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Recognition of Environmentally Vulnerable Depositional Facies in the Chacahua Lagoon, Oaxaca, Mexico

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Abstract- Over the years, human activity and environmental problems have impacted the Chacahua Lagoon in the State of Oaxaca, Mexico. In an attempt to gain more insight into the current environmental conditions of this lagoon, twenty-eight bottom sediment samples were collected in August 2003. Using depth, physical properties (grain-size and texture) and biological characteristics (organic matter and $CaCO_3$ contents) of sediments as environmental indicators, three depositional facies were identified implementing cluster analysis, each facies seems to be under the influence of different processes. In terms of environmental concern, it was determined that the central part of the lagoon presents a high potential of pollutant sorption, thus this sector should be closely monitored.

Keywords- coastal lagoon, Oaxaca, sediments, multivariate analysis, facies.

INTRODUCTION

Coastal lagoons are critical environments for the survival of many species of birds, fish, invertebrates and mammals, some of them under danger of extinction. There are approximately 123 coastal lagoons in Mexico, most bordered by mangrove swamps. Given its ecological, economical, social and tourist value, the Chacahua Lagoon is one of the most important coastal lagoons in the State of Oaxaca (southwestern Pacific coast), this water body is situated within one of the oldest ecological reserves of Mexico, the Chacahua Lagoon National Park. Over the years, natural and anthropogenic influences have modified the structural and dynamic characteristics of this ecosystem and few studies have addressed the ensuing environmental problems. The passing of hurricanes, littoral drift, increased siltation, fishing activities, deforestation, soil erosion, farming activities, reduction in freshwater inputs, the construction of coastal structures and the dumping of urban and industrial waste, have caused serious environmental impacts to this ecosystem (Sanay 1997, SEMARNAT 1999).

Bottom sediments have proved to be very useful for studying environmental conditions as they are integrators of many environmental processes (Golterman *et al.,* 1983). Sediment characteristics represent a powerful tool to document spatial changes in local environmental conditions, therefore they may be used as indicators of the health of an ecosystem (Schrimm *et al.,* 2004). Physical properties of sediments (grain-size and texture) allow delineating depositional environments and transport mechanisms (Klovan 1966, Friedman 1979), as well as inferring the local hydrodynamic regime (Pejrup 1988, Flemming 2000); whereas their biological characteristics (organic matter and carbonate content) are indicative of the contaminant characteristics of sediments and associated water quality (Riggs 1996) as well as of the biological richness of estuarine and marine systems (Incera *et al.,* 2003).

In an attempt to gain more insight into the current environmental conditions of the Chacahua Lagoon, this paper examines the surface sediment characteristics of this lagoon with the object of identifying and characterizing different depositional environments (facies). This will contribute to our knowledge of the physical, chemical and biological processes operating in each facies allowing delineating the environmentally vulnerable sectors of the lagoon.

Study Area

The Chacahua Lagoon is located on the southwest coast of the State of Oaxaca, and is part of the Chacahua Lagoon National Park (Lat. 15º57´-16º02’N, Long. 97º32’-97º47’ W), which consists of two large lagoons (Chacahua and Pastoría) that are connected by a narrow and shallow channel. The lagoon has a surface area of 6.5 km^2 and is surrounded by mangrove species. Presently, the lagoon connects with the ocean through an artificial inlet (Fig. 1). Over the last years, input of freshwater from the Verde River to the lagoon has been significantly reduced as river waters have been used for irrigation purposes (Contreras, 1993). In the past, as a result of the construction of a jetty at the entrance channel of the Pastoría Lagoon, the inlet mouth shoaled and closed, leaving the Chacahua Lagoon completely isolated from the ocean for twelve consecutive years. This situation seriously modified the estuarine conditions of the lagoon by reducing the areas covered by mangroves and affecting the lagoon’s productivity. Over this period, the lagoon only exchanged waters with the Pastoría Lagoon. In 1993, measurements were taken to permit the communication of the lagoon with the ocean, resulting in the construction of an inlet (Salinas *et al.,* 2004). Presently, dredging operations are needed to maintain this inlet open. On several occasions the lagoon has been hit by hurricanes, the last of this to strike was Hurricane Paulina in 1997. The population living in the Chacahua Lagoon National Park amounts to 3,692 and most of them are engaged in fishing activities (SEMARNAT, 1999).

Geomorphology and Geology

The Chacahua Lagoon is protected from the Pacific Ocean by an east-west trending bay barrier, which has a beach ridge complex (Goman et al., 2005). The mean depth of the lagoon is 2.5 m, and the highest depth (12 m) occurs in the inlet communicating with the sea. The lagoon system is composed of alluvial material from the late Quaternary, the zone displays low relief and is subject to tectonic subsidence. Mica-rich schists and gneiss of Precambrian age are the main rock type found in the area (Vargas, 1997).

