Beach sand composition and provenance in a sector of the southwestern Mexican Pacific

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ABSTRACT

Sandy sediment samples from eleven beaches in southwestern Mexico were texturally, petrologic and chemically analyzed. Our goals were to interpret the provenance of the sands in terms of grain size, petrogrology and geochemistry and to observe if the beach environment reflects accurately the source rock in three adjacent river basins dominated by sedimentary, volcanic and plutonic rocks respectively. Three littoral segments were divided in terms of lithological differences: the Cihuatlán (western), Armería (central) and Coahuayana (eastern) river basins and their respective beach segments. The Cihuatlán river basin is influenced by granitoids, whereas the Armería and Coahuayana river basins are dominated by the influence of intermediate to basic volcanic rocks and sedimentary rocks represented by limestones. This is supported by the enrichment of Fe_2O_3*, CaO, MgO,* TiO_2*, V, Cr, Co and Zn, and a depletion of* SiO_2*,* Al_2O_3*,* Na_2O K_2O*, Ba, Sr and Rb from the western segment toward the eastern segment. The chemical index of alteration (C.I.A.) values were higher in beaches from the Armería and Coahuayana river segments. This is probably caused by weathering feldspars in the volcanic lithics due to more humid conditions in the source area. Sedimentary calcareous lithics in the Armería and Coahuayana river basins are depleted due to their low resistance to high energy of fluvial and river-marine conditions. Despite the fact limestone outcrops are more than 40 % in the central (Armería) and eastern (Coahuayana) basins, the beach sediments do not reflect limestone sources. Heavy minerals concentration is related to the influence of Armería and Coahuayana river basins and likelly produced by the erosion of intermediate to mafic Quaternary lavas.*

Key words: sand, beach, composition, provenance, Colima, Pacific, southwestern Mexico.

RESUMEN

Se analizó la textura, petrología y geoquímica de sedimentos arenosos de once playas del suroeste de México. El objetivo fue interpretar la procedencia de las arenas en términos del tamaño de grano, petrología y geoquímica y observar si el ambiente de playa refleja con precisión la roca fuente en playas de tres cuencas adyacentes en las que dominan rocas sedimentarías, volcánicas y plutónicas. En función de diferencias litológicas y climáticas, se consideraron tres segmentos litorales sujetos a la influencia de

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las cuencas de los ríos Cihuatlán, Armería y Coahuayana. La cuenca del Río Cihuatlán está influenciada por granitoides, mientras que las cuencas de los ríos Armería y Coahuayana están dominadas por la influencia de rocas volcánicas intermedias a básicas y rocas sedimentarias representadas por calizas. Esto se ve apoyado por el enriquecimiento de Fe_2O_3, CaO, MgO, TiO_2, V, Cr, Co y Zn y el empobrecimiento de SiO_2, Al_2O_3, Na_2O K_2O, Ba, Sr and Rb, desde el segmento occidental hacia el segmento oriental. El elevado índice químico de alteración (C.I.A.) en las arenas de playa de los segmentos Armería y Coahuayana se debe a condiciones de mayor humedad en las cuencas de aporte de estos dos ríos, las cuales probablemente están causando el intemperismo de feldespatos y de los líticos volcánicos. Los líticos calcáreos en las arenas de los segmentos Armería y Coahuayana se encuentran empobrecidos debido a su baja resistencia química y mecánica a condiciones fluviales y marinas de alta energía. A pesar de que los afloramientos de calizas son mayores que 40 % en las cuencas central (Armería) y oriental (Coahuayana), los sedimentos de las playas no reflejan la presencia de calizas como roca fuente. La concentración de minerales pesados se asocia con la influencia de la litología de las cuencas Armería y Coahuayana y son posible producto de la erosión de las lavas cuaternarias intermedias y máficas.

Palabras clave: composición, arena, playa, procedencia, Colima, Pacífico, sur de México.

INTRODUCTION

The composition of littoral sediments and their textural, compositional and geochemical variation is controlled by diverse factors like waves, wind, and longshore currents, climate relief and source composition (Folk, 1974; Komar, 1976; Ibbeken and Schleyer, 1991; Carranza-Edwards and Rosales-Hoz, 1995; Carranza-Edwards, 2001; Kasper-Zubillaga and Carranza-Edwards, 2005). Coasts formed by non-consolidated sediments are around 40 % percent of the global coastline composed of sand and gravel beaches (Bird, 2000). Beaches are exposed to different marine, fluvial, and eolian processes such as wave and tidal regimes, fluvial discharges and wind transport among others factors. Furthermore, these factors control the grain-size and sand composition of the beaches in terms of mineralogy and geochemistry.

In addition, geomorphological features in the coast may also have a control in the grain-size, composition and geochemistry of beaches (Le Pera and Critelli, 1997). For instance, some beaches in protected embayments may have coarse grain sizes as result of little energy and removal of finer sizes offshore (Komar, 1976). Furthermore, provenance of coastal sands may be related to different tectonic settings, as it has been documented in several papers (Klitgord and Mammerickx, 1982; Nesbitt and Young, 1982; Carranza Edwards *et al.*, 1994; Kasper-Zubillaga *et al.*, 1999).

The studied southwestern coastline shows a landscape of high relief due to the presence of the Mexican Volcanic Belt and alluvial deposits that probably provides of different beach and river sand compositional characteristics.

The goal of this paper is to characterize the composition and provenance of sand samples collected from eleven beaches and three major fluvial basins draining throughout continental rocks in southwestern Mexico, in order to analyze and distinguish among their grain size, petrography and geochemistry. Our objective is to establish the influence of the lithological character of the source rocks in the texture and composition of the beach sands. We are interested to know how much the extensive limestone, volcanic and plutonic rock outcrops are reflected in the composition of the studied beach sands associated with the river basins. This coastal area was chosen due to its importance from the geological point of view because it is likely that beach sands are compositionally influenced by a mix of plutonic, volcanic source rocks.

STUDY AREA

The study area is located in the coastal area of the Cihuatlán, Armería, and Coahuayana basins, Mexico (Figure 1). For our goal, 35 sand samples were collected and analyzed in terms of grain size, petrology and geochemistry as part of a long-term regional project (Figure 1). Three protected beaches (sites B, C, D,) are located near cliffs and protected embayments. The rest of the beach sites are located as open-sea coastal sedimentary environments in barrier beaches. Relief (INEGI *et al.*, 1990) is relatively low in the coastal eastern portion (Figure 2) and the highest elevations are related to the Volcan del Fuego de Colima (3838 m asl) and the Nevado de Colima (4240 m asl) volcanoes (Tamayo, 2002). The Colima coastal region is part of the south limit of the geomorphic region known as Southwestern Coastal Plain.

There are three main river systems that supply sediments from the potential source rocks to the beach: a) Cihuatlán river basin (sites A, B, C, D); b) Armería river basin (sites E, F, G, H, I that are related to the barrier beach of Cuyutlán Lagoon, which receives sediments from the Armería river); and c) Coahuayana river basin (sites J, K) (Figure 1). The plutonic rocks (Padilla y Sánchez Aceves-Quesada, 1990) are mainly granite-granodiorite found in the Cihuatlán river basin. These crystalline rocks are now exposed and are a potential source for quartz and feldspars to the beach sediments transported through the Cihuatlán

