5 SAND TRANSPORT PATHS IN THE MOJAVE DESERT, SOUTHWESTERN UNITED STATES

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ABSTRACT

Remote sensing and field evidence are used to describe sand deposits found in associated pathways of emplacement in the eastern Mojave Desert. Two separate pathways are identified here: one extending eastward from the Bristol Playa through the Cadiz and Danby Playas and Rice Valley to the Colorado River, and a second parallel path extending eastward from Dale Playa through the Palen and Ford Playas to the Mule Mountains near the Colorado River. The preferential location of sand ramps on the west slopes of mountains along each path suggests that the eastward moving, wind-driven sand was not confined by topographic divides between separate drainage basins around the individual playas and valleys. Sediment analysis of selected samples shows that there are discreet associations of sand characteristics along the sand pathways, with an inferred similarity between the stabilized (vegetated) sands in Rice Valley, west of the Colorado River, and stabilized sand dunes on Cactus Plain and La Posa Plain in Arizona, east of the Colorado River. Sand transport along the paths appears to have been episodic, based on multiple paleosols present in several dissected sand ramps. Future testing of the sand transport path hypothesis will require additional sediment analyses, spectral studies of remote sensing data, and obtaining dates for selected soil horizons along the sand paths.

INTRODUCTION

Wind has long been recognized as a powerful agent for sediment transport in arid environments. Sand transport in the hyper-arid Sahara Desert in northern Africa can be traced for thousands of kilometers, providing physical evidence of the wind patterns prevalent throughout the region (Wilson 1971, El-Baz et al. 1979, El-Baz and Maxwell 1982). However, significant aeolian transport is not restricted to hyper-arid deserts. Semi-arid regions also can preserve evidence of substantial deposits of aeolian sand, but many of these deposits may be stabilized at present by a variety of desert flora adapted to the intermittent rainfall.

The advent of airborne and satellite-based remote sensing data allow both the surface materials and their associated flora to be examined in a regional context. In particular, spacecraft images have been used to identify aeolian deposits throughout the Earth (Breed and Grow 1979), as well as on Mars (Sagan et al. 1972, Greeley and Iversen 1985) and Venus (Greeley et al. 1992).

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Conclusions derived from remote sensing data must be corroborated by "ground truth" investigations at key localities. The present study combines preliminary field observations with satellite remote sensing data to document aeolian deposits along hypothesized sand transport pathways in the eastern Mojave Desert of California. While a considerable amount of field work remains to be carried out, our intent here is to describe the primary features which suggest that an association exists between various sand deposits. Integrated pathways of sand transport would imply that aeolian processes have regional significance well beyond the confines of individual drainage basins. The time scale of this aeolian activity is not well constrained at present, but exposures described here suggest that the dissected sand ramps in the eastern Mojave Desert contain climatic information which predates the Holocene activity evidenced by the present isolated accumulations of active dunes.

BACKGROUND

The Mojave Desert is located in southern California at the southern end of the Basin and Range physiographic province. It is an important field geology study area because it contains numerous, accessible, well-exposed examples of a variety of geologic features (Dohrenwend 1987). The Garlock and San Andreas faults define sharp boundaries to the western margin of the Mojave Desert, while the eastern boundary with the arid region surrounding the Colorado River is more gradational. The sand transport paths described in this study lie in the eastern part of the Mojave Desert, possibly including sand deposits east of the Colorado River (Figure 1). A synopsis of the geology of the study region can be found in Jahns (1954) and in Bassett and Kupfer (1964).

Aeolian activity has formed sand sheets at several locations in the Mojave Desert. Sand ramps over 100 m thick occur in places where topography has impeded local sand migration (H.T.U. Smith 1967, R.S.U. Smith 1982). These sand ramp deposits include soil layers and other features that contain paleoclimatic information (Tchakerian 1991). The deposition of each layer presumably followed the desiccation of pluvial lakes lying upwind, with soil formation occurring between pulses of aeolian activity (Smith 1982, McFadden et al. 1987, Wells et al. 1987, Chadwick and Davis 1990, Tchakerian 1991). Some sand ramps are so large that they surmount the windward side of the topographic obstacle responsible for their formation. This study presents a hypothesis of regional aeolian transport that provides a unifying framework in which to interpret the results obtained from widely distributed sand ramps in the Mojave region.

A synoptic view of the Mojave Desert is best obtained from remote sensing data. Several recent remote sensing and field studies have focused on aeolian processes in the Mojave region (e.g., Blount et al. 1990, Paisley et al. 1991, Lancaster et al. 1992, Laity 1987, 1992, Zimbelman and Williams, in preparation). These efforts revealed that active sand can be distinguished from sand

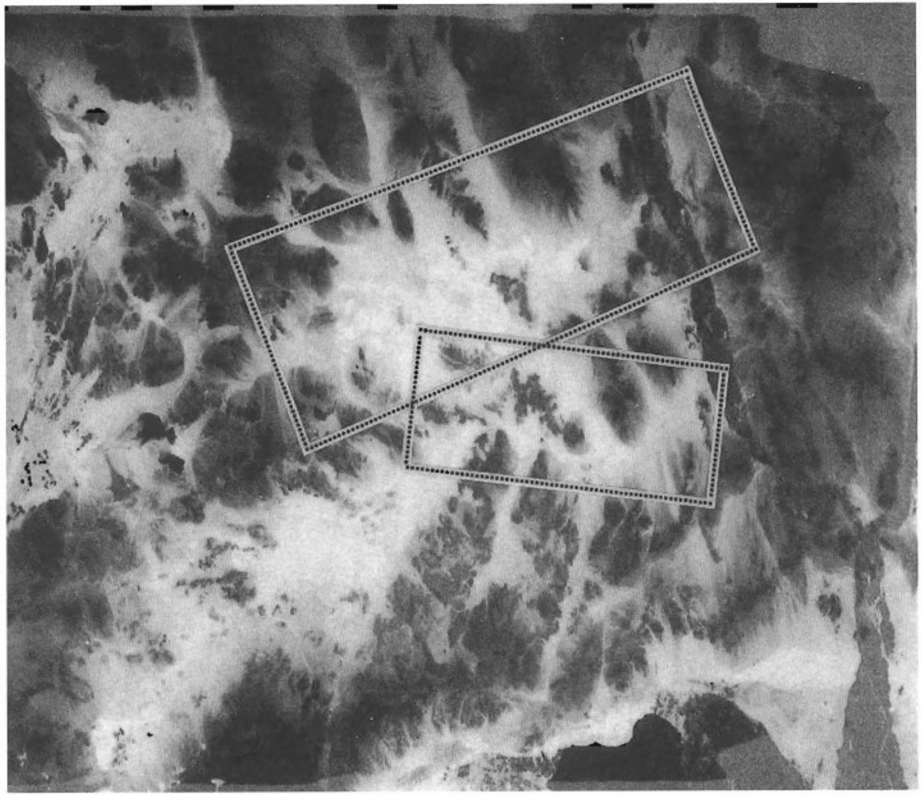

Figure 1. (a) Oblique view of the eastern Mojave Desert, taken with the Linhof camera on board the Space Shuttle. This view shows the Mojave Desert area from the outwash plains of the Mojave River (near Barstow, California) at left, to the agricultural fields along the Colorado River at right. The line of sight is nearly coincident with the paths of sand transport described in the text. Dotted lines show the locations of Figures 2 (top) and 7 (bottom). See Figure 1b for selected feature names near the pathways. Portion of frame 51B-146-111, obtained during Shuttle flight STS 51B, between April 26 and May 6, 1985.

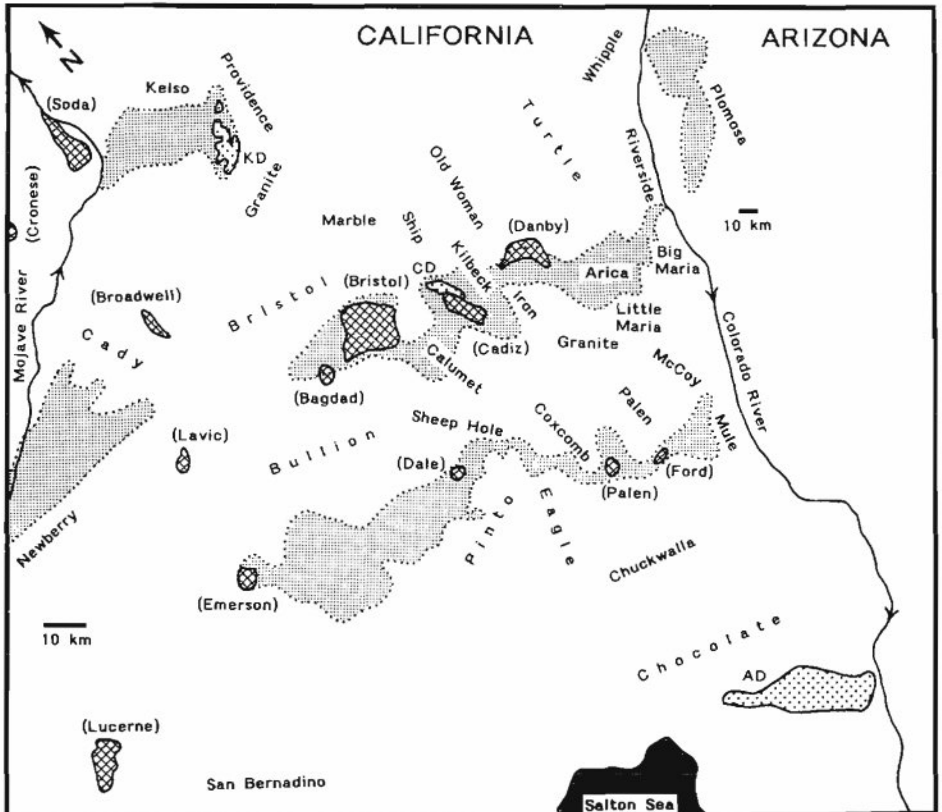

Figure 1. (b) Simplified sketch map of the area shown in Figure 1a. Selected playas (gridded pattern, names in parentheses), mountains (names listed at appropriate location), and rivers (arrows show direction of flow) are labeled for reference. Sand deposits are shown in dotted patterns; the open pattern represents active (relatively unvegetated) dunes (KD = Kelso Dunes, CD = Cadiz Dunes, AD = Algodones Dunes) and the dense pattern represents inactive (stabilized by vegetation) deposits. Note that foreshortening due to the oblique viewing geometry causes horizontal scale variations across the area.

stabilized by vegetation through subtle but consistent differences in reflectance properties between the Landsat Thematic Mapper spectral bands. Similar spectral differences exist in the Landsat data used in the present study, although the differing plant populations appear to play a significant role in the reflectance properties of aeolian deposits in the Mojave region (Zimbelman and Williams, in preparation). Consequently, seasonal variations may prove to be critical to the spectral response of certain Mojave sand deposits. These relationships are still under active investigation, so the results presented here will be based primarily on morphology as observed in a single spectral band.