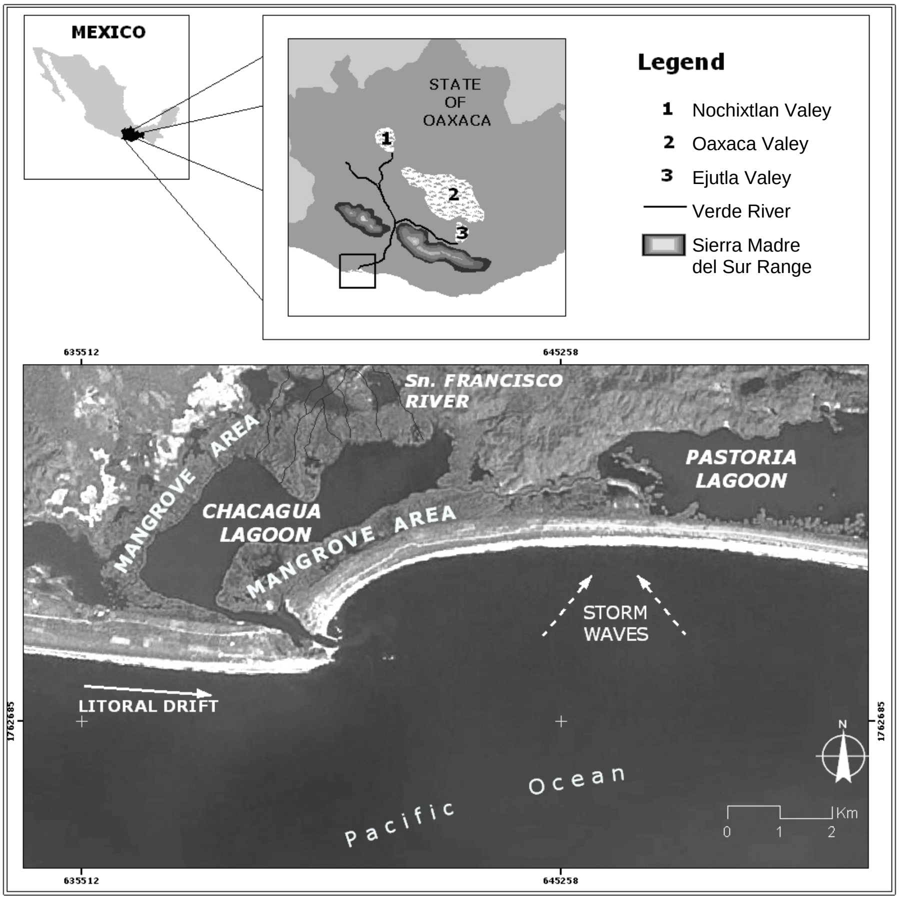

Figure 1 – Chacahua Lagoon location map.

Climate

The area has a tropical climate of subhumid type. Annual temperature and precipitation range between 18°C-22ºC and 500-2500 mm, respectively (CONABIO, 2005). The highest precipitation occurs in September.

Meteorology and Oceanography

There is no meteorological station at the study area; however wind data measured from January to December of 2004 at an inland weather station (Pinotepa Nacional; 16° 20' 59" N, 98° 03' 09" W) located 56 Km from the study area, indicate that southwesterly and south-easterly winds prevail in the area throughout the year, blowing most of the time with speeds in the range of 5 and 25 km/h (Fig.2) .The lagoon has semidiurnal mixed tides within a microtidal range (Sanay, 1997). Water temperature varies between 28 and 34.5ºC, and the salinity range is 31 to 47 ppt throughout the year (Contreras, 1993).

MATERIALS AND METHODS

Sampling and grain size distributions

A total of 28 surface sediment samples were collected from the lagoon using a Ponar grab sampler (sampling top 7 cm) in August 2003. Depths to the lagoon bottom were measured using a staff and a sounding line (Fig. 2). Positioning of sampling stations was determined by GPS. After removal of organic matter by treatment with hydrogen peroxide and sample splitting by wet sieving, standard dry-sieving and pipette analyses were used to determine the size distribution of the coarse and fine fractions of samples, respectively, (Lewis, 1984). The data was combined at 0.5 phi intervals and moment measures of grain-size (mean, sorting and skewness) were obtained using the computer program GRADISTAT (2001). The grade scale of Wentworth (1922) was used to describe mean grain-size.

Sediments were classified into textural classes according to the classification proposed by Flemming (2000).

Analyses of biological characteristics

Organic matter and carbonate contents were determined by weight-loss on ignition at 550ºC and 1000 ºC, respectively, for one hour (Dean, 1974). All volatiles lost at 1000ºC were reported as Carbonate weight percent.

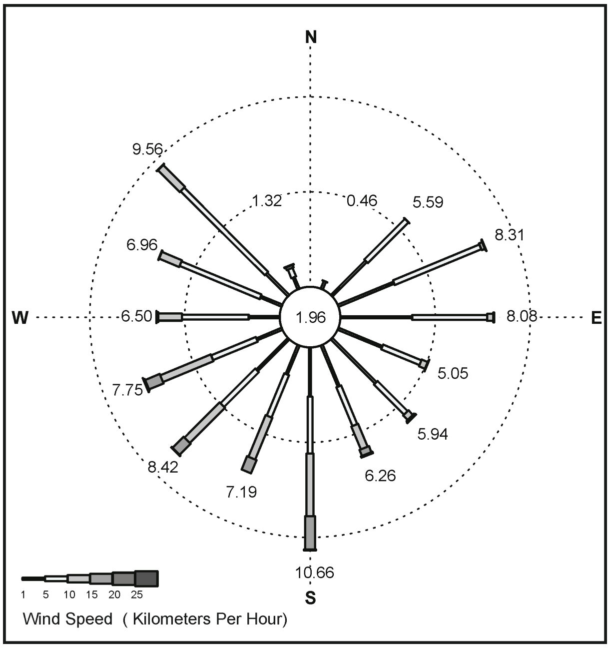

Figure 2 – Rose diagram for winds measured from January to December, 2004, at a nearby weather station. Calms included at center. Rings drawn at 5% intervals. Wind flow is from the direction shown.

Correlation and multivariate analyses

In order to explore the relationship between variables, Pearson correlation coefficients were calculated considering $p<0.05$ as the significant level.

As data was expressed in different units, the data was standardized prior to the application of the multivariate analysis to ensure that equal weight was given to all variables.

Principal Component Analysis (PCA) with varimax rotation was used to establish which of the physical and biological characteristics contributed to the differences among stations. The number of variables significantly correlated was examined and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were used to determine if PCA could be conducted in this investigation, despite the small sample size. We applied the Kaiser criterion to determine the number of factors. Factor loadings of 0.50 and higher were considered in the interpretation of the factors (Hair *et al.*, 1999).

