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Sediment Transport Patterns Inferred from Grain-Size Trends: Comparison of Two Contrasting Bays in Mexico

Alberto Sanchez and Concepción Ortiz Hernández

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1. Introduction

The analysis and description of geological processes in sedimentary environments have been widely defined by the frequency distribution of grain size (Friedman, 1961) whereas the change in the sediment textural characteristics has been used to evaluate the net sediment transport (Mc Laren and Bowles, 1985). The evaluation as a grain-size trend analysis (GSTA) is defined in Gao and Collins (1991, 1992) and LeRoux (1994a,b). The use of textural characteristics (grain size, sorting, and skewness) to infer the sediment transport was originally shown by a decrease in particle size in the direction of flow. In Sunamura and Horikawa (1971) a combination of grain-size and sorting identified four possible examples where it is possible to infer the direction of the sediment transport. In the early 1980s, the use of grain size, sorting, and skewness were proposed to infer sediment transport on the basis of the statistical analysis of sediment-transport paths along the transect (Friedman, 1961). Later bidimensional models of sediment transport proposed by Gao and Collins (1992), LeRoux (1994a) and Poizot et al. (2008) are supported by analytic geometry, vector analysis, and statistics to obtain more robust results of the magnitude and direction of the transport vectors. The GSTA is an excellent approach for establishing sediment transport in a variety of environments such as rivers, beaches, harbors, estuaries, continental shelf, and submarine canyons (Carriquiry and Sánchez, 1999; Carriquiry et al., 2001; Sanchez et al., 2008, 2009, 2010; Sanchez and Carriquiry, 2012).

1.1. Bahía Chetumal

Bahía Chetumal is located in the Mexican Caribbean at the mouth of the Río Hondo, which defines the border between Mexico and Belize and is one of the few surface runoffs from the Yucatan Peninsula. Organic and inorganic wastes of the extensive cane crops adjacent to the river are discharged directly into the Río Hondo (Ortiz Hernández and Sáenz Morales, 1999) and subse-

quently are transported and deposited into the bay. Although studies have been made in Bahía Chetumal concerning the sedimentology (De Jesús Navarrete et al., 2000; Sanchez et al., 2008), the distribution of metals (García Ríos and Gold Bouchot, 2003; Díaz López et al., 2006; Buenfil Rojas and Flores Cuevas, 2007), and aromatic hydrocarbons (Álvarez Legorreta and Sáenz Morales, 2005) only in last study there is a good relationship between fine sediments and the concentration of aromatic hydrocarbons in the deepest parts of the bay reported.

1.2. Bahía Magdalena

The lagoon complex Bahía Magdalena-Almejas is an ecosystem with high biodiversity, fisheries, and tourism on the peninsula of Baja California. Recently, a synthesis and integration of studies on biology, ecology, physical oceanography, and social sciences in this lagoon complex was made for the purpose of providing accessible information for making decisions on the use and sustainable exploitation of the natural resources and to identify possible areas for ecological protection (Funes Rodríguez et al., 2007). However, the sedimentary processes in this bay were not integrated into this synthesis, but they are of importance in the assessment of the ecological risk and the recovery and rehabilitation of marine environments (Carriquiry and Sánchez, 1999; Sanchez et al., 2008). In contrast to Bahía Chetumal, in the lagoon complex there is no evidence of impacts derived from human activities, at least for metal contamination (Shumilin et al., 2005).

In our work, the transport and dispersion of the surface sediments are compared in these two contrasting bays. The interpretation of spatial trends of textural characteristics and their comparison with hydrographic records may form the basis of a framework for implementing environmental monitoring schemes in both bays, in addition to expanding our knowledge of the biogeochemical processes and their relationship with the sedimentary dynamics that determine the functioning of the ecosystem.

2. Setting

2.1. Bahía Chetumal

Bahía Chetumal is semielongated (~ 110-km long and ~ 20-km wide) with a maximum of 49 km in its central area and a minimum of 5 km at the head (Fig. 1). The bathymetry of the bay is relatively shallow (4-m on average) with a center channel from 6- to 8-m depth with a SW direction. There are some narrow, deep depressions known locally as pozas. The Río Hondo and some smaller streams that flow into the bay cause estuarine conditions with a salinity of 10 to 18, decreasing from the mouth to the head of the bay. In the summer, rainfall is highest and accentuates the estuarine conditions in the bay (Carrillo et al., 2009). In this Caribbean region, the tides are mixed semidiurnal with a microtidal range between 10 and 20 cm (Kjerfve, 1981). Local winds are dominated by easterly and southeasterly trade winds and by large-scale perturbations, such as tropical storms, hurricanes, and cold fronts (Gallegos et al., 1997; Mooers and Maul, 1998). The winds are easterlies-south easterlies with a mean speed of 3.1 m s^{-1} and the maximum air temperature ($> 34.6^\circ\text{C}$) is during August (Carrillo et al., 2009). The dry season

lasts from late March to early June and the winds are mainly from the southeast. The mean annual river discharge into the bay is about 1,500 million m³. Recently, from observations during 2005–2006, it was estimated that the Rio Hondo discharge varies from about 9 to 24 to over 78 m³ s⁻¹ during the dry and the wet seasons. It can be as high as 220 m³ s⁻¹ during the wet season (SARH-CNA, 1987).

