Regional Aeolian Dynamics and Sand Mixing in the Gran Desierto: Evidence from Landsat Thematic Mapper Images

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Spatial variations in sand composition were mapped on a regional scale in a terrestrial sand sea, the Gran Desierto of Sonora, Mexico. Mesoscale mapping on a satellite image base allowed quantitative interpretation of the dynamic development of sand sheets and dunes. The results were used to interpret the Quaternary geologic history of the tectonically active region at the mouth of the Colorado River. Landsat thematic mapper multispectral images were used to predict the abundance of different mineralogies of sand grains in a mixed aeolian terrain. A spectral mixing model separated the effects of vegetation and topographically induced shading and shadow from the effects produced by different mineral and rock types. Compositions determined remotely agreed well with samples from selected areas within the spectral limitations of the thematic mapper. A simple discrimination capability for active versus inactive sand surfaces is demonstrated based on differences in the percentage of low-albedo accessory grains occurring on dormant aeolian surfaces. A technique for discriminating between low-albedo materials and macroscopic shade is implemented by combining thermal images with the results of the spectral mixing model. The image analysis revealed important compositional variations over large areas that were not readily apparent in the field.

INTRODUCTION

The erosion, transportation, and deposition of sand by aeolian processes is important on Earth, Mars, and possibly Venus. In order to determine the recent geologic history of an aeolian terrain, mixing trends among all possible sediment sources must be understood. Such trends are controlled by sediment sources, transportation pathways, and wind regimes [Goudie et al., 1987]. A knowledge of the spatial and stratigraphic relationships between juxtaposed sand bodies can be used to infer the conditions responsible for their emplacement. In order to develop an understanding of regional aeolian deposits it is necessary to use remote sensing data to determine the provenance areas and transport paths which led to their formation. Sand sheets and dunes comprise 6% of the Earth's land area [Brookfield, 1984] and most of Mars can be considered an aeolian terrain. Aeolian deposits have also been suggested for Venus [Greeley and Iversen, 1985]. Mapping and geologic interpretation based on remote sensing may be influenced by aeolian activity. In particular, bedrock may be obscured by windblown sediments [Breed et al., 1987; Guinness and Arvidson, 1988]. Even where ambiguities can be resolved by in situ measurements, the regional scale of aeolian processes dictates a synoptic view to correctly identify provenance, transportation pathways, and deposition sites of surficial sediments.

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Paper number 90/JB00143.
0148-0227/90/90JB-00143$05.00

Spectral data from the Landsat thematic mapper (TM) were used to provide a synoptic view of the Gran Desierto (El Desierto de Altar) of Sonora, Mexico. The Gran Desierto is a sand sea covering ~5700 km² which has received sediment from several sources. It is located adjacent to the Colorado River delta at the head of the Gulf of California and has been affected by variable wind regimes, tectonic processes, and sea level fluctuations. Active aeolian sands are juxtaposed on both volcanic and crystalline source rocks. A Quaternary history of aeolian deposition in the area has been proposed [Blount and Lancaster, 1990] in which the Gran Desierto is situated atop an abandoned channel of the Colorado River.

Field work was conducted to obtain data on variations in grain composition, size, and surface alteration. Point counts of samples were used to verify the accuracy of mineral fractions predicted by a spectral mixing model. Laboratory spectra were measured for calibration of the remotely sensed data and to establish the degree of spectral resolution required to resolve individual sand populations. The sand populations delineated were then used to describe sediment source areas, transport paths, and deposition sites.

GENERAL GEOLOGIC SETTING

The Gran Desierto is the largest sand sea in North America [Breed et al., 1984] and is situated along the U.S./Mexico border east of the Colorado River delta. About half of the area is covered by sand sheets and dunes <1 m to >120 m in height. The Gran Desierto extends from near Yuma, Arizona, southeastward to Puerto Penasco, Sonora. Other major dune fields in the region include the Algodones Dunes (40 km northwest), the Mohawk Dunes (75 km north-northeast), the
The eastern margin of the Gran Desierto abuts the Cenozoic volcanic complex of the Sierra Pinacate [May, 1973; Wood, 1974; Greeley et al., 1985], a composite volcanic field covering more than 1800 km². The Sierra Pinacate serves as a topographic barrier which defines the eastern limit of the dune field. Most sand deposits lie 20-120 m above sea level. To the north, the sands thin out at an elevation of 200 m against the distal margins of alluvial fans from the Tinajas Altas and Tule Mountains along the Arizona-Mexico border. The Sierra del Rosario form a prominent NW-SE trending granite inselberg within the northern third of the sand sea. Several smaller inselbergs occur within the sand sea to the west of the Rosaritos and immediately west of the Pinacate volcanic complex. The western sand sea is bounded by the Sonora Mesa, a topographic high (elevation 100 m) paralleling the Colorado River delta. The mesa surface is characterized by lag gravels and indurated silts and clays representing abandoned channel deposits from the Quaternary Colorado River. On the southwestern side, the Gran Desierto lies on the Mesa Arrenosa, a fault block with maximum elevations of 120 m. On the southeastern side, elevations decrease (60 m) toward the coastline, forming a sandy plain from Bahia Adair eastward to Puerto Penasco, Sonora. Along the coast are outcrops (thickness 120 m) of Pleistocene deltaic deposits [Colletta and Ortlib, 1984] and raised beaches, the most prominent of which is 8 m above present-day mean sea level.

More than two-thirds of the Gran Desierto are covered by sand sheets and streaks. The remaining area is equally divided between star dunes in the west and transverse or crescentic dunes in the east. An isolated area of longitudinal dunes occurs in the extreme northeastern corner of the sand sea [Lancaster et al., 1987]. Breed and Groll [1979] have noted that the star dunes range from simple to complex and grade eastward into complex crescentic dunes with superposed star crests which, in turn, grade eastward and southeasterward into compound crescentic dunes. Differences in dune morphology between the western and eastern dune populations suggest that the star dunes have been subjected to a multidirectional wind regime whereas the transverse dunes have been dominated by unidirectional southerly winds from the Gulf of California.

Figure 1 shows the general geologic setting of the area. Gneissic, granitic, and metagranitic rocks form a potential sand source along the northern margins. Most granitic outcrops are lightly to moderately stained by desert varnish, a coating that is conspicuously absent on grus surfaces. A dark crust that occurs on many grus surfaces and on alluvial fans was found, by scanning electron microscopy, to be microcolonial fungi, which occurs as macrobotryoidal layers. Alluvial fans are covered by inactive aeolian sand with an armored surface of granitic grus. Well-developed drainage channels, ranging from 1 to 50 m wide, are ubiquitous on fans. Channels up to 15 km long carry bedloads of quartz, feldspar, biotite, and hornblende onto the margins of the sand sea. Mean grain size in the channels is a function of the distance from the outcrop, ranging from boulders at the source to granules (2-3 mm) or very coarse (1.2 mm) sand at the fan perimeter. Sediments are transported during flash floods, discharging "juvenile" grains as a veneer over existing sand surfaces.

Pinacate volcanic rocks are dominantly hawaiites and form cinder cones and lava flows. Gutmann and Sheridan [1978] estimate that most of the flows are Pleistocene in age and some evidence indicates that the most recent eruptions may have occurred in late pre-Columbia times. Large phenocrysts of yellow labradorite are common. Volcanic materials readily form sand-size grains which are transported downstream in arroyos. However, they are not significant components of the sand sea except immediately downhill from the Pinacates and its associated drainage channels. The paucity of basalt grains on active sand surfaces may be due to abrasion by more competent quartz and feldspar grains.