Cluster analysis using Ward's hierarchical agglomerative method and euclidean distance measure to group sampling stations in terms of the physical and

Mapping

Contours of the data were generated using the Kriging method of gridding incorporated in the program Surfer 8.0 (Golden Software Inc.)

RESULTS

Table 1 shows grain size characteristics and the organic matter and carbonate contents of sediments. Sediments from the central and upper part of the lagoon are black and have a strong H_2S smell, suggesting highly reduced/anoxic conditions in those sectors, which is typical of a mangrove habitat. This observation confirms the findings of Phole (1979) regarding the low oxygen concentrations both in the Chacahua and Pastoria lagoons.

Textural and grain-size analyses

According to the textural classification of Flemming (2000), eight textural classes were identified on the basis of sand/silt/clay ratios (Tab. 2). Samples from the center of the lagoon were classified as silty clay (E-IV), whereas those from the inlet were classified as sand (S).

Clayey sediments having a black appearance cover 61% of the lagoonal bottom. The spatial distribution of this textural component shows that very fine-grained sediments with a clay fraction (> 8 ϕ) of more than 60% occupy the interior parts of the lagoon.

Surface sediments within the lagoon range in mean grain size from 0.93 ϕ (coarse sand; station 1) to 8.73 ϕ (clay; station 23). Clean coarse-grained sediments (< 4 ϕ), mostly medium and very fine sand, containing less than 12% silt with little to no clay component occur in the tidal channel. Sediment sorting varies from very poorly sorted (3.29 ϕ, station 8) to well sorted (0.40 ϕ, station 5), with most sediment being classified as poorly sorted. The areal distribution shows that the highest degree of sorting (i.e. a relatively narrow range of grain-sizes is present) is observed in the channel region where sands occur. Skewness values vary between –2.13 to 3.11 (strongly coarse-skewed to strongly fine-skewed) at stations 5 and 3, respectively. Negatively-skewed sediments (abundant coarse particles) are found in the channel and interior parts of the lagoon. Two tongues of positively-skewed sediment (abundant fine particles), separated by coarse skewed sediment, are observed in the lower part of the lagoon (Fig. 3).

Table 1 – Water depth, grain-size characteristics, organic matter and CaCO3 content

Station	Depth (m)	Mean (□	Sorting (□	Skewness	Sand (%)	Silt (%)	Clay (%)	Mud (%)	Organic Matter (%)	$CaCO_3$ (%)
1	2,20	0,93	0,75	-0,62	97,90	0	0	0	0,83	2,94
d	1,40	1,93	0,57	-0,61	99,90	0	0	0	1,13	3,78
2	1,35	1,54	0,61	-0,20	99,70	0	0	0	0,91	3,16
c	5,20	2,65	0,44	-1,85	99,80	0	0	0	1,52	5,13
3	6,30	3,29	1,38	3,11	93,70	2,60	3,60	6,20	2,69	6,27
b	2,70	1,72	1,79	-0,72	82,10	0	0	0	1,76	13,55
4	2,05	3,76	1,90	1,71	84,50	7,40	7,20	14,60	2,40	6,55
5	2,05	3,15	0,40	-2,13	100	0	0	0	1,97	4,78
6	2,60	3,77	2,07	1,41	79,50	12,00	8,30	20,30	2,83	10,53
a	2,25	6,99	1,12	-0,81	93,80	5,73	0,47	6,20	7,16	31,52
7	2,10	8,36	1,43	-1,09	6,10	32,20	61,70	93,90	17,05	10,15
8	2,10	3,10	3,29	0,43	54,20	14,00	12,90	26,90	10,69	10,13
9	1,60	8,25	1,62	-1,01	2,10	34,30	63,60	97,90	13,69	7,93
10	1,60	8,45	1,39	-1,11	0,60	32,20	67,20	99,40	14,95	7,67
11	1,40	8,35	1,48	-1,07	0,46	33,63	65,91	99,54	24,51	9,16
12	2,00	8,44	1,41	-1,20	0,95	31,82	67,23	99,05	17,21	10,40
13	1,70	8,48	1,57	-1,57	2,00	26,80	71,20	98,00	21,36	9,40
14	1,60	8,43	1,40	-1,23	0,54	31,14	68,31	99,46	16,17	12,18
15	1,90	8,59	1,33	-1,50	0,90	28,18	70,92	99,10	16,25	10,16
16	1,30	8,60	1,28	-1,35	0,21	28,06	71,73	99,79	23,38	8,47

Table 1 – Cont.

17	1,70	8,54	1,33	-1,33	0,78	28,17	71,06	99,22	15,73	11,55
18	1,45	8,43	1,29	-0,96	0,73	31,64	67,63	99,27	21,06	8,71
19	1,60	8,54	1,23	-1,40	1,33	11,80	86,87	98,67	0,29	10,70
20	1,70	8,55	1,16	-0,75	1,31	37,57	61,12	98,69	0,30	11,43
21	1,30	8,65	1,21	-1,36	0,51	24,31	75,18	99,49	0,27	10,95
22	0,95	8,48	1,32	-1,27	5,53	28,98	65,49	94,47	0,17	31,26
23	1,55	8,73	0,98	-0,24	1,48	24,59	73,94	98,52	0,19	13,87
24	1,60	8,63	1,21	-2,00	16,25	16,47	67,28	83,75	0,31	22,45

Table 1 – Textural classes identified based on sand/silt/clay ratios using Flemming's classification (2000).

