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Geochemistry of sediments from Quaternary sand ramps in the southeastern Mojave Desert, California

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Abstract

Trace element analyses of sediment from sand ramps in the Bristol Trough and Clark's Pass aeolian corridors of the Mojave Desert, California were conducted to determine their depositional history and relation to sources of sediment within sand transport corridors. Sand ramps are topographically controlled depositional systems consisting of amalgamated accumulations of aeolian, fluvial and talus deposits. These landforms contain a variety of deposits formed in different environments and are, therefore, a valuable source of paleoenvironmental information. Sediments were studied from three sand ramps, the Iron Mountain, Big Maria, and Dale Lake sand ramps; and from two sand sheets, Rice Valley and Cactus Plain. Cactus Plain is located on the eastern side of the Colorado River, in Arizona, but previous researchers have suggested that it is related to the corridors of the western (California) side. Geochemical data from units within individual sand ramps indicate that sources for each sand ramp changed through time, probably as sediment availability from different local fluvial/playa systems changed in response to climate fluctuations. Analyses also indicate that each sand ramp is composed of sediment from discrete, local sources. Sand deposits in the Bristol Trough are not integrated, and thus the corridor does not act as a coherent sand transport pathway. Comparisons of sand from Cactus Plain and sediment from the Bristol Trough and Clark's Pass corridors indicates that the Cactus Plain sand, on the east side of the Colorado River was not derived from sources on the west side of the river.

1. Introduction

The use of geochemical fingerprinting of sediments as a means to determine source origins or transport history has become a valuable technique (Muhs et al., 1995; Wasklewicz and Meek, 1995; Honda and Shimizu, 1998; Wolfe et al., 2000; Pease and Tchakerian, 2002; Zimbelman and Williams, 2002; Muhs et al., 2003). Geochemical analyses of sediments from Quaternary sand ramps in the Mojave Desert were conducted to determine their depositional history within proposed sand transport corridors described by Zimbelman et al. (1995) and Clarke and Rendell (1998). Sand ramps are similar to climbing or falling dunes, but can also contain paleosols and interbedded fluvial and talus deposits, and thus, are a valuable source of paleoenvironmental information (Fig. 1) (Tchakerian, 1991; Lancaster and Tchakerian, 1996; Tchakerian and Lancaster, 2002). Sand ramps can potentially test the hypothesis of Mojave Desert sand transport corridors described by Zimbelman et al. (1995) and Clarke and Rendell (1998). Three topographically controlled aeolian transport corridors have been identified in the region (Lancaster, 1993; Zimbelman et al., 1995; Clarke and Rendell, 1998). The first, and northernmost, corridor starts at the Mojave River Wash, from where sand continues westward into the Devil's Playground sand sheet and terminates at the Kelso Dunes (Lancaster, 1993). This paper focuses on two other aeolian corridors identified by Zimbelman et al. (1995) (Fig. 2). The corridors provide a topographic control that funnels the prevailing winds to a northeasterly direction and thus play a key role in the development of sand ramps in the area (Zimbelman et al., 1995). The long-term control of wind direction has caused the development of sand ramps within the study area on the northwest and west sides of mountains where the sediment-transporting corridor winds are most prominent. The northernmost of the two corridors identified by Zimbelman et al. (1995) is in the Bristol Trough (Fig. 2). The Bristol Trough corridor is

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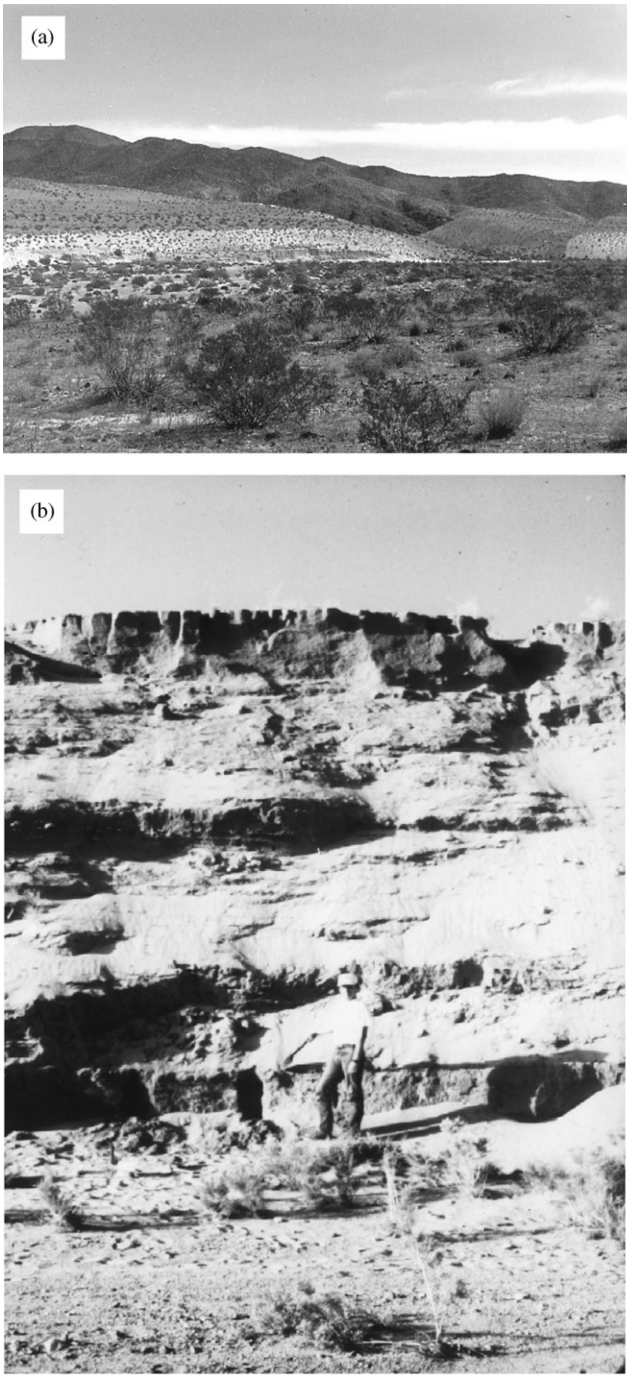

Fig. 1. Photographs of Dale Lake sand ramp: (a) shows the upper part of the sand ramp. Note the stream cut along the base of the ramp, (b) shows a closer view of part of the section exposed by the stream cut shown in (a) (after Zimbelman et al., 1995).

hypothesized to begin in the Bristol Lake area, traverse Cadiz and Danby lakes, and terminate on the east side of the Colorado River in Arizona. Clark's Pass, the southern corridor, parallels the Bristol Trough, beginning in the 29 Palms Valley. Sand is theorized to be transported through Clark's Pass via the Dale Lake sand ramp, after which the corridor continues past Palen and Ford lakes and terminates near Mule Mountain.