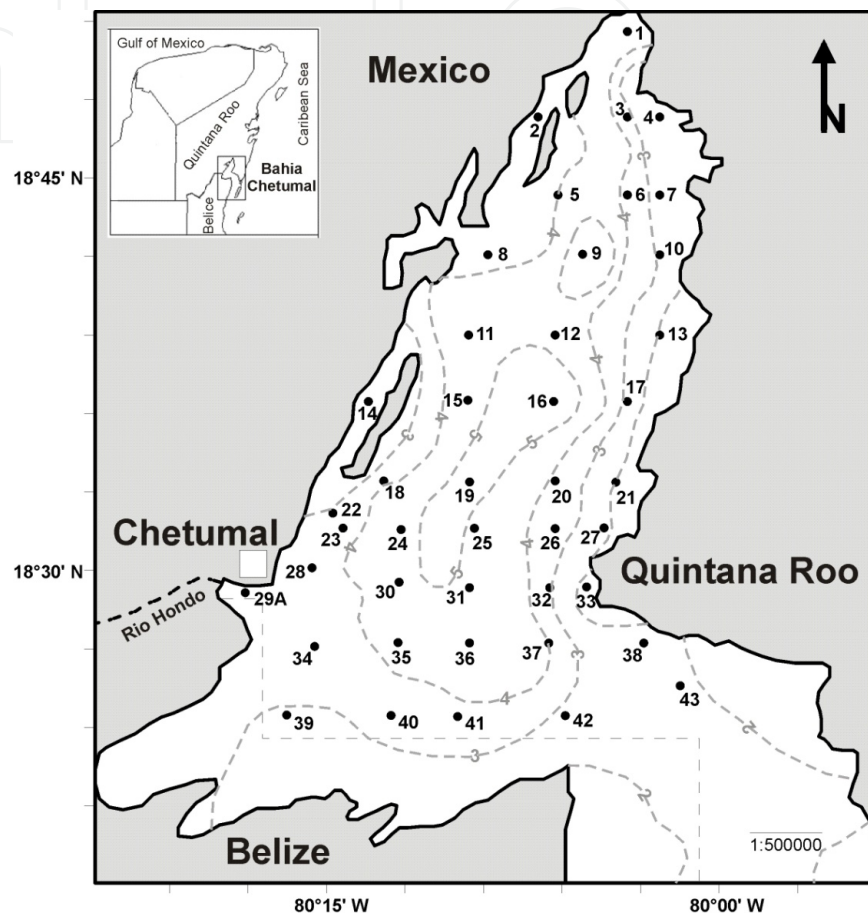


Figure 1. Study area and sampling stations in Bahia Chetumal. The dotted lines denote the bathymetry of the bay.

2.2. Bahia Magdalena

Bahia Magdalena is on the southwestern coast of the peninsula of Baja California (Fig. 2). The bay is characterized by a relatively shallow area with marshes, lagoons, and channels with a depth < 10 m. In the central part of the bay, the depth is greater than 20 m, with a channel that connects the bay with the ocean (Álvarez Borrego et al., 1975). In the ocean there is an area of seasonal upwelling (Zaitsev et al., 2003) that transports nutrients into the bay during spring tides. Inside the bay, the speed of the tidal current is ~23 cm s⁻¹ during the flood tide and 20 cm s⁻¹ during the ebb tide (Acosta Ruíz and Lara Lara, 1978), with a maximum tidal-current speed of 1.09 m s⁻¹ in the mouth (Obeso Nieblas et al., 1999). In Morales Zárte et al. (2006) is described the circulation and passive transport of particles in Bahia Magdalena. Seeded particles tend to concentrate in the shallow and internal bay, along Isla Margarita and specific areas in the northern part of the bay. The maxi-

imum particle concentration occurred off the northern part of Isla Margarita, and was associated with transport generated by wind and the residual tidal flow.

