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Clay minerals as dynamic tracers of suspended matter dispersal in the Gulf of Cadiz (SW Spain)

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ABSTRACT: The dispersal of suspended matter in the Gulf of Cadiz (SW Spain) is related to its geographical position near the Strait of Gibraltar, and the continental margin, and to Atlantic and Mediterranean water flows and their interaction with the littoral tidal processes. The main direction for transport of suspended matter is towards the southeast, along the continental margin, from the mouths of the rivers Guadiana and Guadalquivir to the Mediterranean. This general transport pattern is perturbed by littoral processes such as those occurring in Cadiz Bay, where a portion of Atlantic suspended matter, driven by flood tide, comes into the inner bay and is deposited in the shallow waters of lagoons and salt marshes. Subsequently, because of the southeast wind and waves, these sediments are remobilized and transported to the west by the ebb tide, to deeper Atlantic waters. This dynamic interaction between Atlantic and littoral waters generates a different type of sediment layout, the origin of which is difficult to establish.

In order to understand the dispersal of the suspended matter and its effects on the inner continental shelf, the distribution of the main clay minerals has been determined by means of X-ray and Q-mode and R-mode factor analysis. The suspended matter dispersal paths were established through the distribution of main clay mineral associations and from the ratios amongst these minerals. The results allow us to determine the importance of the tidal flows in the suspended matter transport system of the Gulf of Cadiz. Therefore, a record was kept of which of the outgoing tidal flows from the inner parts of Cadiz Bay reached the continental shelf. The flows intercept the clear Atlantic waters giving rise to a complex sediment distribution and to the mix of clay minerals. The study has also allowed us to establish the sediment source areas and the extent of sediment transport and the paths they follow.

KEYWORDS: clay minerals, sedimentary dynamic, suspended matter flow, Gulf of Cadiz, Spain.

The suspended fine matter sedimentary dynamic in the Gulf of Cadiz (SW Spain) is controlled by three main factors: supplies from the rivers Guadiana and Guadalquivir, continental margin physiography and the surface Atlantic water and Mediterranean outflow currents. The suspended matter is dispersed from the estuaries of the rivers Guadiana and Guadalquivir towards the southeast, along the continental margin, entering the Mediterranean Sea through the Gibraltar Strait. This general transport pattern is affected by local processes which take place in littoral zones, e.g. in Cadiz Bay and the Guadiana and Guadalquivir estuaries, where the suspended matter content in the Atlantic waters is partially driven towards the littoral by the flood tide and is deposited in lagoons, tidal flats and salt

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marshes. The ebb tides and southeast wind and waves generate outflows towards the west which inject a substantial amount of suspended matter in the Atlantic current waters coming from remobilization of those shoal muddy bottoms In this work the suspended matter dispersal in a sector of the Gulf of Cadiz is studied through the sedimentological and mineralogical analysis of later Holocene marine sediments. Clay mineral associations have been used in order to study the sediment dynamics. The suspended matter traces and sediment transport paths were established through the distributions of the main associations and from the ratios amongst clay minerals.

STUDY AREA

The study area is located in the Gulf of Cadiz, between the Strait of Gibraltar and Guadalquivir river mouth, SW Spain, (Fig. 1). The coast is mainly oriented from NNW to SSE, with east–west sectors, resulting from both old and recent tectonic fractures which give a stepped coastal morphology (Baldy *et al*., 1977; Sanz de Galdeano, 1990). The continental shelf has an average width of 40 km and is oriented from NNW to SSE with NNE–SSW sectors (Fig. 1).

The hydrodynamic system is controlled by two main currents: North Atlantic Surface Water flow (NASW), which sweeps the continental shelf towards the southeast, and is responsible for the dispersal of fine sediments from the Guadalquivir and Guadiana rivers (Gutiérrez Mas *et al*., 1996); and the Mediterranean Outflow Water (MOW), which is confined to deeper water (Baringer & Price, 1999). Wind and surge action are also essential factors in the sedimentary dynamics. Western winds are the most frequent, although Eastern winds are important (Ramos, 1991). Waves present a seasonal character, with the strongest storms in the November–March period (MOPT, 1992). Waves from west, northwest and southwest are dominant in the offshore zone. The main coastal current flows towards the southeast, as a consequence of the coastal configuration. During the biggest storms, strong bottom return currents carry sediments from the beach and inner shore towards deeper zones. Tidal action is significant in Cadiz Bay, where tidal flows are responsible for fine sediment transport. The mean tidal range is 2.39 m and the mean spring tidal range is 3.71 m.