Marine sediments include the Chione coquina along the coastline. Sediments derived from this outcrop and from
modern beach deposits are dominantly carbonate shell hash and fine quartz and gypsum sands. Marine quartz sand is well rounded and lacks both iron staining and aeolian frosting. Gypsum grains occur as lightly frosted tabular to prismatic shards [Ives, 1959]. Marine sands form a broad, ≈10 km wide, mostly inactive sand sheet between the coastline and the southern active margins of the sand sea. Aeolian activity is vigorous near the coastline and large reversing dunes (up to 12 m in height) are common for distances up to 3 km inland.

A ubiquitous gravel deposit occurs throughout the western Gran Desierto from near Yuma to the coastline on the Gulf of California. This deposit is composed almost exclusively of well-rounded cobbles with minor epipode and quartzite. Fragments range in size from 5 to 100 mm and are interpreted as fluvial; pebble- to cobble-size components form well-developed armored surfaces in many areas, particularly on the southern and western margins of the sand sea. Sand on these surfaces is generally inactive and often contains substantial concentrations (10-20%) of vegetative detritus. This surface extends into and under the Gran Desierto and is situated axial to the deltaic facies described by Colletta and Ortlieb [1984] along the coastline.

Sand from the western star dunes is generally medium- to coarse-grained and moderately to heavily stained by iron oxides. Surface frosting ranges from nil to fully opaque. Eastern transverse dune sand is generally fine-grained and is primarily composed of nentic sands mixed with basaltic grains in the south and granitic sands and "red" sand in the north.

Detrital material in the Gran Desierto can be identified in the field from each of the major local sources: (1) granitic grus composed of quartz, feldspar, hornblende, and biotite; (2) basaltic sand; (3) carbonate shell hash, gypsum, and quartz sand; and (4) well-rounded fluvial gravels. The distribution of these components (gravels excepted) were systematically defined by point-counts performed for this study. Although Gran Desierto sands are predominantly quartz (≥90%), the distribution of accessory grains plays the major role in controlling spectral response at VNIR wavelengths and determining the provenance of sand populations. Grain mineralogy includes quartz, feldspar, carbonate, basalt, hornblende, biotite, amphibole, illmene, magnetite, and miscellaneous accessory (this category included zircon, garnet, gypsum, and organic detritus).

The sands can be classified as either active or inactive. Breed and Grow [1979] and Blount et al. [1986] note that active sand surfaces have higher albedos than inactive surfaces. The Pinacate volcanic complex and the sand sea shows reflectance differences of 20% between active and inactive surfaces. Active surfaces show evidence of recent wind-induced movement and are characterized by features such as ripples, slip faces, or deflation. Inactive surfaces exhibit evidence of recent dormancy, including the formation of silt-crusted surfaces, lag deposits, accumulations of fluvial or atmospheric detritus, and the obliteration of wind-induced surface features.

**Tectonics:** The Gran Desierto is adjacent to a rapidly subsiding basin, the Salton Trough, an embayment created by rifting initiated during the Pliocene along the East Pacific Rise and the San Andreas fault system [Larson et al., 1968; Angelier et al., 1981]. Regional subsidence has propagated to the northwest as rifting and strike-slip faulting continues into the present-day. The southernmost extension of the San Andreas fault system, the Cerro Prieto fault, passes almost directly through the area before continuing offshore into the Gulf of California [Merriam, 1965]. Strike-slip movement in the area is as high as 60 mm/yr [Gastil et al., 1975; Curray and Moore, 1984]. Since 1900, one magnitude 6.3 and two magnitude 7.1 earthquakes have originated within the study area; six magnitude 4 or greater earthquakes had epicenters within the Gran Desierto during a 10-year period between 1938 and 1968 alone [Gastil et al., 1975]. Such regular seismicity may have an effect on dune morphology, effectively limiting the vertical growth of sand surfaces which are already at or near the angle of repose. Most seismicity within the Gran Desierto originates at depths of 5-6 km, corresponding to the transition between deltaic deposits and basement crystalline rocks [Vonder Haar and Howard, 1981]. Local uplift is still occurring along the Mesa Arrenosa, a fault block interpreted by Colletta and Ortlieb [1984] to be the result of drag folding along the Cerro Prieto fault.

It was originally thought that alluvial sedimentation from the Colorado River into the incipient Gulf of California began as early as 8 m.y. before present (Ma) [Merriam and Band, 1965]. Recent evidence presented by Luchitii [1985], however, shows that the lower Colorado River was captured by the Gulf of California during Pliocene time and did not establish its current gradient until ≈1.2 Ma. Conglomeratic sands and silts beneath Mesa Arrenosa were dated at between 700,000 and 1,200,000 years ago [Colletta and Ortlieb, 1984]. Near Salina Grande, paleodeltaic deposits correlate with a nearshore unit that is stratigraphically below the Chione coquina, a ubiquitous indurated shell deposit dated at 146,000 + 13,000/–11,000 years ago [Colletta and Ortlieb, 1984]. The Chione coquina is in turn overlain by fluvi-avulsion sands that grade into the aeolian sands of the Gran Desierto. This stratigraphic relationship implies a maximum age of ≈159,000 years for the southern Gran Desierto. Soils formed on Pinacate lava flows have been described by Slate [1985], to be a net deposition site for aeolian sand sand and dust beginning between 140,000 and 1,150,000 years ago.

**FIELD PROCEDURES**

Rock samples were obtained at 35 localities. Except for the Sierra del Rosario inselberg, all bedrock outcrops are on the margins of the sand sea, mostly on the eastern and northern sides. Over 200 sand samples (100-400 g) were also gathered for correlation with remote sensing data. Most sand samples were gathered by troweling at a depth of ≤10 mm. In addition, 30 samples were obtained on surface tapes in which 50 mm-wide strips of adhesive tape were used to gather the topmost veneer of grains. Samples from inactive sand surfaces were gathered both at the surface and at depths as great as 300 mm.

Point counts were performed on 188 of the 244 sand samples gathered for this study. All were sieved at 1 phi intervals from -1 to 4 phi inclusive (2 mm to 62.5 μm). Each size fraction was examined separately for point-count analysis of grain mineralogy. The number of subsamples for an individual bulk sample could vary from one (for the most unimodal samples) to seven (for a poorly sorted sample). The whole-phi interval was selected to isolate grains for point-counting of mineral constituents as a function of grain size. Half-phi analysis of complementary samples (gathered simultaneously) was conducted by Lancaster et al. [1987] and systematic variations in both grain size and sorting within the Gran Desierto have been described. In general, textural trends within the Gran Desierto are controlled by distance from the sand source and intensity of aeolian activity. These parameters are in turn related to dune type. The finest and best sorted sands occur in the mature crescentic dune complexes of the eastern sand sea. Western star dune sand is equally well sorted but coarser, whereas western reversing dune sand is even coarser. Dune sand is better sorted and
finer than grains from sand sheets or zibars in the Gran Desierto. Sands become finer and better sorted as they are transported from juvenile crescentic dunes around the margins of the sand sea into areas of multi directional wind regimes where reversing and star dunes are formed.

SPECTRAL DATA

A Landsat 5 thematic mapper (TM) scene acquired at 1040 LT on January 3, 1985 (scene ID: Y5030817405 X0), was used in this study. The TM instrument recorded spectral radiance in six visual-near infrared (VNIR) bands between 0.45 and 2.35 μm and thermal emission in a 10.5- to 12.5-μm band. Spectral resolution of the TM is coarse compared to laboratory instruments: nominal TM bandwidths range from 0.06 to 0.27 μm (60-270 nm) versus the 0.01 μm (10 nm) spectral resolution typical of laboratory instruments. The digital number (DN) values recorded by the TM represent radiance and were converted to reflectance for comparison with laboratory spectra. This preprocessing step included removal of the solar curve and a first-order atmospheric correction [Osterman et al., 1980].

