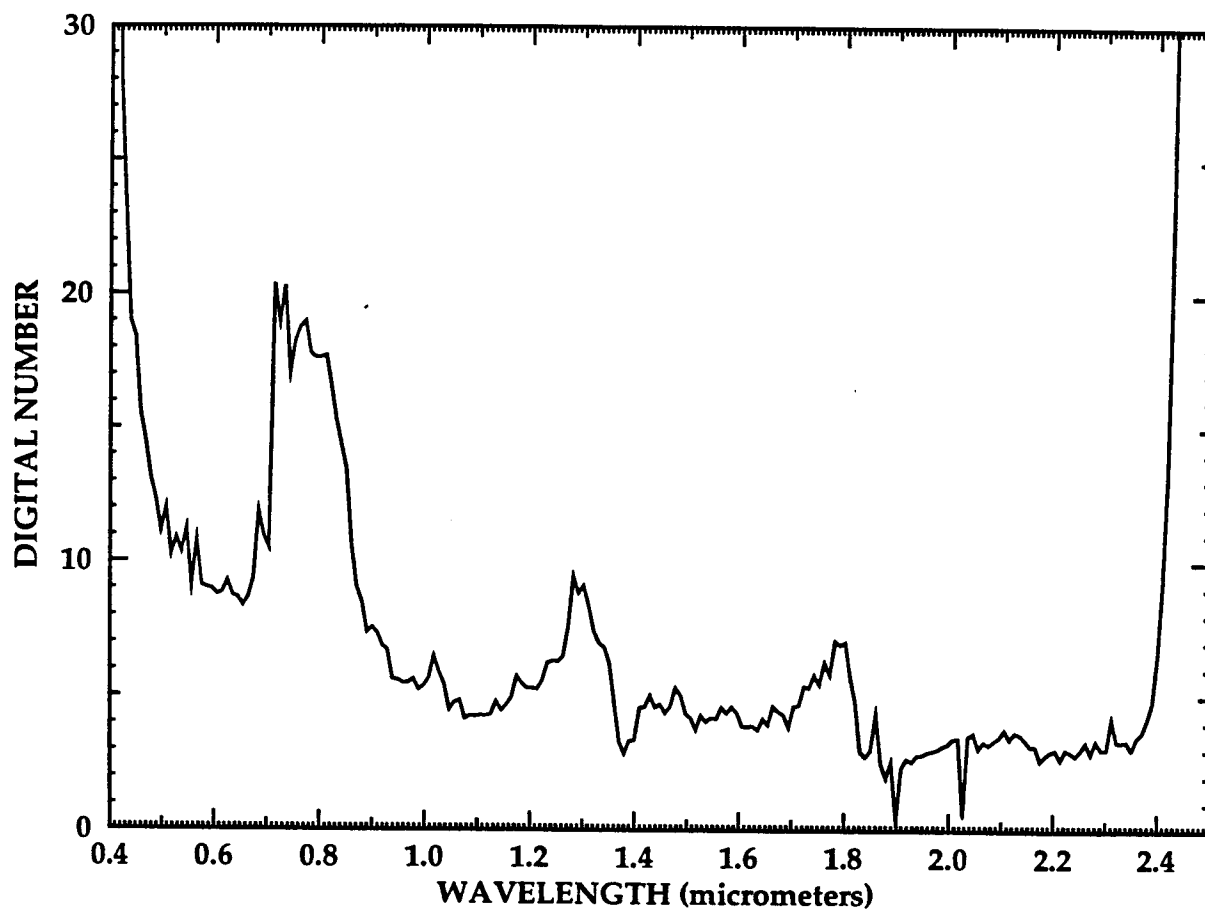   Mtns. site.

Figure 5.   Signal-to-noise ratio for 1987 AVIRIS for
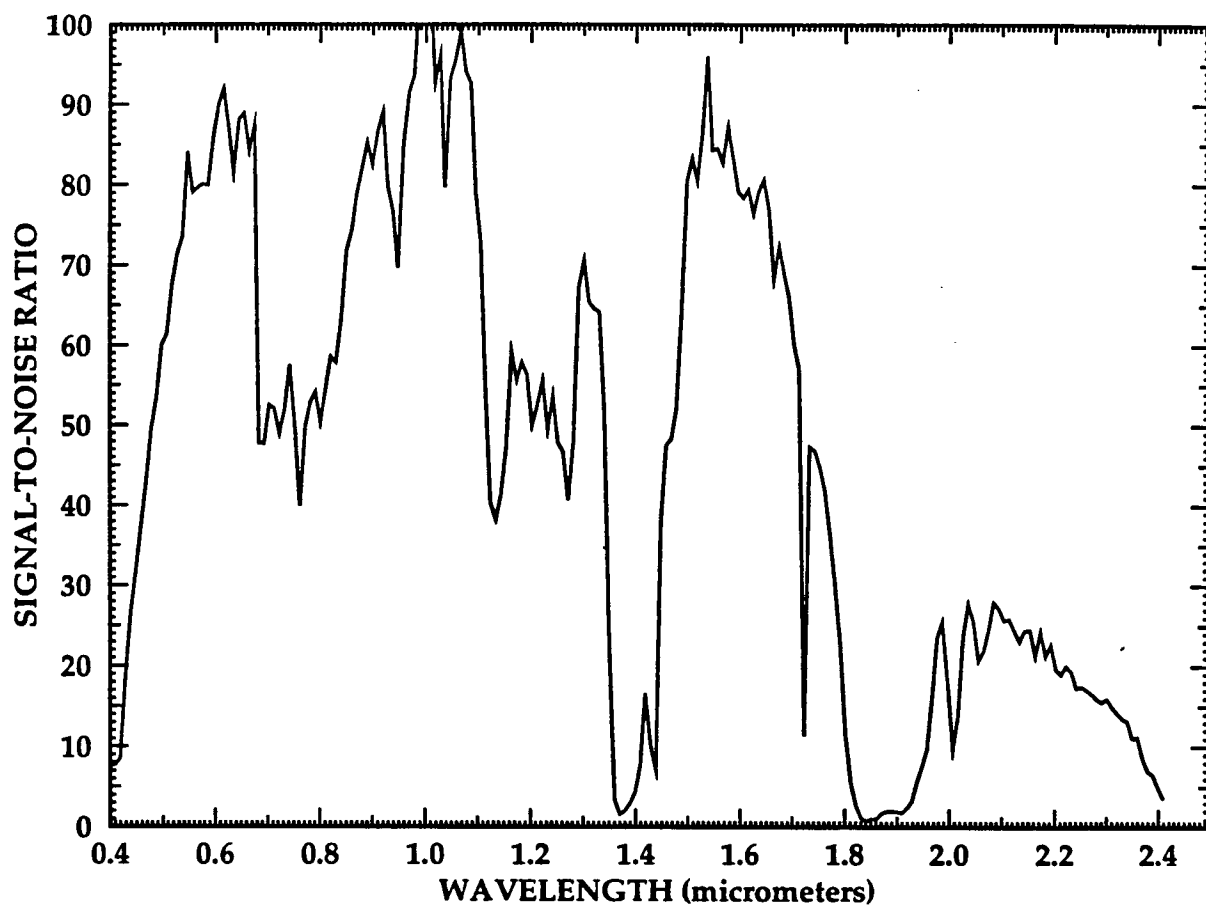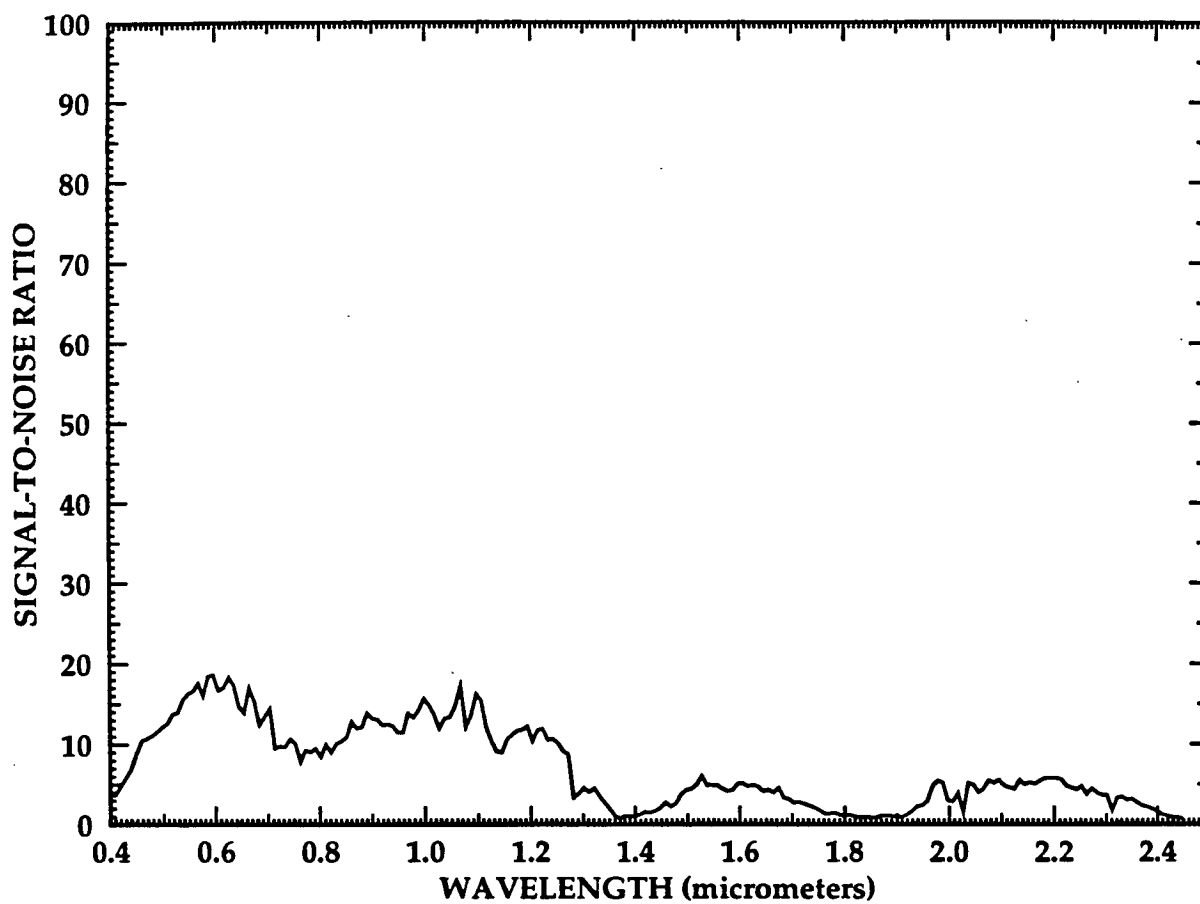   northern Grapevine Mtns. site.

Figure 6. Signal-to-noise ratio for 1987 AVIRIS for Cripple Creek/Canon City site.

flight line) and rubber sheeting using a 3rd order polynomial to fit the map. A National High Altitude Photograph (NHAP) co-registered to the map base was used to make a detailed comparison of the AVIRIS and corresponding topography. Mismatches (residual errors) between the AVIRIS and the topographic base were on the order of 2 to 4 pixels.

SPATIAL RESOLUTION

Spatial resolution was calculated by measuring known ground distances on the AVIRIS images in both the line and pixel directions. For the Cripple Creek/Canon City site, the calculated ground resolution is 16.8 m in the line direction and 17.3 m in the pixel direction. At the northern Grapevine Mountains site, the calculated ground resolution is 17.8 m in the line direction and 17.0 m in the pixel direction. Note that for both locations the spatial resolution is better than 20 m and within 15% of the specification. This is probably caused by the altitude of the test sites (~3000 m and 1700 m for Cripple Creek and the northern Grapevine Mtns., respectively). The similarity of the x and y scales is another indication of the good geometry of the data.

SPECTRAL RESOLUTION

The spectral resolution was calculated using the AVIRIS raw data and fitting a modeled atmospheric curve to the data for the 1.14 μm atmospheric water absorption band (Gao and Goetz, 1989). This procedure consists of extracting spectra from the raw AVIRIS data, dividing out the solar spectrum (Iqbal, 1983), and iteratively fitting an atmospheric model spectral curve to the water absorption feature at 1.14 μm (Gao and Goetz, 1989). The Malkmus (1967) model was used for the spectral calculations. The absorption band parameters were calculated from the spectral line parameters compiled in the HITRAN Data Base (Rothman et al., 1987). Figures 7, 8, and 9 show the fit for three different spectral resolutions. The variance of each fit was calculated and plotted against resolution (Figure 10). The minimum of the

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Figure 7.   1.14 μm atmospheric water band at 9.8 nm resolution

Signal V.S. Wavelength

Percent Difference V.S. Wavelength
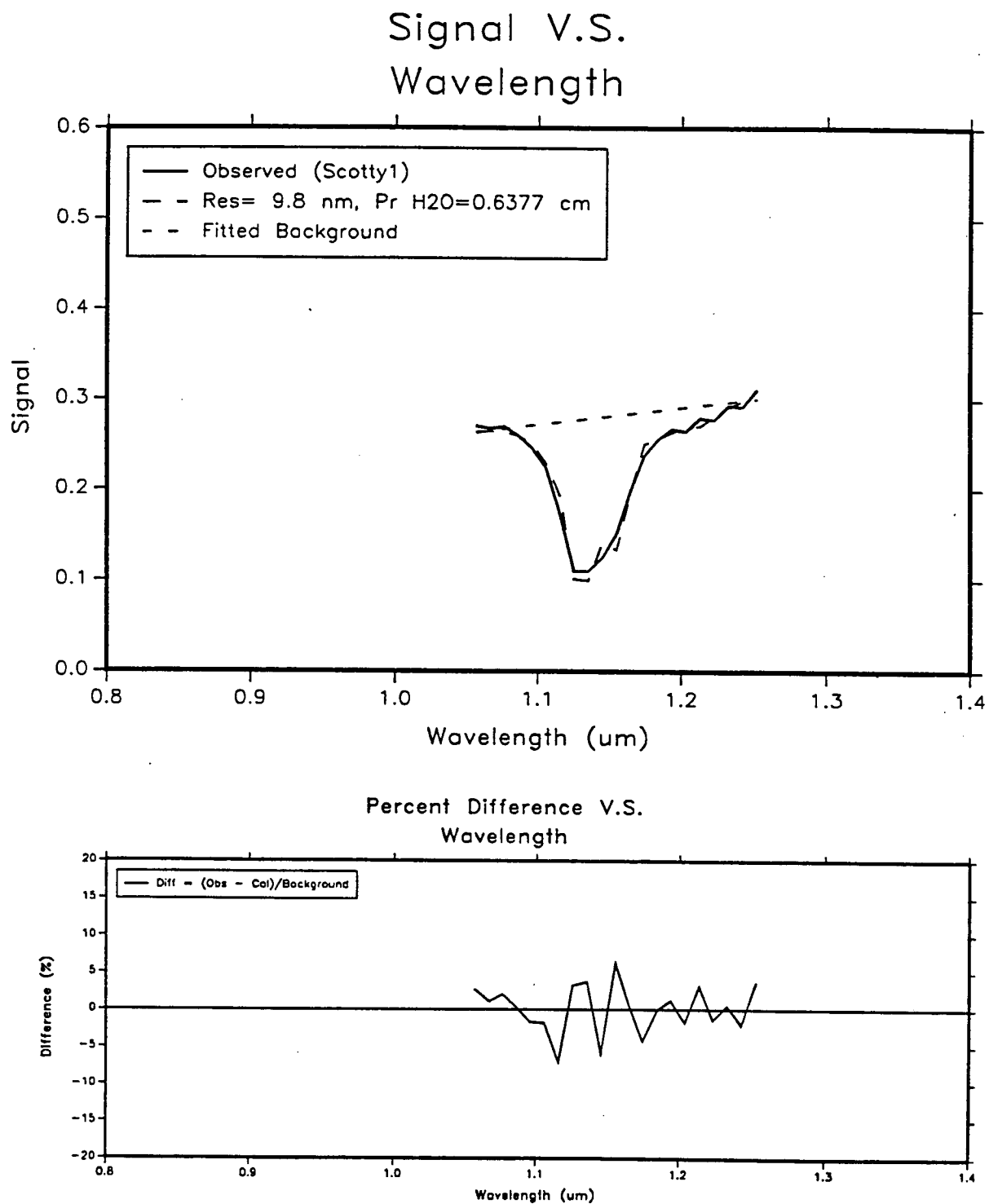
Figure 8. 1.14 μm atmospheric water band at 19.6 nm resolution

