Grain size discrimination between sands of desert and coastal dunes from northwestern Mexico

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ABSTRACT

A textural study of grain-size distribution parameters (mean graphic size M_z, sorting σ, skewness Ski, kurtosis K_G) was carried out in the state of Sonora, in NW Mexico. The aim was to distinguish between desert and coastal dunes based on the textural parameters of the sands. Sixty two sand samples were collected from the slip face and crest of linear and sand sheet dunes from the desert and coastal zone of the Altar Desert, Sonora. Textural parameters were determined by a Laser Particle Size Analyzer (Coulter). Among the four groups of dunes studied, El Pinacate desert dune sands are significantly different from the rest of the dune groups in terms of grain size and skewness. This is due to the selectiveness of the northwesterly winds that concentrates finer sizes with longer wind transport from the source (Colorado River delta sediments) to the El Pinacate dune fields. In contrast, the grain size distributions for the rest of the dune fields are affected by their proximity to the sediment sources, tidal transport, long shore drifts and southwesterly and southeasterly winds. Coastal dune sands are coarser than the desert dune sands. This may be caused by the effect of the tidal currents and local winds of the Colorado River delta sediments that locally carry coarser grains onto the beach and landwards. Bioclasts of the beach sand in Puerto Peñasco also exerts a control in the grain size distribution of the dune sand. The linear discriminant analysis and ANOVA test are useful tools to discriminate between desert and coastal dune sands. Some similarities were detected for the grain size distributions between the Altar Desert sands (Mz=1.34ϕ – 2.79ϕ; σ=0.35ϕ – 1.60ϕ) and the Kalahari Desert sands (Mz=1.55ϕ – 2.38ϕ; σ=0.51ϕ – 1.52ϕ) that are probably associated with the sediment source of the sands, dune morphology and wind patterns.

Key words: coastal dunes, desert dunes, grain size distribution, Altar Desert, Sonora, Mexico.

RESUMEN

Se realizó un estudio textural sobre la distribución de tamaño de grano (media Mz, clasificación σ, asimetría Ski y curtosis K_G) en el Estado de Sonora, Noroeste de México. El objetivo fue distinguir entre las arenas de dunas desérticas y costeras con base en sus parámetros texturales. Se colectaron sesenta y dos muestras de arena de flancos y crestas de dunas lineales y parabólicas del desierto y de la costa del Desierto de Altar, Sonora. Los parámetros texturales fueron determinados por medio de un Analizador Láser de Tamaño de Partícula (Coulter). Entre los cuatro grupos de dunas estudiadas, las dunas de El Pinacate son significativamente diferentes del resto de las dunas en términos de tamaño de grano y asimetría. Esto es debido a la selectividad de vientos del noroeste que concentran tamaños finos con mayor transporte desde la fuente (delta del Río Colorado) hasta las dunas de El Pinacate. En contraste, las distribuciones de tamaño de grano para el resto de los campos de dunas están afectadas por la cercanía a la fuente de sedimentos, el régimen de marea, las corrientes litorales y los vientos hacia el sureste y noreste locales. Las dunas costeras muestran tamaño de grano más grueso que las dunas desérticas. Esto puede ser causado por el efecto de las mareas y vientos del suroeste y noroeste que transportan sedimentos gruesos del delta del Río Colorado a la playa y tierra adentro. Los biógenos de la playa en Puerto Peñasco influyen también en los parámetros texturales de la duna. El análisis *de discriminación lineal y prueba ANOVA son herramientas útiles para discriminar entre las dunas desérticas y costeras. Algunas similitudes se detectaron en las distribuciones de tamaño de grano entre el Desierto de Altar (Mz=1.34ϕ – 2.79ϕ; σ=0.35ϕ – 1.60ϕ) y Kalahari (Mz=1.55ϕ – 2.38ϕ; σ=0.51ϕ – 1.52ϕ) que están probablemente asociadas con la fuente de sedimento, morfología de dunas y con los patrones de viento.*

Palabras clave: dunas costeras, dunas desérticas, distribución de tamaño de grano, Sonora, México.