SAND TRANSPORT PATHS

Three principal locations of aeolian deposits in the eastern Mojave Desert are described here: the Bristol Trough (which includes the Bristol, Cadiz, and Danby playas), Clark's Pass (which includes the Dale, Palen, and Ford playas), and the Cactus and La Posa Plains in Arizona (Figure 1). Both the active and stabilized (vegetated to the point of nonmobility) sand deposits observed at these locations are hypothesized here to be part of regional sand transportation paths which cross the Mojave Desert southeast to the Colorado River, and possibly beyond the river. These locations are all south and east of the Kelso Dunes (Figure 1), the most prominent and intensively studied dune field in the Mojave Desert (Sharp 1966, 1978, Paisley et al. 1991, Lancaster et al. 1992, Lancaster 1993). The sand in the Kelso Dunes originated in broad outwash plains associated with the Mojave River, was transported to the southeast by the prevailing winds, and collected at the base of the >1800-m Providence and Granite Mountains, which formed an insurmountable barrier to the windblown sediments (Sharp 1978). The sands associated with the Bristol Trough and Clark's Pass also are oriented along the prevailing northwest-to-southeast wind direction (Greeley and Iversen 1985), but these sand deposits have traversed several distinct drainage basins on their way to the Colorado River. Sand from the Bristol Trough may have even contributed to a third major sand deposit, a field of stabilized dunes on the Cactus Plain and La Posa Plain east of the Colorado River. Each of the three sand localities is described in greater detail in the following sections.

Bristol Trough

The most prominent association of sand deposits begins at the Bristol Playa near the head of a broad topographic low called the Bristol Trough (Thompson 1929). Sand occurs continuously over a distance of almost 150 km, eventually terminating at the Colorado River (Figure 2). The sand deposits concentrate around three large playas (Bristol, Cadiz, and Danby), and consist of both active dunes and vegetation-stabilized sand sheets and linear dunes (Figure 2). The relation of the sand deposits to the mountains they traverse indicates that the sand movement was toward the east-southeast, with prominent sand ramps present on the west side of several mountain ranges along the pathway.

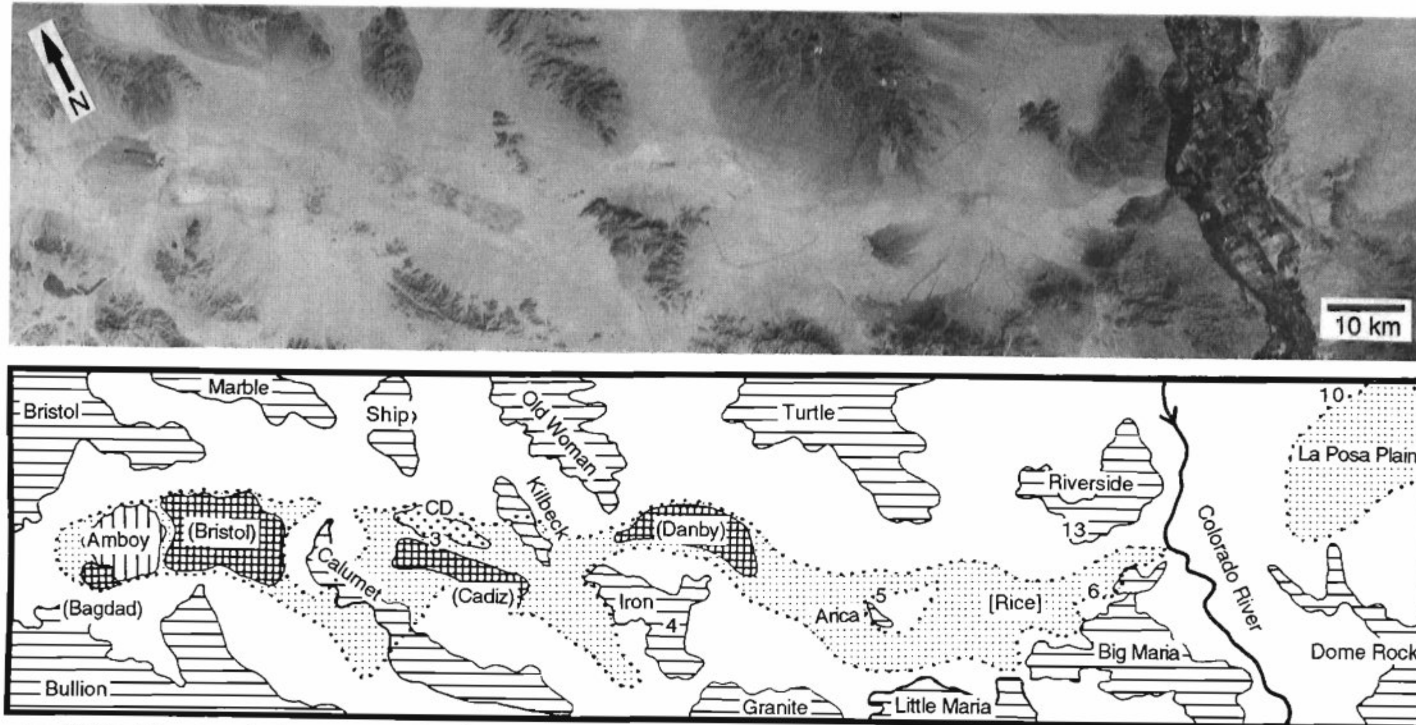

Figure 2. Bristol Trough sand path, seen on a portion of a Large Format Camera photograph, frame 2063, taken during the STS 41-G Space Shuttle flight between October 5 and 13, 1984. The sketch map below the photograph labels mountains (horizontal lined pattern), playas (gridded pattern), and sand deposits (dotted pattern). The active Cadiz Dunes (CD) are shown in a large dotted pattern. Rice Valley is identified by the name within square brackets. The Amboy lava flow (vertical lined pattern) is a Holocene basaltic eruption that covered the western portion of Bristol Playa. Numbers indicate the approximate centers of the orbital views shown in the corresponding figures.

Sand accumulations first become discernible west of the Bristol Playa, in the broad valley between the Bristol and Bullion Mountains (Figure 2). The Holocene basalt flow associated with the Amboy cinder cone covered the western portion of the Bristol Playa, leaving the small Bagdad Playa west of the Amboy flow as a remnant of the ancestral Bristol Playa (Bassett and Kupfer 1964). Sand derived from Bristol Mountains alluvium traverses the Amboy lava flow from WNW to ESE (Greeley and Iversen 1985), consistent with the annual wind flow in the region during the Holocene (Laity 1992). A prominent low-albedo wind streak is present downwind from the Amboy cinder cone (Figure 2). Sand transport across the flow is obstructed by the cinder cone, and enhanced turbulent wind scour in the lee of the cone aids in inhibiting sand migration into the wind streak (Greeley and Iversen 1978, 1985). There is no evidence, either in remote sensing data or on the ground, that sand from the Mojave River has traversed the Cady Mountains to enter the Bristol Playa basin from the west (Figure 1); the Bristol area is interpreted here to represent the beginning of the aeolian sand deposits that extend east to the Colorado River (Figure 2).

Sand is abundant southeast of the Bristol Playa, where it has built large ramps against the western slopes of the Calumet Mountains (Figure 2). The sand ramps provide shallow slopes for saltating sand to climb the western flanks of the mountains, as well as shallow slopes along which the sand moves

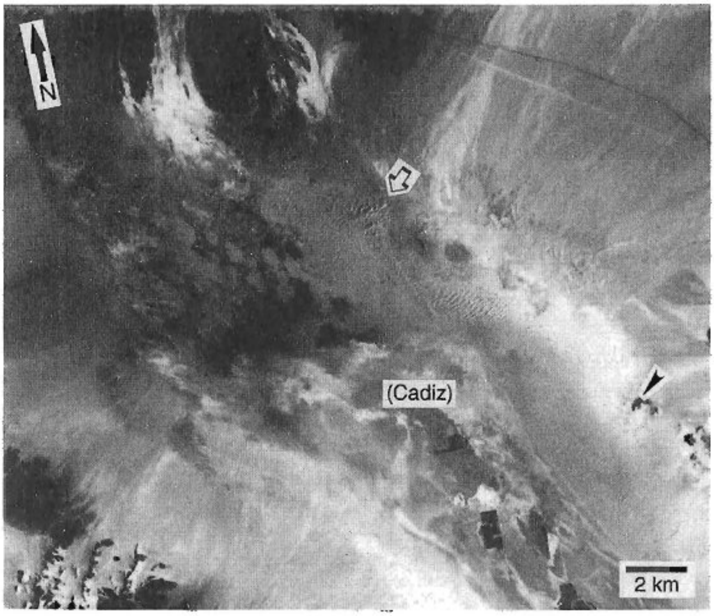

Figure 3. (a) Portion of a Landsat Thematic Mapper image showing the northern end of Cadiz Playa and the Cadiz Dunes north of the playa. The largest dunes (open arrow) have 30 m of relief. Transverse dunes are present along the northern margin of the playa; the dark arrow shows the location and orientation of Figure 3b. Landsat TM band 5, obtained on September 26, 1986.

