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# Sedimentological, modal analysis and geochemical studies of desert and coastal dunes, Altar Desert, NW Mexico

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## Abstract

**Sedimentological, compositional and geochemical determinations were carried out on 54 desert and coastal dune sand samples to study the provenance of desert and coastal dunes of the Altar Desert, Sonora, Mexico. Grain size distributions of the desert dune sands are influenced by the Colorado River Delta sediment supply and wind selectiveness. The desert dune sands are derived mainly from the quartz-rich Colorado River Delta sediments and sedimentary lithics. The dune height does not exert a control over the grain size distributions of the desert dune sands. The quartz enrichment of the desert dune sands may be due to wind sorting, which concentrates more quartz grains, and to the aeolian activity, which has depleted the feldspar grains through subaerial collisions. The desert dune sands suffer from little chemical weathering and they are chemically homogeneous, with chemical alteration indices similar to those found in other deserts of the world. The desert sands have been more influenced by sedimentary and granitic sources. This is supported by the fact that Ba and Sr concentration values of the desert sands are within the range of the Ba and Sr concentration values of the Colorado River quartz-rich sediments. The Sr values are also linked to the presence of Ca-bearing minerals. The Zr values are linked to the sedimentary sources and heavy mineral content in the desert dunes.**

**The Golfo de Santa Clara and Puerto Peñasco coastal dune sands are influenced by long shore drift, tidal and aeolian processes. Coarse grains are found on the flanks whereas fine grains are on the crest of the dunes. High tidal regimens, long shore drift and supply from Colorado Delta River sediments produce quartz-rich sands on the beach that are subsequently transported into the coastal dunes. Outcrops of Quaternary sedimentary rocks and granitic sources increase the sedimentary and plutonic lithic content of the coastal dune sands. The chemical index of alteration (CIA) values for the desert and coastal dune sands indicate that both dune types are chemically homogeneous. The trace element values for the coastal dune sands are similar to those found for the desert dune sands. However, an increase in Sr content in the coastal dune sands may be due to more $CaCO_3$ of biogenic origin as compared to the desert dune sands. Correlations between the studied parameters show that the dune sands are controlled by sedimentary sources (e.g. Colorado River Delta sediments), since heavy minerals are present in low percentages in the dune sands, probably due to little heavy mineral content from the source sediment; grain sizes in the dune sands are coarser than those in which heavy minerals are found and/or the wind speed might not exert a potential entrainment effect on the heavy mineral fractions to be transported into the dune.**

**A cluster analysis shows that the El Pinacate group is significantly different from the rest of the dune sands in terms of the grain-size parameters due to longer transport of the sands and the long distance from the source sediment, whereas the Puerto Peñasco coastal dune**

**sands are different from the rest of the groups in terms of their geochemistry, probably caused by their high $CaCO_3$ content and slight decrease in the CIA value. Copyright © 2006 John Wiley & Sons, Ltd.**

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**Keywords: desert dunes; coastal dunes; grain size parameters; modal analysis; major elements; chemical index of alteration (CIA); trace elements (TEs); Sonora, Mexico**

## Introduction

Regional variations in the sedimentological, mineralogical and geochemical composition of desert and coastal dune sands have been reported in several studies (Bagnold, 1941; Folk, 1971; Lancaster, 1988, 1989, 1992, 1995; Liu *et al.*, 1993; Honda and Shimizu, 1998; Livingstone *et al.*, 1999; Kasper-Zubillaga and Dickinson, 2001; Honda *et al.*, 2004; Muhs, 2004; Wang *et al.*, 2003; Sweet *et al.*, 1988). Some of these studies have focused on modal analysis (composition analysis by point counting of minerals) whereas others have utilized major and trace elements composition as proxies for mineralogy.

The Altar Desert in the northwestern part of Mexico (also called the Gran Desierto) covers an area of 5700 km$^2$ (Blount and Lancaster, 1990; Lancaster, 1992) and is a good natural laboratory for inland desert and coastal dune research. It has three possible sediment sources: (1) fluvial and deltaic sediments from the Colorado River (Merriam, 1969), (2) beach sediments from the Gulf of California (Ives, 1959) and (3) alluvial fan and stream sediments that originate in the Pinacate Volcanic Complex and the PreCambrian plutonic rocks in the northern part of the study area. In addition, river discharges in the south of the Altar desert may also have influenced the composition of the coastal dunes. The area has been studied in terms of grain-size and detrital modes for provenance implications (Merriam, 1969; Blount and Lancaster, 1990; Lancaster 1992). However, no sedimentological, modal analysis or geochemical research has been carried out in either the desert or the coastal sand dunes from the Altar Desert for provenance interpretation. To the north of our study area, however, Zimbelman and Williams (2002), Muhs *et al.* (2003) and Muhs (2004) studied the sand dunes in the southwestern United States, providing a framework of mineralogical, geochemical and magnetic mineralogical data to infer the aeolian transport pathways of the sands.

In this paper, we focus our attention on the provenance of the inland desert and coastal dunes of the Altar Desert, based on the sedimentology, modal analysis and geochemistry of major and trace elements of the sands. Our study uses grain size parameters and petrographic and geochemical data as a contribution to the origin of dunes in desert and coastal dunes and it provides a new database for the Altar Desert in northwestern Mexico.

## Study Area

The study area is located in the state of Sonora, in northwestern Mexico (31–32° 25′N; and 113° 85′ to 115° W) (Figure 1). Sampling sites are located in the San Luis Río Colorado, El Pinacate, Golfo de Santa Clara, and Puerto Peñasco areas (Figure 1). The climate in the Altar Desert is dry with an average annual rainfall of less than 10 cm. Between 60 and 80 per cent of the total rainfall occurs during the July–September season (Stensrud *et al.*, 1997). Onshore winds are northwesterly, southwesterly and southeasterly. They occur 20–40 per cent of the time per month with velocities between 2 and 6 m s$^{-1}$ (Pérez-Villegas, 1990). Overall, winds generate 25–30 per cent of annual potential sand transport as opposed to long shore currents (Blount and Lancaster, 1990). Long shore currents in the coastal area of the northern Gulf of California are induced by tides, winds, density gradients, and geostrophy (Lavin and Badan-Dangon, 1997; Marinone and Lavin, 1997). A northward long shore drift in winter is approximately 4 cm s$^{-1}$ (Fernandez-Eguiarte *et al.*, 1990). The semidiurnal tides in the area (up to ~10 m amplitude) induce current velocities from 1·5 to 3 m s$^{-1}$ (Thompson, 1968; Cupul, 1994). Annual discharge of the Colorado River varies from 7·3 to $24{\cdot}6 \times 10^9$ m$^3$ with a mean of $20{\cdot}3 \times 10^9$ m$^3$. However, the water storage capacity in dams along the river is approximately four times the mean annual flow (Andrews, 1991). At present, no direct water flow to the Gulf of California is observed because of water storage in the Morelos Dam, Mexico (Vandivere and Vorster, 1984). To the east, the Sonoyta River flows intermittently throughout the southern part of the area and discharges into the Gulf of California (Figure 1). The geology of the area comprises volcanic, sedimentary, metamorphic and plutonic rocks (Ortega-Gutiérrez *et al.*, 1992) (Figure 1). The desert and coastal dunes are dominated by linear, parabolic, crescentic and star dunes, and aeolian sand sheets (Blount and Lancaster, 1990; Lancaster, 1995).

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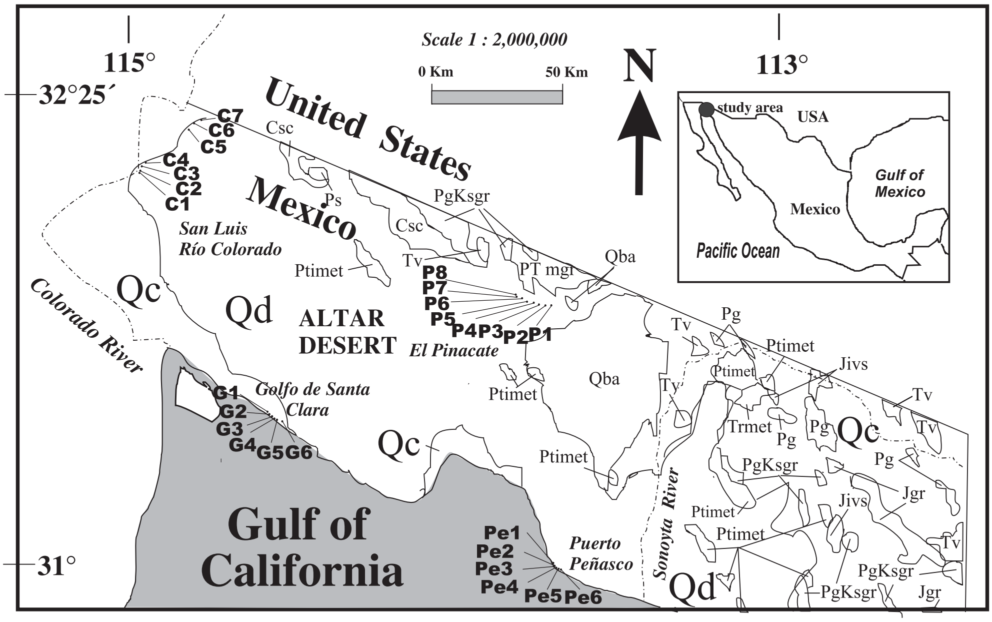

**Figure 1.** Geology and sampling sites of the studied area. Volcanic and sedimentary units are Qba, Quaternary volcanic rocks (andesites and basalts); Tv, continental volcanic rocks (Mezosoic) (basalts, andesites, dacites, ryolites); Jivs, volcano-sedimentary units (Jurassic); Csc, continental sedimentary units (Cenozoic); Ps, marine sedimentary units (Upper Paleozoic) (orthoquartzites, limestones, sandstones, conglomerates, siltstones); Qc, continental sedimentary units (Quaternary) (sandstone, quartzites); D, sand dunes.

Metamorphic and plutonic units are PT mgr, Proterozoic granitic rocks; Ptimet, metamorphic (Proterozoic) (quartzites, gneiss, schists, and amphibolites); Trmet, metamorphic (Triassic); PgKsgr, granitic rocks (Upper Cretaceous to Early Cenozoic); PgKsgr, granitic rocks (Upper Cretaceous); Jgr, granitic rocks (Jurassic). (From Ortega-Gutiérrez *et al.*, 1992; Fernández *et al.*, 1993).

