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Dynamics of Sediments Exchange and Transport in the Bay of Cadiz and the Adjacent Continental Shelf (SW - Spain)

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1. Introduction

In the framework of sediment exchange between the continents and ocean basins, the study of continental margins is of particular interest. Indeed, the deposits sequences represent the sedimentary record of the processes that have taken place in the continent and the ocean (Seibold and Berger, 1982; Agi, 1987). In this context, the continental shelves represent the most sensitive marine areas and of high economic interest, where the deposits are forming a mosaic of relict and modern sediments (Shepard, 1932, Emery, 1968). The littoral zones play an important role in the morphodynamic evolution of the adjacent marine environments, through eustatic changes and the transport of sediments from different input sources (Zazo et al, 1994, 1996, Hernandez-Molina et al, 1996, Gutiérrez-Mas et al, 1998; Achab & Gutierrez-Mas, 1999a). To describe sediment transport dynamics and to understand many land-shelf-ocean interaction processes, the quantification of suspended particulate matter (SPM) and the investigation of its dynamics are of major importance. During the past decades, studies on sediment dynamics have focused on the actual processes that control the sediment transport on continental shelves and the final fate of most particulate matter derived from the continents. (Wegner, 2003).
The study area was the object of numerous multidisciplinary works realized with the objective of determining the recent sedimentary facies distribution and their sources areas, as well as the recognition of the geological formation located in river basin (Achab et al, 1999b; Achab, 2000; Gutierrez Mas et al, 2004; Achab et al, 2005b). Several studies focused on sedimentary dynamics associated with water mass movements have been realized by several authors (Madelian, 1970; Kenyon and Belderson, 1973; Melières, 1974; Palanques et al, 1987; Grousset et al., 1988; Maldonado & Nelson, 1999a; Nelson et al, 1999; Lopez-Galindo et al, 1999; Lobo et al, 2000). Others studies have been focused on the dynamics of fine sediments and clay minerals in the Cadiz bay and the adjacent marine deeper zones (Gutierrez Mas et 1996b, 1997; Achab et al, 1998, 2000b; Achab et al, 2008). Also, they have been approached studies about the dispersal of the suspended matter in the bay of Cadiz and its effects on the inner continental shelf as well as their influence on the recent marine

sedimentation en general (Palanques et al, 1987, Gutierrez Mas et al, 1999; Achab et al, 2000a; Gutierrez Mas et al, 2006). In the bay of Cadiz, the study of the dynamics of sedimentary exchange between the coastal zones and the continental shelf is complex, and presents difficulties due to the diversity of sedimentary processes and environments, as well as to hydrodynamic factors and the physiography of the coast and sea bottoms. The main objective was to elaborate a global hydrodynamic model of exchange and transport of sediments in the Cadiz bay and the adjacent continental shelf. This model take in consideration the sedimentological and mineralogical data complemented by satellite images and suspended matter analyses as well as data obtained from side scan sonar records and other available information.

2. The study area

The study area is located on the margin of the Gulf of Cadiz between the mouth of the Guadalquivir River and the western entrance to the Strait of Gibraltar (Fig.1).

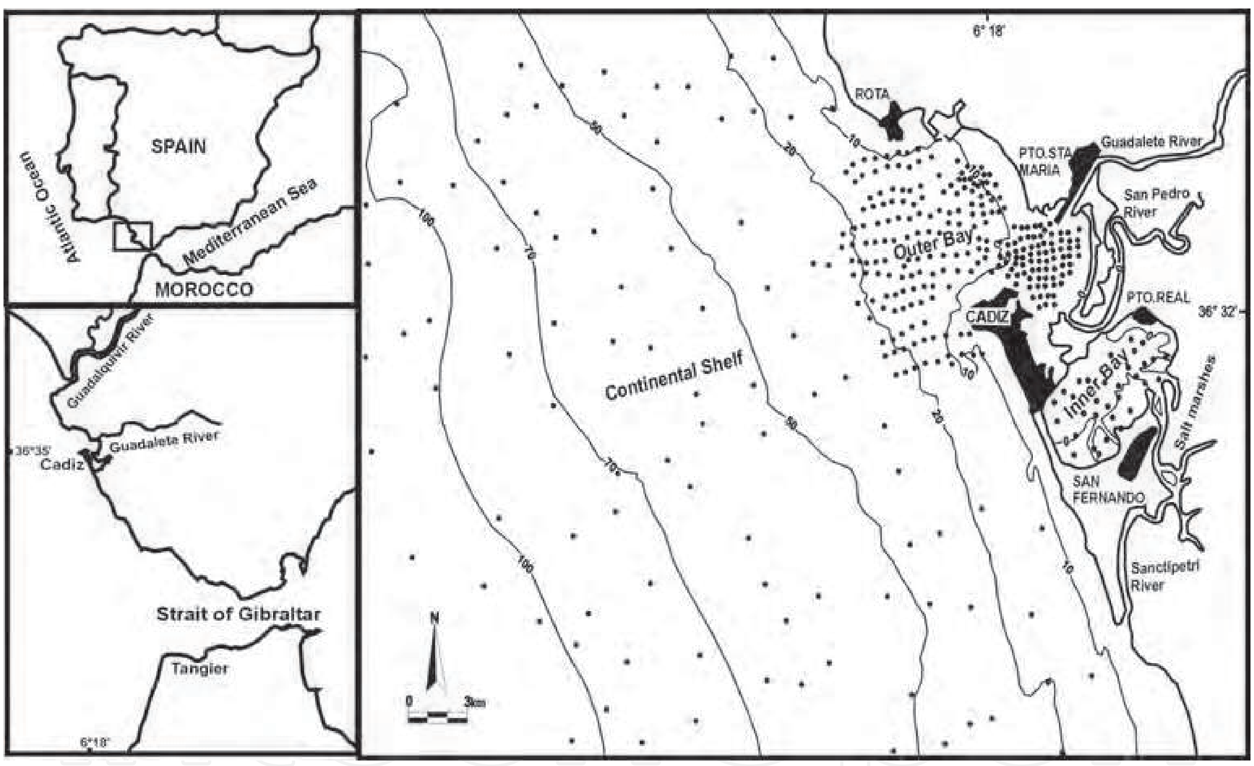

Fig. 1. Geographic situation of the study zone with dept (in m), and location of the samples

2.1 Geological setting

Geologically, the study zone is included in the Tertiary Guadalquivir basin, which represents the foreland basin of the Betic Mountain Ranges. The Bay of Cadiz was generated as a tectonic depression during a distensive tectonic phase in the Late Miocene-Pliocene (Benkhelil, 1976). The depression was occupied by a deltaic system that gives rise to a characteristic stratigraphic sequence (Viguier, 1974; Zazo, 1980). Different geological units and formations constitute the sedimentary strata outcropping in the surrounding area of Cadiz bay (Fig.2).

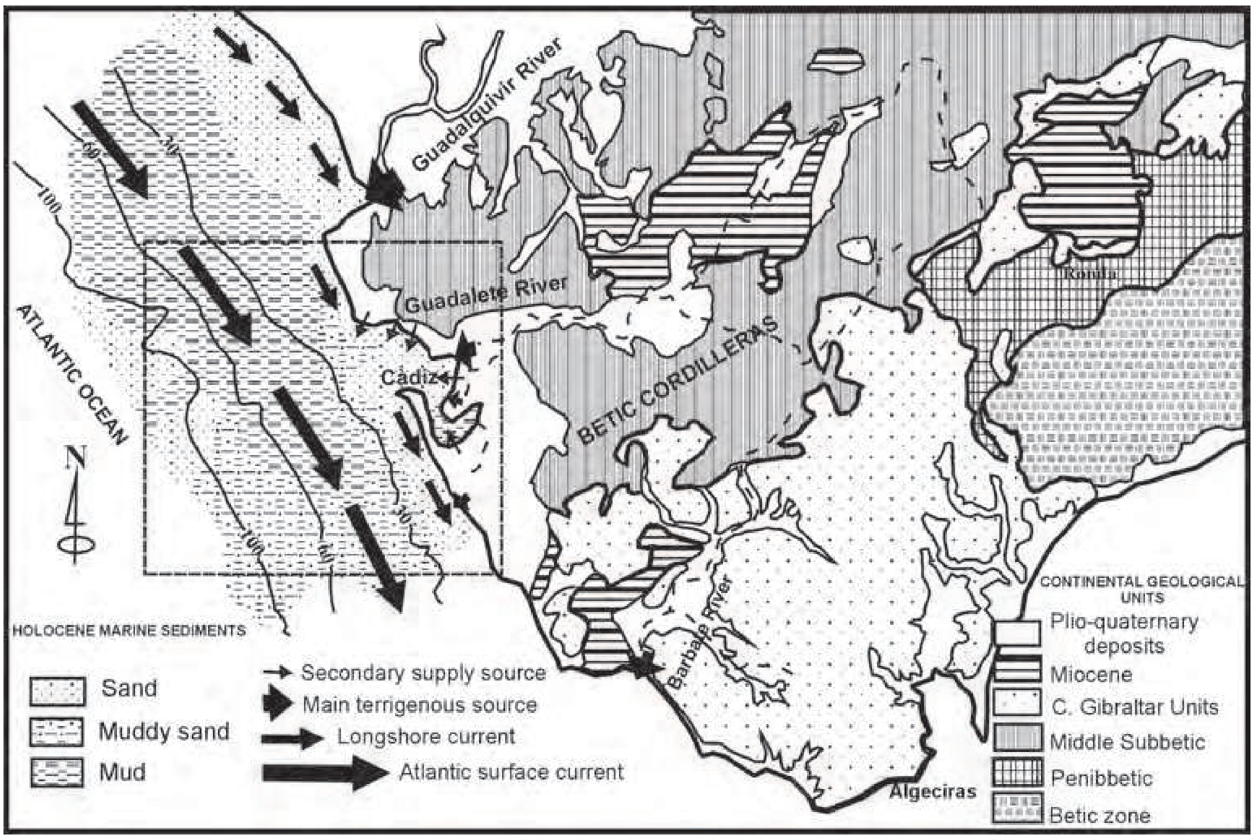

Fig. 2. Schematic geological setting showing supply sources and marine sediments distribution on the study zone