Signal V.S. Wavelength

Percent Difference V.S. Wavelength
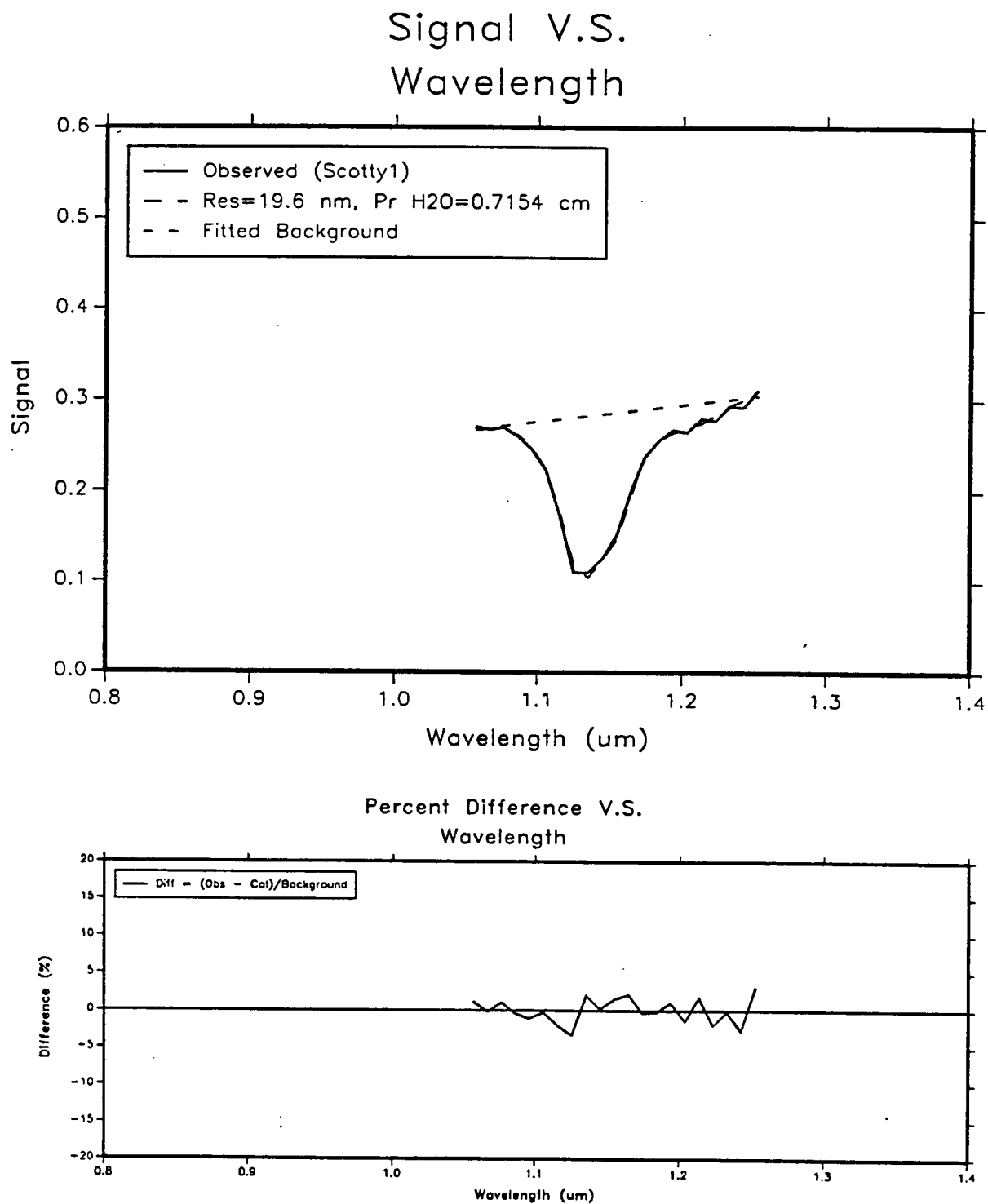
Figure 9.   1.14 μm atmospheric water band at 29.4 nm resolution.

Signal V.S. Wavelength

Legend:
- Observed (Scotty1)
- Res=29.4 nm, Pr H2O=0.8178 cm
- Fitted Background

Percent Difference V.S. Wavelength

Diff = (Obs − Cal)/Background

Figure 10. 1987 AVIRIS spectral resolution vs variance for the northern Grapevine Mtns. site. The minimum of the curve represents the actual resolution of the data.

Variance V.S. Spectral Resolution
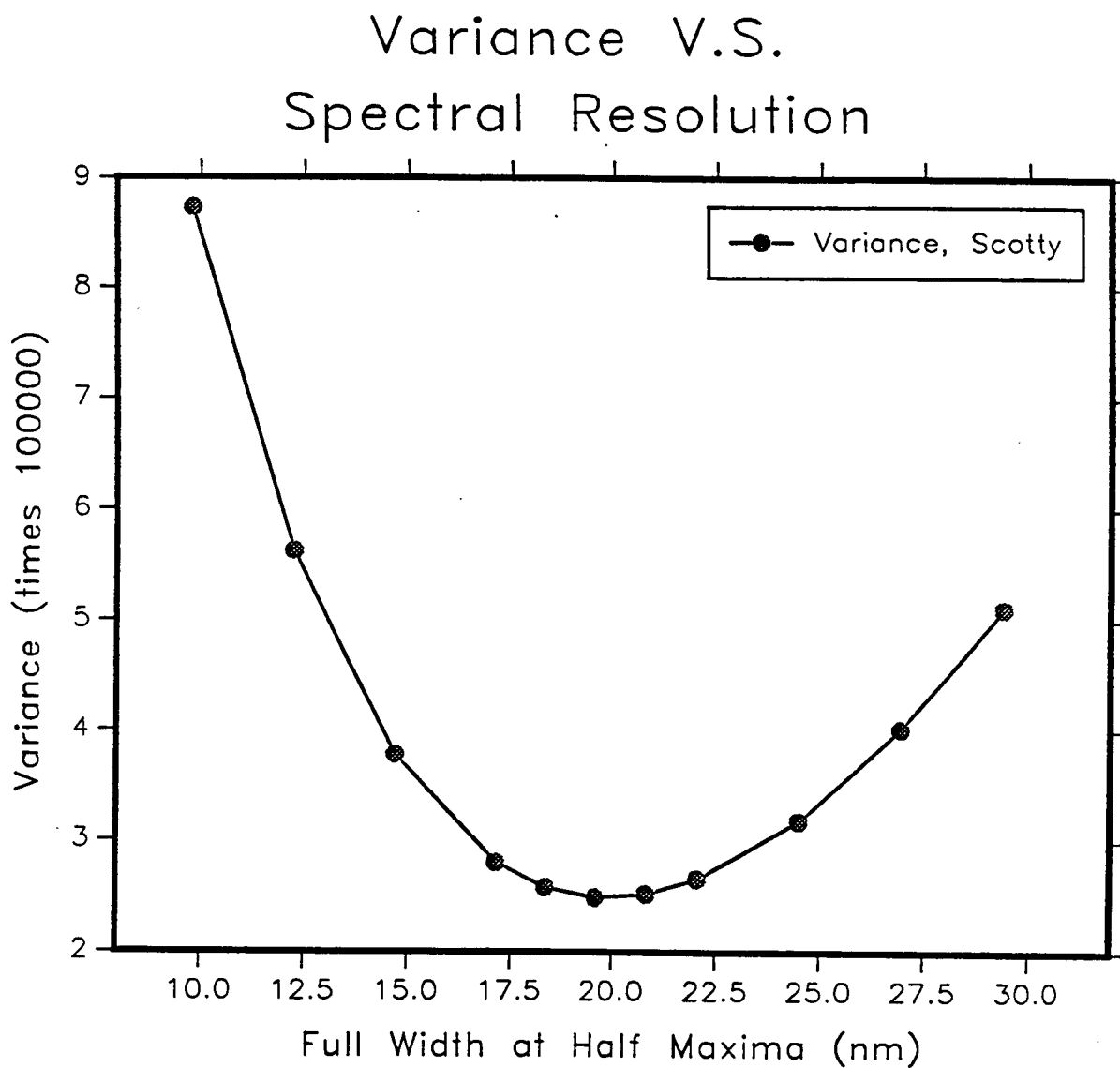
resulting plot gives the true spectral resolution of the data.
Figure 10 shows that the resolution (FWHM) for the 1987 northern
Grapevine Mountains AVIRIS data is 19.6 nm. This does not meet
the JPL specification for FWHM of ≤ 10 nm.

MINERAL IDENTIFICATION AND LITHOLOGICAL MAPPING

The 1987 AVIRIS data were adequate for identification
of mineral groups (eg. clays vs carbonates). Figure 11 shows
laboratory spectra (resampled to AVIRIS resolution) for selected
minerals known to occur at the northern Grapevine Mountains,
Nevada site. Figure 12 shows unsmoothed AIS spectra that allowed
identification of these minerals using the AIS data. Unsmoothed
spectra from the 1987 AVIRIS data were extremely noisy (Figure
13). Figures 14a through 14d show comparisons of smoothed spectra
extracted from the 1987 AVIRIS data with the resampled laboratory
spectra. Figure 14a compares muscovite and a smoothed AVIRIS
spectrum for an area known to contain sericite (fine grained
muscovite). Although the main absorption feature is in
approximately the correct wavelength location (2.2 μm), the
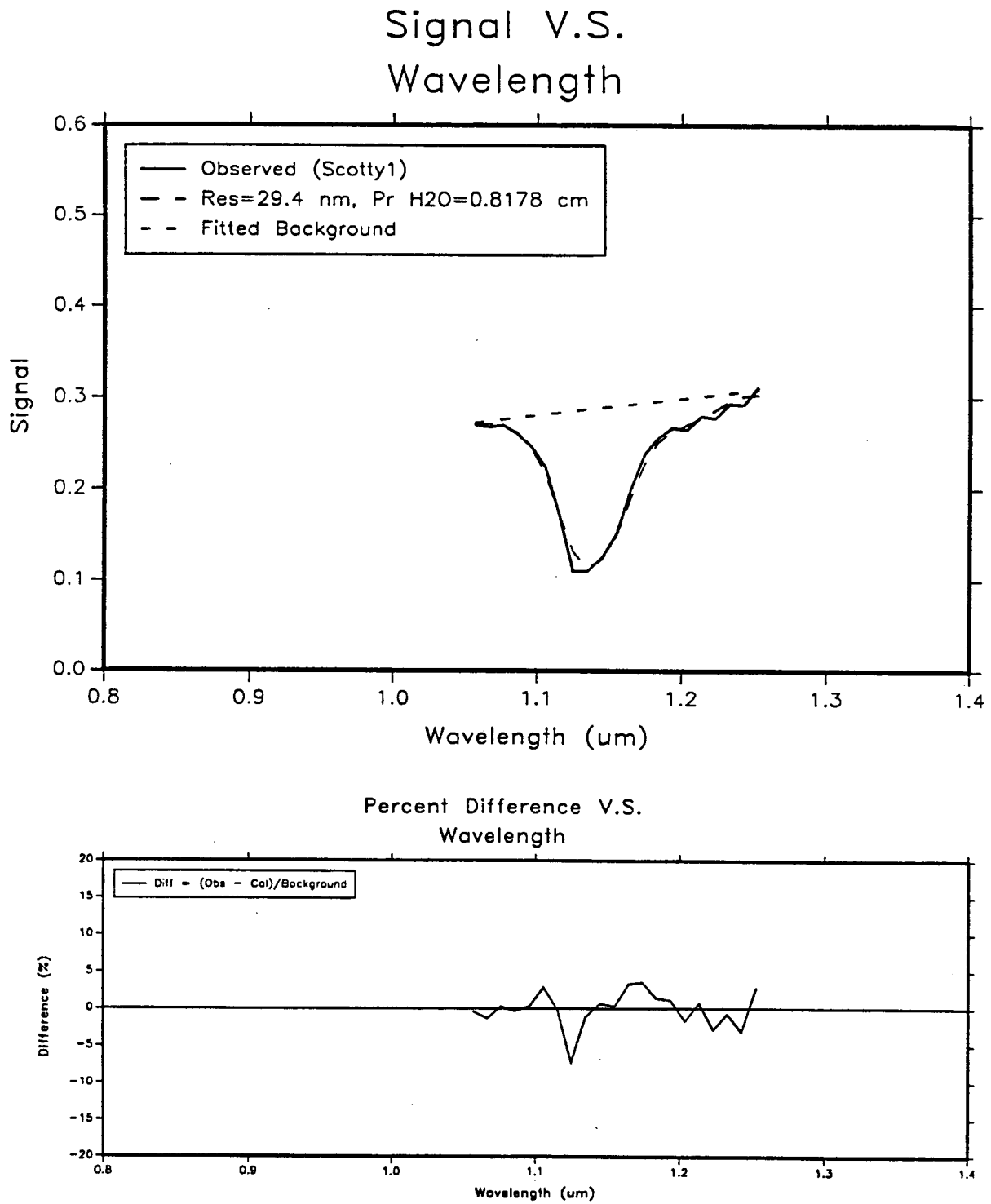absorption band is very broad, and the secondary feature near 2.35
μm is not resolved. The AVIRIS spectrum can not be used to
unambiguously distinguish between sericite and montmorillonite.
Figures 14b and 14c compare two different AVIRIS spectra
corresponding to known locations of calcite and dolomite
respectively to a laboratory spectrum of dolomite. Although the
spectra are somewhat different, neither spectrum resembles
dolomite very closely, and the wavelength position of the
strongest absorption feature does not match either dolomite or
calcite. Additionally, the position of the absorption feature is
identical in both spectra. Consequently, these data can be used
to identify the carbonate group minerals, but can not be used to
identify individual minerals. Figure 14d compares a spectrum for
an area known to contain the mineral goethite and laboratory
spectra of hematite and goethite. This spectrum has not been
smoothed. Note that it more closely resembles hematite than

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Figure 11. Laboratory spectra resampled to AVIRIS wave-
lengths for the minerals calcite, dolomite
and sericite.