High spectral resolution laboratory data (bandwidth 0.01 μm or 10 nm) were obtained for 45 whole rock and sand samples. These data were used as an intermediate step to calibrate the TM image to nominal reflectance according to the technique described by Adams et al. [1986]. Data from the VNIR bands are converted to true reflectance by simultaneously solving for the instrument gains and offsets required to obtain the best root-mean-square (RMS) fit of the image data to the laboratory spectral library. The resulting gain and offset values represent combined effects from uncorrected atmospheric and instrumental contributions.

The laboratory spectra also facilitated assessment of mixing systematics and identification of the spectral resolution required to separate ambiguous ground targets. Data for 21 of these spectra were generated on the RELAB system at Brown University and 24 additional spectra were produced by the Beckman DK2A spectrophotometer of the University of Washington.

High-resolution lab spectra were convolved against the TM5 filter set [Markham and Barker, 1985] to generate spectra of the same wavelength resolution as the TM by

\[ R_c = \sum R_{ln} \times T_{mn} / \sum T_{ln} \] (1)

where \( R_c \) is convolved reflectance; \( R_{ln} \) is laboratory reflectance at wavelength \( n \), and \( T_{mn} \) is the transmission of the TM filter at wavelength \( n \). After convolution, synthetic TM spectra from basalt samples were used in conjunction with the corresponding image spectra on the Pinacates to obtain an estimate of the additive and multiplicative atmospheric terms affecting the TM data. The derived atmospheric spectrum corresponds to the spectrum of "shade," a generally featureless low-reflectance vector found in fully shadowed scenes on the TM image.

APPLICATION OF MIXING ALGORITHM

Source outcrops in the Gran Desierto are spectrally distinct at the wavelengths and resolutions of the TM. Image spectra for major geologic and vegetative components were obtained from the TM image by taking the mean of a 10 by 10 pixel area centered on previously checked field sites. Image spectra are referred to as spectral end-members if they cannot be replicated by any combination of other type spectra within the scene. Spectral end-members were identified at 26 field sites according to the spectral end-member selection techniques described by Johnson et al. [1985]. Because shade represents one end of a continuum of reflectance values for all components, it is also treated as a spectral end-member.

The uniqueness of the selected image end-member spectra was confirmed by projecting scatter-plots of TM image data into three dimensions. The TM end-member spectra of both geologic and vegetative units in the Gran Desierto are summarized in Figure 2. The spectral mixing relationships between the end-members are usually more apparent when the reflectance values are projected as points on a trivariate plot as in Figure 3. In this perspective presentation, each axis represents reflectance at a given wavelength and endmember data points are plotted according to their values in three of the six VNIR bands. A polygon such as Figure 3 is referred to as a "mixing polygon" and the volume within it a "mixing volume" or "mixing space." Vectors between vertices are "mixing vectors." Any combination of bands can be used to generate a projection of a mixing volume. A six-dimensional polygon thus encloses a spectral volume into which all pixels in the TM scene must fall. The endmembers defined by vertices of the \( b \)-dimensional polygon (where \( b \) represents the number of TM bands being used) for this scene are carbonate, granite, basalt, active sand, inactive sand, vegetation, halite evaporites, seawater, and macroscopic shade (the distribution of halite and seawater is not addressed further). When all actual image data are projected into such a volume, considerable overlap can be

![Spectral end-members for the Gran Desierto derived from TM image data.](image.png)
found among some end-members which have significant degrees of natural variance. For example, not all pure carbonate sands are as bright as the point represented in Figure 3 for carbonates. The point utilized is representative of the most extreme position of the carbonate vertex.

Scale of mixing. As discussed by Mustard and Pieters [1987], the spectral contrast and the scale of mixing, macroscopic versus intimate, determines whether a linear or nonlinear technique must be used to predict end-member concentrations. Intimate mixing involves particles which are in physical contact and modeling of such mixtures recognizes that light may be scattered by more than one grain before photons are reemitted. Such multiple scattering implies that the compositional effects of more than one grain are being recorded by a photon. Compositional predictions based on an intimate mixing model must account for the type of scattering involved for each composition within the field of view and its magnitude. Nonlinearities in the spectral response of intimate mixtures manifest themselves as variations in the depth of absorption bands; however, these variations are far too fine to be detected by the TM because of the broad spectral bandpasses mentioned earlier and the relatively low signal-to-noise ratio compared to the magnitude of the absorption being observed. Macroscopic mixing treats the reflected light from a surface as representing discrete photons which have only interacted with one particle or one composition. By assuming that each photon represents reflectance from a single composition, the macroscopic mixing model can be used to generate linear concentration predictions based only on the spatial distribution and spectral attributes of defined end-members within the field of view. Shipman and Adams [1987] have pointed out that both types of mixing may be present simultaneously because remotely sensed data integrates reflectance values over wide spatial scales ranging from sub-millimeter up to the size of the pixel. Vegetation, boulders, and other large (>1 m) objects superposed on sands must, therefore, create macroscopic mixtures as defined by Singer and McCord [1979]. Considered alone, aeolian sands are probably intimate mixtures as defined by Hapke [1981]; however, spatially juxtaposed sand populations are treated here as macroscopic mixtures. At this time, no a priori rule exists for determining if a mixture is intimate or macroscopic based on a single observation. Although the two methods can deliver widely different concentration predictions [Smith et al., 1985], it has been found that a simple linear mixing approach is sufficient to extract geologically important compositional trends from mixed aeolian sands. End-member spectral variations which can be mapped with the TM are used to trace spatial differences in the composition, spatial differences which can be used to infer grain provenance, transport path, deposition site, and relative stratigraphy.

Mixing with shade. An area representing macroscopic shade lies near the origin where a DN value of =0 is found on all VNIR bands. In addition to mixing between geologic and floral end-members, each component must also mix with shade, either as macroscopic shadowing or due to attitudes other than horizontal. Reflectance varies as a function of the angle from illuminating source to target to detector. Surfaces which are oriented at an angle away from the sun will thus have their reflectance values lowered even though they are fully illuminated. Brightness variations can also be caused by macroscopic shadowing caused by surface topography (hills) or ground clutter (boulders, bushes, etc.). Mixing between a geologic unit and shade will manifest itself within a mixing volume as a change in the vector connecting the origin of the polygon (where 100% shade is found) and the position occupied by the fully illuminated end-member component.

Quantifying mixing trends. The DN coordinates (in mixing space) of the end-member components may be thought of as spectral "training sites" and used on individual data pixels to predict the fraction of each component present at a respective ground location (assuming the end-member is spectrally distinct from all other units at one or more wavelengths). When the spectra from a mixed-component ground point plot as a mixing vector between its known end-member components, a relationship can be demonstrated between the fractional composition (on the ground) and its position in mixing space. The ability to make such fractional estimates has been attributed to differences in reflectivity and spectral contrast (depth of absorption bands) which are large enough to manifest themselves in relatively coarse resolution data [Pieters, 1978]. Therefore, quantitative abundance estimates can be obtained from spectral data only if the end-members have significant albedo or absorption differences.

Depending upon the wavelength and spectral resolution used, differences in surface composition can be mapped on a regional scale [Goetz et al., 1983]. A linear mixing approach has been used [Adams et al., 1986, 1987] to classify reflectance data according to the fraction of each spectral end-member present. The linear mixing model proposed by Sasaki et al. [1983] may be utilized for TM data [Adams and Smith, 1986] by letting

\[ DN_b = \sum_{n} DN_{n,b} \times F_n + E_b \]  

and solving for \( F_n \), the aerial fraction of each pixel occupied...
by a spectral end-member contributing the the corrected TM reflectance (DN<sub>b</sub>) for a given band. DN<sub>n,b</sub> represents the reflectance of end-member n in band b and \( \varepsilon_b \) is the error in fitting the observed DN<sub>b</sub> to the library end-members (DN<sub>n,b</sub>). An additional constraint is that the total of all end-member fractions contributing to a given DN<sub>b</sub> equals 1/(Σ F<sub>n</sub> = 1).

