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# Optimum Spectral Bands for Rock Discrimination

## Based on aircraft scanner data, the optimum combination of spectral intervals was 1.18 to 1.30, 4.50 to 4.75, 0.46 to 0.50, 1.52 to 1.73, and 2.10 to 2.36 $\mu$m.

### INTRODUCTION

VARIOUS INVESTIGATIONS into the application of remote sensing techniques to geologic problem-solving have been based on the ability of multispectral systems to detect specific rock types and rock alteration products. An experimental approach to define this ability must assume, by design, that rocks which differ in the fundamental properties of composition, texture, or both also will differ in the derived properties of spectral reflectance and spectral emissivity. (This standard nomenclature for spectral quantities is given by Suits (1975, Chapter 3).) Only with this assumption may these spectral quantities be used as a basis for differentiating geologic materials. Rock discrimination based on spectral reflectance and spectral emissivity is undertaken in this work using discriminant analysis on data sets collected by the 24-channel Bendix Multispectral Scanner and Data System (MSDS) over geologically diverse sites in Utah. The objective is to analyze a diversity of rock types over a large number of spectral bands to determine the optimum band, or combination of bands, for rock discrimination.

ABSTRACT: *Discrimination of rock types was undertaken using discriminant analysis on spectral reflectance and spectral emissivity data collected by the 24-channel Bendix Multispectral Scanner and Data System (MSDS) over several geologically diverse sites in Utah. Of the various spectral bands analyzed, the optimum band, or optimum combination of bands, was defined as that one which most often provided the greatest power to discriminate specific rock types and rock alteration products in the Utah sites. The spectral interval 1.18 to 1.30 micrometres most frequently allowed maximum separation of lithologies; thus, the band including this interval was the optimum band for rock discrimination. Similarly, the combination of spectral intervals which most frequently allowed maximum discrimination was 1.18 to 1.30, 4.50 to 4.75, 0.46 to 0.50, 1.52 to 1.73, and 2.10 to 2.36 micrometres. This optimum combination proved to be more successful in differentiating diverse geologic materials than either simulated Multispectral Scanner (MSS) bands or simulated Thematic Mapper (TM) bands.*

Previous work on the ability of remote sensing systems to detect specific lithologies has been considerable. Much of the effort has emphasized the evaluation of characteristic features in the spectral behavior of compositionally identified geologic materials. That wavelength interval in which individual minerals and rocks exhibit unique behavior has been hypothesized as the best spectral range for the detection and discrimination of geologic materials.

In a laboratory environment, Hunt *et al.* (1971, 1973), Hunt and Salisbury (1970, 1974), Vincent *et al.* (1975), Adams (1975), McCord *et al.* (1976), Hunt (1977), and others studied the absorption by minerals and rocks of electromagnetic radiation in the ultraviolet, visible or infrared portion of the spectrum. Characteristic spectral patterns were isolated for individual materials and distinct ab-

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 46, No. 9, September 1980, pp. 1207-1215.

sorption features were matched to specific chemical compositions.

However, the strict conditions necessary to replicate characteristic rock spectra rarely are obtained outside a laboratory environment (Hunt, 1977; Conel *et al.*, 1978). The research approach of Goetz *et al.* (1975), Abrams *et al.* (1977), Rowan *et al.* (1977), and Conel *et al.* (1978) emphasized *in situ* measurements collected over field samples with a portable, backpack spectrometer. Further, numerous researchers (Rowan *et al.*, 1974; Lyon, 1977; Podwysocki *et al.*, 1977; and others) pursued lithologic recognition using Landsat scanner information. The common objective of both approaches was to identify any unique spectral features attributable to specific rock types.

