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Clay minerals in recent sediments of the continental shelf and the Bay of Cádiz (SW Spain)

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ABSTRACT: The distribution of clay minerals in recent sediments on the continental shelf and in the Bay of Cádiz has been analysed as part of a wider study of sedimentary exchange between the continent and the continental margin. The clay minerals included in the muddy sediments consist mainly of illite, kaolinite, smectite, randomly mixed-layered illite-smectite, chlorite, vermiculite and randomly mixed-layered illite-chlorite. Distribution of the minerals indicates that inheritance from the adjacent continental areas is the most important process involved.

The relations between the clay minerals were established by Q-mode and R-mode factor analysis. The main clay mineral associations are: (1) illite-kaolinite, (2) smectite-random mixed-layered illite-smectite, and (3) kaolinite-random mixed-layered illite-smectite-vermiculite. The main sources of sediment supply to the continental shelf are the Guadalquivir and Guadiana rivers. Sediment from these rivers and from the rivers flowing into the Bay of Cádiz (mainly the Guadalete) is transported to the part of the shelf outside the bay by ebb-tide currents. The path of this outflow to the continental shelf, where the sediment is partially deposited, is influenced by the morphology of the coast and by hydrodynamic processes.

In most of the marine coastal regions of the world, the detrital clay associations reflect the combined influences of the petrographic nature and the climate of the adjacent continent, as well as the hydrodynamic system of the offshore waters (Chamley, 1989). In temperate zones in particular, chemical weathering is not so intense as to prevent recognition of geological sources, and yet it is sufficient to allow the mineralogical expression of pedological and erosional processes. In the coastal sediments of the North Atlantic Ocean, there is a general predominance of illite and chlorite, together with quartz and random mixed-layer clays, as well as smaller amounts of kaolinite and smectite (Windom, 1976).

The sedimentary dynamics associated with water mass movements have been well stablished on the continental shelf of the Gulf of Cádiz in the SW of the Iberian Peninsula (Madelian, 1970; Melières, 1974; Palanques *et al.*, 1987; Nelson *et al.*, 1993), but some aspects of present sediment distribution and facies in relation to hydrodynamics are poorly explained.

This paper presents the results of the mineralogical study of the clay fraction of recent sediments from the continental shelf and Bay of Cádiz (Fig. 1), the aim being to establish the distribution by area of the different components, the mineralogical associations and sources areas and their relations to hydrodynamic factors.

GEOLOGICAL SETTING

In this sector of the continental margin of the Gulf of Cádiz, the shelf and coastline are oriented NNW–SSE and stepped E–W. Both are affected

