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Structural and physiographic control on the Holocene marine sedimentation in the bay of Cadiz (SW Spain)

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Abstract

The Quaternary tectonic activity in the Gulf of Cadiz has considerably influenced the depositional regime and distribution of Holocene marine deposits. The aim of this work is to determine the nature of the recent sedimentary filling in the Bay of Cadiz sea bottom and adjacent continental shelf and to establish the main controlling factors on the Holocene marine sedimentation.

The sedimentary record indicates siliciclastic sedimentation supplied from the continent, with alternating episodes of high and low sedimentation rates. The recent sedimentary evolution of this marine area was controlled by the Late Quaternary eustatic fluctuations. Bathymetric, geophysical and drilling data have been employed to prepare a detailed isopach map of the non-consolidated recent sedimentary cover. Thickness distribution shows significant variations related to the infilling of former fluvial palaeochannels incised during the Late Pleistocene lowstand, and highly controlled by the structural neotectonic trends of faults and joints: NNW-SSE, NNE-SSW and ENE-WSW. The general distribution of isopachs in this area is clearly influenced by these morphostructural lines, which controlled the sedimentary processes during the Holocene. These results are coherent with the main regional neotectonic structures previously described in the nearby continental area, and confirm their prolongation towards the marine domain.

Keywords: Holocene marine sedimentation; Quaternary tectonics; Cádiz

1. Introduction

A full understanding of recent marine sedimentation in the transitional zone between the coast and the continental shelf needs to take into account the different factors that control the nature and distribution of the deposits: 1) sea level fluctuations, 2) sediment source areas, 3) hydrodynamic regime acting on the zone and 4) physiography and structure of the geological substratum, often related to the recent tectonic activity. The first factor affects wide regions, whereas the others act more locally.

In the Gulf of Cádiz (SW Spain) the Holocene marine sedimentation was mainly related to the last transgressive maximum and the later sea-level stabilisation [36]. The inner continental shelf deposits usually form prograding wedges, ordered in many minor sequences, especially near the main river mouths [19]. Most recent research on the Late Quaternary coastal and marine sedimentation has focused on the study of the characteristics of the depositional units recognised in the zone. Several Holocene phases of coastal progradation have been distinguished and dated in the coastal spit-bars [36]. Late Quaternary sedimentary cycles have also been deduced from the inner architecture of the continental shelf deposits by using high-resolution seismic reflection techniques [18, 19, 22, 32]. Textural and compositional data have been used to study the present day sedimentary dynamics and provenance of the Holocene deposits [1, 14, 16, 17].

The shelf hydrodynamic regime is controlled by the North Atlantic Surface Water current, sweeping towards the SE and

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responsible for the distribution of fine sediments supplied by the main rivers of the zone [13]. The Mediterranean Outflow Water runs in deeper waters [4] and does not influence the present-day coastal sedimentary dynamics. The main coastal current flows towards the SE, as a consequence of the coastline configuration, facing Westerly and SW winter storms. Although Westerly winds prevail, Easterly winds are also important, generating currents towards the North and NW.

Neotectonic activity is mainly associated with the convergence between Africa and Eurasia plates, with a present rate of about 4 mm/year in the region [2, 29]. This tectonic activity has been responsible for some major historical earthquakes in the region. Earthquake focal mechanisms show a combination of thrust faulting and strike-slip motion associated with NNW-SSE compression [8, 31]. The tectonic activity had a considerable influence on the distribution, development and nature of the recent marine deposits in the Gulf of Cádiz [25]. Many indicators in areas near the Bay of Cadiz, like faults affecting Quaternary sediments, morphostructural lineaments and other geomorphological features [5, 12, 37], confirm this neotectonic activity. An Early Quaternary compressive tectonic episode has been deduced from reverse faults observed in marine sediments of the continental margin [21, 26, 27, 28].