SEDIMENTS AND DEPOSIT ENVIRONMENTS

Recent Holocene marine sediments have a siliciclastic character. The sandy facies predominate in the inner continental shelf, while mud and clay are

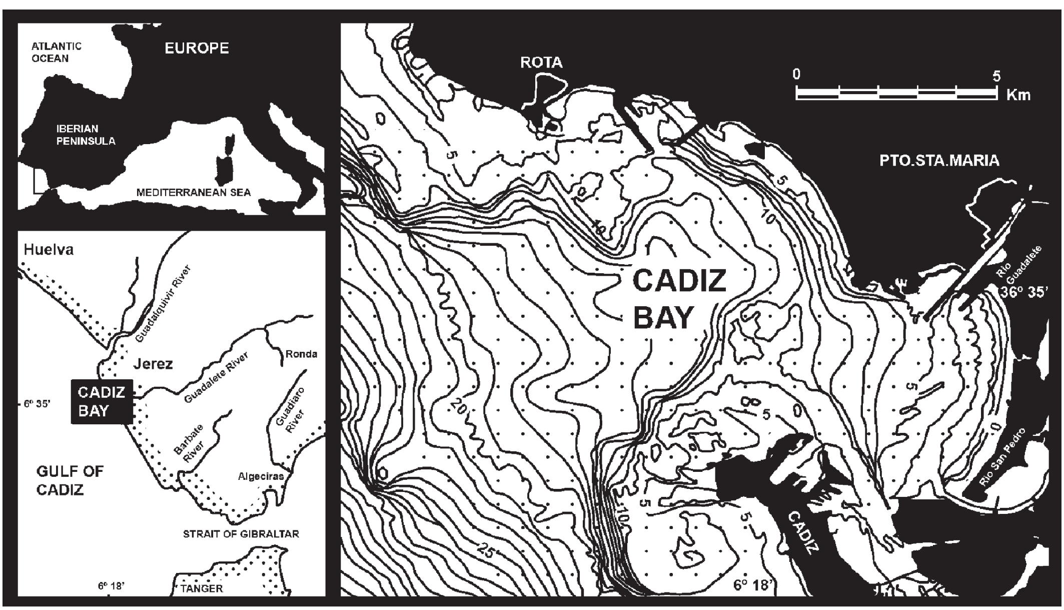

FIG. 1. Map of the study zone. The bathymetry and sampling station locations are indicated.

present in the outer shelf and inner zones of Cadiz Bay (Fig. 2). The mineralogy of the fine sediments, mainly inherited (Gutiérrez-Mas *et al*., 1999), is conditioned by the mineral layout of the geological outcrops present in close continent and coastal zones (Gutiérrez-Mas *et al*., 2003). The most important geological formations present in close continental areas are mainly pre-orogenic units from the Betic Range (Subbetic, Prebetic and Campo de Gibraltar units) and post-orogenic units from the Neogene Guadalquivir Depression (Upper Miocene, Plioquaternary and Quaternary) which inject marnes, clays and sands into Cadiz Bay (Mabesoone, 1963, 1966; Viguier, 1974; Segado *et al*., 1984; Gutiérrez-Mas *et al*., 1990).

Two main sedimentary environments may be considered, Cadiz Bay and the adjacent continental shelf (Fig. 1). In Cadiz Bay, four subenvironments with different hydrodynamic characteristics are differentiated: (1) 'External bay' is the most open and unprotected sector and it is connected to the continental shelf; (2) 'Lagoon' is the most landward marine area; (3) 'Tidal creeks' and 'tidal channels' drain the salt marshes and the tidal flat; and (4) 'Salt marsh' and 'tidal flat' occupy the most internal and sheltered areas. The salt marsh is occupied by halophytic vegetation and is furrowed by a complex system of tidal creeks of great importance in the hydrodynamic.

METHODS

We studied >250 sediment samples retrieved using a van Veen dredge and a gravity piston corer in the salt marsh areas, tidal creeks and marine bottoms of the Cadiz Bay and adjacent continental shelf (Fig. 1). Sample analysis included grain-size analysis and compositional determinations. The grain-size distribution of marine sediments was used to describe the sedimentary facies and relate their physical properties to the marine dynamic. The grain-size analysis was performed using sieves or a laser diffraction analyser (AMD) to compute the characteristic statistic indexes.

The mineralogical analysis was carried out using X-ray diffraction (XRD) techniques. The <2 μm fraction was separated by a standard sedimentation method (Tucker, 1988). The mineralogical composition was determined using a Philips PW-1710 diffractometer with Cu-$K\alpha$ radiation, automatic slit and graphite monochromator. A semi-quantitative clay mineralogical composition was calculated using data from Schultz (1964), Biscaye (1965) and Ortega-Huertas *et al*. (1991). A sample XRD pattern is shown in Fig. 3.