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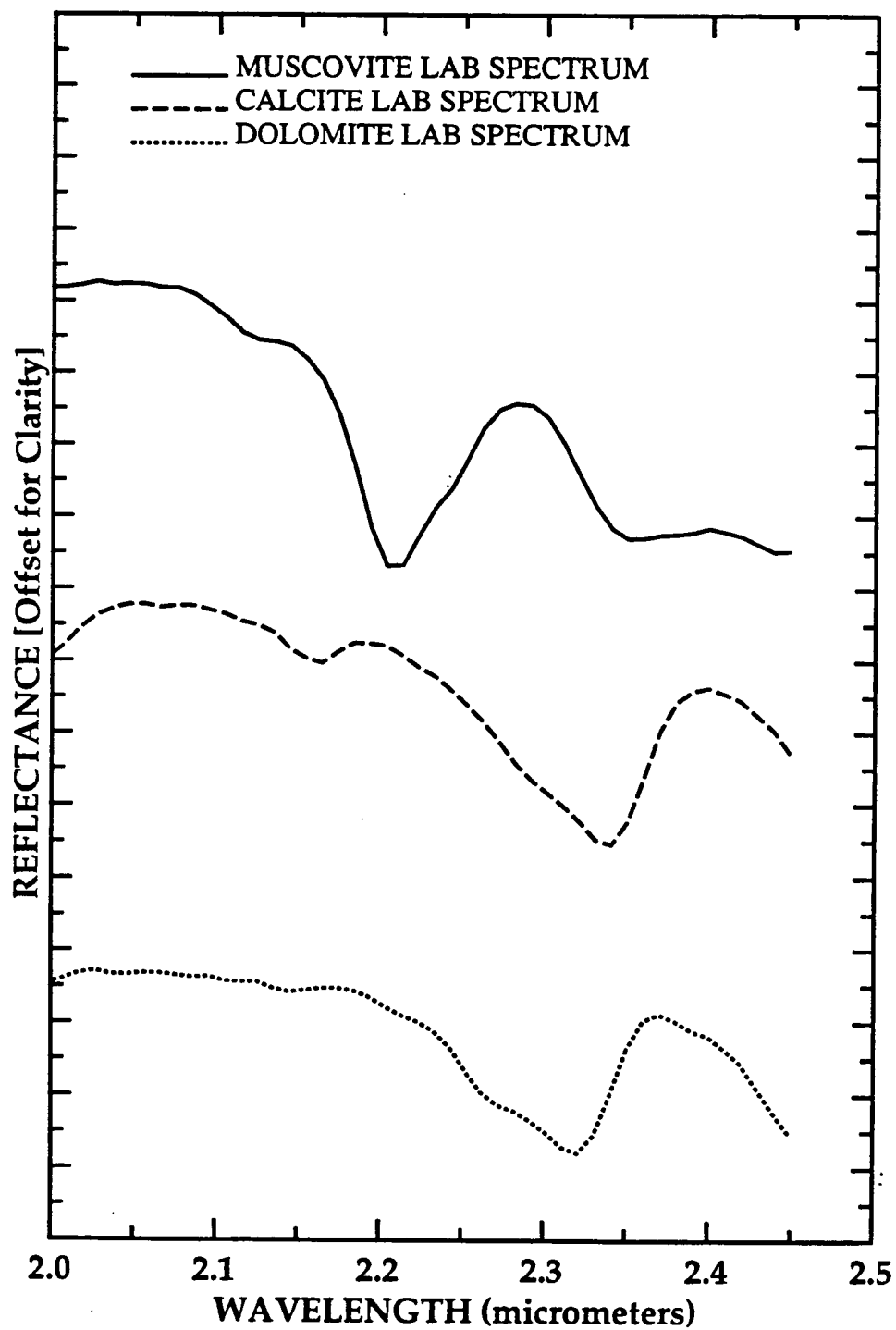Figure 12. AIS IAR reflectance spectra for the northern Grapevine
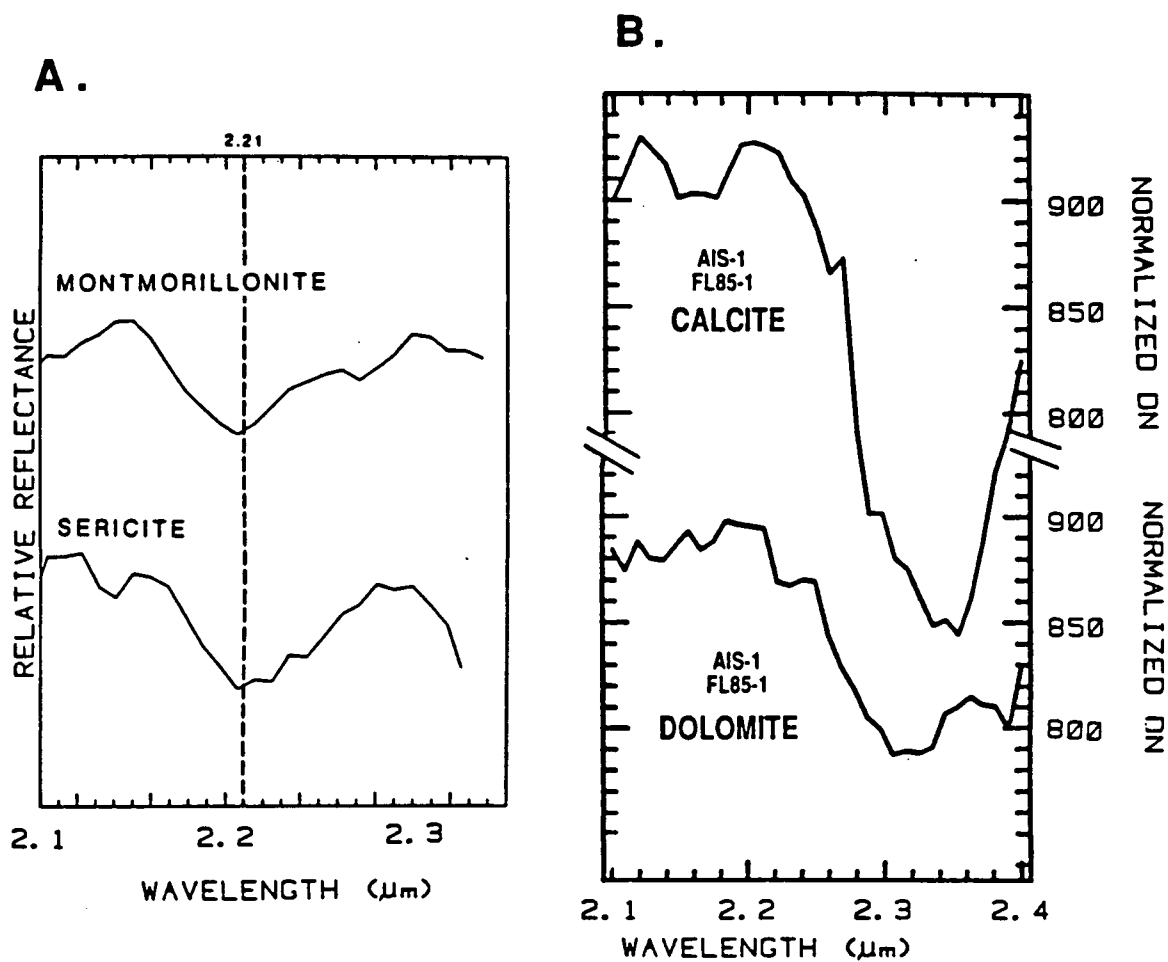Mtns., NV, site.

A.

B.

Figure 13. Unsmoothed 1987 AVIRIS reflectance spectra for the northern Grapevine Mtns., NV, site.
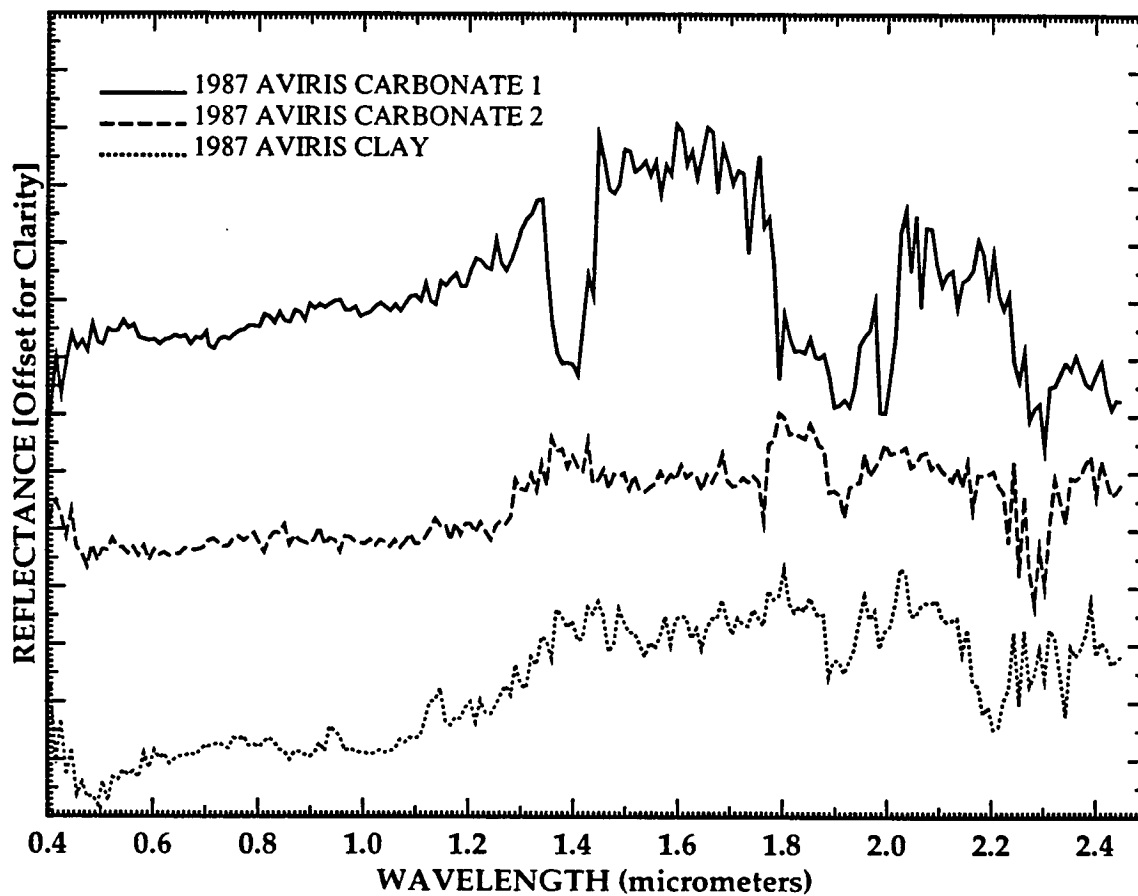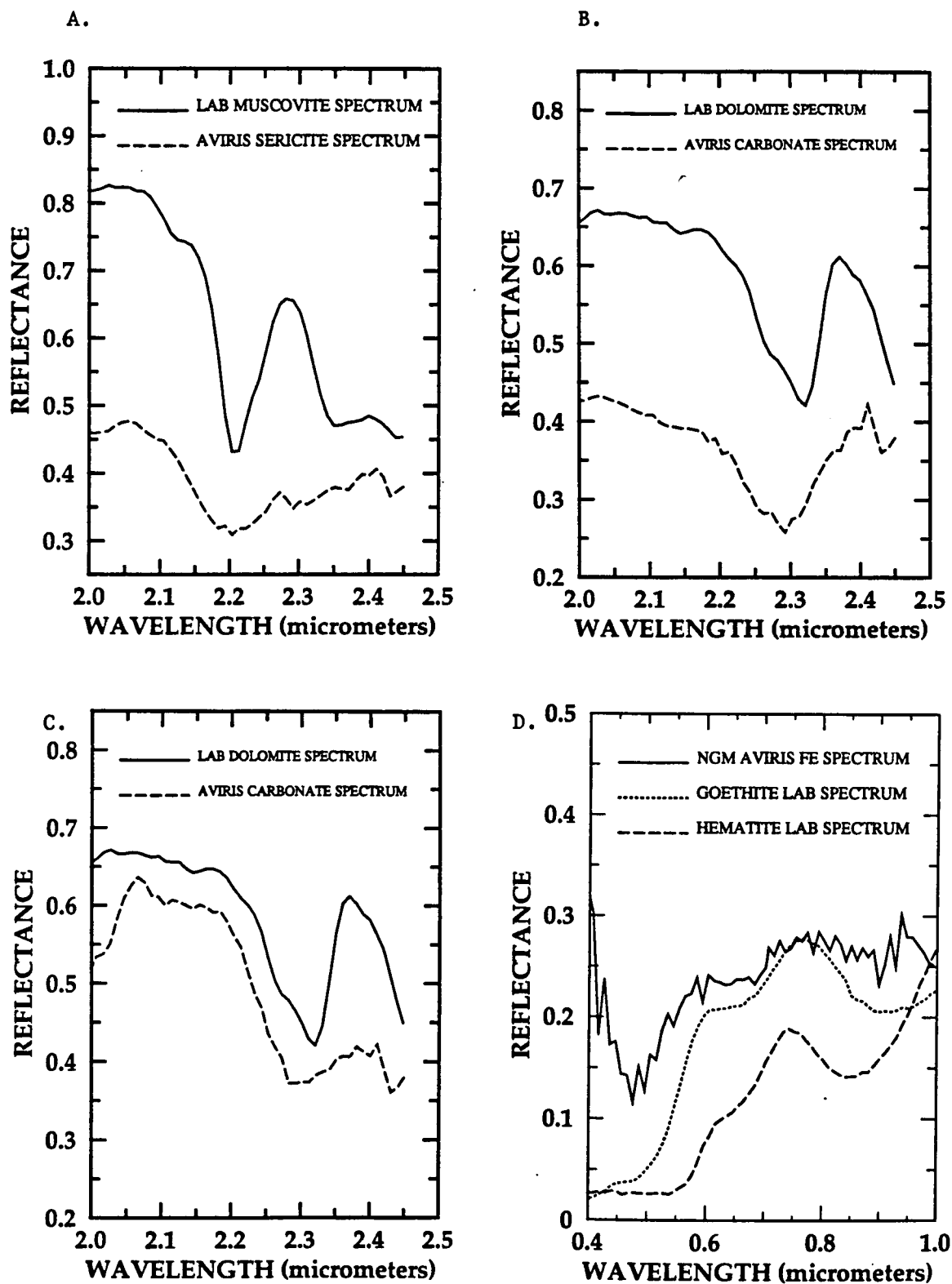
Figure 14. 1987 smoothed AVIRIS reflectance spectra for the northern Grapevine Mtns., NV, site: a) 1987 AVIRIS sericite, b) 1987 AVIRIS carbonate 1, 1987 AVIRIS carbonate 2, d) 1987 AVIRIS Fe oxide.