2. Setting

The study area is located in the Mojave Desert of southern California (Fig. 2), near the California–Arizona border. The prevailing winds in the region blow from the west and south, but are controlled to a large extent by valley corridors bounded by fault block mountains (Zimbelman et al., 1995), which are part of the southern Basin and Range Province. The local mountains, which supply sediments to the valley corridors, are dominantly granitic (Jahns, 1954; Bishop, 1963; Jennings, 1967; Miller et al., 1982). Some Tertiary volcanic rocks, mostly basalt, are present locally in the area.

2.1. Sand ramps

Sand ramps are topographically controlled landforms. Sand ramps develop against the upwind side of mountains, creating a ramp of sediment extending up the side of the topographic obstacle (Fig. 3). In some cases the sand slope reaches to the top of a topographic obstacle and allows aeolian sand to be transported in the lee of a mountain range or topographic high. Sand ramps are composed primarily of aeolian sand derived from upwind sources along with layers of fluvial and colluvial sediments derived from local mountain sources, and paleosols representing stable geomorphic periods (Lancaster and Tchakerian, 1996). Based on their size and composite nature (combining aeolian, fluvial and paleosol units) Lancaster and Tchakerian (1996) suggested that they should be distinguished from climbing and falling dunes.

2.1.1. Dale Lake

The Dale Lake sand ramp is located in the Clark's Pass corridor on the southwestern end of the Sheep Hole Mountains, about 10 km east of the Dale Lake playa. The ramp is situated in Clark's Pass, a narrow gap between the Sheep Hole and Pinto mountains (Fig. 2). The development of the sand ramp in Clark's Pass might allow sand to migrate over the mountains and continue along the Clark's Pass corridor (Zimbelman et al., 1995) for an unknown distance. The Dale Lake sand ramp reaches a thickness of 70 m and consists of several layers of amalgamated deposits. It is thought that sand deposited in the ramp was derived from the Landers-29 Palms Valley, which lies to the west (Rendell et al., 1994). The surface of the Dale Lake sand ramp is covered with a thin talus composed of gravel and the ramp is incised in several locations by ephemeral streams (Fig. 1a and b) (Tchakerian, 1991). The bulk of the Dale Lake sand ramp is comprised of aeolian

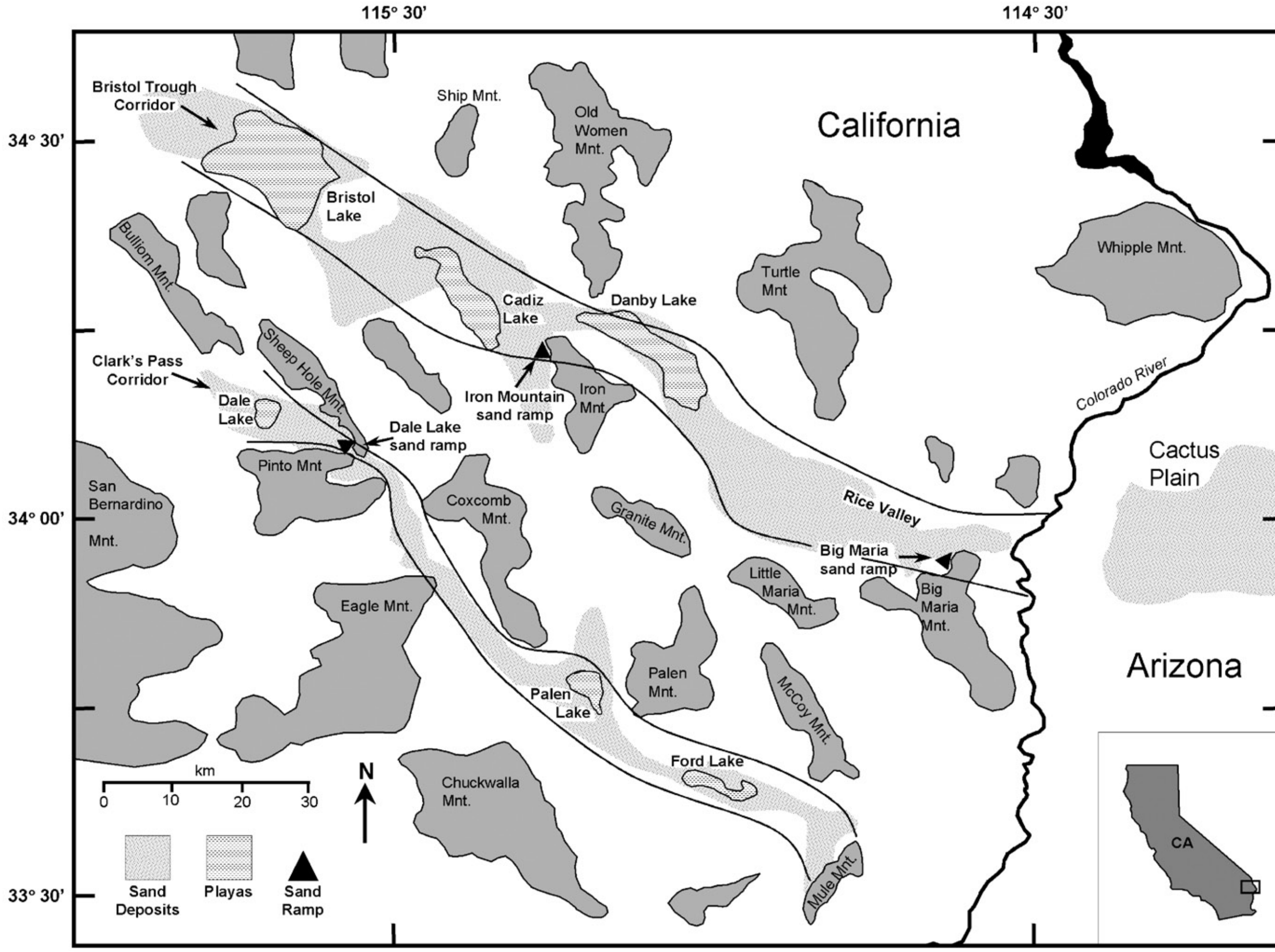

Fig. 2. Map of the study area. Triangles indicate the location of sand ramps examined in the study. The Bristol Trough and Clark's Pass corridors are bracketed within the lines (after Zimbelman et al., 1995).

sheet sands (Rendell et al., 1994) of fine to medium sand, with a mean diameter ranging from 1.74 to 2.34 mm (Table 1). Intermittent layers of grus, gravel, and small boulders have been deposited within the developing ramp through fluvial and mass movement processes (Rendell et al., 1994).

In this study, four Quaternary aeolian units from the Dale Lake sand ramp are examined. From oldest to youngest stratigraphic position they are DL_Qe1, DL_Qe2, DL_Qe3, and DL_Qe6. Rendell et al. (1994) generated the ages for the aeolian units using thermoluminescence (TL) methods. DL_Qe1 is estimated to be >30 ka, DL_Qe2 between 25 and 35 ka, DL_Qe3 ≈ 15 ka, and DL_Qe6 <10.5 ka (Table 1).