By utilizing the linear mixing model (equation (2)), calibrated TM data may be used to predict the fraction (F<sub>n</sub>) of each end-member, n, within a scene. Figure 4 schematically illustrates the processing path for this technique. Implementation of the algorithm requires a matrix solution of b linear equations in n unknowns to estimate the fraction of each end-member present at a pixel ground location. A detailed treatment of a principal components solution to the model is given by Smith et al. [1985] and Johnson et al. [1985]. It has been applied to Viking lander data [Adams et al., 1986, 1987; Smith and Adams, 1988] and to Viking Orbiter data by Guinness and Arvidson [1988]. The model has been applied to whole rock mapping of olivines by Rivard et al. [1988] (A least squares solution to the mixing algorithm is described by U. W. Posolto, M.O. Smith, and J.B. Adams in Linear Mixing Models for Multispectral Images, a paper currently submitted to J. Geophys. Res., 1990.)

The output of the algorithm consists of n+1 fraction images (representing the F<sub>n</sub> and \( \varepsilon_b \) terms above) consisting of pixels with DN values ranging from 0 to 255 which are proportional to the percentage of each end-member present. The images are scaled for display so that a DN of 0 equals a fraction of 0/255 (or 0%) and a DN of 255 indicates a fraction of 255/255 (or 100%) of the selected end-member (exceptions will be noted later). The error image (\( \varepsilon_b \)) is scaled so that a DN of 0 equals 0% error at a given pixel, and a DN of 255 equals an error of 100%. In theory, an error image consisting of an array of zero-valued pixels indicates a perfect fit of the end-members (DN<sub>n,b</sub>) and their predicted fractions (F<sub>n</sub>) to the original image reflectance data.

Any geologic unit whose spectral signature falls within the mixing space of two or more included end-members will contribute to their fraction images. Although a dark error image indicates that all spectral classes have been included, it does not imply that all geologic units within the scene are spectral end-members. Conversely, a high DN value on the error image would indicate pixel vectors in the original data which cannot be accounted for in the spectral mixing space of the defined end-members. Geologic units which are not spectral end-members may be discriminated if their position within the mixing volume is unique. The existence of a mixing volume between end-members does not require, or imply, that mixing actually occurs within the volume, only that it may occur. If not, and if a non-end-member unit is uniquely located within such a volume, it can be spectrally discriminated (although the fractions will be meaningless).

Sediment mixing. As rocks weather and erosional products are transported from a source area (where the fraction, Σ F<sub>n</sub> = 100%) onto a ground location where mixing has occurred, the fraction of a given end-member will decrease to a minimum (or equilibrium) value. The spatial ground location at which this minimum occurs will vary among sources. Thus it is possible to use the fraction images to trace the fractional spatial distribution (via spatial variations in concentration) of each end-member in the scene. Specific levels of mixing may represent unique sand populations that have undergone similar histories of mixing with local source area grains and mixing with other sand populations.

As erosional products from a source travel into the sand sea, the b-dimensional position of their spectra will change in response to variations in grain size, admixing with other mineralogies and chemical modification of the grain surface. When such changes occur on a regional scale, as in a sand sea, the shape of the end-member mixing polygon will be

![Diagram](image_url)

4. Schematic representation of processing steps required to generate fraction images from corrected TM data sets.
altered to accommodate the newly formed spectral end-members.

Mixing vectors for sand in the Gran Desierto define a mixing space which is volumetrically larger than the polygon defined by the source end-members alone. Two vertices of this expanded polygon are the spectrally distinct categories of high-albedo "active sand" and lower-albedo "inactive sand" surfaces. The b-dimensional positions of these subdivisions form two vertices of the mixing polygon shown in Figure 3.

RESULTS

Analysis of even simple radiance data from the TM shows that, for this area, active sand surfaces are consistently brighter than adjacent inactive sand surfaces at visual and near-infrared wavelengths (0.45-2.35 μm) [Blount et al., 1986]. The same relationship between surface activity and albedo has been reported by Maxwell and Hayes [1989] and used to trace the movement of active sand chernox in the Western Desert of Egypt. The reasons for this difference in spectral response can be explained by a textural and compositional analysis of the two surfaces.

Granulometric analysis. Grain size analyses of 42 active and inactive samples from the western Pincate/sand boundary are shown in Figure 5. It was found that active sands contain a higher relative percentage of salination-sized grains (125-250 μm) and are much more unimodal than inactive sands. Similar grain size distributions on inactive surfaces have been summarized by Goudie et al. [1987]. Inactive sands contain larger proportions of both coarser (>250 μm) and finer (<62 μm) grains. Trenching into inactive surfaces along the western Pincate/sand boundary shows that most coarse fragments occur as distinct layers which are transported onto sand surfaces by overland sheet flooding from catchment basins on the adjacent and topographically higher Pincates. The higher percentage of sand-sized grains in brighter active sands is, in itself, in agreement with Gerbermann [1979], who showed that reflectivity increases directly with weight percent sand in sand/silt/clay mixtures. While Gerbermann's observations appear to explain the albedo difference between active and inactive sands, his conclusion is apparently contradictory to the silicate characteristic of increasing reflectance with decreasing grain size [Salisbury and Hunt, 1968]. The size/albedo relationship responsible for this apparent contradiction is, however, based on an assumption of constant mineralogy. An equally important phenomenon occurs when grains of different compositions are mixed [Clark, 1983]. Samples from the Gran Desierto show a strong correlation between grain size and composition. The coarser size fractions (>500 μm) are dominated by opaque volcanic lithics from the adjacent Pinacates. With the exception of the silts, reflectance values for the individual size fractions do become brighter as grain size decreases. However, an observed brightness difference between the 1 phi and 2 phi size fractions is due to a compositional change from basalt to quartz, not to the grain size/albedo relationship.

Point counts of grain mineralogy as a function of grain size were performed to determine if compositional variations in the <500 μm size range could be responsible for the observed brightness differences between active and inactive surfaces. Both active and inactive surfaces show a well-sorted quartz fraction in the very fine to fine sand size range (62-250 μm). Coarser fractions are dominated by volcanic lithics and the silt size fraction contains abundant quartz and aggregated fines of amphibole and volcanic lithics (particles morphologically similar to the electrostatic aggregates discussed by Krinsley and Leach [1981]). Figure 5 also shows the volume percentage of dark grains (obtained from point-counting of samples from both active and inactive surfaces) plotted with mean grain size distributions for both active and inactive sands. Active sands are depleted with respect to inactive sands in the coarse and very fine size fractions: the size fractions which are dominated by darker grains, leading to the conclusion that the apparent darkness of inactive sands at visual/near-infrared wavelengths is due to a relative enrichment of the size fractions containing abundant dark grains. While this explanation is suitable for inactive sands containing an abundant coarse fraction, some darker inactive sands were observed which lack any coarse fraction, and all of the darkening of these sands is attributed to an enrichment of low-albedo silt size grains. This observation is consistent with the compositional data which shows that the silt size fraction contains a higher percentage of low-albedo grains than does the sand-size fraction.

A preferential segregation of dark lithics into the coarsest and finest size fractions can be explained from a dynamic standpoint. As initially coarse fragments of dark basalt lithics enter a saltating environment, they are abraded more rapidly than existing (and more competent) quartz and feldspar grains. This interpretation would lead to a deduction that less competent rock fragments (in this case, sand-sized grains of basalt) should concentrate in the coarsest and finest size fractions, in agreement with the point count observations. About 40% of silt-sized dark grains from inactive surfaces are composed of amphibole, a mineral which does not occur anywhere in the vicinity of the samples under discussion and is rare in samples from active surfaces (although, as noted previously, active surfaces are depleted in the silt size fraction). It is proposed that amphibole fines arrive as atmospheric fallout which accumulates on inactive surfaces. On an active surface, such fines remain in suspension (i.e., are never deposited) or, if deposited, are quickly taken back into suspension and concentration is thus inhibited. In summary, the silicate characteristic of increasing albedo with decreasing grain size holds true in Gran Desierto sands; finer quartz and finer basalt grains do have higher albedos than their coarser counterparts. But this relationship does not describe mixed-composition sands in which albedo may decrease with bulk grain size due to the concentration of some components in specific size ranges.