Table 1
Mean values of grain size, sorting, and percent silt and clay for selected samples from the Mojave Desert, California

Aeolian unit	Mean (ϕ)	Standard deviation	Skewness	Kurtosis	% silt and clay
Dale Lake					
Unit 1	2.24	0.83	0.10	1.17	2.90
Unit 2	1.91	0.91	0.14	1.15	3.10
Unit 3	2.15	0.85	0.08	1.10	3.25
Unit 4	1.70	1.21	0.05	1.05	1.25
Unit 5	2.23	0.78	-.07	0.93	2.40
Calumet Mtns	2.91	0.97	0.22	1.29	4.83
Cadiz Dunes	2.35	0.29	-.03	0.89	
Iron Mtns	2.45	0.88	0.15	1.10	7.20
Rice Valley	2.95	0.75	0.20	1.25	6.25
Cactus Plain	2.87	0.87	0.25	1.35	5.98

down the eastern flanks of the mountains. Neither climbing nor falling dunes are observed on the Calumets, but Landsat spectral data indicates that stabilized sand dominates a 10-km-long reach of the central portion of the mountains, where sand ramps were evident on the ground. Alluvial fan deposits around the northern end of the Calumets lack any prominent sand accumulations, leading to the interpretation that most sand from the Bristol area crossed the central Calumets instead of going around the northern alluvial fans.

East of the Calumet Mountains, sand deposits are concentrated around the Cadiz Playa, which is in the broad valley between the Calumet Mountains and the Kilbeck Hills (Figure 2). The sand deposits attain a considerable thickness on the northern margin of the Cadiz Playa; individual dunes display 30 m of relief and are clearly resolved in Landsat Thematic Mapper data (Figure 3a). Ground investigation showed that the dunes north of Cadiz Playa are the only substantive area of active dunes observed along the Bristol Trough path. The active sand gradually thins to the east, where transverse dunes with 1-2 m of relief become the dominant aeolian landform (Figure 3b).

Stabilized sand sheets extend eastward from the Cadiz Valley across the southern end of the Kilbeck Hills into the Danby Valley (Figure 2). Extensive sand ramps are present around the southern Kilbeck Hills, and are particularly well developed on the western slopes of the Iron Mountains (Figure 4a). Where ephemeral streams dissect the Iron Mountain sand ramps, tens of meters of sand are exposed within the channels, both in the western sand ramps (some of which have active dunes on the channel crest, Figure 4b), and in stabilized sand ramps on the northern flanks (Figure 4c).

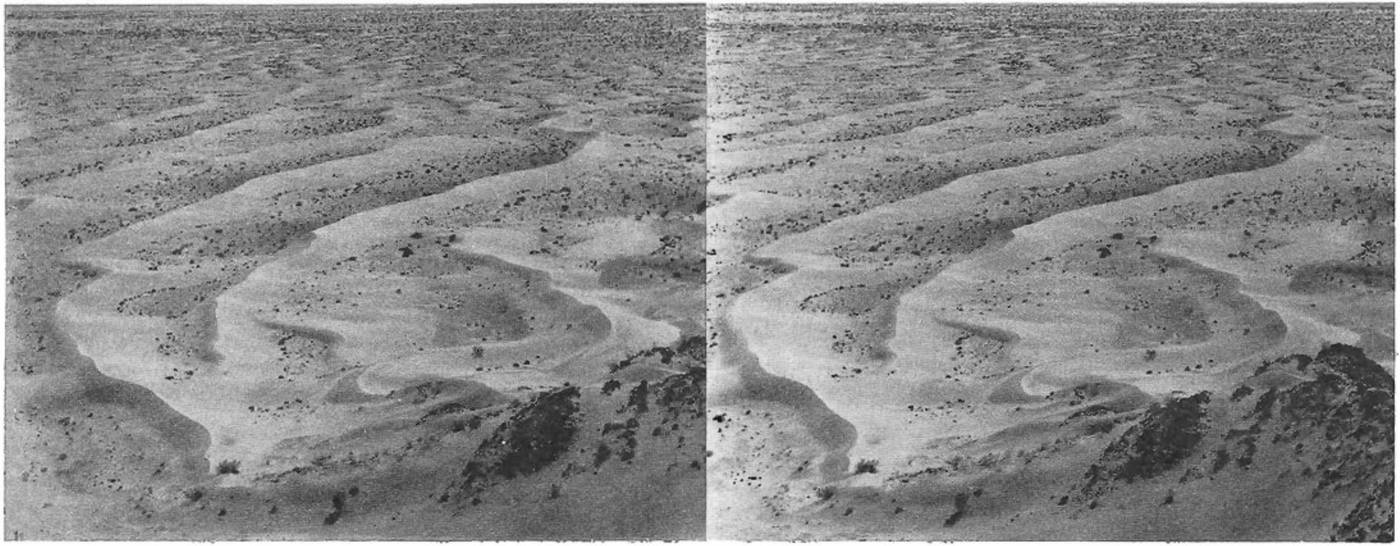

Figure 3. (b) Oblique stereo pair of transverse dunes north of the Cadiz Playa, looking southwest. Stereo view shows exaggerated topography; the dunes have 1 to 2 m of vertical relief and an average spacing of 40 m. Photographs taken on September 26, 1986, from the top of a small hill north of the playa.

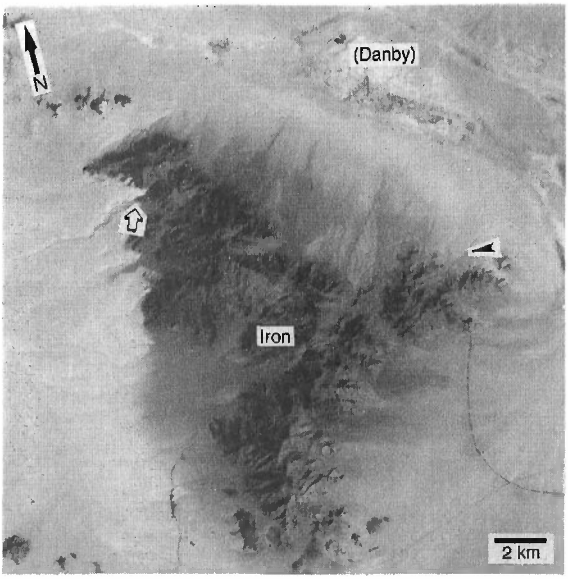

Figure 4. (a) Portion of a Landsat Thematic Mapper image showing the Iron Mountains south of Danby Playa. Prominent sand ramps are present on the western slope of the mountains; open arrow shows the location and orientation of the photograph in Figure 4b. Less active (more vegetated) sand ramp on the northern slope was sampled in 1991; the dark arrow shows location and orientation of the photograph in Figure 4c. Landsat TM band 5, obtained on September 26, 1986.

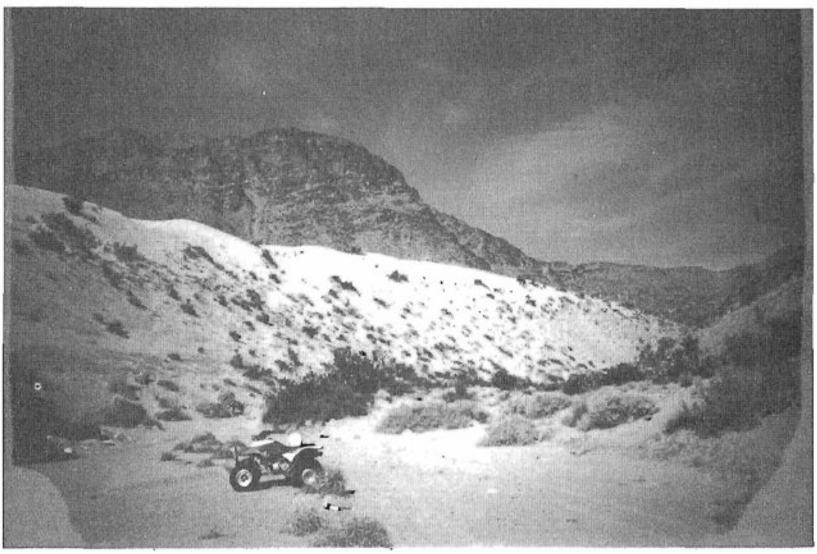

Figure 4. (b) View of entrenched sand ramp on the western slope of the Iron Mountains, taken from the channel floor. The 25-m-high channel wall has considerable vegetation cover at this locality, but the channel crests consist of active dune patches. Photograph was taken on October 9, 1993.

