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# Multicycle sediments on the continental shelf of Cadiz (SW Spain)

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**Abstract**

The study of recent sedimentation in the Gulf of Cadiz continental shelf (SW Europe) is of interest due to its proximity to the Strait of Gibraltar, where the Atlantic and Mediterranean waters are interchanged and the Western Mediterranean Alpidic Orogen closes through the Gibraltar Arch. The existence of relict materials hinders the distinction of the past and present hydrodynamic regimes in present day sediments. An adequate combination of techniques has allowed the establishment of the multicyclic character of the sediments, as well as the stages undergone by the terrigenous grains. Different stages were identified: eolian and energetic fluvial provenance, chemical alterations acquired in a pedological environment, and a marine coastal origin.

To verify the source areas, textural and mineralogical features of marine sediments were compared with those found in geological units from fluvial basins. Three zones were differentiated: (a) a sandy littoral, which receives local sediment supplies; (b) a clayey zone between the Guadalquivir River and Cadiz, controlled by contributions from this river provenant of the Iberian Massif and Betic Mountain range; and (c) a sandy continental shelf, between Cadiz and the Cape of Trafalgar, with a low rate of supplies coming from the Guadalete and Barbate rivers, which include materials from the Occidental Betic Mountain range and Neogene units.


*Keywords:* marine sediments; continental shelf; quartzose sands; multicyclic sands; Gulf of Cadiz

## 1. Introduction

The importance of the oceanographic literature and marine geological studies on the Gulf of Cadiz continental margin (SW Europe) emanates of its proximity to the Strait of Gibraltar, a point of singular geographic interest, being it the place where the Atlantic Ocean and Mediterranean Sea interchange their water masses and where the Western Mediterranean Alpidic Orogen (Betic and Rif Mountain range) meet through the Gibraltar Tectonic Arch. Therefore, this zone has been object of numerous studies, some of them related with the influence of Atlantic and Mediterranean flows on the sea bed (Baraza & Nelson, 1995; Grousset et al., 1988; Heezen & Johnson, 1969; Kenyon & Belderson, 1973; Maldonado, 1992; Maldonado & Nelson, 1988; Melieres, 1974; Nelson et al., 1999), and also those studies related with the sedimentary facies distribution and sediment source areas (Gutiérrez-Mas, Domínguez, & López, 1994; Gutiérrez-Mas, Hernández, & López, 1996; Gutiérrez-Mas, López, & López, 1997; Gutiérrez-Mas et al., 1999; López, Rodero, & Maldonado, 1999).

These studies have discussed diverse themes. Nevertheless, there are some details, which still have not been exposed by previous works, as the study of the dissimilarities among the sediments on the continental shelf, which are essential data for the differentiation of the deposits formed under diverse hydrodynamic conditions and sea level situations. The coexistence on the continental shelf of relict, palimpsests and present sediment makes it very difficult to distinguish those sediments deposited as a consequence of the current hydrodynamic regime from those, which were deposited when the sea level was in different stages. The matter is even more complicated when the sediments come from several source areas.

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A selective sediment sampling and an adequate combination of sedimentological techniques, such as textural and compositional feature analysis, in combination with the exhaustive study of the marine sediments and continental basins, have allowed for the contribution of ideas and methods to clarify the character, origin and disposition of the recent marine sediments in a sector of the Gulf of Cadiz continental shelf between the Guadalquivir river mouth and the Cape of Trafalgar.

Several criteria have been established for the identification and diagnosis of the marine siliciclastic sediments. The textural features of Holocene grains have been compared with the textures present in siliciclastic grains found in diverse geological units present in nearby fluvial basins. The comparative study has permitted further knowledge of the source areas and sediment transport paths, hitherto not proved. The dominant mineralogical assemblages have been established for each sediment fraction, sedimentary dynamic and processes that act in the depositional environments, as well as factors of prominence in the study of the sedimentary transference between the continent and oceanic zones.

### *1.1. Geographic and geological characteristics of the studied zone*

The study area is located in the Gulf of Cadiz (SW Spain), near the Strait of Gibraltar (Fig. 1), between the Guadalquivir River mouth and the Cape of Trafalgar. The continental shelf has an average width of 40 km, the slope dropping away sharply from a depth of between 150 and 200 m. Different geological formations are present in the neighboring continental areas: northward and northeast, the Paleozoic Iberian Massif and the Mesozoic sedimentary formations from the Betic Mountain range are to be found. Other units present are Postorogenic sedimentary formations from the Guadalquivir Basin.

The coast line is orientated from NNW to SSE, with E–W sections, having a stepped aspect (Fig. 1) as a result of old and recent fractures (Baldy et al., 1977; Sanz de Galdeano, 1990). The sea bed physiography shows a strong concordance with the shoreline, the isobaths being parallel to the coast. The northern coastal area is flat and sandy, while the southern one, between Cadiz bay and Cape of Trafalgar, is more abrupt and cliffy (Gutiérrez-Mas, Martín, Domínguez Bella, & Moral Cardona, 1990). The submarine pre-Holocene materials belong to the upper Miocene, Plio-Quaternary and Mesozoic formations. The fluvial sources to the continental shelf and littoral zones are the rivers that drain the Atlantic margin of Andalucia such as, Guadiana, Odiel and Tinto and Guadalquivir by the North and Guadalete and Barbate Rivers by the South.

### *1.2. Hydrodynamic regime*

The hydrodynamic regime is controlled by the *North Atlantic surface water* current, which sweeps cross the shelf towards the SE and is responsible of the distribution of fine sediments supplied by the main rivers (Grousset et al., 1988; Gutiérrez-Mas et al., 1994;