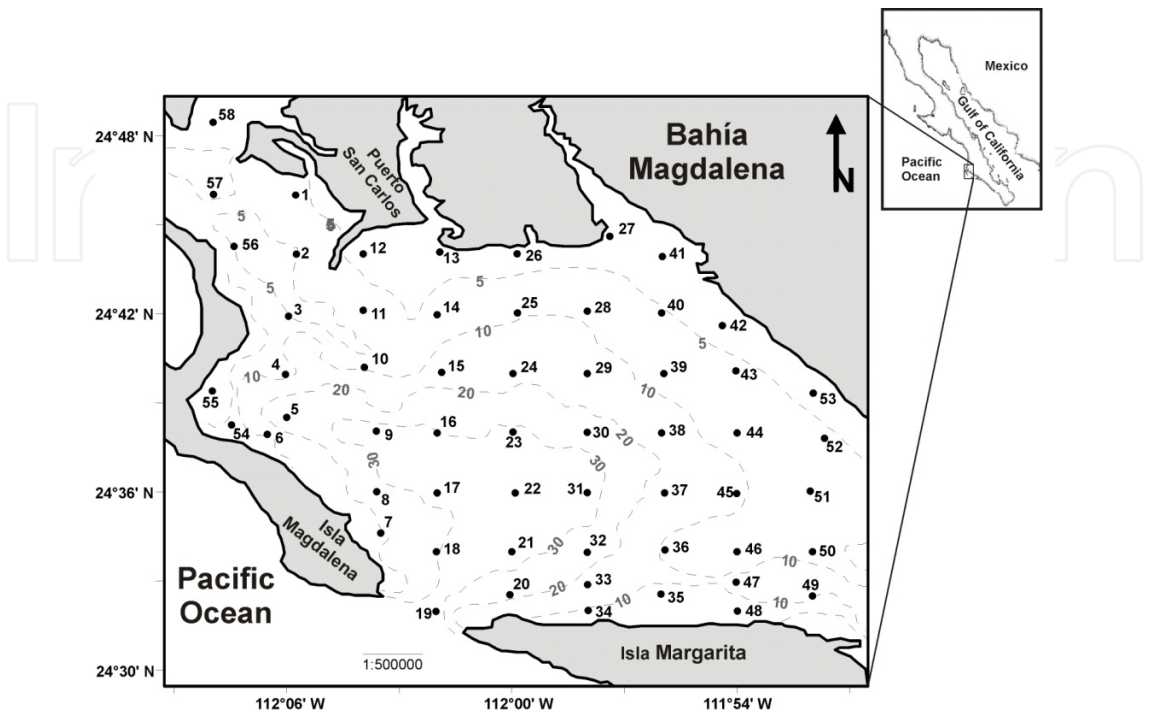


Figure 2. Study area and sampling stations in Bahía Magdalena. The dotted lines denote the bathymetry of the bay.

3. Methods

3.1. Sampling and analysis of surface sediments

In September 1998, the first 2 cm of the surface sediment was collected by scuba diving and Van Veen grab samples at the 43 sampling stations in Bahía Chetumal and the 58 in Bahía Magdalena (Fig. 1, 2). The sieve analysis was made by the sieving method (Ingram, 1971). The textural characteristics (grain size, sorting, and skewness) were calculated using granulometric data (Folk, 1974).

3.2. Multivariate statistical analysis

The principal component analysis (PCA) is a classical statistical method. This linear transform has been widely used in data analysis (Carriquiry et al., 2001). If X is a $n \times m$ data-matrix (n samples of m variables, here we choose grain size, sorting coefficient, and skewness, and X is demeaned and the covariance matrix is R , then a set of orthogonal eigenvectors $U = [u_1; u_2; \dots; u_n]$ exists:

$$RU = U\Lambda$$

Define:

$Y - XU$

Then $Y = [y_1; y_2; \dots; y_n]$ also forms an orthogonal set. The $\{y_i\}$ are the principal components (PC), the $\{u_i\}$ are the eigenvectors of the covariance matrix, and the proportion of the total variance that each eigenvector "accounts for" is given by the magnitude of the eigenvalue. Here, we do not provide the principal components, but show the principal component weights (eigenvector) of the first PC that indicates the dominate relation among the three grain-size characteristics (Davis, 1986).

3.3. Sediment-transport model

Sediment-transport models have allowed coastal oceanographers to infer the residual-sediment transport based on spatial trends of sediment (Mc Laren and Bowles, 1985; Gao and Collins, 1992; LeRoux, 1994a; Poizot et al., 2008). In our study, the model proposed by LeRoux, (1994a,b), based on the principles of analytic geometry and vector analysis of textural data, was used. With this method, the magnitude and direction of the vector of transport were obtained by comparison of the textural characteristics of five neighboring sampling stations (one central and four satellites). The general considerations of the model are (1) textural trends resulting from the hydrodynamic conditions of the environment, (2) applicable in the coastal zone and shelf where sediment transport is unidirectional, (3) the gradient between textural parameters is constant in the area where we compared the five sampling stations, (4) textural parameters in the model have the same weight and importance, and (5) the distance between the five stations (interseasonal) is not critical, especially if there is a clear textural gradient between stations.

4. Results

4.1. Grain size trends

4.1.1. *Bahia Chetumal*

The average grain size was 1.6ϕ with maximum grain size of -0.43ϕ and minimum of 2.4ϕ . In general, the spatial trend of grain size is to decrease toward the central part and head of the bay and in the area around the mouth of the Rio Hondo and the city of Chetumal, whereas the central area of the coast has a finer grain size than the eastern coastal area (Fig. 3A). The sediments with better sorting are associated with stations where the grain size is fine and vice versa (Fig. 3B). The coefficient of determination between these variables (grain size vs. sorting) is $R^2 = 0.52$ ($F_{1, 41, \alpha = 0.05} = 43.7$, $P = 0.0000$). The skewness (Fig. 3C) of the surface sediments is negative (toward coarse sediments) throughout the bay, except in the coastal margin, south of Isla Tamalcab (Fig. 3C), where skewness is moderately positive (toward fine sediments). The surface sediments are dominated 87% on average by sand (minimum 76% and maximum 96%) and a minor proportion of mud 13% on average (minimum 4% and maximum 24%).