The Post-orogenic materials (autochtonous units) are mainly from the Neogene Guadalquivir depression, and correspond to Plioquaternary and Quaternary sands, clays, marls, sandstones and some limestone and conglomerate levels (Fig.3B). The pre-orogenic materials (Allochtonous units) outcropping in the study area correspond to different units of the Betic Mountain Range, being constituted by calcarenites and marls of Upper Miocene, red marls and gypsum of Subbetic Trias, and the Aljibe sandstones of Oligocene-Lower Miocene (Fig.2). Upon all those materials, appear Quaternary deposits constituted by muddy marshes, beach sands and continental deposits (Mabesoone, 1966; Viguier, 1974; Zazo et al., 1983; Gutiérrez Mas et al., 1990; Moral Cardona et al., 1996; Dabrio et al., 2000; Achab et al., 2005a).

2.2 Physiographic aspects

In this sector of the continental margin of the Gulf, the shelf and the coastline physiography are oriented NNW to SSE, with shorted East-West sections, having a stepped aspect resulting from both old and recent tectonic fractures (Baldy et al, 1977; Sanz de Galdeano, 1990). These, are manifested by several systems of recent fault and diaclase, affecting so much to continental domain as marine bottoms (Fig.3A) (Gracia et al, 1999; Gutierrez-Mas et al, 2004). The tectonic activity had a considerable influence on the distribution, development and nature of the recent marine deposits in the Gulf of Cadiz. Many indicators in areas near the Bay of Cadiz, like faults affecting Quaternary sediments, morphostructural lineaments and other geomorphological features, confirm this neotectonic activity (Benkhelil, 1976; Zazo et al, 1999). An Early Quaternary compressive tectonic episode has been deduced from reverse faults observed in marine sediments of the continental margin (Maldonado & Nelson, 1999; Maldonado et al, 1999b).

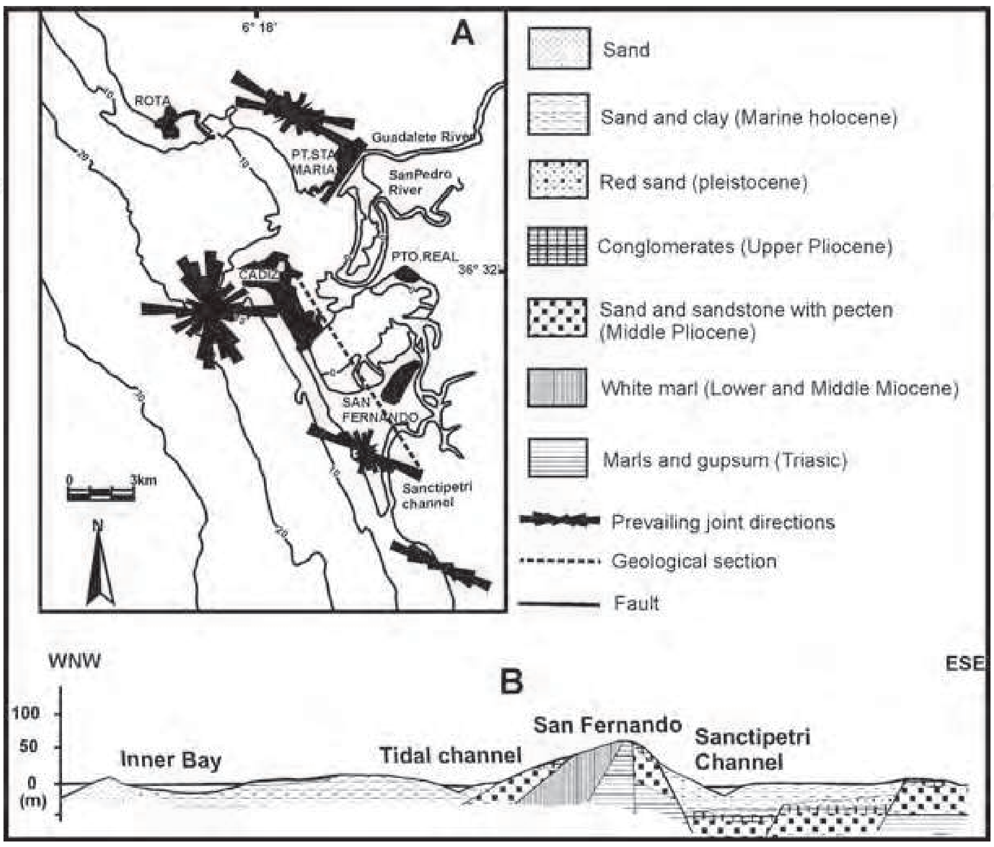

Fig. 3. A: Prevailing joint directions affecting Plio-Quaternary and Pleistocene units outcropping in the coastal zone; B: Cross section showing the main geological formations of the Bay of Cadiz

2.3 Hydrodynamics setting

Different water mass movements and currents control the shelf hydrodynamic regime (Fig.4). The most important being North Atlantic Surface Water (NASW) and littoral currents moving towards the southeast, and are responsible for the dispersal of fine sediments from the Guadalquivir and Guadiana Rivers (Gutierrez-Mas et al, 2006; Achab et al, 2008); and the Mediterranean Outflow Water (MOW) moving west to deeper water (Maldonado & Stanley, 1981;Baringer & Price, 1999). The tidal regimes in the Bay of Cadiz is mesotidal and of a semidiurnal character, with a mean tidal range of 2.39 m, mean spring tidal range of 3.71 m and neep tide of 0.65m (Benavente et al., 2000). The tidal currents are considered to be responsible of fine sediment transport (Achab et al., 1998, 2008). Wind and wave action are also essential factor in the sedimentary dynamics. Western winds are the most frequent blowing with 13.6% of average frequency. Eastern winds are also important with a frequency of 12.3% (Ramos, 1991). Waves present seasonal character and the storm average frequency is of 20 days/year. The strongest storms occur in the fall-winter period and there exists an accused calm during the summer. The significant wave height is 0.6-1m; during storm weather, the maximum wave height can reach 4m (Ramos, 1991). The Sea wave (6.96%) presents a relative predominance of east component, while the Swell wave

(10.26%) dominates the west component (MOPT, 1992). The mean littoral-drift currents are controlled essentially by northwestern waves, generating currents toward the southeast, as a consequence of the coastal orientation, facing westerly and SW winter storms. Easterly winds are also important, generating littoral-drift towards the North and NW.

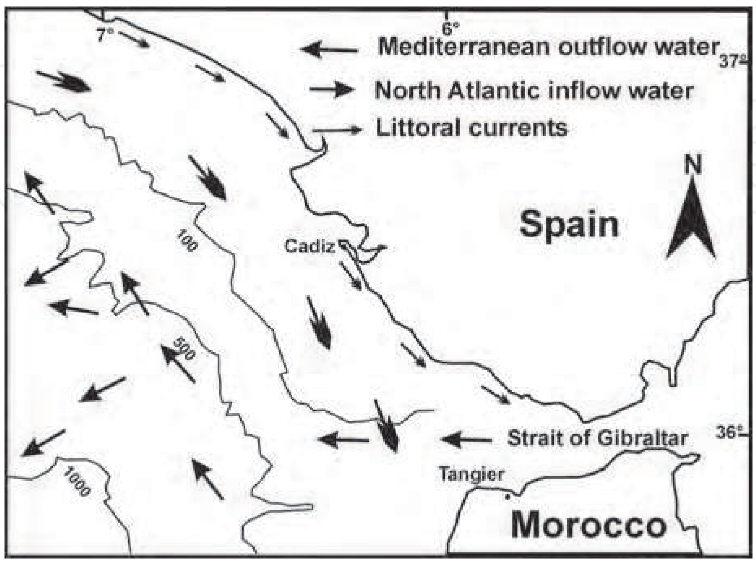

Fig. 4. General circulation patterns of water masses in the Gulf of Cadiz. Modified from Nelson et al (1999).

