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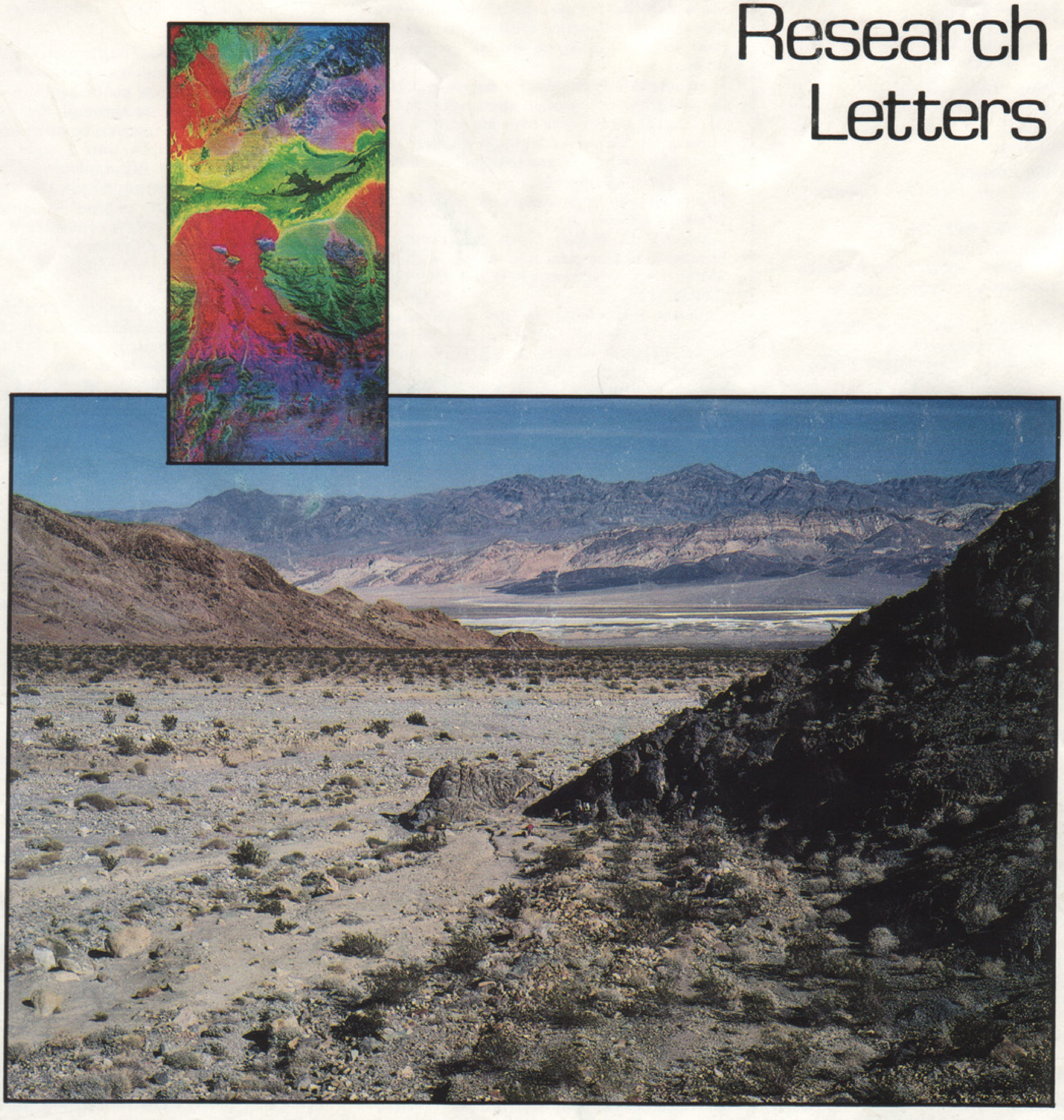

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ACTIVE AIRBORNE INFRARED LASER SYSTEM FOR IDENTIFICATION OF SURFACE ROCK AND MINERALS

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Abstract. Emissivity and reflectivity in the thermal infrared spectral region (8-13 μm) may be used to discriminate among rocks and minerals. Although considerable success has been achieved in remote sensing classification of rock types based on emissivity measurements made with NASA's Thermal Infrared Multispectral Scanner (TIMS), classification based on reflectivity offers several advantages: much narrower bandwidths are used, higher signal to noise ratios are possible, and measurements are little affected by surface temperature. As a demonstration, an airborne CO_2 laser instrument was flown along the margin of Death Valley, California. Measurements of spectral reflectance collected with this device were compared with emissivity measurements made with the TIMS. Data from either instrument provided the means for recognizing boundaries between geologic units including different rock types and fan surfaces of different ages.

Introduction

Remote sensing provides a means for discriminating among rock and mineral types and identifying them on the basis of their specteral characteristics (see Goetz and Rowan [1980] and their references). The thermal infrared spectral region (8-13 μm) contains the maximum thermal emission at ambient terrestrial temperatures, is a good atmospheric window, and contains the important reststrahlen bands for silicates (Si-O stretching vibrations). This spectral region has been viewed in emission using passive airborne multispectral scanners with good success [Vincent et al., 1972; Kahle and Rowan, 1980; and Kahle and Goetz, 1983]. However, the passive technique is presently limited by the broad spectral bandwidths (0.5-1.0 μm) necessary to achieve an acceptable signal-to-noise ratio, by uncertainties introduced by the presence of atmospheric gases, and by the strong dependence of emission on temperature. These limitations may be avoided by active laser remote sensing techniques which measure reflectance rather than emittance. A typical laser system bandwidth is less than 10^{-6} μm. A number of laser wavelengths are available which can be selected to minimize interference for geologic applications. The emissivity of most geologic materials varies between 0.7 and 1.0 in the wavelength range from 8-12 μm while reflectivity varies between 0.0 and 0.3. Thus the absolute range of the reflectance is much larger than for emissivity and it is therefore inherently more sensitive.