This treatment was applied to the data from all the samples and sedimentary environments in the tidal flat, salt marsh, tidal creeks and peripheral areas. R-mode and Q-mode Factor Analysis was

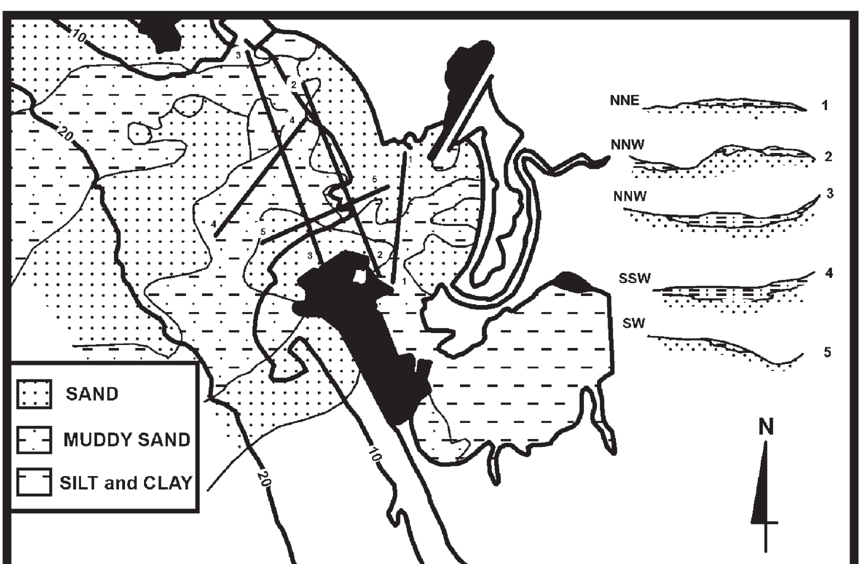

FIG. 2. Sedimentological map of the seabed of Cadiz Bay with representative geological profiles.

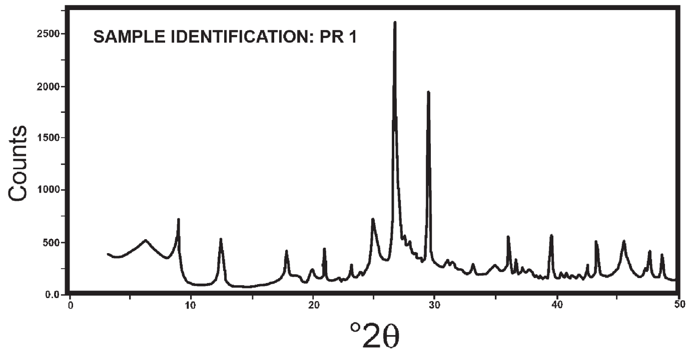

FIG. 3. Typical XRD pattern for the <2 μm fraction of modern marine sediment samples from Cadiz Bay.

used to determine the mineralogical associations and to establish the sediment transport paths. Considering the different hydrodynamic behaviour of the different clay minerals and with the goal of creating a model of the flow traces and the sediment transport paths of the fine material, the areal distribution of clay mineral content mean values ratio were established and are represented cartographically here.

RESULTS AND DISCUSSION

Mineral and sedimentary facies

The modern marine sedimentary deposits in the inner Cadiz Bay consist mainly of silty-clayey sediments, while in the external zones the sand fraction dominates, with gravel patches where rocky banks shoal at the sea floor. The types of sediment and their distribution on the sea bed reflect the coastal morphology, submarine topography, the location of rocky outcrops, the distance to the coast, and water depth. Rocky outcrops occupy a substantial portion of the seafloor and include Plio-Quaternary and Quaternary conglomerates (Gutiérrez Mas *et al.*, 1996).

The sediment grain size decreases progressively with depth, from coarse–medium sand in the shallower areas to fine and very fine sand and mud in deeper zones. The limits between facies are parallel to the coastline and the bathymetric contour, as a consequence of the structure and morphology of the submarine rocky outcrop and deep current direction. Coarse and very coarse sand occurs near rocky floors. The finer sediment is represented by silt and clay, dominant near the river and tidal channel mouths (Gutiérrez-Mas *et al.*, 1996) (Fig. 2).

Quartz is the dominant mineral, representing, on average, ~50% of the sediment and up to a maximum of 80% in sandy areas and <20% in muddy zones. Feldspars are scarce, on average 5%, demonstrating a high degree of compositional maturity of the sediment. Quartz is replaced by mollusc shell fragments where the sediments are coarse.