INTRODUCTION

Grain size distribution has been widely used by sedimentologists to elucidate transport dynamics. Grain size distribution in dune sands is largely influenced by aeolian and marine selective mechanisms and by the source material, sand availability and transportation distances (Folk, 1971; Bagnold and Barndorff-Nielsen, 1980; Pye and Tsoar, 1990; Lancaster, 1995a, 1995b; Livingstone *et al.*, 1999; Abuodha, 2003). Numerous grain-size distribution studies on different sand dune types have been performed (Vincent, 1984; Lancaster, 1986; Livingstone, 1987; Sweet *et al.*, 1988; Khalaf, 1989; Blount and Lancaster, 1990; Wang *et al.*, 2003). Moreover, differences in grain-size distribution characteristics of dune sands are closely related to dune morphology, where the sediment transport is controlled mainly by aeolian processes in the desert and aeolian and long shore drift mechanisms in the coast (Watson 1986; Thomas, 1988; Wiggs, 1997; Honda and Shimizu, 1998; Muhs *et al.*, 2003; Muhs, 2004). However, no research on grain size of desert and coastal dune sands within the region has been reported. The desert and coastal area of the Altar Desert, Sonora, Mexico provides a good area to observe the aeolian and/or marine mechanisms that dominate grain size distribution of desert and coastal dune sands. This is due to the fact that current fluvial discharges (*i.e.*, Colorado River) are, at present, negligible in their contribution to the grain size distribution in near shore sediments (Carriquiry *et al.*, 2001). Carranza-Edwards *et al.* (1988) found that sands from the backshore of the Golfo de Santa Clara and La Cholla (west of Puerto Peñasco) are medium sands, however the backshore from Las Conchas (near Puerto Peñasco) are characterized by coarse sands. These results from Carranza-Edwards *et al.* (1988) contrast with previous works on coastal dune sands where the marine, aeolian and fluvial processes determined the textural parameters and composition of the coastal dune sands (Kasper-Zubillaga and Dickinson, 2001; Abuodha, 2003). Hence, we consider that the study of desert and coastal dune sands within the same area may elucidate the dominant processes that characterize the grain size distribution of the sands from desert and coastal dunes. The aim of this paper is to distinguish between desert and coastal dunes on the basis of textural parameters of the sands in an area where the climate is the same and the river discharges are negligible.

STUDY AREA

The area is located in NW Sonora, México (Figure 1). The sampling sites are located near San Luis Río Colorado, Colorado River delta, Pinacate–Altar Biosphere Reserve, Golfo de Santa Clara and Puerto Peñasco (Figure 1).

The mean annual rainfall is less than 10 cm. Between 60 and 80% of the total rainfall occurs in July–September (Stensrud *et al.*, 1997). Onshore winds are northwesterly, southwesterly and southeasterly winds. They occur 20 to 60% of the time in one month with velocities between 2 to 6 $m \cdot seg^{-1}$ (Pérez-Villegas, 1990)

Longshore currents in the coastal area are induced by tides, winds, density gradients and geostrophy (Lavín *et al.*, 1997; Marinone and Lavín, 1997). Tides are of semidiurnal type (up to ~10 m amplitude) and induce current velocities from 1.5 to 3 $m \cdot seg^{-1}$ (Thompson, 1968; Cupul-Magaña, 1994).

The Colorado River water annual flow varies from 7.3 to 24.6×10^9 m^3 with a mean of 20.3×10^9 m^3. However, the water storage capacity in dams along the river is approximately four times the mean annual flow (Andrews, 1991). The small amount of water from the Colorado River in Mexico is stored in the Morelos Dam, hence there is no direct flow into the Gulf of California (Vandivere and Vorster, 1984).

The geology of the surrounding area comprises high-grade metamorphic and granitic (tonalite, granite and granodiorite) rocks, basalt flows and cinder cones from El Pinacate volcanic fields, and dune sands of Quaternary age (Ortega-Gutiérrez *et al.*, 1992) (Figure 1).

In the studied area, desert and coastal dunes are of linear, parabolic, crescentic, star types and sand sheets (Blount and Lancaster, 1990, Lancaster, 1995b). The desert dunes of the Altar Desert were primarily originated from the old and modern flood plains of the delta of the Colorado River since middle Pleistocene time (Blount and Lancaster, 1990).

MATERIALS AND METHODS

Sixty two sand samples were collected from the crest and slip face of linear dune sheets from the desert (San Luis Río Colorado and El Pinacate Biosphere Reserve, n=38) and the coastal zone (Golfo de Santa Clara