2.1.2. Iron Mountain

The Iron Mountain sand ramp is developed on the northwest flank of Iron Mountain (Figs. 2 and 3). The ramp rises to a local elevation of 200 m above Cadiz Lake, which is situated 8 km to the northwest. The Iron Mountain sand ramp is composed mostly of aeolian sand, with a mean grain size of 2.06–2.73 mm (Table 1). Aeolian deposition has been intermittently interrupted by colluvium and alluvium derived from Iron Mountain, and by paleosol development during more humid phases.

Three stratigraphic units have been identified in the Iron Mountain sand ramp (Lancaster and Tchakerian, 1996) and are examined in this study. They are labeled, from oldest to youngest, IM_Qe1, IM_Qe2, and IM_Qe3. Unit IM_Qe2 is capped by a talus and paleosol subunit, labeled IMQe2_Pal. Ages generated from TL dating indicate that IM_Qe1 is >20 ka, IM_Qe2 is between 15 and 9 ka, and IM_Qe3 is <10 ka (Table 1).

2.1.3. Big Maria

The Big Maria sand ramp is located on the northwest flank of the Big Maria Mountains, just west of the Colorado River (Figs. 2 and 3). The sand ramp reaches a thickness of about 150 m, rising from Rice Valley,

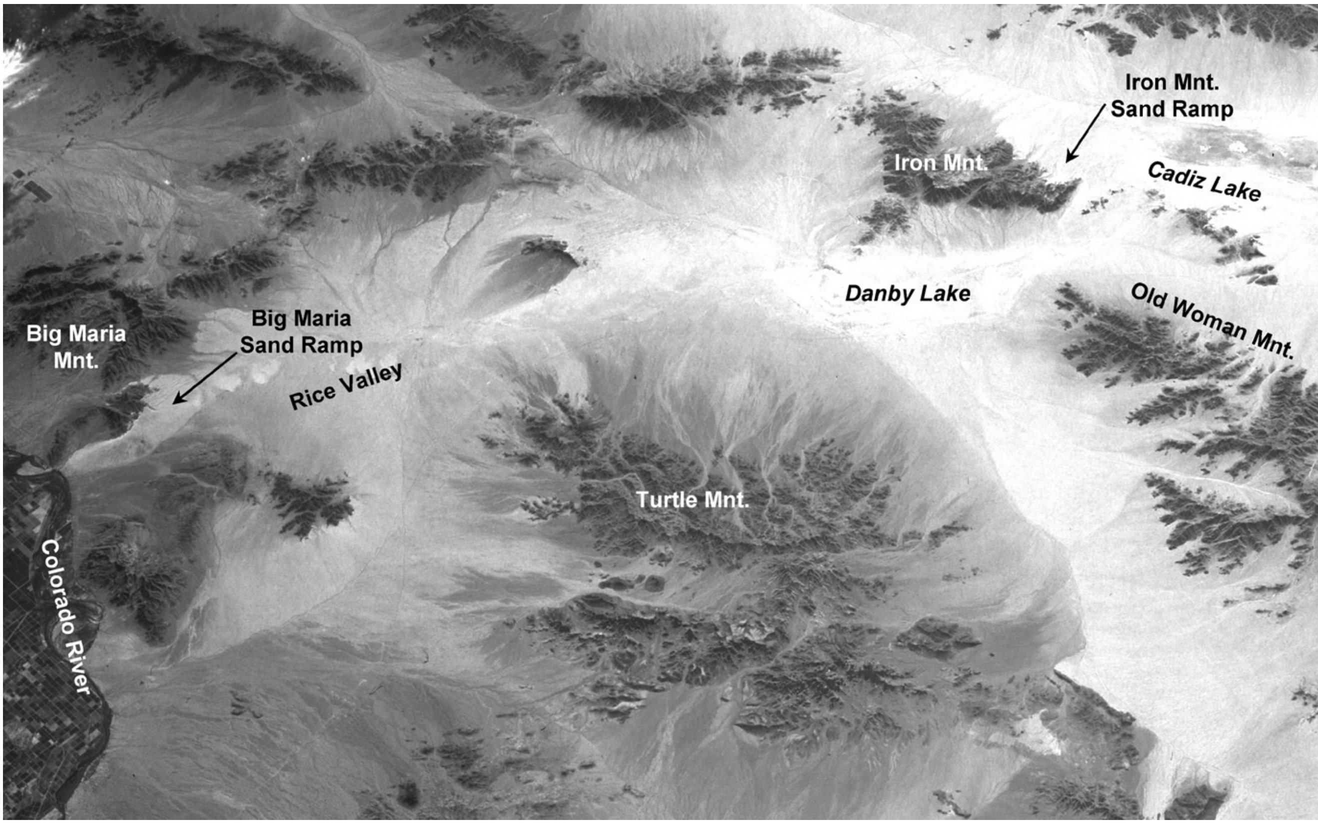

Fig. 3. NASA Space Shuttle photograph of part of the eastern part of the Bristol Trough corridor. The top of the photograph is south-southwest.

which is located just to the northwest of the ramp. Three stratigraphic units were identified the field in the Big Maria sand ramp. The older two, BM_Qe1 and BM_Qe2 are used in this study. Grain size varies somewhat between these units, the older having a mean grain size of 2.03 mm and the younger 1.73 mm (Table 1). Two paleosol units were also examined. Both paleosols cap the respective aeolian units and they are designated BMQe1_Pal and BMQe2_Pal. TL age estimates for Big Maria units are >22 ka for BM_Qe1 and 15–6 ka for MB_Qe2 (Table 1).

2.1.4. *Rice Valley and Cactus Plain*

Sand from Rice Valley and Cactus Plain was also examined in this study. Rice Valley lies at the eastern end of the Bristol Trough corridor (Figs. 2 and 3) and is comprised of partially stabilized, vegetated, linear dunes and sand sheets with a mean grain size of 2.13 mm. Sand from Rice Valley is a possible local source for sand in the Big Maria ramp. A thin strip of sand from Rice Valley extends eastward, just to the north of the Big Maria Mountains and reaches the Colorado River.

The Cactus Plain lies on the eastern side of the Colorado River, across from the termination of Rice Valley. Cactus Plain is composed of partially stabilized linear dunes, parabolic dunes, and sand sheets with a mean grain size of 2.60 mm. Zimbelman et al. (1995) thought that there was no obvious local source for the dunes on the Arizona side of the river, and they did not favor the Colorado River itself as a source. Zimbelman et al. (1995) pointed out similarities in grain size and non-pedogenic silt/clay content between Cactus Plain and Rice Valley and hypothesized that the Bristol Trough corridor and the terminal Rice Valley were possible sources for the Cactus Plain sand. They proposed that the sand was transferred to the eastern side of the Colorado River by meander cutoffs which would allow sand previously on the west side of the river to be isolated on the eastern side.