JPL has developed a laser absorption spectrometer (LAS) for remote measurement of atmospheric gases [Shumate et al., 1981, 1982]. The system uses two CO_2 infrared laser transmitter/receiver systems mounted in a small aircraft to measure the two-way transmittance between the aircraft and the ground. Heterodyne detection techniques are used to measure the laser radiation backscattered from the ground and distinguish it from thermal background radiation. The LAS system responds to the effects of both atmospheric absorption and surface reflectance variations. Wiesemann et al. [1978] have suggested the use of an instrument of this type for identification of surface materials.

To demonstrate this application, the LAS was flown over a site in Death Valley, California in July 1983 where image data for the passive Thermal Infrared Multispectral Scanner (TIMS) acquired in August 1982 was already under evaluation. Data from the LAS flight and data extracted from the TIMS image for the same flight track were compared to determine the correlation between the emissivity and the reflectivity as inferred from the two data sets. The LAS wavelengths were selected so as to look for the broad silicate reststrahlen band near 9.2 μm. Figure 1 shows laboratory reflectance spectra of rock samples from Death Valley, with the location of the TIMS bands 3 and 5 and the selected LAS bands.

Instrument Description

The two LAS CO_2 laser transmitter-heterodyne receiver systems transmit beams having less than 1 mrad divergence, aimed at the same point on the surface below the aircraft. The operating wavelength of each system is independently selectable between 9.1 and 10.8 μm. The wavelengths 9.23 and 10.27 μm were selected to achieve good geologic discrimination with a minimum of loss in the atmosphere. The signals recorded by the instrument are proportional to the intensity of the bidirectional spectral reflectance signal returned from the surface. The major contribution to the ratio of the two received signals is the differential absorption which occurs in the surface material. From an altitude of 3 km, the instrument footprint was approximately 3 m by 50 m with the longer axis oriented along the flight path. Ground track photographs were used to locate the path followed by the LAS laser beams on topographic maps, geologic maps, and TIMS images.

Geologic Setting

The flight line was 35 km long with a bearing of 350°, along the western edge of Death Valley where large alluvial fans descend from the Panamint Range to the west. Vegetation is sparse or absent. The bedrock units are Cambrian and Ordovician dolomites with some shale, limestone, and

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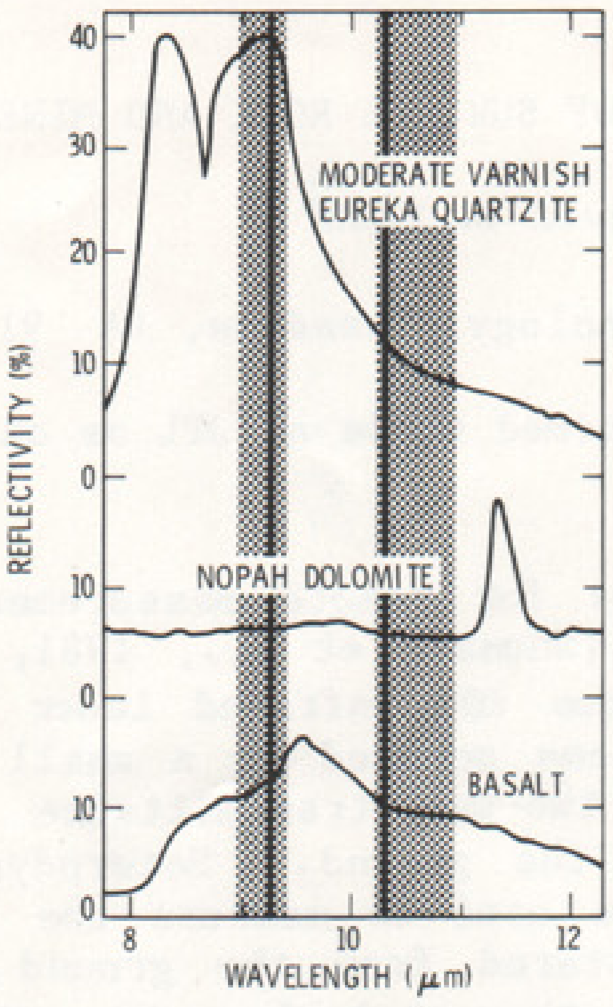

Fig. 1. Laboratory reflectance spectra of various rocks, and spectral range of TIMS (stippled) and LAS (solid lines) data used here.

quartzite and with scattered outcrops of Tertiary volcanics, mainly rhyolitic tuffs and basalt. Some of the alluvial fans have a fairly local source in the primarily carbonate sedimentary rocks. The source of other fans is higher in the Panamint Range and includes much more quartzite and shale. Hunt and Mabey [1966] mapped the bedrock geology and the age units of the alluvial fans. They differentiate three major fan age units in the area of the test flight - Qg_2, Qg_3, and Qg_4, with Qg_2 being the oldest. The composition of a given fan varies with age due to changing source area and differential weathering and erosion. The development of desert varnish and desert pavement on the fans is also a function of age and erosional history.

Data Processing and Interpretation

The reflected signal from the lasers was recorded on a strip chart. The chart was later digitized at an interval corresponding to approximately 16 m on the ground. Figure 2 shows a plot of the reflectance data for each laser and the ratio between them as a function of distance along the flight line, for a typical 6 km segment of the flight line (between km 17 and 23, Figure 4). Both rock-type boundaries and boundaries between age units on the alluvial fans are easily recognizable on this plot. Although the age units are not specifically identified, their boundaries, as seen on maps and/or air photos, generally correspond to the rapid changes in signal level on the scale of tens of meters.

TIMS bands 1 (8.1 - 8.5 μm), 3 (8.9 - 9.3 μm) and 5 (10.2 - 10.9 μm), have been used to discriminate boundaries of some major rock units as well as the age and compositional units of the alluvial fans (described in the accompanying paper, Gillespie et al., 1984). The silicate fans could be subdivided into units having Trail Canyon, Blackwater Canyon, or Tucki Wash origin. Figure 3 is a map derived from the TIMS data showing some of the compositional units that could be discriminated by TIMS, but not showing the higher-spatial-frequency age units.