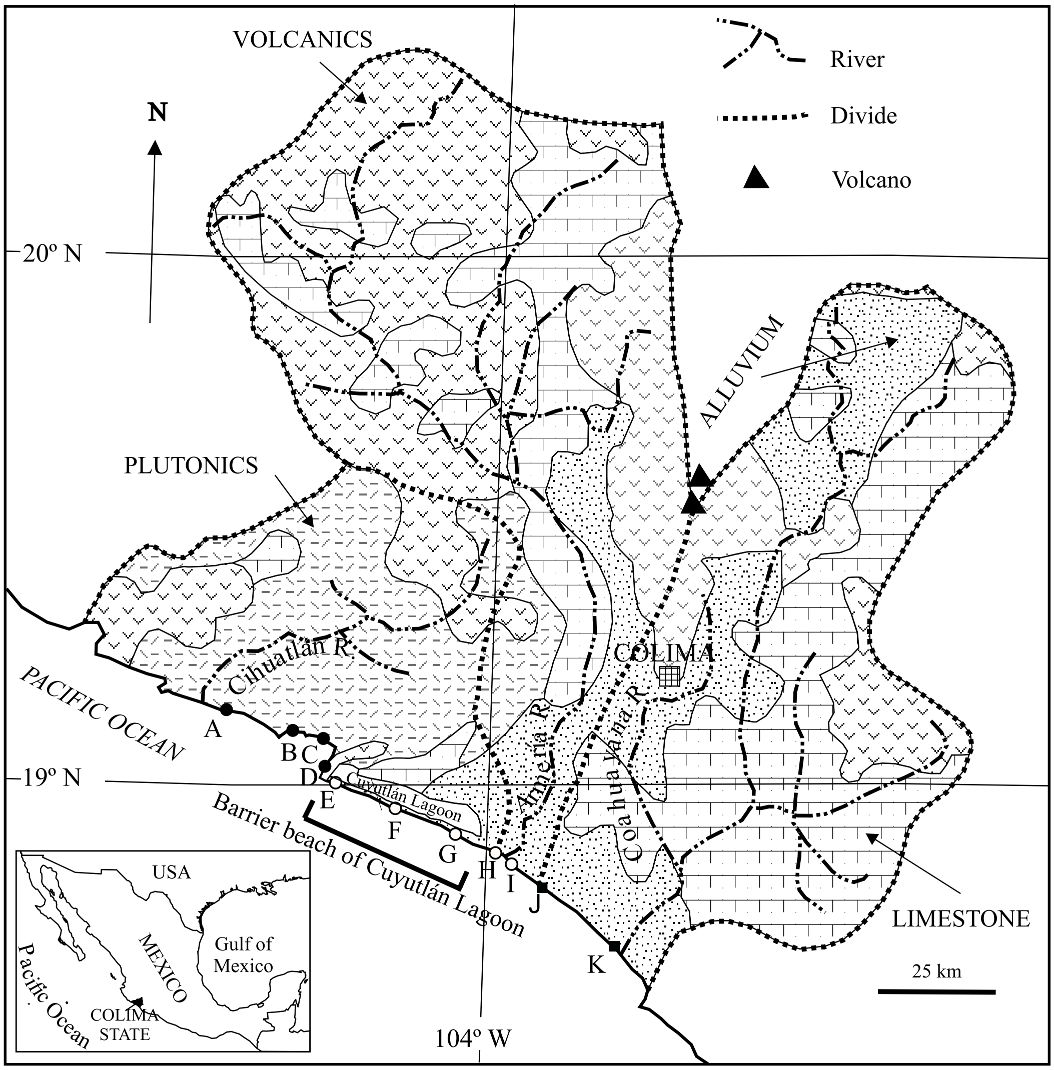

Figure 1. Location of the studied beaches. Synthesized lithological map of Cihuatlán, Armería and Coahuayana basins State (after Padilla y-Sánchez and Aceves-Quesada 1990) and related fluvial basins and rivers basins: a) Ciahuatlan river (western basin), b) Armería river (central basin), whose influence is extended along the Cuyutlán Lagoon barrier, and c) Coahuayana river (eastern basin). NC: Nevado de Colima Volcano, VC: Volcan de Colima. A to K: beach locations. A: Playa de Oro, B: Santiago Bay, C: Manzanillo Bay; D: Playa Ventanas; E: Playa de Punta Campos; F: Playa West Cuyutlán ; G: Playa Cuyutlán; H: Playa Paraíso; I: Boca de Pascuales; J: Tecuanillo; K: Boca de Apiza.

river. In the other two basins (Armería river and Coahuayana river), the exposed rocks are mainly volcanic of intermediate to mafic composition and sedimentary rocks, mainly limestone (Figure 1, Table 1). The Armería and Coahuayana basins are expected to be a source of volcanic and sedimentary lithic fragments for the study area beach sediments. The eastern portion of Colima belongs to the Colima rift (Luhr *et al.,* 1985; Campos-Enríquez and Alatorre-Zamora, 1998). The outcrops (Figure 1) of this volcanic activity and the alluvium are a superficial expression of the Colima graben or Colima rift. The Colima Volcano is found inside the Colima rift zone (Verma and Luhr, 1993). In contrast, the western portion of the studied coast, the Jalisco block is a tectonic block or micro-plate; more or less rigid (Stock, 1993). Cretaceous granitic rocks from an arc root tectonic environment have been reported in this block (Ortega Gutiérrez *et al*., 1992).

The modern climate is tropical with a rainy summer. The average annual precipitation varies from 800 mm in the low areas to 1,200 mm in the highest divides (Tamayo, 2002). No data are available to give a more accurate scenario of the coastal dynamics in Colima. Terrain in the three main basins varies from lowlands to highlands as shown in Figure 2.

MATERIALS AND METHODS

Approximately 200 grams of sand samples were collected by hand from the uppermost centimeter of the

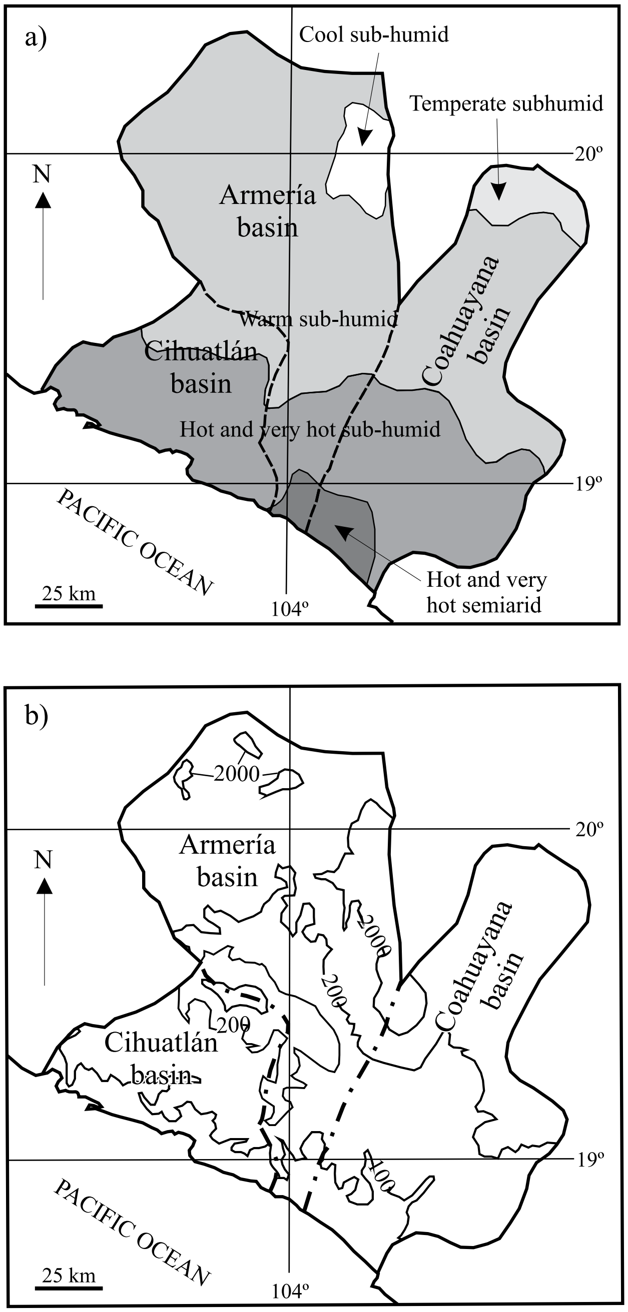

Figure 2. a) Climate (García, 1990) and (b) relief, with elevations in meters above sea level (INEGI *et al.*, 1990), of the main basins associated with the beach sands.

Table 1. Main lithological units (% of exposed surface) for the basin

	West	**Central**	**East**
Alluvial	9.68	16.00	39.68
Limestone	12.90	42.67	41.27
Plutons	58.07	9.33	-
Volcanic	19.35	32.00	19.05

West: Cihuatlán; Central: Armería; East: Coahuayana.

following beaches: A) Playa de Oro, B) Bahía de Santiago, C) Bahía de Manzanillo, D) Ventanas, E) Punta Campos, F) West Cuyutlán, G) Cuyutlán, H) Paraíso, I) Boca de Pascuales, J) Tecuanillo, and K) Boca de Apiza. The beach profiles are shown in Figure 3. Sand samples were taken from inshore, foreshore and backshore environments. Sand sampling sites were choosen taking in account coastal areas near small protected embayments like the Santiago and Manzanillo bays and coastal areas directly exposed to the open sea in order to observe the grain-size, petrographic and geochemical trends. Beach profiles were surveyed using a stadia, rod, and level. Distance measurements along the beach profile were performed with an optical device with one centimeter precision.

Particle size was determined by sieving each sample. The textural parameters (Table 2) were obtained using the formulas and limits suggested by Folk (1974). In our sedimentary petrographic analysis, we counted 300 grains per slide, using the point counting method of Franzinelli and Potter (1983), to survey the provenance of lithic fragments and not only of monomineralic fractions. The observed grain classes fields (Table 3) were: monocrystalline quartz (Qm), polycrystalline quartz (Qp), total feldspars (Ft), volcanic lithic fragments (Lv), metamorphic lithic fragments (Lm), plutonic lithic fragments (Lp), sedimentary lithic fragments (Ls), and diverse heavy minerals (HM). In this study we used the light minerals to infer the source rocks.

Major and trace elements concentration (Tables 4, 5) were determined with a SIEMENS sequential X-ray fluorescence spectrometer, equipped with an end-window Rh target tube and a 125 µm thin Beryllium window. CaO content includes carbonates present in the analyzed sand fraction. For the analysis of major elements, one gram of each sand sample was grinded and fused with nine grams of a 1:1 mix of $Li_2B_4O_7$:$LiBO_2$. Trace elements were analyzed in pressed powder briquettes, prepared by adding 10% of wax-C. Traceability controls were achieved with reference material AGV-1. The error estimated as Error = ((Vchem-Vmeas)/Vmeas)×100 in all the measured elements was always under 1.8 % (Lozano and Bernal, 2005).