FRACTION IMAGES

Nineteen end-member groups were examined using different combinations of image spectra from plagioclase
and microcline granite, basalt, carbonate, active sand, inactive sand, vegetation, and macroscopic shade. Fraction images expressing the concentration of each end-member were generated. The number of end-member groups is constrained by the fact that only six end-members can be solved for simultaneously with TM data. Except as noted, the images presented here are scaled so that fractions between 0 and 1 correspond to DN values in the range 0 (darkest) to 255 (brightest).

Except as noted, the effects of vegetation and macroscopic shade were removed from all subsequent geologic end-member images by normalizing with respect to vegetation and shade. This procedure involves dividing each fraction image by the sum of all other images except vegetation and shade and allows the interpretation of the remaining fraction images in terms of geologic end-members only:

$$F_{n,\text{norm}} = \frac{F_n}{\sum F_i \cdot (F_{\text{veg}} + F_{\text{shade}})}$$

Such an approach allows for the extraction of geologic information from pixels containing some vegetation or representing partially shaded ground locations (i.e., a nonshade end-member fraction may not be recovered from a fully shaded surface). In practice, pixels in full shadow are almost always saturated at 100% shade concentration and information within them is lost to the shade end-member fraction image.

**Error.** The $E_B$ error image (Figure 6, not normalized) serves as a quality check on the suitability of the selected end-members. High errors (>60-80%) occur over evaporite deposits in the Colorado River delta (area B7) and along the coastline (C5-C7) as well as over the waters of the Gulf of California. These errors are not within the area of interest but could nevertheless be removed by including halite and turbid water as input end-members. The highest error within the study area was 7%; this value has been stretched to full brightness, causing the Colorado delta and offshore areas to be saturated to a DN of 255. Within the study area, the largest errors (i.e., areas of poor fit between the spectral end-members and the observed spectral vector) occur in the southern Tinajas Altas mountains (G3-H3) and on the sunward facing sides of cinder cones (I4-J5). Due to the geometry of TM image acquisition, sunward facing slopes produce specular reflections (here termed the “glint” component) which are analogous in mixing properties (although opposite in direction) to mixing with shade. The glint component produces values outside the defined end-member mixing space and appears as an error.

**Vegetation.** The vegetation end-member (Figure 7, not normalized) depicts the distribution and concentration of flora. Because of the generally low fractions, this image was stretched so that 40% vegetation = DN 255. Saturated values occur over cultivated fields in the Colorado River floodplain (B1-B4). Bright patches in the western sand sea (e.g., E2) are farms surrounded by deciduous trees. The broad area of high vegetation in the north central sand sea (F2-F3) originates from the distal ends of intermittent streams from the north and represents an ephemeral grass community with fractions of 30-40%. The generally dark areas of the sand sea correspond to vegetation fractions of 10% or less. The drainage patterns on the Pinacates (I4-J5) are very well-defined due to high concentrations of mesquite, palo verde, and acacia along arroyos. Predicted fractions are consistent with field estimates of 35-40% vegetation cover at the brightest localities performed prior to implementation of the mixing model. The medium tones on rubble slopes (I3) and on the Pinacates (I4-J5) correspond to fractions of 15-25% on distal flows, also in close agreement with field estimates.

6. Fraction image for RMS Error scaled so that 7% error equals full brightness.
Shade. The shade fraction image maps the occurrence of all spectrally flat, low-albedo ground pixels and the mixing of such spectral features with other end-members. As a result, the shade fraction image (Figure 8, not normalized) can delineate topographic features associated with shadow and slope variations. In particular, the shade fraction image has proven capable of isolating small-scale aeolian bedforms previously undetectable on TM imagery [Blount and Greeley, 1987]. Because basalt and other low-albedo materials are spectrally similar to shade, their occurrence is contained within the shade fraction image. The two can be used as spectral end-members only if weathered rather than fresh basalt is used as an end-member. Nevertheless, data points from the two overlap considerably and a simple first-order mixing approach is not sufficient to diagnostically separate dark basalt from shade.

Basalt. The basalt end-member image (Figure 9, normalized to remove vegetation only) correctly maps the major basalt flows (J4-J6) of the Pinacate volcanic field, with predicted fractions of ~90%, as well as several smaller stocks and plugs (H3-I3). In the central sand sea (e.g., F5), basalt fractions of up to 40% are predicted. These values are erroneous for basalt content, but are correct for the fractions of other low-albedo accessory grains such as hornblende, biotite and magnetite. At the low spectral resolution (0.06-0.27 µm or 60-270 nm) of the TM, the basalt end-member image maps fractions of all low-albedo grains with DN coordinates near that of basalt. A second-order modeling approach was required to solve the problem. To generate a second-order fraction image, the first-order shade fraction image is used as a “spectral” data set in conjunction with the thermal (TM band 6) data. With only two input arrays, the mixing volume formed by TM band 6 and the first-order shade image deflates to a plane. In this case, both basalt and shade will have high values from the first-order shade fraction image resulting in one common point. Basalt and other illuminated low-albedo materials, however, will have high values in the thermal band, whereas shaded areas will have low values. The basalt vector will have a slope near zero, while the shade vector will be strongly positive or negative depending on the coordinate axes chosen. Thermal responses related to nonmineralogic causes (i.e., groundwater content, etc.) are a minor component of the spectral variance thus allowing the major variance between warm basalt and cool shade to be separated. Results of this process are shown in Figures 10 and 11 in which shade and basalt have been split into distinct fraction images. All subsequent fraction images were normalized relative to the first-order shade image and the vegetation image. Note that the second-order images are derived from the first-order shade image with finite fractional values for any low-albedo surface.

Granite. The granite end-member image (Figure 12) illustrates the capacity of the model to trace individual components into the sand sea. Fractions are saturated at 80% on the main outcrops of the Tinajas Altas (F1-G2), Sierra del Rosario (F4) and Sierra Blanca (I5). A thin line of high granite values can be seen immediately west of the Sierra Blanca (I5) and represents the exposed tips of the Sierra Enternada (literally “buried hills”), a granite inselberg which has been nearly covered by transverse dunes. Fractional values on alluvial fans vary with distance from their source, decreasing to ≤15% at their distal margins. Field evidence indicates that granitic components are entering the sand sea in the northern field area; the fraction image reflects this observation as a diffuse haze (E1) of
8. Fraction image for shade. Similarities between the spectral signature of shade and dark basalt lead to a first-order fraction which maps the distribution of both.

10. 2nd-order fraction image for shade.

11. 2nd-order fraction image for basalt.
gradually decreasing fractions along the alluvial fan/sand sea boundary. Ground observations of a ubiquitous coarse lag deposit of albite and quartz grains on this surface show a decrease in both fractional percentage and grain size with distance from the fan source. The biotite component, common on grus surfaces, is rare on active sand surfaces. The image indicates that the granitic bajada surface on the east side of the Sierra del Rosario is being covered by another unit. Field observations confirm sand movement to the northwest (climbing onto the fan) in this area. The high granite fractions which appear to be emanating from the coast (H7-J8) are zones of carbonate sand moving inland. As will be discussed subsequently, the mixing volumes occupied by granite and carbonate sand overlap in the original data and cannot be resolved at TM spectral resolution.