3. Methods

3.1. *Sample collection and preparation*

Sediment samples, for geochemical analyses were collected from representative sites. Access to the stratigraphic profiles was gained at sites of stream incision, where thick sections of the sand ramps were exposed. Samples were sieved at 0.25 phi intervals for grain size statistics and in preparation for chemical analyses. Sieving procedures followed standard

Table 1
Luminescence age dates and grain statistics for sand ramp units

Locality and unit	Unit age (ka)	Mean grain size (ϕ)	Standard deviation (ϕ)	Skewness
Dale Lake				
Unit 6	$\leqslant$10.5	2.34	0.99	−0.19
Unit 5[a]	$\approx$20–15	—	—	—
Unit 4[a]	$\approx$15–12	—	—	—
Unit 3	$\approx$15.8	2.24	0.96	−0.14
Unit 2	35–25.5	1.74	1.25	−0.31
Unit 1	> 30	2.26	0.90	−0.16
Iron Mountain				
Unit 3	$\leqslant$10	2.06	1.08	−0.10
Unit 2	15–9	2.73	1.12	−0.29
Unit 1	$\geqslant$20	2.20	0.96	−0.14
Big Maria				
Paleosol 2	$\geqslant$6[b]	—	—	—
Unit 2	15–6	1.73	0.97	0.26
Paleosol 1	22–15[b]	—	—	—
Unit 1	$\geqslant$22	2.03	0.74	0.06
Rice Valley				
Sample 1	—	2.04	1.24	0.10
Sample 2	—	2.21	0.94	0.12
Cactus Plain				
Sample 1	—	2.55	0.90	0.29
Sample 2	—	2.65	1.02	0.25

[a] Not used in this study.
[b] Estimated relative ages. Age dates are from Rendell et al. (1994). Some inconsistencies exist, especially in Dale Lake units 3–5, and are explained by Rendell et al. (1994).

techniques for sieve analysis (e.g., Boggs, 1987). The modal fraction was separated during the sieving process and used for further mineralogical and geochemical analysis. This fraction was used to standardize the samples and reduce variations in mineralogical/chemical composition between grain size fractions within a sample (Honda and Shimizu, 1998). Although some researchers have found the clay fraction of sediments useful in determining sediment origins (Cullers et al., 1987), we used the sand fraction exclusively. Clay-size sediments in dominantly sand-sized deposits are very likely of secondary origin, either from pedogenesis or later aeolian influx.

3.2. Geochemical analysis

Sediment geochemistry was determined by instrumental neutron activation analysis (INAA). INAA has the capability of providing quantitative values for many trace elements including some rare earth elements (REE), with detection limits ranging from ppm to ppb, depending on the particular isotope (Parry, 1997). Sample preparation and analysis was done at the Texas A&M University Nuclear Science Center. Irradiations were carried out in a 1 MW, FLIP TRIGA reactor. Element concentrations were counted on a high purity germanium detector at the Center for Chemical Characterization and Analysis at Texas A&M University.

4. Results and discussion

4.1. Comparisons between units in individual sand ramps

4.1.1. Dale Lake

Samples from the four main aeolian units in the Dale Lake Sand Ramp show significant compositional variability. Elemental ratios were used to examine the variability of aeolian units. Elemental ratios can be useful when determining sediment sources because they omit the problems encountered with dilution by quartz or carbonate. Fig. 4 shows eight elemental ratios for Dale Lake aeolian units, plotted in stratigraphic order. Descriptions of the ratios are included in the figure caption, but generally elements were chosen either for their immobility (La, Cr, Co, Th, Sc) or for their presence in common minerals (Rb, Sr, Ba), particularly potassium feldspar and plagioclase. At least some variation is present in all ratios between units of different ages. The sediment from Dale Lake sand ramp is consistent with on overall granitic source. The unit DL Qe3 has elevated Rb and Ba levels relative to the

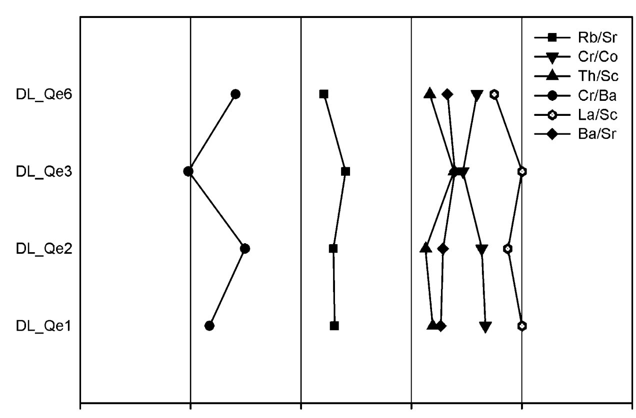

Fig. 4. Six elemental ratios for each stratigraphic unit in the Dale Lake sand ramp. The lines are not meant to imply a continuum between units. Ratios were selected based on the likely behavior of elements in minerals: Rb/Sr: Rb commonly substitutes for K and is commonly found in potassium feldspar, Sr substitutes for Ca and is common in plagioclase; Cr/Co: both are compatible, relatively immobile transition elements that should remain stable during weathering; Th/Sc: Both are relatively immobile, high field strength elements. Sc is more compatible, Th is less so; Cr/Ba: Cr is a compatible, relatively immobile element common in mafic minerals, Ba is an incompatible element found in felsic minerals such as potassium feldspar: La/Sc: La is a LREE, enriched in felsic minerals and relatively immobile, Sc is an immobile, Compatible element common in mafic minerals: Ba/Sr: both are low field strength, large ionic lithophiles, more enriched in felsic mineralogies. Both are commonly found in K-feldspar.

other units, indicating a higher presence of potassium feldspar, as well as relatively high levels of Th and Yb that might indicate an elevated level of ziron (Henderson, 1984; Taylor and McLennan, 1985; Rollinson, 1993). Units DL Qe2 and DL Qe6 have higher REE levels than the other units, and an increase in the importance of Cr and Sc. Chromium and Sc indicate Fe and Mg-bearing mafic minerals.

REE are useful in examining sediment characteristics and sources because they are among the least soluble of the trace elements and are less mobile during weathering than many other trace elements (McLennan, 1989; Rollinson, 1993). REE content in clastic sediments is controlled primarily by the source rock material (Fleet, 1984; McLennan, 1989), because of the insolubility of the REE and their very low concentration in freshwater. REE content that is mobilized during weathering is usually re-precipitated at the site of weathering and remains a useful indicator of source (McLennan, 1989; Rollinson, 1993). REE plots in this paper are normalized to chondritic meteorites, using values by Haskin et al. (1968).