As an option to visually interpreting remotely sensed data sets, Goetz *et al.* (1975), Borden and McMurtry (1977), Podwysocki *et al.* (1977), Lyon *et al.* (1978), Conel *et al.* (1978), and many others quantitatively distinguished diverse suites of rock materials using multivariate statistical methods. In particular, Goetz *et al.* (1975) and Conel *et al.* (1978) performed stepwise discriminant analyses on similar data sets to separate specific rock classes and to rank the analyzed wavelength intervals by their usefulness in obtaining an accurate separation. The data used in the analyses were collected by a field spectrometer held directly above bare rock such that the field of view was approximately 200 square centimetres. Scans were repeated and spectra were averaged to obtain a sample spectrum of the specific rock class. Bands were obtained from the continuous spectrum by dividing the wavelength range into 0.05 micrometre intervals. Using field-acquired spectra between 1.0 and 2.4 micrometres, Goetz *et al.* (1975) determined that 1.3, 1.6, and 2.2 micrometres were the optimum bands for separating altered rocks from unaltered rocks. Similarly, Conel *et al.* (1978) used field-acquired spectra between 0.45 and 2.45 micrometres to determine that 1.25, 0.95, 2.20, 2.15, 2.05, 1.75, 2.45, 2.10, 1.60, 1.55, and 0.75 micrometres were the optimum bands, in order of decreasing usefulness, for separating uranium-altered rocks, hydrothermally altered rocks, and unaltered rocks.

Similar to those investigations mentioned above, our study used stepwise discriminant analysis on remotely sensed data to separate rock materials and to rank the analyzed bands by their usefulness. However, this study differed in the following important aspects: (1) Data used in the analyses were collected by an aircraft multispectral scanner; (2) data were composed of spectral reflectance and spectral emittance values which included bare rock plus any other products present on the rock surface (such as soil, vegetation, etc.); (3) a sample of a specific rock class consisted of 500 randomly chosen pixels from a training area of 5000 pixels, or 0.24 square kilometres (as opposed to 200 square centimetres for the field spectrometer sample); (4) spectral data were simultaneously recorded in 15 discrete wavelength intervals between 0.34 and 4.75 micrometres; and (5) a diversity of geologic units was analyzed to determine the optimum combination of spectral intervals for discriminating a wide variety of rocks.

## APPROACH

A rock may be defined as an aggregate of constituents, or mineral particles. The characteristic properties of the aggregate are derived from the combined properties of its constituents and the characteristics of their association.

Spectral reflectance and spectral emissivity are characteristic properties of a rock which are derived from the fundamental properties of the mineral particles; specifically, their composition and texture. Thus, the spectral characteristics of a rock theoretically may be expressed as a complex function of the kinds and proportions of its mineral particles, their sizes and shapes, and their spatial arrangement and packing density. The derived properties of rock spectral reflectance and spectral emissivity may be symbolically expressed as

$$P_s = f(m, s, sh, o, p)$$

where $P_s$, an index spectrally characterizing the rock, is a function, $f$, of the properties of its constituents; and the constituents are the kinds and proportions of mineral particles, $m$, their sizes, $s$, shapes, $sh$, spatial arrangement or orientation, $o$, and spatial density or packing, $p$ (Griffiths, 1967, Chapter 3).

Rocks which differ in the fundamental properties of composition ($m$), texture ($s$, $sh$, $o$, $p$), or both, also may differ in the derived properties of spectral reflectance and spectral emissivity. Thus, as indicators of rock type specificity, spectral quantities may be used as a basis for differentiating geologic materials.

### GEOLOGIC TEST SITES

Seven geologically diverse targets in southern Utah were selected as test sites. Measurements of spectral quantities were collected from these locations and tested for their usefulness in differentiating geologic materials. Figure 1 serves to locate the test sites while Table 1 identifies each of them by name and geographical flight line coordinates. Each site is approximately 50 square kilometres in size.

The Confusion Range test site is located within the Basin and Range physiographic province. This area was chosen for its complete exposure of the Paleozoic stratigraphic section. The predominant rock types in the site are carbonates with minor sandstone and shale interbeds. Other rock strata include Mesozoic limestone and shale, and

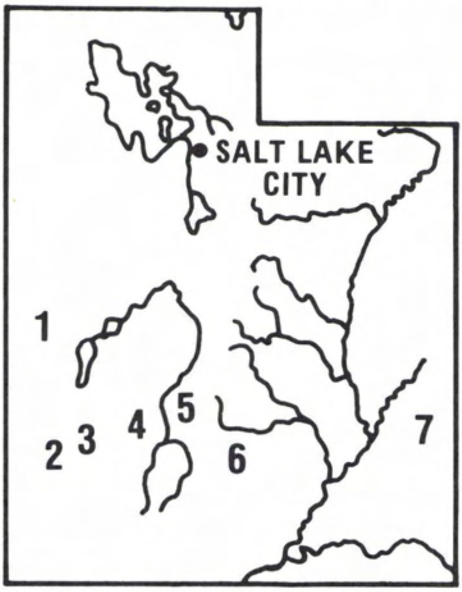

FIG. 1. Test site locations.