A.

B.

C.

D.

goethite, but that the low signal-to-noise ratio makes the comparison somewhat problematic. This spectrum allows identification of iron oxides as a group, but not individual minerals.

Plate 1 is a thematic image map derived from spectral analysis of the northern Grapevine Mountains, Nevada, AIS data (Kruse, 1988) that was used in the assessment of the AVIRIS data. Seven flightlines were mosaicked together and overlain on the topographic base. The images were classified in the spectral domain based upon their absorption band position, depth, and widths. The hues on Plate 1 represent the absorption band position; red=2.34 μm (calcite), yellow=2.32 μm (dolomite), green=2.2 μm (clays). Individual spectra (Figure 12) were used in combination with the image to produce the map shown in Figure 15.

Plate 2 is a color-coded thematic image map derived from spectral analysis of the 1987 northern Grapevine Mountains, Nevada, AVIRIS data. The AVIRIS spectra shown in Figures 14a, 14b, and 14c extracted from areas of known mineralogy were used to attempt to characterize the spatial distribution of the minerals sericite, calcite, and dolomite respectively. These spectra were used as a spectral library for image classification. Binary encoding (Mazer et al., 1988; Kruse et al., 1990) of the spectrum for each pixel of the AVIRIS image was used to select those areas that most closely matched the library spectra. Areas that matched within specified tolerances were color coded and overlain on a gray scale image to produce the thematic image map.

Comparison of Plate 2 to both Plate 1 and Figure 15 shows that the AVIRIS "calcite" (red) and "dolomite" (yellow) classes do not match very well similar classes mapped using the AIS and verified in the field. Instead, the differences between the two classes seem to correspond to the difference between shaded and illuminated slopes. If the calcite and dolomite classes are taken together, however, they appear to do a good job of mapping carbonates as a group. The green areas on Plate 2 correspond to areas with spectral characteristics similar those shown on Figure 14a (sericite), however, it is clear from comparison of the AVIRIS

MINERALOGICAL MAP
FROM 1984-1986 AIS DATA
NORTHERN GRAPEVINE MOUNTAINS,
NEVADA/CALIFORNIA
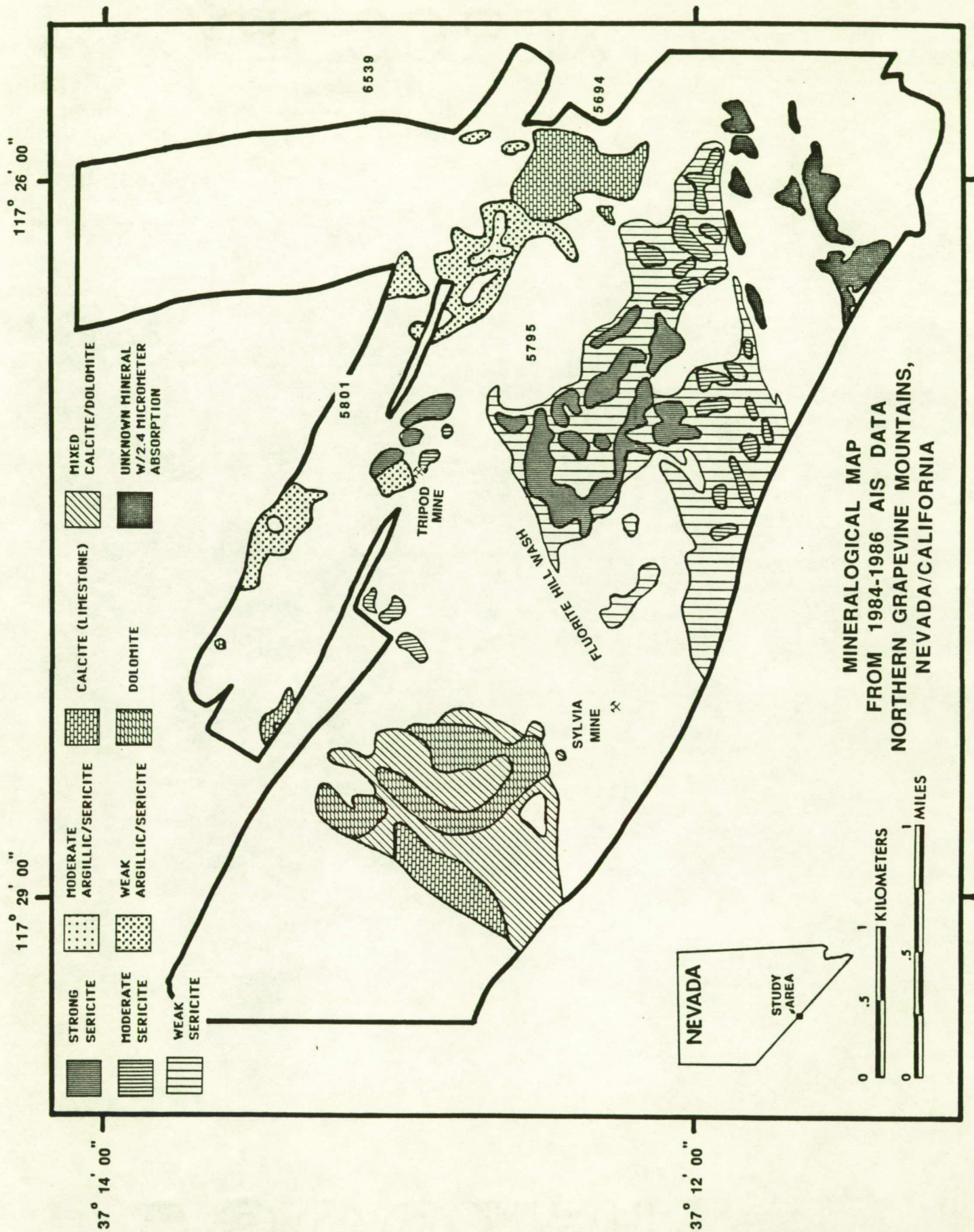
Figure 15. Mineral map derived from 1984 – 1986 AIS data.

Plate 1. AIS color-coded thematic image map. Red indicates an absorption feature at 2.34 μm (calcite), yellow an absorption feature at 2.32 μm (dolomite), and green an absorption feature at 2.2 μm ("Clays" – sericite and montmorillonite).

Plate 2. 1987 AVIRIS carbonate and sericite thematic image map. Red indicates calcite, yellow is dolomite, and green is sericite.

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thematic map to the AIS thematic map (Plate 1) and Figure 12 that the 1987 AVIRIS data did not adequately map the distribution of this mineral. Plate 3 shows the distribution of iron oxide minerals at the northern Grapevine Mountains, Nevada, site. These were identified using the binary encoding and color coded as red on the gray scale image. Although the iron oxides could be mapped as a group, the individual species could not be differentiated using the 1987 AVIRIS data (Figure 14d).

We conclude from the above discussions that the 1987 AVIRIS data are not useful for for mapping subtle lithological variation based on identification of individual minerals. Despite the fact that the geometry and spatial resolution of the data were adequate to map the targets of interest we were unable to map known subtle mineralogical variation or extend the mapping to unknown areas principally because of a combination of inadequate spectral resolution and the very poor signal-to-noise ratios of the data.

Plate 3. 1987 AVIRIS Fe oxide thematic map. Red indicates undifferentiated iron oxides.

1989 DATA EVALUATION

<u>SUMMARY</u>

AVIRIS was re-engineered and modified during 1988 and 1989 to correct some of the problems identified during the 1987 flight season. Additional AVIRIS data were acquired for the northern Grapevine Mountains site during July 1989. This AVIRIS evaluation in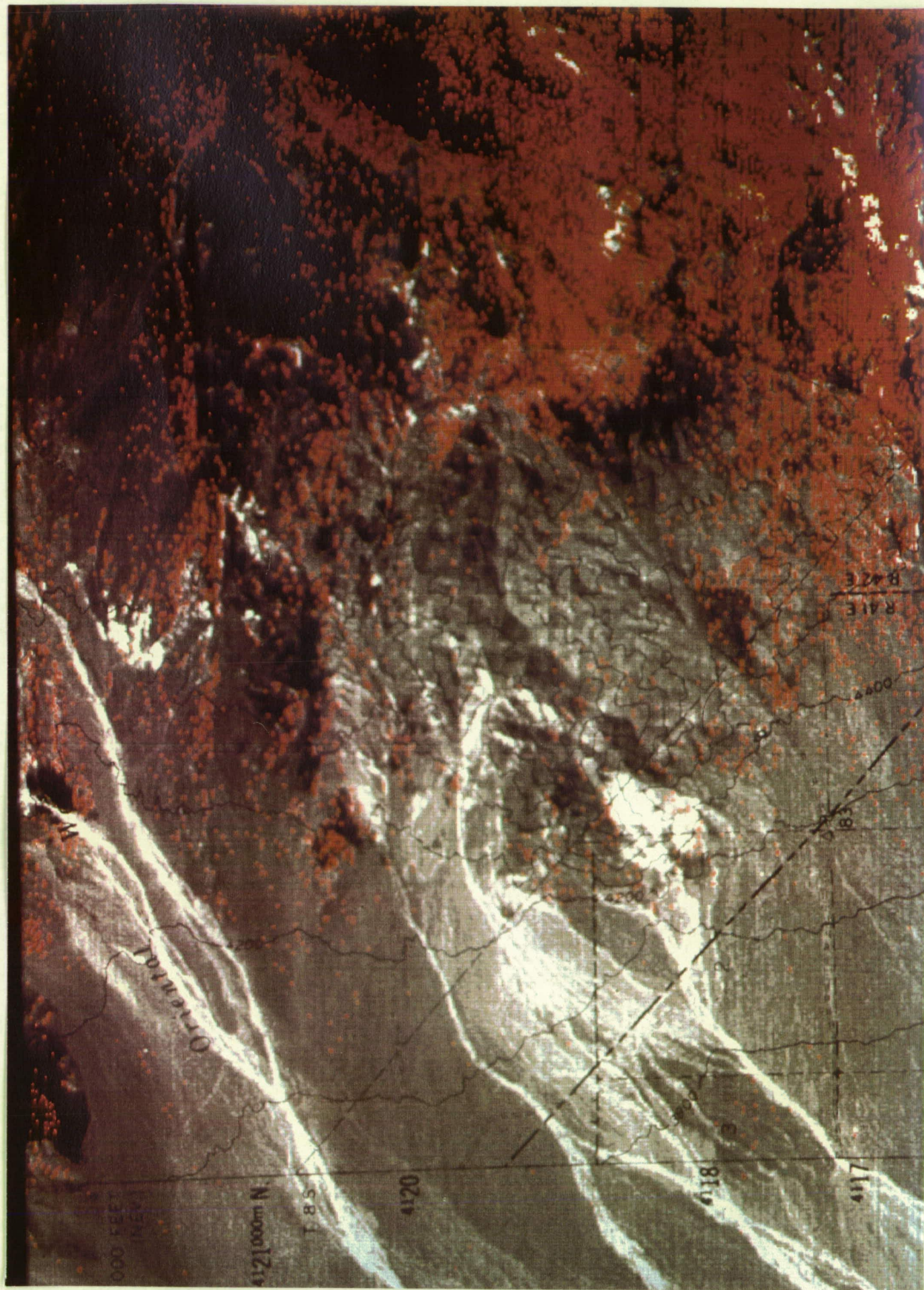vestigation was extended to December 31 1989 at no additional cost to NASA in order to evaluate the 1989 AVIRIS data and to compare the new data to the 1987 data.

The signal-to-noise, geometric characteristics, spatial resolution, and spectral resolution, and the utility of the data for mapping subtle lithological variation were evaluated as described for the 1987 data. The signal-to-noise ratios of the 1989 data were much improved (50/1 at 0.70 and 20/1 at 2.20), but still did not meet specifications. The spatial resolution was 17 m in the line direction and 16.7 m in the pixel direction. The spectral resolution was 15 nm, again not to specifications.

The 1989 AVIRIS data were calibrated to reflectance using ground targets and the empirical line method (Roberts et al., 1985; Elvidge, 1988, Kruse et al. 1990). AIS-1, AIS-2, GERS data, and detailed field mapping were compared with the AVIRIS data and differences in the information available from each data set and the effect of the AVIRIS data characteristics on the quality of the information were assessed. Two wavelength ranges of the AVIRIS data were used to identify and map the distribution of minerals. These involved the use of at least partial data from all four spectrometers The short-wave infrared data from 2.0 to 2.5 micrometers was used to identify and map the distribution of clay minerals, muscovite (sericite), and carbonate minerals. The addition of the visible and short wavelength infrared portions of the spectrum allowed identification and mapping of iron oxide minerals. Mapping of these minerals and their mixtures added significantly to the understanding of the lithological variation at the northern Grapevine Mountains test site.

The results demonstrate that during 1989 AVIRIS was in an operational state. We were able to duplicate results produced

using the AIS instrument and to develop new information using the visible portion of the spectrum (not available with AIS). The spatial coverage of AVIRIS permitted us to extend our studies to new ground. Signal-to-noise characteristics, however, still are not up to specifications and should be improved if possible before the next flight season.

GENERAL QUALITY OF THE DATA

The quality of the 1989 AVIRIS data is much higher than the 1987 data. Simple visual comparison of the AVIRIS quick-look data from the two dates shows that the 1989 data is better. There are fewer dropped lines, essentially no horizontal striping, and no visible gain offsets. There is, however, vertical striping in approximately the first 10 bands (0.41 to 0.49 μm) (Plates 4 and 5). This decreases in severity with increasing wavelength and is not apparent in bands beyond 0.49 μm. Additionally, for the radiometrically corrected and spectrally resampled data, the 1st band (0.40 μm) appears to be all noise and the last 4 bands (206-210, 2.41 - 2.45 μm) contain all zero digital numbers. The signal-to-noise ratios, however, are clearly higher and the geologic targets better resolved both spectrally and spatially.

SIGNAL-TO-NOISE

Signal-to-noise was calculated for the entire AVIRIS scene using techniques described for the 1987 data. Figure 16 shows the signal-to-noise for the full AVIRIS wavelength range. The S/N for the 1989 northern Grapevine Mountains AVIRIS was approximately 50/1 at 0.70 μm and 20/1 at 2.20 μm. Note that overall, the data is much improved over the 1987 data (Figures 5 and 6), however, the instrument still does not meet the design specifications of 100/1 at 0.70 μm and 50/1 at 2.20 μm.