The distribution of clay minerals in recent marine sediments is shown in Fig. 4 and is summarized in Table 1, where the mineralogical composition of suspended matter is also included. Illite is the main clay mineral with an average content of ~65%, followed by chlorite (11%), kaolinite (8%) and interstrafied illite-smectite (6%). A significant change is observed in the particulate matter with an important increase in the smectite content (38%) and a concomitant decrease in the illite content (40%).

Factor analysis has been applied to all data to define the spatial trends in clay mineral distribution on the sea floor and to establish the relationships between the minerals. The R-mode and Q-mode analysis results provide three factors, although factors 1 and 2 explain, by themselves, almost all the variance of the system (Figs 5, 6).

Factor 1 represents 49% of the overall variance and relates to illite, smectites and interstratified I-S. The distribution of ‘factor scores’ for every sampling station (Fig. 5) shows two bands that converge towards the external bay. Other bands are oriented towards the west and NNW following the north margin of the bay.

Factor 2 represents 34% of the overall variance and relates to chlorite and kaolinite. The highest ‘factor score’ is found with local character in sandy-muddy bottoms of the inner bay and also in

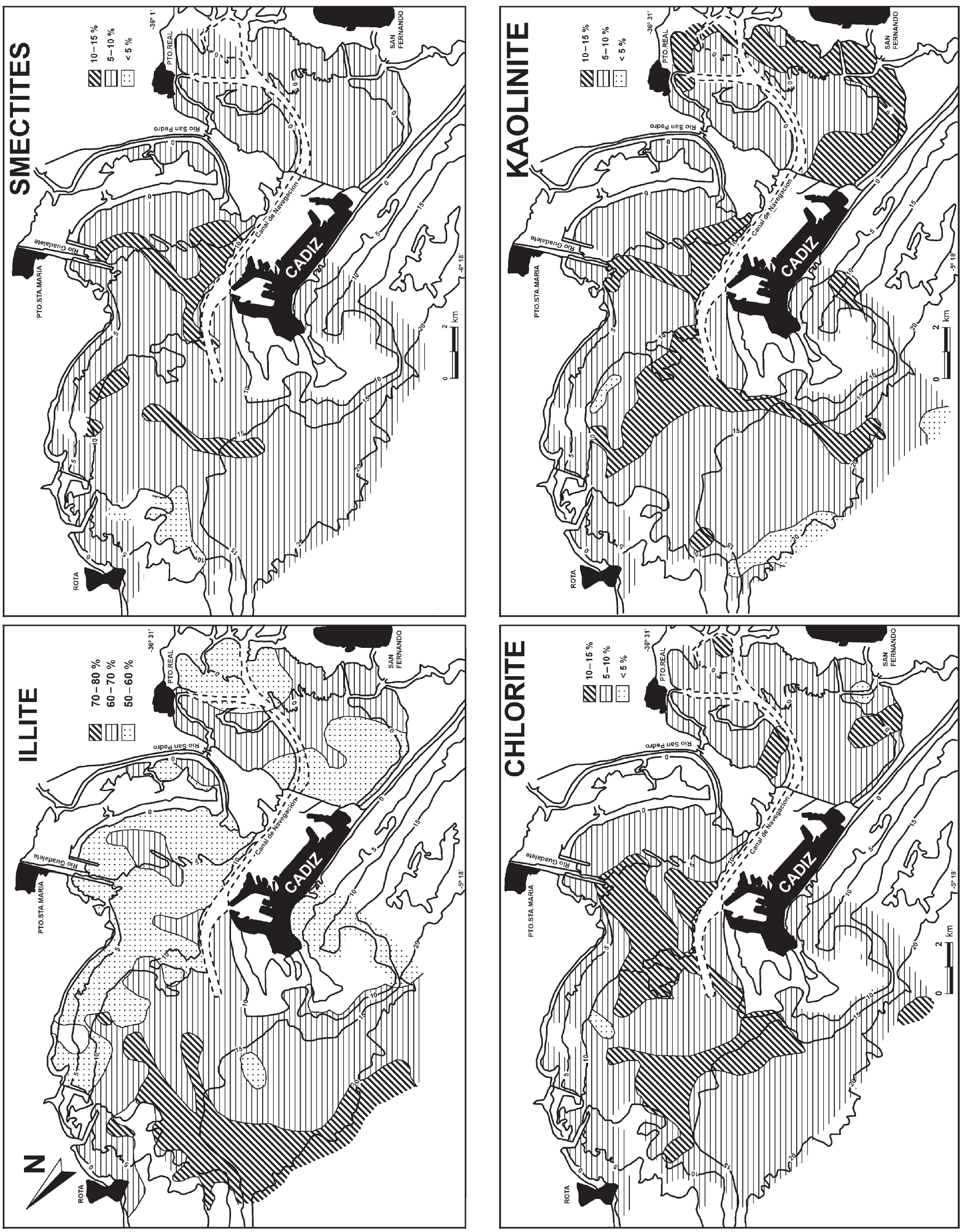

FIG. 4. Distribution maps of the main clay minerals in modern marine sediments of Cadiz Bay.