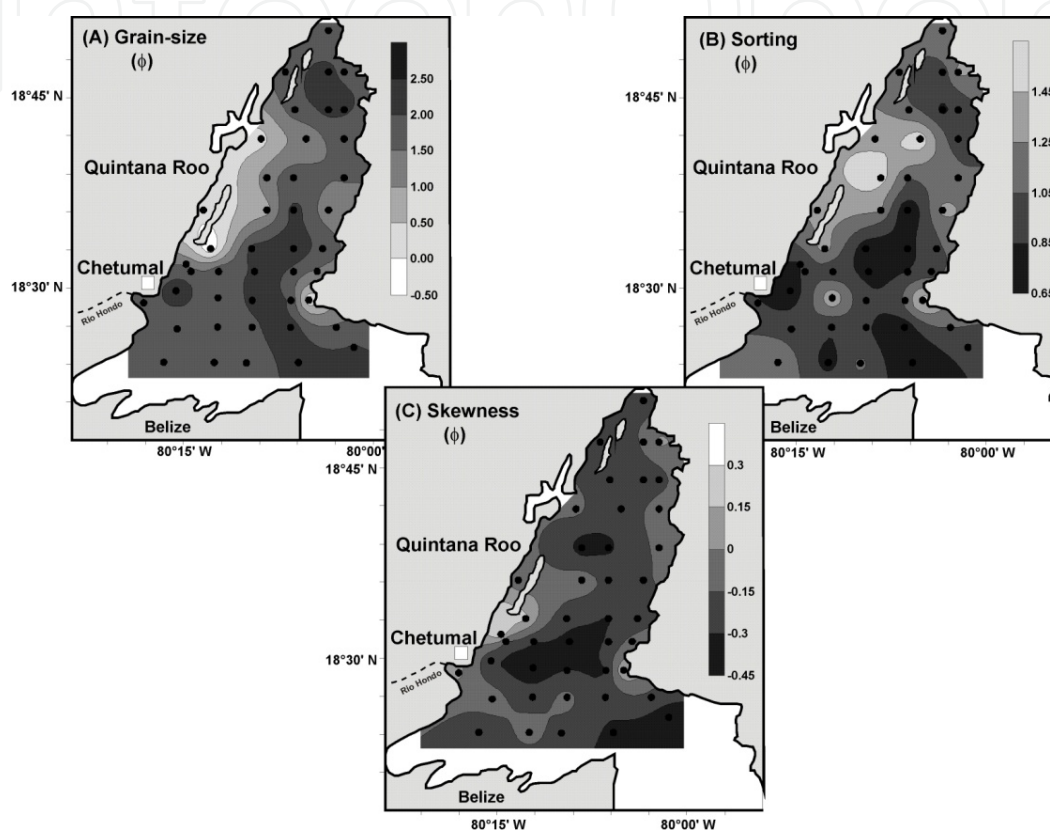


Figure 3. Spatial distribution of textural characteristics (A) Grain size (ϕ), (B) Sorting (ϕ), and (C) Skewness (ϕ) of sediments in Bahia Chetumal.

4.1.2. Bahia Magdalena

The grain-size distribution is relatively homogeneous in the bay with an interval in grain size from 2.5 to 3.5 ϕ with the exception of a textural gradient (increase in grain size) measured toward the mouth of the bay and Isla Margarita (Fig. 4A). In general, the sediments are well-sorted. Sorting is poor toward where the grain size increases (mouth of the bay and Isla Margarita (Fig. 4B). The skewness characteristics were systematically negative throughout the bay with certain trends toward positive values in the west, east, and toward the mouth of the bay and Isla Margarita (Fig. 4C).

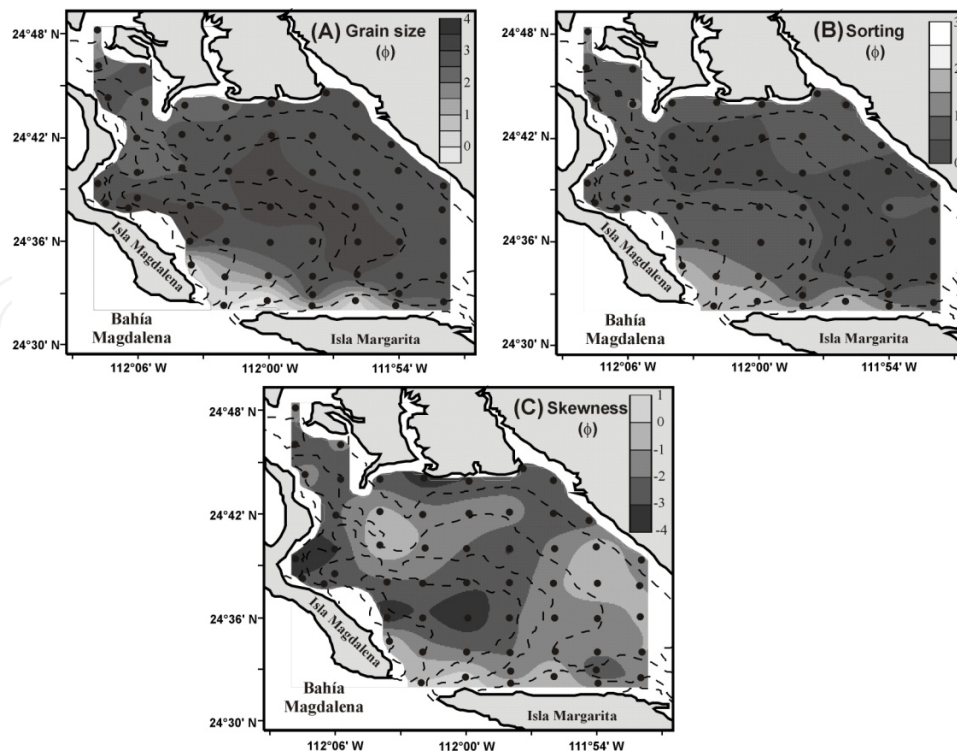


Figure 4. Spatial distribution of textural characteristics (A) Grain size (ϕ), (B) Sorting (ϕ), and (C) Skewness (ϕ) of sediments