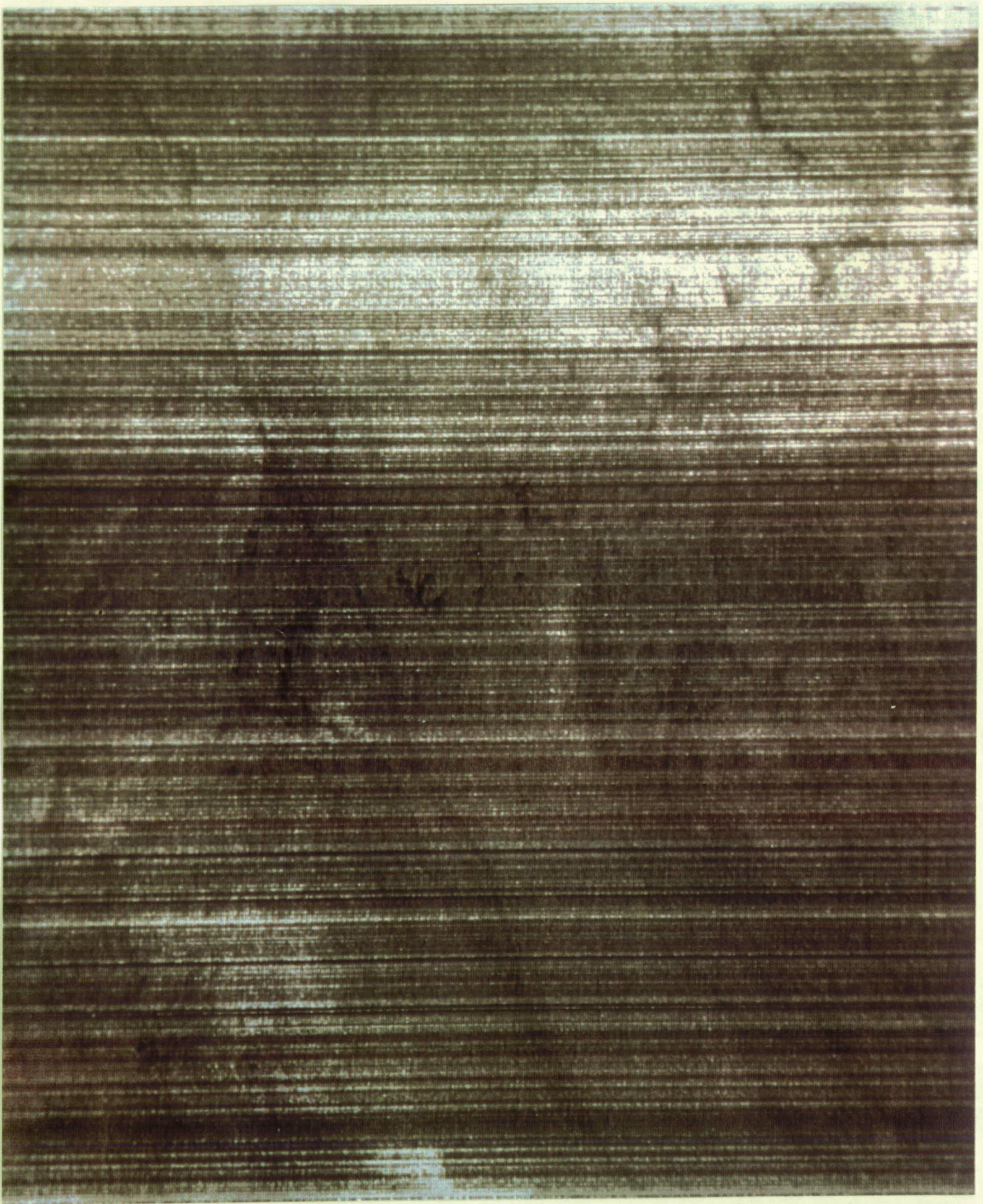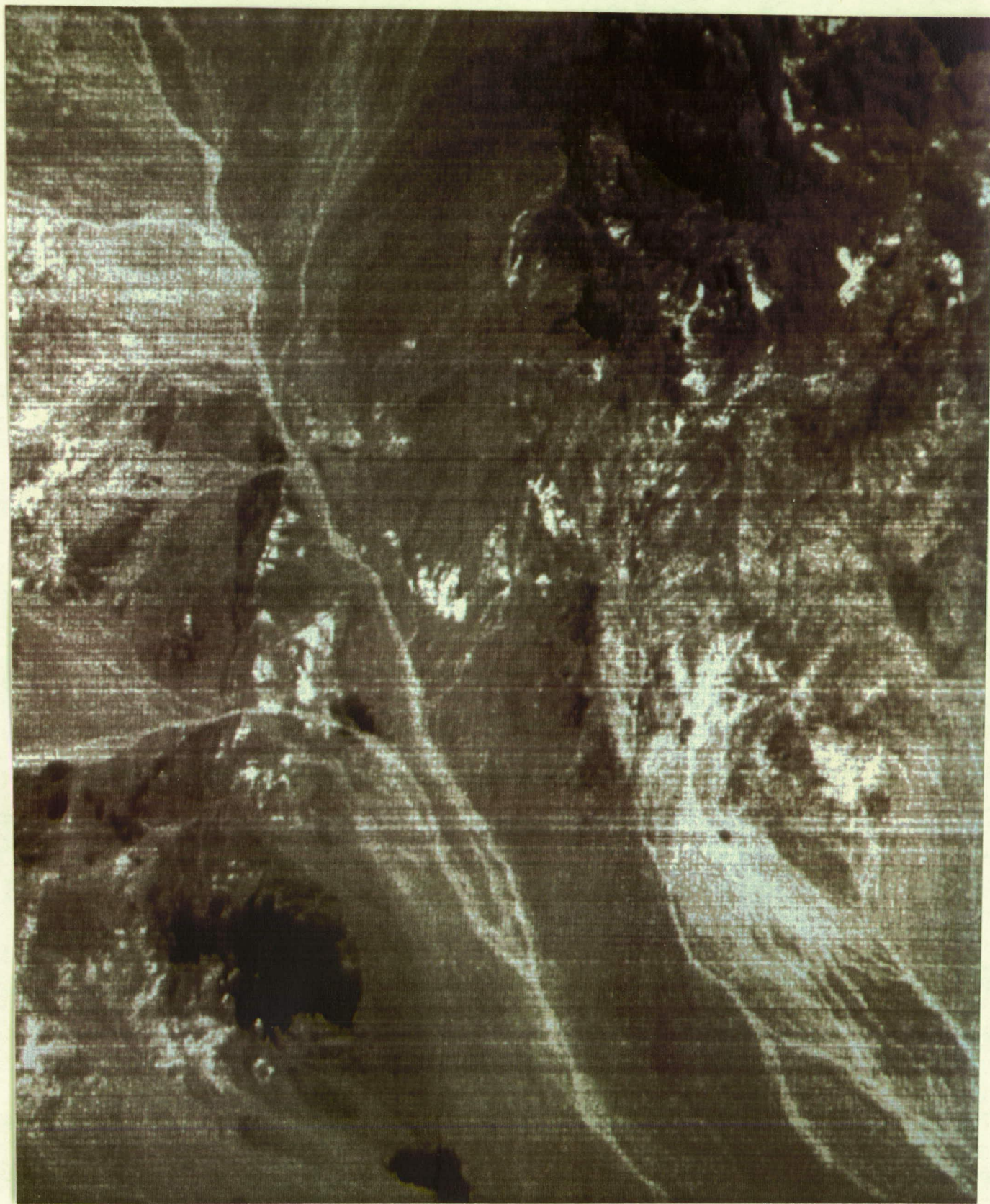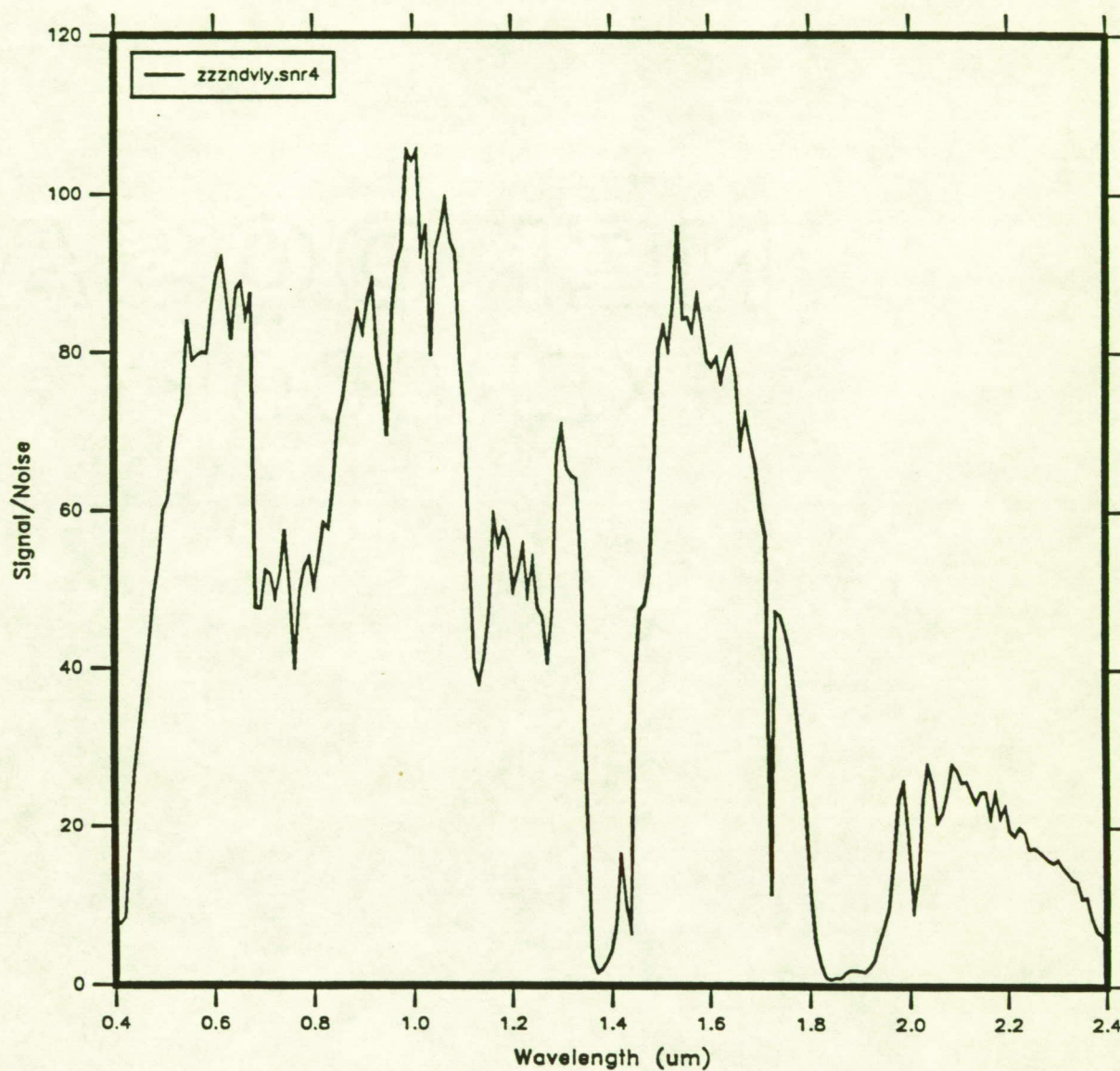Plate 4. 1989 AVIRIS band 2 (0.41 µm) showing vertical striping.

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Plate 5. 1989 AVIRIS band 6(0.45 μm) showing vertical striping.

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Figure 16. 1989 northern Grapevine Mountains AVIRIS signal-to-noise ratio calculated from the entire image.

GEOMETRIC CHARACTERISTICS

Like that of the 1987 AVIRIS data, the geometry of the 1989 AVIRIS images was excellent. Visual assessment and comparison to topographic maps showed no obvious geometric distortions. Linear rescaling and rotation were sufficient to obtain an image corrected to the digital topographic base. Once again, mismatches (residual errors) between the AVIRIS and the topographic base were on the order of 2 to 4 pixels.

SPATIAL RESOLUTION

The adequacy of the spatial resolution of the 1989 AVIRIS data was evaluated by measuring known distances on the image to determine the true ground instantaneous field of view and swath width. The AIS-1 data for the northern Grapevine Mountains site had a ground pixel size of approximately 10.9 x 10.9 meters and a 350 meter swath width. The AIS-2 data for this site had a 14.4 x 14.4 meter ground pixel and a 920 meter swath width. The predominantly vein nature of the alteration and mineralization and the high spatial resolution of the two AIS data sets allowed critical evaluation of the distribution of alteration mineralogy (Figure 15). The 1989 AVIRIS spatial resolution was calculated to be 16.7 m in both the line and pixel directions, resulting in a scene size of 10.25 x 8.6 kms. Note that the spatial resolution is again better than 20 m and within 15% of the specification. The fact that x and y scales are identical is another indication of the good geometry of the data. The question to be answered was weather or not the AVIRIS resolution would be sufficient for mapping relatively narrow mineralogical zones. This will be discussed further in the section below on mineralogical identification and lithologic mapping.

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SPECTRAL RESOLUTION

The spectral resolution was calculated as described above for the 1987 AVIRIS data by using the AVIRIS raw data and fitting a modeled atmospheric curve to the data for the 1.14 μm atmospheric water absorption band (Gao and Goetz, 1989). Figure 17 shows the plot of the variance of the fit versus the FWHM. The minimum of the plot shows that the true spectral resolution of the 1989 northern Grapevine Mountains AVIRIS data is approximately 15 nm. Although improved from the 1987 data, this still does not meet the JPL specification for FWHM of $\leq$ 10 nm.

MINERAL IDENTIFICATION AND LITHOLOGICAL MAPPING

The AIS-1 instrument had a spectral sampling interval of approximately 9.3 nm while the AIS-2 instrument sampled at approximately 10.6 nm intervals. Clark et al. (1990) have shown that spectral resolution and sampling interval can be critical for evaluating certain minerals. We compared the results obtained from the two AIS instruments at the northern Grapevine Mountains site to those obtained from the 1989 AVIRIS data. We evaluated the quality of the spectra produced from the AVIRIS data by comparing them to the other available aircraft data sets and field and resampled laboratory spectra to see if mineral absorption bands were adequately resolved. Figure 18 shows unsmoothed spectra extracted from the northern Grapevine Mountains, Nevada, 1989 AVIRIS data for known occurrences of sericite, calcite, and dolomite. Comparison of the shapes and positions of the absorption features to the resampled laboratory spectra shown in Figure 11 makes positive identification of the three minerals possible. The 1989 AVIRIS data not only allows identification of the carbonate-group-minerals, but allows identification of the individual species (calcite and dolomite) based upon a 20 nm (2 channel) difference between the position of the main absorption feature (2.34 vs 2.32 μm). This distinction was not possible using the 1987 AVIRIS data.

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Figure 17. 1989 northern Grapevine Mountains AVIRIS variance vs
FWHM (resolution).