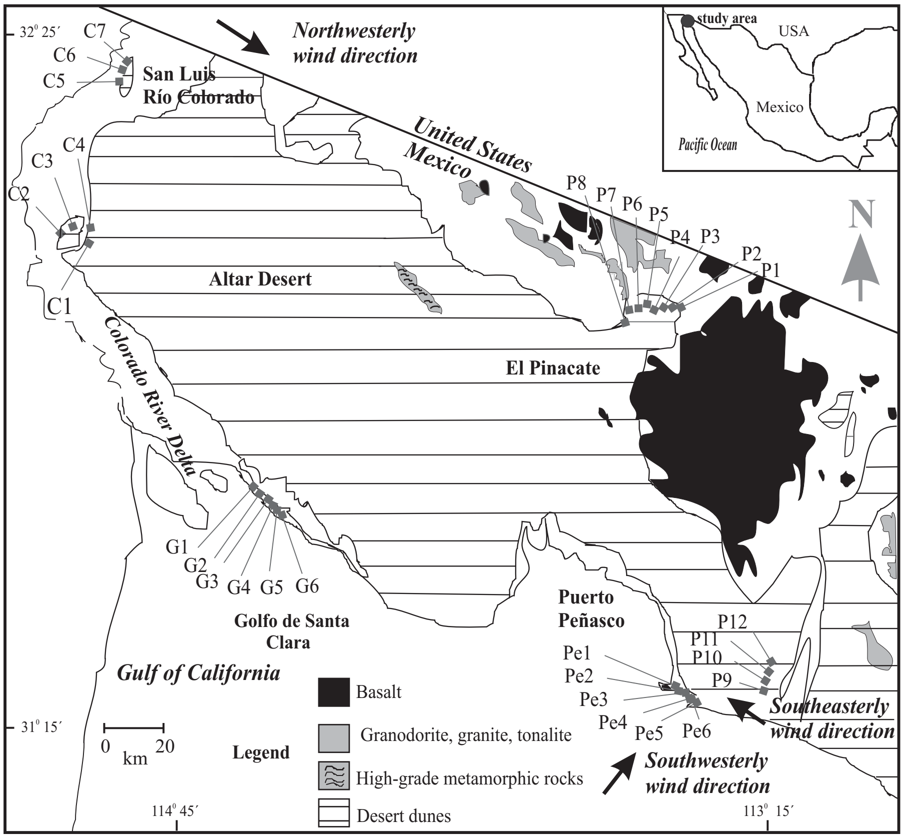

Figure 1. Sampling sites and simplified geologic map of the study area. C and P samples are from the desert dunes; G and Pe samples are from the coastal dunes.

and Puerto Peñasco, n=24) of the Altar Desert (Figure 1). Sampling was carried out during the fall–winter season (October-November).

Approximately 0.1 g of sample was used for grain size determination. Grain size distribution was obtained using a Laser Particle Size Analyzer (Model Coulter LS230),which calculates the diameter of the particle from the diffraction pattern created as the grain drops through the laser beam (Livingstone *et al.*, 1999). The Coulter equipment is used for grain size determinations of particle sizes between -1.0ϕ and 14.6ϕ. Grain size values were determined by channels analogous to sieves for each size interval in the laser equipment. Values were given in micrometer (μm) units and then converted into ϕ (phi) units. This was done in order to compute the grain size parameters on the basis of Folk (1980) classification and formulae. Limits for mean grain size (M_z) values were 0.0ϕ to 1.0ϕ for coarse sand, 1.0ϕ to 2.0ϕ for medium sands, and 2.0ϕ to 3.0ϕ for fine sand. Sorting values (σ) were <0.35ϕ for very well sorted sands, 0.35ϕ to 0.50ϕ for well sorted sands, 0.50ϕ to 0.71ϕ for moderately well sorted sands, 0.71ϕ to 1.0ϕ for moderately sorted sands, 1.0ϕ to 2.0ϕ poorly sorted sands, and 2.0ϕ to 4.0ϕ for very poorly sorted sands. Skewness (Ski) values were between 1.00 to 0.30 for strongly fine-skewed sands, 0.30 to 0.10 for fine-skewed sands , 0.10 to -0.10 for near symmetrical, -0.10 to -0.30 for coarse-skewed sands, and -0.30 to -1.00 for strongly coarse-skewed sands. Kurtosis (K_G) values were between 0.67 to 0.90 for platykurtic curves, 0.90 to 1.11 for mesokurtic curves, and 1.11 to 1.50 for leptokurtic curves (Folk, 1980).

Textural parameters for this study were compared only to those obtained by laser analysis in the Kalahari desert sands, since comparison of absolute grain size values between the laser and sieving techniques might not be appropriate due to differences in the results (Livingstone *et al.*, 1999). Comparisons between the two areas were also established because the morphology of the dunes in the Altar Desert sampled sites, and the Kalahari Desert dunes is similar (*e.g.*, linear dunes).

A linear discriminant analysis was carried out for the sands from dunes of San Luis Río Colorado, Pinacate–Altar, Golfo de Santa Clara and Puerto Peñasco. This was performed to discriminate between the four localities based on the grain-size distribution parameters.

A one-way ANOVA test was performed to assess significant differences in the mean values between the sands of desert and coastal dunes. Kolmogorov-Smirnov normality and Levene´s homogeneity of variances tests were previously performed for the sand groups of desert and coastal dunes.