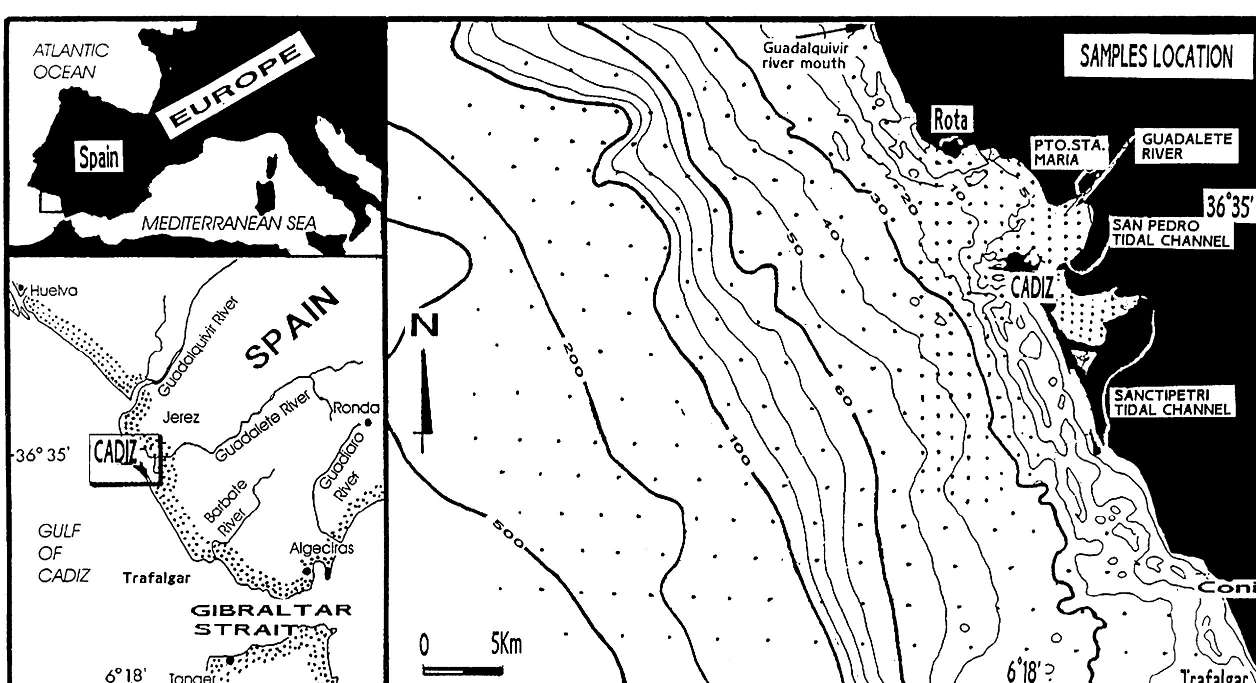


Fig. 1. Geographic situation of the study zone with depth (in m), and location of the samples.

Melieres, 1974). *Mediterranean outflow water* does not influence the present day sedimentary activity in this sector, because it runs in deeper water, as evidenced from temperature and salinity data (Baringer & Orice, 1999; Shull & Bray, 1989). The main littoral current flows toward SE, as a consequence of the coastal configuration, with the littoral facing towards the West and SW storms direction. Nevertheless, there are currents towards the North and NW with winds and waves from the South and SE. During the biggest storms, strong bottom relaxation currents are generated seaward, which carry sediments from the beach shore to deeper zones where the return to the active beach zone is inhibited.

Wind and waves are essential factors of 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 mean frequency of sea waves is 6.96 and 10.26% for swell waves (MOPT, 1992).

The tidal regime is mesotidal, ranging from 1.58 to 3.7 m. The mean tidal range is 2.39 m and the mean spring tidal range is 3.71 m. Tidal action is significant in certain distinct physiographical zones, like the bay of Cadiz, where tidal currents are responsible for the fine sediment transport from inner zones toward the external bay and continental shelf. The combinated effect of tides and waves is very outstanding on the shallow areas when storms coincide with spring tides and this coincidence occurs at an average of 26 times/year (Gutiérrez-Mas, personal communication).

## 2. Methods

A total of 400 sediment samples were extracted and collected from different sectors of the continental shelf, in a zone between the Guadalquivir River mouth and Cape of Trafalgar, through piston core and van veen drag. Samplings were also carried out to recognize the continental areas close to the study zone. The extraction of water and suspension matter was executed to specific depths with oceanographic bottles, for recognition and singling out the fine sediment paths. The sampling stations were allocated in zones where the concentration of suspension matter was highest, such as the tidal channel and river mouths. The sample position was determined by Differential Global Position System (DGPS) and errors made in the horizontal DGPS positioning were verified as being less than 2 m.

After the samples were collected, they were classified and transported to the Sedimentology Laboratory of Marine Sciences Faculty of the University of Cadiz for its detailed analysis. The grain size analysis was carried out by sieving and, afterwards by the use of a laser diffraction analyzer. The granulometric characteristics were studied and the statistic indexes and parameters were calculated. The grain size distribution of sediments was used to describe the sedimentary facies and to relate their physical properties with the marine dynamics. The mineralogical composition was studied by X-ray powder diffraction (XRD). Several fractions were taken into account. The heavy mineral fraction was separated by dense liquids and examined under a polarizing microscope. The grains were counted by thin sections using the Ribbon method (Moral, Gutiérrez-Mas, Sánchez, López, & Caballero, 1997).

Textural analysis of surface features of the quartz grains was performed with a JEOL SEM. The identified surface features were classified into distinct types, using a combination of terminologies from the works of Margolis and Krinsley (1974), Higgs (1979), and Cater (1984). Statistical analysis of data was carried out using the BMDP program. Multivariate factor analysis was used for the establishment of mineral assemblages and to know the distribution of the changes among these associations.

## 3. Results and discussion

### 3.1. Sedimentary facies distribution and depositional regimen

As far as the sediment types point of view is concerned, the sea beds of the Cadiz Bay and adjacent continental shelf are siliciclastic, with only 25% of bioclastic carbonates. Taking into account the process by which the sediments have been incorporated into the continental shelf deposits, the study area can be divided into three specific sectors, in accordance with the sedimentary facies area distribution (Fig. 2).

A sandy and gravel like coastal area, intercepted by small cliffs and bays. This zone is submitted to strong erosive action, caused by stormy weather, waves and littoral currents, being that the sediments are transported toward deeper zones, including to the continental shelf (Fig. 2).

A muddy zone situated in the northern and central sectors of the study area, between the Guadalquivir River mouth and Cadiz Bay (Fig. 2). These muddy sediments are injected by the Guadiana and Guadalquivir River mouths situated northward and deposited in low-energy environments such as a submarine prodelta, characterized by the presence of constructive facies in a sedimentary regime controlled by a high rate of supplies.