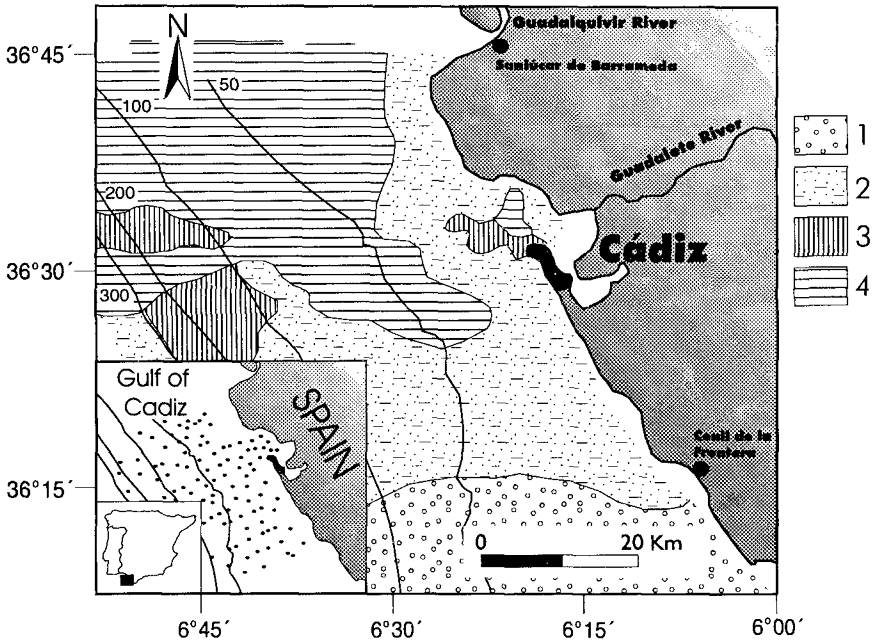

FIG. 1. Geographical setting; lithology and location of sampling on the continental shelf and Bay of Cádiz; (1) sand and gravels; (2) silty sand; (3) silty mud; and (4) clayey mud.

by different water mass movements and currents, the most important being North Atlantic Surface Water and littoral currents moving towards the SE, and Mediterranean Outflow Water moving west. Other currents are generated by SW winds and waves moving north, which affect the littoral and inner shelf.

On the northern continental shelf of the Gulf of Cádiz, sediments are siliciclastic, containing 25% of bioclastic carbonates, and facies distribution is almost parallel to the shoreline and isobaths (Segado *et al.*, 1984; Gutiérrez-Mas, 1992). Quartz is the main mineral in sandy areas (up to 85%), the feldspar content is <10% and phyllosilicate contents range from 10 to 60% (Gutiérrez-Mas *et al.*, 1995). From a granulometric point of view, three different sectors can be distinguished (Fig. 1): (a) a littoral zone of sand and silty sand; (b) a silty-clayey prodeltaic wedge extending from the mouth of the Guadalquivir river westwards to the continental slope and southwards to the Bay of Cádiz; and (c) a southern sector of gravels, sand and silty sand, between the Bay of Cádiz and Cape of Trafalgar. In addition, two sectors can be differentiated inside the Bay of Cádiz itself: an outer sector consisting mainly of sand and silt, and an inner sector consisting mainly of clayey mud.

METHODS

Samples were obtained before 1990 using a Van Veen dredge and from gravity cores from 110 sampling stations on the continental shelf and in the Bay of Cádiz (Fig. 1). Systematic granulometric and mineralogical analyses were carried out to establish facies distribution and mineralogical composition. The <2 μm fraction was separated by a standard sedimentation method (Tucker, 1988) and the mineralogical composition determined by X-ray diffraction analysis, using a Philips PW-1710 diffractometer with Cu-$K\alpha$ radiation, automatic slit and graphite monochromator. Semiquantitative clay mineralogical composition was calculated using data from Schultz (1964), Biscaye (1965) and Ortega-Huertas *et al.* (1991).

Factor analysis, in both R-mode and Q-mode, was used to establish the relation between the different clay minerals and their associations. The

factors have been selected for eigen values and eigen vectors >1, applying a Varimax rotation with 15 iterations. These techniques are used to characterize the data obtained from the analyses, thus reducing the complexity of the 'natural model' and classifying the mineralogical variables and the samples into groups (Imbrie & Van Andel, 1964; Davis, 1973; Jöreskog *et al.*, 1976; Mezzadri & Saccani, 1989; Reyment & Jöreskog, 1993).

The method by Imbrie (1963) was used for Q-mode factor analysis, which is based on the similarity matrix of the samples. The positive values of factor scores represent the composition of its mineralogical associations, while factor loadings are interpreted as the relative contribution of these associations in each sample, and are used to determine their distribution by area.

RESULTS AND DISCUSION

The most abundant clay mineral in this part of the continental shelf is illite (up to 65%), followed by kaolinite (up to 20%) and smectite (up to 25%). Other clay minerals found in lesser quantities are: random mixed-layer illite-smectite (I-S) and illite-chlorite (I-C), vermiculite and chlorite (Fig. 2). In the Bay of Cádiz, the clay fraction consists of illite (50–70%), kaolinite (10–20%), smectite (5–15%), I-S (5–15%) and traces of palygorskite in some samples.