 Aeolian sands. Fraction images based on active and inactive sand are shown in Figures 13 and 14, respectively. Because these components represent spectrally unique mixtures derived from other geologic units, they are viewed as representing regional variations in the degree of mixing.

The active sand fraction image (Figure 13) illustrates several important trends in the Gran Desierto. Sand supply from the northwest is indicated by well-defined active streaks in the upper left corner of the image (D3-E1). Superposed on these streaks is an active sand sheet (D2-E3) which is feeding an area of contemporary star dune formation (E3). Active sand transport is also indicated on the Mesa Arrenosa (E7-G7) where stringers of active sand up to 10 km in length are migrating into areas of lower elevation to the north. The bajada on the southern side of the Sierra del Rosario (F4) is conspicuously clear of active sand, in contrast to the eastern and northwestern sides where advancing sands have covered most of the surface. The sharp boundary between active sands and alluvial fans (G4) confirms a field observation of regional southeast and west directed dune migration (dunes climbing onto the bajada surfaces). In contrast, northern migration of active sands is seen on the southern side of the Pinacates (I6-J7) where transverse dunes accumulate on the flanks of the volcanic complex. These sands continue around the western side of the Pinacates and advance northward as a series of isolated dunes moving across a substrate of inactive sand.

The inactive sand end-member (Figure 14) shows the same features in reverse fashion and highlights inactive sand sheets (G8, I4) and interdune corridors (I6). Inactive sand fractions are low in the main zone of star dunes, supporting field observations that well-defined interdune surfaces are rare. Rather, interdune corridors between star dunes are aligned troughs between dunes, created by the base of one dune overlapping the base of its neighbors. A complex of stabilized transverse dunes (F6-I8) is highlighted between the Mesa Arrenosa and the star dune chains to the north and northeast.

Carbone. The carbonate end-member (Figure 15) delineates regions of carbonate sand along the coast and areas where these sands appear to be migrating inland (H6-J8); predicting values in the 50-100% range along the coast, in agreement with field samples from this study as well as those conducted by Ives [1959]. Pedogenic carbonate on soils of the Pinacate volcanic field (J5-J6) is predicted to range from 5% to 40%. Field studies of Pinacate soils by Slate [1985] indicate carbonate fractions from 3% to 25% occurring as 2-3 mm thick coatings of secondary carbonate minerals on basalt rubble and desert pavement. As discussed previously, carbonate and granite occupy adjacent and overlapping regions in the end-member mixing volume, with the result that the carbonate fraction image also maps the granites in the northern field area (F1-G2).
13. Fraction image for active sand.

14. Fraction image for inactive sand.
COMPARISON OF LINEAR MIXING AND SAND ANALYSIS

Correlation of mixed features with known dynamic elements, such as active sand streaks, indicates that the fraction images are mapping individual sand populations with definite spectral, spatial and stratigraphic relationships. In order to make a direct comparison between the linear mixing algorithm and the results of point counts, lab spectra were obtained for the individual size splits of an inactive sand sample from the Pinacate/Gran Desierto boundary. These data were convolved against the TM filter set using equation (1) and then mixed according to equation (2) to obtain a predicted basalt fraction for each size interval. The results, plotted on Figure 16, show good agreement at finer grain sizes between linear mixing predictions and empirical point counts. Divergence in the curves at coarse size fractions is due to carbonate coatings on larger basalt granules. Such coatings were noted during the point counting process, but the granules were counted as basalt.

Field observations showed that virtually none of the ground sites utilized for selecting image end-member spectra were actually "pure." Pedocals, desert varnish, vegetation, aeolian sands, and local mineralogical variations abound throughout the area. The underprediction of fractions on "pure" end-members is an investigator error in selecting representative end-member spectra (i.e. the "training sites" were mixed). Mustard and Pieters [1988] have encountered a similar phenomenon, though underpredicting fractions, in laboratory tests assuming an intimate mixture and utilizing a nonlinear model.

Predicted fractions based on image end-members are summarized in Figure 17a with respect to major mineralogical components, normalized relative to one another. The plotted points represent the predicted fractions of each major component. The vertices of the triangle represent fractions of 1 (100% concentration of the respective end-member), where the plotted points should lie if their representative end-members were correctly selected. Granite and carbonate are combined as a single end-member in Figure 17b and plotted against basalt and aeolian sands (active and inactive combined). The spectral similarity between carbonates and granites leads to a predictive overlap on their respective fraction images. For example, the data point for carbonate on Figure 17a was predicted as 45% granite and 55% carbonate when the ground location was actually 100% carbonate sand. The results of point counts from several representative ground locations, both "pure" and mixed, are plotted for comparison between predicted and actual fractions. The predicted fractions of source components are systematically underestimated with a concomitant overestimation for mixed samples. The granite/ carbonate end-member overestimates by an average of 7%. The overlap of image data between these two units precludes using TM data for quantitative prediction of the two ambiguous end-members. Figure 18 shows the high-resolution results for ground samples of the granite and carbonate utilized as image end-members. The lab spectra of granite and carbonate become virtually identical when degraded to TM spectral resolution. Figure 18 indicates that narrow passbands at 2.22 \( \mu m \) and 2.35 \( \mu m \) are required to significantly distinguish between these two end-members. Such bands were included in the experimental Shuttle Multispectral Infrared Radiometer (SMIRR) and proved useful for isolating carbonates from spectrally similar siliceous tuffs [Blount, 1985].

The overprediction for basalt is linear and averages 24%. As noted previously, shaded ground is predicted as basalt, a problem which can be overcome by the inclusion of the TM
16. Direct comparison of predicted versus actual content of basalt grains from a mixed sample.

thermal band to generate second-order fraction images. Lowalbedo sand grains (hornblende, biotite, amphibole, and magnetite) all occur in direct relationship to the predicted fraction of basalt in mixed pixels. As discussed earlier, these components are occupying a common mixing volume at the spectral resolution of the TM instrument. Figure 19 shows the high-resolution spectra of two basalt samples from the Pinacate volcanic field. Taken alone, the two basalts are distinctive; however, with respect to the other end-members, they occupy the same mixing space and were mapped in

Figure 11 as two percentages of the same basalt end-member. This points out that even relatively small degrees of natural variance will manifest themselves as differences in the predicted fraction of a single end-member. Empirical errors of this sort may be difficult to avoid. Natural mineralogical variations (i.e., from one basalt flow to another) will manifest themselves as fractional deviations from the mixing space of the input end-member. Increasing the spectral resolution to include more finely subdivided end-members may exacerbate the situation by highlighting mineralogical variations within a geomorphologically homogeneous unit.

In some contexts, it may be desired to map minute spectral variations. Narrow passbands at 0.9 μm and 1.7 μm would allow discrimination of the flows in Figure 19 and their aeolian products as separate end-members. Compositional variations among flows have been mapped previously with supervised classification schemes in which an investigator interactively selects several spectral variations to represent an end-member [Blodget and Brown, 1984; McBride et al., 1986]. Higher spectral resolution will be required to address such a task with an unsupervised mixing model approach in which an automated algorithm will select appropriate end-members.

DISCUSSION

At least three major divisions delineated on composite fraction images can be correlated with empirical variations
18. High resolution lab spectra for two hand samples depicting the spectral similarities between carbonate sands and weathered granites in the test area. When degraded to the spectral resolution of the TM instrument, scatter in the carbonate component overlaps with the granite end-member.