Another zone, located between Cadiz Bay and the Cape of Trafalgar, is characterized by the presence of

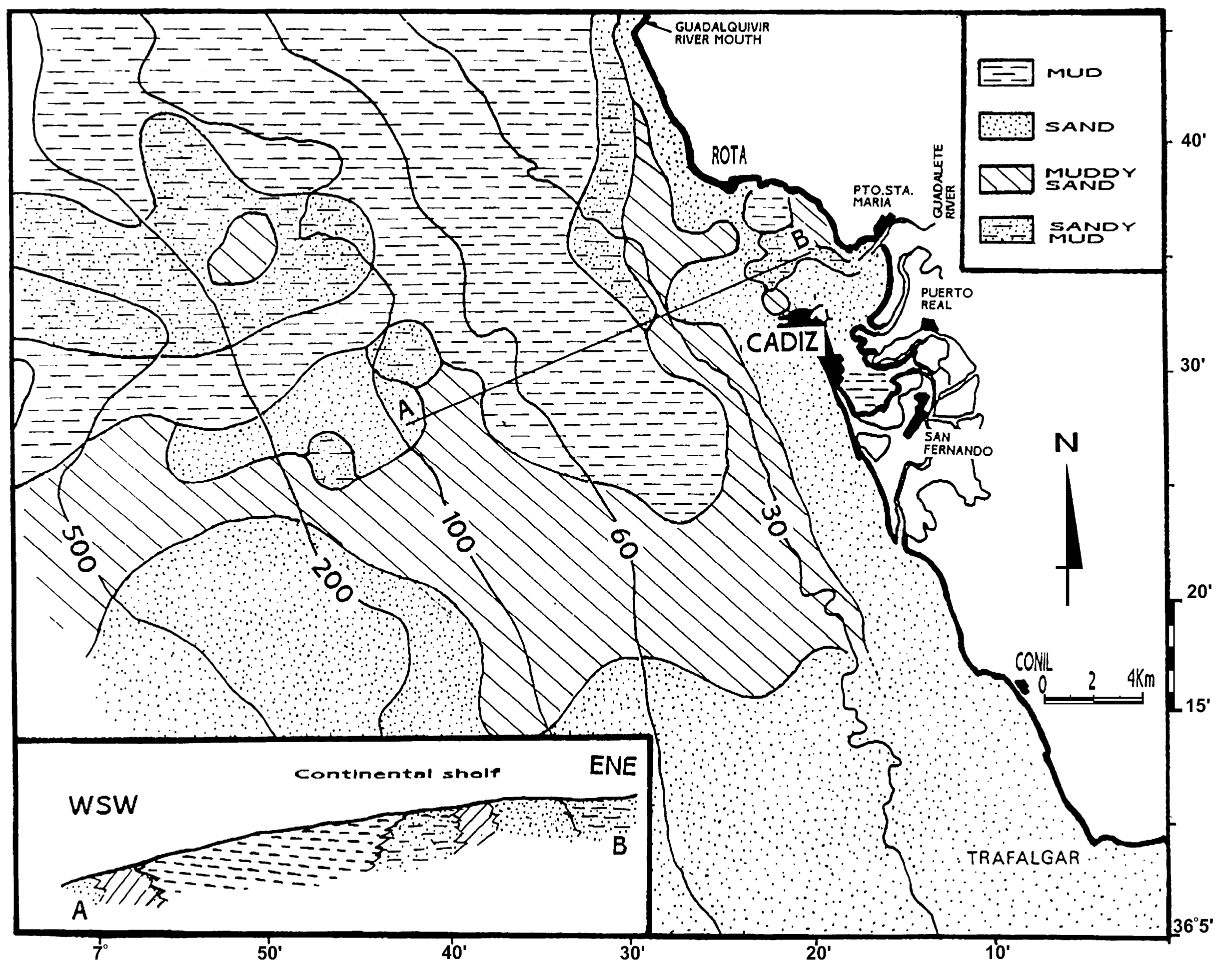


Fig. 2. Sediment distribution on the continental shelf of Cadiz and facies cross section deduced from piston core samples. Depth in m.

bioclastic quartzose sands (Fig. 2). Granulometric analysis shows that these quartzose sands are associated to the energetic media, such as littoral environments affected by waves, although at the present moment they are found in the depths of the continental shelf, due to recent sea level changes. Fluvial supplies are very limited and the rivers release relatively little sediment, being the depositional regime controlled by erosion and transport.

### 3.2. Mineralogical content and assemblages

The mineralogical analysis shows that the main component of the terrigenous sediment is quartz. This predominant mineral accounting for 50% on average and up to a maximum of 80% in sandy zones, while in the muddy zones, as that of the Guadalquivir River mouth, it does not reach 20%. In the sandy fraction, quartz is accumulated in very fine, fine and medium grain sizes, while coarse and very coarse sands are constituted mainly of calcareous shell fragments. Feldspars are sparse, appearing with an average content of 5%, fact that denotes the mineralogical mature character of these sediments, especially in quartzose sands.

Among the carbonate minerals, calcite is the predominant one. It is of biogenic origin and no crystals of inorganic calcite were observed. The maximum content in the sediment of continental shelf is of 30% and the average content 20%. Dolomite is present in concentrations of less than 5%, and aragonite scarcely appears at all. The bioclastic components are mainly constituted of highly fragmented molluscs, which are especially concentrated in coarse and very coarse sand sizes. Among the foraminifers, benthonic species predominate over planktonic forms; other calcareous biota include ostracods, bryozoans, echinoderms, corals, and sponge spicules.

Phyllosilicates are dominant in muddy sediments, with contents greater than 20%. Among the clays, illite is predominant (>50%), followed by kaolinite (10%), smectite (10–15%) and then illite-smectite and illite-chlorite mixed layer clays (<5%). The dominant mineralogical association defined in this fraction is: illite–kaolinite–smectite ($I \gg K > Sm$), which is similar to that found by other authors (Gutiérrez-Mas et al., 1997; Viguier, 1974) in Neogene outcrops which are present in continental areas close to the coast. The results provide evidence that a great mineralogical homogenization exists in this zone, resulting from the continuous sedimentary exchange and hydrodynamic action.

Measurements of suspended matter concentration show an average dry weight content of 6.5 mg/l. The lowest values (down to 1.37 mg/l) were found at the most distant zone from the coast and at the greatest depth of the continental shelf. The highest values (up to 14 mg/l) were found in the Bay of Cadiz. Analysis of the mineralogical composition of suspended matter shows that the most abundant clay mineral is illite (40%) and smectite (39%), followed by kaolinite (10–15%), chlorite (5–10%) and illite-smectite mixed layers (6%). These data indicate that the distribution of clay minerals is similar in all the sedimentary environments present in the zone, from Cadiz Bay to the continental shelf edge.