Three factors explaining the 93% variance were obtained by Q-mode factor analysis (Fig. 3). Factor 1 (80% of the variance) represents the main clay mineral association of illite-kaolinite. The geographical distribution of this association, as established by the factor loadings, enables determination of its predominance in the area (Fig. 4). However, the high illite content does not allow observation of other interesting results and the differences between samples related to source areas and/or transport paths.

These differences were deduced from the less abundant clay minerals and their relations, as the R-mode factor analysis reveals (Table 1 and Fig. 5). In fact, factor 1 relates I-S (positive values) with illite and kaolinite (negative values), which is well

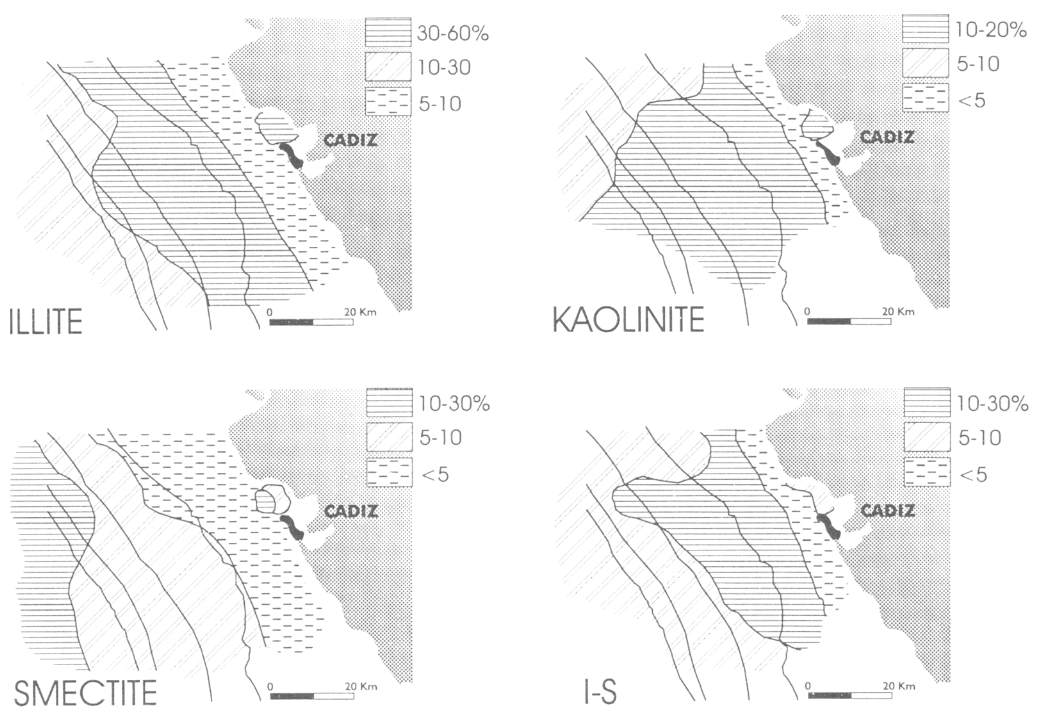

FIG. 2. Distribution patterns of the main clay minerals on the continental shelf and in the Bay of Cádiz.

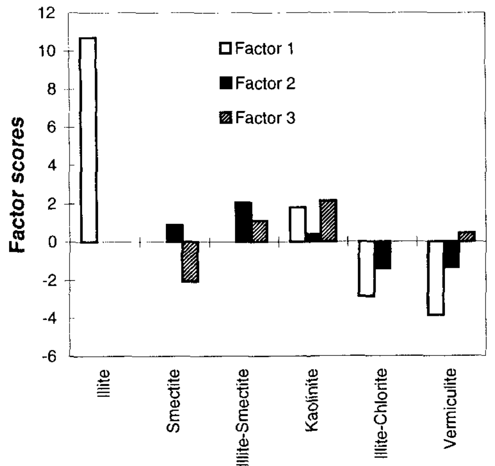

FIG. 3. Main clay mineral associations from Q-mode factor analysis. Factor 1: illite ≫ kaolinite; Factor 2: random mixed-layer illite-smectite > smectite; Factor 3: kaolinite > random mixed-layer illite-smectite > vermiculite.

represented on the continental shelf just in front of the Bay of Cádiz (positive factor scores); factor 2 relates I-C (positive values) with kaolinite, vermiculite and smectite (negative values), which is well represented in the northern sector, near the mouth of the Guadalquivir River; and factor 3 relates vermiculite, illite and I-S (positive values) with smectite (negative values) and it is present at specific locations.