Station	Code	Textural class
1	S	Sand
d	S	Sand
2	S	Sand
c	S	Sand
3	A-II	Slightly clayey sand
b	S	Sand
4	A-I	Slightly silty sand
5	S	Sand
6	A-I	Slightly silty sand
a	A-I	Slightly silty sand
7	D-IV	Clayey slightly sandy mud
8	B-II	Silty sand
9	E-IV	Silty clay
10	E-IV	Silty clay
11	E-IV	Silty clay
12	E-IV	Silty clay
13	E-IV	Silty clay
14	E-IV	Silty clay
15	E-IV	Silty clay
16	E-IV	Silty clay
17	E-IV	Silty clay
18	E-IV	Silty clay
19	E-V	Slightly silty clay
20	E-IV	Silty clay
21	E-V	Slightly silty clay
22	D-IV	Clayey slightly sandy mud
23	E-IV	Silty clay
24	D-V	Very clayey slightly sandy mud

Organic Matter and Carbonate

The organic matter percentage of surface sediment samples ranged from 0.17 (station 22) to 24.51% (station 11). High organic matter values (>15%) were obtained from the central part of the lagoon, where mud contents are highest (>97%). Carbonate contents ranged between 2.94 (station 1) and 31.52% (station A). The highest value (>15%) were found in the north-eastern and north-western parts of the lagoon. The presence of mollusc shell debris in the sand fraction of the sediments indicates that the carbonate content in the sediments of the area is biogenous. In the inlet, carbonate contents are less than 7% (Fig. 4).

Correlation analyses

Table 3 shows the matrix of correlation coefficients between depth, mean grain size, sorting, skewness, percentages of sand, silt, clay, organic matter and carbonate. Depth is positively correlated with sand content and the skewness parameters, indicating the dominance of the coarse fraction along the communication channel. An inverse relationship is observed between depth and mud content (silt+clay). Organic content is positively correlated ($p<0.05$) with both silt and clay contents. A positive correlation was detected between mean grain-size (size diameter decreases with increasing phi values) and carbonate content, reflecting that the fine fractions are richer in bioclastic material. The skewness and sorting parameter are positively correlated, which indicates that samples that have excess coarse material are also poorly sorted. Mean size and skewness show a negative correlation, indicating that coarser sediments were associated with higher skewness.

Multivariate analysis

The results of the Principal Component Analysis are shown in Table 4. The inspection of the matrix correlation (Table 3) reveals that 20 out of 36 correlations (55%) are significant ($p<0.05$). Bartlett's test of sphericity proved that the correlation matrix is significant (chi-square= 294, $p< 0.001$), which means that the dependent variables are correlated. Lastly, the adequacy of the sample was confirmed by the overall KMO value (0.51), which slightly exceeds the minimum requirement of 0.50 (Hair *et al.,* 1999). The first three principal components explain 82% of the sediment characte-

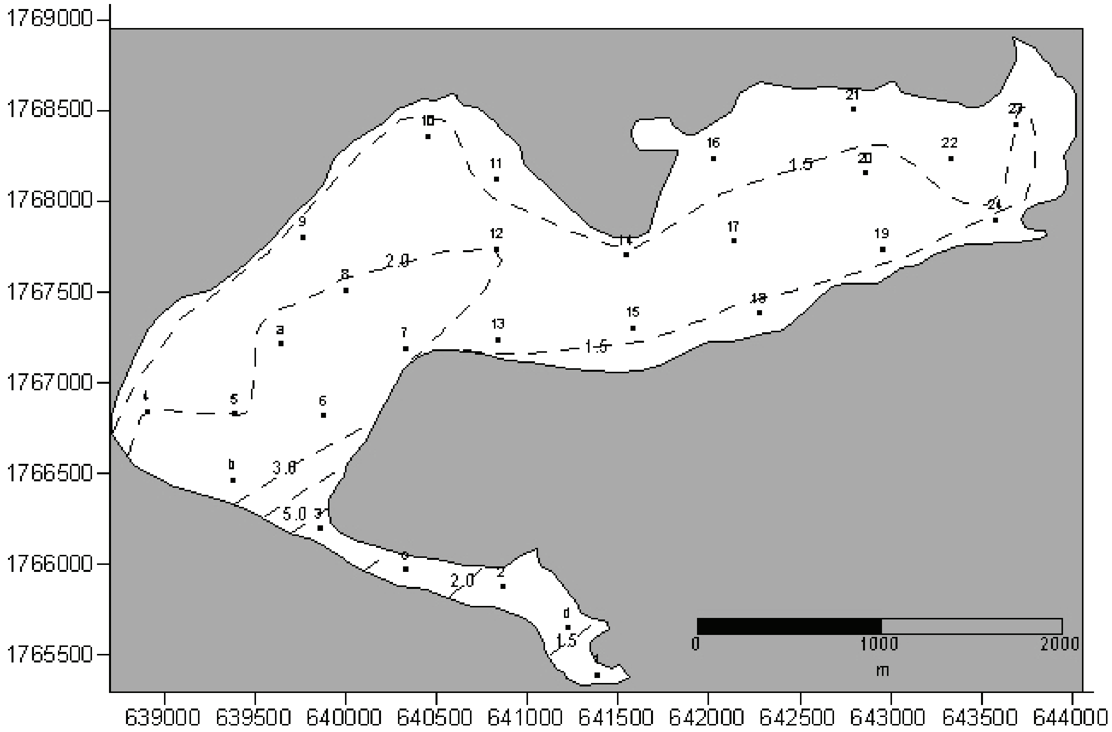

Figure 3 – Locality map with sediment sampling stations and water depths in meters.

ristics in the study area, the first eigenvector accounted for 53.2% of the total variance. The first component was associated primarily with mean grain-size parameter and sediment composition, although organic matter content and depth were moderately important (correlations >0.50). The inverse relationship with depth and sand percentage indicates that moving towards the interior of the lagoon, coarse particles and depth decrease. The second component was associated to the sorting and skewness parameters and the third component was negatively related to carbonate content.