TABLE 1. Clay mineral mean values (%) in modern marine sediments in Cadiz Bay, adjacent continental shelf and suspended matter in sea water.

Deposit environments	Illite	Smectites	Interstratified I-S	Chlorite	Kaolinite
Salt marsh	65.58	6.93	5.93	11.13	8.88
(s.d.)	(4.41)	(1.49)	(2.15)	(3.84)	(2.05)
Lagoon	65.40	7.15	7.85	8.20	9.46
(s.d.)	(1.67)	(0.93)	(0.67)	(1.36)	(0.97)
External bay	66.63	8.46	5.57	8.95	8.49
(s.d.)	(4.49)	(2.77)	(1.52)	(1.74)	(1.70)
Suspended matter	40.2	38.2	6.64	10.56	5.36
(s.d.)	(6.12)	(6.14)	(2.69)	(3.22)	(1.89)
Continental shelf	52.3	17.5	15	6.5	8.5
(s.d.)	(8.1)	(7.3)	(5.7)	(2.5)	(3.2)

the external bay, near the mouths of the Guadalete river and San Pedro tidal channel (Fig. 6).

From the results above, it is clear that the dominant clay mineral in the modern sediments is illite. The bands of 'factor score' values (Figs 5, 6) represent sectors where the relationships among the clay minerals associated with each factor are dominant. These sectors probably result from persistent water flows conveying, in suspension, materials of a fixed clay mineral content.

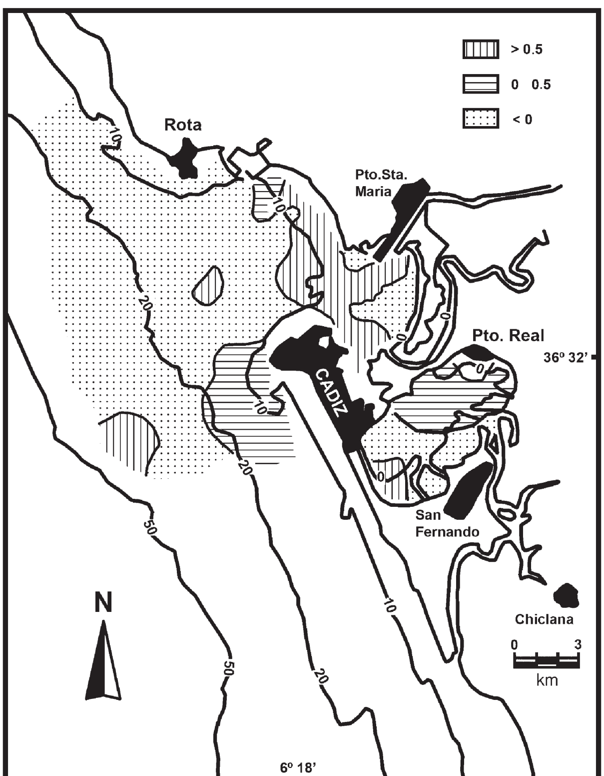

FIG. 5. Factor-score distribution of Factor 1 (illite, smectites and interstratified I-S) from R-mode factor analysis to clay mineral data in modern marine sediments of Cadiz Bay.