## Materials and Methods

During October–November 2002, 54 dune sand samples were collected from the Altar Desert and the Golfo de Santa Clara and Puerto Peñasco areas. Samples were collected from the crest and slip face (flank) in both linear dones and aeolian sand sheets with moderate height (2–5 m) in the desert and coastal area of the Altar Desert (Figure 1(A)). Approximately 0·1 g of sample was used for grain size determination. Textural parameters were determined using a laser particle size analyzer (model Coulter LS230). The Coulter analyzer can be used for grain-size determinations of particle sizes between $-1{\cdot}0\ \phi$ and $14{\cdot}6\ \phi$. Laser particle-size analysis has been used in aeolian sands, producing particle-size distributions of better resolution using much smaller samples (Livingstone *et al.*, 1999). This is because the laser provides an average measure of all possible diameters in a given particle (Livingstone *et al.*, 1999). In contrast, the sieve analysis allows particles whose shortest diameters will fit through a square aperture of a designated size to pass (Livingstone *et al.*, 1999). Shi (1995) found that differences between laser analysis and sieve data were consistent and can be mathematically modeled (Murray and Holtum, 1996; Shillabeer *et al.*, 1992). Although comparison of absolute values between the two techniques (laser and sieving) should be taken with care, comparisons of variability patterns between samples are still valid (Livingstone *et al.*, 1999).

Modal mineralogical determinations were carried out by counting 200 grains per slide based on the method proposed by Rooney and Basu (1994). The grain types counted were total quartz (Qt), including monocrystalline and polycrystalline quartz, total feldspar (Ft), which includes potash feldspars plus plagioclase, and total lithic fragments (Lt), which are subdivided into volcanic lithics (Lv), sedimentary lithics (Ls), metamorphic lithics (Lm) and plutonic lithics (Lp). Accessories were biogenic fragments (mainly broken shells), heavy minerals and mica.

Major and trace element compositions were determined for bulk sand composition using X-ray fluorescence with a Siemens SRS 3000 instrument. Chemical index of alteration (CIA) determinations were based on the equation $\mathrm{CIA} = 100(\mathrm{Al_2O_3}/\mathrm{Al_2O_3} + \mathrm{CaO} + \mathrm{Na_2O} + \mathrm{K_2O})$ (Nesbitt and Young, 1996; Honda and Shimizu, 1998).

## Results and Discussion

### Grain-size parameters of the inland desert dune sands

Aeolian sands from the San Luis Río Colorado and the El Pinacate areas (both inland dunes) are fine grained and moderately to well sorted, respectively (Table I). The San Luis Río Colorado dune sands are fine skewed whereas the El Pinacate dune sands are nearly symmetrical. Sands from both areas show leptokurtic distributions. The San Luis Río Colorado dune sands have an average grain size of 2·07 $\phi$ on the crest and of 2·05 $\phi$ on the flank. Average sorting values are 1·0 $\phi$ on the crest and 0·91 $\phi$ on the flank. The skewness values are 0·2 on the crest and 0·28 on the flank. The kurtosis values are 1·13 on the crest and 1·18 on the flank. The grain-size, sorting, skewness and kurtosis values do not show significant changes between the crest and the flank of the dune.

According to Livingstone *et al.* (1999), grain-size variations between dunes are related to the height of the dune. For example, in the Namib Desert of Africa, dunes with great heights exhibit the greatest variation in grain size. This is due to the fact that coarse grains do not reach the crest in dunes with great heights, leading to coarse and fine grains in the flank and crest, respectively. Moreover it seems that there is a progressive fining of sand from dune base to dune crest (Livingstone, 1987). In our study, the height of the San Luis Río Colorado dunes probably exerts a only modest control over the homogeneity of the grain-size distribution because, according to our field observations, dunes are less than 5 m high. It seems that a more subdued topography leads to less conspicuous grain-size variations across the dune fields. Since no direct height measurements were performed in the dune fields and no direct statistical correlation was established between grain size and dune height, our interpretation is limited to the results observed in other dune fields. For example, Livingstone *et al.* (1999) observed little variation in grain size in the southwest Kalahari Desert, where dunes have a mean height of 13 m. Nevertheless, relationships between dune height and grain-size distributions cannot be adopted as a general rule, since grain-size distributions in the dune may be controlled by other factors, such as aeolian transport (e.g. creep, saltation and suspension) and wind patterns (Livingstone, 1987), among others. The small difference in the sorting values between the crest and the flank of the San Luis Río Colorado dunes may be due to the fact that the dune morphology exerts control over the sorting. Moderate sorting in the San Luis Río Colorado dune sands might result from the wind blowing parallel to the dune but could also be a function of the hypothesized source sediment (the Quaternary deposits of the Colorado Delta) that generates particles with wide ranges in sizes (Blount and Lancaster, 1990).

The El Pinacate dune sands have an average grain size of 2·59 $\phi$ on the crest and of 2·62 $\phi$ on the flank. Average sorting values are 0·39 $\phi$ on the crest and 0·41 $\phi$ on the flank. Skewness values are 0·04 for the crest and flank and the kurtosis values are 1·00 for the crest and 0·99 for the flank.

Significant differences between the average grain sizes from crests and flanks of the dunes were not found. This may be due to the fact that the height of the El Pinacate dunes is also low (less than 10 m). This produces, as in the San Luis Río Colorado dunes, less variable grain sizes across the dune. Sorting in the El Pinacate dune sands is, however, better than in the San Luis Río Colorado dune sands. This may be due to the grain-size distribution of the one (and only) hypothesized sediment source (e.g. the Colorado River Delta) that generates only particles between 2 $\phi$ and 3 $\phi$; hence, dunes have better sorted sands. It could also be due to the fact that the El Pinacate dune field is farther from the source, which allows for longer aeolian transport and better sorting of the sands. The unimodal character of the skewness and kurtosis values shows that the sands are produced by only one sediment source (Khalaf, 1989).

A grain size-sorting diagram shows the separation between the San Luis Río Colorado and the El Pinacate desert dune sands (Figure 2). Concentration of grains is similar to that observed for some terrigenous beach sands in Mexico, suggesting that fine sands are well sorted, especially sands within the 2–3 $\phi$ range (Carranza-Edwards, 2001).

### Modal analysis of the desert dune sands

The San Luis Río Colorado and the El Pinacate desert dunes are quartzolithic sands ($Qt_{80}$ $Ft_9$ $Lt_{11}$ and $Qt_{84}$ $Ft_7$ $Lt_9$, respectively) (Table I). Quartz percentages are similar to those found in the Libyan Desert, the Saudi Arabian Desert and the Kuwaiti Desert (Mizutani and Suwa, 1966; Anton, 1983; Khalaf, 1989). The average data plotted in a Qt–Ft–Lt ternary diagram with the standard deviation polygons show that the San Luis Río Colorado and the El Pinacate desert dune sands have a wider dispersion towards the Qt and Lt poles (Figure 3).

Quartz-rich sources are available in the proximity of the San Luis Río Colorado and the El Pinacate areas exposed as Quaternary deposits of the Colorado River and granitic mountains along the Mexico–Arizona border (Lancaster *et al*., 1987) (Figure 1). Our observations suggest that quartz enrichment over total lithics and heavy minerals of the desert dune sands is due to the wind sorting that concentrates more quartz grains (Honda and Shimizu, 1998; Honda *et al*., 2004). However, quartz enrichment over feldspar grains may be due to the proximity of a quartz-rich source

**Table I.** Grain size parameters and detrital modes of the desert dunes and coastal dunes

| Locality | Sample | Mz | σ | Sk | Kg | Qm | Qp | Ft | Lv | Ls | Lm | Lp | acc | total | Qt | Ft | Lt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| San Luis Río Colorado | C1c | 2·53 | 1·61 | 0·13 | 1·12 | 142 | 1 | 24 | 3 | 16 | 0 | 1 | 13 | 200 | 143 | 24 | 20 |
| | C1f | 2·06 | 0·86 | 0·49 | 1·83 | 166 | 2 | 12 | 2 | 12 | 0 | 3 | 2 | 200 | 168 | 12 | 18 |
| | C2c | 2·05 | 0·85 | 0·12 | 1·52 | 152 | 7 | 12 | 3 | 19 | 0 | 0 | 7 | 200 | 159 | 12 | 22 |
| | C2f | 1·96 | 1·00 | 0·31 | 1·28 | 147 | 1 | 18 | 4 | 15 | 0 | 2 | 13 | 200 | 148 | 18 | 21 |
| | C3c | 1·95 | 0·88 | 0·31 | 1·03 | 149 | 2 | 15 | 5 | 20 | 0 | 5 | 4 | 200 | 151 | 15 | 30 |
| | C3f | 2·15 | 1·05 | 0·33 | 0·89 | 150 | 4 | 18 | 2 | 19 | 0 | 3 | 4 | 200 | 154 | 18 | 24 |
| | C4c | 2·02 | 0·95 | 0·19 | 1·06 | 155 | 3 | 15 | 2 | 17 | 0 | 2 | 6 | 200 | 158 | 15 | 21 |
| | C4f | 2·09 | 0·93 | 0·19 | 0·92 | 157 | 3 | 16 | 2 | 13 | 0 | 2 | 7 | 200 | 160 | 16 | 17 |
| | C5c | 1·96 | 1·13 | 0·34 | 1·14 | 153 | 0 | 18 | 2 | 18 | 0 | 3 | 6 | 200 | 153 | 18 | 23 |
| | C5f | 2·11 | 1·15 | 0·39 | 1·20 | 156 | 0 | 17 | 1 | 16 | 0 | 1 | 9 | 200 | 156 | 17 | 18 |
| | C6c | 1·88 | 0·90 | 0·20 | 1·06 | 154 | 3 | 18 | 1 | 12 | 0 | 1 | 11 | 200 | 157 | 18 | 14 |
| | C6f | 2·06 | 0·78 | 0·15 | 1·14 | 143 | 3 | 20 | 2 | 14 | 0 | 8 | 10 | 200 | 146 | 20 | 24 |
| | C7c | 2·13 | 0·69 | 0·18 | 1·06 | 137 | 8 | 15 | 1 | 18 | 0 | 5 | 16 | 200 | 145 | 15 | 24 |
| | C7f | 1·97 | 0·66 | 0·12 | 1·05 | 148 | 3 | 13 | 2 | 20 | 0 | 1 | 13 | 200 | 151 | 13 | 23 |
| El Pinacate | P1c | 2·50 | 0·40 | 0·06 | 1·05 | 153 | 6 | 20 | 0 | 16 | 0 | 2 | 3 | 200 | 159 | 20 | 18 |
| | P1f | 2·56 | 0·45 | 0·07 | 1·03 | 158 | 6 | 14 | 0 | 17 | 0 | 1 | 4 | 200 | 164 | 14 | 18 |
| | P2c | 2·65 | 0·37 | 0·05 | 0·99 | 160 | 0 | 12 | 1 | 17 | 0 | 7 | 3 | 200 | 160 | 12 | 25 |
| | P2f | 2·62 | 0·39 | 0·04 | 0·97 | 152 | 4 | 14 | 2 | 19 | 0 | 4 | 5 | 200 | 156 | 14 | 25 |
| | P3c | 2·46 | 0·38 | 0·04 | 1·04 | 156 | 0 | 16 | 6 | 16 | 0 | 5 | 1 | 200 | 156 | 16 | 27 |
| | P3f | 2·52 | 0·49 | 0·05 | 0·98 | 166 | 1 | 14 | 4 | 11 | 0 | 3 | 1 | 200 | 167 | 14 | 18 |
| | P4c | 2·68 | 0·39 | 0·05 | 0·99 | 166 | 3 | 14 | 3 | 4 | 0 | 3 | 7 | 200 | 169 | 14 | 10 |
| | P4f | 2·60 | 0·38 | 0·06 | 0·98 | 155 | 2 | 20 | 6 | 10 | 0 | 3 | 4 | 200 | 157 | 20 | 19 |
| | P5c | 2·55 | 0·39 | 0·07 | 1·02 | 163 | 3 | 20 | 1 | 12 | 0 | 1 | 0 | 200 | 166 | 20 | 14 |
| | P5f | 2·71 | 0·42 | 0·04 | 0·98 | 163 | 4 | 13 | 4 | 13 | 0 | 2 | 1 | 200 | 167 | 13 | 19 |
| | P6c | 2·54 | 0·44 | 0·06 | 1·03 | 165 | 5 | 18 | 1 | 8 | 0 | 3 | 0 | 200 | 170 | 18 | 12 |
| | P6f | 2·63 | 0·43 | 0·00 | 1·04 | 166 | 4 | 12 | 2 | 8 | 0 | 2 | 6 | 200 | 170 | 12 | 12 |
| | P7c | 2·76 | 0·41 | 0·03 | 1·00 | 163 | 1 | 5 | 4 | 22 | 0 | 1 | 4 | 200 | 164 | 5 | 27 |
| | P7f | 2·70 | 0·42 | 0·07 | 1·02 | 169 | 2 | 9 | 6 | 8 | 0 | 1 | 5 | 200 | 171 | 9 | 15 |
| | P8c | 2·59 | 0·38 | 0·03 | 0·95 | 165 | 1 | 13 | 6 | 12 | 0 | 0 | 3 | 200 | 166 | 13 | 18 |
| | P8f | 2·68 | 0·37 | 0·03 | 0·97 | 167 | 1 | 12 | 2 | 13 | 0 | 2 | 3 | 200 | 168 | 12 | 17 |