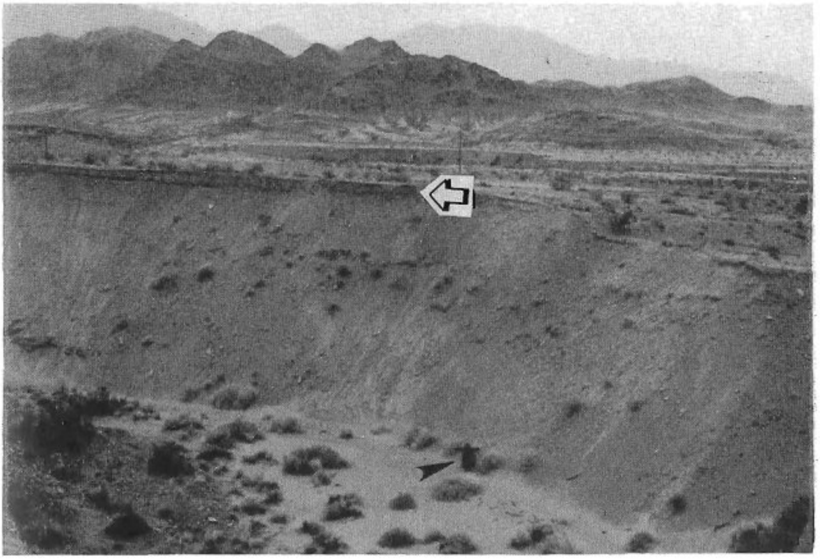

Figure 4. (c) Entrenched sand ramp on the northern slope of the Iron Mountains, with a paleosol complex (open arrow) capping the deposit. Note the outstretched arms of a 1.6 m field assistant (dark arrow) in the ephemeral wash, which exposes the sediments of the sand ramp. The top of the sand ramp is mantled with taluvium (talus and alluvium). Photograph was taken in 1992.

South of Danby Playa, the sand deposits spread to cover much of the Rice Valley with linear dunes and sand sheets, both of which are stabilized by desert vegetation (Figure 2). Sand surrounds the 500-m-high Arica Mountains (Figure 5a); a prominent sand ramp on the western slope almost reaches the top of the highest peaks, while the eastern slope is essentially sand-free (Figure 5b). Fields of stabilized linear dunes cover the southern side of the Rice Valley (Figure 6a). Sand ramps terminate at stream margins within the Big Maria Mountains, exposing up to 10 m of accumulated sand (Figure 6b). A narrow strip of sand exits the eastern end of Rice Valley, extending east to the Colorado River. Basic sedimentological characteristics of four sand deposits sampled along the pathway are listed in Table 1.

Clark's Pass

A second association of sand deposits roughly parallels the Bristol Trough path, but along a more southerly route (Figures 1 and 7). Sand ramps east of the Dale Playa at the eastern end of the Twentynine Palms Valley allowed sand to exit the valley through Clark's Pass, a narrow gap between the Sheep Hole and Pinto Mountains (Figure 8a).

The orientation of the Sheep Hole and Pinto Mountains acted like a funnel to concentrate migrating sand rather than trapping it completely, as at the Kelso Dunes. The sand ramps developed between the mountains allow wind-blown sand to climb more than 250 m from the level of Dale Playa to Clark's Pass.

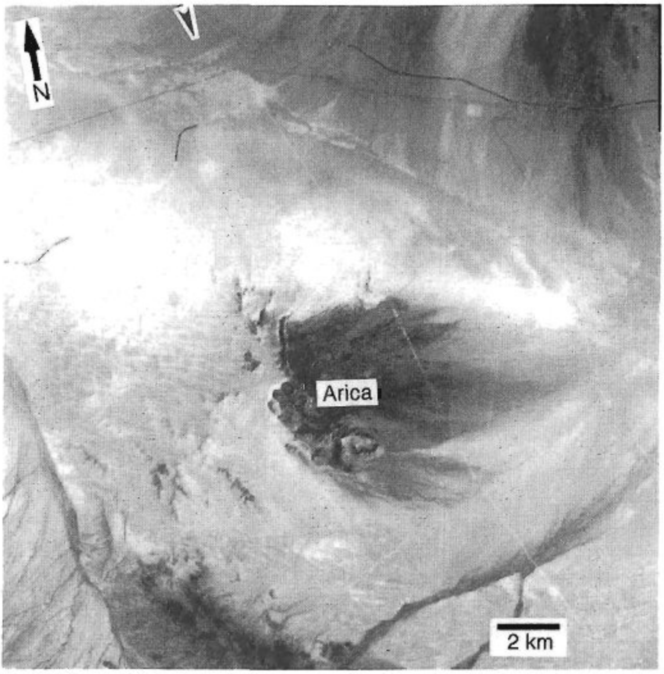

Figure 5. (a) Portion of a Landsat Thematic Mapper image showing the Arica Mountains at the west end of Rice Valley. The dark arrow at the top shows the orientation of the photograph in Figure 5b, taken from a position just off the northern edge of the image. Landsat TM band 5, obtained on September 26, 1986.

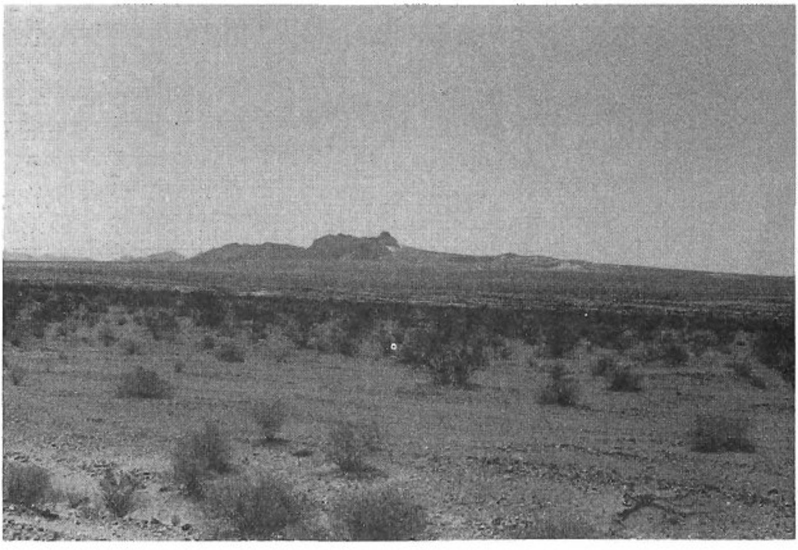

Figure 5. (b) Profile view of the Arica Mountains, looking south from a road that follows the railroad tracks north of Danby Playa. A prominent sand ramp is present on the west slope (right) while the east slope (left) is relatively sand-free, in the lee of the 500-m-high mountains. Photograph was taken in May 1991.

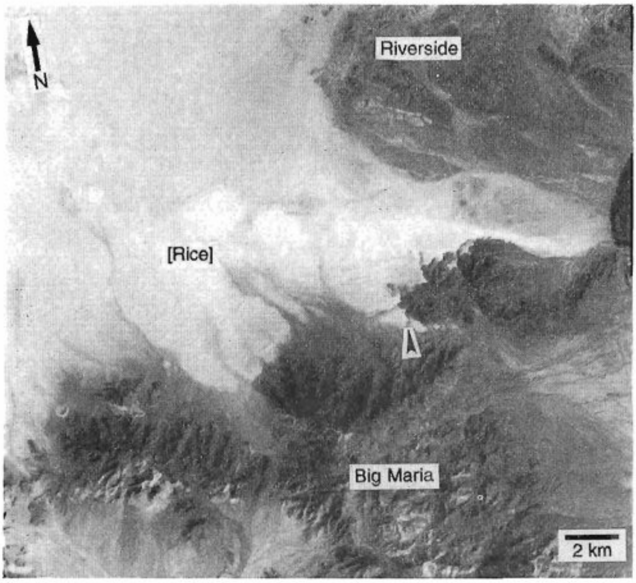

Figure 6. (a) Portion of a Landsat Thematic Mapper image showing stabilized dunes in Rice Valley. The sand deposits occur against the northern slopes of the Big Maria Mountains, and are cut by emphemeral channels from those mountains. The dark arrow shows the location and orientation of Figure 6b. Landsat TM band 5, obtained on September 26, 1986.

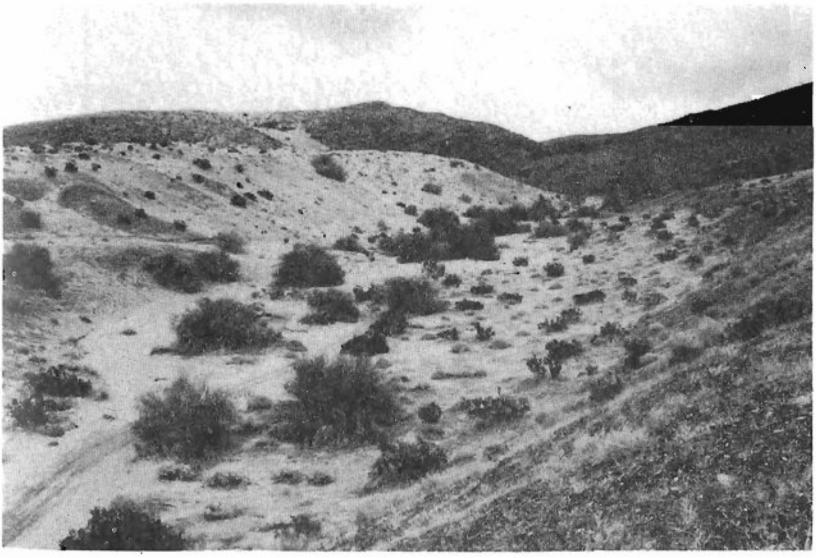

Figure 6. (b) Upper portion of the sand ramp on the northern slope of the Big Maria Mountians. The top of the section exposed by an ephemeral stream is stabilized by vegetation and taluvium, and capped by a prominent paleosol. Photograph was taken in 1991.