Cenozoic alluvium and lacustrine beds. Vegetation is thinly scattered throughout. Spectral measurements of 12 rock types from this test site were sampled for analysis.

The number of exposed rock types in the White Mountain, Star Mountain, Marysvale, and Monroe test sites are, respectively, six, eight, seven, and three. For the purpose of discussion, these sites are considered as a group since all were selected for their exposures of hydrothermally altered rock types.

Exposed rocks in the White Mountain site include Paleozoic limestone, Tertiary andesite and basalt, and Quaternary unconsolidated sediments. The volcanic units which have undergone alteration show a weak to strong development of alunite intimately mixed with kaolinite. These altered volcanics, as well as a few fresh units, show evidence of later hematitic mineralization. Further, the White Mountain site is characterized by subdued topography and scattered vegetation.

Sedimentary detrital and chemical rocks, ranging in age from Pennsylvanian to Jurassic, are the dominant rocks outcropping in the Star Mountain test site. Tertiary granodiorites are also present. Most of the rocks adjacent to the intrusive bodies have been altered by hydrothermal activities and, in some areas, also have been subjected to contact metamorphism. Topographically, the Star Mountain site is characterized by moderate relief.

The Marysvale test site includes portions of the Tushar Mountains, the Antelope Range, and the Big Rock Candy Mountain. The area features a complex of Tertiary latites and rhyolites. The oldest latite units have been intruded by quartz monzonite and have been hydrothermally altered along the contact surrounding the intrusives. The alteration is manifested in the formation of carbonates, alunite, quartz, and kaolinite. Quaternary sediments include landslide and alluvial deposits.

Exposed rocks in the Monroe test site include Tertiary latites, basaltic-andesitic flows, and Quaternary alluvium. Latites in contact with intruding dikes have been hydrothermally altered and, in some areas, metamorphosed. In contrast to the other test areas, the Monroe site has more topographic relief and supports more vegetation.

The Waterpocket Fold and Lisbon Valley sites are located within the Colorado Plateau of Utah. The spectral measurements of 15 rock types from Waterpocket Fold and seven rock types from Lisbon Valley were sampled for statistical analyses. In general, both sites offer good exposures of sedimentary detrital rocks covered by sparse vegetation.

Waterpocket Fold was chosen for its excellent exposure of a near-complete stratigraphic section that extends from Upper Paleozoic limestones and sandstones to Upper Mesozoic sandstones and shales. The dominant rocks exposed in this area are vari-colored sandstones.

The Lisbon Valley test site also exhibits excellent exposures of Upper Paleozoic to Upper Mesozoic sandstone units. Sandstones such as the Wingate Sandstone, the Navajo Sandstone, the Chinle Formation, and the Kayenta Formation are the dominant type of exposed rocks, but the stratigraphic interval includes thickened limestone units in the Upper Paleozoic formations. This

TABLE 1. TEST SITE LOCATIONS AND FLIGHT LINE COORDINATES

| Test Site Location | Flight Line Coordinates |
|---|---|
| 1 Confusion Range | 39°20.3′N/113°46.8′W to 39°13.4′N/113°32.0′W |
| 2 White Mountain | 38°19.4′N/113°30.6′W to 38°17.5′N/113°08.8′W |
| 3 Star Mountain | 38°20.2′N/113°11.5′W to 38°23.1′N/112°59.3′W |
| 4 Marysvale | 38°32.5′N/112°26.6′W to 38°32.1′N/112°09.7′W |
| 5 Monroe | 38°32.7′N/112°12.7′W to 38°42.6′N/111°58.9′W |
| 6 Waterpocket Fold | 37°50.7′N/111°15.8′W to 37°50.0′N/110°53.0′W |
| 7 Lisbon Valley | 38°18.3′N/109°15.8′W to 38°04.1′N/109°16.6′W |