**Table I.** *Continued*

| Locality | Sample | Mz | σ | Sk | Kg | Qm | Qp | Ft | Lv | Ls | Lm | Lp | acc | total | Qt | Ft | Lt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Golfo de Santa Clara | G1c | 1·82 | 0·79 | 0·17 | 1·02 | 154 | 4 | 8 | 4 | 10 | 0 | 10 | 10 | 200 | 158 | 8 | 24 |
|  | G1f | 1·91 | 0·90 | 0·33 | 1·09 | 159 | 1 | 4 | 8 | 17 | 0 | 3 | 8 | 200 | 160 | 4 | 28 |
|  | G2c | 1·67 | 0·61 | 0·16 | 1·29 | 152 | 4 | 14 | 5 | 16 | 0 | 2 | 7 | 200 | 156 | 14 | 23 |
|  | G2f | 1·48 | 0·53 | 0·24 | 1·19 | 159 | 3 | 14 | 5 | 7 | 0 | 7 | 5 | 200 | 162 | 14 | 19 |
|  | G3c | 1·64 | 0·55 | 0·16 | 1·05 | 148 | 6 | 17 | 11 | 5 | 0 | 8 | 5 | 200 | 154 | 17 | 24 |
|  | G3f | 1·85 | 0·65 | 0·12 | 1·10 | 150 | 4 | 16 | 5 | 9 | 0 | 9 | 7 | 200 | 154 | 16 | 23 |
|  | G4c | 1·34 | 0·36 | 0·18 | 1·11 | 164 | 8 | 7 | 3 | 5 | 1 | 6 | 6 | 200 | 172 | 7 | 15 |
|  | G4f | 1·63 | 0·53 | 0·03 | 0·96 | 154 | 3 | 15 | 3 | 12 | 0 | 5 | 8 | 200 | 157 | 15 | 20 |
|  | G5c | 1·58 | 0·55 | 0·29 | 1·19 | 159 | 1 | 10 | 4 | 15 | 0 | 5 | 6 | 200 | 160 | 10 | 24 |
|  | G5f | 1·68 | 0·58 | 0·18 | 1·13 | 160 | 1 | 6 | 6 | 14 | 0 | 4 | 9 | 200 | 161 | 6 | 24 |
|  | G6c | 1·68 | 0·48 | 0·04 | 1·06 | 149 | 4 | 12 | 1 | 23 | 1 | 6 | 4 | 200 | 153 | 12 | 31 |
|  | G6f | 1·72 | 0·57 | 0·12 | 1·04 | 152 | 3 | 10 | 7 | 17 | 0 | 4 | 7* | 200 | 155 | 10 | 28 |
| Puerto Peñasco | Pe1c | 1·35 | 0·77 | −0·18 | 1·19 | 156 | 0 | 10 | 1 | 10 | 0 | 2 | 21* | 200 | 156 | 10 | 13 |
|  | Pe1f | 1·60 | 0·73 | −0·21 | 1·04 | 133 | 4 | 10 | 4 | 10 | 0 | 3 | 36* | 200 | 137 | 10 | 17 |
|  | Pe2c | 1·69 | 0·70 | −0·09 | 1·20 | 152 | 0 | 3 | 1 | 7 | 0 | 2 | 35* | 200 | 152 | 3 | 10 |
|  | Pe2f | 1·48 | 0·70 | −0·05 | 1·25 | 108 | 2 | 9 | 2 | 5 | 0 | 1 | 73* | 200 | 110 | 9 | 8 |
|  | Pe3c | 1·97 | 0·87 | −0·17 | 0·95 | 174 | 0 | 6 | 0 | 2 | 0 | 1 | 17* | 200 | 174 | 6 | 3 |
|  | Pe3f | 1·79 | 0·98 | −0·32 | 1·19 | 138 | 0 | 17 | 0 | 8 | 0 | 4 | 33* | 200 | 138 | 17 | 12 |
|  | Pe4c | 2·14 | 0·60 | −0·12 | 1·09 | 124 | 1 | 14 | 1 | 6 | 1 | 2 | 51* | 200 | 125 | 14 | 10 |
|  | Pe4f | 1·88 | 0·74 | −0·12 | 1·19 | 123 | 1 | 18 | 5 | 7 | 0 | 2 | 44* | 200 | 124 | 18 | 14 |
|  | Pe5c | 2·31 | 0·50 | −0·13 | 1·16 | 122 | 3 | 5 | 0 | 7 | 0 | 2 | 61* | 200 | 125 | 5 | 9 |
|  | Pe5f | 2·03 | 0·62 | 0·02 | 1·04 | 143 | 2 | 11 | 1 | 8 | 0 | 5 | 30* | 200 | 145 | 11 | 14 |
|  | Pe6c | 1·90 | 0·95 | −0·21 | 1·06 | 127 | 3 | 17 | 5 | 11 | 0 | 0 | 37* | 200 | 130 | 17 | 16 |
|  | Pe6f | 1·81 | 0·93 | −0·30 | 1·17 | 145 | 1 | 4 | 1 | 3 | 0 | 1 | 45* | 200 | 146 | 4 | 5 |

Mz = grain size, σ = sorting, Qm = monocrystalline quartz, Qp = polycrystalline quartz, Ft = total feldspar (plagioclase + potash feldspar), Lv = volcanic lithics, Ls = sedimentary lithics, Lm = metamorphic lithics, Lp = plutonic lithics, acc = heavy minerals, biogenic carbonates* Qt = total quartz (Qm + Qp), Lt = total lithics (Lv + Ls + Lm + Lp); c = crest, f = flank.

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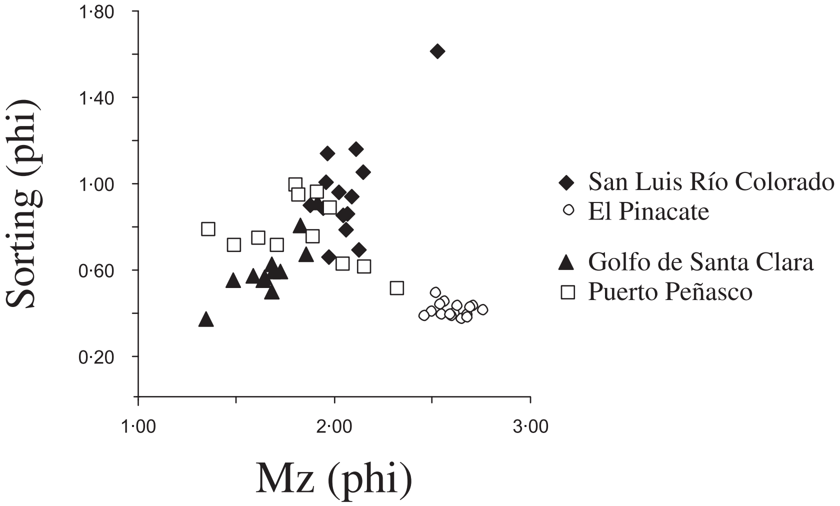