The chemical index of alteration (CIA) was calculated according to Nesbitt and Young (1982). The CIA is a measure of the degree of weathering in sediments and it is expressed as $CIA = Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)\times 100$ (ratio in molecular proportions), where CaO^* refers to the amount of CaO incorporated in the silicate fraction. CaO^* was calculated by using the equation $CaO^*=0.35\times 2(\text{wt. \% } Na_2O/62)$, as suggested by Honda and Shimizu (1998) .

RESULTS

Textural parameters and beach profiles

As it can be observe from part of the Figure 4, the majority of the samples are fine to medium sized, with

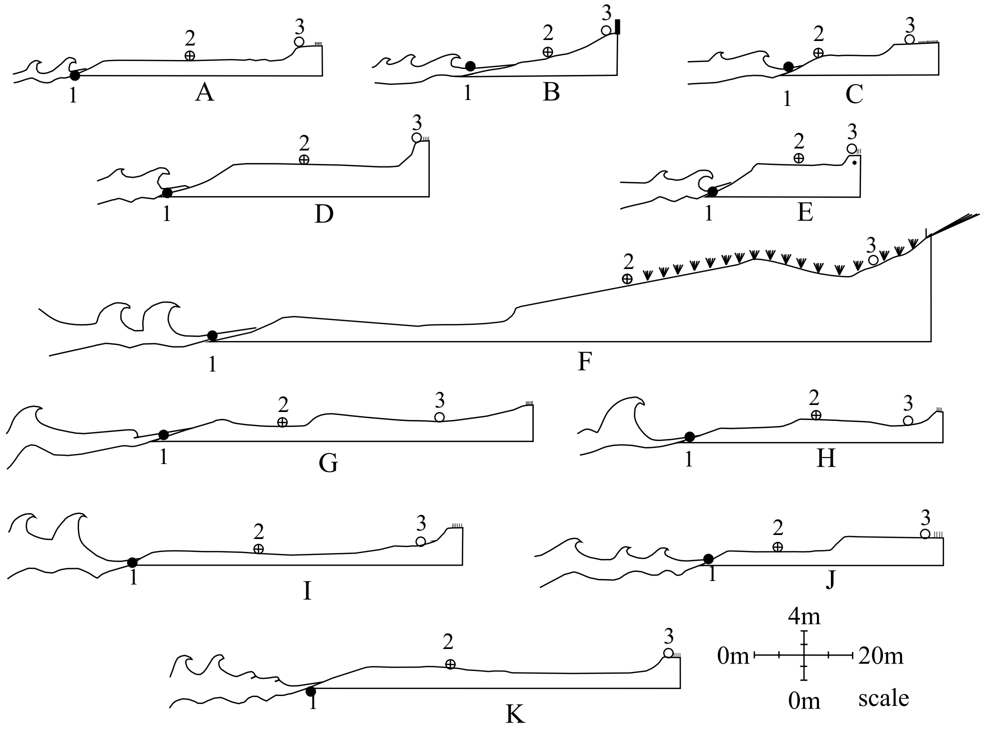

Figure 3. Beach profiles. For beach locations see Figure 1. 1: inshore, 2: foreshore, 3: backshore.

exception of sites A, B, and C from the Cihuatlán river basin, which are coarse sized. The protected Santiago bay at the Cihuatlán river basin has poorly sorted sands in the foreshore zone due to the fact that this beach receives the influence of highly weathered granitoids that supply coarse sands from the cliffs and the wave energy have little impact in abrading debris to smaller sizes. Most samples are in the range of very well sorted to moderately well sorted sands (Figure 4), particularly sands from E to K beaches that are exposed to sea-wave abrassion that reduces the sand size and improves the sorting of the sands. Another possible explanation is that rivers Armería and Coahuayana transport fine-grain sized sands seawards due to a longer fluvial transport.

Most of the samples range between near symmetrical to fine skewed and from mesokurtic to leptokurtic. An exception is Santiago Baya at the Coahuayana river basin that shows samples from very platikurtic to mesokurtic and strongly coarse-skewed to fine-skewed.

A negative correlation between mean grain size (Mzϕ) and sorting ($\sigma\phi$) (-0.50) is observed for the beach sands. The Cihuatlán and some sites of the Armería river basins are beach sites with narrower profiles compared to the rest of the beach localities (Figure 3).

Detrital modal trends

In the Qt-Ft-Lt plot it can be observed that the composition of some Cihuatlán and Coahuayana river basin samples tend toward the Lt and Ft poles, whereas the Armería river basin samples present more Qt and Ft (Figure 5, Table 6). The Lv-Ls-Lp+Lm plot shows a great dispersal of data, being the Cihuatlán river basin sites placed toward the Lp+Lm pole, whereas the Armería and Coahuayana river basins are placed toward the Lv pole (Figure 6; Table 3).

The feldspar content decreases toward the southeast. In contrast, the lithic fraction increases to the southeast. The modal abundance of heavy minerals also increases toward the southeast. The volcanic lithic fragments fraction is high at the D, E, F and G beach sites, as well as in the beach near the Armería river mouth basin (Figure 6; Table 3). Sedimentary lithics are not abundant in the studied beach sands (less than 5% of siltstone and limestone), despite the large area of limestone outcrops (Figure 1, Table 1).

Geochemical data

Major elements like SiO_2, TiO_2, Fe_2O_3 MnO, MgO and CaO exhibit in general high concentrations in southern beaches, mainly at sites I, J and K. Furthermore, it seems that TiO_2, Fe_2O_3 K_2O, Na_2O and Al_2O_3 show significant variations at sites I, J, and K as it will be discussed further.

The CIA values for the studied beach sands slightly increase to the southeast (Table 4), with the highest values corresponding to beaches I, J and K that belong to the Armería and Coahuayana river basins.

The SiO_2 content decreases to the southeast (Table 4). There is an inverse correlation between Mzϕ, Lp and K_2O (Figure 7). Diverse correlations between Lv, Lt, HM,

Table 2. Textural parameters of beach sands.

Sample	Mzϕ	σϕ	Ski	K_G
A1	1.81	0.49	0.12	1.17
A2	1.81	0.51	0.02	1.05
A3	0.57	0.85	-0.03	0.93
B1	1.81	0.57	0.14	1.05
B2	0.68	2.21	-0.66	0.48
B3	0.93	0.65	0.00	1.03
C1	0.90	0.73	0.05	0.98
C2	0.96	0.63	-0.04	0.97
C3	0.27	0.64	0.29	1.07
D1	1.57	0.60	-0.12	1.29
D2	1.63	0.47	0.02	1.07
D3	1.81	0.41	0.03	1.11
E1	1.30	0.48	0.04	1.00
E2	1.28	0.46	0.09	1.06
E3	1.45	0.61	-0.09	1.08
F1	1.60	0.54	-0.08	1.12
F2	1.24	0.63	0.10	0.90
F3	1.74	0.55	0.03	1.04
G1	2.13	0.49	-0.01	1.03
G2	2.27	0.44	0.01	1.08
G3	1.62	0.73	0.14	0.93
H1	1.70	0.52	0.12	1.05
H2	2.07	0.56	0.05	0.97
H3	1.31	0.67	-0.06	1.09
I1	1.69	0.47	0.13	1.15
I2	1.49	0.44	0.17	1.20
I3	1.57	0.56	0.08	1.08
J1	1.88	0.59	0.12	1.04
J2	2.27	0.55	0.07	1.02
J3	1.52	0.53	0.02	1.05
K1	1.79	0.55	0.06	1.05
K2	1.60	0.66	0.01	1.01
K3	2.26	0.62	0.02	0.99

A-D: Cihuatlán, E-I: Armería, J-K: Coahuayana. Mz: mean grain size; σ: sorting; Ski: skewness; K_G: kurtosis.

SiO_2, Lp and other major elements can be observed for the Colima beach sands (-0.51 to 0.77). Furthermore significant positive correlations among TiO_2, Fe_2O_3, V, Rb, Ba and K_2O resulted with values ranging from 0.93 to 0.97. An increase of V, Cr, Co and Zn and a decrease of Ba, Sr and Rb southwards along the basin coast segments can also be observed (Table 5).

DISCUSSION

Grain size and beach profiles

Negative correlations between Mzϕ and σϕ in the beach sands have been also reported for beach sands in the eastern coast of the Gulf of California and dune sands in the Sonora Desert, Mexico (Carranza-Edwards *et al.*, 1996; Kasper-Zubillaga and Carranza-Edwards, 2005), which suggest that fine sands are well sorted. This is mainly associated with the marine, fluvial and aeolian selectiveness that affect the sands and produce fine and well sorted sands in beach and dune sedimentary environments, due to hydraulic sorting of waves and winds respectively.

In the Cihuatlán river basin, coarse grains are dominantly associated with small bays and cliffs in this area that constitutes a local source. In contrast, sediments in the Armería and Coahuayana river basins are exposed to a longer transport and a higher energy regime that enables the redistribution and selectiveness of sands. Sites A, B, C show heterogeneity in the grain size values whereas sites E and I show homogeneity in the grain size values. The rest of the sites have slight dissimilarities in their grain size values.