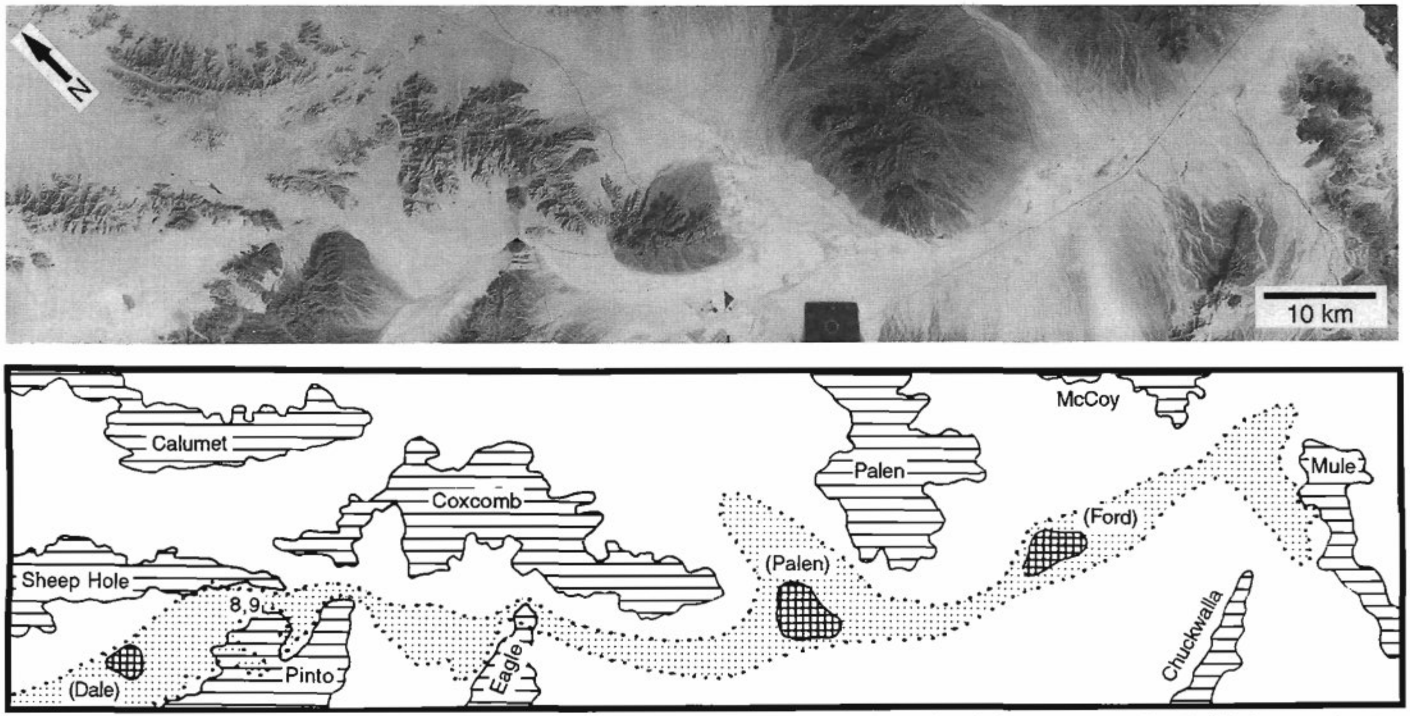

Figure 7. Clark's Pass sand path, seen on a portion of a Large Format Camera photograph, frame 2063, taken during the STS 41-G Space Shuttle flight between October 5 and 13, 1984. The sketch map below the photograph labels mountains (lined pattern), playas (gridded pattern), and sand deposits (dotted pattern).

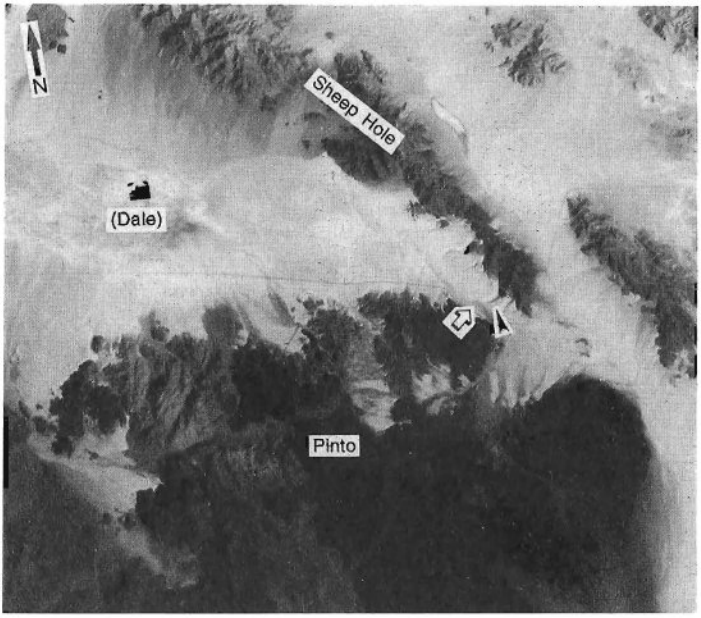

Figure 8. (a) Portion of a Landsat Thematic Mapper image showing the Clark's Pass area. Sand is ramped against the Sheep Hole (top) and Pinto (bottom) Mountains, providing an exit from the Twentynine Palms Valley, past Dale Playa, through Clark's Pass. The dark arrow shows the location and orientation of Figure 8b, and the open arrow shows the location and orientation of Figure 9a. Landsat TM band 5, obtained on September 26, 1986.

Some sand has been trapped in small valleys along the northern margin of the Pinto Mountains (Figure 8a), but the volume of sand deposits within the mountains appears to be much smaller than that of the sand ramps leading up to Clark's Pass. Ephemeral streams from the Sheep Hole Mountains cut into the sand ramps at several locations (Figure 8b), providing a cross-section through tens of meters of sand and exposing several soil horizons.

Several major stratigraphic units are identified within the Dale sand ramp (Tchakerian 1991) by the combination of geomorphic and soil-stratigraphic relations (Figure 9, Table 1). The units are predominantly aeolian in origin, with some intermixed fluvial deposits. Unit 1 contains fine to medium (Mz = 2.24 ϕ) moderately sorted ($\sigma = 0.83$) aeolian sands with grus and a silt/clay content of 2.9%. It is capped by a reddish yellow (5YR/6/6) paleosol with discontinuous carbonate nodules. Unit 2 comprises fine to medium (Mz = 1.91ϕ) poorly sorted ($\sigma = 0.91$) aeolian sands and has a silt and clay content of 3.1%. It contains numerous fluvial cut and fill lenses. The unit is capped by a prominent reddish yellow (7.5YR/6/6) paleosol with calcrete disseminated throughout the matrix, and carbonate enriched root pseudomorphs. Unit 3 consists of mostly yellowish red (5YR/5/8) medium to coarse (Mz = 2.15ϕ) moderately sorted ($\sigma = 0.85$) aeolian sands with large percentages of grus. It is capped by a poorly developed discontinuous paleosol with some calcareous

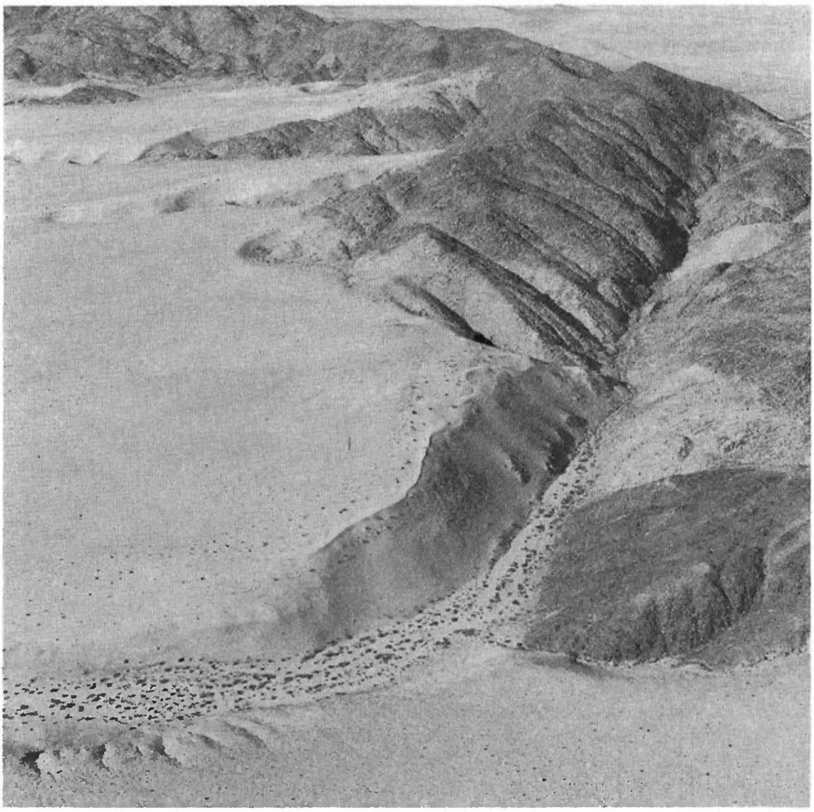

Figure 8. (b) Sand ramp on the western side of the Sheep Hole Mountains near Clark's Pass, at the east end of the Twentynine Palms Valley (Shelton et al. 1978, figure 9-21). Note the active dune along the crest of the channel. Oblique aireal photograph taken by R. Greeley.

rhizoliths. Unit 4 contains primarily fluvially redistributed dune sands, cut-and-fill structures, and coarse gravel alluvial channels. The sediments are mostly coarse sands (Mz = 1.70ϕ), and are poorly sorted (σ = 1.21).