TABLE 2. ROCK TYPES PRESENT WITHIN EACH TEST SITE

| Test Site Location | Sedimentary | | Igneous | | Hydrothermally Altered | Number of Rock Units Sampled |
|---|---|---|---|---|---|---|
| | Detrital | Chemical | Intrusive | Extrusive | | |
| Marysvale | Alluvium<br>Alluvial Fan Deposits | | Quartz Monzonite | Bullion Canyon Volcanics<br>Mt. Belknap Red Rhyolite<br>Mt. Belknap Gray Rhyolite | Altered Bullion Canyon Volcanics | 7 |
| Monroe | Alluvium | | | Dry Hollow Fm.<br>Bullion Canyon Volcanics | | 3 |
| Waterpocket Fold | Navajo Sandst<br>4 Members Moenkopi FM<br>Chinle Fm<br>Wingate Sandst<br>Kayenta Fm<br>Carmel Fm<br>Entrada Sandst<br>Summerville Fm<br>Morrison Fm<br>3 Members Mancos Shale | | | | | 15 |
| Lisbon Valley | Cutler Fm<br>Chinle Fm<br>Wingate Sandst<br>Kayenta Fm<br>Navajo Sandst<br>Burro Canyon Fm | Hermosa Fm | | | | 7 |
| Confusion Range | Alluvium<br>Arcturus Fm<br>Chainman Shale | Gerster Limest<br>Plympton Fm<br>Kaibab Limest<br>Ely Limest<br>4 Members of Guilmette Fm<br>Simonson Dolomite | | | | 12 |
| White Mountain | Alluvium | Callville Limest | | Andesite<br>Basalt | Alunite and Kaolinite<br>Hematite | 6 |
| Star Mountain | Talisman Quartzite<br>Moenkopi Fm<br>Chinle Fm<br>Navajo Sandst | Callville/Pakoon Limest<br>Toroweap Fm<br>Kaibab/Plympton Limest | Granodiorite | | | 8 |

site is characterized by its geologic structure which includes two breached anticlines with parallel fold axes.

Table 2 summarizes the rock formations present within each of the test sites described above.

### AIRCRAFT SCANNER DATA

Data were collected over the selected test sites on 15 June 1976 by the Bendix Multispectral Scanner and Data System (MSDS), mounted in a NC-130B aircraft, flown at an altitude of approximately 3 kilometres (10,000 feet). This scanner has a spatial resolution of 2 milliradians and an active scan angle of 80 degrees. Each pixel is approximately 7 metres on a side.

The MSDS simultaneously records dispersed electromagnetic radiation in 24 discrete wavelength intervals or bands. These bands, listed in Table 3, are all within the reflected solar spectrum and the emission spectrum, and range between 0.34 and 13 micrometres (Zaitzeff *et al.*, 1970).

Several problems exist within the recorded data sets. Instrument settings were not recorded during the overflights; therefore, absolute calibration of the data is not possible. In addition, none of the bands in the range between 6.0 and 13 micrometres was operational, and those covering the 1.05 to 1.09 and 1.12 to 1.16 micrometre intervals were plagued by bit slips.

Only bands 1 through 15 are available for statistical analysis. All of these bands are capable of recording seven bit data. At least the interval scale of measurement is achieved; therefore, almost all parametric statistics are permissible for analyzing the data (Stevens, 1946).