2.4 Depositional environments

Two main sedimentary environments with different hydrodynamic characteristics can be differentiated: the Cadiz Bay and the adjacent continental shelf. The Bay of Cadiz is about 28.5 km long and 13.5 km wide, it can be defined as a mixed morphodynamic system constituted by a wide bay known as the outer bay, with surface of about 118km^2. This zone is well connected to the continental shelf, and is very affected by the waves, currents and storms, especially of a westerly nature who dominate the sedimentary dynamics. The inner bay (Surface ≈ 40 km2) or Lagoon system located to the South; protected from waves and storms of the West and Southwest. The salt marshes and tidal flat whose surface can reach 227km^2, occupy the most internal and sheltered areas and isolated from the open sea by sandy beach ridges and littoral spits. Its development is a consequence of the sedimentary infilling when the sea level was a few meters above the present, and also by growth of inside tidal deltas. After of the last eustatic fall (5.000-6.000 years B.P), the partial emerging of the bottoms has given cause for a wide marshes zone, occupied by halophyte vegetation and drained by a complex system of tidal creeks and channels; that constituted the hydrodynamics and sedimentological transmission from the inner bay zones and the marine environments (Achab et al., 1998; Dabrio et al, 2000; Achab et al, 2008). The continental shelf has a gentle slope and a slight inclination toward the west, with an average width of 40 km, although there are important variations in the area close to the Straits of Gibraltar, where it narrows to 20-30km. The physiography of the sea-bottom shows a close concordance with the shoreline, the isobaths generally running parallel to the coast. The slope break occurs at 150-200 m water depth and shows significant variation north to south in cross section (Gutierrez-Mas et al, 1996a; Lopez-Galindo et al, 1999).

3. Materials and methods

The study has been carried out on 300 samples of surface sediments distributed across different sectors of the bay and the adjacent continental shelf (Fig.1). Bottom sampling was carried out using gravity cores and *Van Veen* dredging. The sampling stations were positioned with a differential GPS system. The textural and mineralogical analyses were carried out to establish facies distribution and mineralogical composition. The grain size analysis has been made in several phases: i) Humid separation of coarse and fine fractions using a sieve of 0.063 mm, ii) The coarser material was dry-sieved during 15 minutes, iii) The fine fraction sizes analysis was made by use of a laser diffraction analyser (AMD). The characteristic statistic indexes and parameters were calculated using standard method (Folk & ward, 1957; Folk, 1980). The grain size distribution of sediments was used to describe the sedimentary facies and to correlate their physical proprieties with the marine dynamics. The composition of the sand fraction was established by optical microscopy counting 500 grains in each sample. The mineralogical analysis of samples was performed with a Philips PW-1710 X-ray diffractometer, equipped with Cu-Kα radiation, automatic slit and graphite monochromator, using the crystalline powder technique for the bulk mineralogy and oriented aggregates of the < 2 μm for the clay mineralogy. Quantification of different mineralogical phases was calculated by the classic method of area measurement of peaks, considering the different reflection capacities of the minerals (Pevear & Mumpton, 1989; Ortega –Huertas et al, 1991). The factor analysis (Principal Components Analysis) was used to establish the mineral assemblages, as well as the relation between different minerals, grains size fraction and their associations (Reyment & jöreskog, 1993). It was also used to establish possible sediment transport paths from the bay toward the continental shelf. The method by Imbrie (1964) was used for this analysis, which is based on the samples similarity matrix. The associations obtained by this analysis are based on those variables showing the highest scores in each factor; the factor scores represent the weight or influence of each variable and components within the corresponding factor (Mezzadri and Saccani., 1988).
The study of concentration of suspended particulate matter (SPM) was based on the analysis of 30 water samples taken in zones where the concentration of suspended matter was highest, such as the tidal channel, river mouths and the inner zones of the bay. The climatic and hydrodynamic conditions prevailing the sampling time were wind from the north and northeast, average speed of 55km/hr and mean wave height of 0.6 and maximum of 1.5m. The extraction of water samples was executed to specific depths with oceanographic bottles, simultaneously with the passage of the Landsat satellite over the study zone, in order to obtain a synoptic picture of the turbid plumes, by comparing sample data with the satellite images. The separation of SPM has been achieved following the method of Green-Berrg et al (1992), which consists to the filtration of a volume of 5 liters of water through pre-weighed filters by MILLIPORE (0.45 microns). Filters were washed with distilled water, dried at about 60Â° and weighed. The use of satellite images in study of sediment dynamics is based on the utilization of inorganic suspended particulate matter as a natural tracer. Satellite images of the Bay of Cadiz have been recorded by the satellite Landsat TM, using bands 2 and 5, and a spatial resolution of 30x30 m. These images has been analysed to obtain data about extent and direction of turbidity plumes and fine sediments transport in several hydrodynamic situation in Cadiz bay and inner shelf waters. The process of the images has been carried out according to the methodology described by Ojeda et al (1995). In order to

establish the distribution pattern of bottom currents and the flow regime, different bedforms fields have been identified based on the analysis of side scan sonar records, obtained in different oceanographic campaigns, using sonar model Klein 500Khz. The sweeping width is of 100m, resolution > 7.5 cm and overlapping of 30% (Parrado Roman et al, 2000).

4. Results and discussion

4.1 Grain size analysis

4.1.1 Grain-sizes classes

Taking into account the variety of grain size distributions in the modern sediments of Cadiz bay and the continental shelf bottoms, we can differentiate various types of sediment, corresponding to different grain size classes, which reflect the energy level of each depositional environment and the processes of sediment transport. Grain size analysis show that samples are mainly composed of sand and mud, and subordinate amounts of gravel. The grain size distribution histograms and cumulative frecuency diagrams reveal the existance of different sediment types, highlighting fundamentally six classes, as most representative of all Cadiz bay sediments (Fig.5). The class A, is the most frequent with 33% of the total, and related to sandy facies with a very fine sand mode (3.49 Phi; 94 µm) which represent more than 69% of the total sample. The grains size distributions are mesokurtic and coarse skewed. Sands are moderately well sorted with 93% of the grains between 3 and 4 Phi (125 and 63 µm). These sands are mostly located on the outer bay and inner continental shelf, especially in littoral zones, at depths lower than 25m. The class B (28% of the total), characterised by poorly sorted sediments and have a bimodal grain-size

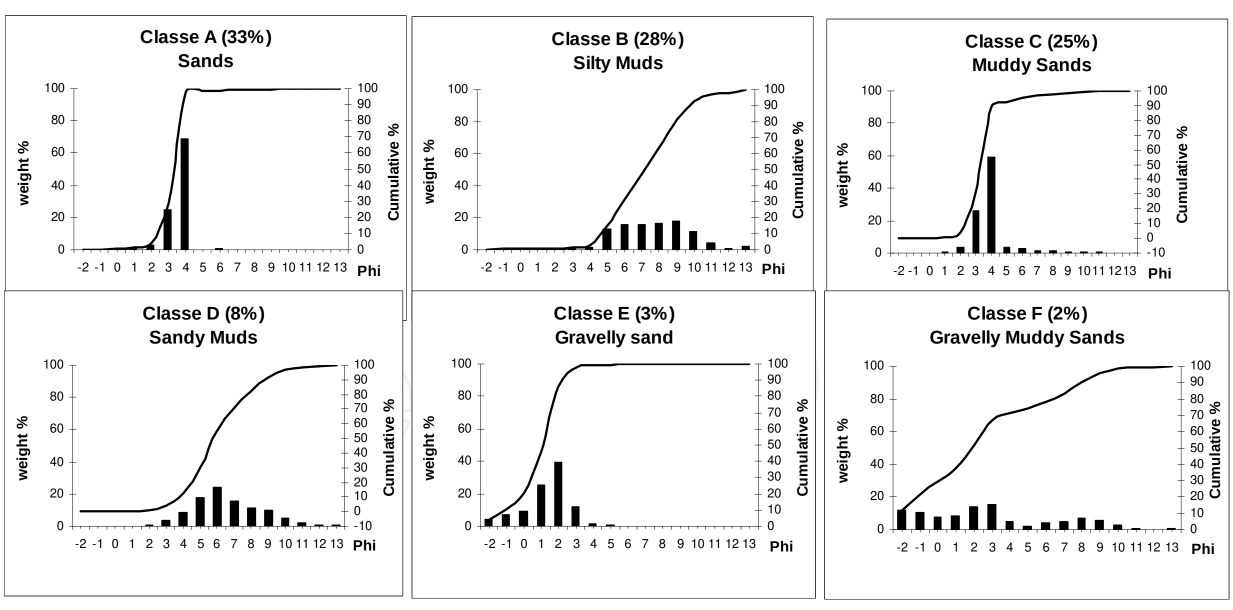

Fig. 5. Histogram distribution of grain size and cumulative frequency curves characteristic of the study zone