All of the Dale Lake units have similar REE patterns (Fig. 5). Although the general patterns of the REE curves are similar between all Dale Lake samples, DL Qe2 and DL Qe6 show greater similarity to one another, with slightly higher concentrations. Units DL Qe1 and DL Qe3 show similarities in concentration as well as a positive Yb anomaly. Ytterbium can be concentrated in garnet (Grauch, 1989), monazite, and zircon (McLennan, 1989; Rollinson, 1993). Unlike the other REE, Eu has a stable 2+ ionic state and commonly substitutes for Ca. The negative Eu anomaly usually reflects an absence of plagioclase or other Ca bearing minerals.

4.1.2. *Big Maria*

Overall, the two aeolian units in the Big Maria sand ramp are distinguishable from one another, but are similar to their respective paleosol units (Fig. 6). This is most evident in the ratios that help to distinguish felsic and mafic minerals (La/Sc and Th/Sc). BM Qe2, and the overlaying paleosol, BMQe2 Pal, have higher Th values than BM Qe1 and BMQe1 Pal. Thorium is more common in felsic minerals, and is commonly found in zircon and monazite in pegmatitic rocks (Jahns, 1954; Clark, 1984; McLennan, 1989). Other elemental ratios show considerable inconsistency, with BM Qe2 showing similarity to BMQe1 Pal, and BM Qe1 showing greater similarity to BMQe2 Pal (Fig. 6). There is a slightly higher Sr content in BM Qe1 over BM Qe2, which indicates higher Ca levels. The Ca could be in plagioclase or amphibole, or from carbonates that are present in the Little Maria Mountains.

The patterns are more distinct in the REE curves (Fig. 7), where BM Qe1 and BM Qe2 show clear differences in their composition, as do the associated paleosols. The most significant variation between Big Maria aeolian units is seen in the light REE (LREE)

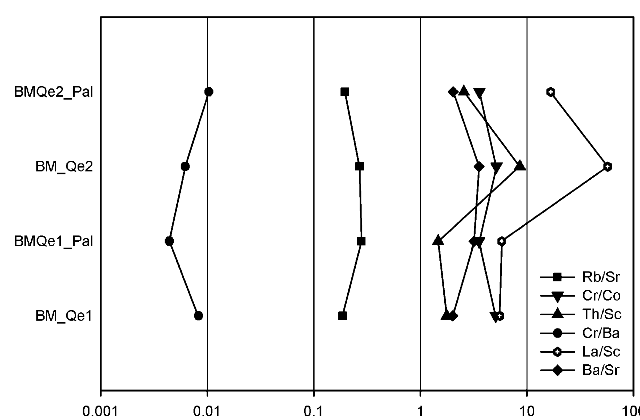

Fig. 6. Six elemental ratios for each stratigraphic unit in the Big Maria sand ramp. The lines are not meant to imply a continuum between units. See Fig. 4 for information regarding the element ratios.

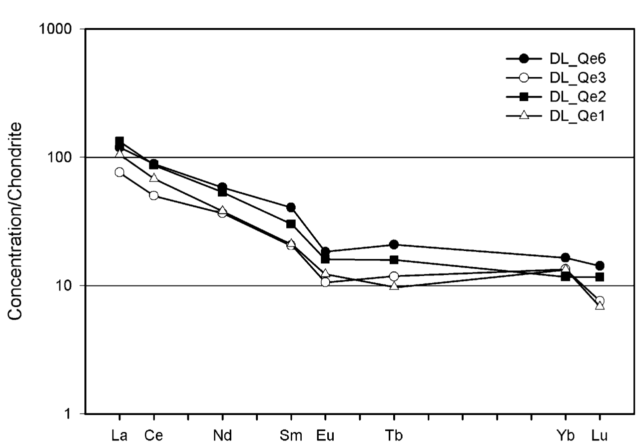

Fig. 5. Chondrite normalized rare earth element plot for the Dale Lake sand ramp units.

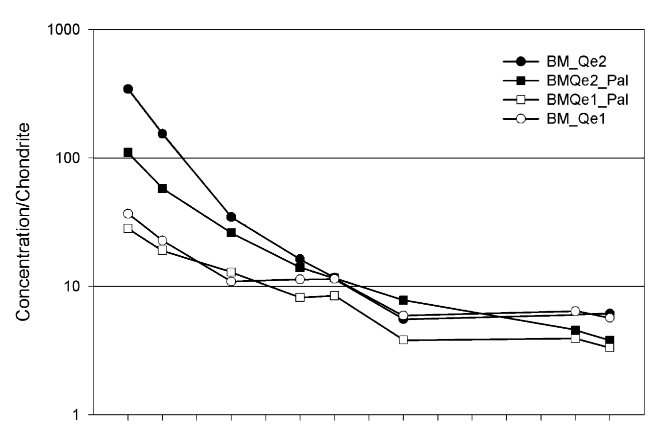

Fig. 7. Chondrite normalized rare earth element plot for the Big Maria sand ramp units.

La-Sm content of BM Qe1. The upper units of Big Maria have much steeper REE slopes, resulting from an enrichment of LREE, particularly La and Ce. The slope for BM Qe1 is 6.5 whereas the Big Maria 2 slope is 56. REE are generally incompatible and are more readily concentrated in felsic minerals during fractional crystallization. The slightly larger ionic radius of the LREE makes them somewhat more incompatible and, therefore, more concentrated in late-stage felsic crystallization (Krauskopf and Bird, 1995). The flatter slope of sand from BM Qe1 and BMQe1 Pal is an indication of a relatively less felsic composition and indicates a change in source. Decreases in feldspar or heavy minerals by quartz dilution could explain a decrease in REE, but such a decrease would be seen across all REE. The BM Qe1 and BMQe1 Pal units show decreases only in the LREE. A slight positive Eu anomaly is also present in the sand from the lower Big Maria units. The Eu enrichment indicates the presence of plagioclase, particularly anorthite, and other Ca-bearing minerals such as amphibole, pyroxene, and carbonates. These minerals are also consistent with the decreased slope in the REE curve of the lower units.

4.1.3. Iron Mountain

The most chemically distinct sample in the Iron Mountain sand ramp is the paleosol unit. IMQe2 Pal is enriched in Rb and Ba, indicating higher concentrations of potassium feldspar (Fig. 8). The aeolian units of the Iron Mountain sand ramp show a fair amount of similarity, but with two exceptions. One is the enrichment of Zr, Th and Hf in IM Qe3 (Fig. 8 and Table 2) related to higher zircon content. Zircon is an indication of a granitic source, and possibly pegmatite (Clark, 1984; McLennan, 1989). The slightly higher Ba/Sr ratio in IM Qe3 (Fig. 8), compared with IM Qe2 and IM Qe1, indicates higher amounts of potassium feldspar in the upper unit, and more plagioclase in the lower two units.