Sigma Squared V.S.
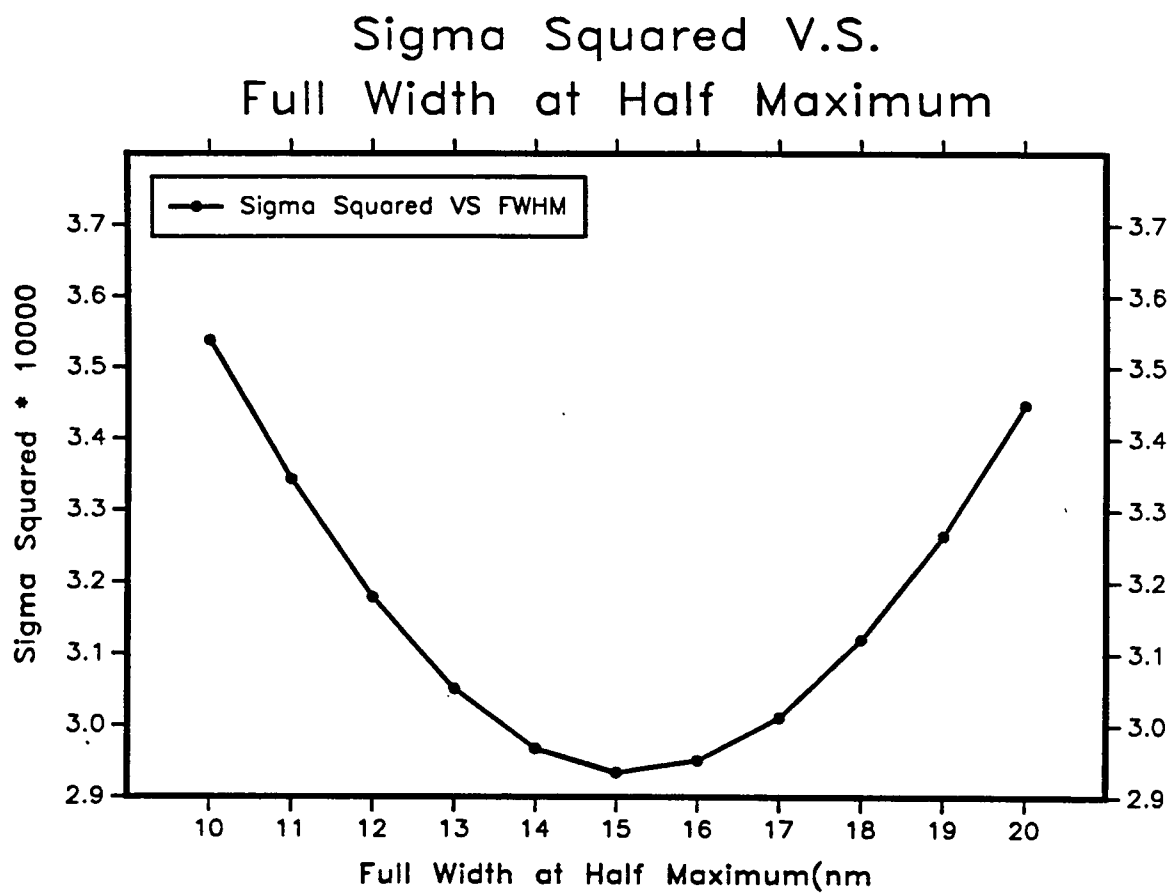## Full Width at Half Maximum

Figure 18. 1989 AVIRIS SWIR reflectance spectra for the northern
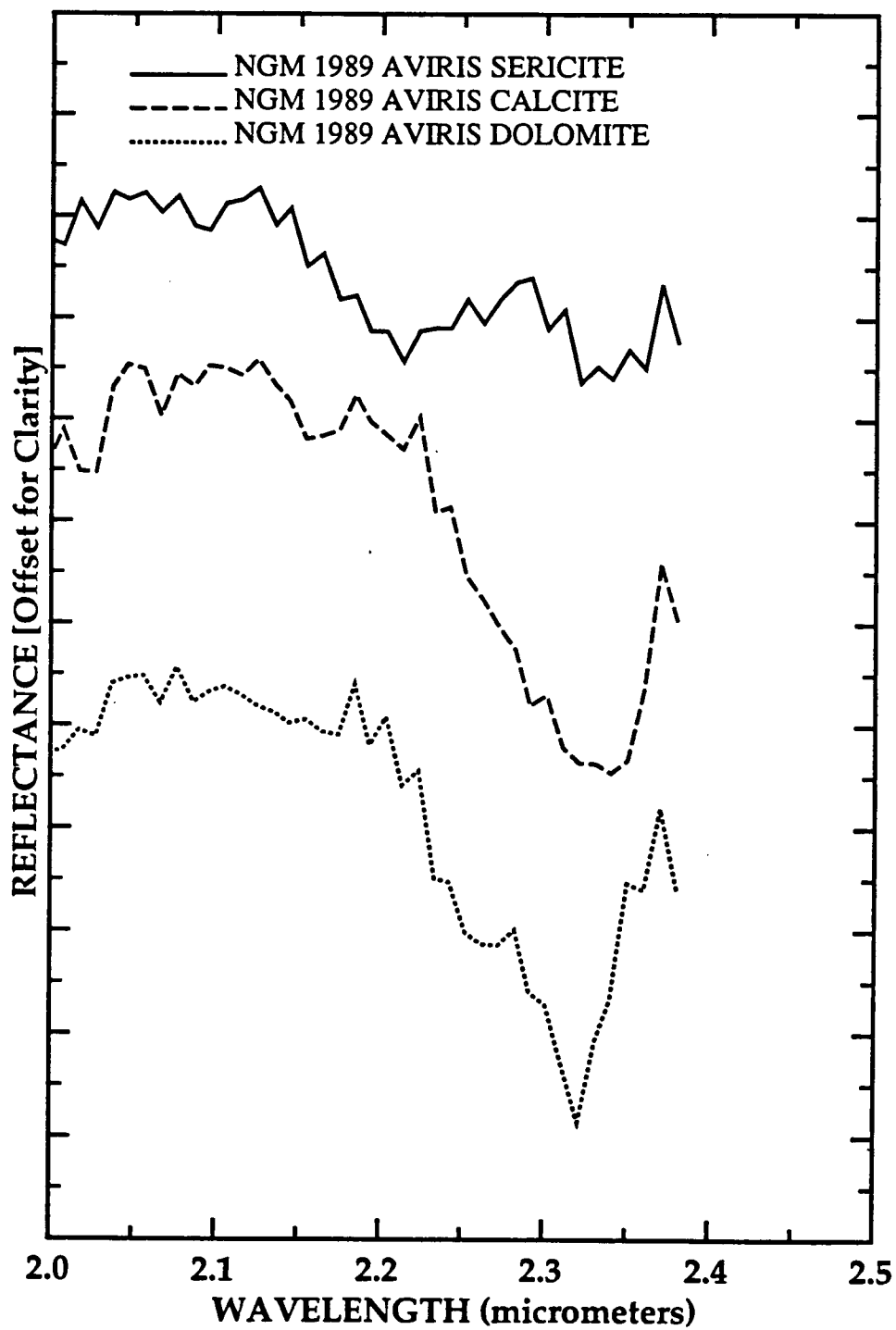Grapevine Mtns., NV site.

Figure 19 shows unsmoothed spectra extracted from the northern Grapevine Mountains, Nevada, 1989 AVIRIS data for known occurrences of hematite and goethite. Note the positions of the broad absorption feature near 0.9 μm for goethite and 0.85 μm for hematite. Note also the position of the visible absorption shoulder near 0.48 μm for goethite and near 0.58 for hematite. Comparison of these spectra to the resampled laboratory spectra for goethite and hematite shown in Figure 20 allow positive identification of the two iron oxide minerals. This distinction was not possible using the AIS data because of lack of spectral coverage or with the 1987 AVIRIS data because of S/N problems.

The final step in the analysis of the northern Grapevine Mountains, Nevada, 1989 AVIRIS data was to map the spatial distribution of the minerals identified from interactive inspection of image spectra. The calcite, dolomite, sericite, goethite, and hematite spectra extracted from the image were used as a spectral library for image classification. Binary encoding (Mazer et al., 1988; Kruse et al., 1990) of the spectrum for each pixel of the AVIRIS image was used to select those areas that closely matched the library spectra. Areas that matched within specified tolerances were color coded and overlain on a gray scale image to produce a thematic image map. Plate 6 shows a thematic image map of the distribution of calcite (red) and dolomite (yellow). Comparison of this to Plate 1, which shows the distribution of calcite and dolomite in the same colors mapped using the AIS data, clearly shows that the signal-to-noise of the 1989 AVIRIS data is marginal for detailed mapping of the distribution of these spectrally very similar minerals. Calcite and dolomite were grouped together as "carbonate" for subsequent mapping. Plate 7 shows a thematic map of the spatial distribution of the minerals sericite (green), carbonate (dark blue), hematite (red), goethite (orange), sericite+goethite (yellow), sericite+hematite (olive green), carbonate+goethite (magenta), and carbonate+hematite (cyan). Mixtures were determined by identifying the individual minerals (using the SWIR to identify sericite and carbonates and the visible to identify the iron

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Figure 19. 1989 northern Grapevine Mtns., NV, AVIRIS Fe oxide
reflectance spectra.

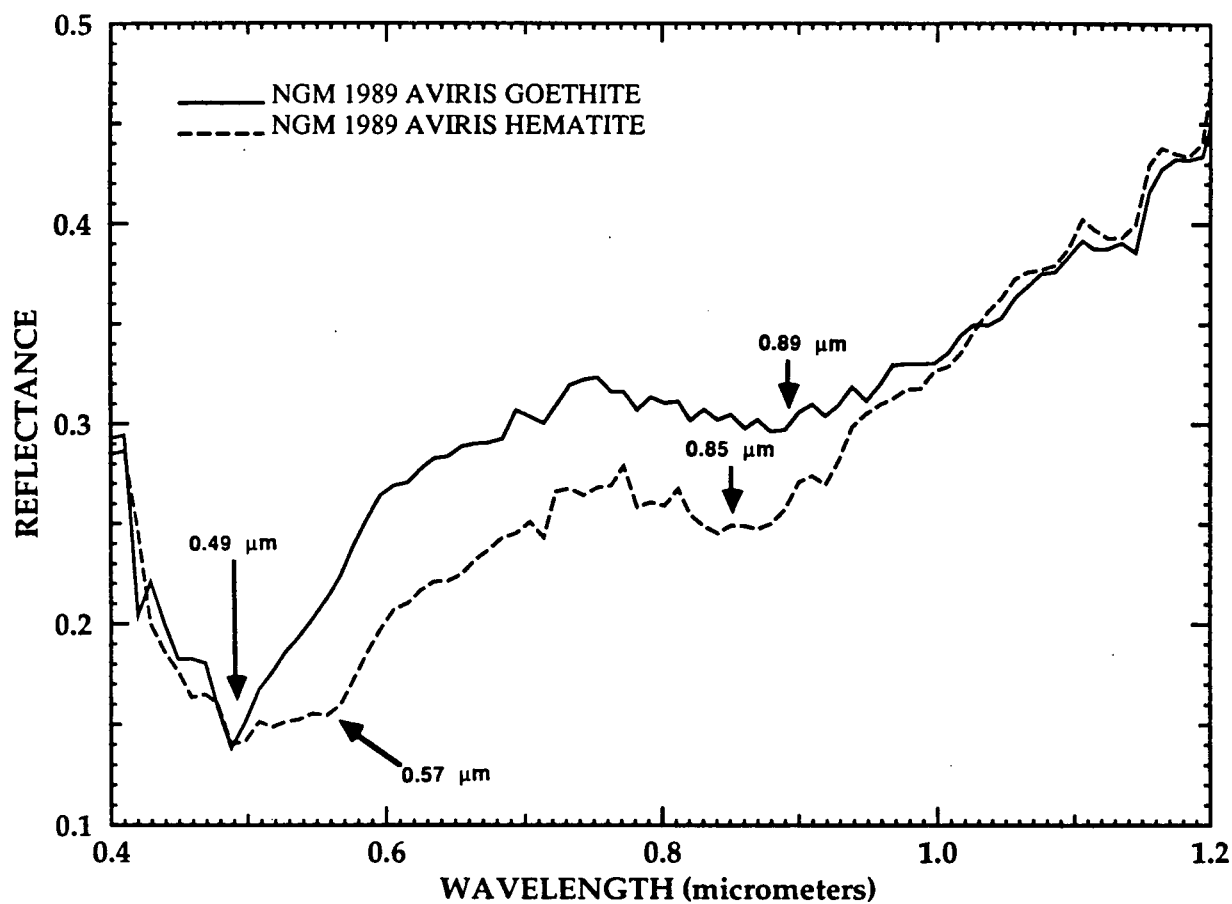Figure 20. Laboratory Fe oxide reflectance spectra.