4.2. Principal component analysis

4.2.1. Bahia Chetumal

The principal component analysis used for the textural data of sediment (grain size, sorting, and skewness) is shown in Figure 5A-C. The first eigenvalue, the grain size, and sorting explain 67% of the variance (Fig. 5A, B) and the second eigenvalue, skewness explains 28% of the variance (Fig. 5C). These two eigenvalues explain 95% of the variability of the textural characteristics. Only 5% of the variability is caused by other factors. The grain size and sorting showed a negative correlation. Thus, fine sediments are related to well-sorted clastic material and coarse-grained sediments are poorly sorted, whereas the skewness coefficient has a poor correlation with those textural characteristics.

4.2.2. Bahia Magdalena

The multivariate statistical analysis of principal components used for the Bahia Magdalena textural data indicated that two factors explain 98% of the total variability (Fig. 5D-F). Factor 1 is constituted by the grain size and sorting, and explains 74% of the variability (Fig. 5D, E), and factor 2, with 24% of the variability, corresponds to the skewness of the sediment (Fig. 5F). The grain size is inversely correlated with sorting, i.e. fine-grained sediments are better sorted with an skewness towards negative values. Only 2% of the variability is caused by other factors.

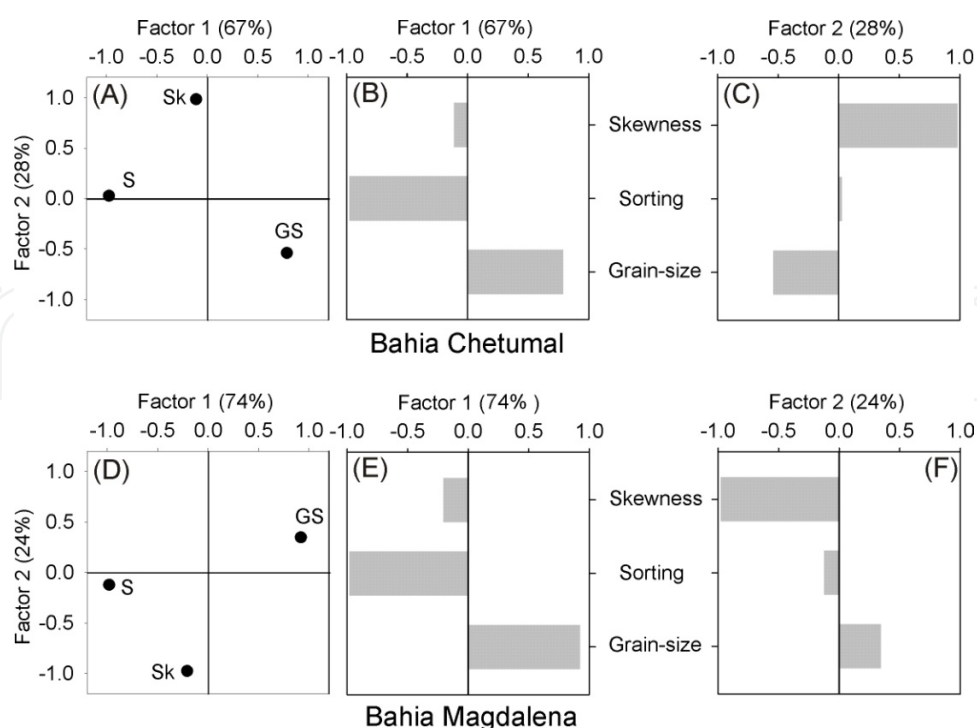


Figure 5. Graphic representation of the main factors and their respective loads obtained from the principal component analysis of sediment textural-data. GS: Grain-size, S: Sorting, and Sk: Skewness.

4.3. Net sediment transport

4.3.1. Bahia Chetumal

The vectors for the residual sediment transport are shown in Figure 6. In the north of the bay, the transport vectors show a SW direction. In the central region of the bay, transport vectors have a S-SE direction, except in the central-eastern margin, where the vector has a SW transport (Fig. 6). In the southern zone, the residual transport vectors showed a preferential direction to the S-SE. Stations 28, 29A, and 34 near the mouth of the Rio Hondo have a net sediment transport to the E-NE. In general, the surface sediment transport in Bahia Chetumal during sampling was from the head to the mouth of the bay (SW to SE direction). The smaller magnitudes of the transport vectors are located in the central part of the bay (Fig. 6) and this coincides with those areas of the bay in which the grain size tends to finer sizes.