The dendrogram summarizing the clusters identified using Ward linkage, is shown in Fig. 5. At a distance of 2.0, three clusters (sedimentary facies) emerge:

a) Cluster 1 consists of those stations located in the inlet and channel sector (stations 1, 2, 3, 4, 5, 6, 8, A, B, C and D) where depths are highest. This sedimentary facies is characterized by coarse sediments, ranging in size from Coarse sand to Fine silt, a high sand content (>50%), a predominantly low clay content (<9%), and low organic matter concentration (<11%). With respect to degree of sorting, skewness and carbonate content, there seems to be 2 different subfacies, sediments from the channel sector (stations 1, 2, c, d) have the highest degree of sorting, are strongly coarse-skewed and have a low carbonate content (<6%), whereas those from the lower sector of the lagoon (stations 4, 6, 8) have the lowest degree of sorting, are strongly fine-skewed and contain a higher carbonate percentage (>6%).

b) Cluster 2 brings together the stations located in the central part of the lagoon (sta-tions 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18); this facies is comprised of poorly sorted dark coloured fine-grained sediments (mud), having excess of coarse particles, with less than 3% of sand and highest content of mud (≥98%), a high organic matter (>13%) and a medium carbonate content (>7%).

c) Cluster 3 comprises the stations located in the upper sector of the lagoon (stations 19, 20, 21, 22, 23, 24). This facies also contains poorly sorted fine-grained sediments (clays), and is characterized by excess coarse particles and high clay content. This facies differentiates from the previous facieses by the lowest organic matter concentration and the highest carbonate content in sediments.

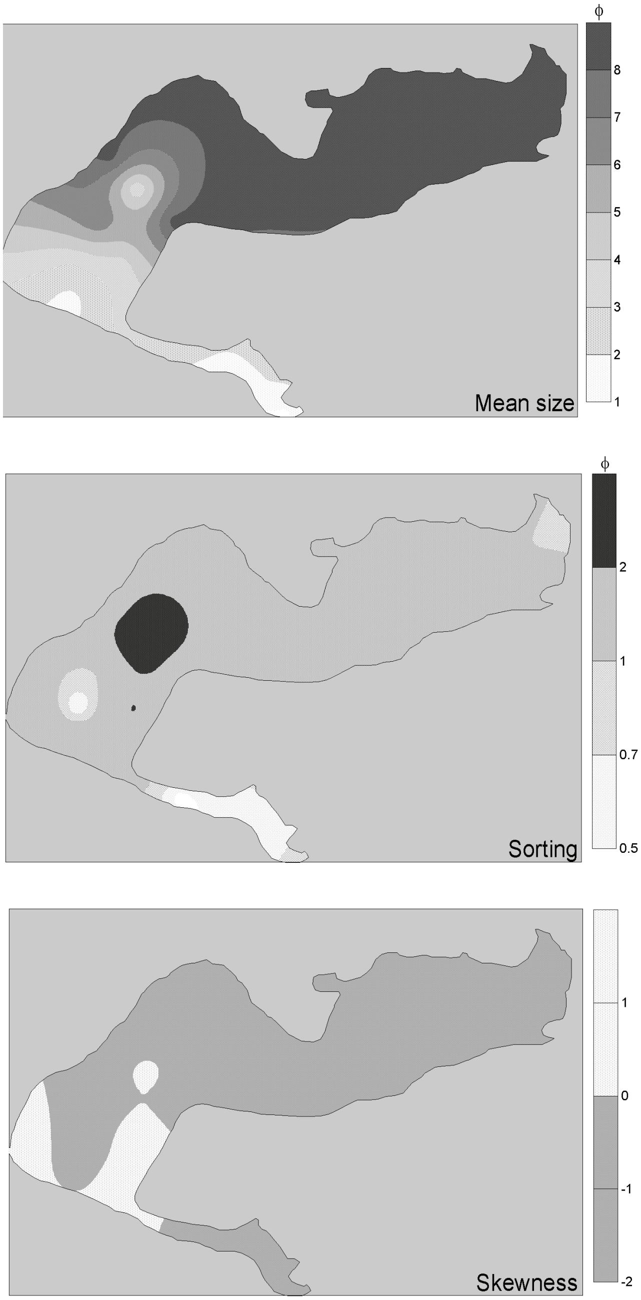

Figure 4 – Spatial distribution patterns of grain-size parameters.

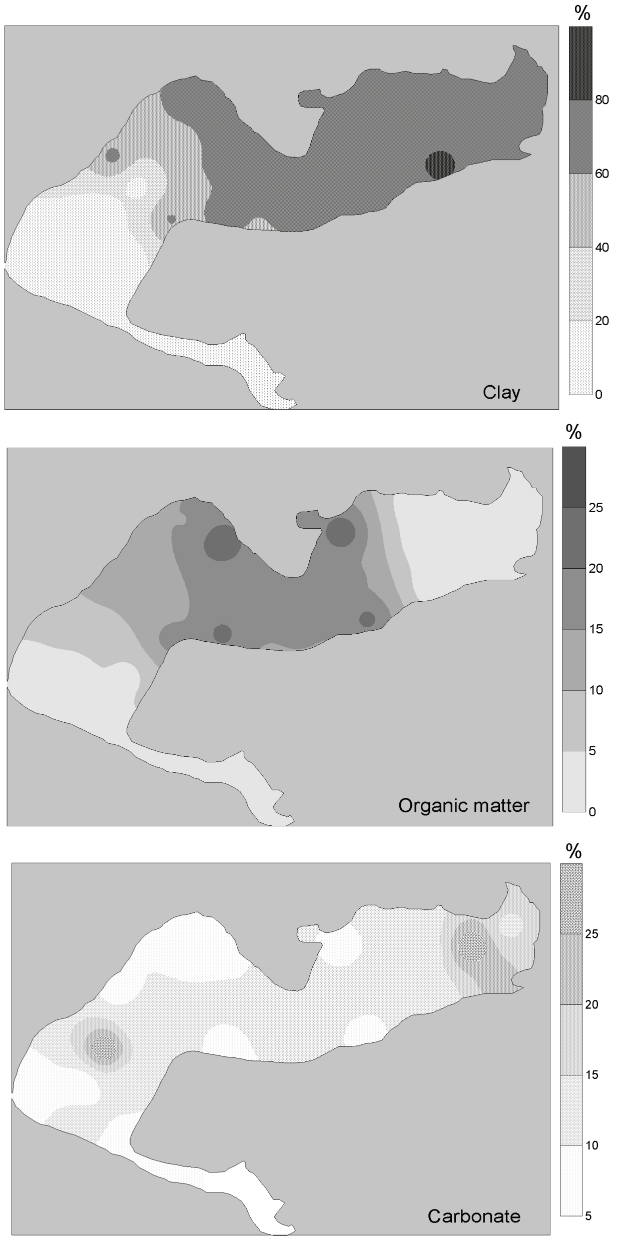

Figure 5 – Spatial distribution patterns of clay, organic matter and calcium carbonate contents.