The section is topped by weakly consolidated sand that forms the surface of the sand ramp. Unit 5 contains brownish yellow (10YR6/6) fine to medium (Mz = 2.23ϕ), moderately well sorted (σ = 0.78) aeolian sands, with a silt/clay content of 2.4%. The uppermost section of Unit 5 is obscured by loose aeolian sands. However, about 500 m to the west of this section, further aeolian depositional units have been identified which are stratigraphically equivalent to or younger than Unit 5. They consist of brownish yellow, fine to medium, moderately well sorted aeolian sands similar in composition to Unit 5. Additional units in the area are similar, with respect to grain size, sorting, percent silt/clay, and quartz grain surface micromorphologies (SEM analysis), to Unit 5, suggesting emplacement by a single aeolian episode with multiple depositional pulses (Tchakerian 1991).

After exiting through Clark's Pass, the sand traversed the northern end of the Eagle Mountains and passed the Palen and Ford Playas (Figure 7). The sand deposits around the Palen and Ford Playas are primarily in the form of broad sand sheets, with very limited development of isolated, stabilized dunes. There is no evidence at present that sand reached the Colorado River after passing the Mule Mountains (which have prominent sand ramps on their western slopes), but the lack of visible sand likely results from the extensive agricultural activity along the Colorado River in the vicinity of Blythe, California.

Cactus Plain–La Posa Plain

A third accumulation of sand deposits possibly may be related to the proposed sand transport pathways through the Mojave Desert. Large fields of stabilized linear dunes are present on the eastern bank of the Colorado River near the town of Parker, Arizona (Figure 10). These dunes are directly opposite the termination point of the Bristol Trough path at the Colorado River (Figure 1). There is no obvious source for the stabilized dunes on the Cactus Plain and the La Posa Plain (Figure 10); the adjacent mountains display typical alluvial fan development with no apparent accumulation of sand-sized materials to supply the sand to the extensive dune fields. The Colorado River could be a source for the sand, except that the Cactus Plain–La Posa Plain area is the only sand accumulation next to the river but not next to a large lake or playa (such as the Algodones Dunes near the Salton Sea; Figure 1).

The Arizona linear dunes generally have from 2 to 4 m of relief and are oriented approximately transverse to the prevailing wind direction evident within the Bristol Trough (Greeley and Iversen 1985, Laity 1992). No prominent sand ramps are evident around the dunes; the sand accumulation progressively thins leading up to the adjacent mountains. However, the silt/clay content of the Cactus Plain dunes is nearly twice as large as that of the Dale units exposed within the Clark's Pass path, but is similar to the silt/clay content of the Iron Mountain and Rice Valley sands from the eastern portion of the Bristol Trough path (Table 1). The increased silt/clay content does not appear to be pedogenic in origin; the loose sand covers the dunes but they are no longer mobile because of the desert vegetative cover. The adjacent locations and the overall similarities between the Rice Valley and Cactus Plain sands raise the possibility that the Arizona sands may be genetically related to the "apparent" termination of the Bristol Trough path at the Colorado River; this intriguing possibility is discussed in the following section.

DISCUSSION

The alignment of the Mojave sand paths is because of a combination of topography and prevailing winds. Our observations led to the hypothesis that the paths represent the aeolian part of a combined aeolian/alluvial/fluvial drainage system, as discussed below. Also described are the possibility of net sand migration across the Colorado River, and some paleoclimatic implications of the sand transport path hypothesis.

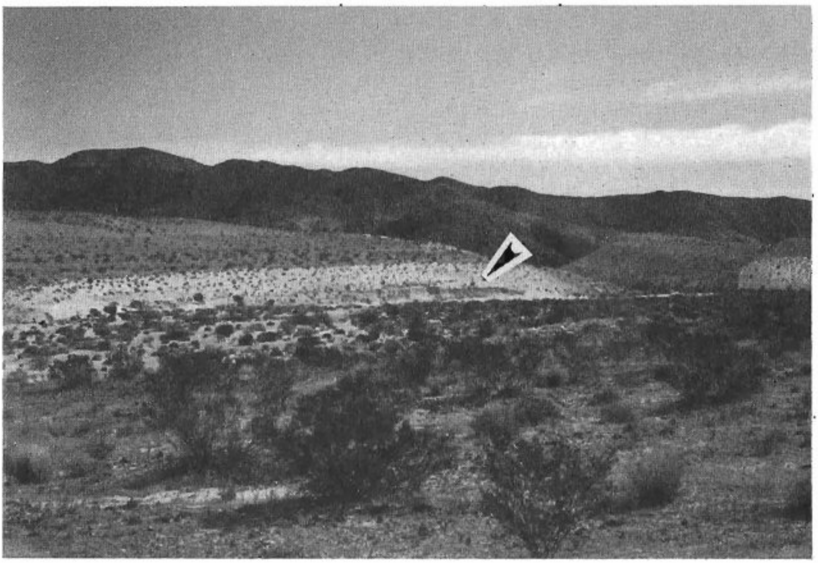

Figure 9. (a) The upper part of the Dale Lake sand ramp, with an ephemeral fluvial wash in the foreground (see also Figure 8). The Sheep Hole Mountains are in the background. The dark arrow points to the paleosols shown in Figures 9b and 9c, exposed by the streamcut in the sand ramp. Photograph taken in 1987.

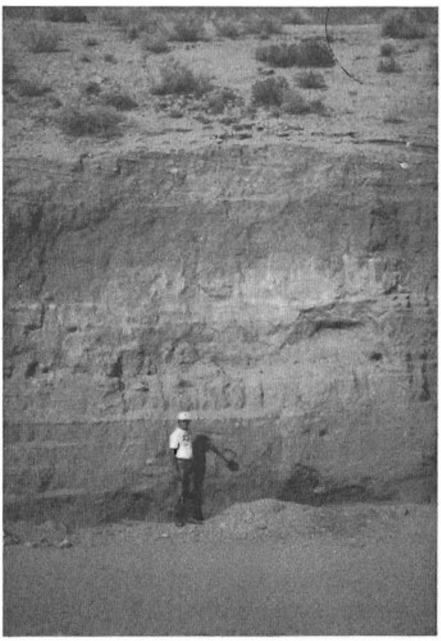

Figure 9. (b) A close up view of the middle section of the sand column exposed in the wash of the ephemeral stream described in Figure 9a. The section exposed here is about 10 m thick. Photograph taken in 1987.

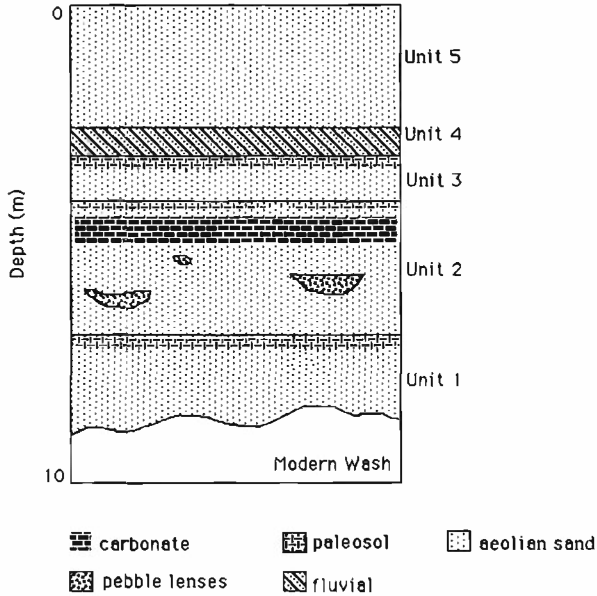

Figure 9. (c) A detailed geomorphic and soil-stratigraphic cross-section of the sand ramp exposure shown in Figure 9b.

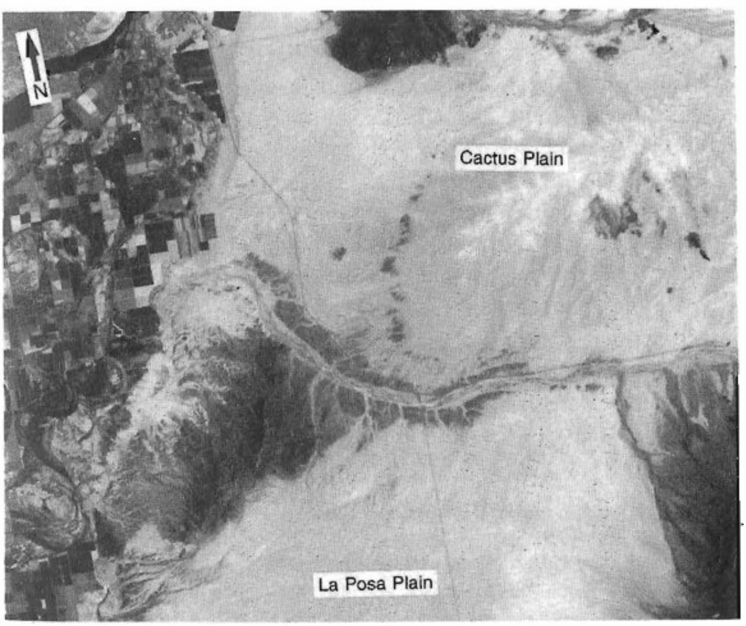

Figure 10. Portion of a Landsat Thematic Mapper image showing the stabilized dunes near Parker, Arizona. Agricultural use of the Colorado River floodplain is evident at left. The dunes are concentrated on the Cactus Plain (top) and the La Posa Plain (bottom), with no apparent source area evident in the sourrounding mountains. Landsat TM band 5, obtained on June 9, 1984.