### STATISTICAL ANALYSIS

Stepwise discriminant analysis was performed on the spectral quantities measured in the 15 bands for each site. The technique requires *a priori* knowledge of the correct geologic classification of the rock types being discriminated. This information was provided by geologic maps compiled for the sites and by aerial photographs taken during the scanner overflight. In addition, this technique requires the identification of training areas for each specific geologic unit in order to compute sample statistics to serve as estimates of the population parameters. Figure 2 shows the training areas for the available geologic populations plotted on a generalized geologic map of the White Mountain test site. The training area for each geologic unit includes approximately 5000 pixels or 0.24 square kilometres (59.3 acres); however, to reduce the amount of data entered into the analysis without reducing the information content, 500 pixels were randomly sampled from each of the individual units. A comparison study of discriminant analyses of the White Mountain test site data indicated that the results obtained with 5000 pixels per geologic unit were nearly identical to those obtained with any subset of 500 per unit. Additional studies were not conducted to establish the lower limit for data sampling without loss of information, and indeed a valid sample of the population may contain considerably fewer than 500 observations.

Every geologic unit to be discriminated was defined as a matrix of spectral measurements, 500 pixels (rows) by 15 bands (columns). Table 2 summarizes the geologic units present in each site which, thus defined, were entered into the analyses.

The goal of discriminant analysis was to separate the various known geologic units or groups based on their spectral reflectance and spectral emissivity. To accomplish this, linear combinations of the bands were derived which provided the greatest separation of the means of the geologic groups, and which also provided the least

TABLE 3. DEFINITION OF SCANNER DATA

| Band Number | Bandwidth, μm | Midpoint, μm | Detector |
|---|---|---|---|
| 1 | 0.34–0.40 | 0.37 | Photomultiplier |
| 2 | 0.40–0.44 | 0.42 | Photomultiplier |
| 3 | 0.46–0.50 | 0.48 | Photomultiplier |
| 4 | 0.53–0.57 | 0.55 | Silicon |
| 5 | 0.57–0.63 | 0.60 | Silicon |
| 6 | 0.64–0.68 | 0.66 | Silicon |
| 7 | 0.71–0.75 | 0.73 | Silicon |
| 8 | 0.76–0.80 | 0.78 | Silicon |
| 9 | 0.82–0.87 | 0.84 | Silicon |
| 10 | 0.97–1.05 | 1.01 | Silicon |
| 11 | 1.18–1.30 | 1.24 | Germanium |
| 12 | 1.52–1.73 | 1.62 | Germanium |
| 13 | 2.10–2.36 | 2.23 | Indium Antimonide |
| 14 | 3.54–4.00 | 3.77 | Indium Antimonide |
| 15 | 4.50–4.75 | 4.62 | Indium Antimonide |

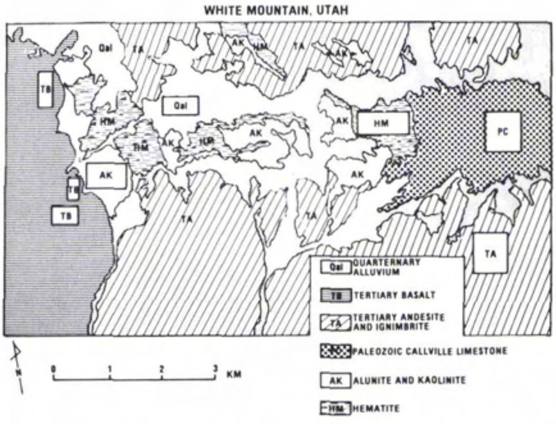

FIG. 2. Generalized geologic map of the White Mountain test site.

inflation of the variance within the groups. A stepwise procedure was followed to enter individual bands into these linear combinations or functions in order of their decreasing discriminatory power. At each step, the band that added the most to the separation of the groups was entered into the discriminant function. Thus, the band with the greatest separation capability was the first band entered, and produced the maximum difference possible between the geologic groups with a single band. Similarly, the next band added increased the discriminatory power of the function more than any other candidate band.

The significance of the separations produced between groups may be tested if the following assumptions about the nature of the data are fulfilled: (1) pixels (observations) in each geologic group are random samples, (2) spectral values within bands (variables) are normally distributed within each group, (3) variance-covariance matrices of the groups are equal, and (4) none of the pixels used to calculate the discriminant function was misclassified (modified from Davis, 1973, Chapter 7).