Differences in grain size values may be attributed to the open sea influence in sites E and I, where waves can originate well-sorted, medium-sized sands despite to the fact that the mouth of the Armería river is located close to the site where the sorting or the grain size characteristics are not affected. Besides, the grain size of discharges to the

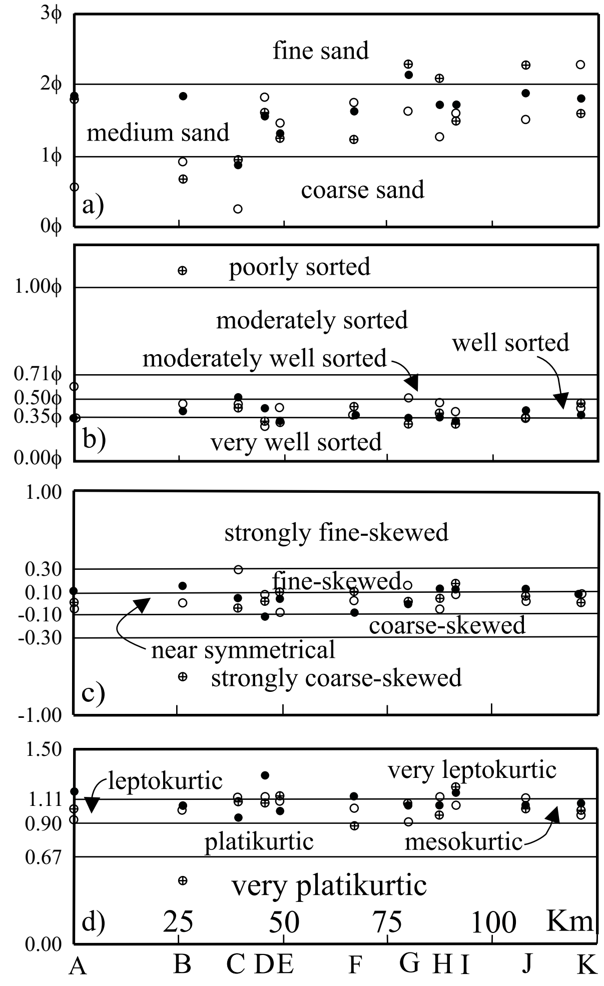

Figure 4. Textural patterns along the beach sands. Filled circle = inshore; open circles with a cross = foreshore; open circle = backshore.

Table 3. Petrologic framework of beach sands.

Sample	Qm	Qp	Qt	Ft	Lv	Ls	Lm	Lp	Lt	HM
A1	22.0	3.8	25.8	13.8	9.0	0.6	2.5	36.0	48.1	12.3
A2	27.0	2.0	29.0	28.0	13.0	1.0	1.0	15.0	30.0	13.0
A3	27.0	0.0	27.0	35.0	9.0	7.5	0.0	20.0	36.5	1.5
B1	14.0	0.0	14.0	38.5	3.5	0.0	5.5	19.5	28.5	19.0
B2	28.5	0.5	29.0	49.4	1.0	0.0	0.0	5.3	6.3	15.3
B3	20.0	0.0	20.0	36.5	1.5	1.0	2.5	24.5	29.5	14.0
C1	5.5	0.0	5.5	16.0	26.0	1.5	6.0	39.0	72.5	6.0
C2	11.5	0.0	11.5	19.0	25.0	2.0	0.5	40.0	67.5	2.0
C3	4.5	0.5	5.0	16.0	13.5	0.0	1.5	63.5	78.5	0.5
D1	0.5	0.0	0.5	9.0	61.5	0.5	0.0	4.5	66.5	24.0
D2	2.0	0.0	2.0	12.0	58.0	0.0	0.0	9.0	67.0	19.0
D3	1.5	0.0	1.5	40.0	46.5	0.5	0.5	0.0	47.5	11.0
E1	1.5	0.0	1.5	7.5	67.5	0.0	0.0	2.0	69.5	21.5
E2	2.0	0.0	2.0	10.0	73.0	2.0	0.0	1.0	76.0	12.0
E3	2.0	0.0	2.0	31.0	65.0	0.0	0.0	0.0	65.0	2.0
F1	5.0	0.0	5.0	12.0	77.0	0.0	0.0	0.0	77.0	6.0
F2	12.5	2.0	14.5	10.0	60.5	0.0	0.0	6.0	66.5	9.0
F3	20.0	2.0	22.0	15.0	44.0	0.0	0.0	4.0	48.0	15.0
G1	13.5	1.5	15.0	17.5	41.5	0.0	0.0	2.0	43.5	24.0
G2	8.5	2.0	10.5	19.0	51.5	0.0	0.0	0.0	51.5	19.0
G3	8.0	1.0	9.0	14.5	63.0	0.0	0.0	1.0	64.0	12.5
H1	16.0	2.5	18.5	24.0	29.0	1.5	0.0	11.0	41.5	16.0
H2	19.0	4.0	23.0	14.5	21.5	1.0	0.0	9.0	31.5	31.0
H3	10.0	3.5	13.5	9.0	30.0	2.0	0.0	7.5	39.5	38.0
I1	3.0	1.5	4.5	6.0	17.5	0.0	3.5	12.5	33.5	56.0
I2	3.5	0.0	3.5	4.0	53.5	0.0	0.0	4.0	57.5	35.0
I3	2.0	1.0	3.0	19.5	27.5	0.0	4.0	7.0	38.5	39.0
J1	4.0	0.0	4.0	9.5	27.0	1.0	3.5	6.0	37.5	49.0
J2	8.0	0.0	8.0	15.0	25.0	4.0	0.0	1.5	30.5	46.5
J3	6.5	0.0	6.5	14.0	39.0	5.0	0.0	2.5	46.5	33.0
K1	16.0	5.0	21.0	15.0	19.0	6.0	1.5	1.5	28.0	36.0
K2	10.0	4.0	14.0	18.5	21.5	2.0	4.0	0.0	27.5	40.0
K3	15.5	6.0	21.5	21.5	15.0	3.5	3.5	0.0	22.0	35.0

Percentages are relative to the modal analysis.Qm: Monocrystalline quartz; Qp: polycrystalline quartz; Qt: total quartz; Ft: total feldspar; Lv: volcanic lithic fragments; Ls: sedimentary lithic fragments; Lm: metamorphic lithic fragments; Lp: plutonic lithic fragments; Lt: total lithics; HM: heavy minerals.

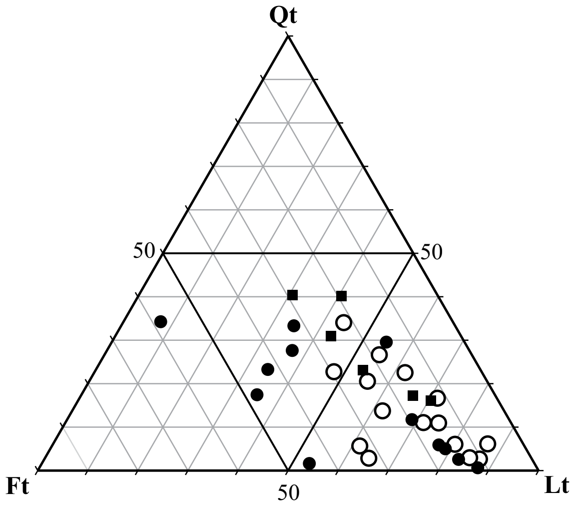

Figure 5. Qt-Ft-Lt diagram with samples from the beach sands. Fill circle: Ciahuatlán river segment (sites A, B, C, and D), empty circle: Armería river basin segment (sites E, F, G. H. and I), filled square: Coahuayana river basin segment (sites J and K). Qt: total quartz; Ft: total feldspar; Lt: total lithics.

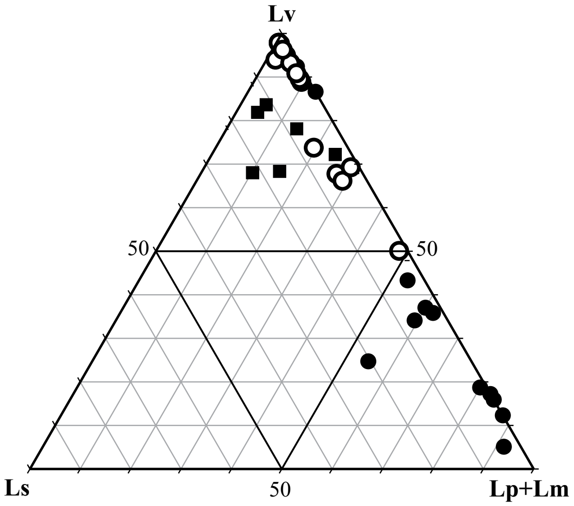

Figure 6. Lv-Ls-Lp+Lm diagram for the beach sands samples. Fill circle: Ciahuatlán river basin (sites A, B, C, and D), empty circle: influenced by Armería river basin (sites E, F, G. H. and I), filled square: Coahuayana river basin (sites J and K). Lithic fragments: Lv: volcanic; Ls: sedimentary; Lp: plutonic; Lm: metamorphic..