RESULTS AND DISCUSSION

Grain size parameters of the sands from the four sampled localities are shown in Tables 1, 2 and 3. The results of the linear discriminant analysis for the grain size parameters are presented in Tables 4 and 5.

San Luis Río Colorado and El Pinacate desert dune sands are formed by fine grained sands whereas the Golfo de Santa Clara and Puerto Peñasco coastal dune sands are medium sands (Table 3). The San Luis Rio Colorado, Golfo de Santa Clara and Puerto Peñasco dune sands are moderately sorted whereas the El Pinacate desert dune sands are well sorted. San Luis Río Colorado and the Golfo de Santa Clara are fine-skewed sands whereas those from Puerto Peñasco coastal dune sands are coarse-skewed sands. The El Pinacate sands are symmetrical and kurtosis values indicate that the dune sands from the four localities have leptokurtic distributions; this is commonly observed in sands from the dune environment (Khalaf, 1989; Wang *et al.*, 2003).

Fine-grained sands from the San Luis Río Colorado and El Pinacate dunes might have been transported by northwesterly wind patterns coming from the Salton Trough and with their source in the Colorado River delta sediments. These wind patterns have also been observed for the Algodones dune fields near the US and Mexican border and close to the San Luis Río Colorado site (Muhs *et al.*, 2003; Muhs, 2004). The fine grain size is due to selectiveness of the wind to concentrate fine particles in the dune. In contrast, coarse-grained sands from the Golfo de Santa Clara and Puerto Peñasco dunes are related to high tidal regimes, longshore drifts, and aeolian processes, since the Golfo de Santa Clara coastal dune sands are likely to be controlled by tidal waves that induce current velocities from 1.5 to 3 $m \cdot seg^{-1}$ and longshore drifts with velocities of 4 $cm \cdot seg^{-1}$(Cupul-Magaña, 1994; Fernandez-Eguiarte *et al.*, 1992). These currents and longshore drifts may concentrate medium sands in the beach that are transported onto the dune by onshore southwesterly and southeasterly winds, having velocities from 4 to 6 $m \cdot seg^{-1}$ (Pérez-Villegas, 1990). Coarsening of the Golfo de Santa Clara dune sands may be due to wind deflation of fine grains leaving behind the coarse fraction in the sands (Khalaf, 1989). The Puerto Peñasco sand dunes concentrate medium-size grains because a large proportion of the beach sand composition corresponds to shell debris. The area is located in a semi-protected bay with negligible direct fluvial discharges and clear waters that enables the preservation of small mollusks in the beach sand (Komar, 1976, Carranza-Edwards, *et al.*, 1996). Hence, biogenic debris are transported and deposited from the beach onto the dune by local wind action.

Table 1. Grain size parameters of sands from desert dunes (n=38).

Sample	Mz	σ	Ski	K_G
C1c	2.064	0.856	0.125	1.121
C1f	2.528	1.609	0.491	1.828
C2c	1.960	1.002	0.117	1.515
C2f	2.046	0.845	0.307	1.280
C3c	2.147	1.046	0.314	1.026
C3f	1.947	0.881	0.335	0.892
C4c	2.090	0.934	0.191	1.060
C4f	2.024	0.951	0.191	0.920
C5c	2.114	1.152	0.335	1.136
C5f	1.963	1.133	0.391	1.202
C6c	2.061	0.777	0.196	1.057
C6f	1.880	0.895	0.155	1.140
C7c	1.972	0.655	0.178	1.059
C7f	2.125	0.689	0.122	1.051
P1c*	2.562	0.449	0.057	1.046
P1f*	2.498	0.403	0.074	1.026
P2c*	2.617	0.393	0.052	0.995
P2f*	2.651	0.368	0.040	0.967
P3c*	2.517	0.490	0.040	1.040
P3f*	2.464	0.382	0.054	0.981
P4c*	2.602	0.380	0.054	0.986
P4f*	2.677	0.385	0.059	0.982
P5c*	2.712	0.423	0.074	1.022
P5f*	2.547	0.386	0.043	0.977
P6c*	2.630	0.429	0.058	1.028
P6f*	2.543	0.436	-0.004	1.040
P7c*	2.697	0.421	0.026	1.004
P7f*	2.759	0.409	0.065	1.025
P8c*	2.680	0.371	0.035	0.951
P8f*	2.590	0.384	0.033	0.968
P9c**	2.756	0.495	-0.017	1.027
P9f**	2.796	0.560	-0.090	1.143
P10c**	2.566	0.562	-0.022	1.013
P10f**	2.648	0.513	-0.029	1.038
P11c**	2.460	0.644	-0.092	0.967
P11f**	2.443	0.720	-0.169	0.938
P12c**	2.665	0.715	-0.252	1.218
P12f**	2.348	0.842	-0.237	0.944
average	2.404	0.658	0.087	1.069
S.D.	0.291	0.291	0.160	0.170

M_z: mean graphic size; σ: sorting; Ski: skewness; K_G: kurtosis. C: San Luis Río Colorado; P*: El Pinacate north; P**: El Pinacate south S.D.: standard deviation; c: crest; f: flank; values in ϕ units.