**Figure 2.** Grain-size and sorting diagram of the desert and coastal dune sands.

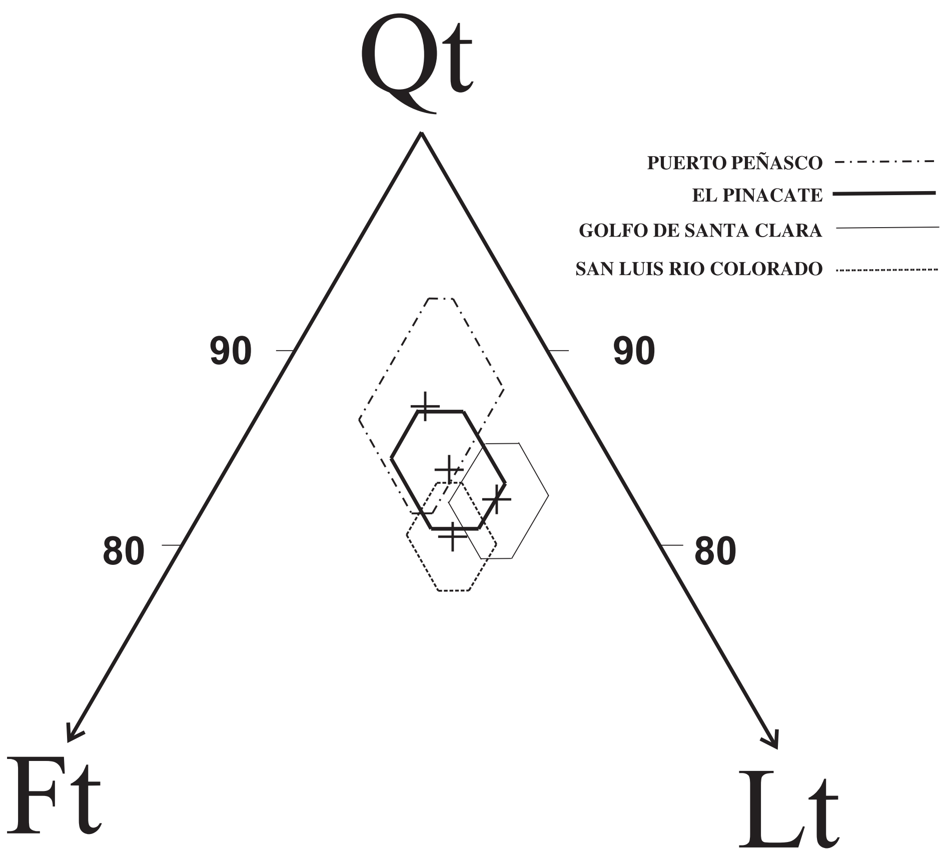

**Figure 3.** Qt–Ft–Lt diagram with the average and polygons of the desert and coastal dune sands.

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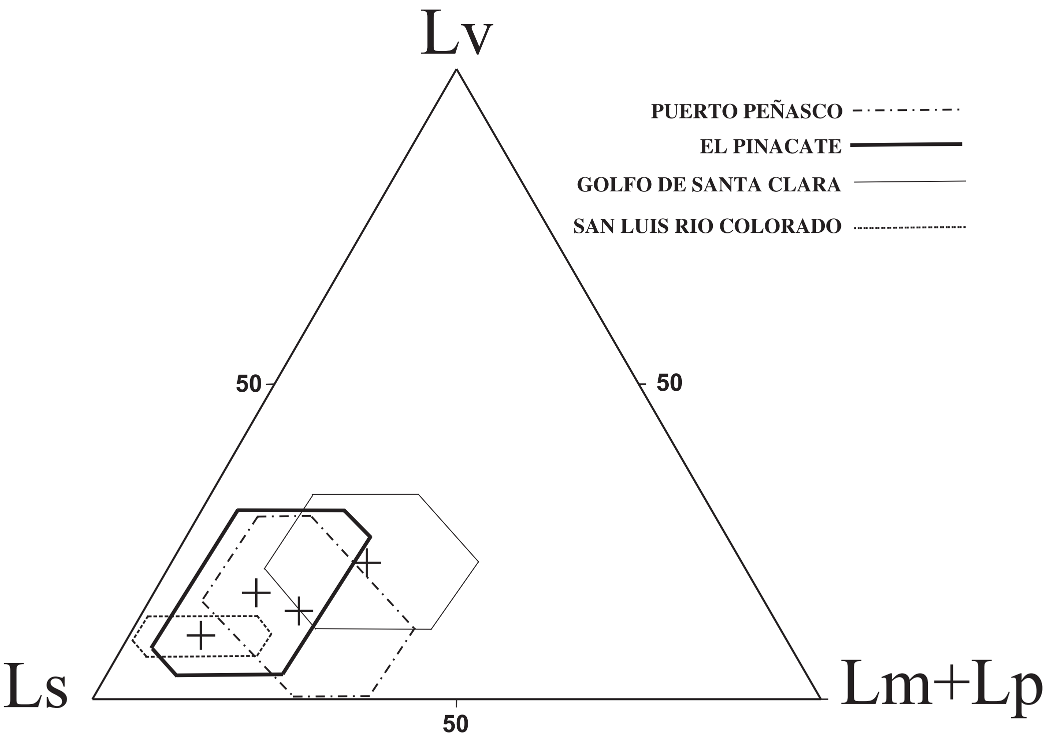

**Figure 4.** Lv–Ls–Lm + Lp ternary diagram with the average and polygons of the desert and coastal dune sands.

(Colorado Delta River sediments) to the dune fields. This observation is supported by the studies of Muhs *et al.* (1995) and Muhs (2004) in the Algodones dunes near the Mexican–US border and the Colorado River sediments, where sands are mature or quartz rich. This maturity process will be discussed latter.

Despite the fact that little lithic content was observed for the inland desert and coastal dune sands, a ternary plot with the Lv–Ls–Lm + Lp poles was drawn (Table I; Figure 4). The triangle shows a strong dispersion for the San Luis Río Colorado and the El Pinacate desert dune sands towards the Ls and the Lv poles, respectively (Figure 4). The Ls and the Lv poles are associated with a supracrustal influence, whereas the Lm + Lp pole is associated with a deep-seated crust. The Lv–Ls–Lm + Lp plot shows that the San Luis Río Colorado desert dune sands are enriched with sedimentary lithics. However, the standard deviation polygon of the San Luis Río Colorado dune sands shows a wider dispersion towards the Ls–Lm + Lp poles than the El Pinacate polygon (Figure 4), suggesting that variable concentrations of sedimentary and plutonic lithics are dominant in the composition of the San Luis Río Colorado dune sands due to the depletion of metamorphic fractions in the sands. In contrast, the standard deviation polygon of the El Pinacate dune sands shows a dispersion in the Ls–Lv poles. The San Luis Río Colorado and the El Pinacate desert dune sands are surrounded by Quaternary deposits of the Colorado River, which supply high percentages of sedimentary lithics and low percentages of volcanic lithics to the sands (Figure 1). Moreover, the low influence of volcanic lithics in the El Pinacate desert dunes might be the lack of production of volcanic sands size particles that can be wind transported into the El Pinacate desert dunes and/or to the dominance of the northwesterly and northerly winds that transport quartz-rich sands from the Colorado River Delta.

## Major and trace elements of the desert dune sands

A ternary plot with $SiO_2$–$Al_2O_3 + Na_2O + K_2O$–$Fe_2O_3 + TiO_2 + MgO$ poles is used to show relative abundances of quartz ($SiO_2$), feldspar ($Al_2O_3 + Na_2O + K_2O$) and heavy mineral ($Fe_2O_3 + TiO_2 + MgO$) content in the sand samples (Carranza-Edwards *et al.*, 2001) (Figure 5). In our study, the polygons of the San Luis Río Colorado and the El Pinacate desert dune sands show a slight overlap among them. The mean lies towards the $SiO_2$ pole whereas the polygons are slightly dispersed towards the $SiO_2$ and $Al_2O_3 + Na_2O + K_2O$ poles, suggesting that the desert dune sands from both areas are compositionally homogeneous.

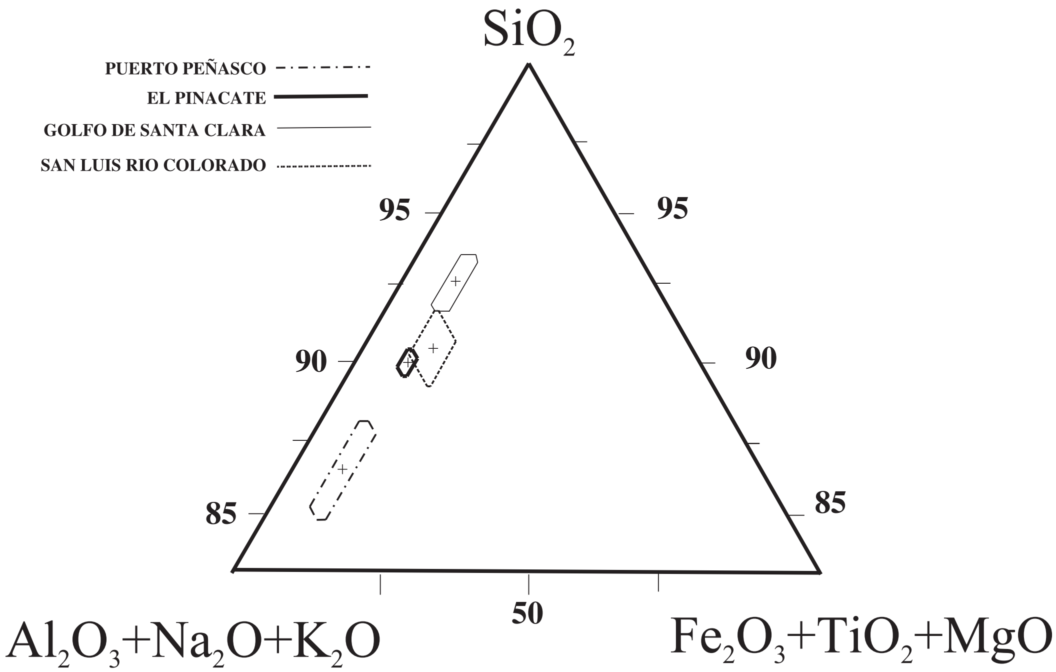

**Figure 5.** $SiO_2$–$Al_2O_3 + Na_2O + K_2O$–$Fe_2O_3 + TiO_2 + MgO$ ternary diagram with the average and standard deviation of the dune sand samples.

Muhs (2004) found that the Algodones dune sands and the Colorado River sediments are quartz ($SiO_2$) enriched sediments and low in $K_2O$, $Na_2O$ and $Al_2O_3$, which are associated with feldspar grains. Furthermore, the San Luis Río Colorado and the El Pinacate dune sands are slightly more mature ($SiO_2 = 91$–$93$ per cent) (Figure 4) than the Colorado River sands ($SiO_2 = 76$–$85$ per cent) and the Algodones dune sands ($SiO_2 = 82$–$87$ per cent). This silica (quartz) enrichment might be due to ballistic impacts of the feldspar that increase the maturity of sands. This observation has also been reported for dunes in Nebraska, where winds capable of reducing feldspar to smaller sizes occur 5–13 per cent of the time (Muhs, 2004). In our study, onshore northwesterly winds occur 40 per cent of the time in one month and may exert a control in the maturity of the sands. The low heavy mineral content agrees with the low $Fe_2O_3 + TiO_2 + MgO$ content, suggesting that the relatively coarse grain size of the dune sands precludes a high content of heavy minerals, which are normally confined to finer sizes (Fletcher *et al.*, 1992; Honda and Shimizu, 1998; Honda *et al.*, 2004). It has been shown also that heavy minerals occur in high-energy regimens that separate the fine-grained and heavy minerals from the coarse quartz and feldspar by selective sorting (Komar and Wang, 1984; Abuodha, 2003). Northwesterly wind speed is between 2 and 4 m s$^{-1}$ (Pérez-Villegas, 1990), which might contribute to a moderately high-energy wind system in the dune. However, the low content of heavy minerals might be due rather to a small supply of heavy minerals from the source and/or the wind speed might not exert a potential entrainment effect on the heavy mineral fractions to be transported onto the dune (Komar and Wang, 1984; Fletcher *et al.*, 1992).