The heavy fraction in the sediments was never more than 5%. The highest values correspond to sublittoral sandy areas and its distribution shows great differences between the northerly and southern sectors, with a predominance of ultrastable minerals in the southern sector. This is due to the fact that reworking processes are more frequent in this zone, with the consistent progressive selection of minerals, in accordance with the most mature character of these sediments with respect to those found in the northerly zone. The ultrastable heavy minerals appear predominantly in the sandy areas, whereas in muddy zones the metastable are predominant. The heavy mineral association deduced is: epidote–garnet–rutile (Ep > G > Rut), in great part, similar to that found by other authors in the close continental areas (Mabesoone, 1963; Mabessone, 1966; Moral et al., 1997; Viguier, 1974).

### 3.3. Morphology and surface features of siliciclastic grains

The study of the morphology and surface features of siliciclastic grains, quartz and heavy minerals, has allowed for detection of mechanical and chemical textures and marks generated as a consequence of sedimentary processes undergone by sediments during different stages and geological cycles of erosion, transport and deposit, originating from the primitive source areas to their layout on the continental shelf. Diverse morphologies have been noted in the quartz grains.

#### 3.3.1. Mechanical textures

Mechanical textures are conchoidal fractures, arcuate steps, mechanical V's (features of abrasive subaqueous actions), linear or curved grooves and upturned plates. The conchoidal fractures may be angular or polished. In the latter case, reworking in the form of both mechanical and chemical textures may be shown. Conchoidal fractures are the most commonly found feature and differ in their sizes and degrees of development; in some cases they affect the greater part of the grain surface (Fig. 3a–d).

#### 3.3.2. Chemical textures

Chemical textures are oriented etch pits, solution pits, silica globules, and silica pellicles. The oriented etch pits and solution pits seem to overprint older mechanical marks, often widening them (Fig. 4c). Chemical precipitation in the form of *silica globules* and *pellicles* is found inside *solution cavities* (Fig. 4d).

In the group of heavy minerals, the following morphologies have been observed: idiomorphic grains (especially minerals as tourmaline, zircon, and epidote) and subidiomorphic and xenomorphic grains as epidote, zircon garnet, tourmaline and andalucite. The xenomorphic form appeared may be due to fracturing or rounding of the idiomorphic and subidiomorphic grains.

### 3.4. Sedimentary stages and cycles

If the surface features present in quartz grains are considered, a sequence of differentiated processes and stages can be described on the strength of the association and juxtaposition of textures (Table 1):

1. The oldest phase is represented by the upturned plates which occur on the primitive surface of some quartz grains from the inner continental shelf, more frequently near the coast than further out. Despite being present on quartz grains of current marine sediments. This feature has been cited as being indicative of an eolian environment (Margolis & Krinsley, 1974) and appear together with *curved grooves* which clearly indicate an eolian origin (Fig. 3d).
2. A second stage is defined in association with the mechanical features (conchoidal fractures and arcuate steps) attributed to very energetic aqueous environments (littoral and fluvial). These appear more frequently in sediments found on shallow seafloors (<30 m), although their presence is also notable on the shelf and upper continental slope.
3. The third stage is represented by an assemblage of surface features consisting of mechanical V's and grooves. Numerous papers refer to these features as the result of subaqueous abrasive action typical of fluvial media (Higgs, 1979; Krinsley & Donahue, 1968; Krinsley & Margolis, 1969). The mechanical V's are infrequent and appear in samples collected in shallow areas in the Cadiz continental shelf and the upper slope, being absent from the shelf itself. The grooves are present in different proportions and in all the sectors.
4. A fourth stage is characterized by chemical features, developed in littoral sediments and from the continental shelf. It is represented by two types of features: solution textures (oriented etch pits,