The LAS flight path was registered to the TIMS image. Emissivity data were extracted from each pixel of the TIMS image from bands 3 and 5, the TIMS bands closest to the wavelengths of the lasers. The emissivity of band 3 was ratioed to that of band 5 and the result was smoothed using a running average algorithm and plotted along with the ratioed laser reflectivity data (Figure 4). The two plots show a high negative correlation (r = -0.90). As stated in Kirchoff's Law, the emissivity should equal one minus the reflectivity. Also indicated in the center of Figure 4 are the geologic units from Figure 3. Both TIMS and LAS reveal essentially the same compositional information about the surface materials, although some systematic differences due to the noncoincidence of wavelengths are noted.

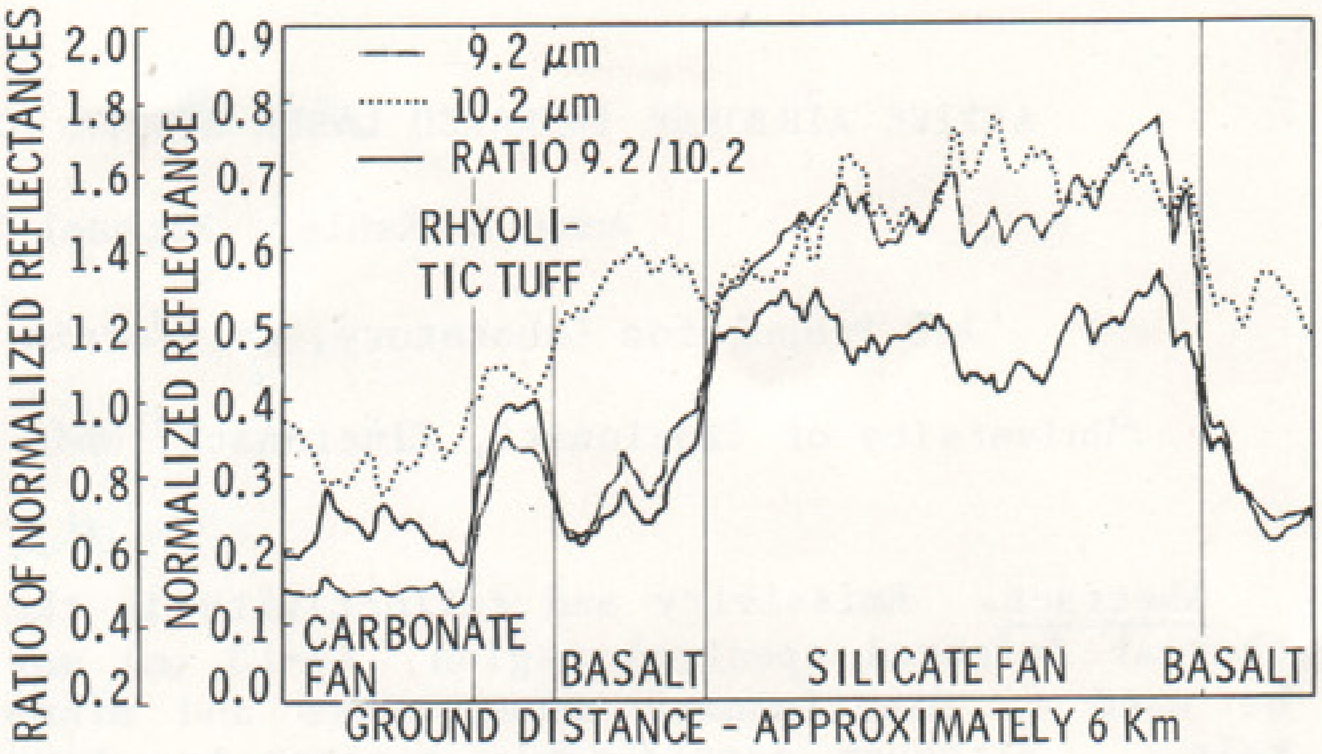

Fig. 2. Normalized reflectance for the 9.23 μm and 10.27 μm CO_2 laser systems and their ratio (9.23 μm/10.27 μm) for a 6 km segment of the flight line A - B shown in Fig. 3.

To further assess the abilities of the TIMS and LAS instruments to discriminate among various targets of geologic interest, the flight path was divided into geologic units (Table 1). These units were selected by subdividing the units mapped by Hunt and Mabey [1966] into subunits identifiable from the TIMS imagery or from photographs collected by the LAS boresight camera. Both instruments were able to discriminate among the different ages of the fan surfaces as well as among fans having different source materials, and were also able to distinguish most other identifiable geologic units along the flight path.

MAP EXPLANATION

s Saline playa and lake sediments

v Intermediate rhyolitic volcanic rocks and fans

b Basaltic lava

q Quartzite

a Argillaceous sedimentary rocks

c Carbonate rocks and fans (dominantly dolomite)