Results obtained in all these previous studies do not include the nature and structural controls observed in the spatial distribution of the recent sedimentary units, and their concomitant neotectonic implications. There is still a significant lack of information about the topic in the Bay of Cadiz and adjacent continental shelf. This paper focuses on the main factors that controlled the recent shelf sedimentation in the Bay of Cadiz, paying special attention to physiography and structure, in order to provide additional information about the neotectonic control on the Holocene marine sedimentation. Data were obtained from the analysis of sediment samples, drills and cores, bathymetry and seismic profiles previously made in the zone.

2. Study zone

The Bay of Cadiz is located in the northern sector of the Gulf of Cadiz (SW Spain), between the Guadalquivir River mouth and Trafalgar Cape (Fig. 1). Geologically, the Bay is included in the Tertiary Guadalquivir Basin, which represents the foreland basin of the Betic Ranges.

The surroundings of the Bay are constituted by low hills where post-Orogenic Neogene and Quaternary sands, clays and marls outcrop. Other materials like diatomites (Lower and Middle Miocene), gypsums and red marls (Late Triassic) are also present in the coastal areas. The bay was generated as a tectonic depression during a distensive tectonic phase in the Late Miocene-Pliocene [5]. The depression was occupied by a deltaic system that gave rise to a characteristic stratigraphic sequence, containing a Plio-Quaternary shelly conglomerate, locally known as *roca ostionera*. This unit developed during the Middle and Late Pliocene until the Early Pleistocene [6] and represents the rocky substratum and the acoustic basement in the Bay of Cadiz marine zone. An unconformity separates this unit from a more recent thin deposit constituted by fluvial red sands and quartzite pebbles [34, 35].

Recent Quaternary marine siliciclastic sediments overlay all these units. They are constituted of sands, silts and clays, and were presumably deposited in Late Pleistocene and Holocene times [16, 17, 35]. During the Late Quaternary, postglacial eustatic sea level fluctuations and tectonic movements controlled the spatial distribution of coastal environments [24]. In the inner Bay and Guadalete mouth the Flandrian transgression favoured the aggradational accumulation of estuarine deposits [9]. During the following sea level highstand, from 6.500 yr BP to the present, progradational estuarine and marine sediments have overlaid all the previous units [9, 19, 20, 32].

At present the Bay is about 30 km long and 15 km wide, and consists of two wide embayments separated by a rocky headland at Puerto Real. The coastal zone presents wide tidal flats isolated from the open sea by sandy beach ridges and littoral spits. The coastline is oriented NNW-SSE, with some E-W sections that give the coast a stepped outline, strongly controlled by tectonic fractures [14]. The continental shelf has an average width of 40 km, and the slope drops away sharply from a depth of about 150-200 m. The physiography of the seabed shows a close concordance with the shoreline, the isobaths generally running parallel to the coast. Submarine pre-Holocene materials include Plio-Quaternary, Late Miocene and Mesozoic units. The main sedimentary sources to the continental shelf and littoral zones are the Guadiana and Guadalquivir rivers, and sediments supplied by them are transported to the Bay of Cadiz by a West-to-East longshore current. In the Bay of Cadiz the Guadalete River is still a major supplier of sediments.

3. Methods

Sedimentological and geophysical data were obtained during several oceanographic cruises between 1989 and 2002 [10]. Sediment sampling was performed using two basic techniques: vibrocore drilling and *van veen* dredging. A total of 250 samples were collected (Fig. 1). The resulting non-deformed sediment cores were described and finely sampled for granulometric and mineralogical analysis. These data were employed for the determination of the thickness, nature and disposition of the recent marine sedimentary cover. Grain size determinations were carried out by dry sieving and laser diffraction analysis with a subsequent calculation of statistical parameters. Grain size distributions were used to describe the sedimentary facies and to correlate their physical properties with the marine dynamics. Mineralogical composition was studied by X-ray powder diffraction (XRD).