DISCUSSION

The superficial sediments are in a wide range of grain-sizes, ranging from clean coarse sands to dark-coloured muds reflecting different hydrodynamic conditions in the lagoon. This energy variation is also reflected by the textural composition of samples. According to the textural classification scheme used in this study, the closer a data set is located to the silt endmember, the higher is the energy level; the closer it is to the clay end member, the lower is the energy (Fig. 6).

Consequently, the inlet and channel sectors constitute sedimentary Facies 1 and clearly represent the most energetic environment (Fig. 8). According to Hayes (1979) and Cooper (1994), wave and tides are the main factors that control a lagoon geomorphology, thus, Facies 1 may be subdivided into two subfacies given the influence of wave and tides predominating at each subfacies. This way, sediments from Subfacies A are deposited under the more intense hydrodynamic conditions existing in this sector, which is directly exposed to wave turbulence as this section of the coast is a high energy area with

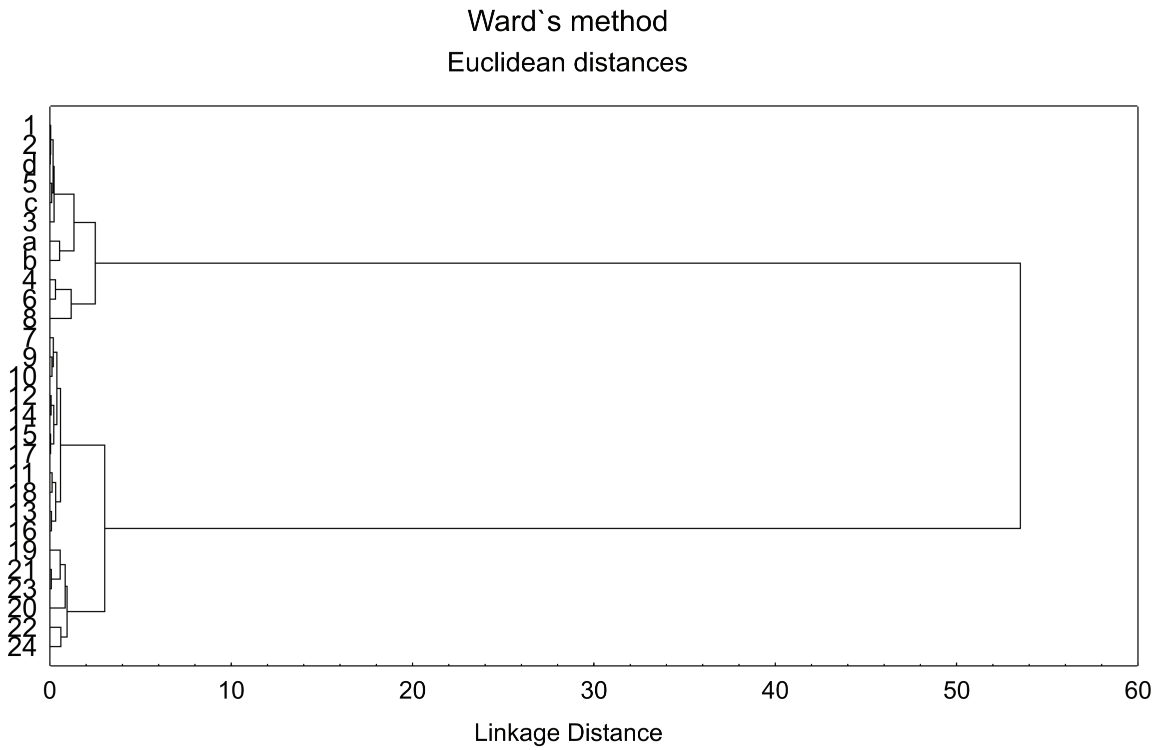

Figure 6 – Classification of sampling stations using depth, grain-size characteristics, organic matter and $CaCO_3$ contents in sediments as variables.

wave heights of up to 2.4 meters (Meisburger, 1962). The predominant action of waves would explain the presence of the well sorted-negatively skewed siliciclastic sediments found at the inlet with no clay content at all. Given the micro-tidal regime existing in the lagoon, the influence of tidal currents on the lagoon geomorphology would not be that significant, nevertheless their intensity would certainly intensified at the channel, allowing the deposition of poorly sorted-fine skewed siliciclastic sediments with some clay content, defining Subfacies B.

In the lower and central part of the lagoon, clay content in all samples is greater than 60%, which indicates that this sector is much less eneretic than Facies 1. This sector constitutes Facies 2, where calmer hydrodynamic conditions promote the deposition of fine-grained siliciclastic-bioclastic sediments rich in organic matter (Figs. 7 e 8)

Facies 3 is defined by the upper part of the lagoon where content of clay is highest indicating that this sector represents the less energetic sedimentary sub-environment of the system (Figs.7 e 8), where fine silt and clay occur in the water as part of sediment flocs (Pejrup, 1988) and deposition takes place by gravitational settling. The less intense hydrodynamic conditions of this facies would be caused by the combined effect of shallow depth, the reduced wave turbulence and the small intensity of tidal currents.