m Breccias, rocks and fans of mixed composition

t Fan gravels of Tucki Wash

bw Fan gravels of Blackwater Wash and Trail Canyon

bt Fan gravels of mixed Blackwater, Tucki, and Trail source

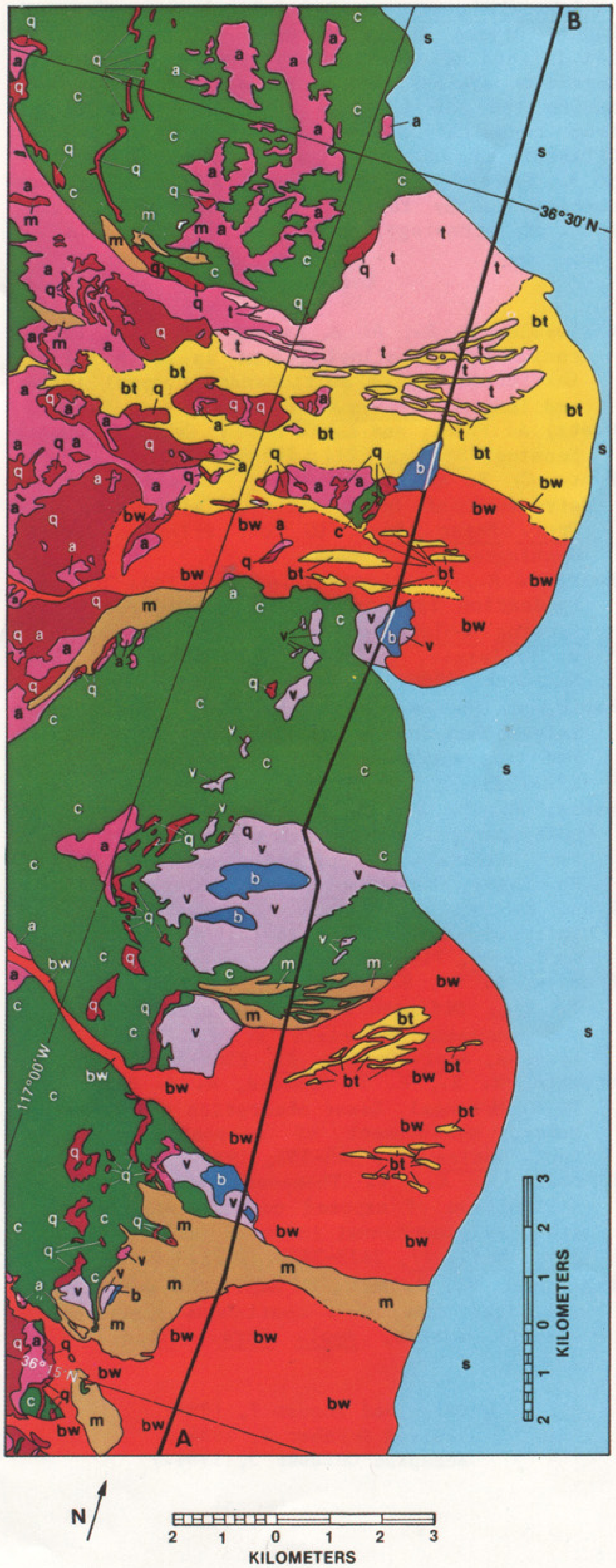

Fig. 3. Map of Death Valley study area, based on TIMS data [Gillespie et al., 1984]. The line A - B is the flight line of the LAS.

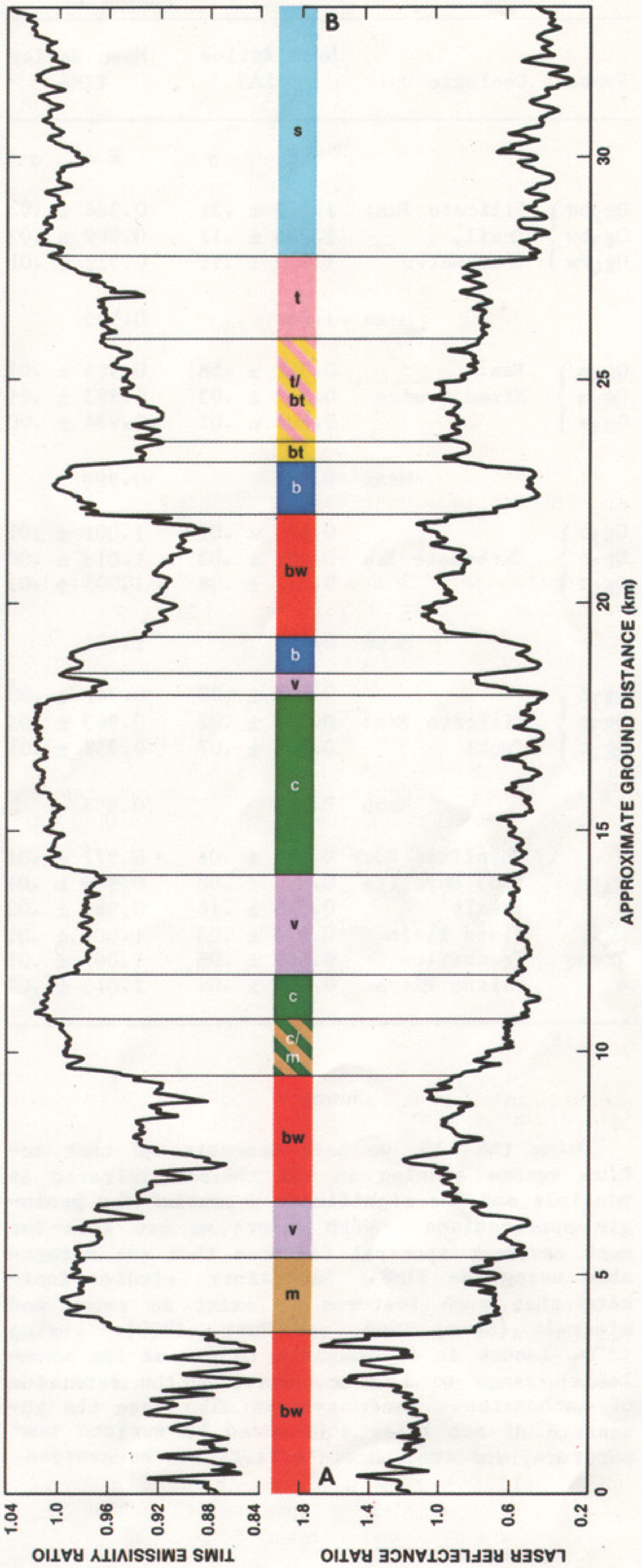

Fig. 4. The ratio of TIMS band 3 (8.9 - 9.3 µm) to band 5 (10.2 - 10.9 µm) and the ratio of the 9.23 µm and 10.27 µm LAS lasers along the flight line A - B (Fig 3).