The assumptions of normality and equality of variances are the most difficult to justify. To determine if assumption (2) is fulfilled, Pearson $\beta$ statistics were calculated from the moments of the observed frequency distributions and tested against the hypothesis that they were derived from normal distributions. The first hypothesis being tested is

$$H_0 : \sqrt{\beta_1} = 0$$

where $\sqrt{b_1}$, an estimate of $\sqrt{\beta_1}$, is a measure of the symmetry or skewness of a distribution. If the sample statistic is derived from a normal distribution, it has an expected value of 0 and a variance which depends on the sample size. The alternative hypothesis

$$H_1 : \sqrt{\beta_1} \neq 0$$

implies that the observed frequency distribution is more asymmetric than would occur by chance in selecting samples from a normally distributed population. The second hypothesis being tested is

$$H_0 : \beta_2 = 3$$

against

$$H_1 : \beta_2 \neq 3$$

where $b_2$, an estimate of $\beta_2$, is a measure of the "peakedness" or kurtosis of a distribution. The null hypothesis states that the sample statistic, $b_2$, is not significantly different from 3, the value of $\beta_2$ for a normal distribution. The alternative hypothesis states that the observed distribution is either platykurtic (flat) when $\beta_2$ is less than 3 or leptokurtic (peaked) when $\beta_2$ is greater than 3. The level of significance, $\alpha$, at which both the null hypotheses are tested is 0.05.

The observed frequency distributions of spectral values within individual bands over an entire site (Waterpocket Fold) were analyzed by M. L. Labovitz (personal communication, 1978). The sample statistics $\sqrt{b_1}$ and $b_2$ calculated from the moments of these distributions failed to reject the null hypotheses which stated that they were derived from normally distributed populations. In other words, there was no evidence to reject the hypothesis that the data within individual bands, over an entire test site, are normally distributed.

Further, the observed frequency distributions of values within individual bands for each geologic unit were analyzed. Figure 3 is a plot of the $\sqrt{b_1}$ versus $b_2$ statistics calculated for the bands of each geologic unit in all test sites. The window outlines the $\alpha = 0.05$ level of significance based on a sample size of 500 observations (Pearson and Hartley, 1954). Roughly one half of the sample statistics plotted within this window; therefore, there was no evidence to reject the null hypotheses, which stated that these statistics were calculated from the moments of a normal distribution.

Significant departures from normality occurred in both the skewness and kurtosis of the other half of the distributions. They were skewed either positively or negatively (asymmetric) as well as leptokurtic (peaked). Departures of the observed from the expected normal may have arisen due to (1) incorrect sampling procedures, (2) parent populations being non-normal, or (3) a combination of both (Griffiths, 1967, Chapter 12). Retaining the theoretical model that the parent populations are indeed normally distributed, the procedure for obtaining random samples from individual geologic units becomes suspect.

Discriminant analysis is not seriously affected by limited departures from normality or limited inequality of variances (Davis, 1973, Chapter 7). In consideration of this in respect to the above results, it may be stated that the data reasonably conformed to the assumptions previously outlined. Thus, the separations between geologic groups may be tested. If significant, the discriminant functions may be used to classify each of the original pixels into one of the previously defined geologic groups. That portion of the pixels which is assigned back into the group from which it originated can be determined and reported as the percent of pixels (observations) correctly classified.

The computer program used to calculate the discriminant functions was BMDP7M Stepwise Discriminant Analysis, revised in December 1977, and is included in Biomedical Computer Programs P-Series (Dixon and Brown, 1977).

## RESULTS

Of the various spectral bands evaluated for their discriminatory power, the optimum band, or combination of bands, may be defined as that one