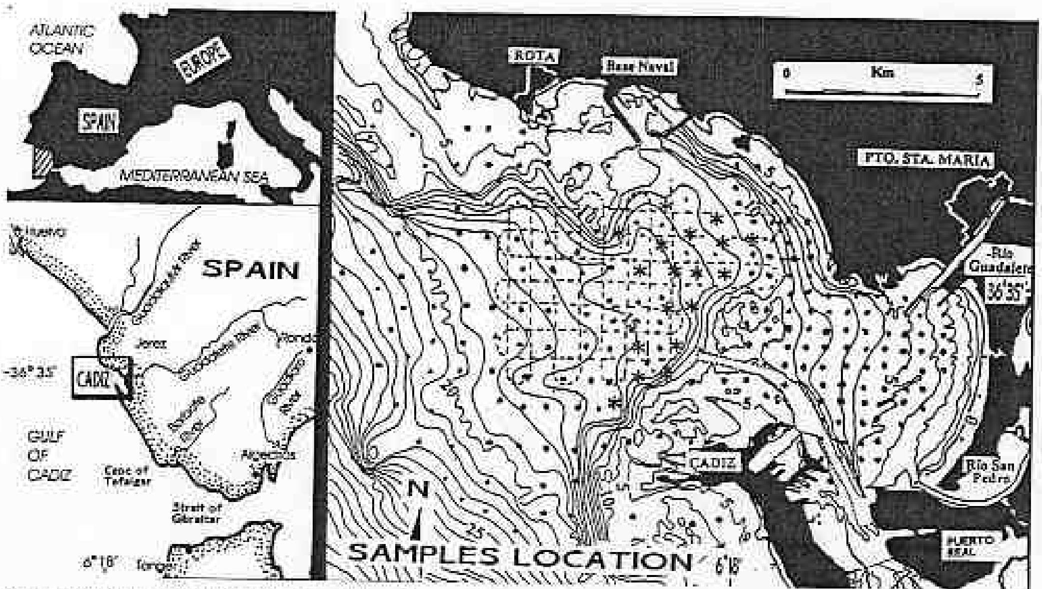

Fig. 1 Geographical situation of the Bay of Cadiz, sample location and bathymetric map of the study zone. Points indicate location of *Van Veen* dredger samples. Asterisks indicate location of vibrocore drills. Discontinuous lines indicate position of seismic profiles.

Geophysical data consisted of several high-resolution 3.5 kHz seismic reflection profiles (Fig. 1). These were used as complementary information for the determination of the geological substratum depth, thickness and nature of the sedimentary cover in zones where drilling information was not available. A series of representative geological cross-sections were performed by a correlation analysis between drilling and seismic profiling data. This procedure gave information about the substratum geometry, lateral variations in sedimentary thickness and location of the most important depocenters.

All these data were combined and represented in maps of surface sedimentary facies and isopachs. In a further step, these maps were used for drawing the most relevant structural lineaments, in order to deduce morphostructural controls on bottom physiography and depocenter distribution. A distribution analysis of orientations was applied to the obtained lineaments and the results were compared with existing neotectonic data (like directions of emerged morphostructures, recent faults affecting Quaternary deposits in the nearby coastal zones, isobath anomalies, etc.).

4. Results

4.1. Sedimentary facies and sequences

Three main zones can be distinguished in Cádiz Bay by taking into account the textural characteristics of the marine deposits and the sedimentary environments (Fig. 2):

- an inner sector relatively sheltered from wave action, where muds and clays prevail in the sea bottom;
- an outer sector between 15 and 20 m depth, more exposed to waves, with predominance of sands and silts;