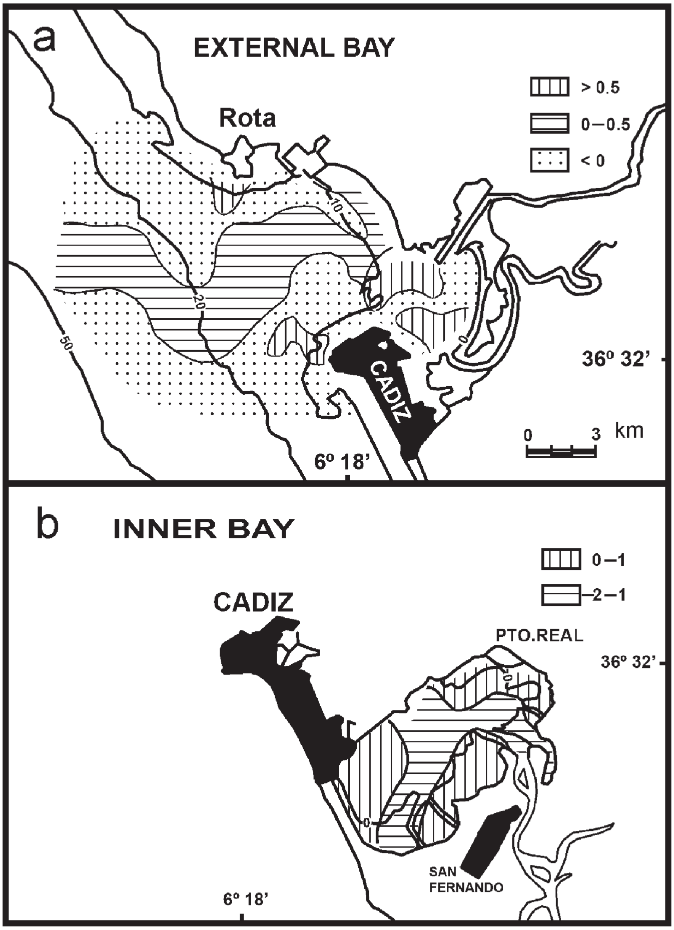

FIG. 6. Factor score distribution of Factor 2 (chlorite and kaolinite) from R-mode factor analysis to clay mineral data in modern marine sediments of Cadiz Bay.

Clay mineral associations and transport paths

To determine the clay mineral association, Q-mode Factor Analysis was performed, excluding illite, because its high content and presence in all samples obscures the remaining clay minerals in the factor analysis. If the amount of this clay mineral is subtracted, the relationships between the remaining clay minerals show new and interesting associations. The results show two main factors, although Factor 1 alone explains 81% of the variance and it represents the main clay mineral association in the modern marine sediment of the Cadiz Bay and adjacent continental shelf.

Factor 1 associates Chl > K > S > I-S. The 'factor loadings' distribution (Fig. 7) shows a range of very pronounced alignment values, as bands perpendicular to the coast. These bands might correspond to sea floor marks generated by flows between the bay and the continental shelf. These results are consistent with the tidal flow pattern in Cadiz Bay defined by Alvarez *et al*. (1999).

The ratios between the mean content of different clay minerals in the samples has been described by Fernández Caliani *et al*. (1997) who studied the content distribution of illite and kaolinite in the Odiel-Tinto estuary, province of Huelva, SW Spain, and in the adjacent inner continental shelf, showing that the ratio of illite/kaolinite (I/K) increases offshore, as the two minerals have different hydrodynamic behaviours and respond in different ways to the transport effects. A similar result, although with other clay minerals, was reported in

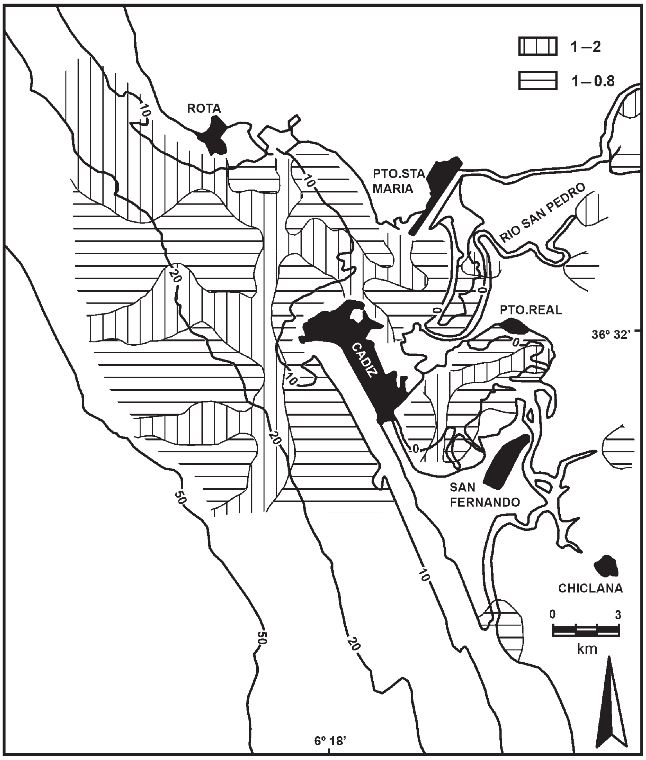

FIG. 7. Factor loading distribution of Factor 1 (Chl > K > S > I-S) from Q-mode factor analysis to clay mineral data in modern marine sediments of Cadiz Bay, excluding illite.

other estuaries and river mouths by Edzwald *et al.* (1975) and Feulliet *et al*. (1980).