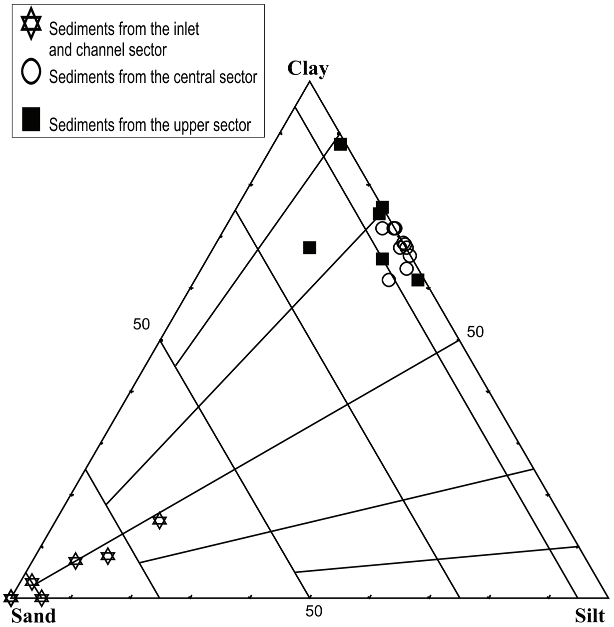

Figure 7 – Ternary diagram for textural classification of sediments from the Chacahua Lagoon, based on Flemming (2000).

An increase in salinity would also enhance deposition in the interior parts of the lagoon, under the influence of flocculation. Surface salinity measurements made in the lagoon in May, 2003 (Ríos, unpublished data), indicate that this parameter varies from 36 ppt in the channel to over 40 ppt in the interior parts, thus in addition to the quiescent conditions existing in the interior parts of the lagoon, flocculation of clay particles supplied by rivers, may be playing an important part in the local process of sediment accumulation specially during the dry season when the lagoon becomes hypersaline. Part of the mud fraction found throughout great part of the lagoon is mainly supplied by the San Francisco river during the rainy season (May-November), contributing to shallowing the lagoon (Staines & Rodríguez, 1999). The surrounding vegetation (mangroves), local soil erosion enhanced by farming activities in the catchment, and deforestation are also believed to be important sources of fine-grained terrigeneous sediments. Clays found in the lagoon are probably formed by chemical weathering of biotite-rich gneiss and schists found in the area, these would be carried into the lagoon by water runoff and erosion. According to Nichols & Allen (1981), fluvial sediment supply is the primary source of sediment in the low latitude humid climatic zone. Nevertheless, the fluvial discharges into the lagoon have been significantly reduced over the years while there is some evidence (reduction of depth) that the Chacahua lagoon continues silting up, which suggests that soil erosion and deforestation are now playing a more important role in the morphological development of this lagoon. Sand for the inlet and channel sector is derived from coastal littoral drift which is southeasterly during the rainy season when wave action increases (Staines & Rodríguez, 1999).

The spatial distribution of grain-size parameters reflects erosion/accretion processes in the study area. The pattern of sandier, negatively skewed sediments found in the Subfacies A suggests that a coarse size fraction is being transported from the sea into the lagoon; the lower values for the moment standard deviations (i.e., sorting) of these sediments reinforces the hypothesis that waves are the predominant transportation and deposition agent in this subfacies (Friedman, 1979, Folk, 1980). The change in the skewness sign observed north of Subfacies A, indicates a switchover from coarse to fine grain domination in the grain size distributions, which indicates a change in the way (modes) particles are transported (Flemming & Ziegler, 1995) and the different depositional conditions caused by the decreasing hydrodynamic energy conditions, mentioned before. Thus, the predominant mode of transport over Subfacies A is bed load as sediment is composed of grains coarser than 2.6 phi, whereas in Subfacies B and Facieses 2 and 3 sediments experience stronger suspension transport. Under the suspended mode, coarser grain sizes are left behind and the fines are carried beyond Subfacies A where settling processes predominate producing the positive skewness. Sediments from Facieses 2 and 3 are negatively skewed probably due to the abundant bioclasts in the mud fraction and the silt size particles supplied by the San Francisco River and the Pastoría Lagoon. It is also possible that the traces of coarse sediments found in this sector could have been supplied during the passage of Hurricane Paulina in 1997 when sustained winds of up to 115 knots are believed to have hit the coastline of Oaxaca (Lawrence, 1997). Thus, the granulometric fingerprint of this high-energy episode could still be present in this sector, buried under the mud deposited since 1997, given the low quiescent conditions and the cohesive nature of these sediments, which restrains their erosion behaviour. The poorly sorted sediments suggest very weak currents and low wave action in Facies 3, supporting the observations inferred from the textural composition.

Organic matter (OM) content in sediments was similar to those reported for the lagoon by Sandoval (1999). The high organic matter content, especially in the central sector, points to an input from the mangrove belt surrounding the lagoon, a setting which is typically associated with a strong export of organic matter. The distribution of organic matter is tightly coupled with the texture of samples, this way highest OM percentages are found in stations enriched in muddy sediments. This is explained by the similar settling velocity of the organic and fine-grained mineral particles (Tyson, 1995) and by the fact that organic matter, as well as contaminants, adsorb onto silt/clay particles given their greater surface area (Rullkötter, 1999). Thus, hydrodynamic conditions and sediment texture seem to play a important role in controlling OM content in this lagoon. The distribution of this parameter shows that the central part of the lagoon is the main sink of organic matter related to the highest mud content in sediments. In this regard, the central sector present favourable conditions for the accumulation of contaminants (metals and trace metals), as shown by Arcega (2001) who concluded that the concentrations of Co, Cu, Li, Mn, Ni, Pb and Zn in the sediments of the lagoon are higher than those reported for the San Francisco and Verde rivers. These chemically active organic-rich muds (ORM) would play a major role in the degradation of both sediment and water quality of this lagoon, as well as of the associated biological community (Riggs, 1996). At the same time, ORM are a source of food and energy, thus carbonate content is high in those sectors where abundant food is available for molluscan fauna. In the upper sector of the lagoon, a richer benthic community (as suggested by the high carbonate content), the restricted water circulation and the geomorphology seem to promote higher rates of organic matter decomposition by additionally supplying and retaining macroalgae- and mangrove-derived detritus (Alongi *et al.*, 1996), explaining the low OM content detected there.