distribution, with more than 95% of the samples are finer than 4 phi (63 µm). These types of samples cover a large part of the middle continental shelf in the northern area and inner bay of Cadiz. The class C is quite frequent (25%), beinig associated with muddy sands facies, characterised by a very fine sand mode (59%), symmetrical and very leptokurtic distributions and moderately sorted sediments. Muddy sands distributions contain about 88% of material larger than 4phi and have mud content less than (12%). They are largely located to the south of the continental shelf and in the central and eastern parts of the outer bay. The class D (8%) presents modes of coarser silt (25%), composed of 78.4 % fraction between 5 and 9 phi (31 and 2 µm) and have sand content less than 13%. The samples are very poorly sorted and show mesokurtic and fine skewed distributions. These type of samples correspond to sandy muds facies, located in the occidental part of the outer bay and to the north of the continental shelf at depths between 25 and 40m. The class E (4%), characterised by pseudo-bimodal distributions, the main mode corresponds to medium sand (39.8%) and the secondary to very fine gravel (11%). The grains size distributions are coarse skewed and leptokurtic with poorly sorted sediments. This class was found to be related with energetic coastal environments of the bay of Cadiz, especially near rocky shoals. The class F is very scarce (1%) presents variable modes and very poorly sorted distribution. The samples have gravel content more than 22% and contain about 28% of material finer than 4phi. They correspond to sediments located in isolated pockets off the bay of Cadiz.

4.1.2 Grain-size parameters

The analysis of different grain size parameters shows the prevalence of unimodale distribution, however bimodal and polymodal distributions are also present. The average value of the main mode is 3 phi, corresponds to the boundary between fine and very fine sand, and represents the most common and more stable size fraction for the existing energitic conditions and for the dominant transport processe. The mode values increase in coastal areas and near rocky shoals and decreases towards the central zone of the outer bay and in the inner bay. The mean has an average value of 3.5 phi (very fine sand). The low values of means are located in the center of the outer bay, while the highest appear mainly in coastal areas. The average value of the sorting (1.76 phi) indicate poorly sorted sediments. The distribution of this parameter allows us to distinguish two sectors, an eastern one, characterized by well-sorted sediments, and a western sector where the sorting is generally poorer. The high degre of heterogeneity of grain size distributions is due to the variety of energy of the depositional environments and to the mode of transport affecting the sediments. The average value of skewness is about 0.17, corresponding to grain size distributions of positive skewness (fine skewed), which are predominant in the sediments with symmetrical distributions. The kurtosis (1.56) present heterogeneous and leptokurtic distributions, these prevail together with the mesokurtic distribution. The grain size of marine sediment varies by physiographic zones, it decrease progressively with depth, from coarser-medium sand of shallower area, characterised by well-sorted, negatively skewed and very leptokurtic distribution, to finer sand and mud of deeper zones, where the sediments trend to be poorly sorted and positively skewed. The general trend and the variability of different grain-size parameters of surface sediments of the bay of Cadiz and the continental shelf, reflect the control that physiographic and hydrodynamic factors exert on different types of sediment.

4.1.3 Grain size fractions

The grain size of sediments depends of numerous factors, especially the mineralogical composition of grains, erosive and depositional history of these. The combination of these factors gives place to different grain size distributions; whose interpretation was found to be related with sedimentological analysis. Their distribution in the marine environment is primarily a function of the interaction between the strength of waves and currents and the size of individual sediment grains (Nombella et al., 1987, Gao and Collins, 1994 and Olabarria et al, 1996). The distribution of different grain size fractions shows the predominance of the coarser fractions in the outer bay, more exposed to wave action and currents. The finer fractions such as silt and clay appear in more sheltered zones of the bay and in the continental shelf. (Fig.6A). The gravels are underrepresented in the sediments (less than 5%). These coarser fractions are mainly composed of bioclasts and rock fragments, derived from erosion of rocky shoals and coastal cliffs. The sand is the dominant fraction of the outer bay sediments, with an average of 75%. In some areas, this fraction changes laterally to muddy sand; due to the recent action of transport processes taking place in this area of the Cadiz bay. Its origin and distribution is related to several factors: i) the proximity to coastal areas affected by swell and with the presence of numerous sandy beaches that transport sediments to deeper areas of the bay, especially in storm period. ii) The presence of some significance river mouths (Guadalete River among others), as well as abundant valleys and ravines, which act in times of flood and important runoff. iii) The Existence of sandy sediments of relict or palimpsest character, largely reworked by actual processes, which were deposited when sea level was several meters below the present, or because to the action of special dynamic event that eroded beaches and transported sand to the deeper areas. The silt appears in low proportions (10%), giving the highest values in some sectors of the outer bay and the continental shelf. It distribution is of great importance to understand the modern sediment dynamics in the Bay of Cadiz, especially the sediment exchange between the inner and outer bay. These fine materials are deposited on sandy materials of the outer bay, indicating the path followed by water flows that control the sediment

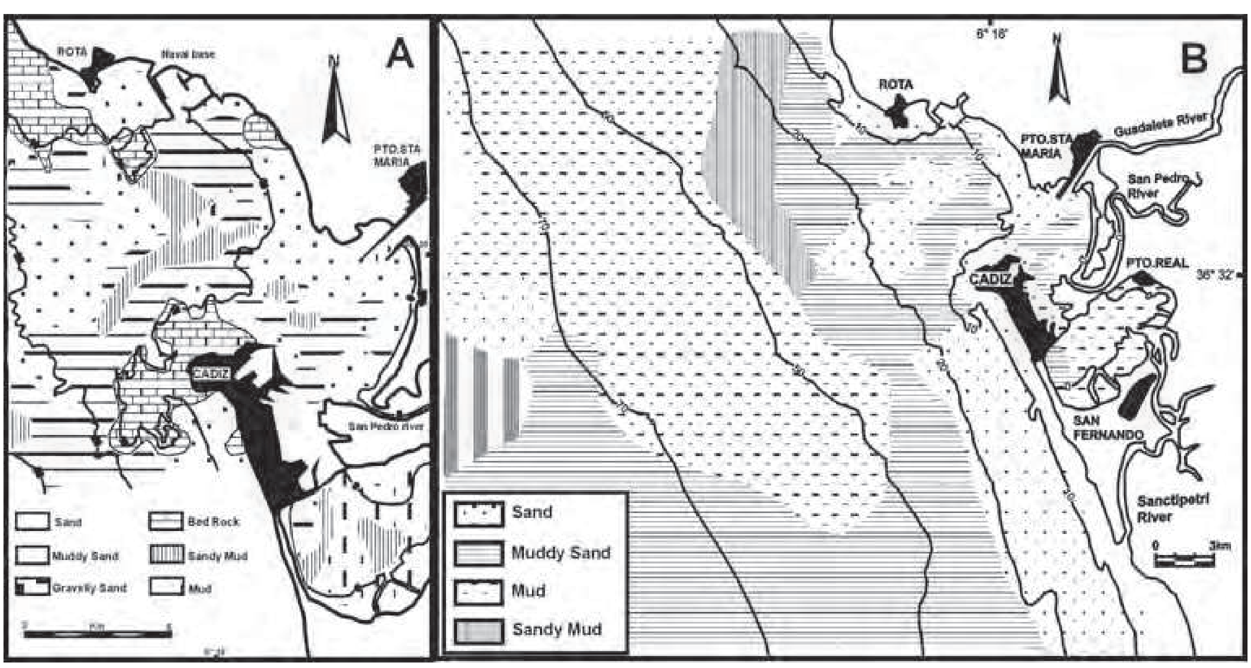

Fig. 6. Recent Holocene marine sediments distribution in the sytudy zone. A: Bay of Cadiz; B: Continental shelf

dynamics between the outer bay and the inner shelf. The clays are an important sedimentary fraction, especially in low-energy sedimentary environments where concentrations reach 90% such as inner bay and the tidal channels that drain the salt marshes, as well as to the northwest sectors of the study area. In the outer bay, the contents are very low (<5%). The abundance of clay fraction in the inner bay and the salt marshes is related to the existence of sedimentary environment of very low hydrodynamic energy. In these areas, predominate the flow and ebb tidal flow, whose action gives rise to a wide intertidal zone dominated by clayey mud deposits. The complex network of tidal channels, the inputs of fine material from the salt marshes, and the abundance of algae (seagrass type) determine the progressive deposition of fine materials in the inner bay bottoms.