Table 2. Grain size parameters of sands from coastal dunes (n=24).

Sample	Mz	σ	Ski	K_G
G1c	1.905	0.895	0.172	1.021
G1f	1.823	0.787	0.329	1.091
G2c	1.476	0.534	0.164	1.292
G2f	1.671	0.607	0.237	1.194
G3c	1.850	0.653	0.159	1.050
G3f	1.637	0.547	0.128	1.101
G4c	1.629	0.534	0.178	1.108
G4f	1.340	0.356	0.030	0.958
G5c	1.679	0.576	0.286	1.190
G5f	1.582	0.554	0.179	1.132
G6c	1.720	0.571	0.042	1.061
G6f	1.677	0.479	0.115	1.044
Pe1c	1.602	0.732	-0.184	1.187
Pe1f	1.346	0.772	-0.206	1.035
Pe2c	1.477	0.702	-0.090	1.196
Pe2f	1.693	0.700	-0.051	1.246
Pe3c	1.793	0.977	-0.167	0.955
Pe3f	1.967	0.871	-0.320	1.194
Pe4c	1.876	0.741	-0.123	1.085
Pe4f	2.137	0.603	-0.121	1.190
Pe5c	2.031	0.616	-0.131	1.160
Pe5f	2.308	0.498	0.022	1.039
Pe6c	1.808	0.931	-0.208	1.060
Pe6f	1.900	0.946	-0.301	1.167
average	1.747	0.674	0.006	1.115
S.D.	0.233	0.165	0.189	0.088

M_z: mean graphic size; σ: sorting; Ski: skewness; K_G: kurtosis. G:Golfo de Santa Clara; Pe: Puerto Peñasco; S.D. : standard deviation; c: crest; f: flank; values in ϕ units.

Table 3. Average values of grain size parameters for each locality and results of ANOVA tests for each parameter between localities.

Locality	Type	Mz	σ	Ski	K_G
		Average values			
SLRC	DD	2.07	0.96	0.25	1.16
PN	DD	2.61	0.54	-0.05	1.02
PS	DD	2.58	0.63	-0.11	1.03
GSC	CD	1.67	0.59	0.17	1.1
PP	CD	1.83	0.76	-0.16	1.13
		ANOVA test (F values)			
SLRC–PN	DD–DD	**149.17**	**85.02**	**46.21**	**6.83**
SLRC–GSC	DD–CD	**42.84**	**22.18**	**3.68**	0.64
PN–PS	DD–DD	0.23	**49.92**	**43.99**	1.62
GSC–PP	CD–CD	**3.19**	**7.98**	**74.11**	0.38
PP–PN	CD–DD	**117.32**	**83.71**	**67.83**	**27.52**
PP–PS	CD–DD	**49.65**	**3.93**	0.96	**4.57**

M_Z: mean graphic size; σ: sorting; Ski: skewness; K_G: kurtosis. DD: desert dunes; CD: coastal dunes; values in ϕ units. F: values for significance; SLRC: San Luis Río Colorado; PN: El Pinacate north; PS: El Pinacate south; GSC: Golfo de Santa Clara; PP: Puerto Peñasco. Bold type face are the most significant F values with confidence level (ρ)=0.00, 0.06, 0.08.

The sorting values suggest that the San Luis Río Colorado, Golfo de Santa Clara and Puerto Peñasco dune sands have been subjected to little transport from the source area to the dune system and to different physical processes like tides, longshore drifts and winds that control grain size distributions. In the San Luis Río Colorado desert dune sands, it is likely that the closeness of the dune system to the sediment source may have influenced the moderately sorted values. It has been observed that with a short distance between the dunes and the source of sediments, moderately to poorly-sorted sediments are present (Blount and Lancaster, 1990). Better sorted sediments are linked to longer transport, and more homogeneous processes in the sediments (Leeder, 1982; Carranza-Edwards, 2001). The Golfo de Santa Clara and the Puerto Peñasco coastal dune sands are probably more influenced by mixing of sediments produced in a high tidal regime and by aeolian processes, resulting in moderately sorted sands. However, in the Puerto Peñasco site, the dunes are not only affected by marine and aeolian mechanisms but also by the high content of shell fragments. Waves do not seem to play a role in the concentration of the shells since they have negligible influence on the redistribution of the sands due to their low amplitude (~0.30 m) (Buoy Weather, 2005).