TABLE 1. Mean LAS and TIMS ratios for Geologic Units

Symbol	Geologic Unit	Mean Ratios LAS		Mean Ratios TIMS	
		x̄	σ	x̄	σ
Qg_2bw	Silicate Fan:	1.178	± .21	0.884	± .03
Qg_3bw	Trail,	1.036	± .11	0.909	± .02
Qg_4bw	Blackwater	1.030	± .11	0.922	± .01
	Mean	1.081		0.905	
Qg_2m	Fan:	0.712	± .58	0.985	± .01
Qg_3m	Mixed Source	0.712	± .03	0.983	± .01
Qg_4m		0.604	± .01	0.994	± .00
	Mean	0.676		0.988	
Qg_2c		0.485	± .02	1.001	± .01
Qg_3c	Carbonate Fan	0.481	± .03	1.018	± .00
Qg_4c		0.517	± .06	1.005	± .01
	Mean	0.494		1.005	
Qg_2t		0.891	± .08	0.941	± .02
Qg_3t	Silicate Fan:	0.758	± .02	0.963	± .01
Qg_4t	Tucki	0.796	± .07	0.959	± .01
	Mean	0.815		0.954	
v	Rhyolitic Rock	0.552	± .06	0.977	± .01
Q_4v	Fan: Rhyolite	0.737	± .08	0.969	± .01
b	Basalt	0.546	± .14	0.986	± .02
Q_4f	Flood Plain	0.473	± .03	1.006	± .01
Trans	Transition	0.469	± .06	1.007	± .01
s	Saline Playa	0.431	± .09	1.013	± .02

Summary

Using the LAS, we have demonstrated that active remote sensing in the thermal infrared is possible and has significant potential for geologic applications. With lasers we can look for much narrower spectral features than are detectable using the TIMS. Laboratory studies indicate that such features do exist in rocks and minerals [Lyon, 1965; and Hunt, 1980]. Using $C^{14}O_2$ lasers it is possible to extend the wavelength range to 11.4 μm, enabling the detection of carbonates. Laser systems also have the advantage of not being influenced by surface temperature, and atmospheric effects can be avoided.

Acknowledgements. Don Malleck and others at NASA's Dryden Flight Research Center, made the LAS flights possible. E. Nordquist and L. Maldonado of JPL assisted in the acquisition of data during the LAS flight. The authors benefited from consultations with F. Palluconi and A. Gillespie of JPL, and from the manuscript review of R. Vincent of Geospectra. This research was carried out by the Jet Propulsion Lab, Calif. Inst. of Technology, under contract with NASA.

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MAPPING ALLUVIAL FANS IN DEATH VALLEY, CALIFORNIA, USING MULTICHANNEL THERMAL INFRARED IMAGES

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Abstract. We have mapped alluvial fans in Death Valley, California using NASA's 8-12 µm six-channel airborne Thermal Infrared Multispectral Scanner (TIMS). We are able to recognize both composition and relative age differences. Age unit boundaries are generally consistent with those obtained by conventional mapping. Composition was verified by field investigation and comparison with existing geologic maps. Bedrock and its young derived fan gravels have similar emissivities. The original composition of the fans is modified by differential erosion and weathering, permitting relative age mapping with TIMS.

Introduction

Recently Kahle and Goetz [1983], describing the first results from NASA's airborne Thermal Infrared Multispectral Scanner (TIMS), showed they could readily distinguish the mapped quartzites, carbonates, volcanic rocks and saline deposits in Death Valley. They used color images constructed from data acquired in the spectral region 8-12 µm. Differences among the colors representing alluvial fans appeared to be related to source materials for the gravel, the ages of the surfaces, and the development of desert varnish. We have now studied the TIMS images of these fans in greater detail, and present here an interpretation based upon examination of the images and of the fan gravels in the field, previous laboratory spectroscopic studies, and the geologic mapping of Hunt and Mabey [1966].

Geologic Setting

Death Valley is a deep, narrow north-south graben in the Basin and Range province. The graben is partly filled by saline lake sediments, and is flanked by alluvial fans and by remnants of Tertiary volcanic rocks. The climate is hot and arid, and vegetation is sparse. A lithologic map of the study area, generalized from Hunt and Mabey [1966] is given in Figure 1. The study area covers part of the western margin of Death Valley and the adjacent Panamint Mountains.

Bedrock Geology. In the study area the Panamint Mountains consist of a sequence of lightly metamorphosed Precambrian-Paleozoic sedimentary rocks underlying Miocene volcanic rocks. In Figure 1 these are grouped by composition into units that could be readily distinguished in the TIMS data (Figure 2). The most widespread sedimentary rocks are dolomite and limestone, which resist erosion here. Argillaceous rocks such as shale of the Johnnie Formation are common between Blackwater Wash and Tucki Wash. They are fissile and readily eroded. Quartzites, found throughout the stratigraphic section, are most evident near Blackwater Wash. The steeply dipping sedimentary rocks are highly faulted and the section is commonly repeated. The volcanic lavas and tuffs range in composition from basalt to rhyolite. The Amargosa thrust complex in the southern part of the study area, contains a breccia of the sedimentary rocks, older metamorphic rocks, and felsite dikes and granite.

Quaternary Sediments. Most of the Quaternary deposits are lake sediments (evaporites, saline silts and sand) and alluvial fans. Hunt and Mabey [1966] mapped four Quaternary alluvial fan units, based upon relative weathering and geomorphic characteristics but not upon lithologic composition. The three younger fan units occur within the study area. Of these, the youngest unit (Q_4) comprises active channels containing silt, sand and gravels reworked from the older fan deposits. The intermediate unit (Q_3) consists of similar gravels in inactive channels. These are moderately coated by desert varnish [Hooke, 1972]. The oldest unit (Q_2) is typified by heavily varnished pebbles forming desert pavement. Hooke [1972] subdivided Q_2 into three units of different age. In the older units the pavement had been partly eroded, reducing the amount of varnish and locally exposing caliche. The fan gravels reflect the lithologies found in the drainages of the Panamints.