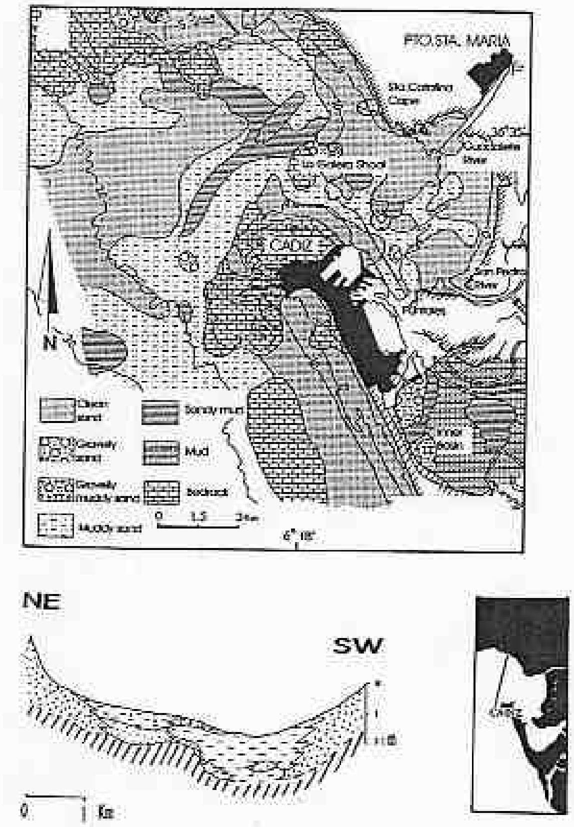

Fig. 2 Map of sedimentary facies distribution of the Bay of Cadiz seabed and representative cross section of the recent sedimentary cover, obtained from drill core data.

- a transition zone to the continental shelf, between 20 and 30 m depth, where muddy sediments are dominant although sands are also present.

In the outer sector, the sedimentary facies distribution show alternating strips or bands of sands, muddy sands, sandy muds and muds (Fig. 2). Contacts between bands are parallel or normal to the coastline and to isobaths, reproducing the general coastal physiography and the distribution of rocky shoals.

The mineralogical composition of sediments shows a clear prevalence of quartz, with average proportions ranging from 65% in sandy deposits to 50% in muddy sediments. Feldspars show an average concentration of 9%, slightly higher in sandy deposits. Carbonates appear mainly as bioclasts, and are mostly represented by calcite (content ranging between 10% and 20%). Phyllosilicates prevail in the muddy zones and are mainly constituted by Illite (60%), Chlorite (15%), Kaolinite (10%), Smectite (7%) and interlayered Illite-Smectite (< 5%).

Seismic profiles (Fig. 3) demonstrated the existence of an acoustic basement constituted by an eroded rocky substratum, probably the Plio-Quaternary conglomerates (*Roca ostionera*). The top of this unit shows a paleorelief in which furrows and palaeochannels can be clearly identified. Recent marine deposits overlay this eroded surface, showing a general finning upward textural distribution (Fig. 2). According to their acoustic response, two main levels can be distinguished within them:

A basal layer of gravels directly overlay the acoustic basement, sometimes including eroded fragments from the underlying Plio-Quaternary conglomerates.

An upper bed constituted by finer sediments like sands, muddy sands or sandy muds. Sands were dominant in all the cores, although some layers of very fine sands, muddy sands and muds were also present. The top of the sequences usually was represented by a 20 cm level of medium to coarse sands with plants and bioclastic fragments, covered by a very thin level of bioclastic fine sands.

4.2. Distribution and orientation of isopachs

Geophysical and drilling data were used for the construction of isopach maps and geological cross sections. Fig. 4 shows the isopach and thickness distribution together with the bathymetric lines. In general terms, isopach lines are oriented following two prevailing directions: A NNW-SSE to NW-SE strike, the most important in the Bay, and a secondary one E-W, almost normal to the former.