The chemical index of alteration (CIA) proposed by Nesbitt and Young (1982) is a measure of the weathering degree in sediments. The CIA is $Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O) \times 100$. Molar proportions are used in the calculation (Honda and Shimizu, 1998; Honda *et al.*, 2004). CIA values for fine to medium sands in the Taklimakan Deserts sands range from 52·5 to 58·0 (Honda and Shimizu, 1998). Beach sands in arid regions of Mexico show CIA values from 46·3 to 56·3 (Carranza-Edwards *et al.*, 2001). The average CIA value, 54·6, for the inland desert dune sands lies within the range of the CIA values obtained for the Taklimakan desert sands in China (Honda and Shimizu, 1998). This suggests that the San Luis Río Colorado and the El Pinacate desert dune sands have experienced little chemical weathering and that they are chemically homogeneous (Honda and Shimizu, 1998) with CIA values from 51·50 to 56·48. According to Garzanti *et al.* (2003), sands transported long distances display a relatively homogeneous composition due to the maturity process. This also implies that the aeolian activity has been more active for the San Luis Río Colorado and the El Pinacate desert dune sands as compared with cooler deserts such as the Taklimakan Desert. This statement is supported by the fact that the Taklimakan desert is climatically controlled due to glacial activity with less aeolian activity (Honda and Shimizu, 1998) and that it is confined to an endorreic basin that limits the redistribution of sediments by the wind. The presence of subangular to subrounded quartz observed in the San Luis Río Colorado and the El Pinacate dune sands and the angular to subangular quartz observed in the Taklimakan Desert dune sands suggests little transport of the quartz grains in the sands for the Taklimakan Desert and long active transport for the Altar Desert sands (Honda and Shimizu, 1998).

The trace element results reveal that Ba, Zr and Sr have the highest values for the inland desert dunes (Figure 6(A)). Ba and Rb are trace elements that may substitute for K in the lattice of silicate minerals and are abundant in K feldspar and mica (Sawyer, 1986; Gallet *et al*., 1996; Canfield, 1997; Muhs *et al*., 2003). Ba content values in the inland desert dune sands (average Ba = 506 ppm) are slightly higher than in the coastal dune sands (average Ba = 469). $K_2O$ values are also higher for the inland desert dunes than for the coastal dune sands ($K_2O = 1{\cdot}83$, $K_2O = 1{\cdot}73$, respectively). Furthermore, it can be observed that the Ba values for the desert dune sands are between 467 and 566 ppm. These values are within the range of Ba content in Colorado River sediments (~450–600 ppm) (Muhs *et al*., 2003). This suggests that the desert dune sands are closer to the source rocks and are slightly enriched in K-bearing minerals as compared with the coastal dune sands, although K-bearing minerals are low for both the desert and coastal dune sands. Moreover, the Ba content reflects also the maturity of the desert dune sands, since Ba abundances are proxies for K-feldspar content that, overall, are low for the desert dune sands compared to their high $SiO_2$ content (Table II; Figure 5) (Muhs and Holliday, 2001). High Zr values are indicative of high zircon content and are common near granite sources, recycled sedimentary rock sources and sediments high in heavy minerals (Carranza-Edwards *et al*., 2001; Di Leo *et al*., 2002). Sr is an element that resides mainly in K-bearing minerals (K feldspar), carbonate (calcite and dolomite) and silicate minerals (plagioclase) such as feldspar, calcite, dolomite and plagioclase (Yang *et al*., 2003; Muhs *et al*., 2003). Sr values for the inland desert dune sands are between 136 and 170 ppm, which are within the range of the values obtained for the Colorado River sediments (100–250 ppm) (Muhs *et al*., 2003). This indicates that the desert dune sands resemble in composition the Colorado River Delta sediments and implies that K feldspars are associated with an increase of Ba and Sr content in the desert sands. However, the Sr content might be

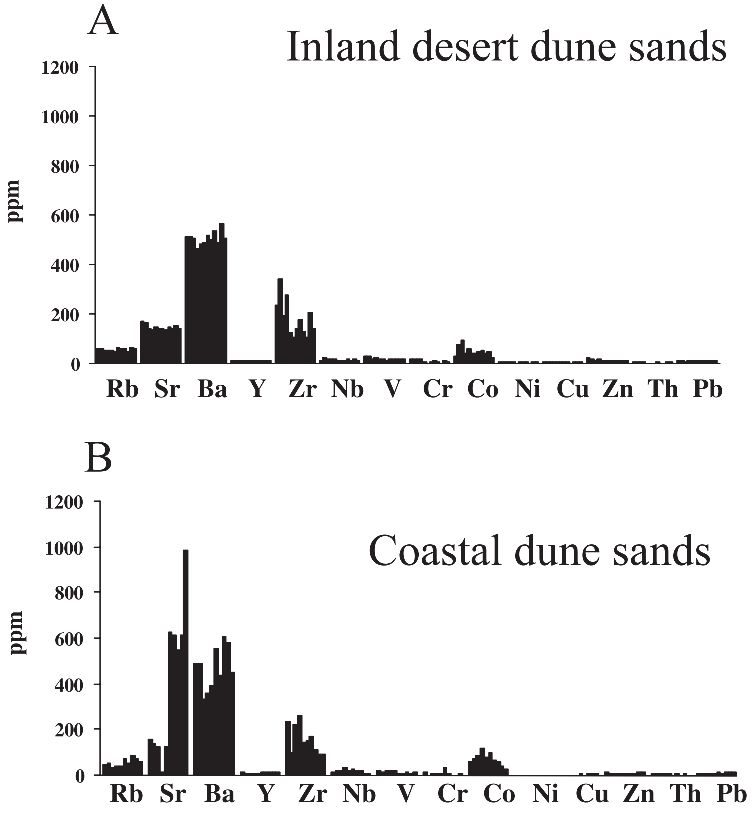

**Figure 6.** Concentration (ppm) of trace elements in (A) desert dune sands and (B) coastal dune sands of the Altar Desert.

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**Table II.** Major element content (%) of the whole bulk composition of sand samples from the desert and coastal dunes of the Altar Desert

| Sample | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI | total | CIA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1f | 85·79 | 0·26 | 5·56 | 1·57 | 0·01 | 0·75 | 1·65 | 0·82 | 1·84 | 0·08 | 2·08 | 100·41 | 56·48 |
| C2c | 85·78 | 0·28 | 5·58 | 1·82 | 0·02 | 0·55 | 1·85 | 0·93 | 1·76 | 0·05 | 1·78 | 100·41 | 55·33 |
| C3c | 89·24 | 0·17 | 4·79 | 1·18 | 0·02 | 0·38 | 1·32 | 0·77 | 1·60 | 0·03 | 0·96 | 100·47 | 55·22 |
| C4f | 88·49 | 0·24 | 4·70 | 1·41 | 0·01 | 0·46 | 1·29 | 0·72 | 1·65 | 0·05 | 1·30 | 100·32 | 55·31 |
| C5f | 87·68 | 0·13 | 4·44 | 0·87 | 0·01 | 0·44 | 2·12 | 0·66 | 1·68 | 0·05 | 2·17 | 100·25 | 54·79 |
| C6c | 87·84 | 0·12 | 4·20 | 0·82 | 0·00 | 0·42 | 2·35 | 0·59 | 1·60 | 0·04 | 2·30 | 100·28 | 55·40 |
| P1c | 88·92 | 0·17 | 5·51 | 0·91 | 0·00 | 0·35 | 0·71 | 0·96 | 2·02 | 0·05 | 0·86 | 100·46 | 53·09 |
| P3f | 89·41 | 0·22 | 5·00 | 1·11 | 0·00 | 0·32 | 0·73 | 0·98 | 1·82 | 0·05 | 0·77 | 100·41 | 51·50 |
| P5f | 89·20 | 0·17 | 5·39 | 0·9 | 0·00 | 0·33 | 0·70 | 0·93 | 2·00 | 0·05 | 0·82 | 100·49 | 53·08 |
| P6c | 88·81 | 0·19 | 5·63 | 1 | 0·01 | 0·35 | 0·71 | 0·85 | 2·00 | 0·05 | 0·75 | 100·35 | 55·36 |
| P7f | 87·80 | 0·21 | 5·86 | 1·11 | 0·01 | 0·37 | 0·86 | 0·89 | 2·08 | 0·058 | 1·10 | 100·35 | 55·29 |
| P8f | 89·42 | 0·19 | 5·31 | 0·96 | 0·00 | 0·32 | 0·73 | 0·82 | 1·94 | 0·04 | 0·74 | 100·47 | 54·73 |
| G1c | 88·70 | 0·22 | 4·52 | 1·19 | 0·01 | 0·33 | 1·78 | 0·74 | 1·55 | 0·05 | 1·49 | 100·58 | 54·68 |
| G3c | 90·71 | 0·11 | 4·24 | 0·68 | 0·00 | 0·29 | 1·08 | 0·69 | 1·68 | 0·04 | 0·89 | 100·42 | 53·09 |
| G4c | 91·26 | 0·25 | 3·06 | 1·24 | 0·01 | 0·31 | 1·51 | 0·50 | 1·07 | 0·05 | 1·21 | 100·47 | 54·49 |
| G5f | 92·15 | 0·21 | 3·22 | 1·14 | 0·00 | 0·26 | 1·07 | 0·51 | 1·16 | 0·038 | 0·78 | 100·54 | 54·57 |
| G6c | 91·32 | 0·19 | 3·62 | 0·97 | 0·01 | 0·29 | 1·21 | 0·56 | 1·31 | 0·04 | 0·88 | 100·40 | 54·82 |
| Pe1c | 68·40 | 0·13 | 6·35 | 0·63 | 0·01 | 0·33 | 11·71 | 1·37 | 2·27 | 0·53 | 8·61 | 100·34 | 50·25 |
| Pe2f | 70·07 | 0·14 | 4·69 | 0·7 | 0·00 | 0·36 | 12·50 | 1·08 | 1·62 | 0·43 | 8·89 | 100·49 | 49·57 |
| Pe3c | 71·22 | 0·12 | 6·80 | 0·64 | 0·01 | 0·33 | 9·61 | 1·55 | 2·53 | 0·55 | 7·03 | 100·39 | 49·02 |
| Pe4c | 69·90 | 0·11 | 6·19 | 0·58 | 0·02 | 0·35 | 11·18 | 1·39 | 2·29 | 0·511 | 8·05 | 100·58 | 49·31 |
| Pe6f | 53·24 | 0·12 | 5·28 | 0·61 | 0·01 | 0·40 | 20·87 | 1·28 | 1·86 | 0·61 | 16·13 | 100·41 | 48·57 |

LOI = loss on ignition; CIA = chemical index of alteration (Nesbitt and Young, 1982; see the text).