TIMS Data Acquisition and Processing

Six channels of calibrated TIMS digital radiance images with an 18-m nadir pixel size were acquired over Death Valley near noon on August 27, 1982. TIMS acquires data at wavelengths near 8.3, 8.7, 9.1, 9.8, 10.4 and 11.3 µm. This spectral region contains diagnostic emissivity minima for silicate minerals [Lyon, 1965; Hunt, 1980]. The depth and position of the minima vary with the crystal structure. To display these spectral differences, we used a decorrelation technique [Soha and Schwartz, 1978; Kahle et al., 1980] that suppressed temperature information while exaggerating emissivity features. Following Kahle and Rowan [1980] and Kahle and Goetz [1983], we created a color composite image from the enhanced channels 1, 3 and 5 displayed as blue, green and red, respectively (Figure 2). Colors referred to in this article are those of this enhanced image, and not "natural" colors.

Figure 2 clearly shows several units that are differentiable by texture and color. Textural differences related to topography allow us to distinguish bedrock from alluvial fans and lake deposits. Comparison with the lithologic map (Figure 1) shows that image color is related to composition [Kahle and Goetz, 1983]. Carbonate rocks appear green and quartzites are deep red. Other clastic sedimentary rocks such as the shale of the Johnnie Formation appear purple, as do most volcanic rocks. Basalts appear blue. Rocks

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of the Amargosa thrust complex are orange or brown. Lake deposits, to be discussed in a later paper, are yellow, green and blue in Figure 2, which may be due to different saline facies.

The alluvial fans are represented by the same wide range of colors as the bedrock of the Panamints. The larger fans are red (Blackwater Wash or Trail Canyon) or purple (Tucki Wash). Smaller fans are green, purple, yellow, or brown. The range of colors within a given fan is limited, but distinct variations are present. In general, contacts appear sharp, not gradational.

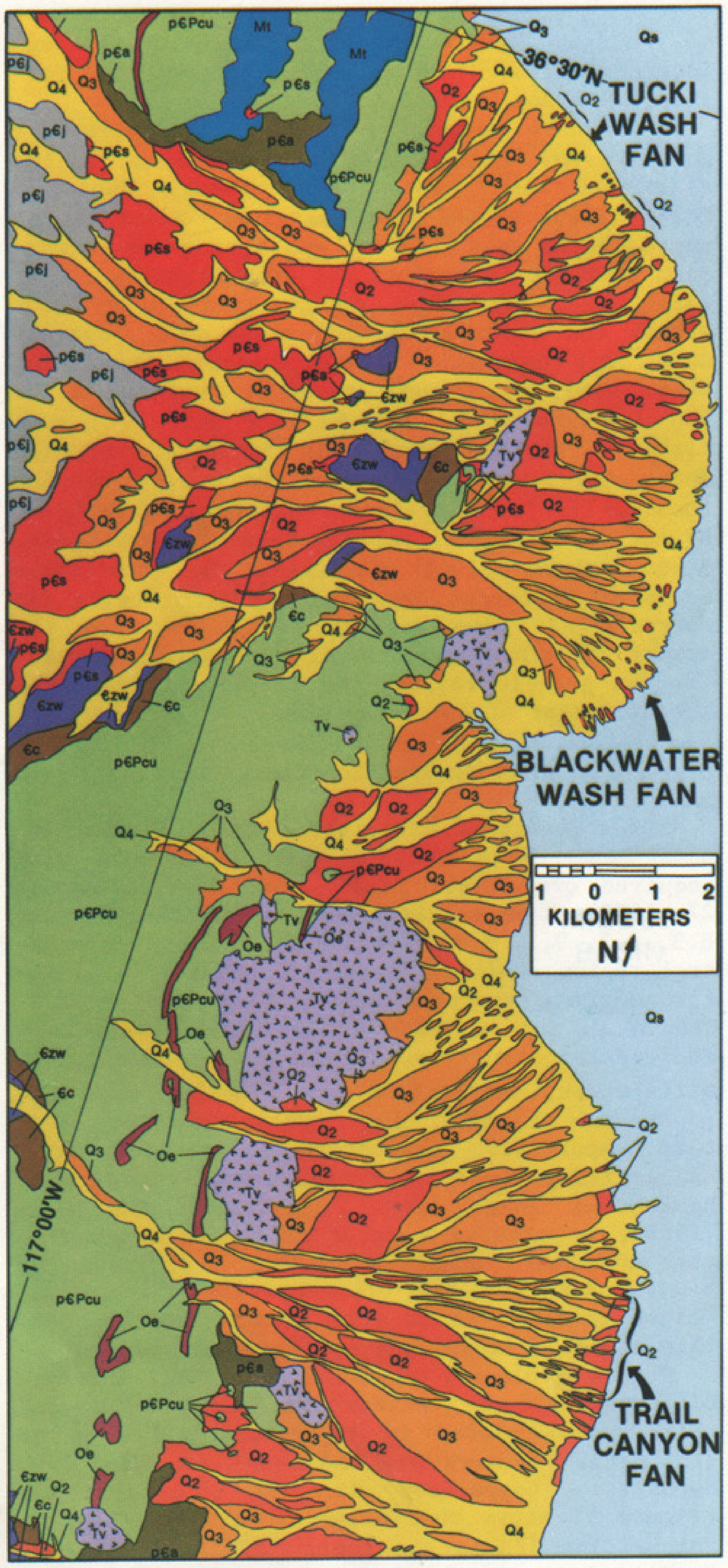

Fig. 1. Simplified lithologic map of the study area, after Hunt and Mabey [1966]. Units are those that can be distinguished in Fig. 2. Explanation on the next page.