4.3.2. Bahia Magdalena

The vectors of the residual-sediment transport described a cyclonic gyre in the central part and deep bay, whereas in the southeastern they describe an anticyclonic gyre (Fig. 7). In the northwestern margin of the bay, the residual-transport vectors showed a southeasterly direction (Fig. 7). On the coastal margin of Isla Margarita, the residual transport vectors denoted a pathway of sediment particles in a southwesterly direction (Fig. 7). The sediment transport to the mouth of the bay was not defined because only one sample was collected.

5. Discussion

5.1. Frequency distribution of magnitude vector

The vector analysis of the textural characteristics is a qualitative property that indicates the relative magnitude and the predominant direction of each vector, where two neighboring stations are exchanging material, without needing to provide quantitative data on the amount of material exchanged. The frequency distribution of the magnitude of the vectors was in the range of 0.4 to 0.7 (90% of the vector quantities) obtained in Bahia Chetumal. For Bahia Magdalena, the frequency distribution of the magnitude of the vector was heterogeneous, with only 34% of the vector magnitude in the range of 0.4 to 0.5 and the remaining 66% varied between magnitudes 0.1 to 0.4 and 0.6 to 1.0. Other studies have shown that 80% of vectors were characterized by vector magnitudes between 0.4 and 0.5 in the North Sea (Gao and Collins, 1994) and 0.9-1.0 for the northern Gulf of California (Carriquiry et al., 2001). This may suggest that hydrodynamic conditions in Bahia Magdalena are less homogeneous than those of Bahia Chetumal, the North Sea, and the northern Gulf of California, and therefore reflect the sedimentological environmental gradients. This suggests a higher variability in the exchange of materials between nearby stations (Carriquiry and Sanchez, 1999).

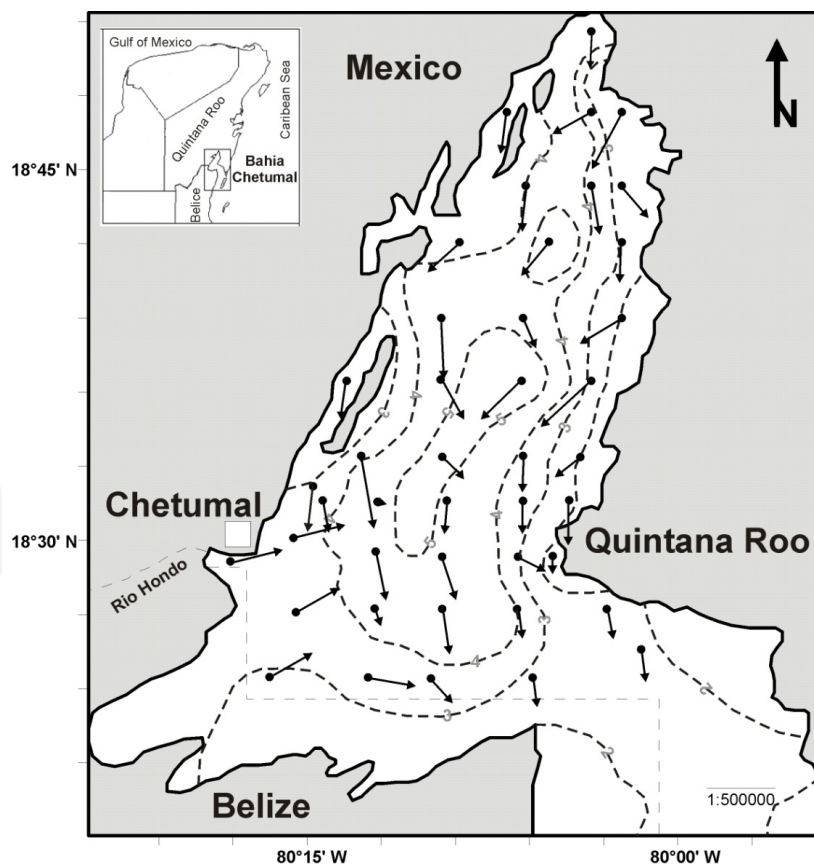


Figure 6. Dispersion of sediments in Bahia Chetumal inferred by the transport vectors. The vectors describe the main trajectory of the sedimentary material.

5.2. Transport and dispersion of sediments

The grain-size trend analysis has been widely used in marine and coastal environments to establish the net transport of sediments. In these studies, the net transport and dispersion of sediment were validated by comparing the residual vector transport with ocean currents (Carriquiry and Sanchez, 1999; Van Wesenbeck and Lanckneus, 2000; Carriquiry et al., 2001; Liu et al., 2002; Jia et al., 2002; Duman et al., 2004, 2006; Friend et al., 2006; Lucio et al., 2006; Duc et al., 2007). Thus, the GSTA is a useful tool to infer the movement of sediment particles in places where environmental hydrodynamics are poorly understood.