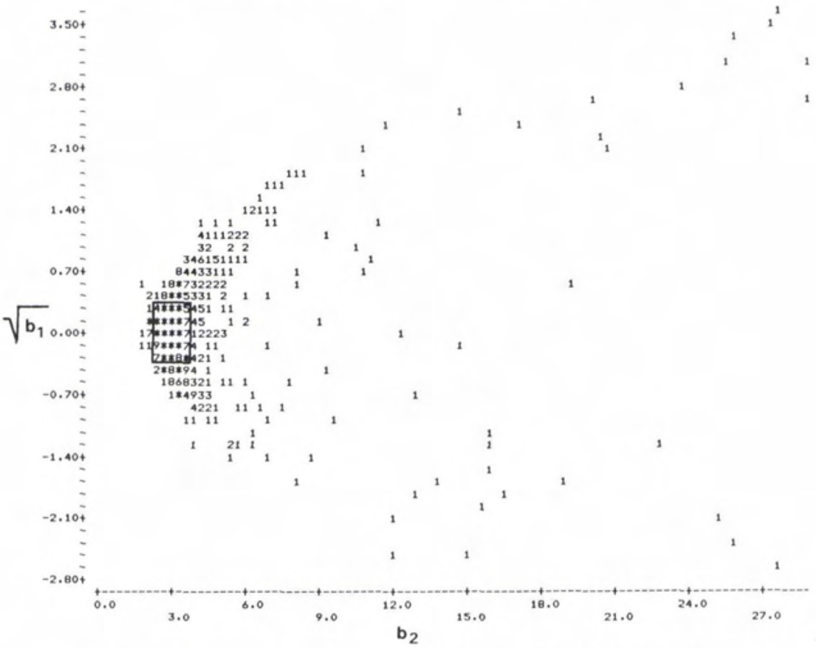

FIG. 3. $\sqrt{b_1}$ versus $b_2$ statistics for the bands of each of the geologic units in all of the Utah test sites. The rectangular window outlines the $\alpha = 0.05$ significance level based on a sample size of 500 observations. A count of points plotting on the same spot is given. An "*" is given if the count is 10 or more.

which most often permits the maximum separation of the geologic units within the Utah test sites. The bands which were included in the discriminant function for each test site are presented in Table 4 in order of their inclusion into the functions and, therefore, in order of their decreasing ability to separate geologic units.

The band including the 1.18 to 1.30 micrometre interval most frequently was the first band entered into the functions. It most frequently yielded the greatest discriminatory power and, thus, is the optimum band for rock discrimination. Goetz *et al.* (1975) and Conel *et al.* (1978) have independently determined that spectral data in the approximate 1.2 to 1.3 micrometre interval is optimum for distinguishing altered from unaltered rock classes.

The bands including the 1.18 to 1.30, 4.50 to 4.75, 0.46 to 0.50, 1.52 to 1.73, and 2.10 to 2.36 micrometre intervals most frequently were the first through fifth bands, respectively, entered into the functions. Therefore, this set is the optimum combination of bands for rock discrimination. In general, the Monroe, Waterpocket Fold, and Lisbon Valley test sites departed from this optimum set by including bands located in visible wavelengths. These results suggest that successful rock discrimination within these targets may be influenced by certain visible characteristics. For example, the separation of rock types may have depended on features such as vegetation or rugged topography in the Monroe site; colorful varieties of sandstones in both the Waterpocket Fold and

TABLE 4. OPTIMUM MSDS BANDS FOR ROCK DISCRIMINATION BY TEST SITE

| Test Site Location | MSDS Band Rank (Band Midpoint, μm) 1 | 2 | 3 | 4 | 5 | Classification Accuracy (%) Optimum MSDS | Simulated MSS | Simulated TM |
|---|---|---|---|---|---|---|---|---|
| Confusion Range | 1.24 | 4.62 | 0.48 | 0.66 | 2.23 | 63 | 45 | 62 |
| White Mountain | 1.24 | 0.48 | 2.23 | 3.77 | 1.62 | 96 | 86 | 90 |
| Star Mountain | 1.24 | 4.62 | 1.01 | 0.84 | 1.62 | 72 | 60 | 68 |
| Marysvale | 1.24 | 4.62 | 2.23 | 1.62 | 1.01 | 81 | 72 | 75 |
| Monroe | 0.37 | 1.24 | 0.66 | 0.48 | 1.01 | 96 | 88 | 93 |
| Waterpocket Fold | 0.48 | 4.62 | 1.24 | 1.01 | 1.62 | 61 | 24 | 27 |
| Lisbon Valley | 1.24 | 0.37 | 0.60 | 0.66 | 4.62 | 96 | 53 | 52 |
| Optimum | 1.24 | 4.62 | 0.48 | 1.62 | 2.23 | | | |

Lisbon Valley sites; and outcrop attitude (prominent strike line) of specific sandstone beds in the Lisbon Valley site.