The map of Fig. 4 represents the areal distribution of sediment thickness and confirms the results obtained in the seismic profiling (Fig. 3 & 5): the recent non-consolidated sediments cover a previous surface of erosive origin formed upon a rocky substratum. The average thickness of the recent sediment cover was found to be only 5 m, with a complete absence in some places. Zones of very reduced thickness appear in areas of low water depth, close to the coast and also

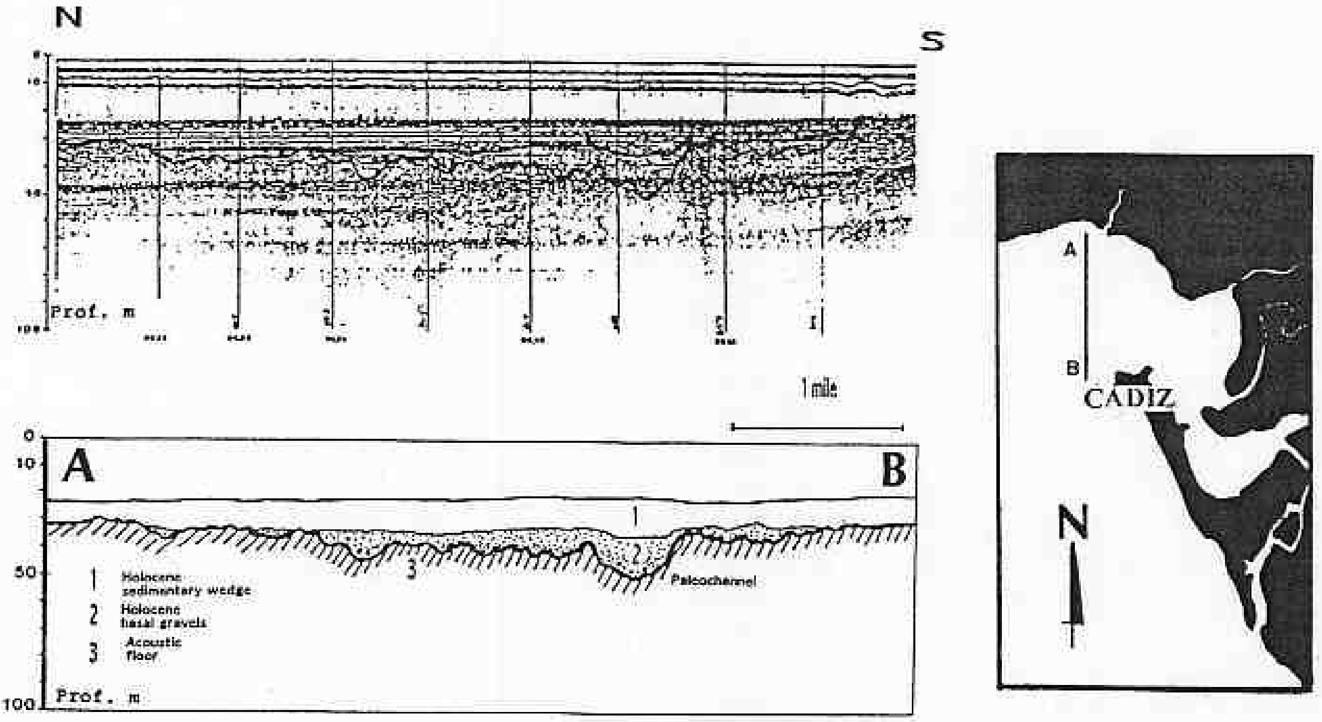

Fig. 3 Seismic profile (3.5 kHz) representative of the geologic substratum and thickness of the sedimentary cover. 1) Holocene sedimentary wedges (sands or sandy muds), 2) Basal gravels in contact with the acoustic basement, 3) Rocky substratum (Plio-Quaternary) with a channelised palaeorelief.