If the previous mineralogical results from Gutiérrez-Mas (1992) are considered, along with the clay mineral associations determined in this study and the siliciclastic character of the sediments, inheritance is probably the main sedimentation mechanism, this being controlled by the petrography of the source areas, by climate and by the hydrodynamic system. Two aspects must therefore be examined, one concerning sedimentation mechanisms and source areas, the other regarding the dynamics of sedimentation.

The clay mineral associations found in this study are similar to those of North Atlantic Ocean sediments, in which there is a predominance of illite and chlorite, together with quartz and random mixed-layer minerals, whereas kaolinite and smectite are only found in small proportions (Windom, 1976).

In nearby continental areas, the clay mineral associations are: smectite > illite > kaolinite for the Neogene-Pliocene (Viguier, 1974) and illite > kaolinite > smectite for Pliocene-Quaternary (Mabesoone, 1963; Zazo, 1980). These authors located the source areas in Sierra Morena (Iberian Massif), located to the N and NW of the Guadalquivir river, and in the Betic Cordillera, located to the E and NE of the Guadalete river. The differences between the clay mineral associations found by these authors and those described in this paper can be explained because they do not distinguish between smectite and I-S and because illite and smectite behave differently in marine environments, with important differences in settling processes (Chamley, 1971; Roux & Vernier, 1977) which produce an increase of expandable minerals with increasing distance from the shore.

As regards the dynamics, three different sectors have already been established on the continental shelf (Gutiérrez-Mas, 1992): (a) a northern sector consisting mainly of mud supplied by the Guadalquivir river and extending west and south-

TABLE 1. Factor loadings of the clay minerals, R-mode factor analysis.

Minerals	Factor 1	Factor 2	Factor 3
Illite	−0.8		0.3
Smectite		−0.4	−0.8
Illite-smectite	0.9		0.5
Kaolinite	−0.7	−0.6	
Illite-chlorite		0.9	
Vermiculite		−0.4	0.9
% explained variance	35	28	21

Values <0.25 are excluded.