Table 5. Mahalanobi´s square roots distances from the linear discriminant analysis.

	San Luis Río Colorado	El Pinacate	Golfo de Santa Clara	Puerto Peñasco
San Luis Río Colorado	0	41.85	10.94	21.51
El Pinacate		0	**52.90**	29.60
Golfo de Santa Clara			0	16.90
Puerto Peñasco				0

Bold type face value is the largest distance between the two groups.

Table 4. Linear discriminant analysis summary of the sands from San Luis Río Colorado, El Pinacate, Golfo de Santa Clara and Puerto Peñasco dunes.

Variable*	Wilks' Lambda	Partial Lambda	F-remove	p-level	Tolerance
Mz	0.12	0.14	**106.15**	0.00	0.84
σ	0.03	0.52	16.73	0.00	0.80
Ski	0.06	0.28	**46.45**	0.00	0.85
K_G	0.02	0.91	1.74	0.16	0.76

* Fcritical (12,145)=42.480, p<0.0000. M_Z: mean graphic size; σ: sorting; Ski: skewness; K_G: kurtosis. Bold type face values are the most significant values.

Skewness values of the four localities suggest that the San Luis Río Colorado and Golfo de Santa Clara dune sands are fine skewed whereas Puerto Peñasco coastal dune sands are coarse skewed. The skewness values reflect the influence of coastal processes in the grain size distribution but also of the mixing of siliciclastic and biogenic debris in the dune sands from Puerto Peñasco. The symmetrical curves of El Pinacate desert sands reveal the dominantly aeolian character of the sands. This has also been observed in the Kuwaiti desert dunes (Khalaf, 1989).

Kurtosis values for the four localities of the dune sands shows that the central part of the distribution is better sorted than the tails. The general trend for the four dune fields is shown in Figure 2. It can be observed that fine-grained sands are better sorted than coarse-grained sands. This pattern has been reported also in beach sands (Carranza-Edwards, 2001).

Discrimination between desert and coastal dune sands

Average mean grain size values for the desert and coastal dune sands are 2.40ϕ and 1.74ϕ, respectively, *i.e.*, from medium to fine sands (Table 6). Average sorting values are 0.65ϕ and 0.67ϕ for the desert and coastal dune sands respectively. These values indicate moderately well sorted sands in both environments.

Average skewness values are 0.08ϕ and 0.006ϕ and show symmetrical and slight coarse curves for the desert

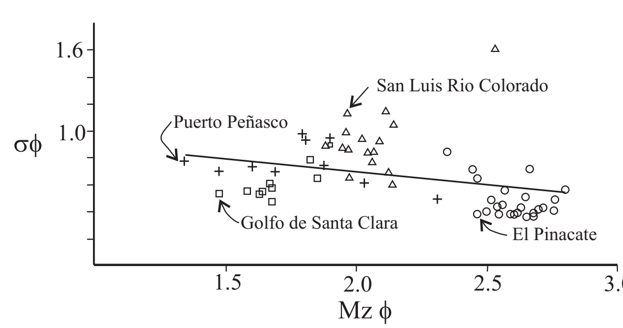

Figure 2. Grain-size and sorting diagram for the desert and coastal dune sands.in the Altar desert.

Table 6. Summary of the average and range of grain size data of sand dunes from the Altar Desert, Mexico and the Kalahari Desert, Southern Africa.

	Type areas		
	Altar desert dunes (SLRC, EP)	**Altar coastal dunes (GSC, PP)**	**Kalahari Desert, Southern Africa**
Mz (ϕ)	2.4 (1.88–2.79)*	1.74 (1.34–2.30)*	(1.55–2.38)**
σ (ϕ)	0.65 (0.36–1.60)*	0.67 (0.35–0.97)*	(0.51–1.52)**
Ski	0.08 (-0.09–0.49)*	0.006 (-0.30–0.32)*	(0.08–0.34)**
K_G	1.06 (0.93–1.82)*	1.11 (0.95–1.29)*	(1.20–1.86)**

M_z: mean graphic size; σ: sorting; Ski: skewness; K_G: kurtosis. * range values from this study; ** range values from Livingstone *et al.* (1999); ϕ=phi units. SLRC: San Luis Río Colorado; EP: El Pinacate; GSC: Golfo de Santa Clara; PP: Puerto Peñasco.

and coastal dune sands respectively. Average kurtosis values of 1.06 and 1.11 for the sands of desert and coastal dunes indicate leptokurtic distributions (Table 6).

The linear discriminant analysis shows that the variables that better discriminate the sands between the San Luis Río Colorado, El Pinacate, Golfo de Santa Clara and Puerto Peñasco dunes are grain size and skewness (Table 4). Furthermore, the group formed by the El Pinacate desert dune sands is separated from the rest of the groups (Figure 3).