Table 4. Major elements (wt. %) in whole sand samples and chemical index of alteration (CIA). LOI: Loss on ignition.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CIA	LOI	Total
A1	68.65	0.66	14.58	3.84	0.08	1.43	3.37	4.28	1.99	0.14	61	0.88	99.90
A2	68.92	0.48	15.19	2.95	0.06	1.14	2.99	4.51	2.30	0.12	60	1.09	99.75
A3	70.85	0.23	15.98	1.63	0.03	0.43	2.10	4.68	2.97	0.09	59	0.69	99.69
B1	61.05	0.63	17.12	4.53	0.10	2.50	6.20	4.40	1.90	0.20	65	1.05	99.68
B2	60.41	0.73	16.84	5.05	0.11	2.60	6.41	4.30	1.83	0.32	65	1.02	99.61
B3	62.04	0.55	18.66	3.84	0.08	1.79	5.16	4.72	2.45	0.13	64	0.95	100.30
C1	64.78	0.46	17.00	3.49	0.06	1.74	3.75	4.59	2.45	0.14	62	1.09	99.54
C2	65.20	0.43	17.00	3.40	0.06	1.70	3.69	4.51	2.44	0.13	63	2.13	100.60
C3	66.36	0.29	17.62	2.32	0.03	0.89	3.19	4.74	3.12	0.12	61	0.92	99.60
D1	58.18	0.74	13.90	7.27	0.14	6.09	6.41	3.55	1.45	0.19	65	1.71	99.62
D2	58.95	0.76	14.57	7.06	0.14	5.91	6.16	3.75	1.40	0.17	65	1.19	100.06
D3	57.72	0.77	14.66	7.57	0.14	6.40	6.35	3.59	1.24	0.18	67	1.08	99.68
E1	59.36	0.75	16.33	6.45	0.11	4.48	5.66	4.14	1.45	0.20	66	0.97	99.88
E2	58.08	0.79	14.48	7.63	0.15	6.84	6.36	3.67	1.26	0.18	66	0.60	100.03
E3	57.47	0.77	12.86	8.62	0.17	8.54	6.48	3.12	1.08	0.17	67	0.68	99.96
F1	60.17	0.70	17.32	5.64	0.10	3.48	5.52	4.26	1.48	0.19	67	1.01	99.85
F2	60.86	0.69	17.35	5.50	0.10	3.15	5.19	4.43	1.54	0.19	66	1.13	100.10
F3	58.64	0.75	15.33	7.11	0.13	5.71	6.05	3.76	1.28	0.18	67	0.78	99.72
G1	59.22	0.70	16.67	6.11	0.11	4.03	6.04	4.10	1.39	0.17	67	1.11	99.65
G2	58.42	0.75	15.89	6.99	0.14	5.48	6.55	3.84	1.24	0.16	67	1.00	100.45
G3	58.56	0.77	14.58	7.51	0.14	6.14	6.37	3.63	1.30	0.19	66	0.72	99.90
H1	60.71	0.70	16.80	5.77	0.10	3.32	5.87	4.22	1.50	0.18	66	1.13	100.30
H2	55.67	0.99	12.50	10.10	0.18	8.35	6.91	2.88	1.01	0.17	68	0.92	99.69
H3	57.28	0.92	12.69	9.27	0.17	7.75	6.69	3.06	1.14	0.17	67	0.85	99.99
I1	48.96	1.51	5.81	16.48	0.30	15.81	8.15	1.05	0.34	0.12	73	1.13	99.65
I2	57.94	0.75	11.64	8.73	0.18	8.95	7.08	2.83	1.04	0.13	67	0.78	100.03
I3	58.55	0.82	11.62	9.00	0.18	8.38	6.46	2.77	1.10	0.15	67	0.75	99.78
J1	54.35	1.06	8.76	12.18	0.24	12.39	7.94	1.93	0.68	0.12	69	0.45	100.10
J2	47.40	2.18	7.05	19.80	0.30	13.62	7.43	1.35	0.41	0.19	72	0.28	100.00
J3	55.66	1.28	10.57	12.32	0.21	9.26	6.55	2.39	0.93	0.15	68	0.74	100.00
K1	58.64	0.92	13.17	8.59	0.16	6.44	6.33	3.16	1.16	0.15	67	1.14	99.87
K2	58.06	1.19	12.51	10.48	0.18	6.34	6.03	3.12	1.24	0.14	66	1.17	100.48
K3	47.47	2.73	9.38	22.09	0.25	8.78	5.97	1.99	0.70	0.20	70	0.43	100.00

littoral tend to be fine in the Armería and Coahuayana river basins, where longer fluvial transport takes place.

Detrital modal trends

The majority of the beach sands trend toward the Lt and Ft poles. However, the segment of the Cihuatlán shows a higher content of Ft and Qz due to the influence of plutonic sources. The sediments of the Armería and Coahuayana river basins are associated with volcanic and sedimentary (mostly calcareous) rock sources, and most of these samples tend toward the Lt pole (Figure 5). This interpretation is supported by the Lv-Ls-Lp+Lm plot diagram (Figure 6) where the Cihuatlán river basin samples are located toward the Lp+Lm pole, whereas the Armería and Coahuayana segments are near to the Lv pole and relatively far of the Ls pole, in spite of the great abundance of Ls sources (around 40% of the total area of that basins).

Feldspars are mostly composed of plagioclase derived from intermediate volcanic sources, as the content of Na_2O is higher than K_2O (Table 4). Lithics are dominantly composed of volcanic and plutonic rocks, as shown in Table 3. This is also supported by the Lv/Lp and Ls/Lp ratios (Table 6). Volcanic rock fragments clearly dominate in the Armería and in the barrier beach of Cuyutlán Lagoon (nourished by Coahuayana river (Table 3). The trend of this barrier reflects the dominant transport toward the northwest, because the average longshore current velocities are 6 cm/s in winter and 9 cm/s in summer having southeastern and northwestern directions respectively (Fernández-Eguiarte *et al*., 1992a, 1992b). The Lv-Ls-Lp+Lm plot (Figure 6) is an evidence of the volcanic influence for the Armería and Coahuayana segments, and the Cihuatlán segment shows an enrichment toward the Lp+Lm pole, being more abundant the Lp.

Armería and Coahuayana rivers do not supply potash feldspar as is revealed by the southward decrease in the feldspar content, whereas the Cihuatlán beach segment shows a major content of feldspars that is related to the influence of plutonic sources. The barrier beach of Cuyutlán Lagoon

Table 5. Trace elements (ppm) in whole sand samples.

Sample	Rb	Sr	Ba	Y	Zr	Nb	V	Cr	Co	Ni	Cu
A1	46	502	627	18	159	22	73	36	47	45	32
A2	56	533	733	15	141	19	54	34	49	44	34
A3	74	560	979	12	146	11	30	23	28	35	46
B1	36	862	864	15	162	11	82	35	42	69	35
B2	35	829	780	18	188	16	92	44	54	70	27
B3	49	976	1139	12	179	11	64	29	28	66	51
C1	51	749	968	14	146	11	73	43	34	56	41
C2	52	754	995	13	147	9	71	41	21	55	76
C3	65	820	1159	11	156	10	42	25	28	52	52
D1	26	554	553	15	156	10	144	180	42	81	36
D2	21	528	447	15	127	10	161	165	33	65	22
D3	18	601	548	13	152	13	156	220	63	89	27
E1	23	720	668	15	186	11	141	129	57	83	37
E2	17	514	446	14	121	11	172	213	33	77	23
E3	16	495	494	13	139	7	171	286	51	91	28
F1	26	796	743	14	192	12	123	87	47	81	38
F2	27	802	765	15	200	11	127	66	36	76	44
F3	20	642	597	13	160	10	149	175	44	92	29
G1	23	757	646	13	173	10	135	105	41	84	38
G2	19	608	428	13	119	8	153	133	30	62	23
G3	20	601	594	13	157	9	154	191	47	83	34
H1	27	752	695	14	184	11	121	88	40	80	45
H2	15	475	423	14	128	9	214	266	46	88	25
H3	17	485	492	13	138	7	196	251	42	83	31
I1	6	169	127	13	73	6	365	681	68	86	5
I2	15	380	354	13	90	9	177	290	37	100	16
I3	19	412	411	14	122	7	182	266	44	79	26
J1	9	277	255	13	73	8	237	406	41	121	35
J2	7	217	129	16	173	11	512	659	103	76	5
J3	17	350	341	15	125	10	282	353	68	75	17
K1	22	492	440	15	138	8	175	179	47	75	32
K2	21	419	397	15	147	7	226	175	29	60	74
K3	14	309	220	19	211	11	615	372	67	64	6

Table 6. Q-F-L (%) and main lithic ratios.