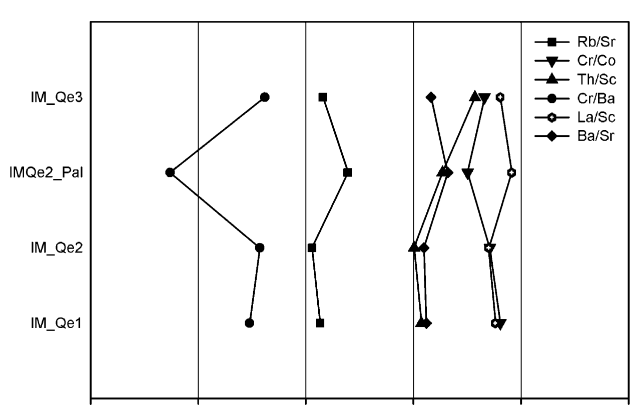

Fig. 8. Six elemental ratios for each stratigraphic unit in the Iron Mountain sand ramp. The lines are not meant to imply a continuum between units. See Fig. 4 for information regarding the element ratios.

The influence of zircon in IM Qe3 can also be seen in the higher Yb concentration on the REE pattern (Fig. 9) (Henderson, 1984; Taylor and McLennan, 1985; Rollinson, 1993). The drop in Eu in IM Qe3 is probably a reflection of the greater prominence of potassium feldspar over plagioclase. Sands from IM Qe2 and IM Qe1 show remarkable similarity in their REE patterns and are likely from the same source. The paleosol unit is most distinct with an overall drop in REE content that might reflect quartz dilution.

4.2. Comparisons between different sand ramps

Data from the different sand ramps, and from samples collected in Rice Valley and the Cactus Plains (Fig. 2) are combined to test the hypothesis presented by Zimbelman et al. (1995), that the corridors represent a linked sand supply and that local sediment was not necessarily the dominant source of aeolian sand for adjacent sand ramps. Zimbelman et al. (1995) hypothesized that the Bristol Trough corridor is fully integrated, as a "river of sand" and local playas serve primarily as intermediate storage points. If so, than the sand ramps deposited within the corridor should have a well-mixed composition and show strong chemical similarities.

Mean normalized concentrations of REE for each site, including the Rice Valley and Cactus Plains samples, are shown in Fig. 10. Dale Lake and Iron Mountain sites show remarkable similarities in composition despite being in different corridors. The similarity probably occurs because sediments are derived locally from geologically similar outcrops around the Bullion Mountains and represent first cycle sediments derived from granitic sources. There is some comparability between the Rice Valley and Big Maria samples from the Bristol Trough corridor, although the patterns diverge in the LREE La and Ce. This divergence is caused mostly by the strong enrichment in LREE in the BM Qe2 unit (see Fig. 7), which skews the mean values on that end of the curve. Rice Valley is the most immediate potential source of sediment for the Big Maria sand ramp, and so the general comparability between these two sites is not surprising. The fact that the two curves are not more closely fit is probably an indication that Rice Valley contributed only part of the sediments that make up the Big Maria sand ramp.

Cactus Plain is located on the east side of the Colorado River, and Zimbelman et al. (1995) hypothesized that the dune sand was derived from one, or both, of the corridors on the west side of the Colorado River. The REE concentrations of Cactus Plain samples do not show a correlation with the other sites (Fig. 10). The Cactus Plain samples show less similarity to the Iron Mountain and Dale Lake sand ramps which are located farther away, than with closer sites. The lower overall

Table 2
Geochemical Data for sample used in this study

Sample ID	Concentration PPM				
	Ba	Ce	Co	Cr	Cs
DL_Qe6	993.4	78.4	6.5	25.4	1.3
DL_Qe3	929.5	44.2	3.0	8.9	0.7
DL_Qe2	706.7	76.6	5.1	22.0	0.8
DL_Qe1	690.8	59.9	2.2	10.2	0.7
IM_Qe3	784.6	74.1	7.2	32.8	2.1
IMQe2_Pal	846.0	25.3	1.4	4.6	1.5
IM_Qe2	747.3	58.4	5.5	28.0	1.2
IM_Qe1	707.1	49.8	3.3	21.2	1.2
BM_Qe2	1186.3	135.6	1.4	7.4	0.8
BMQe2_Pal	891.2	51.1	2.6	9.2	1.1
BM_Qe1	1062.0	20.0	1.7	8.8	0.8
BMQe1_Pal	1036.0	16.8	1.3	4.6	1.1
Rice Valley 1	1133.9	29.0	3.0	10.6	1.8
Rice Valley 2	998.4	49.5	1.2	8.4	0.9
Cactus Plain 1	491.9	34.9	1.5	7.5	0.5
Cactus Plain 2	570.1	16.4	1.4	7.5	0.9

	Eu	Fe	Hf	La	Lu
DL_Qe6	1.3	23,791.3	7.1	39.4	0.5
DL_Qe3	0.7	8809.1	2.1	25.2	0.3
DL_Qe2	1.1	18,036.6	3.4	44.1	0.4
DL_Qe1	0.8	8909.9	2.2	34.6	0.2
IM_Qe3	1.2	21,571.7	7.0	44.1	0.5
IMQe2_Pal	0.6	5479.2	2.3	13.9	0.1
IM_Qe2	1.3	18,131.5	5.7	30.6	0.3
IM_Qe1	1.1	11,682.1	4.1	25.8	0.2
BM_Qe2	0.8	5149.6	3.4	113.5	0.2
BMQe2_Pal	0.8	7686.0	1.8	36.5	0.1
BM_Qe1	0.8	6777.7	2.5	12.1	0.2
BMQe1_Pal	0.6	4883.7	3.1	9.3	0.1
Rice Valley 1	0.9	9483.8	4.2	14.9	0.2
Rice Valley 2	1.0	5646.1	2.7	28.0	0.2
Cactus Plain 1	0.6	4683.5	1.3	18.8	0.1
Cactus Plain 2	0.4	4345.8	1.3	8.0	0.1

	Na	Nd	Rb	Sc	Sm
DL_Qe6	26,553.6	35.0	75.8	7.0	7.4
DL_Qe3	25,412.1	22.0	94.9	2.5	3.7
DL_Qe2	28,473.6	32.0	71.4	5.9	5.5
DL_Qe1	27,246.2	22.8	75.4	3.4	3.8
IM_Qe3	24,298.7	37.6	77.7	6.9	6.3
IMQe2_Pal	22,115.5	11.8	99.7	1.7	2.0
IM_Qe2	28,431.9	24.9	68.6	6.1	4.7
IM_Qe1	31,055.3	28.5	73.1	4.5	4.2
BM_Qe2	16,769.5	20.8	89.7	2.0	2.9
BMQe2_Pal	22,466.0	15.6	85.6	2.2	2.5
BM_Qe1	21,833.1	6.5	98.6	2.2	2.0
BMQe1_Pal	16,254.5	7.7	90.8	1.6	1.5
Rice Valley 1	22,956.2	13.7	101.0	2.5	2.5
Rice Valley 2	24,344.9	22.4	94.3	1.8	3.2
Cactus Plain 1	4963.7	13.9	42.2	1.5	2.5
Cactus Plain 2	5443.6	6.2	44.6	1.4	1.2