4.2 Facies distribution pattern

Recent Holocene marine sediments in Cadiz bay and the adjacent continental shelf have a siliciclastic character (Gutierrez-Mas et al, 1996a; Achab et al, 1999b). Considering the relationships between grain size sediment and different sedimentary environment, the study area can be divided into several specific sectors (Fig.6B): The sandy facies predominate in the outer bay of Cadiz, especially in the littoral zone. Quartzose sands with less amount of gravel and with high content of bioclastic remains, associated to energetic environments, also cover the southern zone of the continental shelf. These transgressive sands of relict character were developed during the Holocene transgression (Rodero et al., 1999). Muddy-sand sediments occupy a central part of the continental shelf; this palimpsest facies is characterized by the mixture of fine materials coming from the Guadalquivir prodelta with relict sands facies. In the outer bay, those sediment facies extend into the 20-30 m deep inner shelf, being configured in two bands, one by the north margin of the bay and another one more to the South, bordering the city of Cadiz. They derive from resuspension of fine-grained materials in the marshlands of the bay and from fine materials supplied by the Guadalete River during periods of rainfall and floods. The presence of mud and sandy mud facies covering sandy bottoms indicates actual processes of deposit and transport of fine sediments from the inner bay toward the external zone reaching the inner continental shelf. Mud and sandy mud facies are the dominant fractions in the inner bay, agrees with sedimentary processes of low-energy characterizing the sheltered zone (Achab et al., 2005b). Their hydrodynamic regime is almost exclusively dominated by tidal currents and wind drifts, especially of the East sector. Muddy facies are also present in the continental shelf as a prodeltaic muddy zone situated to the north and deposited in low energy environment. These fine grained sediments are related to supplies coming from the Guadalquivir River. The salt marsh, tidal creeks and emerged alluvial plain are characterized by the presence of argillaceous-sandy nature sediments in their borders, whereas sandy sediments are present in beaches. The sedimentation is basically controlled by the action of flows and ebb tides. These are responsible for the transport of sediments, and the erosion of tidal creeks and salt marsh border, due to the action of small surge that beats riversides, as well as to the effect of collapses and superficial erosion of argillaceous grounds (Achab et al., 2000b). The pattern of particles size distribution is controlled by the action of hydrodynamic agents, the recent eustatic (sea level) changes during the terminal Holocene as well as the coastal and bottoms physiography (Alvarez et al, 1999; Achab & Gutierrez-Mas 1999a)

The mineralogical analysis (Fig.7) shows that quartz is the most abundant terrigenous mineral; its content is variable, based on the distribution of different grain sized facies, representing an average content of 55%, with maxima of up to 80% in sandy area, while in muddy sands the content is less than 25%. Feldspars are sparse; the content ranges from 5 to 10%, indicating a high degree of compositional maturity of the sediment. Locally they can reach values of 20% in sandy deposits. The calcite, displays average contents of 20 %, being also the second mineral more abundant in sediments after the quartz. Others mineral are the dolomite with very low contents (6%) and the aragonite (<5%), their origin is fundamentally biogenic. Phyllosilicates prevail in the muddy zone and its distribution is very conditioned by grain size. They are mainly constituted by illite (60%), smectite (13%), interstratified illite-smectite (10%), kaolinite (8%) and chlorite (7%).

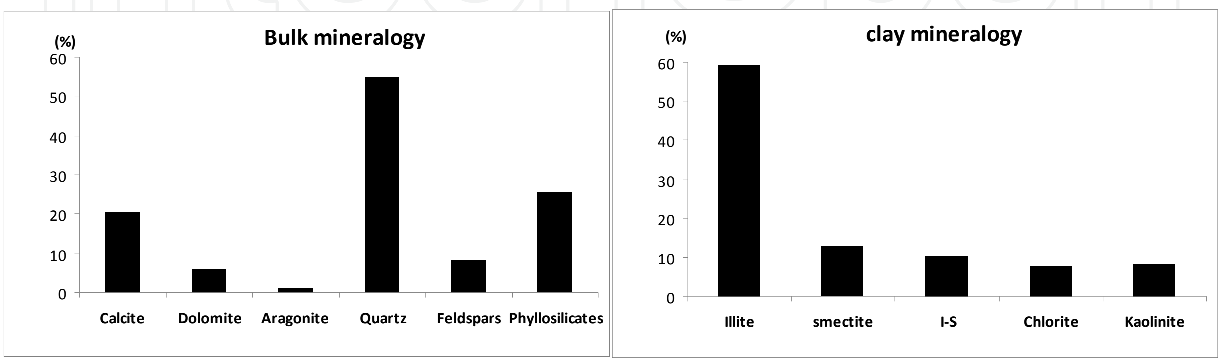

Fig. 7. Bulk and clay mineralogy of surface sediments in the study zone

The microscopic analysis show that the quartz trends to accumulate in very fine and medium grain sizes of the sand fraction (Fig.8), heavy minerals have been also observed specially in the finest fraction (very fine and fine sand). Bioclastic components and rock fragments mainly compose the coarsest sub-fractions. Especially calcareous shell fragments and continental plant remains (pieces of small trunks, small branches, etc.). The rock fragments corresponds to small cobble rocks grains of very diverse nature and lithology. Mainly fragments of "Ostionera rock" of plio-quaternary age coming from the erosion of rocky bottoms and coastal cliffs. They are also present small rolled cobbles of quartzite and sandstone fragments. Other calcareous biota include numerous benthic and planktonic foraminifers, echinoderms, bryozoans, sponge spicules and ostracods.

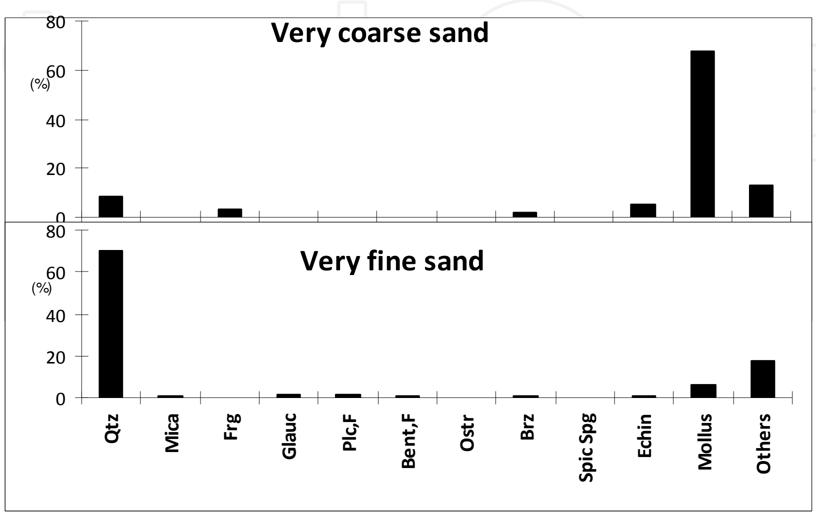

Fig. 8. Sand fraction components of surface sediments in the study zone

4.3 Sediment transport patterns

Sediment transport on marine environments and shelves is mostly a function of wave-current interactions; it depends on surface-wave conditions, bottom-boundary-Layer currents, and bed characteristics, including grain size, density, and surface roughness (Van Rijn, 1984, 1993; Cacchione & Drake, 1990; Wiberg, 1996 and Soulsby, 1997). On the other hand, the distribution of terrigenous sediments in the marine environment can reflect the direction of water mass movement (Mead, 1972; Poulos et al, 1996). Therefore, it is very important to establish a correlation between the transport of sediments and the hydrodynamic system, to understand the processes of dispersion of fine sediments from different supply sources (Gutiérrez Mas et al, 1999; Achab et al, 2000b).Taking into account the different types of data and results obtained in this work, together with knowledge of the sedimentary environments and characteristics of the local hydrodynamic system, a global model of exchange and transport of sediments in the Cadiz bay and the adjoining continental shelf can be elaborated. This model take in consideration the sedimentological and mineralogical data complemented by satellite image and suspended matter analysis, as well as data obtained from recording of side scan sonar.

4.3.1 Transport mode

The distribution of different granulometric facies allows differentiate the fundamental modes of particles transports (Visher, 1969; DeGiovanni, 1970, Komar, 1977). In our case, the limits to distinguish particle transport modes correspond to a storm situation (high energy), in which very fine sand fraction can be transported in suspension (Parrado Roman & Achab 1999). The different types of sediment grains are moved in three possible modes according to its size, forms, density and the hydrodynamic conditions. Bed-load transport (rolling or sliding motion) dominates the higher-energy environments such as coastal zone mainly composed of coarse fractions and shallow areas associated with rocky shoals. The areas affected by this type of transport and its significance increases substantially during storm periods. The suspended transport predominates in the inner part of the Bay (including tidal channels and marshland areas) and to the north of the continental shelf characterized by mud-clay bottoms deposited in low energy conditions. In general, suspension transport is the dominant transport mode on many marine environments including continental shelves (Cacchione & Drake, 1990). The intermediate transport (saltation-suspension) predominates in the outer bay especially the western sector and the central part of the continental shelf. Areas affected by this type of transport coincide with sandy-mud and mud facies bottoms, and may indicate the transport paths of fine sediments and suspended matter in the study area.