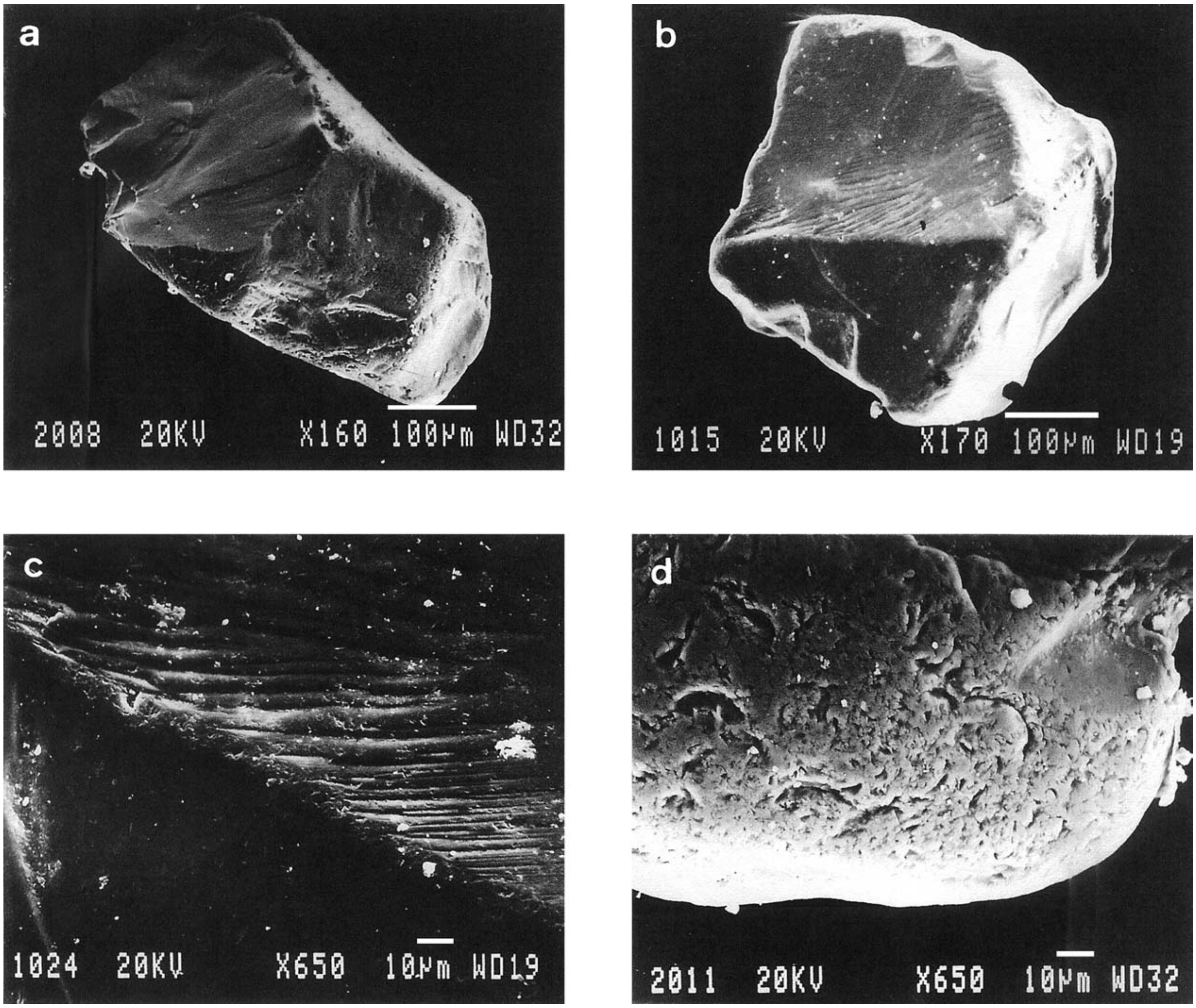


Fig. 3. Quartz grain surface features (Scanning Electron Micrographs, SEM). (a) Angular conchoidal fracture. (b) Conchoidal fractures and arcuate steps. (c) Magnification of a grain showing a conchoidal fracture and arcuate steps bearing mechanical Vs. (d) Curved grooves of eolian origin.

solution pits and hollows) and, less frequently, by precipitation textures (silica globules and pellicles). See Fig. 4b–d.

5. The most recent stage of textural evolution corresponds to the presence of conchoidal fractures caused in periods of high mechanical energy, such as the occurrence of transport to the coast by torrential rivers and later coastal erosion. Other grains show sharp conchoidal fractures affected by solution hollows, which are interpreted as older coastal deposits currently reworked below sea level.

These data indicate a multicyclic character and a high textural and mineralogical maturity of the recent sediments present on the continental shelf of Cadiz (Moral et al., 1997). The data exhibit a long history of mechanical and chemical processes, generated during several stages and at different depositional environments. In relation with the textural characteristics (Table 2) of the heavy fraction minerals, the data are indicating the coexistence of idiomorphic, subidiomorphic and xenomorphic grains, and the predominance of ultrastable minerals, particularly in sandy zones, which is a further indication of a high degree of reworking of these sediments.

### 3.5. Source areas and sediment transport paths

Facies and minerals distribution of the marine sediments point to sicliciclastic continental source areas, as may be metamorphic and igneous rocks, but the presence of policyclic terrigenous grains and the preponderance of ultrastable heavy minerals in numerous zones denotes a clear origin from detritic materials. Through regional geology data of continental zones close to the study area, it has been deduced that the continental shelf of Cadiz receives supplies from different areas of Andalucia and Iberian Peninsula (Figs. 5–7), as is demonstrated through the assemblages of heavy minerals and clay minerals found in sediments on the shelf