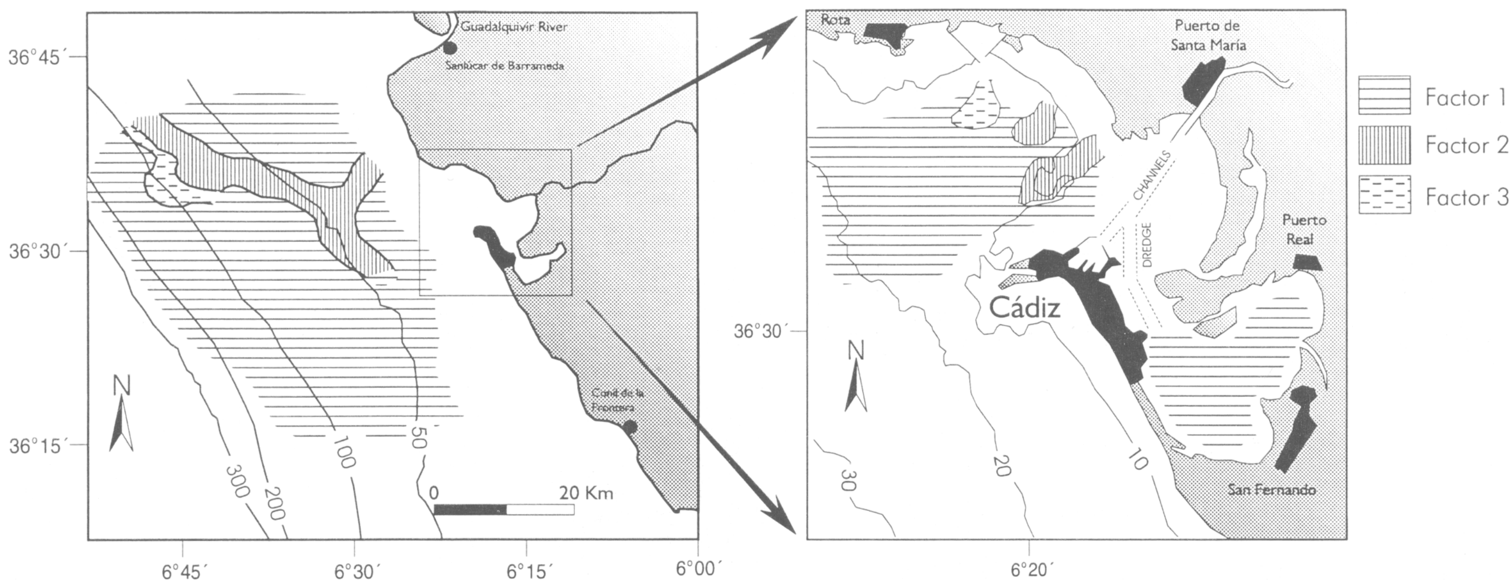

FIG. 4. Geographical distribution of the clay mineral associations on the continental shelf and the Bay of Cádiz from the Q-mode factor analysis. (1) Factor 1 (illite ≫ kaolinite); (2) Factor 2 (random mixed-layer illite-smectite > smectite) and (3) Factor 3 (kaolinite > randomly mixed-layer illite-smectite > vermiculite).

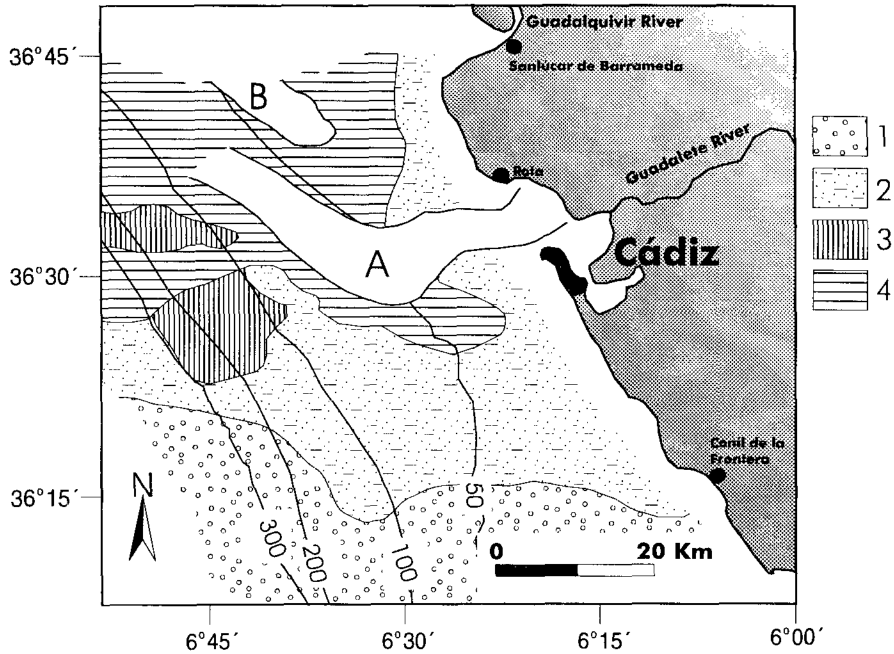

FIG. 5. The transport path model on the continental shelf derived from the R-mode factor analysis of the clay mineral relations. (A) Factor 1: random mixed-layer illite-smectite; (B) Factor 2: random mixed-layer illite-chlorite. 1: sand and gravels; 2: silty sand; 3: silty mud; and 4: clayey mud.

east; (b) a central sector outside the Bay of Cádiz that partially is supplied by the Guadalquivir river and partially by input from the Bay itself by the action of ebb-tide currents; and (c) a southern sector consisting mainly of sand and gravels, where the sedimentation rate is low due to lack of fluvial supply. In addition, the Bay of Cádiz itself is an additional sector with a outer zone of sand and another inner zone of mud.