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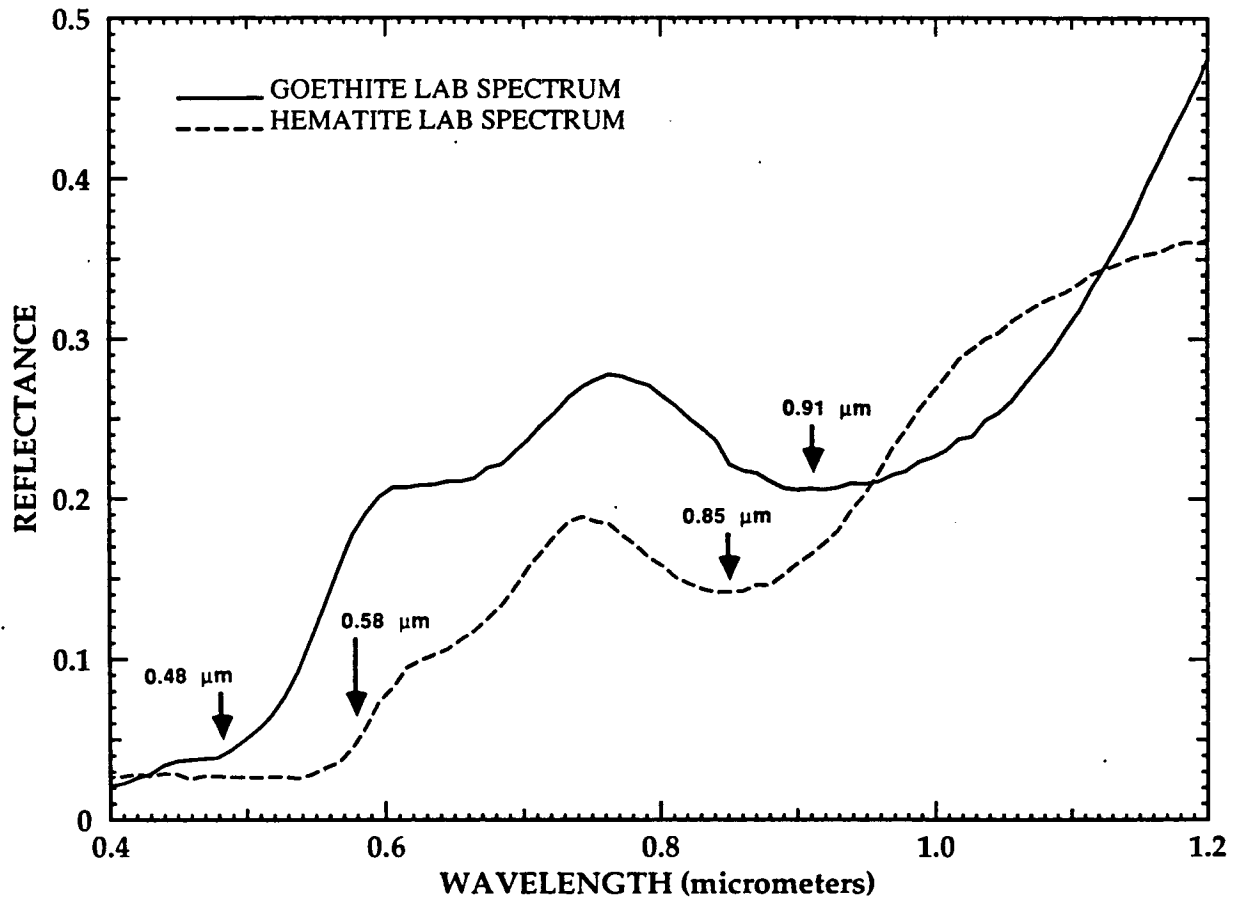
Plate 6. 1989 AVIRIS carbonate thematic image map. Red is calcite and yellow is dolomite.
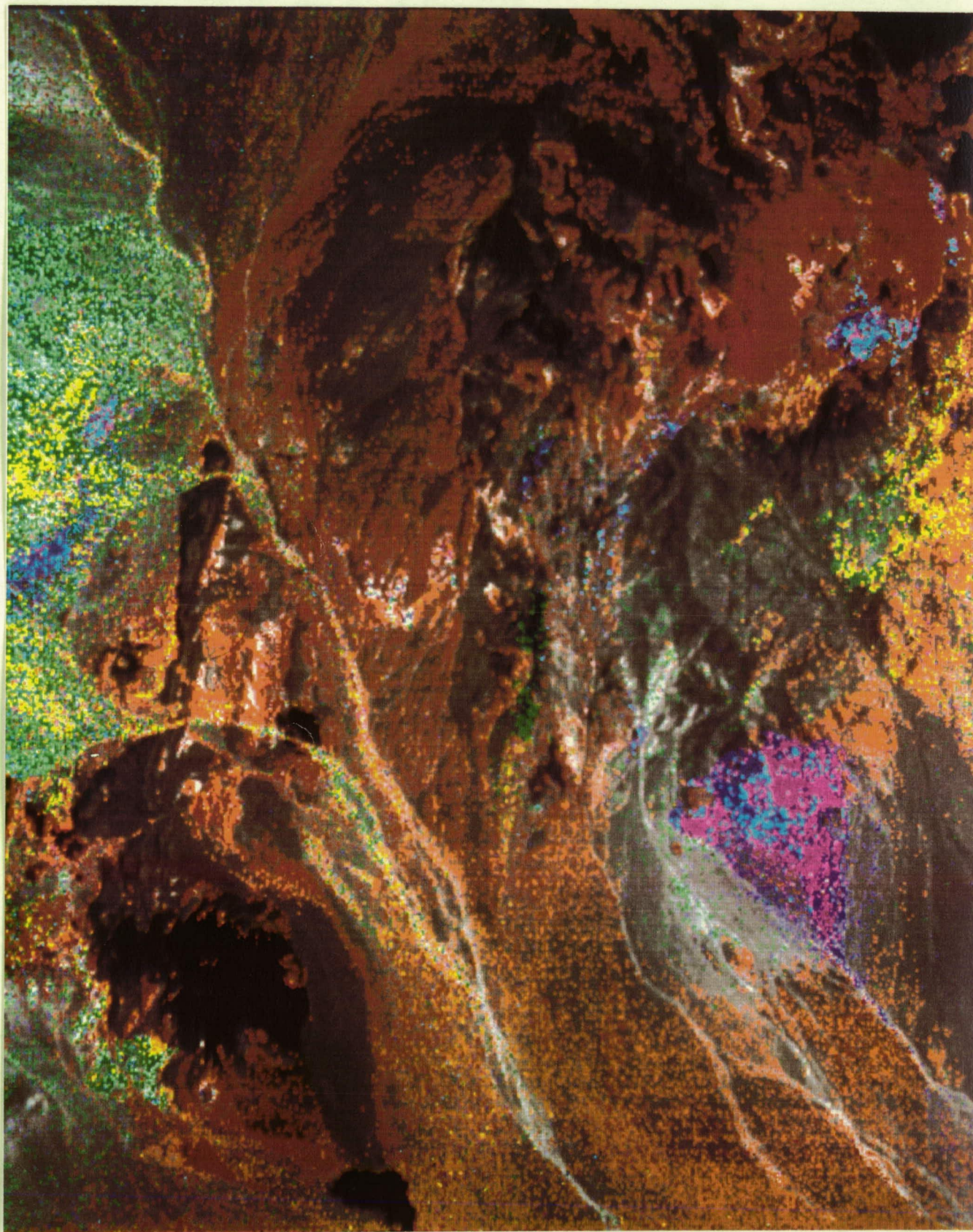
Plate 7. 1989 AVIRIS combined thematic image map. Green is sericite, carbonates are dark blue, hematite is red, goethite is orange, sericite + goethite are yellow, sericite + hematite are olive green, carbonate + goethite are magenta, and carbonate + hematite are cyan.

oxides) and using standard image processing techniques to combine the classifications where overlap occurred.

From the above examples, we conclude that the sampling interval and the current signal-to-noise ratios of the 1989 AVIRIS data are sufficient to identify the known minerals present at the northern Grapevine, Nevada, test site, however, natural spectral variation and random noise make spatial mapping of minerals with very similar characteristics such as calcite and dolomite difficult. Identification and mapping of subtle lithological variation would be much improved by increasing the signal-to-noise ratios of the data.

COMPARISON OF 1987 AND 1989 AVIRIS DATA

The modifications made to the AVIRIS instrument during 1988 and 1989 were effective in improving the usefulness of the data for geologic mapping. Figure 21 contrasts the signal-to-noise ratios of the 1987 and 1989 AVIRIS data. Figure 22 shows the difference between the 1987 and 1989 data for the same area dominated by the mineral sericite. Comparison of these two spectra to the resampled laboratory spectrum of muscovite (sericite) shown in Figure 11 shows that the 1989 AVIRIS data resolves both the 2.2 and 2.35 μm bands while the 1987 data does not. The overall signal-to-noise ratio of the 1989 data is much better. Note, however, the non-random up/down noise present in the 1989 data. The source of this noise is not known.

Figure 23 is a comparison of the 1987 and 1989 AVIRIS data for a known occurrence of calcite. Note that the 1989 data resolves the absorption band at 2.34 μm while the 1987 data does not, because of the very low signal-to-noise of the 1987 data. Figure 24 is a comparison of the 1987 and 1989 AVIRIS data for a known occurrence of dolomite. Again, the 1989 data resolves the absorption band at 2.32 μm while the 1987 data does not. Note also that the 1989 spectra in Figures 23 and 24 are different enough that you can tell them apart, while the 1987 spectra are

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Figure 21   Comparison of signal-to-noise ratios for the 1987
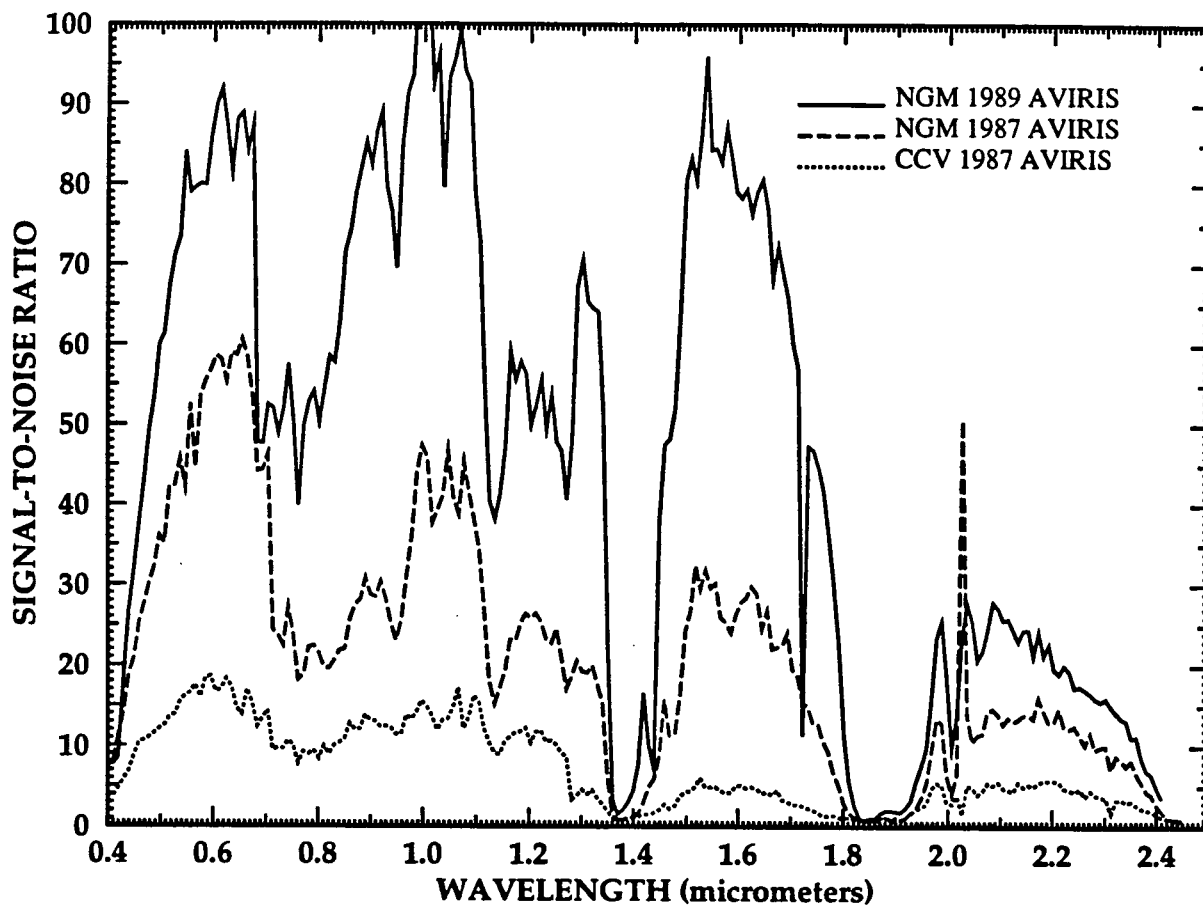   and 1989 AVIRIS data.