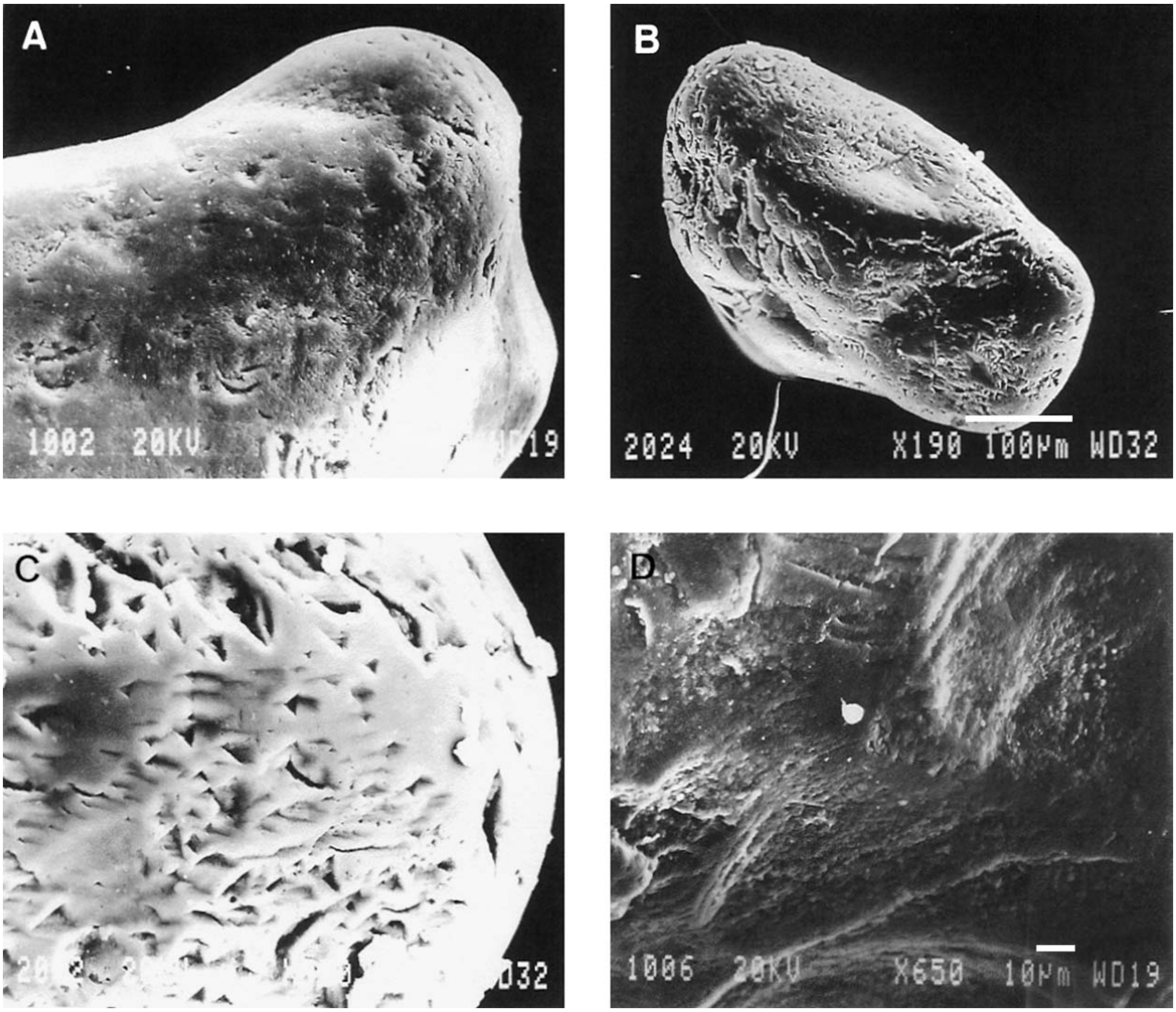


Fig. 4. Quartz grain surface features from SEM. (a) Generalized polished surface. Note ancient mechanical marks widened by dissolution. (b) Rounded quartz grain showing old mechanical marks (grooves) and oriented etch pits. (c) Close-up of a grain showing oriented etch pits and grooves widened by solution. (d) Detail of silica deposits on a quartz grain.

and continental outcrops (Gutiérrez-Mas et al., 1994; Mabesoone, 1963; Mabessone, 1966; Viguier, 1974). Clay minerals present in marine sediments indicate that inheritance from the adjacent continental areas is the most important process involved, being the Guadiana and Guadalquivir Rivers the main sources of suspension particles (Gutiérrez-Mas et al., 1997).

In the northern sector, the sedimentary supplies are provided by the Guadiana, Odiel-Tinto and Guadalquivir Rivers, which supply sediments from Sierra Morena (Iberian Massif). These sediments are mostly of first-cycle and present unmature grains provenant from igneous and metamorphic rocky areas. The Guadalquivir River also drains metamorphic and sedimentary regions of the Betic Mountain range and Postorogenic Neogene sedimentary materials (Late Miocene and Pliocene) (Melieres, 1974; Viguier, 1974), whose mineral grains present a high degree of maturity.

Other sediment sources are the Guadalete River, whose mouth is situated in the inside of Cadiz Bay, and the Barbate River, located at south of the study zone. These rivers inject sediments provenant from the erosion of Preorogenic outcrops of the Betic Mountain range, as the Aquitanian Numidic sandstone (Aljibe Sandstone), present in nearby continental areas (Gutiérrez-Mas et al., 1990; Fig. 7), constituted by silica sandstone (>90% quartz) initially deposited in deeper marine environment as turbidity currents. This sandstone contains very well rounded quartz grains, whose origin is attributed to succeeding sedimentary processes, which have given way to a very characteristic mature grain.

Other sources of mature grains are the Postorogenic Neogene units from Late Miocene and Plio-Pleistocene calcarenites in the middle and lower Guadalete basin, and which are transported to the continental shelf by this river. These grains have also been found in the

Table 1
Sedimentary facies present on the continental shelf of Cadiz

| Environments | Depth (m) | Granulometry | Mineral and biogenic components |
|---|---|---|---|
| Littoral zone | 0–15 | 1) Sand | Quartz (50–80%) and bioclastic carbonates (20%) |
| Transition between littoral and continental shelf in front of Cadiz Bay | 10–30 | 2) Sandy mud | Phyllosilicates and quartz |
| Continental shelf between Guadalquivir River mouth and Cadiz Bay | 25–200 | 4) Clay | Phyllosilicates: illite (>50%), kaolinite (10%), smectite (10–15%), illite-smectite and illite-chlorite mixed layers (<5%) |
| Continental shelf between Cadiz Bay and Cape of Trafalgar | 25–200 | 3) Muddy sand | Quartz and phyllosilicates |
| | 25–200 | 1) Sand | Quartz (50–80%) and bioclastic carbonates (20%) |

Depositional environments and granulometric and mineral components (See map Fig. 2).

Plio-Quaternary quartziferous sands present in fluvial terraces, glacis and alluvial fans from the basin of the Guadalete River. These data coincide with the heavy mineral distribution in the area, which present differences between the northerly and southern zones, with a predominance of ultrastable minerals in the southern sandy sector, according to the most mature character of the sediments, in comparison of northerly areas where the metastable minerals are predominant. The first have suffered several sedimentary cycles and stages and they have similar features to those present in some detritic outcrops from continental areas near the continental shelf of Cadiz.

### 3.6. Sedimentary dynamics

Recent marine sediments on the continental shelf of Cadiz are a blend of relict sediments, formed in low sea level stages, and contemporary sediments. In the last case, the granulometric character, sedimentary structures and general layout are in direct concordance with the depth, distance to the coast and situation with respect to the source areas. Besides this, the study zone presents a differential sedimentation rate between the northern and southern sectors, due to the existence of the main fluvial system in northerly zone, while in that in southern sector the fluvial supplies are few.

The sediments close to Guadalquivir River mouth are basically clay and mud, deposited under a depositional regime dominated by the supplies. These supplies bury the pre-existent sediments and do not allow the reworking of facies, nor mineralogical and textural alterations, yielding sediment with a low maturity and predominance of idiomorphic grains and relative abundance of mineral phases. Southward, between Cadiz and the Cape of Trafalgar, the deposition rate is low, because the sediment size is smaller. The fluvial supplies from the Guadalete and Barbate Rivers and the quartzose sands present a high textural and mineralogical maturity.

The physiography of continental margin, with orientation from NW to SE, condition the direction of the currents and situation of river mouths. The main current is the North Atlantic surface water, responsible for the prograding of the muddy prodeltaic deposits over the older sands present in the south sector. Others currents, derived from surge and tides are prominent in littoral areas where the influence of the Atlantic flow is small and the sedimentation is controlled by local factors. From temperature and salinity data it is deduced that the Mediterranean outflow does not influence the present day activity in the study sector, since it runs in deeper waters. The distribution of the more significant heavy minerals in sediments of the continental

Table 2
Textural features and stages differentiated in quartz grains on sediments of the Cadiz Gulf continental shelf

| | | Source areas | | | |
|---|---|---|---|---|---|
| Stage | Surface features | Continental geological units | Lithology | Depositional environment | Age |
| 1 | Upturned plates | Betic Mountain ridge | Aljibe sandstones | Eolian and submarine fans | Early-middle Miocene |
| 2 | Conchoidal fractures Arquate steps | Guadalquivir Basin | Calcarenites | Coastal | Late Miocene |
| 3 | Mechanical V's grooves | Fluvial terraces Aluvial fans Guadalete Basin | Sandstones and conglomerates | Fluvial | Plio-Quaternary |
| 4 | Oriented etch pits Solution pits silica deposits | Guadalete Basin Fluvial terraces Aluvial fans | Sandstones and conglomerates | Fluvial and Pedologic | Plio-Quaternary |
| 5 | Conchoidal fractures | Current marine sediments | Sand and mud | Coastal and neritic | Quaternary (Holocene) |