**Table III.** Trace elements (ppm) of the whole bulk composition of sand samples from the desert and coastal dunes of the Altar Desert

| Sample | Rb | Sr | Ba | Y | Zr | Nb | V | Cr | Co | Ni | Cu | Zn | Th | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **C1f** | 59 | 170 | 510 | 14 | 233 | 12 | 29 | 17 | 28 | 5 | 7 | 25 | 7 | 9 |
| **C2c** | 56 | 163 | 514 | 13 | 343 | 23 | 30 | 17 | 78 | 4 | 5 | 16 | 5 | 11 |
| **C3f** | 51 | 139 | 504 | 10 | 195 | 19 | 17 | 15 | 92 | 3 | 3 | 10 | 5 | 7 |
| **C4f** | 52 | 136 | 467 | 12 | 274 | 15 | 22 | 16 | 42 | 4 | 4 | 15 | 7 | 9 |
| **C5f** | 51 | 146 | 480 | 10 | 122 | 17 | 17 | 3 | 60 | 4 | 5 | 11 | 2 | 11 |
| **C6c** | 49 | 143 | 487 | 9 | 107 | 10 | 16 | 1 | 41 | 2 | 4 | 11 | 2 | 10 |
| **P1c** | 62 | 141 | 520 | 11 | 139 | 12 | 13 | 6 | 40 | 4 | 4 | 13 | 2 | 11 |
| **P3f** | 57 | 138 | 498 | 12 | 174 | 13 | 19 | 10 | 45 | 5 | 3 | 13 | 5 | 10 |
| **P5f** | 61 | 145 | 535 | 12 | 128 | 18 | 15 | 7 | 55 | 3 | 2 | 11 | 2 | 11 |
| **P6c** | 49 | 143 | 487 | 9 | 107 | 10 | 16 | 1 | 41 | 2 | 4 | 11 | 2 | 10 |
| **P7f** | 63 | 155 | 566 | 13 | 204 | 18 | 19 | 10 | 47 | 4 | 4 | 14 | 4 | 11 |
| **P8f** | 59 | 142 | 507 | 12 | 144 | 9 | 15 | 7 | 26 | 4 | 4 | 11 | 6 | 12 |
| **G1c** | 48 | 157 | 488 | 11 | 234 | 16 | 22 | 10 | 58 | 3 | 3 | 11 | 5 | 8 |
| **G3c** | 51 | 137 | 486 | 9 | 97 | 17 | 10 | 1 | 69 | 2 | 2 | 7 | 5 | 9 |
| **G4c** | 33 | 126 | 333 | 9 | 221 | 20 | 21 | 4 | 83 | 2 | 1 | 7 | 5 | 6 |
| **G5f** | 36 | 11 | 360 | 9 | 262 | 31 | 17 | 4 | 116 | 2 | 2 | 4 | 7 | 6 |
| **G6c** | 41 | 126 | 393 | 9 | 146 | 20 | 19 | 4 | 77 | 0·4 | 1 | 7 | 6 | 8 |
| **Pe1c** | 74 | 623 | 556 | 13 | 151 | 25 | 9 | 35 | 100 | 2 | 6 | 6 | 2 | 12 |
| **Pe2f** | 50 | 614 | 438 | 10 | 167 | 21 | 8 | 4 | 64 | 0·4 | 3 | 5 | 5 | 8 |
| **Pe3c** | 84 | 545 | 608 | 15 | 111 | 19 | 10 | 1 | 60 | 3 | 6 | 8 | 3 | 15 |
| **Pe4c** | 74 | 610 | 579 | 13 | 90 | 8 | 6 | 3 | 36 | 3 | 5 | 10 | 4 | 13 |
| **Pe6f** | 59 | 984 | 453 | 11 | 93 | 8 | 11 | 6 | 29 | 1 | 5 | 10 | 2 | 10 |

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rather determined by the presence of Ca plagioclase in the desert dune sands (Muhs *et al.*, 2003). The Zr values are probably linked with the sedimentary sources and heavy mineral content in the desert dunes, as has also been shown by Muhs and Holliday (2001) for the Muleshoe dune fields in Texas.

## Grain size parameters of the coastal dune sands

Coastal dune sands coming from the Golfo de Santa Clara and Puerto Peñasco are medium sands, moderately well sorted to moderately sorted sands, respectively (Table I). The Golfo de Santa Clara dune sands are fine-skewed sands, whereas the Puerto Peñasco coastal dune sands are strongly coarse skewed. Kurtosis values indicate a leptokurtic distribution for the Golfo de Santa Clara and Puerto Peñasco coastal dune sands.

The Golfo de Santa Clara coastal dune sands have an average grain size of 2·60 $\phi$ on the crest and of 1·70 $\phi$ on the flank. Average sorting values are 0·55 $\phi$ on the crest and 0·62 $\phi$ on the flank. The skewness values are 0·16 on the crest and on the flank. Kurtosis values are 1·12 on the crest and 1·08 on the flank. The grain-size values between the crest and the flank of the dune show significant differences. Other grain-size parameters do not differ significantly.

Fine-sand fractions are observed on the crest of the Golfo de Santa Clara coastal dune sands whereas coarse-grained fractions are observed on the flank. This suggests that coarse grains roll down towards the dune flank due to the effect of gravity by sliding off the grains on a dune flank (Livingstone *et al.*, 1999). The height of the dunes in the Golfo de Santa Clara above 10 m suggests that the height also exerts some control on the grain-size distribution. The crest and the flank of the Golfo de Santa Clara dune sands are moderately well sorted, suggesting that sorting of the dune sands is influenced by a mixture of marine and wind processes that produces moderately well sorted sands (Sevon, 1964). The skewness and kurtosis do not show any significant difference between the crest and the flank of the Golfo de Santa Clara coastal dune sands.

The Puerto Peñasco coastal dune sands are the coarsest of all dunes studied. They have an average grain size of 1·89 $\phi$ on the crest and of 1·76 $\phi$ on the flank. Average sorting values are 0·73 $\phi$ on the crest and 0·78 $\phi$ on the flank. Skewness values are −0·15 for the crest and −0·16 for the flank. The kurtosis values are 1·10 for the crest and 1·14 for the flank. Puerto Peñasco dunes are between 2 and 4 m high.

The only parameter that shows differences between the crest and the flank of the Puerto Peñasco coastal dune sands is the grain size. Fine-sand grain sizes are found on the crest of the dune whereas coarse-sand sizes cover the flank. These distributions across the dune follow the same pattern as on the crest and flank of the Golfo de Santa Clara coastal dune sands. These grain-size distributions are found when the sediment source is relatively coarse, producing dune crests with relatively fine sands (Livinstone *et al.*, 1999). Beach sands in Puerto Peñasco and the Golfo de Santa Clara have a grain size average of 1·74, containing shell debris that produces coarse sands in the flank and fine sands in the crest of the dune (Kasper-Zubillaga and Carranza-Edwards, 2005).

The fact that the coastal dune sands of Puerto Peñasco are coarse skewed on the crest and the flank suggests that the coastal dune sands are probably derived in part from the beach sands, which produce coarser grains due to the wind regimens where dry tidal flats are developed during low tidal stands. For instance, in winter, Puerto Peñasco has two potential onshore wind drifts that occur 40 per cent of the time in one month in the northwestern direction with mean velocities from 4 to 6 m $s^{-1}$ and another wind drift in the northeastern direction with mean velocities from 4 to 6 m $s^{-1}$ and a frequency of 60 per cent in one month (Pérez-Villegas, 1990). The latter might be the most important aeolian process that induces transport and deposition of coarse grained sands on the beach and the dune.

A grain-size–sorting diagram shows an overlap between the Golfo de Santa Clara and the Puerto Peñasco coastal dune sands (Figure 2). This trend also shows a dispersal of the samples where the carbonates have an influence on the composition of the Puerto Peñasco coastal dune sands, which is similar to the trend found in some Mexican beach sands that produces moderately to poor sorted sands (Carranza-Edwards, 2001).

## Modal analysis of the coastal dune sands

The Golfo de Santa Clara and the Puerto Peñasco coastal dunes are quartzolithic sands ($Qt_{82}$ $Ft_6$ $Lt_{12}$ and $Qt_{87}$ $Ft_6$ $Lt_7$, respectively) (Table I). The Qt–Ft–Lt ternary diagram with the standard deviation polygons shows that the Golfo de Santa Clara coastal dune sands have little dispersion towards the Qt and Ft with an average towards the Lt pole (Figure 3). In contrast, the Puerto Peñasco coastal dune sands show a wider dispersion of the polygon towards the Qt and Ft poles with an average towards the Qt pole. The Golfo de Santa Clara coastal dune sands might be compositionally influenced by the Quaternary sediments of the Colorado River Delta, because high quartz concentrations are linked to the Colorado River Delta sediments derived from quartz-rich rocks (plutonic). This interpretation is also based on the quartz-rich composition of the Parker and Algodones dune sands in the southwestern USA, close to the Colorado

River (Muhs *et al.*, 2003), where the dune sands are similar in composition to the Golfo de Santa Clara coastal dune sands.

In the case of the Puerto Peñasco coastal dune sands, high quartz content is probably linked to the tidal regimen that produces high energy tidal currents and transports coarse sediments from the beach to the dune (Carranza-Edwards *et al.*, 1988). A southwesterly long shore drift (Fernández-Eguiarte *et al.*, 1990) also transports sand northwards that enriches in quartz the sands deposited in the Puerto Peñasco beaches, probably due to the maturity process in the coast. In addition, wind selectiveness exerts a control in the quartz enrichment of coastal dunes (Kasper-Zubillaga and Dickinson, 2001), implicating that the Puerto Peñasco coastal dune sands have a significant input from the beach sands.

Average values in the Lv–Ls–Lm + Lp diagram for the Golfo de Santa Clara and the Puerto Peñasco coastal dune sands show a slight trend towards the Lm + Lp pole for the Golfo de Santa Clara sands and a trend towards the Ls pole for the Puerto Peñasco sands (Figure 4). Furthermore, the Lv–Ls–Lm + Lp ternary diagram with polygons shows that coastal dune sands from the Golfo de Santa Clara have a wider dispersion of the polygon towards the Ls and Lm + Lp poles as compared with the Puerto Peñasco coastal dune sands, where the polygon disperses towards the Lv and Lm + Lp poles with its average percentage close to the Ls pole (Figure 4).

The abundances of sedimentary and plutonic lithics on the coastal dune sands of the Golfo de Santa Clara could be due to the supply of sedimentary and plutonic lithics from the Quaternary deposits of the Colorado Delta River. Major river discharges, like the Colorado River, may concentrate sedimentary lithics (fine-crystal sandstones, siltstones, chert) and plutonic lithics in the downstream reaches of the river. The Golfo de Santa Clara dune sands seem to be compositionally controlled by the Colorado River sediments, since scarce biogenic debris derived from the beach sands was observed in the dunes.