In the study area, the results of the study indicate that the distribution of mean content values of the illite/interstratified I-S (I/I-S) ratio (Fig. 8) reflects a different hydrodynamic behaviour. It is noted that the highest values of the I/I-S ratio are in the NW margin of Cadiz Bay, where these values constitute a band parallel to the coast line and to the isobaths. This band of alignment values probably represents the trajectory of a practically permanent suspended matter flow generated by the action of littoral current coming from sources located more to the north. The lowest values are given in the muddy bottoms of the inner bay, in silty-clayey deposits of the continental shelf and near the tidal channel mouths.

Sedimentary dynamic

Taking into account the previous considerations, together with knowledge of the sedimentary environments and characteristics of the local hydrodynamic system, a pattern of fine marine sediment dispersal can be defined. This should explain the distribution of facies and clay mineral associations on the sea bed and to establish the transport path between the different sedimentary environments of Cadiz Bay and the adjacent continental shelf.

There are several sources of fine sediments and clay minerals to the marine environments present in Cadiz Bay (Gutiérrez Mas *et al.*, 1999, 2003; Achab *et al*., 1998; Achab, 2000). The main sources are the rivers that have their estuaries in the Gulf of Cadiz, e.g. Guadiana, Odiel-Tinto, Guadalquivir, Guadalete and others. A portion of the injected material arises from the erosion of geological formations that crop out in the nearby continental areas, coast and marine bottoms, especially the Plio-Quaternary cliffs (sands, coquinoid conglomerates and bioclastic sandstones).

Other sources of fine sediments are: (1) from the erosion of salt marshes by superficial water runoff,

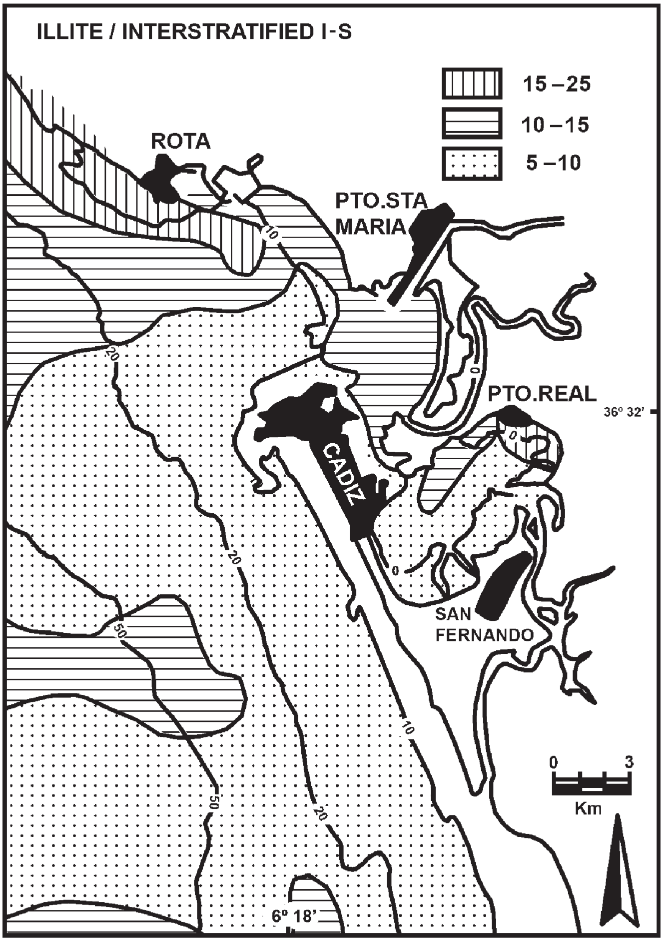

FIG. 8. Distribution of mean content ratio illite/interstratified I-S to clay mineral data in modern marine sediments of Cadiz Bay.

discharging fine material into the tidal channels and lagoon; (2) from erosion of tidal channel edges and salt marsh borders, especially by gravitational transport (slide and slumps). These processes discharge to the marine environment a lot of organic matter in the form of halophytic vegetation and humus, which were present on the surface in the salt marshes; (3) from remobilization of fine sediments in the bottom of the tidal channel and lagoon. This process is particularly active when the southeast wind is blowing and the waves retrieve the fine sediments from shallower sea beds. Once the fine material is incorporated in the marine waters, the ebb tides transport it to the adjacent continental shelf. The transport is governed by four main factors:

(a) Coast and bottom morphology: conditioning the direction and speed of the current. Cadiz Bay is open to the west and the out flows are consistently driven towards the west and southwest.