Sample	Qt(%)	Ft(%)	Lt(%)	Lt/Qt	Lt/Ft	Lv/Qt	Lv/Ft	Lv/Lp
A1	29.4	15.7	54.8	1.8	3.4	0.3	0.6	0.2
A2	33.3	32.2	34.5	1.0	1.0	0.4	0.4	0.8
A3	27.4	35.5	37.1	1.3	1.0	0.3	0.2	0.4
B1	17.3	47.5	35.2	2.0	0.7	0.2	0.0	0.1
B2	34.2	58.3	7.4	0.2	0.1	0.0	0.0	0.1
B3	23.3	42.4	34.3	1.4	0.8	0.0	0.0	0.0
C1	5.9	17.0	77.1	13.1	4.5	4.7	1.6	0.6
C2	11.7	19.4	68.9	5.8	3.5	2.1	1.3	0.6
C3	5.0	16.1	78.9	15.7	4.9	2.7	0.8	0.2
D1	0.7	11.8	87.5	13.3	7.3	123.0	6.8	13.6
D2	2.5	14.8	82.7	33.5	5.5	29.0	4.8	6.4
D3	1.7	44.9	53.4	31.6	1.1	31.0	1.1	--
E1	1.9	9.6	88.5	46.3	9.2	45.0	9.0	33.7
E2	2.3	11.4	86.4	38.0	7.6	36.5	7.3	73.0
E3	2.0	31.6	66.3	32.5	2.0	32.5	2.0	--
F1	5.3	12.8	81.9	15.4	6.4	15.4	6.4	--
F2	15.9	11.0	73.1	4.5	6.6	4.1	6.0	10.0
F3	25.9	17.6	56.5	2.1	3.2	2.0	2.9	11.0
G1	19.7	23.0	57.2	2.9	2.4	2.7	2.3	20.7
G2	13.0	23.5	63.6	4.9	2.7	4.9	2.7	--
G3	10.3	16.6	73.1	7.1	4.4	7.0	4.3	63.0
H1	22.0	28.6	49.4	2.2	1.7	1.5	1.2	2.6
H2	33.3	21.0	45.7	1.3	2.1	0.9	1.4	2.3
H3	21.8	14.5	63.7	2.9	4.3	2.2	3.3	4.0
I1	10.2	13.6	76.1	7.4	5.5	3.8	2.9	1.4
I2	5.4	6.2	88.5	16.4	14.3	15.2	13.3	13.3
I3	4.9	32.0	63.1	12.8	1.9	9.1	1.4	3.9
J1	7.8	18.6	73.5	9.3	3.9	6.7	2.8	4.5
J2	15.0	28.0	57.0	3.8	2.0	3.1	1.6	16.6
J3	9.7	20.9	69.4	7.1	3.3	6.0	2.7	15.6
K1	32.8	23.4	43.8	1.3	1.8	0.9	1.2	12.6
K2	23.3	30.8	45.8	1.9	1.4	1.5	1.1	--
K3	33.1	33.1	33.8	1.0	1.0	0.6	0.6	--

is constructed by the northwestern transport of fluvial sediments mainly from the Armería river.

The modal abundance of heavy minerals increases toward the Armería and Coahuayana river basins. This indicates that finer fractions concentrate heavy minerals, because they occur in areas of high wave energy. This condition occurs when the coarse grains are removed toward the offshore, leaving behind a fine-grained heavy mineral deposit (Komar and Wang, 1984). Heavy mineral concentration near the Armería and Coahuayana river basins is likely associated with erosion of volcanic outcrops near the H to K sites (Table 3).

Volcanic lithic fragments are preserved even in wave-dominated coastal areas, supplied as fine-grained volcanic fragments like those from the barrier beach across Cuyutlán Lagoon, that initiate west of the Armería river mouth. In contrast, sedimentary lithic fragments are easily fragmented, and carbonate cement and limestone detritus are dissolved by chemical weathering in the source area and along the river, and mechanically reduced in wave-dominated areas as in the Armería and Coahuayana river basins (Table 3). This is observed in sites D, E, F, G, H and I, but not in sites J and K with fluvial influence of the Coahahuayana river that, although has a similar lithology of the adjacent Armería basin, has a relatively more extensive area affected by hot sub-humid climate (Figure 2a).

Feldspar content shows a peak at site B, which can be associated with a local source and the low abrasion effect of the grains in an area. The increase in feldspar content is also associated to the proximity of plutonic rocks (Lancin and Carranza-Edwards, 1976) that occur only a few meters from the Bahía de Santiago at the Cihuatlán river basin (Figure 1). Large modal abundance of plutonic fragments occur at sites A, B and C due to the influence of granitic rocks both in local drainages and along the Armería river basin. The negative correlation between plutonic lithic fragments and Mzϕ (Figure 7) is related to coarser fractions (Table 2) and plutonic detritus (Table 3) as in the northwestern coast of the study area.

Sedimentary lithic fragments are sparse in the beach

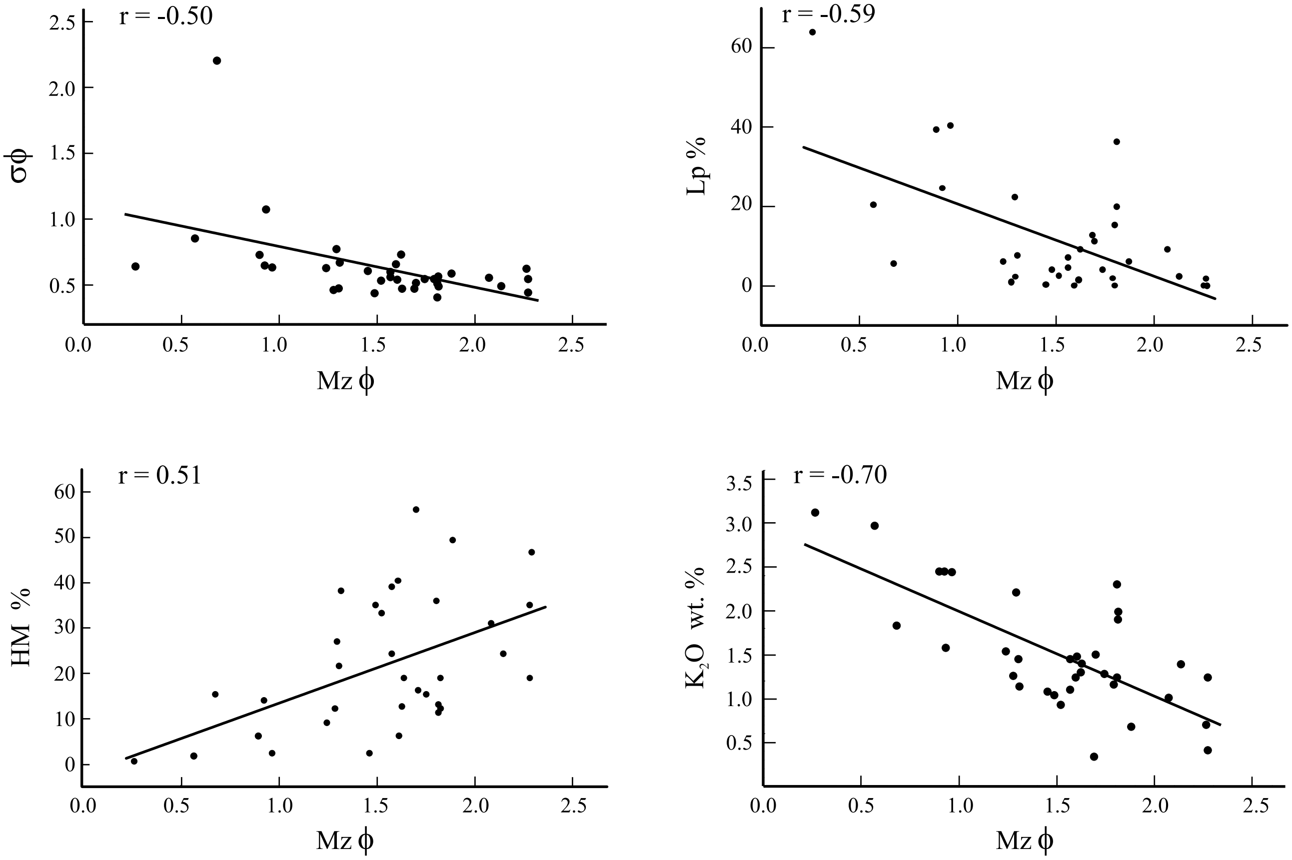

Figure 7. Significant correlations of Mzφ. σϕ: sorting, HM: diverse heavy minerals. Significance level greater than 95%.

sands. This probably indicates the effect of high relief, humid climate and high wave energy in the beach environment depleted in sedimentary debris.

Geochemistry of Colima beach sands

Indicators of degree of weathering

Sand samples have CIA values from 59 to 73 as it can be seen in the A-CN-K diagram (Figure 8) proposed by Nesbitt and Young (1982). The highest CIA values are observed for samples I1, J2 and K3, sites that belong to the Armería and Coahuayana segments. These can be explained by the extensive sub-humid conditions (Figure 2a) in the lower Coahuayana river basin, where samples have a low Lv content (Table 3, Figure 6), because of weathering of plagioclase contained in the volcanic rock fragments, even that sands influenced by high energy wave regimes are likely to produce low CIA values, as shown in previous studies (Rosales-Hoz and Carranza-Edwards, 1995), due to the removal of Al_2O_3 in the superficial weathered envelope of feldspars in the beach environment related to humid basins. Furthermore, these samples also tend toward the A pole (Figure 8) suggesting a higher degree of weathering indicated by the presence of higher Al_2O_3 content.