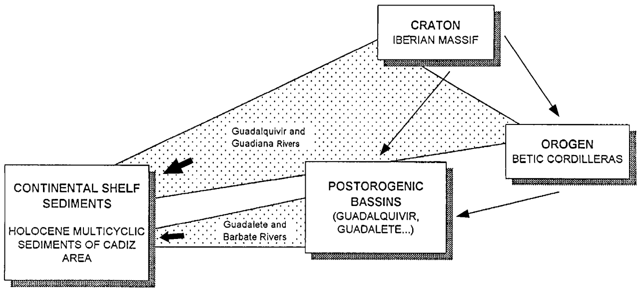


Fig. 5. Schematic geological map showing the main sedimentary supplies sources to the continental shelf of Gulf of Cadiz and the transport paths.

slope bottom shows that they follow the path of Mediterranean flow (Gutiérrez-Mas et al., 1994; Melieres, 1974), and their contents are clearly discordant with those existing on the continental shelf. Other previous descriptions consider this same transport model (Gutierrez-Mas et al., 1996, 1997; López et al., 1999; Melieres, 1974; Nelson et al., 1999).

The North Atlantic surface water flow is responsible for the transport of a large volume of sediments from the Guadiana and Guadalquivir Rivers toward the SE, along the continental shelf, but other currents, such as those derived from surge and tides, are prominent in littoral areas, where the influence of the Atlantic flow is minor. These flows control the sediment transport toward the inner continental shelf and they are very effective near the Cadiz Bay.

The determination of the flow routes and the establishment of the sediment transport paths has been possible through the observation of small local variations of mineral associations used as natural tracers. To achieve this, factor analysis was applied to clay mineral data. The first and most significant factor found associates illite, kaolonite and smectite ($I \gg K > Sm$). This association complies with the dominant clay mineral assemblage in the zone. This factor is well represented on the continental shelf (Fig. 7). A second factor associates the interstratified mineral illite–smectite and illite, and is significant in the Bay of Cadiz continental shelf.

The cartographic score values of the first factor (Fig. 7) indicate that highest scores are present on the largest area of the continental shelf floor. The lower score values appear oriented in perpendicular bands to the coast line, running from Cadiz Bay out to the continental shelf. Sediment transport paths are reached by the factor score variations. These variations do not affect the overall mineralogical composition, but they do cause a decrease in the values of the factor scores at those sampling stations situated in a place under the influence of outgoing flows. The alignments of the first factor lowest scores indicate that the transport paths followed by flows, which go from Cadiz Bay to the continental shelf, where they are overlapped by the main

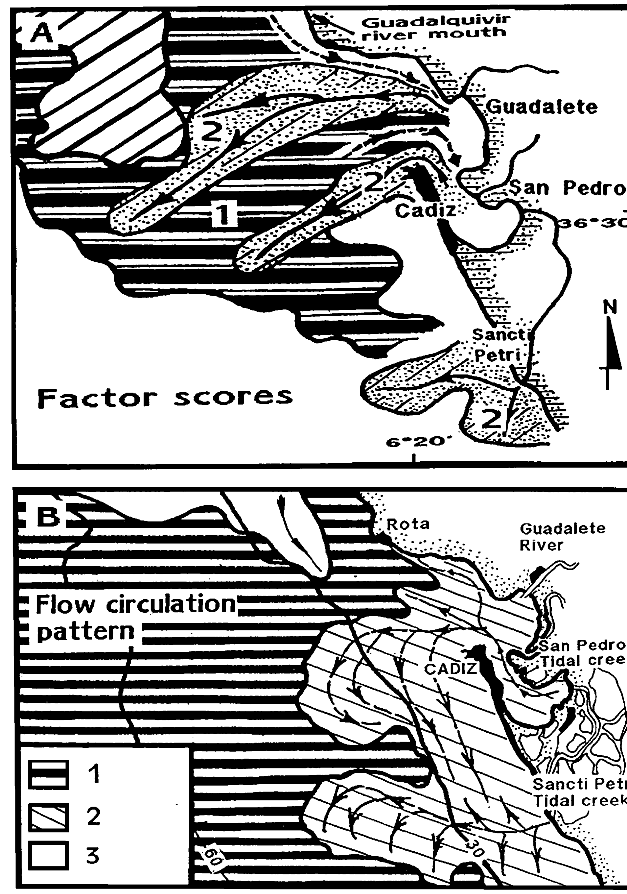


Fig. 6. Flow circulation pattern deduced from clay mineral data Factor Analysis. (A) Factor score map: 1. Highest score values (>1); 2. Lowest score values (<1). (B) Flow dynamic sketch between Cadiz Bay and the continental shelf: 1. Zone little affected by the outflows; 2. Zone affected by the outflows; 3. Continental shelf affected by flows and supplies from other source areas (Guadiana and Guadalquivir rivers).

flow (Atlantic flow), whose transport path is represented by the highest score values of this factor (Fig. 7).

Other control factors of the Holocene sedimentation on the continental shelf have been the recent eustatic changes, which controlled the general sea level trend and period of stillstand which resulted in deposition of retrogradational sedimentary bodies. They explain the present day facies distribution through the variations and evolution of the different deposit environments, hydrodynamic system and fluvial contribution. Finally, a sedimentary dynamic pattern could assume that the muddy facies in the northern zone correspond to prodeltaic depositional environments, whereas the sandy sediments in southern zone corresponds to a more energetic media, typical of littoral zones subjected to surf action (Gutiérrez-Mas et al., 1996). These data are consistent with a dynamic model of prograding character, in which the sediments supplied by the Guadalquivir River and other fluvial courses as the