4.3.2 Clay minerals and assemblages

Due to their fine grain size, the clays can be transported large distance by rivers, wind and currents, indicating the dominant trajectories of fine sediments and the suspended matter (Maldonado & Stanley, 1981; Gutierrez-Mas et al, 1998; Achab et al, 1998). To establish the transport pathways of suspended sediments, local variation present in the seabed marine sediment was considered. Mineralogical assemblages determined in the clay fraction have been analyzed. Their origin is clearly detrital or inherited, and may reflect the combined effects of the influence of the source areas, the type of weathering on the adjacent continents, and the process of transport and sedimentation (Millot, 1970; Sawheney & Frink, 1978; Stanley & Liyanage, 1986; Weaver,1989; Chamley, 1989; Naidu et al, 1995). In the present study, clay minerals have been used as tracers, since their small size makes them the only particles susceptible of being transported away from the bay, out towards the continental shelf (Gutierrez-Mas et al, 2006; Achab et al, 2008). Other studies indicate that the clay mineral assemblages deposited in front of the rivers mouth and toward deep marine areas can be used as dynamic tracers to deduce transport path and the sources areas of clay minerals (Neiheisel & Weaver, 1967; Bhukhari & Nayak, 1996; Parhan, 1996). Factor analysis was used to establish the relationships between different clay minerals, their associations and the possible sedimentary and dynamic connections among different studied environments (Reyment & Jöreskog, 1993). The Q-mode factor analysis results provide three factors explaining the 100% of the total variance. (table.1). Factor 1 alone explains 96 % of the variance, and it represents the main clay mineral association in the modern marine sediment of the cadiz bay and the adjacent continental shelf. Factor 1 associates illite >> smectite > chlorite > kaolinite > interstratified illite-smectite.

Minerals	Factor 1 (96%)	Factor 2 (3%)	Factor 3 (1%)
Illite	**2.15**	**1.32**	**0.45**
Smectite	**0.32**	**1.7**	**0.7**
Illite-smectite	**0.28**	**0.21**	**2.03**
Chlorite	**0.3**	**0.36**	**-0.11**
Kaolinite	**0.29**	**0.21**	**0.35**

Table 1. Factor scores of the clay minerals in the Cadiz bay and the adjacent continental shelf, Q-mode factor analysis.

The factor loadings distribution shows a range of very pronounced alignment values, as bands perpendicular to the coast (Fig. 9). This association has great significance in the inner continental shelf sediments, which represent the transition zone toward offshore of deposit processes taking place in the proper bay. In this zone two bands are observed: one oriented towards the West and NW and the other one toward the SE and the South. These bands might correspond to sea floor marks generated by flows between the bay and the continental shelf; agreement with the tidal flow pattern established by Alvarez et al (1999) in the Cadiz bay.

The data from clay minerals contents and assemblages have been used to establish the model of transport paths in different area of the study zone. Two flows paths have been differentiated: i) The inflows coming from external marine areas located to the north, in particular the Guadalquivir river mouth and other sources. These flows can transport suspended matter and fine sediments to the Cadiz bay bottoms by the action of marine currents, specially the littoral and the Atlantic Surface water currents of SE direction. Different input flow paths have been established (Fig. 10). The first one (B1) derived from the Atlantic flow, affected by wind and wave of NO, West and SW, and promoted by the coastal configuration of NNW-SSE direction. This flow can reach the Cadiz bay by his northern margin and to mix with the ebb-tidal current, depositing part of its loads in inner zones of the bay. Other flow (B2) oriented E-W, located between the main entrance of the bay and inner shelf and affect bottoms of the transition zone characterized by the exchange between outflows and the inflows to the bay. This is directed towards the SE at depths between 50 and 60m. Parts of these inflows (D) are oriented to the southwest, reaching depths of 100m in the outer shelf. The outer and deeper part of the continental shelf are affected by currents generated by the Southwest storms and the action of deepest flows presents in the study area. ii) The outflows coming from Cadiz bay and littoral zones; can reach the continental shelf by mean of ebb tide currents. The Fig. 10 shows the existence of several flows that appear to move from the innermost zones of the bay to the outer one. These flows (A1) are configured in three main bands: one oriented towards the NNW following the north margin of the bay. Other band oriented towards the West and the third one goes towards the SSW bordering the Cadiz city. To the south of the bay, output flows (A3) are also observed and coming from the Sanctipetri tidal creek mouth that head towards the offshore, are capable to reach depth of 50m (Achab et al, 2000b; Gutierrez-Mas et al, 2006; Achab et al, 2008).

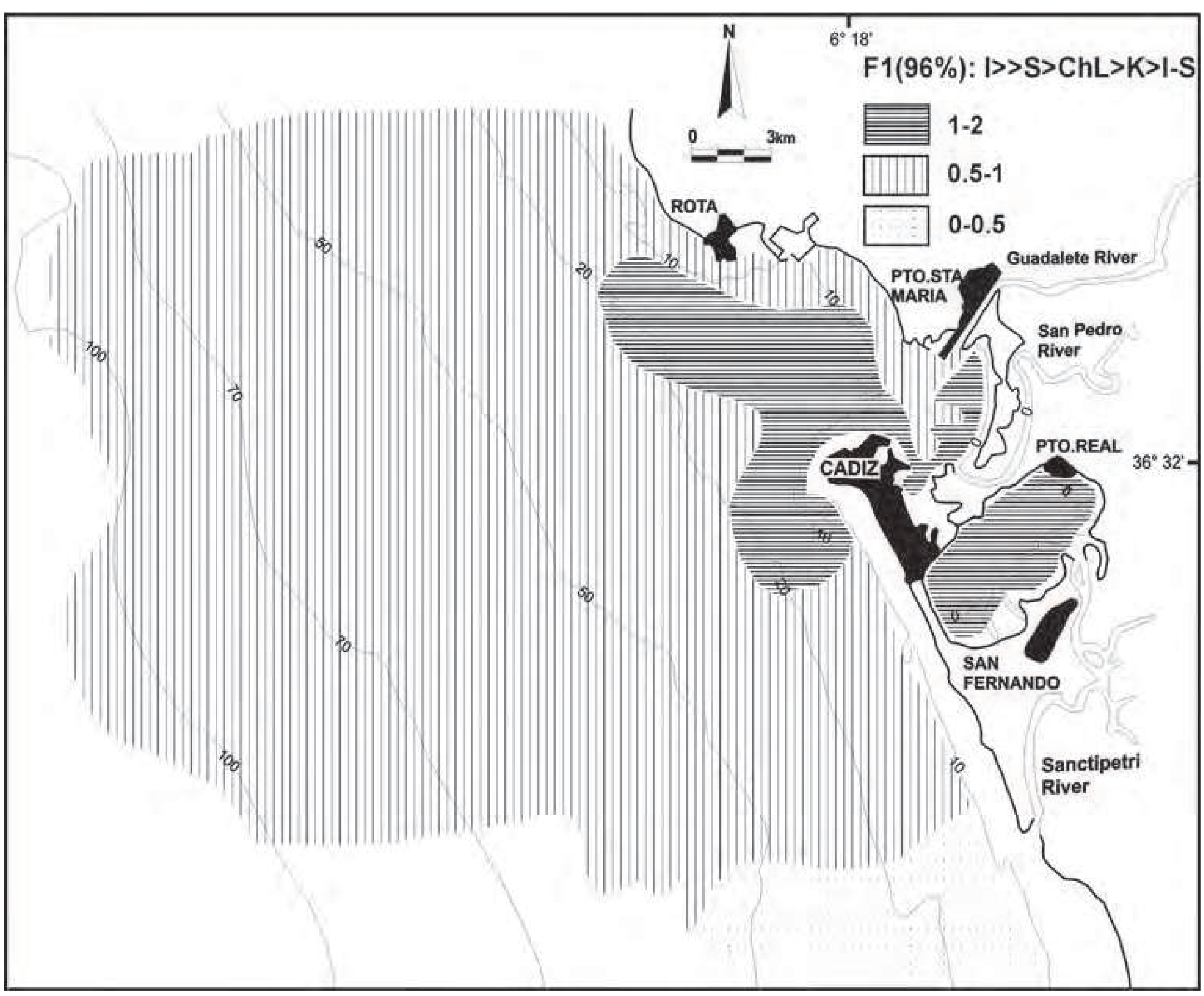

Fig. 9. Factor loading distribution of Factor 1 in the study zone from Q-mode factor analysis