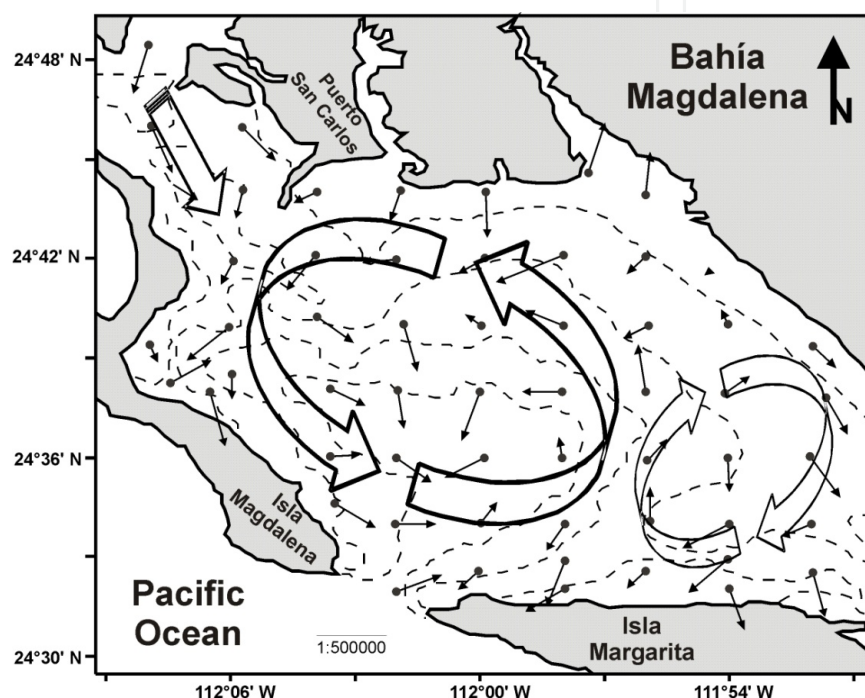


Figure 7. Dispersion of sediments in Bahia Magdalena inferred by the transport vectors. The circular arrows describe the main trajectory of the sedimentary material and residual tidal circulation.

The residual transport vectors allowed us to define that the net sediment transport is S-SW and S-SE inside Bahia Chetumal with a convergence towards the central part of bay consistent with the contours of the grain size and sorting. Hydrographic information is limited for Bahia Chetumal. The only earlier data come from Morales Vela et al. (1996) who measured the surface and bottom currents over a year inside the bay. The average surface current was 12 cm s^{-1} with a direction $183^\circ \pm 88^\circ$. On the bottom, the currents were slightly lower at 9 cm s^{-1} and a dominant direction of $182^\circ \pm 81^\circ$. Although the directions of surface currents varied between 137° and 240° and the bottom was 136° and 236° , both streams were in the S-SW and S-SE direction. Bahia Chetumal has a microtidal regime and tidal currents are expected to be weak. Therefore, the wind remains as a candidate to mix the water column. The prevalent wind direction was E-SE in the 70% of the total observed data. The role of prevailing winds and wind events is related to the orientation of the estuary. In Bahia Chetumal, the role of wind forcing in the circulation needs to be studied in detail (Carrillo et al., 2009). The persistence of relatively

mixed conditions caused by strong wind events and the response of the plume to the direction of the wind deserve further study. However, the dispersion of sediment (S-SW and S-SE) is consistent with the direction of surface and bottom currents and winds reported for Bahia Chetumal (Morales Vela et al., 1996; Carrillo et al., 2009). The spatial distribution of fine to coarse sand suggests that the hydrodynamic conditions are sufficiently intensive to limit the deposition of silt and clay in the central and deep bay (Morales Vela et al., 1996; Sanchez et al., 2008). In Carrillo et al. (2009) it has been suggested that the magnitude of the surface and bottom currents are relatively low, consistent with Lankford (1977) who placed the Bahia Chetumal as a low energy environment. However, the currents (Morales Vela et al., 1996) inside the bay are able to resuspend (Shepard and Keller, 1978) and transport (Komar, 1977) sediment of 3ϕ to 5ϕ in the S-SW and S-SE directions (Sanchez et al., 2008).

The net sediment transport described a cyclonic gyre in the central part and deep portion and an anticyclonic gyre in the southeastern part of Bahia Magdalena. Studies of the circulation inside the bay are limited but useful to validate the sedimentary transport inferred from textural trends. In Sánchez Montante et al. (2007) the residual currents that result from the rectification of the forced circulation with the M2 tidal component were calculated. The results of residual tidal currents pointed to the presence of a cyclonic circulation in the central region of the bay and an anticyclonic circulation in the southeastern region. An experiment using the release of 58 particles inside the bay demonstrated the presence of a cyclonic gyre (Sánchez Montante et al., 2007), which corresponds to the residual tidal circulation and sediment transport and dispersion in the interior of the bay (Sanchez et al., 2010). An experiment with particles seeded in the bay shows they tend to remain inside and concentrate in areas that corresponded with the actual distribution of fish stocks. The areas of particle concentration were located along the coastal margin of the bay and the coasts of Islas Margarita and Magdalena. The sediment transport vectors defined convergence zones, which coincide with those areas in which the particles tend to be concentrated (Morales Zárate et al., 2006).