	Sr	Ta	Tb	Th	Yb
DL_Qe6	469.7	0.3	1.0	10.3	3.3
DL_Qe3	375.8	0.1	0.6	6.1	2.7
DL_Qe2	364.5	0.3	0.7	8.0	2.3
DL_Qe1	374.1	0.2	0.5	5.4	2.7

Table 2 (*continued*)

Sample ID	Concentration PPM				
	Sr	Ta	Tb	Th	Yb
IM_Qe3	538.2	0.3	25.6	25.6	3.8
IMQe2_Pal	405.5	0.3	0.3	3.1	0.8
IM_Qe2	595.7	0.7	0.7	6.2	2.0
IM_Qe1	536.0	0.7	0.5	5.3	1.6
BM_Qe2	334.7	0.1	0.3	17.0	—
BMQe2_Pal	438.0	0.4	0.4	5.6	0.9
BM_Qe1	528.1	0.1	0.3	3.8	1.3
BMQe1_Pal	324.2	0.2	0.2	2.4	0.8
Rice Valley 1	328.9	0.1	0.4	4.3	1.5
Rice Valley 2	445.6	0.5	0.4	5.5	1.4
Cactus Plain 1	169.5	0.1	0.2	5.6	—
Cactus Plain 2	153.2	0.1	0.1	2.5	0.5

	Zn	Zr
DL_Qe6	63.2	137.7
DL_Qe3	25.9	—
DL_Qe2	34.3	—
DL_Qe1	26.4	194.3
IM_Qe3	53.1	232.7
IMQe2_Pal	37.7	
IM_Qe2	46.5	85.6
IM_Qe1	20.1	74.7
BM_Qe2	17.5	—
BMQe2_Pal	13.6	41.4
BM_Qe1	24.6	—
BMQe1_Pal	9.3	40.8
Rice Valley 1	14.0	164.5
Rice Valley 2	9.2	62.1
Cactus Plain 1	13.9	—
Cactus Plain 2	12.1	42.6

Only elements with consistent results are included. Blanks in the table indicate no data because of detection limits.

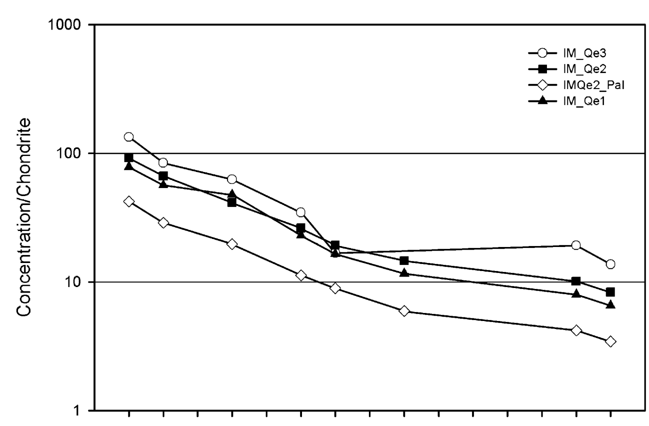

Fig. 9. Chondrite normalized rare earth element plot for the Iron Mountain sand ramp units.

concentration of REE in the Cactus Plain samples is probably the result of quartz dilution. The likely source for sand in the Cactus Plain area is the Colorado River, which is quartz rich (Muhs et al., 1995).

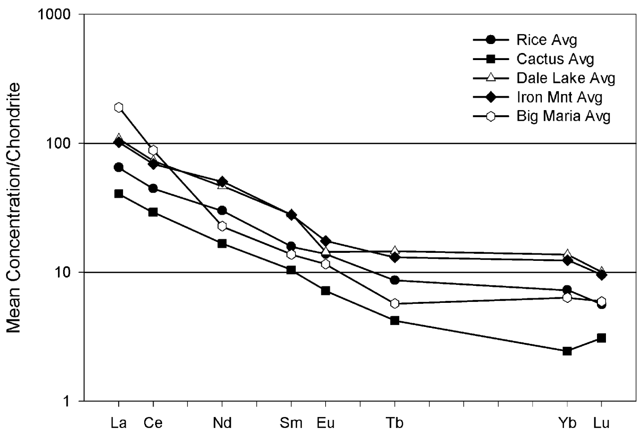

Fig. 10. Mean chondrite normalized rare earth element plots. Aeolian units only were used to obtain mean values.

5. Discussion

5.1. Comparisons within individual sand ramps

The composition of individual sand ramps show a range of values from one unit to another. Those results suggest that the source of sand supplied to individual ramps have changed through time. The composition of sand moving through the corridor might have changed through time as new lithologies were exposed in basins, wind regimes altered, or new rock types were made available through volcanic activity (e.g. the Holocene-age Amboy cinder cone in the Bristol Trough). The precise nature of the changing sources is not known, but we suspect it reflects changes in the availability of local sources through time. Changes in the activity of ephemeral streams, or source stability related to vegetation cover, could allow for changes in source dominance under a uniform prevailing wind regime.

We think it is also possible that cyclic changes, such as those seen in the Dale Lake sand ramp might result from changes in either sediment delivery or sediment stability related to climate fluctuations. During humid or sub-humid phases local streams would have delivered more sediment to playa edges, ephemeral washes, and alluvial fans, providing an abundant source of sand. During more arid phases when additional material is not added, these supplies might have been reactivated, and eventually depleted, and playas became more important as they desiccated (cf. Tchakerian and Lancaster, 2002). Tchakerian and Lancaster (2002) point out that dune-building periods were highly episodic during Pleistocene and Holocene times. The intermittent nature was driven by variations in climate and sediment availability. Tchakerian and Lancaster (2002) further state that the link between low-lake stands and aeolian deposition is weak; the main control being a more complex relationship between sediment supply, storage, and transport pathways. Likewise, humid and arid phases would be accompanied by changes in vegetation cover and thus source stability. All of this implies that local, not regional sand sources are more dominant in sand ramp development, and that the sources change through time as local systems adjust to climatic fluctuations or other changes.

The overall similarity of rock types in the area around the Clark's Pass and Bristol Trough corridors make distinction of discrete sources difficult without more detailed studies on the subtle variability of granitic outcrops in the study area. Some general conclusions on the source changes can be made. The sediment from Dale Lake sand ramp is consistent with on overall granitic source as indicated by the REE pattern. The unit DL_Qe3 has elevated Rb and Ba levels relative to the other units, indicating a higher presence of potassium feldspar. The higher potassium feldspar can be an indication of a greater dominance of that mineral in the parent rock, or that the sand has undergone relatively less weathering. Units DL_Qe2 and DL_Qe6 have higher REE levels than the other units, and an increase in the importance of Fe, Co, Cr, Sc and other elements indicative of heavy minerals associated with metamorphic or mafic sources in the Bullion and San Bernardino mountains (Table 2).