Interpretive Map

Figure 3 is an interpretive map based on the TIMS image (Figure 2). Identification of the mapped bedrock and alluvial units was based upon our field inspection and Hunt and Mabey [1966]. The old gravels (Q_2) of Hunt and Mabey were consistently recognizable in the TIMS image as deep red or pink areas in the reddish purple fans. The Q_2 of some, but not all, of the green fans are depicted as light orange. However, distinction between the younger Q_3 and Q_4 gravels was not always possible in the TIMS image.

Hunt and Mabey [1966] mapped alluvial gravels based on relative age only. We further subdivided the gravels according to composition and provenance. We recognized six suites of fan gravels, distinguished by their assemblages of lithologies. Fans below the major canyons contained a wide mixture of rock types, dominated by the shales and quartzites found near the crest of the mountains. The fan gravels of Tucki Wash were largely shales of the Johnnie Formation, with lesser amounts of the resistant dolomite member. Fans below Trail Canyon and Blackwater Wash had more Stirling Quartzite and less shale. The fan gravels between Tucki Wash and Blackwater Wash contained quartzite and shale, but little dolomite. Lithologically, these fans were intermediate between those of Tucki Wash and Blackwater Wash. Fans of the fourth type were composed dominantly of carbonate clasts. These fans were found below smaller drainages that did not penetrate deep into the mountains, but were cut into only the resistant carbonate rocks at the range front. Fans beneath large exposures of the Tertiary volcanic rocks consisted largely of the volcanic rocks. Finally, some fans contained a mixture of volcanic, carbonate, argillaceous and other rock types. We mapped these compositionally complex fans as undifferentiated mixtures.

Discussion

The colors depicting the alluvial gravels appear to be controlled primarily by the prove-

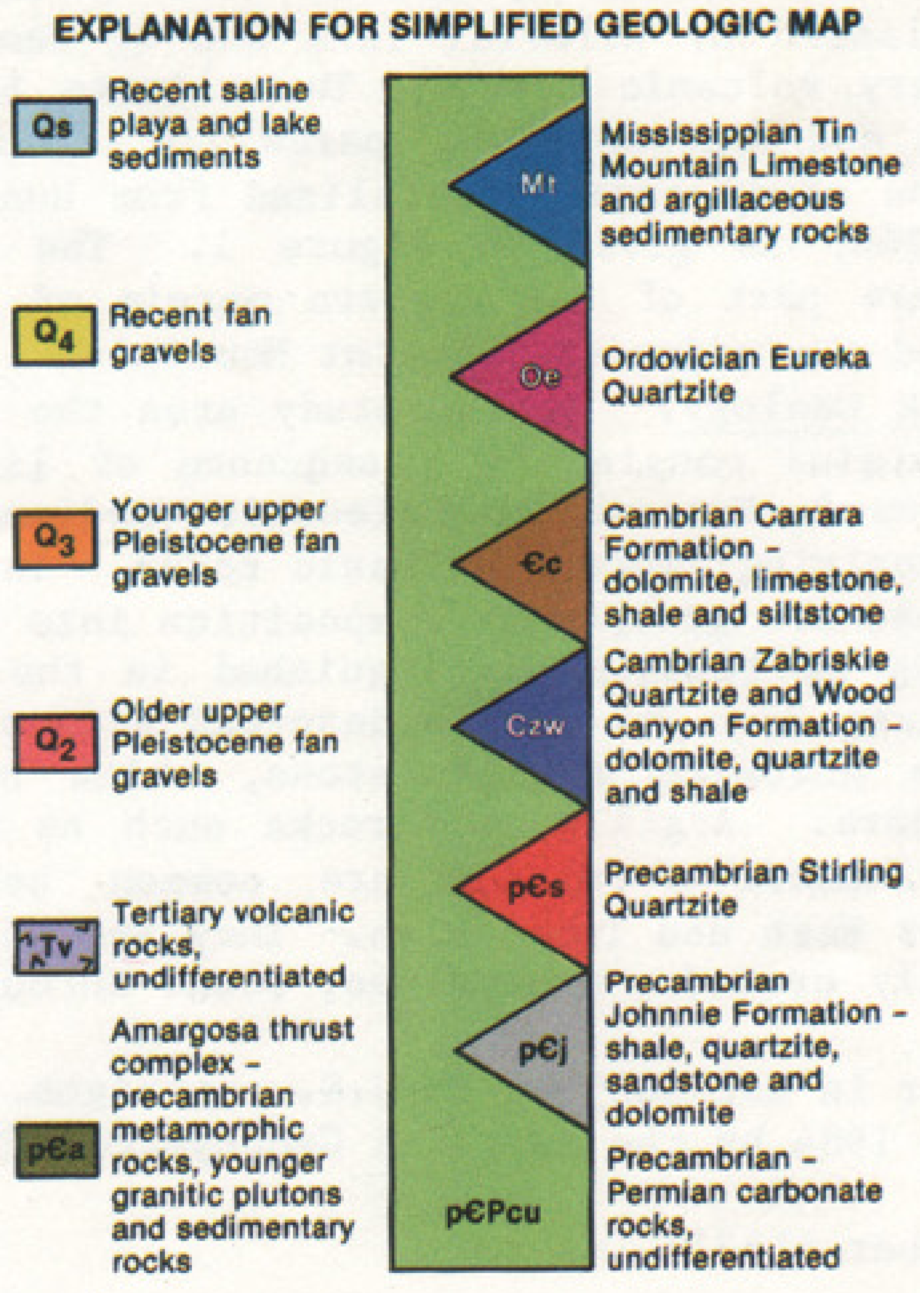

Fig. 2. Enhanced TIMS radiance image. Scales and orientation are shown in Fig. 3.

nance. Debris from slopes consisting of a single rock type is the same color as the bedrock, and in some cases the contact between debris and bedrock cannot be distinguished. This is especially evident in Blackwater Wash, for source regions of Stirling Quartzite (red) and carbonate rocks (green). The color of fan gravels of mixed lithologies can be predicted from the colors of the source rocks. Thus, in Blackwater Wash and Trail Canyon, the magenta of the younger gravels (Q_3 and Q_4) arises from mixing red Stirling Quartzite and purple shale of the Johnnie Formation.