The Puerto Peñasco coastal dune sands receive a major influence on their composition from the Quaternary sedimentary rocks in the Sonoyta River Valley (Figure 1(A)). Sedimentary lithics such as fine-grained sandstones and chert fragments are resistant to mechanical abrasion during their transport cycles (Harrell and Blatt, 1978). Thus, it is possible that the source rocks are only supplying large amounts of sedimentary lithics throughout the Sonoyta River that, once they reach the coast, are transported by long shore currents and southwesterly winds to the Puerto Peñasco beaches (Figure 1(A)). Low volcanic lithic content and depletion of metamorphic lithics in the coastal dune sands may be due to the absence of river drainages cutting the major volcanic fields seawards and few exposed metamorphic outcrops near the Sonoyta River (Figure 1(A)).

Accessories in the Puerto Peñasco are composed mainly by broken shells associated with the siliciclastic detritus (Table I). In the case of the Puerto Peñasco coastal dune sands, therefore, biogenic detritus is also influencing the composition of the sands.

## Major and trace elements of the coastal dune sands

The ternary plot with the $SiO_2$–$Al_2O_3 + Na_2O + K_2O$–$Fe_2O_3 + TiO_2 + MgO$ poles shows that the average values of the Golfo de Santa Clara and the Puerto Peñasco coastal dune sands diverge towards the $SiO_2$ and the $Al_2O_3 + Na_2O + K_2O$ poles, respectively (Figure 5). Yet, both areas have a dispersal in the $SiO_2$ and the $Al_2O_3 + Na_2O + K_2O$ poles (Figure 5), indicating that the coastal dune sands from both areas are less homogenous in the content of Na–K feldpars than the inland desert dune sands.

The average CIA value (51·8) for the coastal dune sands is within the CIA range of medium to fine sands (Nesbitt and Young, 1996) and is slightly lower than the CIA value found for the desert dune sands. The Golfo de Santa Clara and the Puerto Peñasco coastal dune sands show no significant differences in CIA values as compared to the inland desert dune sands, due to compositional and geochemical affinities between the desert and coastal dune sands.

The trace element values for the coastal dunes are similar to those determined for the desert dune sands (Figure 6). However, the Sr values are higher in the coastal dune sands than the inland desert dune sands (Figure 6). This increase in Sr values in the coastal dune sands might be associated to the calcium from the $CaCO_3$ in the shells (Muhs and Holliday, 2001). This is especially observed for the Puerto Peñasco coastal dune sands, where $CaCO_3$ and loss of ignition values are the highest for the whole data set, supporting the high carbonate content of biogenic origin in the sands (Table II). There is a slight decrease in the Zr content in the coastal dunes (Table II, Figure 6) that can be associated with less heavy mineral supply (Table I).

## Correlations of the desert and coastal dune sands

The most significant correlations were found between the grain-size distribution parameters, detrital modes and geochemical data. Significant correlations were less than 0·56 at $\rho = 0{\cdot}01$ for $n = 22$. Correlations were established by means of standard error and Student *t* tests.

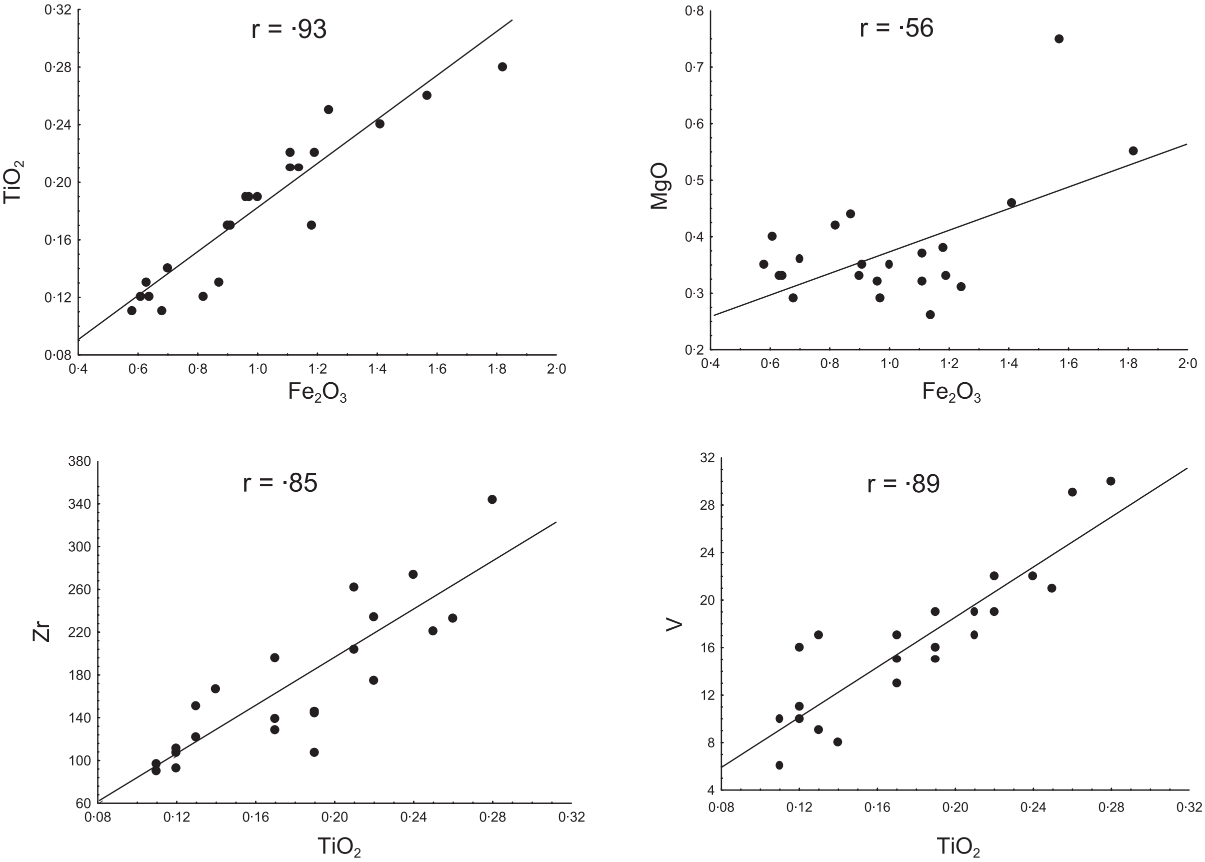

**Figure 7.** Significant correlations of $TiO_2$, $Fe_2O_3$, MgO, Zr and V.

Looking at the best correlations for the sedimentological, petrographic and geochemical parameters, meaningful and significant correlations were observed for $Fe_2O_3$, $TiO_2$, MgO, Zr and V (Figure 7).

The positive correlation between $Fe_2O_3$, $TiO_2$ and MgO suggests the coexistence of heavy minerals, probably associated with plutonic and sedimentary sources (Carranza-Edwards *et al.*, 2001; Ohta *et al.*, 2004). The positive correlation between Zr and $TiO_2$ can be associated with the presence of heavy minerals (García *et al.*, 2004, Muhs and Holliday, 2001). The positive correlation between V and $TiO_2$ implies that the sands are influenced by magnetite and ilmenite minerals.

## $SiO_2/Al_2O_3$–$Na_2O/K_2O$ and $K_2O$–Rb diagrams for the desert and coastal dune sands

A $SiO_2/Al_2O_3$–$Na_2O/K_2O$ diagram was used to observe the maturity and weathering trends for the desert and coastal dune sands of the Altar Desert (Figure 8(A)) where $SiO_2$, $Al_2O_3$, $Na_2O$ and $K_2O$ are associated with quartz, all feldspar, plagioclase and K feldspar respectively. This diagram is based on the maturity and weathering profiles of medium-grained sands in a fluvial environment (Robinson and Johnsson, 1997). We observed that the medium to fine dune sands from the Altar Desert are more mature (more weathered) than the Taklimakan Desert sands (Honda and Shimizu, 1998). This is because the Altar Desert sands are affected by the frequent wind reworking whereas the Taklimakan Desert sands receive new glaciogenic sand on a regular basis (Honda and Shimizu, 1998). Also, this difference is supported by the fact that the quartz observed in the Altar Desert dune sands is more rounded than the quartz observed in the Taklimakan Desert dune sands. This suggests that the Taklimakan Desert dune sands have experienced little aeolian transport and probably have had a short residence time after transportation of sands into the desert (Honda and Shimizu, 1998). In contrast, the Altar Desert dune sands have been transported more extensively without much fresh sediment input.

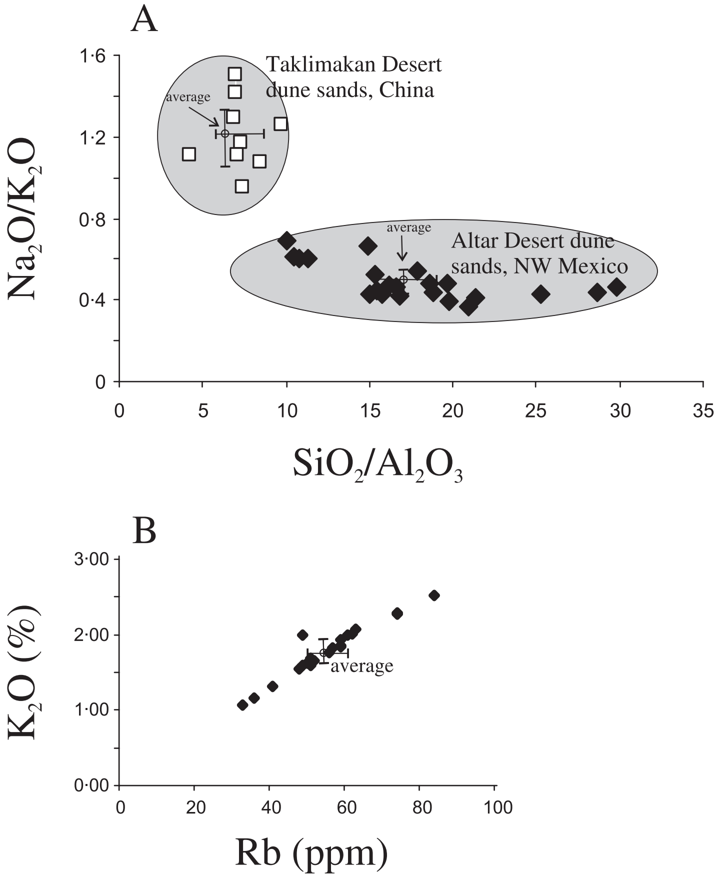

**Figure 8.** Bivariate diagrams with (A) $SiO_2/Al_2O_3$–$Na_2O/K_2O$ ratios and (B) $K_2O$–Rb plots for the desert and coastal dune sands with the average value and confidence levels at 95 per cent. For the $SiO_2/Al_2O_3$–$Na_2O$ diagram, data from the Taklimakan Desert China for sands approximately from 1·6 $\phi$ to 2·70 $\phi$ in size (Honda and Shimizu, 1998) are compared with the Altar Desert data, NW Mexico.