Figure 22.   Comparison of 1987 and 1989 northern Grapevine
              Mtns., NV, AVIRIS sericite spectra.
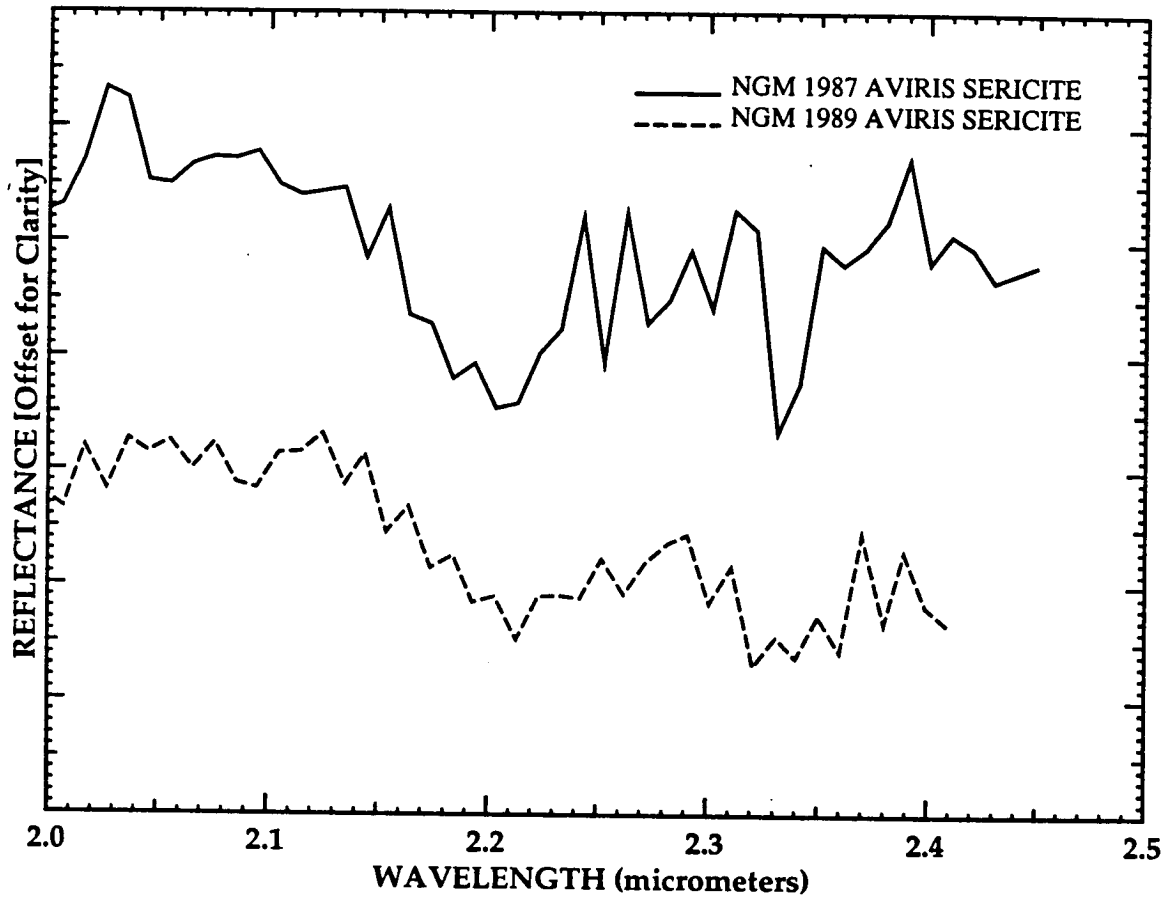
Figure 23.   Comparison of 1987 and 1989 northern Grapevine
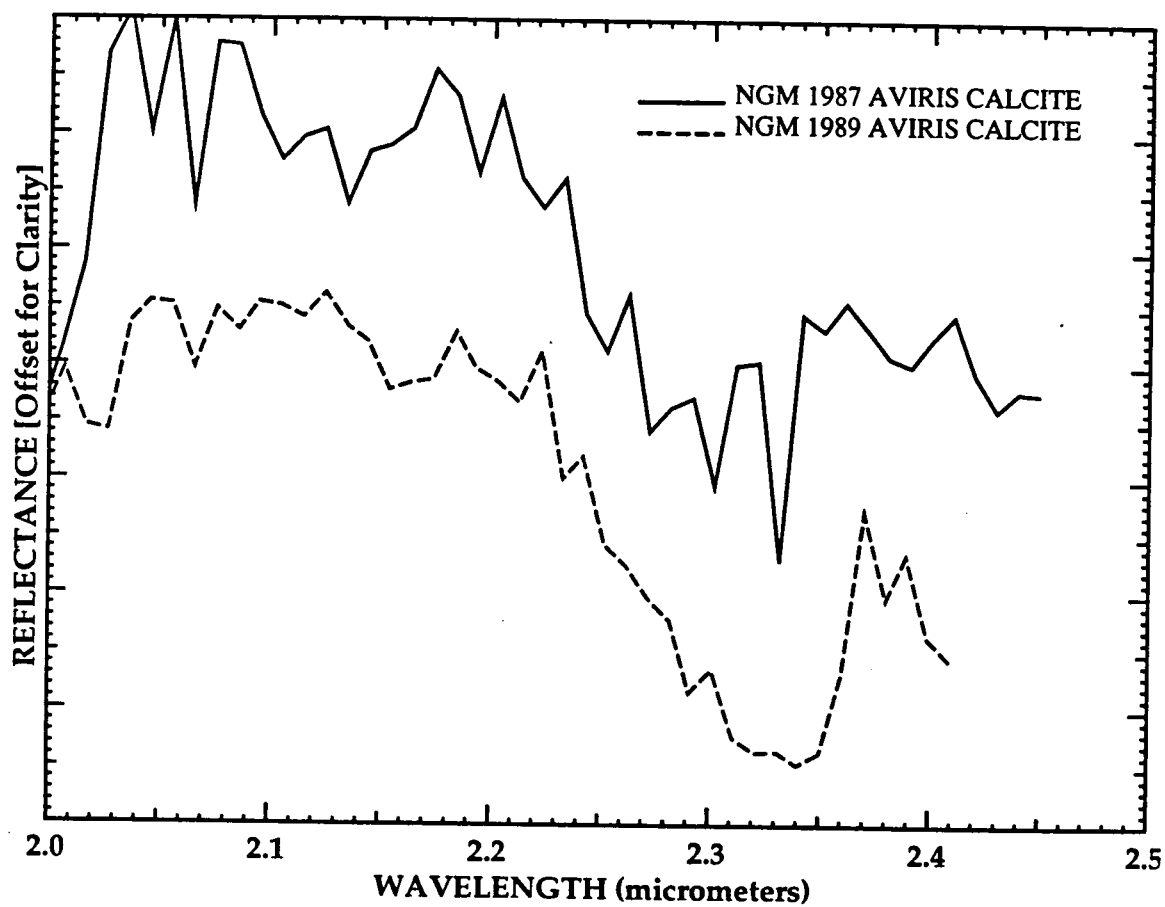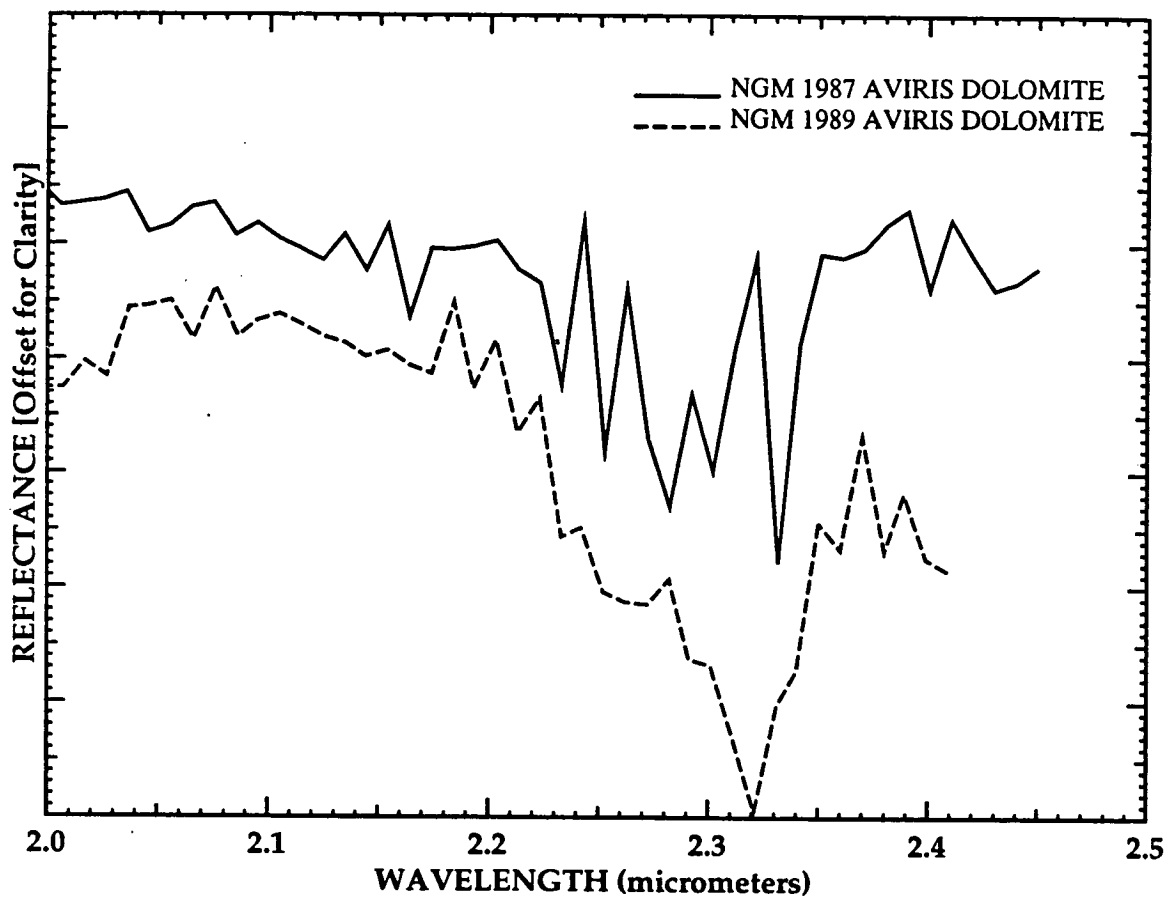   Mtns., NV, AVIRIS calcite spectra.

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Figure 24.   Comparison of 1987 and 1989 northern Grapevine
              Mtns., NV, AVIRIS dolomite spectra.

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very similar within the noise variance. Figure 25 compares iron oxide spectra from the 1987 and 1989 AVIRIS data. It is not clear where the FE^{+3} absorption feature occurs in the 1987 data because of the high noise. The 1989 AVIRIS data, however, has a high enough signal-to-noise ratio to be able to properly locate the 0.9 and 0.85 μm absorption bands for goethite and hematite respectively.

Detailed comparison of Plates 2 and 3 (1987 data) and Plates 6 and 7 (1989 data) shows very well the effect of noise on spectral classification and mineralogical mapping. Clearly, the 1989 data does a much better job of mapping the surface mineralogy. In addition to being able to identify the individual minerals, the distribution of these minerals is more spatially coherent in the 1989 AVIRIS data.

CONCLUSIONS

The goals of this research were to 1) evaluate geometric, spatial resolution, and spectral resolution characteristics of the AVIRIS data, and 2) to use the AVIRIS data to look at subtle lithological variation including primary sedimentary layering, facies, and weathering; and subtle mineralogical differences caused by hydrothermal alteration of igneous and sedimentary rocks.

The AVIRIS data were compared to AIS and GERS data, laboratory and field spectra, and detailed field mapping. Data acquired for both sites during 1987 was generally low quality; signal-to-noise ratios did not meet specifications. Images had both horizontal striping and large gain changes along the flightlines that made calibration difficult and interfered with data analysis. The geometry of the images was excellent, requiring only simple scaling and rotation to match a topographic base. The spatial resolution met the specification of 20 m, however, the spectral resolution of 19.6 nm (FWHM) did not meet the requirement of $\leq$ 10 nm. For the Canon City/Cripple Creek

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Figure 25. Comparison of 1987 and 1989 northern Grapevine Mtns., NV, AVIRIS iron oxide spectra.
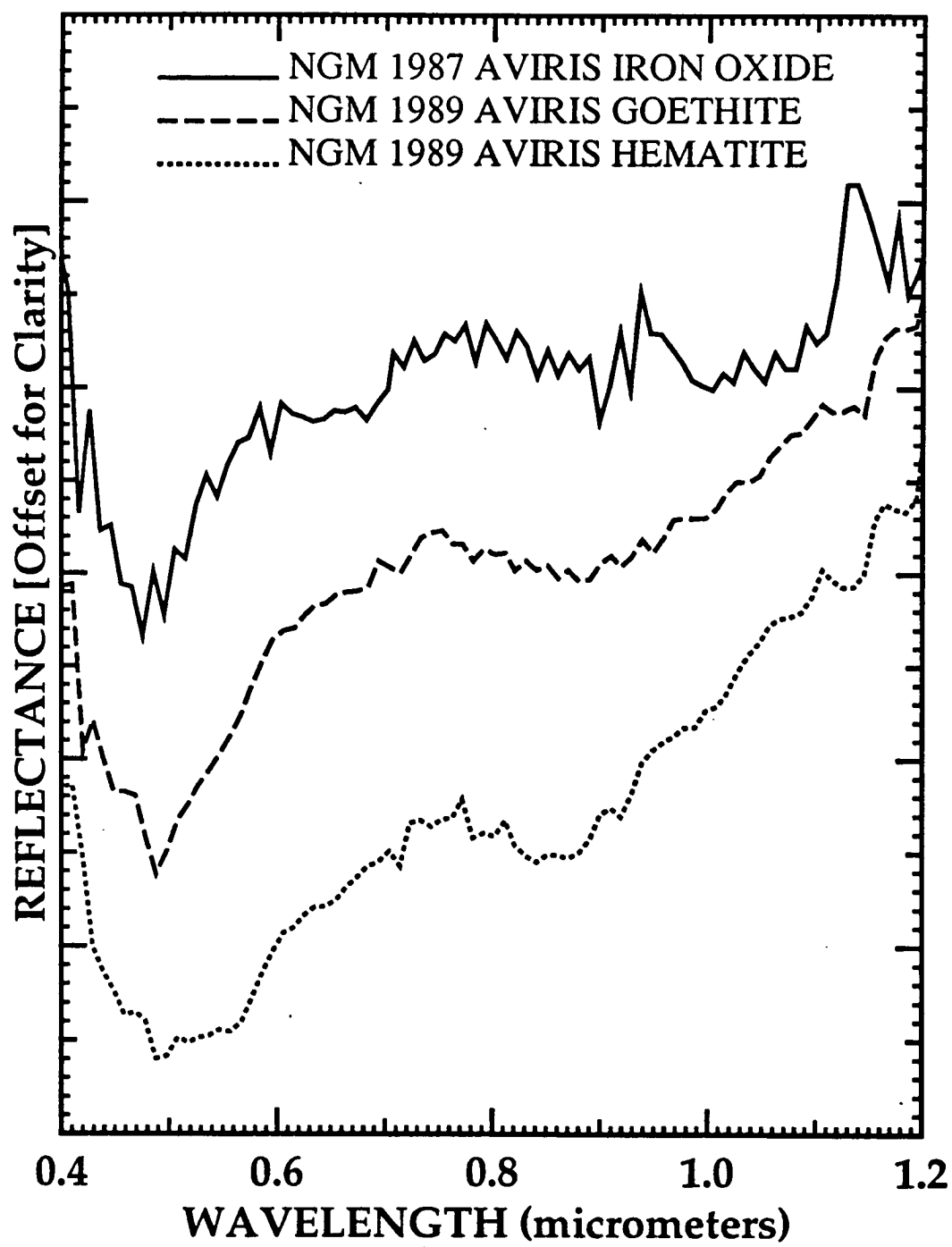
site, all attempts at spectral mapping of known mineralogy failed. All that could be accomplished was simple discrimination between those areas covered by vegetation, and those without vegetation. Mineralogical mapping using the 1987 AVIRIS data was somewhat more successful at the northern Grapevine Mountains site, primarily because of a slightly higher signal-to-noise ratio, arid conditions, and strong mineral absorption bands in well exposed surficial materials. It was not possible, however, to reproduce detailed mineralogical maps derived from the AIS and GERS data. Although clays and carbonates could be detected as mineral classes, the minerals sericite (fine grained muscovite), calcite, and dolomite previously identified using the AIS and GERS instruments and verified by field and laboratory work could not be identified using the 1987 AVIRIS data.

There was a significant improvement in the data quality of AVIRIS flown during 1989 over that flown during 1987. Spatially, the data looked very good and detailed photogeologic mapping was possible. Spectrally, the signal-to-noise ratios of the data were much improved, however, they still did not meet the specifications of 100/1 at 0.7 µm and 50/1 at 2.20 µm. Despite this problem, the data allowed identification and mapping of the minerals sericite, calcite, and dolomite. Results were comparable to those obtained using the AIS instrument, but complete spatial coverage of the site allowed mapping of additional areas not covered by the AIS data. The 1989 AVIRIS data also allowed mapping of the iron oxide minerals hematite and goethite using the "A" and "B" spectrometers (0.41 - 0.70 µm and 0.68 - 1.27 µm respectively).

The AVIRIS data as flown during the 1989 season has been improved to what can be considered an minimal operational state. Geometric characteristics are such that the data can be used as a high-quality image base for geologic mapping. The spatial resolution of approximately 20 m allows mapping of lithologic variation on scales that field geologists find useful. The spectral resolution of the data, although not up to specifications is sufficient for detailed spectral mapping of mineralogy and permits detection of subtle differences in lithology based on

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small shifts in absorption band position. Signal-to-noise
characteristics of the data are adequate, but performance for
geologic applications could be significantly improved by
increasing signal-to-noise ratios to the originally specified
requirements.

UNRESOLVED DATA-QUALITY ISSUES

1) Signal-to-noise specifications have not been met.

2) The spectral resolution does not meet specified requirements.

2) Coherent zig-zag (up/down in alternate channels) noise is
present in the spectral data. Its cause is not known and
further work will be required to identify the source and
eliminate it.

3) Vertical striping of unknown origin in the visible and near-
infrared wavelengths needs to be characterized, its source
determined, and eliminated.

RECOMMENDATIONS

Future efforts should be directed primarily towards
improvement of the signal-to-noise characteristics of the
instrument. Experience has shown that this is the critical factor
in identification of materials, both minerals and vegetation.
Slight degradation of the spectral and spatial resolution will
still produce acceptable results, however, most algorithms are
extremely sensitive to signal-to-noise ratios, and even small
improvements in this area could potentially give large
improvements in analysis capabilities.

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APPENDIX A - PUBLICATIONS RESULTING FROM THIS RESEARCH

Journal Papers

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