Previous descriptions of the sedimentary pattern consider that the prodelta of muddy sediments on the continental shelf originates from the mouth of the Guadalquivir river and are transported southeast by North Atlantic Surface Water and littoral currents, whereas the muddy sediments originating from the rivers flowing into the Bay of Cádiz (mainly the Guadalete river) are deposited there with no further transport (Madelian, 1970; Melières, 1974; Segado *et al.*, 1984; Palanques *et al.*, 1987; Ojeda, 1989; Gutiérrez-Mas, 1992; Nelson *et al.*, 1993). Some authors have mentioned the existence of opposite flows and presume the presence of littoral currents flowing west and northwest (Bernal, 1986; Guillemot, 1987; Gutiérrez-Mas, 1992).

In this paper, we establish the sediment transport trajectory using clay mineral relations as determined by R-mode factor analysis. Factor 1 indicates that illite has been partially substituted in the sediment by I-S (positive factor scores in the continental shelf), which suggests a transport trajectory out from the Bay of Cádiz towards the continental shelf (Fig. 5). Factor 2, which is well represented near the mouth of the Guadalquivir river, indicates a transport trajectory of sediments south from the mouth of the Guadalquivir. These two transport trajectories converge in the sea off the Bay of Cádiz and the sedimentary deposits show the supply mixture from the two source areas.

The outflow from the Bay of Cádiz begins in the surface waters of the inner part of this bay when the prevailing wind and waves come from the south and east. The sediments are transported towards the external zone by ebb-tide currents and are partially deposited on reaching deeper waters (Fig. 6).