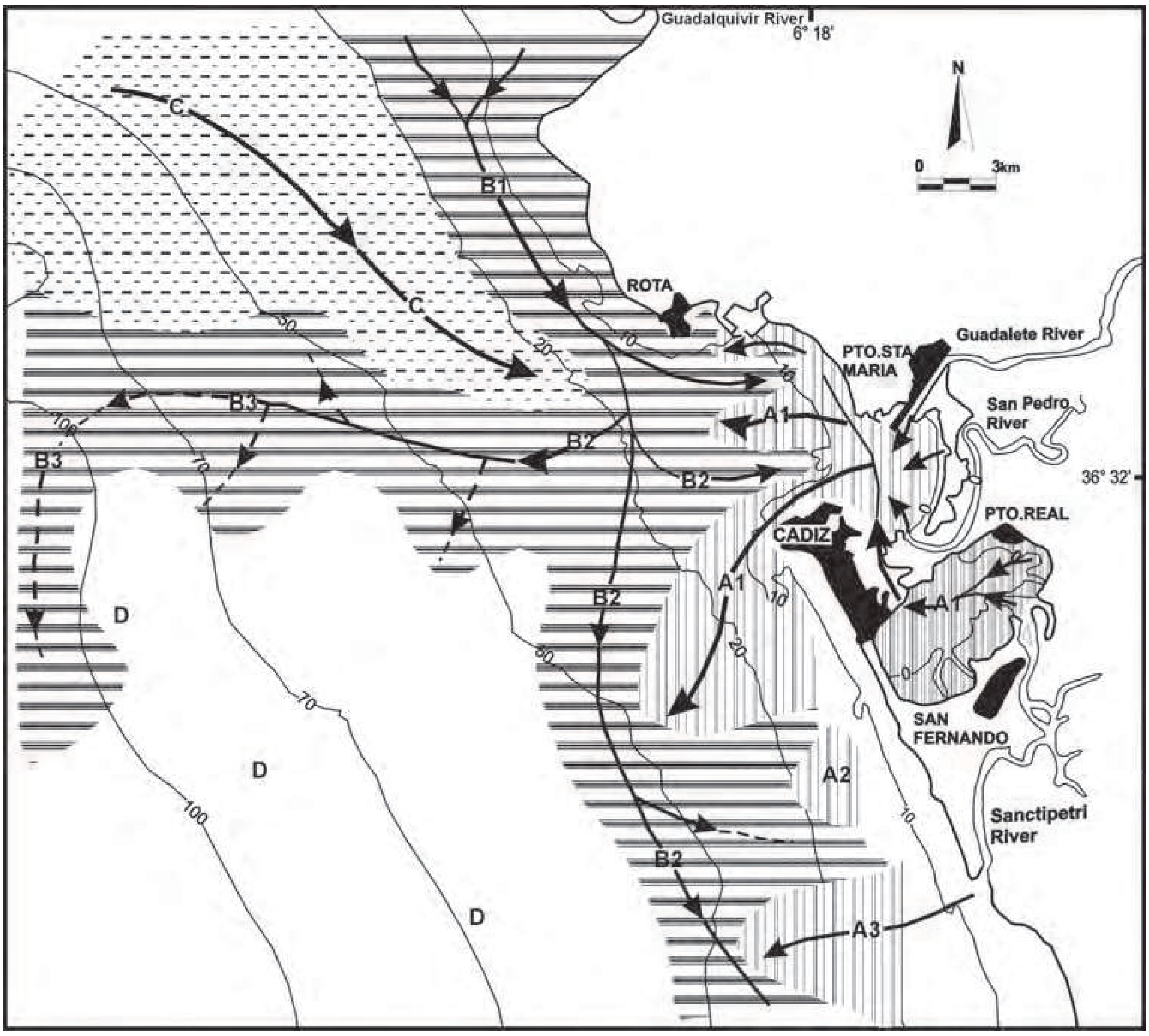

Fig. 10. Diagram of fin sediments transport paths between Cadiz bay and the continental shelf obtained from clay minerals contents and assemblages data. A1: Out flow path coming from Cadiz Bay; A2: Output flow coming from possible old tidal creeks mouth; A3: Output flow coming from Sanctipetri tidal creek mouth; B1: Output flow coming from Guadalquivir river, B2: Inflow path to Cadiz Bay; B3: External flow path to Cadiz Bay; C: Flow path coming from zones located to the north of Cadiz bay ; D: Bottoms affected by external flow path

4.3.3 Land-sat images and suspended matter analysis

The application of remote sensing techniques to the study of suspended matter dynamics allows model for marine and coastal water circulation based on the use of "turbidity patterns" as natural tracers, relating parameters of water quality to satellite images (Balopoulos et al. 1986; Fernández Palacios et al.,1994; Ojeda et al., 1994). The turbidity caused by suspended particles is detectable by the reflective bands of Landsat satellite (Spitzer and Dirks, 1987; Baban, 1995). Therefore, the analysis of these images can provide informations about size and direction of the plumes, deposit area (Lo, 1986) and estimate the concentration of particles in water column (Kleman & Hardisky, 1987, Fielder & Laursen, 1990). In the study area, due to the existence of several sources of fine sediments (Guadalquivir river, Guadalete river, inner bay, tidal channels, etc.), associated to the action of winds, waves and tides regime, is frequently observed turbidity plumes with a high content of suspended matter (Achab et al, 2000a). In the case of the Bay of Cadiz, Bernal (1986) and Guillemot (1987), based on Landsat images showed that depending to hydrodynamic conditions, these plumes follow different directions and can cross the bay area. They reach the inner shelf by the action of tidal ebb, depositing part of its SPM. Once in the open sea, SPM are moved by currents and interact with the general hydrodynamic system affecting coastal areas and the Gulf of Cadiz (Gutiérrez-Mas et al., 2006; Achab et al, 2008).

The concentration of SPM under the hydrodynamic conditions at the sampling time shows values that vary from one area to another, with an average content of 6.5 mg/l. Lower values, between 1.5 mg / l and 5 mg / l are given respectively in the inner shelf and in some areas of the inner bay unaffected by the currents. The highest values occur in the outer bay near the mouth the Guadalete river (25 mg / l). Other high values are given in front of the mouth of the San Pedro River (16 mg / l) and Sanctipetri tidal creek (13 mg / l). The concentrations of SPM are also relatively high in the oriental part of the inner bay reaching 12.87 mg / l. The general transport pattern of the SPM is affected by local processes, which take place in littoral zones, in particular in Cadiz bay and the Guadalquivir estuary (Gutierrez Mas et al. 1999, Achab et al., 2000a). Part of the Atlantic waters rich in SPM coming from the Guadiana and Guadalquivir rivers reaches the bay of Cadiz and can be deposited in lagoons and salt marshes. The resuspension of fine-grained material in the inner zone of the bay during southeast wind and ebb tidal current generate suspended matter outflows towards the outer bay. Considerable quantity of this SPM is injected in the Atlantic waters.

The analyses of satellite images show the existence of water masses of different degrees of turbidity. These, appear as turbid plumes oriented from the inner zone towards the outer bay extending to the continental shelf. These plumes are moved seawards by action of the tidal ebb currents, following the morphology of the coast and the sea bottom (Fig.11). The highest turbidity is observed at the mouths of the Sanctipetri tidal creek and the San Pedro and Guadalete rivers. In particular, these images show that the turbidity pattern coincides generally with the area of the muddiest facies present on the outer bay bottoms and with the geographical locations of the sampling stations providing the highest contents of suspended solids. From the distribution of SPM concentration and the observation of the satellite images, two possible transport paths of turbidity plumes can be deducted: a) one runs preferably by the northern margin of the bay of Cadiz and reaches the Rota city. b) Another flow oriented towards the west, bordering the city of Cadiz, eventually extending to the continental shelf.

4.3.4 Side scan sonar recording analysis

The analysis of bed-forms using Side Scan Sonar recording is considered to be a useful technique in the study of the submarine physiography and to deduce the direction of current and sediment transport (Kenyon, 1970; Belderson et al, 1972, Dalrymple et al, 1978; Fleminig, 1980.). In order to establish the distribution pattern of bottom currents and the flow regime, different bed- form fields have been identified in the bay of Cadiz based on the analysis of Side Scan Sonar recording (Parado Roman et al, 1996, 2000, Gutierrez-Mas et al, 2000). The diferent bed-forms present in the Cadiz bay bottoms (Fig.12) result from the interaction of different hydrodynamic factors (waves, tides, currents, etc.) with seabed sediments. These bed-forms correspond to modern Holocene deposits, coexisting relict forms beside present day and reworked forms. The flow regime has been deducted from typology of bed-forms and grain size of sediments (Rubin and McCulloh, 1980).