The linear discriminant analysis reveals that the San Luis Río Colorado and El Pinacate desert dune sands are statistically different. This is also revealed by the ANOVA test between the two sites (Table 3). Both dune fields show sands with finer sizes than the Golfo de Santa Clara and Puerto Peñasco coastal dune sands (Tables 1, 2 and 3). This suggests that the prevailing mechanism in the first two localities is the wind action, which deposits fine grains due to its selectiveness.

In contrast, medium-size grains deposited in the Golfo de Santa Clara and Puerto Peñasco coastal dune sands respond to the influence of southwesterly and southeasterly winds in tidal flats that transport the grains landwards. Furthermore, the Puerto Peñasco biogenic sediments control the grain size distributions of the dunes as supported by significant differences between the El Pinacate and Golfo de Santa Clara dune fields (Table 3). Coarser grains in the coastal dune sands as compared to the desert dune sands might be controlled by the wind deflation of fine grains, and transport of coarse grains from the beach sands onto the coastal dune (Khalaf, 1989).

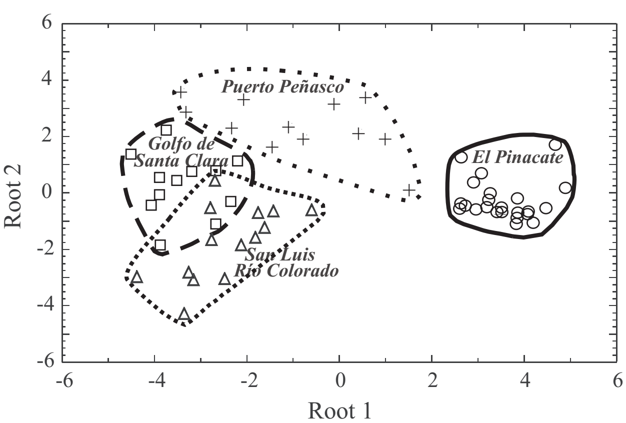

Figure 3. Linear discriminant analysis. Canonical plots of Root 1 *vs.* Root 2 for the four dune groups in the Altar desert. Root 1 and 2 represent the best linear fit when variables are reduced to Roots.

According to Blount and Lancaster (1990) and Muhs *et al.* (2003), three potential sediment sources for the "Gran Desierto Sand Sea" (Altar Desert) can be identified: fluvial and deltaic sediments from the Colorado River (Merriam, 1969), beaches of the Gulf of California (Ives, 1959) and alluvial fans and streams that originate in the Pinacate Volcanic Complex and the metamorphic and plutonic rocks to the north (Figure 1).

In the present study, coarser grains of the coastal dune sands as compared to the desert dune sands may have been inherited from the sediments in the Colorado River delta (Blount and Lancaster, 1990; Muhs *et al.*, 2003). The sediments of the Colorado River delta may have undergone wind deflation that locally transports medium-size grains onto the beach and the coastal dunes (Sagga, 1993; Blount and Lancaster, 1990). This is supported also by the fact that the sands have symmetrical to slight coarse-skewed values indicating addition of coarse grains in the sands (Khalaf, 1989).

Significant differences between the two, desert and coastal dune sites, are also supported by the ANOVA test (Table 3). This is especially observed between the San Luis Río Colorado and Golfo de Santa Clara and the El Pinacate (north and south) and the Puerto Peñasco site (Table 3). Despite the fact that the first two localities are relatively close, they are influenced by: a) northwesterly winds and closeness to the sediment source that might transport medium to fine sand grains to the San Luis Río Colorado dunes, and b) southwesterly and southeasterly winds, tides and longshore drifts that coarsens the Golfo de Santa Clara sands. The El Pinacate and Puerto Peñasco sites are also relatively close together, but northwesterly winds and long distance from the sediment source control the characteristics of the El Pinacate dune sands; near shore, aeolian processes, and biogenic debris influence the grain size distributions of the Puerto Peñasco dune sands.

Sorting is a useful tool to separate groups of dunes based on the dune morphology (Blount and Lancaster, 1990; Livingstone *et al.*, 1999), although in the present study sorting values between desert and coastal dune sands are similar as revealed by the linear discriminant analysis and the ANOVA test (Tables 4, 5 and 7). However, when testing for ANOVA between the San Luis Río Colorado and Golfo de Santa Clara we observed significant differences in sorting values. This could be associated to the closeness of source

Table 7. ANOVA test for statistical significance between the means of grain size (Mz), sorting (σ), skewness (Ski) and kurtosis (K_G) for sands from coastal and desert dunes.