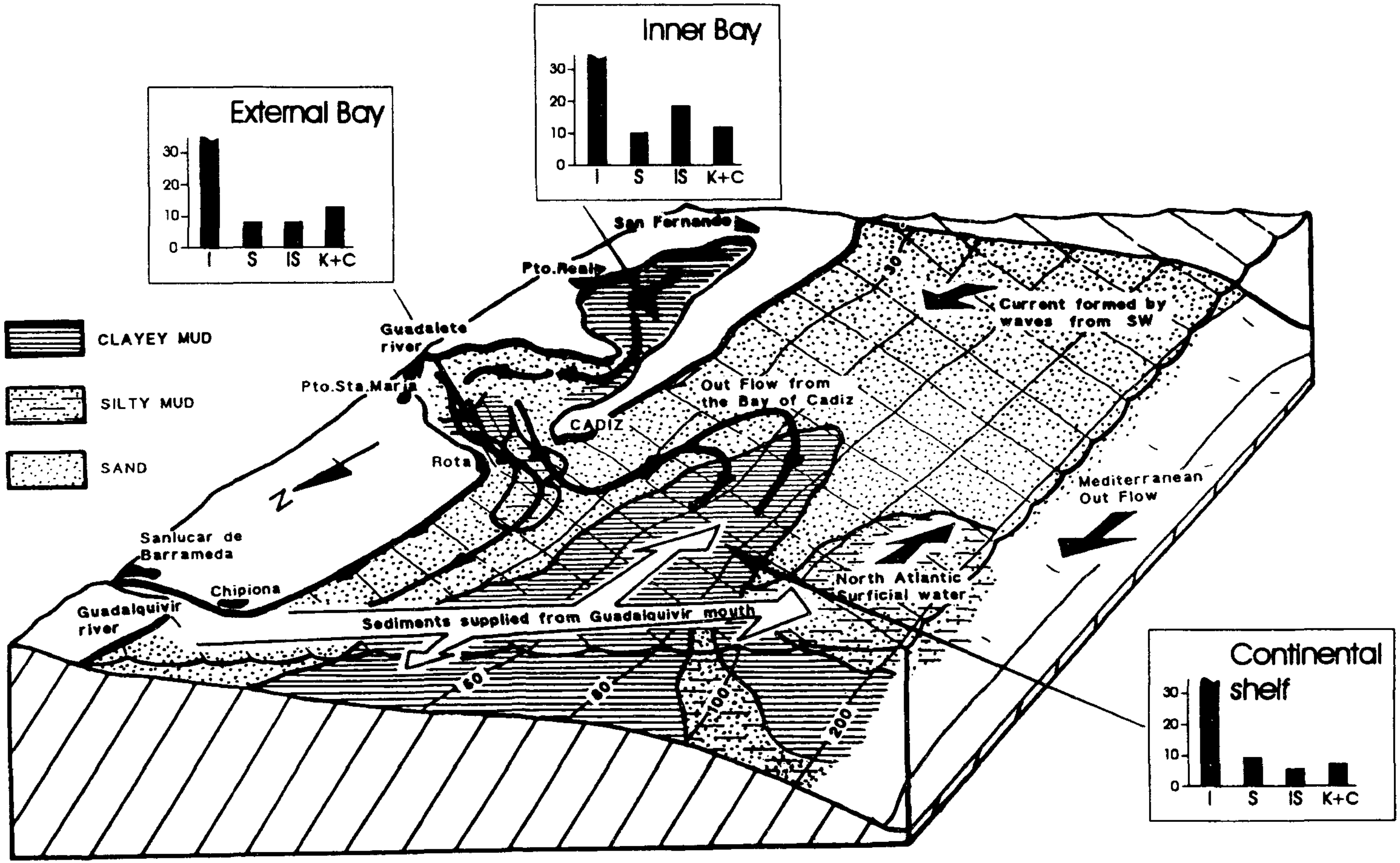

FIG. 6. Sketch showing the hydrodynamic conditions influencing the outflow from the Bay of Cádiz towards the continental shelf. I: illite; S: smectite; IS: mixed-layer illite-smectite; K+C: kaolinite and chlorite.

Several sea-bed bottom shapes in the western part of the Bay of Cádiz have been identified and associated with the effects of tidal currents. Satellite images show that water with suspended particulate matter flows out beyond the limits of the Bay under conditions of easterly winds and/or ebb-tide currents (Guillemot, 1987). One branch of the current flows northwards along the eastern edge of the Bay and then turns west, under the influence of the morphology of the bottom and the coastline, leaving a muddy trail until it reaches the continental shelf.

This flow is affected by several factors: (a) ebb-tide currents capable of moving sediments seawards; (b) aeolian action, mainly due to easterly and southerly winds blowing from the continent, which also generate a surface current of water moving westwards, thus reinforcing the ebb tide; and (c) waves from southwest, which oppose this flow and divert it towards the north and northwest (Fig. 6).

CONCLUSIONS

The clay minerals present in recent sediments on the continental shelf consist mainly of illite, kaolinite, smectite and I-S and, occasionally, chlorite, vermiculite, palygorskite and I-C. The presence and distribution of these minerals indicate that the most important process in this area is detrital supply from adjacent continental areas. Q-mode factor analysis indicates illite-kaolinite is the main clay mineral association and identifies its distribution area on the continental shelf.

Facies distribution is influenced by the hydrodynamic system and fluvial supplies mainly from the Guadalquivir river, the main source areas being Sierra Morena (Iberian Massif) and the Betic Cordillera. The muddy sediments deposited on the continental shelf outside the Bay of Cádiz originate in similar proportions from the Guadalquivir river and the Bay itself.

The transport path model is determined by means of the clay minerals relations established by R-mode factor analysis. This analysis confirms that illite is gradually substituted by I-S along the flow path to the continental shelf.

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