Sand Transport Pathways As "Rivers Of Sand"

The pathways followed by the sand in transport toward the Colorado River can be compared to the path followed by a tributary stream on its way toward a higher order primary river. Both systems show sensitivity to local topography, but windblown sand is not forced always to flow down the local topographic gradient. The longitudinal profile of a river generally is concave upward, in accord with a steady downstream decrease in slope (e.g., Leopold et al. 1964, p. 248-255). In contrast to fluvial systems, aeolian sand can surmount or bypass significant topographic obstacles under favorable conditions of wind orientation and sand supply. Sand deposition on the windward side of the mountain ranges built sand ramps that facilitate continued access by saltating sand up the gentle windward slope of the ramp. Sand along the Bristol Trough path surmounts relief of up to 100 m on portions of the Calumet and Iron Mountains (Figure 11a), while the Clark's Pass path traverses 250 m of relief to provide an outlet for the sand from the Dale Playa (Figure 11b). Sufficient sand was available from the Dale Basin to build the large sand ramps that characterize the Clark's Pass path. In contrast, smaller ramps were sufficient to surmount the topography along the Bristol Trough path.

The Mojave and Colorado River systems may have been connected in earlier epochs (Blackwelder 1933, 1954, Miller 1946). Blackwelder (1954) postulated a Mojave/Colorado connection via the Bristol Trough that coincides exactly with the observed sand path (Figure 12). The hypothesized drainage connection was then disrupted by a combination of climate change, tectonic processes, and the eruption of the Pisgah volcanics. The association of the Mojave Desert sand deposits with (sometimes large) playas contributed to an assumption that the sand was locally derived, solely from the nearest paleolake. Our preliminary remote sensing analysis and field observations suggest that the present-day playas may be intermediate concentration points (at local topographic lows) for a more through-going movement of windblown sand. The tectonic trough enclosing the Bristol, Cadiz, and Danby Playas provides a preexisting trend along which the wind-blown sediments now encounter only minimum topographic obstacles, which were surmounted or bypassed through prolonged aeolian activity. In this sense, the sand transport paths might be considered "rivers of sand" that have reclaimed and actually shortened a possible drainage path from an earlier epoch. Considerable field work remains to be done to test the validity of this hypothesis, as well as much more extensive sediment analyses.

Possible Trans-Colorado River Sand Transport

Two intriguing questions are raised by the possibility of sand transport paths in the Mojave region: what is the ultimate fate of sand in transit along each path, and what is the source of the sands on the Cactus and La Posa Plains? Much of the sand entering the Colorado River is transported downstream, with much of it perhaps contributing to the Gran Desierto dune field in Mexico (Merriam 1969, Lancaster et al. 1987, Blount and Lancaster 1990). However, we

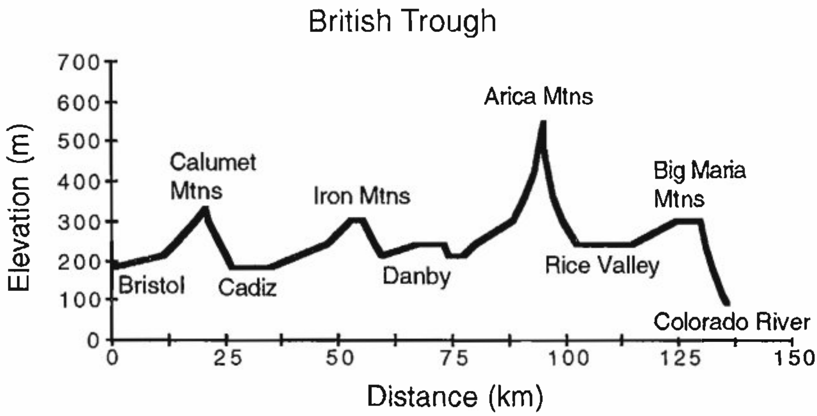

Figure 11. (a) Topographic profile along the Bristol Trough path. Vertical exaggeration is approximately 87X. The profile follows the approximate centerline of the sand path, including both active and inactive sand deposits. Mountain ranges encountered along the path are labeled above the profile; these topographic obstacles are crossed by the sand through emplacement of thick sand ramps. Playa names and Rice Valley are labeled below the profile, which ends at the Colorado River near Quien Sabe Point. Topographic data are from 1:250,000 Needles (USGS 1969a) and Salton Sea (USGS 1969b) map sheets.

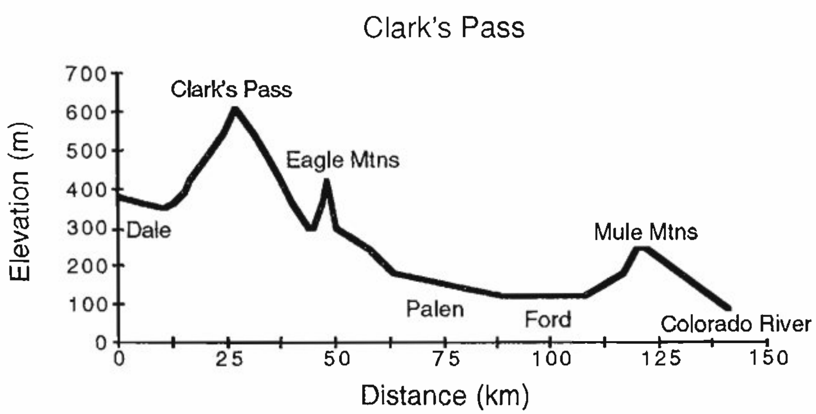

Figure 11. (b) Topographic profile along the Clark's Pass path. Vertical exaggeration is approximately 87X. The profile follows the approximate centerline of the sand path, including both active and inactive sand deposits. Mountain ranges encountered along the path are labeled above the profile; these topographic obstacles are crossed by the sand through emplacement of thick sand ramps. Playa names are labeled below the profile, which ends at the Colorado River near Blythe, California. Topographic data are from 1:250,000 Needles (USGS 1969a) and Salton Sea (USGS 1969b) map sheets.

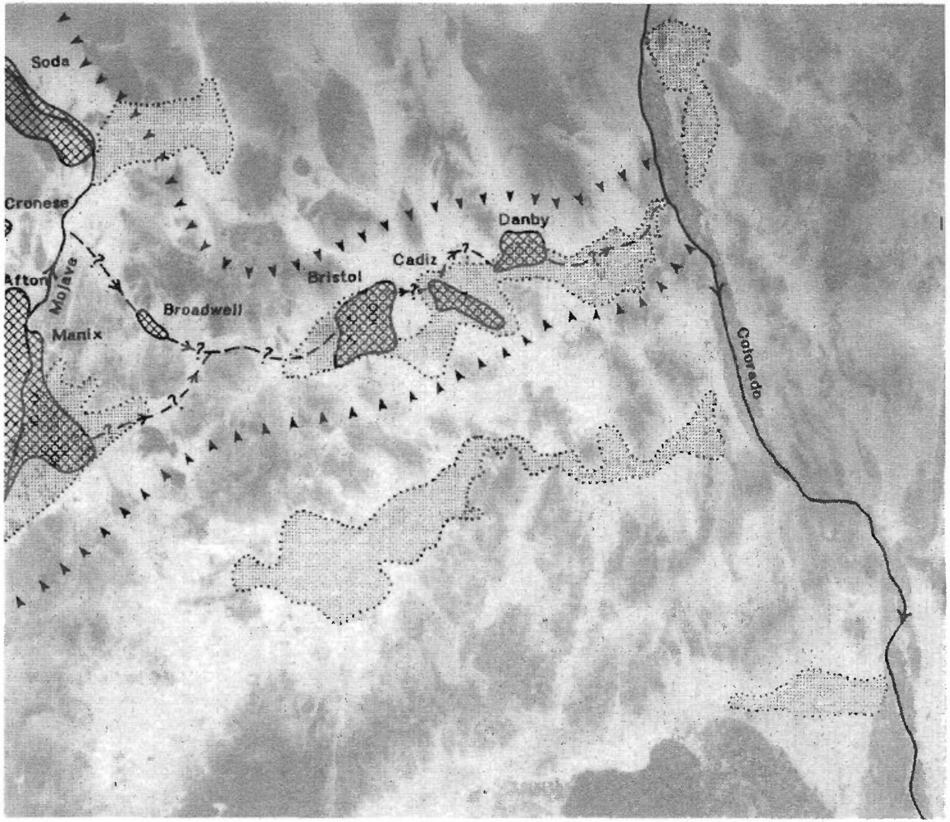

Figure 12. The paleodrainage reconstruction of Blackwelder (1954) is superposed on the oblique photograph in Figure 1a. Arrows outline the drainage into the paleolakes (gridded pattern). Dotted patterns show sand deposit locations from Figure 1b. Note the close match of the Bristol Trough sand path and the inferred drainage from the Mojave River to the Colorado River.

speculate that some of the sand transported down the pathways may have crossed the Colorado River and ended up on the Cactus and La Posa Plains (Williams et al. 1991, Tchakerian et al. 1992). The lack of other sand accumulations east of the Colorado River argues against the river itself as the primary sand source and argues for a mechanism which could bring mobile sand to this particular location. Batches of aeolian sand appear to enter the river floodplain at the western end of the sand transport paths (Figure 13). Eventually, the river may have opened a new meander channel west of aeolian sand deposits on the floodplain, which were then remobilized by the wind and exported onto the Cactus and La Posa dunefields. It is difficult to assess how effective such a process may have been prior to regulation of flow along the Colorado River. However, this mechanism could account for the presence of a large quantity of sand on the plains east of the Colorado River and is coincident with the termination of sand transport paths through the Mojave Desert.