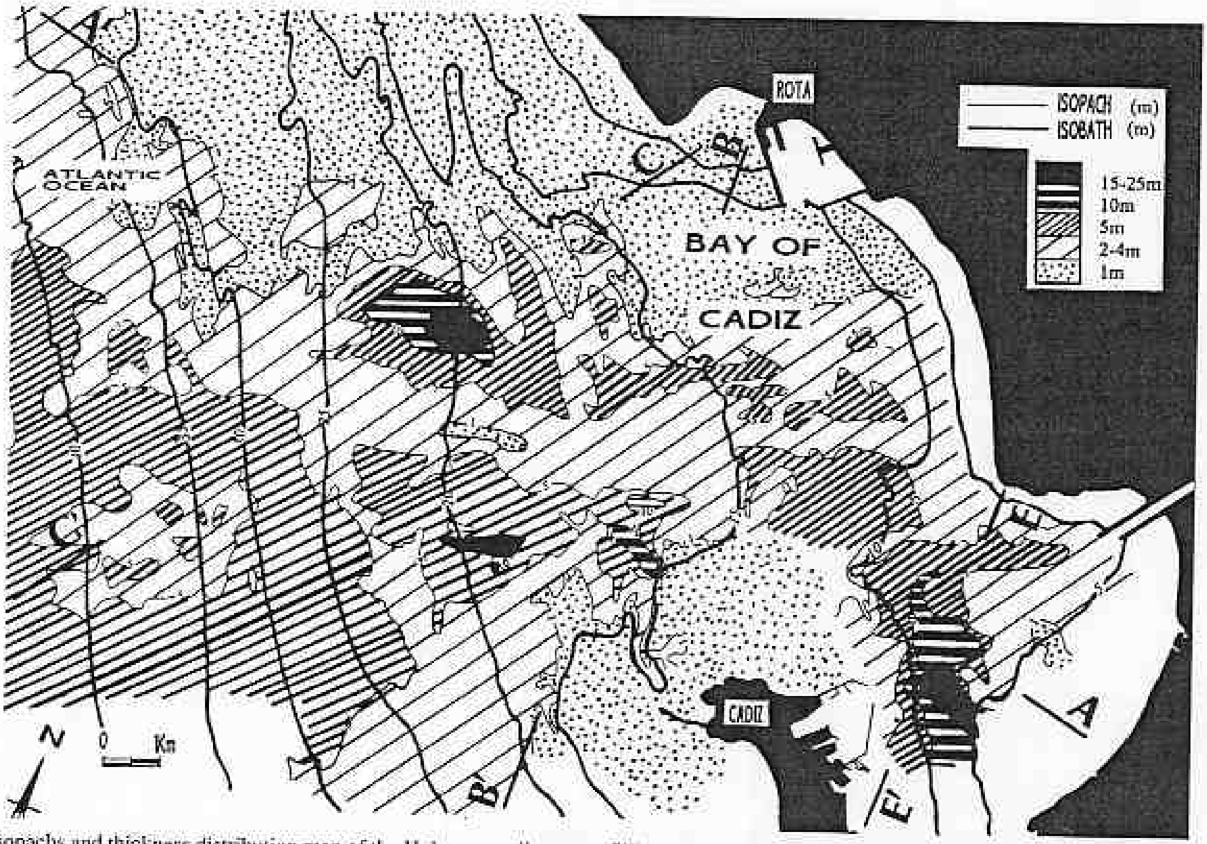

Fig. 4 Isopachs and thickness distribution map of the Holocene sedimentary filling on the seabed in Bay of Cadiz and location of the main depocenters.

upon rocky structural highs (Fig. 5). Seawards, in the continental shelf bottoms, sediment thickness also decreases, reaching values of less than 5 m (Fig. 4). However, beyond 40 m water depth, thickness increases once again, reaching values of more than 25 m, with muddy sediments mainly supplied by the Guadalquivir River (whose mouth is located few kilometres northward the zone).