Variable	Ms effect	Ms error	F	ρ
Mz	6.34	0.72	**86.96**	**0.00**
σ	0.00	0.06	0.06	0.79
Ski	0.09	0.02	**3.29**	**0.07**
K_G	0.03	0.02	1.49	0.22

Ms effect: variance between the two groups; Ms error: variance within each group; F: Ms effect/Ms error; ρ: level of confidence. Boldtype face values are the most significant values.

sediments and to marine processes in San Luis Río Colorado and Golfo de Santa Clara, respectively. Similar differences found with the ANOVA test between the El Pinacate and Puerto Peñasco sorting values are related to differences in local aeolian and marine processes that control the sorting values in both sites (Table 3).

When testing for ANOVA for individual sites we observed less significant skewness differences between San Luis Río Colorado and the Golfo de Santa Clara (ρ=0.06) than the skewness values observed between El Pinacate north and Puerto Peñasco (ρ=0.00) (Table 3). This also supports that the overall trends in skewness values reflect the eolian mechanisms that prevail in El Pinacate dune sands and the marine/aeolian processes and biogenic composition of the sands in Puerto Peñasco.

The Altar Desert and the Kalahari Desert dune sands

In this study, the range and average values of the grain size parameters for the Altar Desert dune sands are approximately within the range of previously published studies, based on laser grain size measurements, in the Kalahari Desert dune sands (Livingstone *et al.*, 1999) (Table 6).

A wider range in the grain size values for the Altar Desert (Mz=1.34ϕ – 2.79ϕ) dune sands as compared to the Kalahari Desert dune sands (Mz=1.55ϕ – 2.38ϕ) are observed. This may be due to the fact that the Colorado River delta sediments are a potential active source for grain size distributions in the Altar Desert (Muhs *et al.*, 2003) whereas the Kalahari Desert dune sands are probably being feed by local sand sheet sources that remain largely inactive for much of the time under the present climatic regimen (Livingstone *et al.*, 1999).

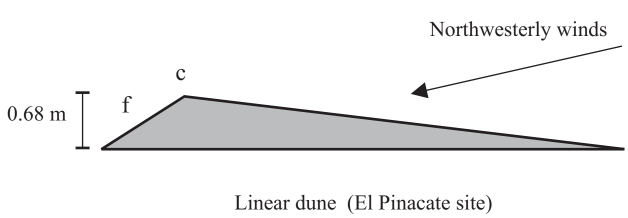

Figure 4. Schematic profile of an example of a linear dune near El Pinacate site (taken from Solís-Limón, 2003) showing the height and dominant wind direction. c: crest; f: flank.

Sorting values in the Altar Desert dune sands (σ= 0.36ϕ – 1.60ϕ) may be compared to the Southwest Kalahari Desert dune sands sorting values (σ=0.51ϕ – 1.52ϕ). From this comparison, we infer that similar aeolian processes are taking place for both desert areas. This statement is supported by the fact that sampling work in the Altar Desert was carried out during the fall–winter, when the northwesterly winds normally blow with a slight perpendicular direction to the linear dunes (Pérez-Villegas, 1990; Blount and Lancaster, 1990) (Figure 4). Besides, similar dune morphology (linear dunes) may control the sorting values for both desert dunes

Skewness values for the Altar Desert and the Kalahari are within the range of near symmetrical and fine-skewed sands corresponding to desert sands (Folk, 1980; Livingstone *et al.*, 1999). Kurtosis values of the coastal and desert dune sands indicate a leptokurtic distribution that might be a response to symmetrical distributions (Folk, 1980). These values cannot be compared to those reported by Livingstone *et al.* (1999) because they do not fit the description made by the author in the Kalahari desert dunes.

CONCLUSIONS

Significant differences between the textural parameters of sands from coastal and desert dunes were found in the Altar Desert. El Pinacate desert dune sands are significantly different from the San Luis Río Colorado, Golfo de Santa Clara and Puerto Peñasco dune sands in terms of grain size and skewness. This is due to the selectiveness of the wind that concentrates finer sizes with longer northwesterly wind patterns that transports sand from the source to the El Pinacate dune sands. The grain size distributions for the San Luis Río Colorado, Golfo de Santa Clara and Puerto Peñasco dune sands are controlled by their closeness to the sediment sources, tidal regimes, longshore drifts and wind direction. However, the grain size distribution of the Puerto Peñasco dune sands is also affected by the composition of the beach sands, which include biogenic debris. The linear discriminant analysis and ANOVA test are useful tools to discriminate between desert and coastal dune sands. Grain size, skewness and kurtosis range values are similar for the Altar Desert sands and the Kalahari Desert sands. These similarities are probably associated with the distance of the sediment source of the sands, similar wind patterns and dune morphology.

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