19. High resolution lab spectra for two hand samples depicting the spectral differences between basalts from two different flows.

in mixture composition, grain coating, and grain size. The sand populations delineated in the fraction images appear to occur in well-defined zones. It is proposed that the spatial distribution of these spectrally distinct sands is related to their emplacement history. The b-dimensional position of these sands occurs in the mixing polygon (Figure 3) with the "active sand" vector delineating one vertex. Sand samples from the east show a higher percentage of basaltic grains apparently derived from the Pinacate volcanic field. The majority of basaltic particles are carried into the sand sea by fluvial drainage and weather rapidly upon delivery into the aeolian environment. Such grains generally were not identifiable in samples taken at downwind distances >3 km from a transporting arroyo. Lithic grains apparently are abraded into a visually unidentifiable microcrystalline form or are taken into suspension by the atmosphere.

Western samples are predominantly associated with granitic detritus such as feldspars, quartz, biotite and hornblende. Grains derived from granitic sources are also transported into the sand sea by fluvial processes. When introduced into the salting environment, these grains travel much further than basaltic lithics and can be identified >20 km from their source.

As discussed previously the morphologic habit of sands in the Gran Desierto can be discriminated on the basis of the textural parameters. Less mature, coarser sands occur on sand sheets and zibar and become progressively finer and better sorted in sand dunes and ultimately in some crescentic dunes. A combination of textural and color variations are discriminated in the spectral data and were used to classify image-derived sand populations into three major categories:

1. Population 1 sand is rounded to well-rounded, medium to fine-grained (125-500 μm) sand with heavy iron-oxide staining (=14-wt% of coating) and heavy frostening. The visual color is light brown to reddish yellow (Munsell 7.5 YR 6/4-6/6). Dominant accessory grains are K-feldspar, epidote and hornblende. Population 1 sands are stratigraphically below other sands in the field area and form the central star dune zone as well as the sand sea margins along the northern alluvial fan boundaries. Evidence for the relative age of these sands includes extensive iron-oxide staining and field observations of recent sediments mantling the surface of population 1 sands. The origin of Population 1 sands is uncertain.

2. Population 2 sand is subangular to rounded, fine to very fine (62.5-250 μm) sand with moderate iron-oxide staining (=8-12%) and very light frostening. The visual color is light yellowish brown (Munsell 7.5 YR 6/4). Dominant accessory grains are granitic fragments of hornblende, plagioclase feldspar and biotite plus zircon. Based on the field relationship of this sand veneering population 1 sands, population 2 is interpreted to be of intermediate age and may represent a mixture of former Colorado River suspension load and locally derived granitic grains. Population 2 sands are concentrated along the northern star dune zone and as a diffuse surficial layer overlying population 1 sands. This unit also forms prominent sand streaks entering the western and northeastern sand sea.

3. Population 3 sand is angular to subrounded, fine to very fine (62.5-250 μm) sand with no iron-oxide staining and light to moderate frosting. The visual color is pinkish grey to very pale brown (Munsell 7.5 YR 7/2-7/4). Dominant accessory grains are carbonate, gypsum, basalt, zircon, and garnet. They are interpreted as marine sands from the Gulf of California on the basis of accessory grain trends such as mixing with local beach materials and they are likely the youngest sands present. Population 3 sand is located in the eastern sand sea from the central sand sheet eastward to the crescentic dune zone.

Transport paths and source areas. A knowledge of the spatial and chronological history of sand delivery can be used to generate relative stratigraphies and geologic interpretations of an aeolian terrain. The close agreement between empirical field studies and the fractional trends generated by the mixing model allows an interpretation of the dynamic processes which have been and are responsible for generating the largest sand sea in North America.

Transport of locally derived sediments can be observed in fraction images by viewing specific DN ranges from the fraction image histogram. By viewing only those DN values which represent 10% of the total fraction (255 * 10% = 25 DN), and scaling through the range from 0 to 100% on the histogram. This visualization technique is analogous to viewing a motion picture film one frame at a time with each new frame showing the spatial distribution of a different fraction bin. This view of the spatial distribution of compositional variations can help establish the nature and magnitude of relationships between source areas and deposition sites. When active sand fractions were viewed in this manner, several trends became obvious: (1) Population 1 sands are concentrated in a topographic low of the central sand sea in direct contact with the gravel base and without a dominant transportation vector leading to the deposition site; (2) population 2 sands can be traced to the south onto the Mesa Arenosa, to the north onto alluvial fans of granitic mountain ranges, and to the northwest towards Yuma, Arizona; and (3) population 3 sands are traced southward to the Gulf of California.

These observations allow the population 2 and 3 sands to be interpreted in terms of sands mixing with local sources;
however, the apparent lack of a definite transport pathway for Population 1 sands requires a more thorough understanding of the geologic events responsible for shaping the Gran Desierto. Although the current dynamic state of the Gran Desierto is just beginning to be understood, it appears that large-scale introduction of new sediments from local source areas (sources in contact with the sand sea) is relatively minor at present [Blount et al., 1987]. Grain migration into the sand sea appears to be occurring via active sand streaks in the south and northwest. Based on the regional discrimination of active/inactive sand distributions, it is estimated that approximately 70% of the exposed sand surfaces in the Gran Desierto are, or have recently been, active. Active sand surfaces are found on both star and crescentic dune forms and on sand sheets supporting contemporary sand transport. The remaining 30% of the sand-covered area is taken up by inactive sand, mostly found in interdune areas, on stabilized sand sheets, and in longitudinal and some coppice dunes.

The conspicuous variations in dune morphology, orientation, and sand composition as a function of location within the sand sea indicate that several aeolian regimes of different ages have existed in the Gran Desierto [Lancaster, 1988]. Field evidence of relict aeolian activity includes stabilized longitudinal dunes in the northeast and relict transverse dune sets at ~15° angles to one another on the northwest side of the Sierra del Rosario. Stabilized sand ramps occur in the Sierra del Rosario, where arrested south directed migration is indicated; farther east, the orientation of stabilized sand ramps indicates north directed migration.

Active longitudinal sand streaks serve as transport paths between the coast and the sand sea. The southernmost active portions of the transverse dune field contain abundant marine sands although the percentage of carbonate shell fragments and gypsum grains is winnowed to 10% or less during overland transport. Surviving quartz sand becomes lightly frosted in the process and arrives as a very fine to fine (=62-250 μm) fraction.

A group of active sand streaks emanating from the area of the Colorado River appear to be a pathway for sediments migrating into the northwestern portion of the Gran Desierto. Trailing (upwind) edges of these streaks are often characterized by lag deposits of coarse sand resting on the gravel surfaces discussed previously.

Although population 1 sands have active surfaces, active transport paths are restricted to population 2 and 3 sands. Population 1 sands occur in association with an inactive "pit and hollow" terrain which appears to represent a relict dune population. The western star dunes and northern marginal dunes generated from population 1 sands are thus interpreted to be formed from the sand deposited under a previous aeolian regime.

Sources. Locally derived sands can be observed entering the Gran Desierto today. Figure 20 depicts the distribution of population 1, 2, and 3 sands with arrows indicating directions of contemporary sand transport observed in the field. The transport pathways between source area and deposition site can be documented on the ground as well as in the fraction images discussed previously. Gravitic grus from block-faulted mountains within and adjacent to the Gran Desierto is the easiest material to trace over long distances as it weatheres and abrades more rapidly. Most of the detritus occurs almost exclusively as a surficial monolayer. Based on the distribution delineated in the active sand fraction image, this sediment is estimated to account for only about 0.1 km³ in volume, <0.01% of the sand sea total.

The same process of transportation and abrasion can be observed on a more limited spatial scale with basalt grains from the Pinacate volcanic complex (estimated volume = 0.01 km³), based on the point count distribution of

20. Distribution of sand populations identified by the mixing approach and confirmed by granulometric analysis of >180 hand samples within the Gran Desierto.
labradorite and basalt grains). Much of this sand, particularly basalt grains, is likely destroyed and does not accumulate except on inactive sand surfaces. On an even smaller volumetric scale, relict aeolian sands are scoured from interdune pits in the eastern star dune area. Indurated sand samples from one site were disaggregated for analysis and proved to be identical in texture, color and mineralogy to population 1 sands.