(b) Tidal current: The tides can reach high speeds, especially the ebb tide, and thus are able to transport much suspended matter for a sufficient period of time to reach the continental shelf.

(c) Wind action: favouring the displacement of the tidal current or being opposed to it (Parrado Román *et al*., 1996; Gutiérrez-Mas *et al*., 1998). The outflows are favoured by the southeast and east winds. The greatest concentration of suspended matter in the water is achieved when the spring tide and the southeast wind coincide. In that particular situation, the fine sediments present in shallower areas are extensively remobilized by wave action and transported towards external areas (Gutiérrez-Mas *et al*., 1999).

(c) Differential sedimentation: in deeper waters, when the current loses speed, the fine particles begin to descend. However, according to mineral composition, the fine clayey material has different hydrodynamic behaviour. This is particularly so in the case of the illite and smectites, as these remain suspended in the water for longer.

Transport diagram

The fine materials transported from the inner areas of Cadiz Bay are partially deposited over older sands present on the floor of the external bay. These deposits are shown in cartography as sedimentary bands which have different mineral associations. These bands probably indicate the trajectories of the suspended matter flows (Fig. 9). The fine particles which were not deposited remain suspended in the water until they arrive at the adjacent inner continental shelf, and even the external shelf, border and continental slope.

The Atlantic water current, when the fluvial input from the Guadiana and Guadalquivir rivers is prominent, contains a lot of suspended matter (Gutiérrez-Mas *et al*., 1998, 1999). Near Cadiz, some of this current drifts towards the bay, where the fine particles are deposited. Subsequently, the southeast waves and the ebb tide remobilize these fine material deposits which are transported as suspended matter towards deeper waters of the external bay and continental shelf, where they are blended with the suspended matter in the Atlantic waters and re-deposited. Simultaneously, a portion of this mix of waters and suspended matter of different character, origin and composition continues towards the southeast, along the continental margin and, pushed by the Atlantic current across the Strait of Gibraltar, penetrates into the Mediterranean Sea.

CONCLUSIONS

The sediment transport pattern and the factors that control the sedimentary dynamic in Cadiz Bay and in the adjacent marine areas have been established, through the use of clay minerals as dynamic tracers.

The tidal flat, salt marsh, river mouths and inner bay constitute important sources of fine sediments and clay minerals to Cadiz Bay and to the deeper waters of the adjacent continental shelf, due to the existence of an active and permanent dynamic interaction, because of the action of the tidal currents.

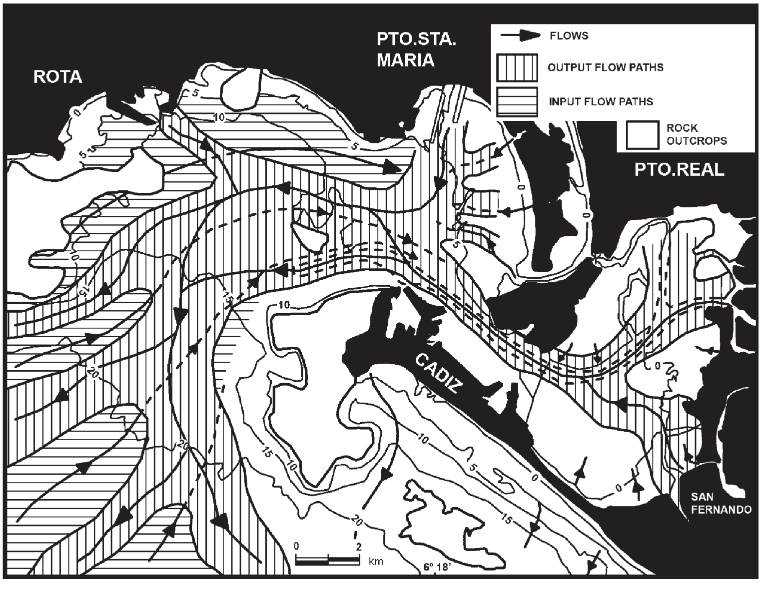

FIG. 9. Transport dynamics diagram of the suspended particles between Cadiz Bay and the adjacent continental shelf.

The incorporation and transport of the fine material to the marine environment take place by direct fluvial action from the river mouths and, also, by erosion of outcrops of geological formations in close continental areas, salt marshes, tidal flats, etc. Another mechanism is gravitational transport from slips and collapse in riversides and tidal creeks.

The hydrodynamic system, fundamentally the tidal currents, is the mechanism responsible for the transport and distribution of fine sediments from Cadiz Bay to the external bay and adjacent continental shelf.

The sediment transport paths have been established using the clay mineral associations obtained from R-mode and Q-mode Factor analysis and the ratios among mean mineral content.

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