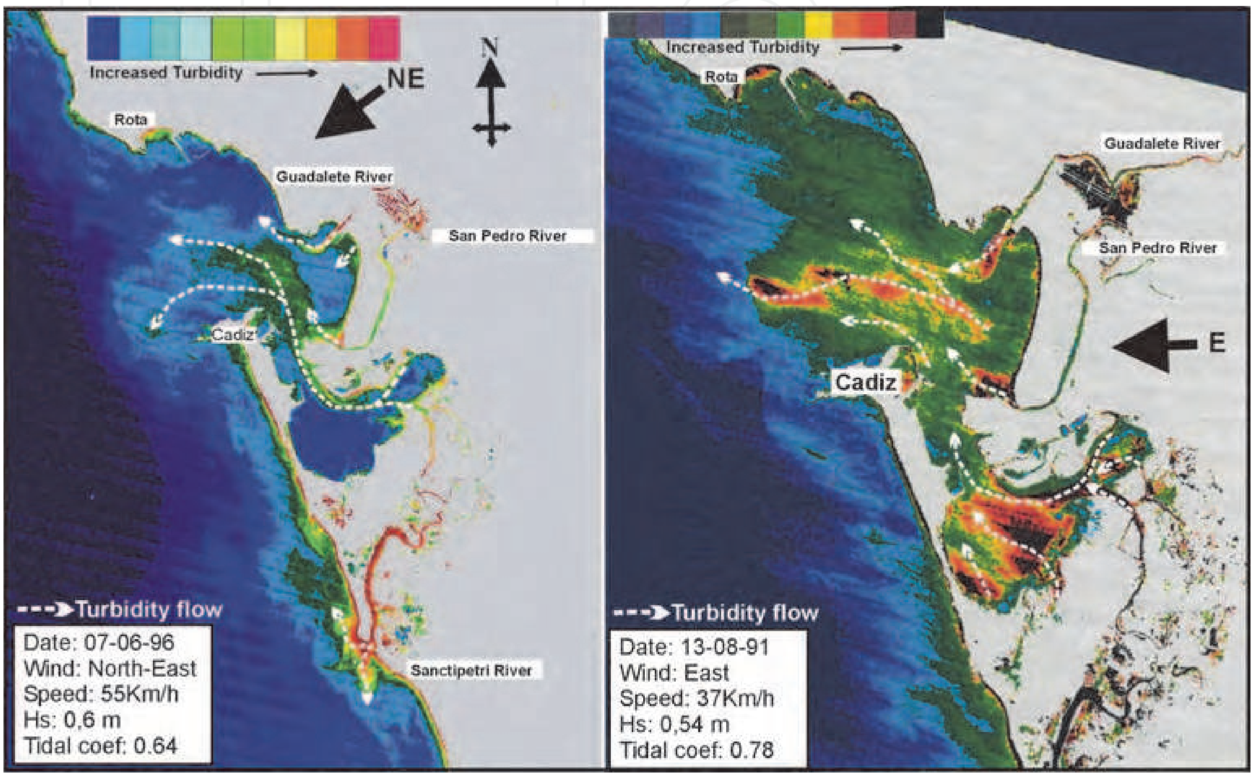

Fig. 11. Turbidity plume paths in the bay of Cadiz during ebb tide from Landsat TM images analysis

In the eastern sector of the bay of Cadiz, especially in Valdelagrana beachfront, rip currents generated by waves are directed to the West and lead to parallel and oblique sand waves of decimeter height. To the south of Santa Catalina tip, the currents are oriented towards the SW and SSW and form sand waves and ripples. North of the main channel, there are small dunes and sand waves formed mainly by effect of tidal currents of NW direction. About the Galera and Diamond shoals, the current is oriented towards the SW and forms large ripples under a high and very high energy, with speeds between 60 and 100cm /s. In the western sector, fields of bed-forms are essentially controlled by the grain size of bottom sediments. In the south part, there are straight and sinuous ripples, some sand waves and low plane bed developed on sandy sediments. To the north and NW, large mud patches appear on muddy bottoms associated to gravitational slides processes. While on sandy bottoms, there are ripples and sand ribbons. These forms indicate an upper-middle energy regime, caused by ebb tidal currents toward the SW, with speed between 30 and 100cm / s. Beside the rocky shoals located near the cities of Cadiz and Rota, we can see straight and sinuous ripples wedged between rocks, which indicate ebb currents to the SW and WSW, with speed between 20and 60 cm /s.

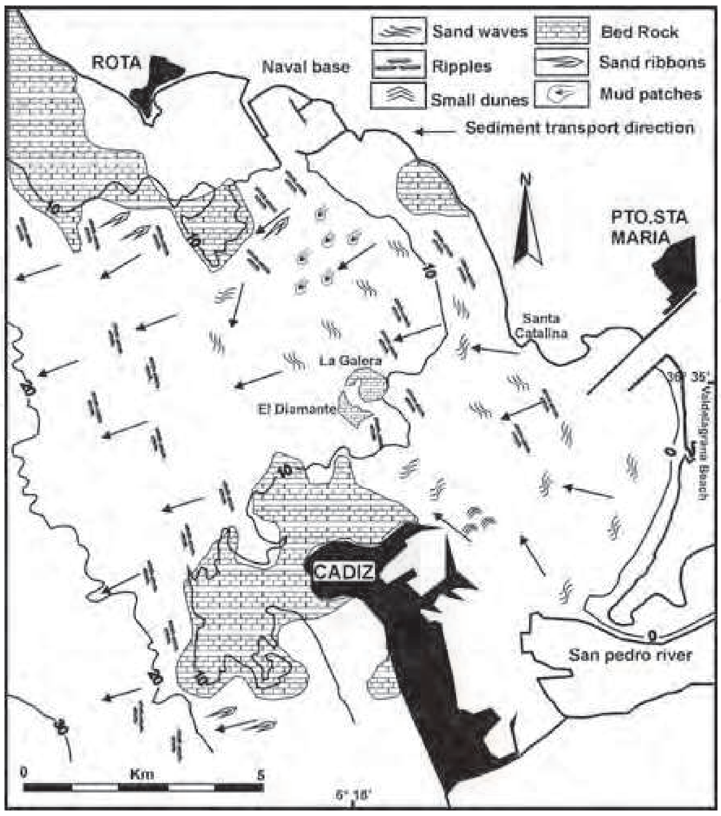

Fig. 12. Bed-forms distribution in the bay of Cadiz and transport direction of prevailing bottom currents (Modified from Gutierrez-Mas et al 2000)

The sonographic data show that different bed-forms fields present in the Cadiz bay bottoms reflect the hydrodynamic regime prevailing in the area and the sedimentary processes. The distributions of these bed-forms indicate that the dominant direction of transport of bottom sediments is toward the west and southwest, and conditioned by the grain size and current velocity. Another factor is the physiography of the seabed, which is particularly evident in sectors with greater presence of rock outcrops.

5. Sedimentary processes and conclusions

The sedimentary dynamics displays a specific behaviour pattern, related with different environments of deposit, and the interaction of these with the hydrodynamic system dominant in the area. The analysis of sediments shows the existence of sedimentary facies with variable disposition and granulometric nature. These facies occupy differents sedimentary environments; sometimes do not correspond with the present oceanographic conditions (Achab and Gutiérrez-Mas, 1999a). The distributions of grain sized and mineralogical facies reflect the action of hydrodynamic agents, which control recent sedimentary dynamics. Cadiz bay bottoms show the presence of muddy-sand and muddy facies covering sediments of coarser nature (sand and gravel), indicating actual processes of transport of fine sediments from the inner bay to be deposited upon sands of the outer bay. This model of transport has been confirmed by means of studies of bed-forms fields carried out in the study area. In situation of strong Easterly winds, suspended matter derived from resuspension of the inner bay bottoms are subsequently transported by ebb tidal currents, with an average speed of 1.02 m / s, which is reduced to 0.77 m / s in the outer bay. This involves the settling of much of the load carried on sandy bottoms. Part of the suspended matter tends to leave the bay being deposited in the inner continental shelf (Gutiérrez Mas et al, 1999 and Achab et al, 2000b). In the continental shelf, the North Atlantic Surface water current transport a large volume of fine sediments from the Guadaiana and Guadalquivir rivers toward the SE. Part of this current can transport fine particles in suspension toward the bay of Cadiz. Satellite images show that water with suspended particulate matter flows out beyond the limits of the bay under condition of easterly winds and ebb tidal current. These flows appear as branch oriented northwards along the eastern edge of the bay and then turn west, influenced by coastline and bottom morphology. A lot of suspended matter no deposited on the outer bay bottoms, can reach the continental shelf. The influence of the hydrodynamic system, the location of terrigenous sources, sea-level changes, and coastal morphology are considered to be the main factors controlling the hydrodynamic model of exchange and transport of sediments between the Cadiz bay and the adjoining continental shelf (Parrado et al., 1996; Gutierrez-Mas et al., 2004; Achab et al., 2005b).

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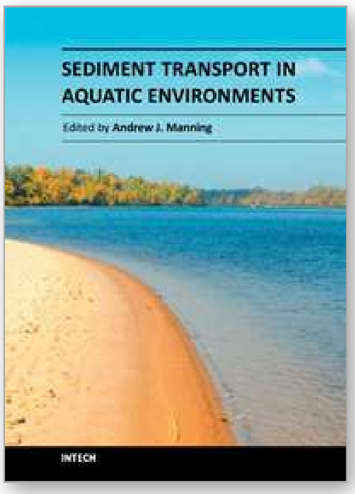

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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.