Combined, the locally derived sand volume currently present in the Gran Desierto is <0.3 km³ (well under 1% of the total sand volume). A generous estimate of their volume still shows that these local sources are little more than overprints on the main mass of sand in the Gran Desierto.

The empirical fact that the Gran Desierto is dominantly quartz sand with less than 5% locally derived grains argues against a uniformitarian interpretation of local sand sources, although the =1% value could represent an equilibrium between the introduction and destruction of local sands. Indeed, because several of the local sources (the Pinacate volcanics and the shoreline) have only come into their current spatial positions since mid- and late-Pleistocene time, a more realistic estimate of their annual contribution is of the order of 2000 m³ annually to generate 0.3 km³ of sand in =146,000 years. This value would date the sand sea to at least Oligocene age (=36,000,000 years) if local materials were the sole sources of sand, again too long to fit within the aforementioned age constraints.

These same arguments were applied to the sediment volumes present in population 1 sand. The ~32 km³ of material involved, if moved at a rate of 12 m³/m²/yr, over a 60-km threshold width from the northwest, would require only 45,000 years to be transported overland from any western or northern source. Population 2 sands with an estimated volume of ~26 km³ would require ~36,000 years to migrate into the sand sea from the north and west. If population 2 sands are indeed older than Population 1 sands, it may be inferred that the later were being emplaced >80,000 years ago.

Most of the detrital load of the Colorado River has been dumped into the Gulf of California where reworked neritic sands are available as a population 3 component. Indeed, van Andel [1964] estimates that >43% of sediments delivered into the gulf have originated from the Colorado River. The extreme tidal range (~8-10 m) of the fluvial/marine interface causes most of these sediments to be carried downslope and distributed across the seafloor where a wedge of sand, silt, and clay associated with the Colorado has been identified in piston cores from the Tiburon Basin 400 km to the south [van Andel, 1964].

The thickest accumulation of these sands is immediately offshore [van Andel, 1964; Thompson, 1968] and adjacent to the Gran Desierto. A large quantity of formerly fluvial, now neritic, sand lies on the "shelf" between the current coastline and the Wisconsin shoreline some 45 km offshore. This material has been mixed with reworked shell fragments to form the main detrital supply for the "shell dunes" described by Ives [1959] for the coastal areas between Bahia Adair and Puerto Penasco.

The Quaternary history of sea level variations along this coast is such that these sands have alternated between a subaerial and subaqueous environment several times in the past. The greatest quantities of these marine sands, an estimated 7 km³, are situated on the central sand sheet, a region roughly bounded within the +50-m contour and encompassing 900 km² which separates the western star dunes from the eastern crescentic dunes.

The northward migration of crescentic dunes containing marine sands suggests that the coastal source is only significant where elevation gradients are low. Like the population 2 sands to the northwest, the population 3 marine sands have covered much of the preexisting population 1 surface and led to extensive mixing of the two sands types.

The trailing edge of these sands is quite uniform at a distance of approximately 10 km from the coastline. If this trailing edge is interpreted as a truncation of the neritic sand supply at the beginning of the Holocene, then a migration rate of =1 m/yr is implied over a 65-km width. Applying the same sand transport estimates used for other sands in the Gran Desierto, it can be shown that the marine source must have been supplying ~100,000 m³ annually for ~90,000 years to generate the observed sand volumes in the area. This value falls within the time span for aeolian activity in the western Gran Desierto.

It has been proposed [Blount and Lancaster, 1990] that during late Pleistocene time, the Colorado River channel lay within the Gran Desierto as a highly competent stream flowing through the area which is occupied today by the western star dune zone. The seashore at this time was at least 45 km south of its present-day location. Primary bedloads of poorly sorted fluvial gravel were deposited from Yuma, Arizona to an area south of the Sierra del Rosario. As rifting of the Gulf of California progressed to the northwest, and uplift of the Mesa Arrenosa began, the river channel shifted westward, leaving primary bedload deposits in the former channel. Seasonal overland floods during the westward transition spread gravels and sands across the western Gran Desierto in a manner analogous to that reported by Sykes [1937] prior to final abandonment of the Gran Desierto channel. It is proposed that population 1 sands, which lack any evidence of a dominant transport pathway were abandoned on the Sonora Mesa by the migration of the river channel. Aeolian processes became dominant after this time and reworked the relict fluvial sands into the massive star dunes of the western Gran Desierto.

Population 2 sands represent overland aeolian transport of medium to fine fluvial sands which were removed from the Colorado River at the gradient break near Yuma, Arizona, after the migration of the main channel to the west. These sands form the prominent active corridors saltating overland from the north and west between Yuma, Arizona, and San Luis, Sonora, in the present day.

Population 3 sands were derived from the Gulf of California beginning during the last low stand of sea level and terminating as a major source in the early Holocene. Sand transport rates and volumes are consistent with a very recent (<90,000 years ago) origin for crescentic dunes in the eastern Gran Desierto. Sands for these dunes were repeatedly submerged and exhumed by Pleistocene sea level variations before becoming permanently subaerial at the beginning of the Holocene and beginning a northward migration driven by onshore winds.

CONCLUSIONS

The ability to determine sand source areas and transportation paths is important for addressing questions about desertification and establishing evidence for changes in climate. The geologic record makes it clear that the Earth has undergone many episodes in which aeolian processes were major factors in shaping some parts of the Earth's surface. The mixing approach demonstrated in this study was successful in establishing the relation between local bedrock geology and surficial sediments. The Gran Desierto test site also provided an example of the interplay between long-term tectonic and relatively shorter-term fluvial/aeolian processes in determining the geologic history of a study area. Although aeolian terrains are common on Mars [McCaulay et
al., 1972; Breed et al., 1979a; Tsao et al., 1979; Ward et al., 1985], considerable controversy has arisen regarding the current activity and recent geologic history of Martian sand seas. Recent attempts [Adams et al., 1987; Arvidson et al., 1987] to determine the distribution of surficial materials on Mars have been hampered by the paucity of spectral data available from the Viking lander and orbiter, respectively, as well as the relatively low spatial resolution of the orbital cameras. Recent evidence [Breed et al., 1987; Guinness and Arvidson, 1988; Christensen, 1988] suggests that Martian surface dust and sand may be uncorrelated with local bedrock geology. It is important therefore that the techniques explored in this study be expanded upon before attempting to determine the surficial geology of Mars, as manifested in aeolian terrains. Data from the anticipated Mars Observer mission, including the Thermal Emission Spectrometer (TES), may allow linear mixing techniques to be applied with a much higher degree of spectral resolution than in the current terrestrial example. Such increased spectral resolution carries the potential for misinterpretation however, if the normal spectral variance of aeolian sands is not taken into account.

Thematic mapper data, although of coarse spectral resolution, delineates distinct sand populations based on variations in grain composition and surface coating. Monochromatic VNIR data can be employed to discriminate active from inactive sand surfaces. The discrimination capability relates directly to the distribution of low-albedo grains as a function of grain size in the two surface types. The problems associated with modeling low-albedo end-members, which have been also been reported by other workers, can be substantially solved by including a thermal band, such as TM band 6, in the mixing model, and generating second-order fractions based on differences between the shade end-member and thermal emission.

The linear mixing approach can be used to predict the fraction of each geologic end-member present in mixed pixels as well as to delineate spectrally distinct sand populations. The accuracy of quantitative compositional mapping from remote sensing data is controlled by the normal variance of the geologic targets being investigated. Spatial variations in the concentration of an end-member can be exploited to successfully map the migration of sediments from source units into an aeolian environment without an a priori knowledge of the geologic units present.

Acknowledgment. This work was supported by the National Aeronautics and Space Administration through the Office of Planetary Geosciences.

REFERENCES