The results of PCA indicate that all analyzed parameters tend to vary together, and that grain-size parameters and textural variables contribute mostly to explaining existing local sedimentological differences, suggesting that physical (waves, currents, river discharges, sediment supply from the catchment and nearshore environment, soil erosion, salinity effects) processes operating within the lagoon seem to play a major role in causing local grain-size variability. A future study should identify which of these factors controls variability in sediment grain-size in the Chacahua Lagoon.

CONCLUSIONS

Cluster analysis allowed identifying three depositional facies on the basis of textural and grain-size characteristics, bathymetry, organic matter and carbonate content.

Given the morphology of the lagoon, Facies 1 is influenced by marine and tidal processes. Subfacies A presents characteristics of a marine sub-environment with moderate hydrodynamic energy and under the influence of wave forcing, this agent transport sediment particles mainly as bed-load. Subfacies B seems to represent an estuarine transitional sub-environment where particles are predominantly transported as suspended load by tidal currents. The relatively high hydrodynamism of this facies permits the deposition of coarser sediments, through which water runs easily, restricting organic matter accumulation by oxidation and reducing biological richness given the stressing conditions for infauna at this facies, which is evidenced by the low carbonate content. In terms of environmental concern, the sediments of this environment would pose little if any hazards to the lagoonal ecosystem as non-cohesive coarse-grained sediments have little sorptive capacity.

Facies 2 presents typical lagoonal conditions, deposition of particles in this sheltered environment is dominated by gravitational settling and the low hydrodynamism favours the accumulation of rich organic muds, which degrade sediment

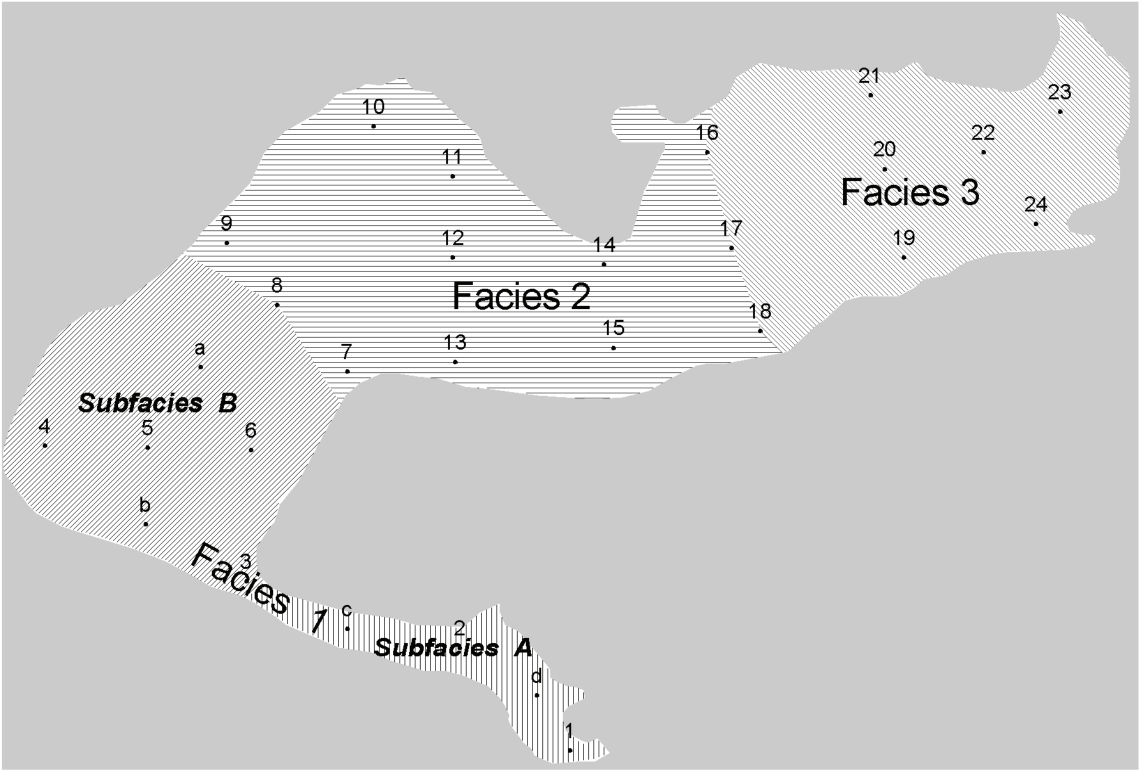

Figure 8 – Depositional environments (Facies) recognized in the Chacahua Lagoon (see text for explanation).

and water quality and enhance biological richness within the environment, as suggested by the higher carbonate content. The high organic matter content of this facies point to a sector with poorly oxygenated bottom waters.

Lastly, Facies 3 represents an extreme low energy lagoonal environment under the direct influence of the discharges from the San Francisco River and the Pastoría Lagoon. Sedimentation in this facies is also dominated by suspension settling and the rates of organic matter decomposition seem to be faster.

Given the high clay and organic matter concentration detected in the sediments of Facies 2, it is concluded that the central part of the lagoon is especially vulnerable to environmental degradation given its high potential for accumulation of pollutants, thus it is recommended that these sediments be closely monitored as they may impact the lagoonal ecosystem. The use of basic sediment properties and characteristics allowed obtaining a preliminary recognition of the present environmental conditions of this coastal lagoon.

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