Differential erosion of bedrock plays a major role in determining the lithologies present in the fan gravels. In Trail Canyon, gravels of easily eroded quartzite and shale, which crop out west of the study area, are transported through 4.5 km of resistant dolomite bedrock before deposition on the alluvial fan. The color of these

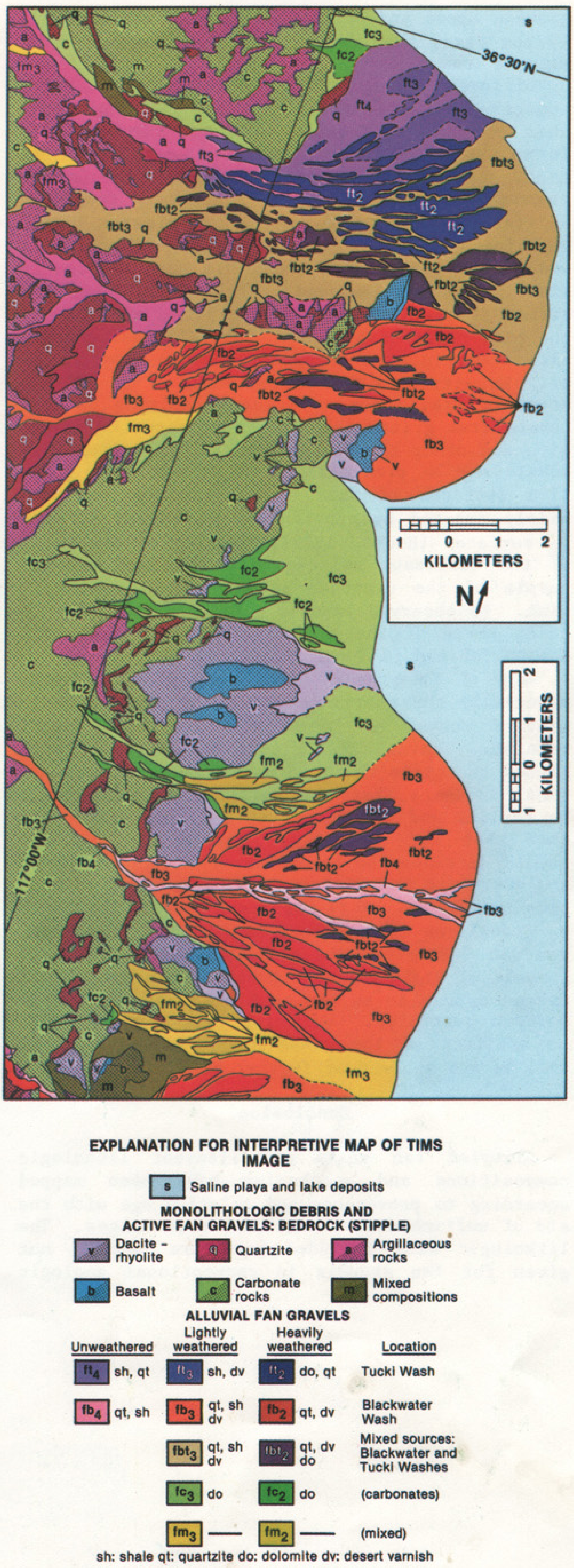

Fig. 3. Interpretation of the TIMS image. Vertical and horizontal scales differ.

gravels above and below the dolomite are virtually the same, showing that the admixture of dolomite is minor.

Differential erosion of gravels within a fan contributes to compositional change over time. This controls the color in the TIMS image and forms the basis for the relative age discrimination. For example, the gravels in the active channels of Tucki Wash are dominately fragments of fissile shale. Surfaces of the older alluvial deposits (Q_2) are a desert pavement of dolomite and quartzite; exposed shale has been reduced to fine grains and removed. This would have the effect of removing purple, and could account for the pink color of this Q_2. Compositional changes also occur in some carbonate fans as they weather. We attribute the yellow color of Q_2 gravels north of Trail Canyon to the dissolving of carbonate from gritty dolomite, concentrating quartzite and other clastic sediments. Dissolved carbonate may be precipitated as caliche near inactive surfaces of fans. Such caliche has been widely exposed by erosion and deflation of some Q_2 surfaces [Hooke, 1972]. Mixing of the green of the carbonate caliche with the deep reddish purple of the uneroded gravels could result in pink. We observed exposed caliche on the pink Q_2 units north of the active channel of the Trail Canyon fan and in Tucki Wash.

Many of the gravels found throughout the area, especially the quartzite and other clastic sedimentary rocks, are heavily coated with desert varnish. Thermal IR reflectance spectra of varnished quartzite (M. J. Bartholomew, pers. comm., 1984) indicate that the emissivity minimum will be smaller and will occur at a longer wavelength than that for unvarnished quartzite. Varnish should decrease the intensity of the red color of the quartzite and perhaps shift the color towards blue or purple. This may occur on the varnished Q_2 gravels on the northern half of the Trail Canyon fan. However, the equally heavily varnished gravels of the Q_2 desert pavement south of Trail Canyon appear to be the same shade of red as the bedrock quartzite. We think this similarity is an artifact of the enhancement process, but it will be the subject of further study.

Conclusion

Alluvial fan units of different lithologic compositions and weathering have been mapped according to provenance and relative age with the aid of multichannel thermal infrared images. The lithologic data included here are usually not given for fan gravels in conventional geologic maps. Boundaries of the age units determined from the thermal images are generally consistent with those of Hunt and Mabey [1966]. The ability to map lithologic composition and relative age of gravels is a significant advance in remote sensing. Compositional mapping with multichannel thermal infrared images is widely applicable, as long as vegetative cover is incomplete.

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