The increase in CIA values in beach sediments associated with the Armería and Coahuayana river basins (sites F, G, H, I, J and K) also suggests the influence of climate, because there is an extensive hot and very hot sub-humid climatic sub-zone (Figure 2a) affecting the wheatering of the volcanic debris. The Coahuayana river (Figure 1) flows through a wide, highly vegetated, low-lying, inclined landscape (Figure 2b) that contributes to the chemical weathering in the fluvial transported sediments, particularly in the low reaches of Coahuayana river.

Provenance

The SiO_2 (and quartz) enrichment in the beaches of the Cihuatlán basin (west segment) indicates that coarse grains are associated with plutonic fragments and quartz content. Plutonic lithic fragments are found in coarse detritus increasing the SiO_2 of beach sands from the sites A, B, C and D (Cihuatlán segment). Moreover, there is an association between coarse grain sizes and the SiO_2 content in the bulk composition of the sands.The SiO_2 reflects primarily the abundance of leucocratic phases (quartz and feldspars) (Nesbitt and Young, 1996) in the beach sands of the Ciauhatlan western region. This is in agreement with

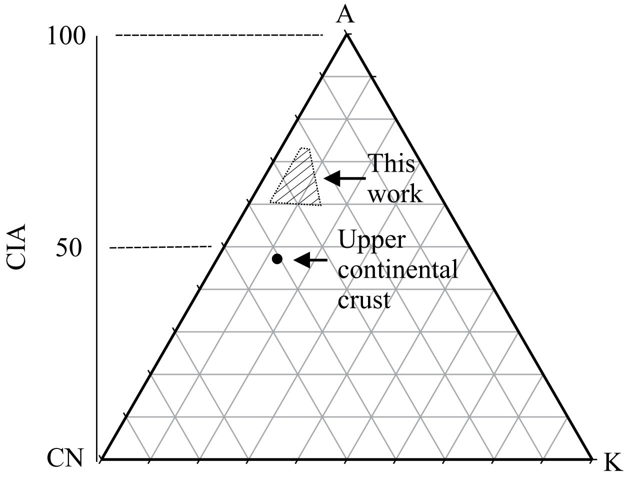

Figure 8. A-CN-K triangle (after Nesbitt and Young, 1982) showing the degree of weathering of the beach sand samples. A: Al_2O_3; CN: CaO+Na_2O; K: K_2O; CIA: chemical index of alteration.

the dominant granitic source rocks (Figure 1).

The negative correlation between Mzϕ and K_2O suggests that coarse grains are also composed of alkali feldspar and plutonic lithic fragments that contain potash feldspar, which increases the K_2O content (Figure 7).

On the other hand, the melanocratic phases (Fe-Ti oxides) are contained in volcanic lithic fragments and they increase the abundances of TiO_2, Fe_2O_3 and MgO. Correlations among HM *versus* Lt, SiO_2, TiO_2 and Fe_2O_3 indicate that volcanic sources imprint the compositional signals observed in most of the analyzed beach sands (Figure 9).

The average values of Fe_2O_3, MgO, CaO, and TiO_2 increase southward and are clearly related to volcanic debris supplied by the Armería and Coahuayana rivers (Figures 1 and 10, Table 6). Furthermore, there are high Lv values associated with the barrier of Cuyutlán Lagoon (Table 3). In the mouth of Armería river the values are lower than those found in the barrier, because the initial discharge of fluvial sediments from Armería is concentrated toward northwest by the action of waves across the barrier where the dominant waves and alongshore drift increases Lv, related to the barrier beach of Cuyutlán Lagoon (Table 3).

The positive correlations among TiO_2, Fe_2O_3 and V shown in Figure 11 have been also reported for dune sands in the Sonora and Vizcaino Desert in Northwestern Mexico (Kasper-Zubillaga and Zolezzi-Ruiz, 2007), beach sands from the Gulf of Mexico and sands from the western coast of Mexico (Kasper-Zubillaga *et al.,* 1999). Our results suggest that ilmenite and magnetite are contained in volcanic lithic fragments and in the HM fraction and they increase the abundances of TiO_2, Fe_2O_3 and V.

Regarding trace elements analyses, the average values of Ba, Sr and Rb decrease southwards (Figure 12; Table 5). Sr resides mainly in carbonate and feldspar (Yang *et al.*, 2003). High concentrations of Sr, mostly in the beach sands, may be a result of higher content of feldspar toward the Cihuatlán segment (mainly in sites A, B, and C) (Table 3). Rb and Ba may substitute for K in the lattice in K-feldspar and mica (Muhs *et al.,* 2003). The correlations among Rb, Ba and K_2O strongly suggest the presence of potash feldspar in the sands.

The correlation between TiO_2 and Fe_2O_3 (Figure 11) supports the presence in the sands of titanomagnetite or iron-titanium oxides, which are common in intermediate and mafic volcanic rocks (Righter and Rosas-Elguera, 2001,

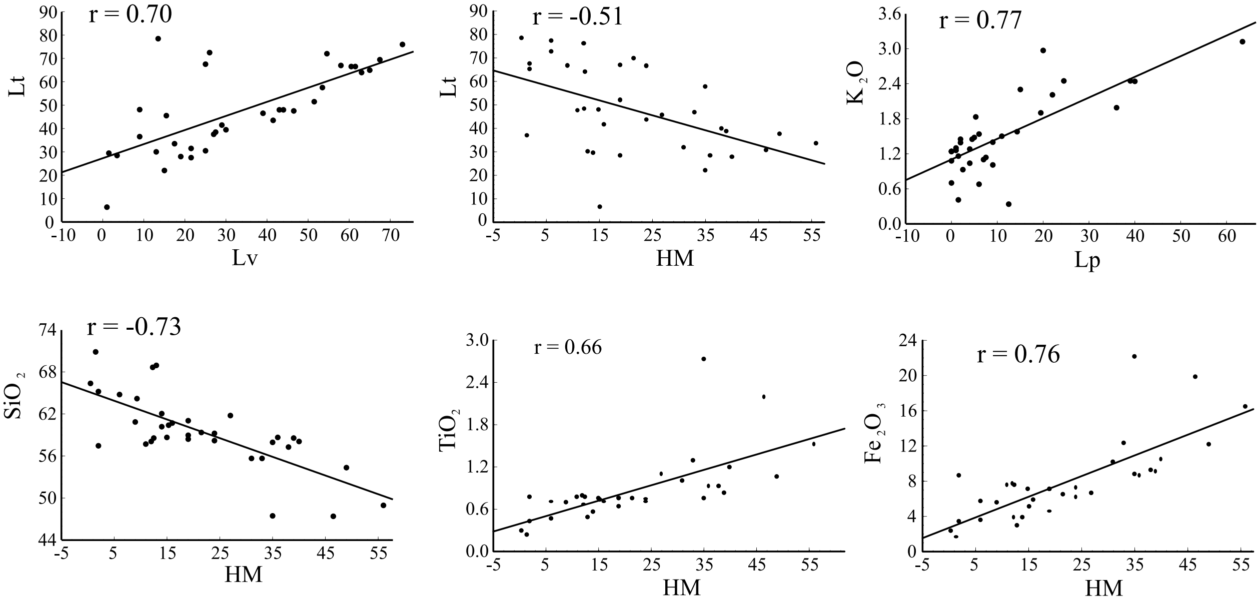

Figure 9. Correlation of some petrographic and geochemical parameters of the beach sands. Significance level greater than 95%.

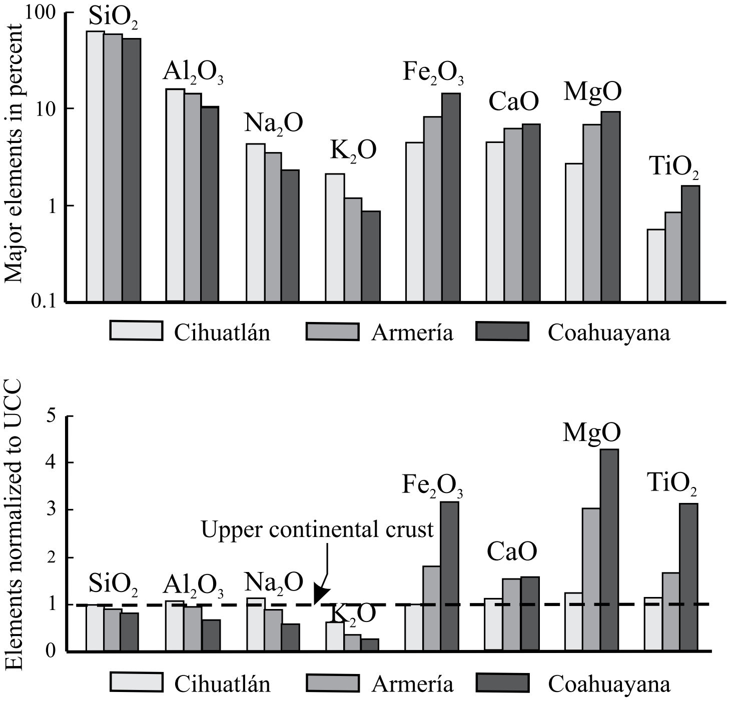

Figure 10. Major elements and upper continental crust (UCC)-normalized patterns. Normalization values from Taylor and MacLennan (1985) and McLennan (1995). See text for explanation.