Paleoclimatic Implications

The presence of well-developed paleosols and multiple aeolian depositional units within the sand ramps along the sand transport paths indicates that aeolian activity in the Mojave Desert has been widespread and episodic. A description of the units exposed in the Dale sand ramp was given earlier, and additional exposures of multiple soil-horizons were observed during a recent reconnaissance survey of the more remote portions of the Bristol Trough sand pathway. Such exposures within the sand pathways may be related to more extensively studied paleosols in the western Mojave Desert.

In the Silver Lake basin (part of Pleistocene Lake Mojave), an aeolian depositional period (Qe2) that took place between 12 and 8.7 ka, has been recognized by Wells et al. (1987) and Brown (1989). An older aeolian depositional episode prior to 22 ka has also been identified by Brown (1989) in sediment cores from the Silver Lake basin. The sedimentary record from Lake Mojave indicates that lake levels were low to intermediate between 13.5 and 9 ka, with final dessication around 8.7 ka (Brown 1989). It seems likely that the sand ramps observed along the sand transport pathways also witnessed increased levels of aeolian sediment input during low stands of the desert paleolakes, as sediments became available for transport from dried lake basins and their surrounding piedmont areas.

Sediment supply from desert lake basins was drastically curtailed after 9 ka, as a result of the changing environmental conditions which caused most lakes either to dry up or to reach very low water levels (Benson et al. 1990). The sand ramps probably underwent a period of stabilization through vegetation development and soil formation because of the reduction in sediment supply. They were subsequently mantled by rock debris from the adjoining mountains and later entrenched by ephemeral streams. In the middle Holocene, from about 7 to 5 ka, the Mojave Desert experienced a drier than present climatic regime, a period referred to as the climatic optimum or the Altithermal, first recognized

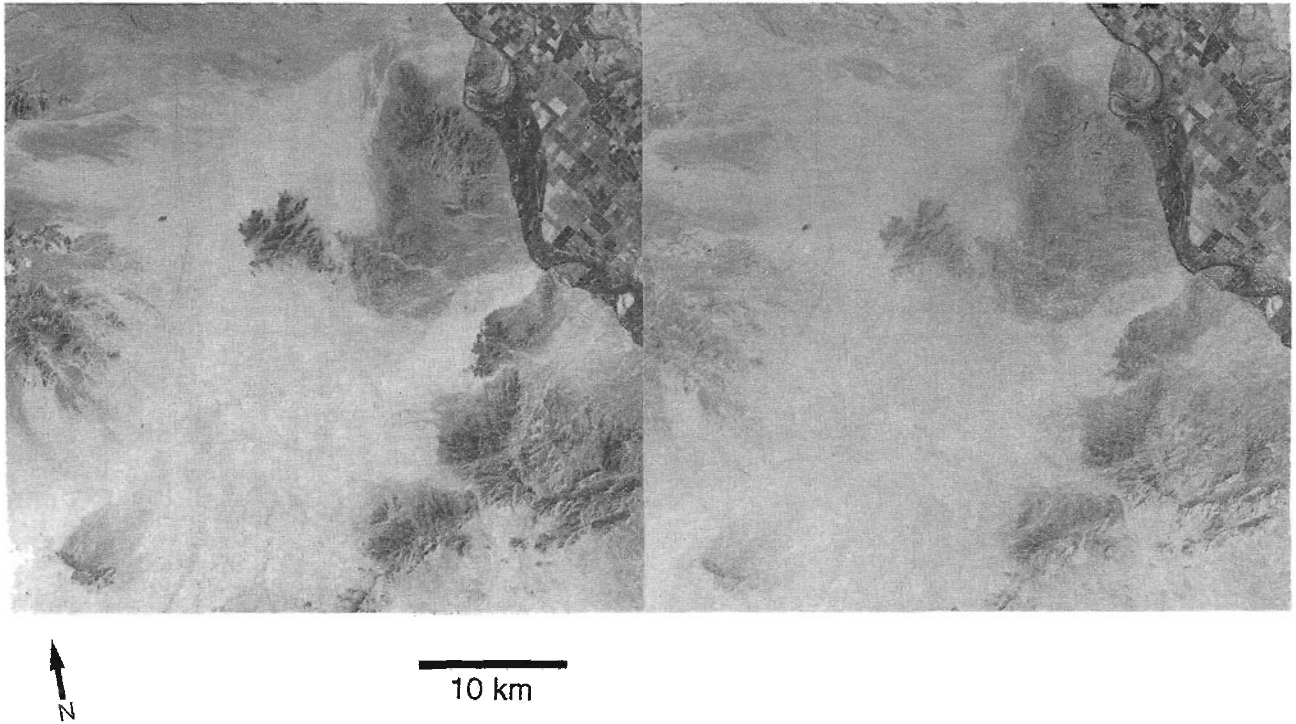

Figure 13. Stereo view of Rice Valley and the Quien Sabe Point area, from portions of Large Format Camera photographs, frames 2062 (left) and 2064 (right), taken during the STS 41-G Space Shuttle flight between October 5 and 13, 1984. The vertical relief is highly exaggerated in this stereo pair, but this view emphasizes the relation between the sand deposits, the mountains, and the Colorado River.

by Antevs (1962). According to Spaulding (1991), Middle Holocene macrofossil (packrat middens) records from the southern Mojave Desert indicate a more arid period than the present between 6800 and 5060 yr B.P. It is thus highly probable that the Middle Holocene period witnessed little aeolian activity as desert lakes were already dessicated by the time of the Altithermal, and most sand ramps fully stabilized.

Accelerator Mass Spectroscopy (AMS) ^{14}C and cation-ratio dating of varnished ventifacts on stabilized debris mantling sand ramps in the Cronese Basin in the Mojave Desert (see left margin of Figure 1b) indicate that aeolian activity ceased or was at a minimum, and that debris deposits were already stabilized, between 5.5 and 5 ka (Dorn et al. 1989). Hence (given the absence of numerical ages directly from dune deposits), most of the sand ramps were probably stable with rock talus and vegetation before the onset of more xeric conditions during the Altithermal, and aeolian activity was at a minimum or mostly restricted to those few desert basin areas that had active sediment input, such as the Mojave River Wash supplying sediments for the Kelso Dunes. Using luminescence dating measures, Lancaster et al. (1991) report a lack of ages older than 5000 yr B.P. from the main Kelso Dune fields, and suggest that the majority of the sediments have been extensively reworked prior to the mid-Holocene.

The entrenched sand ramps within the Bristol Trough and Clark's Pass sand pathways represent a valuable resource for studying paleoclimatic information preserved within the paleosols. The Dale sand ramp is presently the only locality within the sand pathways that has been thoroughly studied for sedimentological characteristics, but our field studies have identified other localities within the Bristol Trough path where entrenched sand ramps expose paleosol sequences. Comparison of the paleosol sequences, both along a given pathway and between adjacent pathways, should provide a test for the emplacement scenarios proposed here. Luminescence dating of key paleosol horizons is perhaps the most critical information required to quantify the climatic information recorded within the sand ramps.

FUTURE WORK

We have presented here the preliminary descriptions and interpretations of the sand deposits present in the eastern Mojave Desert. A considerable amount of field work remains to be carried out, particularly in terms of describing and documenting the sediment characteristics and internal stratigraphy within the thick sand ramps evident at several locations. The sand transport pathway hypothesis can be tested through additional analyses of samples already collected, particularly looking for mineralogical information which could indicate whether or not the sand at the proposed "upstream" end of the pathways could have supplied the sands observed at the termination of the pathways. Additional sedimentological studies may also help to test whether or not the sands along the pathways are consistent with transport away from the inferred source of each pathway. Obtaining samples specifically collected for luminescence dating measurements (Lancaster et al. 1991) from geographically separated soil horizons is essential to the development of a regional stratigraphic history of the eastern Mojave Desert.

The remote sensing data have been used in the present work for basic geomorphic and geographic descriptions, but spectral variations between different bands of Thematic Mapper data should be useful in refining the distribution of active and stabilized sand deposits (Blount et al. 1990). We also hope that the spectral information will be useful for estimating sand thickness throughout the region based on vegetation that is sensitive to particular sand thicknesses (Zimbelman and Williams, in preparation).

CONCLUDING REMARKS

We have presented both remote sensing and field evidence for the emplacement of aeolian sand pathways in the eastern Mojave Desert. Two pathways are described in detail: one extending eastward from the Bristol Playa past the Cadiz and Danby Playas through Rice Valley to the Colorado River, and a second path extending eastward from Clark's Pass past Palen and Ford Playas to the Mule Mountains by the Colorado River. The preferential development of sand ramps on the west slopes of mountains along each path indicates that the eastward-moving, wind-driven sand was not restricted by topographic divides between separate drainage basins around the individual playas and valleys. Preliminary sediment analysis of selected samples shows that there are discrete associations of sand characteristics along the sand pathways, with an inferred possible relationship between the stabilized sands in Rice Valley (within the Bristol Trough path) west of the Colorado River and stabilized linear dunes on the Cactus Plain and La Posa Plain east of the Colorado River. Sand transport along the paths appears to have been episodic, based on multiple soil horizons present in several dissected sand ramps.

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