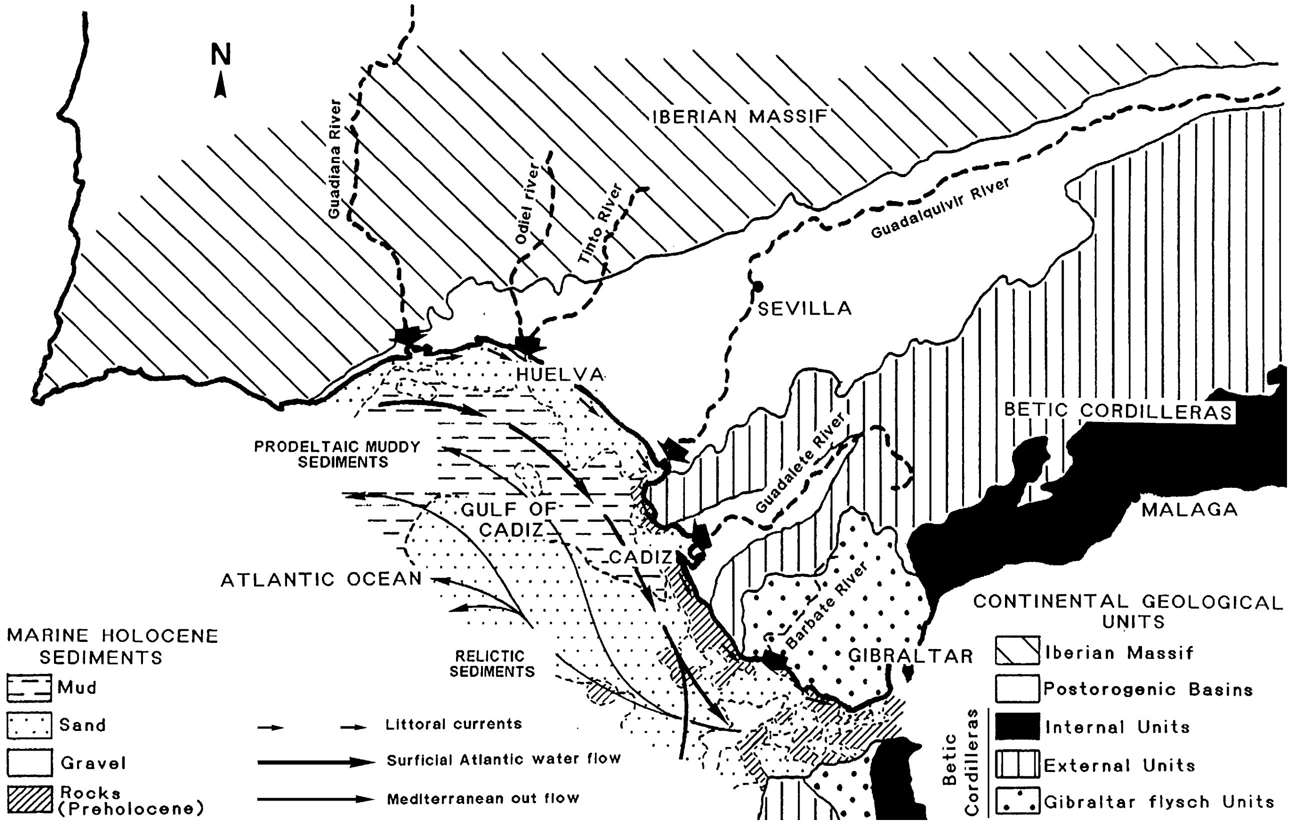


Fig. 7. Schematic geological map showing the sedimentary supply sources and sediment transport paths on the continental shelf of Cadiz.

Guadiana and Odiel-Tinto, advance toward the SE through the action of dominant currents, and cover the quartziferous-bioclastic sands present further south where the rate of sedimentation is lower. The morphodynamic result is a submarine prodelta, in which the muddy facies are oriented parallel to the coastline, following the direction of the dominant current toward the SE (Atlantic flow) (Fig. 2). These prodeltaic muddy deposits have a thickness greater than 25 m and are prograding over the older sands which were deposited at a previous epoch, with sea level conditions differing to those found presently.

## 4. Conclusions

The study and analysis of the dissimilarities between sediments on the continental shelf of Cadiz can contribute the clarification of their origin and provenance, and enlighten the knowledge on the sedimentation on present day shelf. Problems such as the coexistence of relict sediments adjacent to contemporary deposits demand the application of analytical techniques that enable the establishment of criteria to distinguish source areas and stages undergone by the deposits before they reach the sea bed.

Holocene sediments on the continental shelf of Cadiz are siliciclastic with only 25% of biogenic carbonates. The superficial sediments on the continental shelf in front of Cadiz Bay are itemized into three general sectors: a sandy and gravely like littoral zone, a muddy prodeltaic zone in the northern and central sectors and a sandy zone in south sector. Facies distribution is controlled by the Tectonic, which determines the coast and continental margin orientation, and also by the recent eustatic changes and sediment supply. This presents a differential sedimentation rate between the northern and southern sectors. The currents drain the continental margin, especially the North Atlantic superficial water responsible of the prograding of muddy prodeltaic deposits over the older relic sands, present in the south.

The combination of textural, morphological and mineralogical techniques has allowed to determine the multicyclic character of the sediments and to know the different stages the terrigenous grains had experienced before arriving at the continental shelf. Five phases were distinguished: the oldest an eolian media, followed by a energetic fluvial environment and chemical alterations acquired in a pedological media and, finally, a marine coastal environment.

The similarity among mineralogical associations shows the permanence of the source areas and sedimentary dynamics during the Holocene. However, small mineralogical variations may be explained by the action of different flows and sediment sources. The main rivers that inject sediments onto the continental margin are the Guadiana and Guadalquivir Rivers, derived from igneous and metamorphic sources (Iberian Massif and Internal Zones of Betic Mountain Ridge). The presence of policycle terrigenous grains and preponderance of ultrastable heavy minerals, especially in southern sector, also shows detritic material origin as the Neogene deposits from the Guadalquivir depression and outcrops of the occidental Betic Mountain Ridge (Subbetic and Gibraltar Flysch region), drained by the Guadalete and Barbate Rivers. These rivers inject sediments from erosion of sedimentary units containing very well rounded quartz grains whose origin is attributed to a succeeding sedimentary processes, giving way to very mature and highly reworked grains.

The sediment transport paths of the flows have been established by means of local variations in the clay mineral associations. So, two types of flows have been determined: a main flow (Atlantic flow), responsible for the sediment transport along the continental shelf with a SE direction, and tidal flows present between the Cadiz Bay and the continental shelf. These two flows mix in front of Cadiz.

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