Mora *et al.*, 2002). The important sources of TiO_2 and Fe_2O_3 are evident in the Armería and Coahuayana segments, which are Fe-Ti enriched due mainly to the presence of volcanic rock fragments of andesitic nature (Valdéz-Moreno *et al.*, 2006).

An increase of K_2O with Rb and Ba content is observed in the sediments as shown in the correlation plots (Figure 11). This implies that the sands in the northwest segment have been more influenced in their Ba, Sr and Rb contents by granitic sources (Figures 11 and 12) associated with non-weathered K-feldspar and biotite.

Normalized patterns of major and trace elements

Trace elements abundances were normalized to the Upper Continental Crust (UCC) values reported by Taylor and MacLennan (1985) and McLennan (1995). The most notorious trends are given by the average values of each site. A decrease in the SiO_2, Al_2O_3, Na_2O, and K_2O contents and an increase in the Fe_2O_3, CaO, MgO, TiO_2 contents is observed from the western (Cihuatlán) to the eastern (Coahuayana) segments (Figure 10).

The influence of plutonic rocks in the Cihuatlán basin is also reflected by the average of the normalized trace elements Ba, Sr and Rb. In contrast, the increase in V, Cr, Co and Zn indicates a volcanic input from the Armería and Coahuayana basins (Figure 12). This interpretation is supported by the relative increase of Lv/Qt, Lv/Ft and Lv/Lp ratios in the Armería and Coahuayana segments (Tables 3 and 4).

CONCLUSIONS

The beaches of the Cihuatlán basin tend to be narrower compared to those of the Armería and Coahuayana basins. Coarse and poorly sorted sediments are present in the Cihuatlán basin, which is probably related to less removal of coarse grains associated to shorter transport and less wave effect. The Armería and Coahuayana beach segments show similar grain size patterns, being fine grained and better sorted sands.

Sands of the Coahuayana river basin are controlled by plutonic and volcanic sources. An increase in feldspar content in the Cihuatlán river basin is likely generated from larger plutonic sources. Heavy minerals concentration increases toward the influence area of the Armería and Coahuayana rivers, where fine fractions are observed in the beach sands. Beaches from the Cihuatlán basin segment are dominantly influenced by granitoides. In contrast, the Armería and Coahuayana segments are mostly influenced by volcanic sources.

The Coahuayana river basins has around 40 % of exposure limestone outcrops, however the final result of sedimentary lithics content in beach sands is less than 6 % and almost non-existant in the Armería segment. This may be due to intense chemical weathering of limestone in soil and during transport, as well as to low resistance of limestone under high energy river-marine conditions.

The chemical index of alteration (CIA) values increases toward the Armería and Coahuayana segments

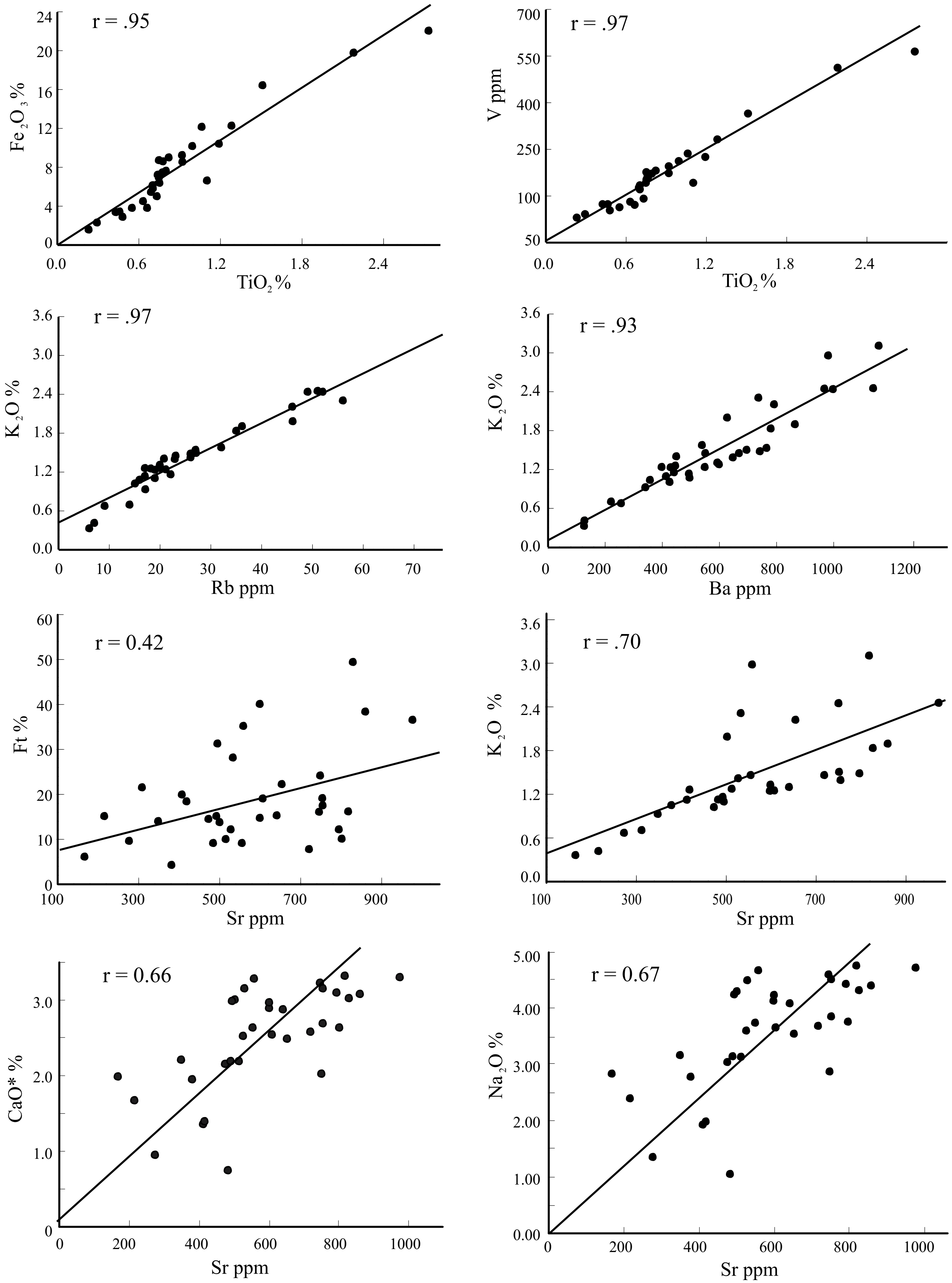

Figure 11. Major and minor elements correlations. Significance level greater than 95%.

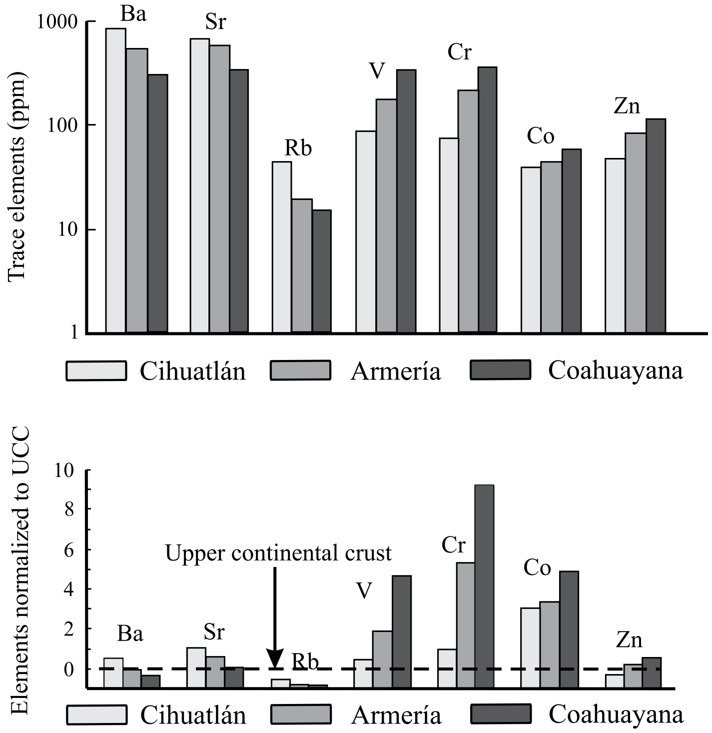

Figure 12. Trace elements and upper continental crust (UCC)-normalized patterns. Normalization values from Taylor and MacLennan (1985) and McLennan (1995).

near the river mouth, which is probably due to an increase in weathered volcanic rock fragments related to a more extensive area with humid conditions.

The influence of plutonic rocks in the Cihuatlán segment is reflected by the high values of Si, Al, Na, K, Ba, Sr and Rb. The increase of Fe, Ca, Mg, Ti, V, Cr, Co and Zn in beach segments closer to the Armería and Coahuayana rivers is controlled mostly by volcanic rock fragments provenance.

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