IM_Qe3, the youngest unit in the Iron Mountain sand ramp is enriched in Zr, Hf, Th and Yb, probably related to a higher zircon content indicative of an acidic mineral composition. The increase in Ba/Sr ratio and the drop in Eu in IM_Qe3, relative to the other Iron Mountain units, is probably a reflection of a greater prominence of potassium feldspar over plagioclase. Therefore, although all samples from the Iron Mountain sand ramp appear to be similar and granitic in origin, IM_Qe3 is clearly distinct from the lower two units and is more similar to the potassium feldspar-rich units of the Dale Lake sand ramp.

The compositional variations in the Big Maria sand ramp are most easily seen in the REE patterns. The upper unit of Big Maria, BM_Qe2, has a much steeper REE slope, resulting from an enrichment of LREE, particularly La. The flatter REE slope of BM_Qe1 is an indication of a relatively greater amount of mafic minerals. Sand in BM_Qe2 is more granitic than BM_Qe1, shown by its enrichment of several highly incompatible elements, including La, Th, and Ba that indicate a source rock of late-stage felsic crystallizations, such as granite pegmatite. The lower BM_Qe2 unit has a mixture of felsic and mafic minerals. The mafic source is most likely from basalt or other volcanics of Turtle Mountain (Fig. 2).

5.2. Comparisons within corridors

If sand transport corridors exist as integrated sediment pathways, the expectation is that compositional similarities should exist throughout the corridor. Zimbelman et al. (1995) noted "discrete associations of sand characteristics along the sand pathways". This study does not find significant similarities in trace element composition between aeolian sediments within the northern, Bristol Trough corridor. Fig. 10 shows that sediment in the Iron Mountain and Big Maria sand ramps are chemically distinct from one another. They also show only a moderate similarity between the Big Maria sand ramp sediments and sand from Rice Valley, even though Rice Valley is the most adjacent source of sand.

The closest correlation shown in Fig. 10 is between the Iron Mountain and Dale Lake sand ramps. Dale Lake rests in the separate corridor, south of the Bristol Trough corridor. There is no indication of between-corridor exchanges of sand (Zimbelman et al., 1995). The similarity is the result of both troughs deriving sediments from geologically similar lithologic bodies that supplied sediments to both valleys.

We argue that sediment does not move continuously through the corridors as a "river of sand" (cf. Zimbelman et al., 1995). We do not believe that there is no down-corridor movement or mixing. What we do suggest is that, despite any long-distance movement of sand through the entire corridor, local sources within the trough are more important in the building of sand ramps. Zimbelman and Williams (2002) inferred a similar conclusion when they stated that Mojave sand is relatively immature and that "Mojave sands have general affinities with the local bedrock." Muhs et al. (2003) also acknowledged the importance of local sources, suggesting locally derived alluvium to be an important source for dune fields in the Mojave.

5.3. Comparison with Cactus Plain

If Zimbelman et al. (1995) were correct in their hypothesis that sand in the Cactus Plain, on the east side of the Colorado River, was derived from the aeolian corridors on the west side of the river, than the most logical source is Rice Valley, which lies adjacent to Cactus Plain, on the opposite side of the river. Zimbelman et al. (1995) suggested that sand from the corridor on the west side of the Colorado River might have been transferred to the east side via meander cutoffs. Our analyses show no chemical similarity between Rice Valley and Cactus Plain sediments. Based on these findings we think it is unlikely that the Cactus Plain dunes were derived from sediments from the west side of the Colorado River.

The same finding have been independently confirmed in two other studies (Zimbelman and Williams, 2002; Muhs et al., 2003). Zimbelman and Williams (2002) used bulk major oxide and trace element data and found that sand from the Cactus Plain area on the Arizona side of the Colorado River was derived from the river. They further found that the Arizona sand and the Colorado River sand was chemically distinct from samples collected on the west side of the river. Using mineralogical, geochemical and magnetic data, Muhs et al. (2003) also identified the Colorado River as the source of sand for dune sand in the Cactus Plain area. Muhs et al. (2003) further suggested that the Colorado River has been an important source of sediment for three major dune fields in western Arizona and northern Mexico. Both studies by Muhs et al. (2003) and Zimbelman and Williams (2002) point out the quartz-rich composition of the Cactus Plain sediments and the Colorado River sediments as an indication that those sediments are more mature than aeolian sand found in the Mojave Desert on the west side of the Colorado.

6. Conclusions

Sand compositions show a great deal of complexity both within individual sand ramps and between different sand ramps. We have shown that there is a lack of correlation between sand ramp sediments within the proposed sand transport corridor of Bristol Trough. Samples from units within the Iron Mountain sand ramp and the down wind Big Maria sand ramp show no similarity in chemical composition. This does not imply, nor do we suggest, that the corridor does not control regional wind patterns, and perhaps some transport of sand through this portion of the Mojave Desert. We do suggest, however, that despite whatever down-trough mixing of sources does occur, discrete, local sources found throughout the corridor supply the bulk of sediments deposited in individual sand ramps. Although this does not preclude long-term mixing, it is likely that the majority of sediment in the Iron Mountain sand ramp was derived from Cadiz Lake and local ephemeral fluvial and alluvial fan sources, and sediment in Big Maria sand ramp were dominantly derived from Rice Valley and local fluvial and alluvial fan sources. This implies that although the corridor likely does control wind patterns in the study area, there remains a disconnection between the discrete sources of sediment within different portions of the corridor. We think it is likely that sources fluctuated over time, driven by climatic change, because of the dissimilarities between stratigraphic units with individual sand ramps.

The two areas in the Bristol Trough that show the most chemical similarities are Rice Valley and Big Maria, although they too show variation in composition. This likely reflects and complexities of multiple sources within the corridor, including playas, alluvial fans, older aeolian units, and possibly the Colorado River, all of which, we suspect, demonstrate varying degrees of importance during climatic fluctuations.

Our analyses also indicate that the Cactus Plain sand on the eastern side of the Colorado River was not derived from the Rice Valley dunes on the western side of the river, nor are they related to sand ramps of the Bristol Trough. We hypothesize that the sand in Cactus Plain was probably derived from the Colorado River and/or other local fluvial sources from nearby mountains.

The paleosols included in this study showed mixed results. The two paleosols from the Big Maria sand ramp showed strong similarities to their parent aeolian units. The Iron Mountain paleosol did not show a correlation with the aeolian units, and we suspect its sediments were largely derived from fluvial sources at the head of the sand ramp.

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