The bands including the 3.54 to 4.00 and 4.50 to 4.75 micrometre intervals were included in the functions for all of the test sites except the Monroe site. In considering the ranking of these thermal bands, it is necessary to re-emphasize that all of the analyses performed for this study are limited to data sets collected on a particular date and at a particular time of day. Seasonal and diurnal variations in surface temperature may lead to a different ranking of the thermal bands when analyzing data sets collected during other seasons or sun angles.

### COMPARISON TO SATELLITE SYSTEMS

To compare the optimum five MSDS bands determined above to present or projected satellite bands, simulations were derived for the bands present on the Multispectral Scanner (MSS) on Landsat 1, 2, 3 and those projected for the Thematic Mapper (TM) on Landsat D. Table 5 presents the aircraft band configurations used to simulate the four bands on the MSS and six* of the seven bands proposed for the TM.

Using the operational procedure previously outlined, discriminant analysis performed on the spectral data for each test site provided classification accuracies for the simulated MSS, the simulated TM, and the optimum MSDS bands. These results are listed by test site and simulated scanner type in Table 4. For every site, the percent of observations correctly classified by the discriminant functions was greater with the five optimum MSDS bands than with either the six TM bands or the four MSS bands. On average, 20 percent more of the pixels were correctly classified by the optimum MSDS bands than by the simulated MSS bands and 14 percent more were correctly classified than by the simulated TM bands.

## CONCLUSIONS

Using stepwise discriminant analysis on MSDS spectral reflectance and spectral emissivity data, bands were ranked by their usefulness in separating specific rock types and rock alteration products present within Utah test sites. The resulting optimum band for rock discrimination included the 1.18 to 1.30 micrometre interval and the optimum combination of bands the 1.18 to 1.30, 4.50 to 4.75, 0.46 to 0.50, 1.52 to 1.73, and 2.10 to 2.36 micrometre intervals.

No satellite system is currently prepared to collect data in the spectral interval of 1.18 to 1.30 micrometres. Thus, comparisons of the optimum MSDS bands to present MSS and to projected TM bands resulted in the optimum bands having more discriminatory power than either the simulated MSS or simulated TM bands.

TABLE 5. SUMMARY OF MSDS DATA USED TO SIMULATE LANDSAT MULTISPECTRAL SCANNER AND THEMATIC MAPPER DATA

| Landsat 1, 2, 3 MSS ($\mu$m) | Landsat D TM ($\mu$m) | MSDS ($\mu$m) | |
|---|---|---|---|
| | 0.45–0.52 | 3 | 0.46–0.50 |
| 0.5–0.6 | 0.52–0.60 | 4 | 0.53–0.57 |
| | | 5 | 0.57–0.63 |
| 0.6–0.7 | 0.63–0.69 | 6 | 0.64–0.68 |
| 0.7–0.8 a | | a 7 | 0.71–0.75 |
| | 0.76–0.90 b | b 8 | 0.76–0.80 |
| 0.8–1.1 c | | c 9 | 0.82–0.87 |
| | | 10 | 0.97–1.05 |
| | 1.55–1.75 | 12 | 1.52–1.73 |
| | 2.08–2.35 | 13 | 2.10–2.36 |
| | 10.4–12.5 | Data not available | |

The results of this study indicate that the spectral interval 1.18 to 1.30 micrometres merits further evaluation of its potential usefulness in problem solving not only in the geosciences but in other disciplines as well.

## ACKNOWLEDGMENTS

We wish to acknowledge Nicholas Short, Herbert Blodget, Melvin Podwysocki, and Herbert Tiedemann for their contributions to the basis of this work and, in particular, for their efforts in selecting the Utah test sites. Christine Onasch is sincerely thanked for her generous help throughout the project.

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* The seventh Thematic Mapper band, 10.4 to 12.5 micrometres, is located in that portion of the spectrum in which aircraft scanner data are not available.

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(Received 7 March 1979; revised and accepted 16 March 1980)

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