A $K_2O$–Rb diagram was used to observe the maturity of the Altar Desert dune sands based on $K_2O$ and Rb as proxies of K feldspar content (Figure 8(B)) (Muhs and Holliday, 2001). Our results of $K_2O$ and Rb content values range from 1 to 2·5 per cent and 33 to 89 ppm, respectively. These values are within the range of the $K_2O$ and Rb concentrations for the Colorado River sediments (Muhs *et al.*, 2003), suggesting that the Altar Desert dune sands are mature sands that have preserved their inheritance from the Colorado River Delta sediments.

## Cluster analysis of the desert and coastal dune sands

Cluster analyses were performed for sands in terms of grain size distributions, modal analysis and major and trace elements. (Figure 9(A)–(D)). The grain-size parameter hierarchical dendrogram shows a separation of the Pinacate desert dune sands from the rest of the dune sand groups (Figure 9(A)), implying that the El Pinacate group is significantly different from the rest of the dune sands in terms of grain-size parameters. According to Goudie *et al.* (1987), dune sands with longer transport history (far away from the source sediments) may generate dunes with fine-grained sands. Lancaster (1995) reported a fining in the grain size distributions from the northwest to the southeast in the Altar Desert sands. In our study, finer and better sorted sands from the El Pinacate area as compared to the rest of the dune sites could result from longer transport from the source to the dune field as compared to the San Luis Río Colorado sands. The rest of the groups are defined not only by the wind action but also by the effects produced by fluvial discharges and marine processes on the grain size distributions, which induce an overlap in the dendrogram.

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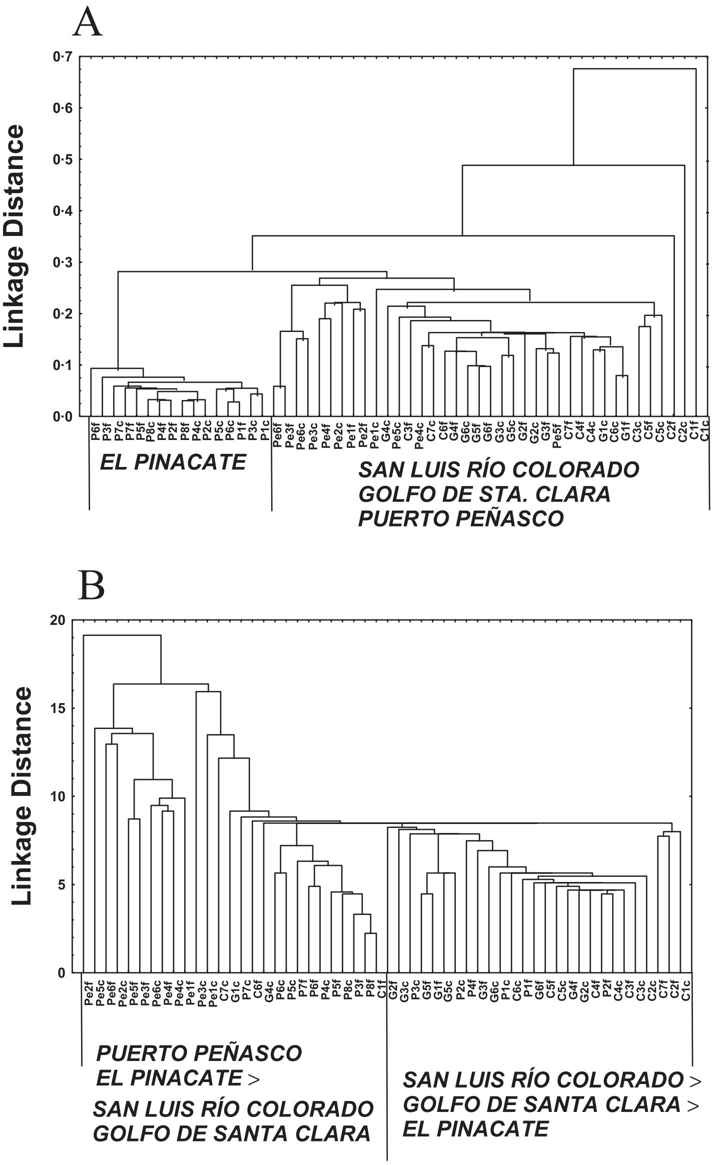

**Figure 9.** Cluster analysis of (A) grain size parameters, (B) modal analysis, (C) major elements and (D) trace elements, for the desert and coastal dune sands.

Compositionally, the second dendrogram shows a dominance and a separation of the Puerto Peñasco sampling sites over the El Pinacate, the San Luis Río Colorado and the Golfo de Santa Clara sites (Figure 9(B)). This dominance and separation suggests that the sands from the Puerto Peñasco coastal area are controlled by river discharges, aeolian processes and marine transport. The Puerto Peñasco coastal dune sands are quartz-rich sands with scarce feldspar, lithics and siliciclastic detritus, but receive a high carbonate supply, as compared with the rest of the dune groups.

The major and trace elements hierarchical dendrogram separates the Puerto Peñasco coastal dune sands from the rest of the groups (Figure 9(C) and (D)). The Puerto Peñasco coastal dune sands show a slightly lower CIA as compared with the rest of the dune sands, which is reflected in the dendrogram. This may be due to the heterogeneity of the Na plagioclase and K feldspar content in the sands that decreases the CIA values. Besides, low heavy mineral content and high carbonate input may have an effect on the low Zr values.

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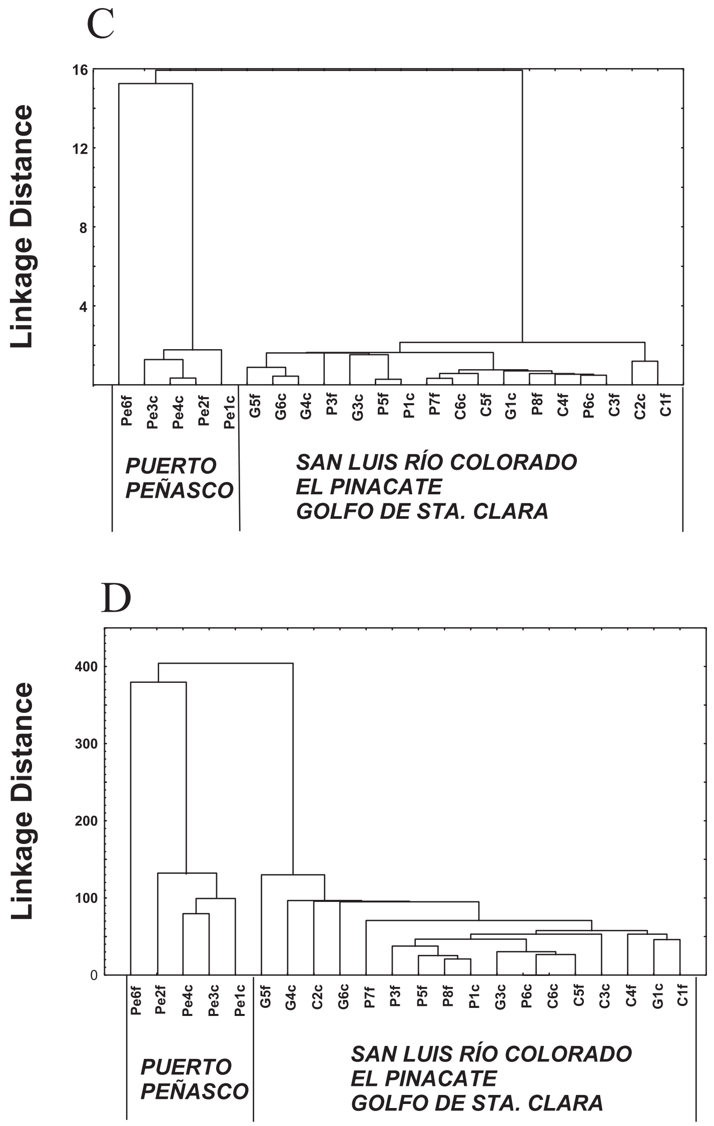

**Figure 9.** *Continued*

## Conclusions

The San Luis Rio Colorado desert dune sands are influenced by the Colorado River Delta sediment supply, which generates coarse and moderately sorted sands. In contrast, fine sizes and well sorted desert dune sands are found in the El Pinacate due to wind selectiveness, long transport and long distance from the same source sediments. Dune height does not exert a significant control over the grain size distributions of the inland desert dune sands. Quartz enrichment of the desert dune sands is due to (a) inheritance from a quartz-rich source sediment (the Colorado River) and (b) aeolian activity, which has depleted the feldspar grains through subaerial collisions. Major sediment supply for the desert dune sands comes mainly from the Colorado River Delta sediments, which are enriched with quartz and sedimentary lithics. The San Luis Río Colorado and the El Pinacate desert dune sands suffer from little chemical weathering and they are chemically homogeneous. This implies that aeolian activity is partially controlling the geochemistry of the sands. These inland desert sands have been more influenced by granitic sources, where Ba and Sr concentration values are within the range of those values observed for the Colorado River Delta sediments. The

Sr values are associated with the presence of Ca-bearing minerals. The Zr values are probably linked with the sedimentary sources and heavy mineral content in the desert dunes.

Coarser sands and moderately sorted sands on the coastal dunes as compared with the desert sands suggest that the Golfo de Santa Clara and Puerto Peñasco coastal dune sands are influenced by aeolian and marine processes. Likewise, the coarse and fine grains found on the flanks and crest of the dunes, respectively, suggest that coarse grains roll down towards the dune flank. Quartz-rich coastal dune sands are supplied by the Colorado Delta River sediments but also by long shore drift. High tidal regimens may also produce quartz-rich sands on the beach that could be transported onto the coastal dunes by southwesterly winds. Granitic and sedimentary sources control the content of sedimentary and plutonic lithics. The CIA values for the desert and coastal dune sands indicate that both dune types are chemically homogeneous. The trace element values of coastal dune sands are similar to those observed for desert dune sands, except for Zr, which is slightly decreased in association with the low heavy mineral content in the coastal dune sands. The correlations between various elements in the dune sands show that they are associated with heavy minerals probably from sedimentary sources. However, the dunes show, overall, low heavy mineral content due to scarce heavy mineral content in the source sediment, grain sizes in the dune sands that are coarser than those sizes where heavy minerals are found and/or wind speeds that may not exert a potential entrainment effect on the heavy mineral fractions to be transported onto the dune. Dunes of the El Pinacate group are significantly different from the rest of the dune sands in terms of grain-size parameters, where fining of grain size is due to a longer distance of transport from the source sediment. The Puerto Peñasco coastal dune sands are geochemically different from the rest of the groups due to their high $CaCO_3$ content from beach sources and slightly lower CIA values.

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