5.3. Variability of textural characteristics

The textural trends of the sediment have been extensively used to infer the possible paths of clastic material in different coastal environments. The combination of textural characteristics defines the existence of several examples for the inference of sediment transport and in all these, the sorting was better in the direction of the current (Sunamura and Horikawa, 1971; Mc Laren and Bowles, 1985; Gao and Collins, 1991, 1992; LeRoux, 1994a,b; Carriquiry and Sánchez, 1999; Carriquiry et al., 2001; Poizot et al., 2008; Sanchez et al., 2008, 2009, 2010; Sanchez and Carriquiry, 2012). The principal component analysis used for the textural characteristics of this study indicated that the spatial trends of grain size and sorting explain 67% and 74% of the variability, whereas the skewness explains 28% and 24% of the variability. The correlation analysis of grain size vs. sorting was significant ($F_{1,101,\alpha=0.05}=430, P<0.0000$) with a coefficient of determination ($R^2=0.88$). For grain size vs. skewness, the coefficient of determination ($R^2=0.28$) is consistent with the explained variability by the principal component analysis (22%). The results of Bahia Chetumal and Magdalena contrast with the variability in spatial trends of grain size and skewness that explain 95% of the variability in the Yellow Sea (Cheng et al., 2004).

In areas influenced by discharges from rivers, such as the Yellow Sea, the flocculation of the particles is one of the important factors affecting sorting and, to a lesser degree, grain size of the particles (Kranck and Milligan, 1991). This allows us to define the conditions of deposition on the basis of the analysis of the grain size (Fox et al., 2004). The difficulty of establishing a trend in the sediment texture is because flocculation can lead to a preference of the deposition of fine particles in the settling of selective sites of sediment that are related to the hydrodynamic conditions. The difference between the principal component analyses can be caused by processes derived from the flocculation of sediment, which allowed the establishment of poorly sorted material in the Yellow Sea. The discharge of ephemeral streams into Bahia Magdalena and the low discharge of the Rio Hondo into Bahia Chetumal promote well-sorted sediment deposition.

5.4. Implication of grain-size trend analysis

In general, the spatial trends of textural characteristics corroborate that the well-sorted fine-grained material is distributed over the central part of the bay and agreed with the preferential accumulation of organic matter, metals, and hydrocarbons in Bahia Chetumal (Ortiz Hernández and Sáenz Morales, 1999; García Ríos and Gold Bouchot, 2003; Álvarez Legorreta et al., 2005). This contrasts with Bahia Magdalena, which has no pollution problems, at least from potentially toxic elements (Shumilin et al., 2005) and organic matter (Sanchez, 2010, 2011).

The results obtained in the present and previous studies are of great significance for the region generally and particularly for the use and sustainable exploitation of natural resources, and for the definition of possible areas of environmental protection. By using the hypothesis that the contaminants preferentially associated with the fine particles of sediment, i.e. silts and clays, would follow the path of the sediment transport, the textural-trend analysis helps to identify the relationship between the discharge of pollutants and their sources, and helps to predict the transport and fate of contaminated sediments in marine environments. The development of Bahia Chetumal and Magdalena, caused by an increase of anthropogenic activities, undoubtedly will contribute to deterioration of these environments. The integration of research studies, including biological, chemical, and sedimentological, can be the basis for proposing monitoring programs, especially in areas where there are concerns about possible sources of pollution or are subject to a possible environmental impact, e.g. in the spawning and larval rearing areas of marine species of economic importance and the habitat and feeding sites of marine mammals such as the manatee and whales.

6. Conclusions

The grain size of surface sediments shows that particles are finer and better sorted with a skewness towards coarse particles in the central region and head of both bays. The principal component analysis indicated that the correlation between grain size and sorting was significant and explained 67% and 74% of the variability of the textural trend of grain size. The remaining 28% and 24% is explained by the skewness. In Bahia Chetumal, the net transport of sediment suggests that clastic material and particles (inorganic and organic) of anthropogenic or natural origin have a transport in the S-SW and S-SE directions, except near the mouth of

the Rio Hondo where the net transport of sediment is preferentially E-NE. This indicates that there can be a greater influence on the dispersion of sediments and particulate pollutants that are discharged directly into the river, through the drainings of agricultural fields and urban waste. The convergence of the transport vectors in the central part of the bay is consistent with previous studies that described the spatial distribution of metals and hydrocarbons.

The net sediment transport described a cyclonic gyre in the central part and deep portion and an anticyclonic gyre in the southeastern part of Bahía Magdalena. These results agree with the residual tidal currents that showed the presence of a cyclonic circulation in the central region of the bay and an anticyclonic circulation in the southeastern region. The release of 58 particles inside the bay demonstrated the presence of a cyclonic gyre that corresponds to the residual tidal circulation and sediment transport and dispersion in the interior of the bay. The textural-trend analysis is a technique that can be useful for predicting the transport and fate of polluting sediments. The results of our research and the preliminary studies of geochemistry could be the basis to suggest new research and the monitoring of water quality and sediment, with special attention of areas where pollution problems exist or may be subjected to an eventual environmental impact.

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Author details

Alberto Sanchez¹ and Concepción Ortiz Hernández²

*Address all correspondence to: alsanchezg@ipn.mx

1 Centro Interdisciplinario de Ciencias Marinas, Instituto Politécnico Nacional, La Paz, Baja California Sur, México

2 El Colegio de la Frontera Sur, Unidad Chetumal, Chetumal, Quintana Roo, México

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