In the Bay four main depocenters can be recognised (Fig. 4 & 5):

- A maximum thickness of 25 m was recorded southward Rota village, at about 20 m depth, in a zone 1.5 km wide and 3.5 km long. In this sector isopach lines are NNW-SSE oriented, parallel to the coastline, although WNW-ESE tendencies can also be seen.
- A second depocenter zone, 15 m thick, is located to the East of Cadiz city, at about 10 m depth, with isopach lines oriented NW-SE, almost parallel to the coastline and to the isobath curves.
- A third depocenter zone, 10 m thick, appears to the North of Cadiz, at about 17 m depth, with isopachs showing a WNW-ESE trend, normal to the coastline, and also in a SW-NE direction.
- Another depocenter zone, 5 m thick and with a NE-SW orientation, is located directly facing the mouth of the Guadalete River mouth.

A distribution analysis of lineaments was applied to the bathymetric and isopach maps, consisting on the identification and measurement of 135 bathymetric and 142 isopach

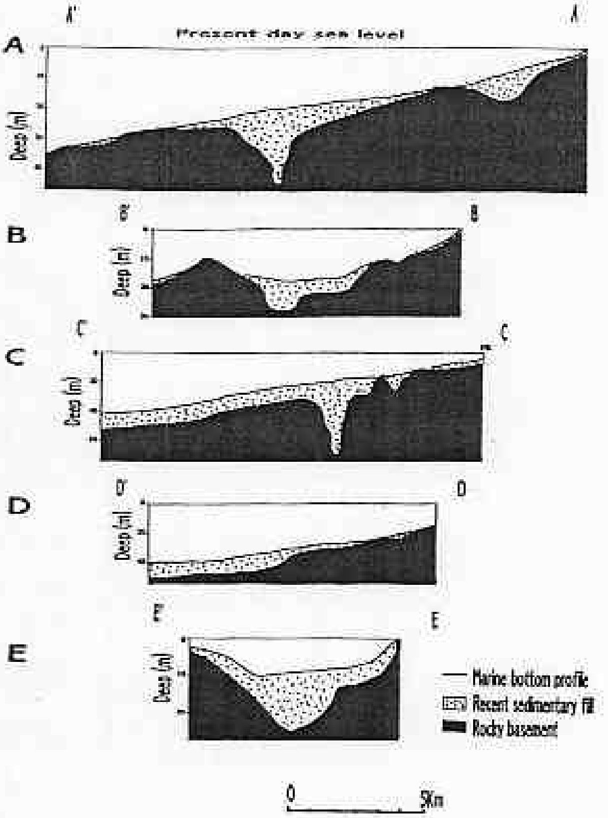

Fig. 5 Representative cross sections of the recent sedimentary filling on the sea bottom in Bay of Cadiz. Location in Fig. 4.

lines (Fig. 6A). In the first case, the maximum occurrence (18.5%) was obtained for the NW-SE (N130°E) direction, with a similar proportion in an E-W (N095°E) strike. Other secondary directions appeared broadly normal to these (N035°E and N-S) and oblique (N070°E). The analysis of the isopach map revealed three clear families of dominant directions (figure 6B): NNE-SSW (N035°E), ENE-WSW (N070°E) and NW-SE (N130°E). Other families can be clearly recognised in the map of Fig. 6, such as N-S and even E-W, although on a larger scale.

The depocenters are mainly located in areas of convergence of lineaments belonging to different families. The main directions responsible for the most important depocenters are NNW-SSE, NNE-SSW and ENE-WSW. The zones of greatest thickness, between 15 and 25 m, appear to be conditioned by NW-SE and ENE-WSW directions, which coincide with the prevailing physiographic lineaments, both coastal and submarine. Thickness between 2 and 4 m seems to be controlled by ENE-WSW and NNE-SSW directions.

5. Discussion

The results obtained on the analysis of sedimentary facies, seismic profiles and distribution and orientation of isopach lines have important implications for the reconstruction of the palaeoenvironmental, neotectonic and recent sedimentary evolution of the Bay of Cadiz.

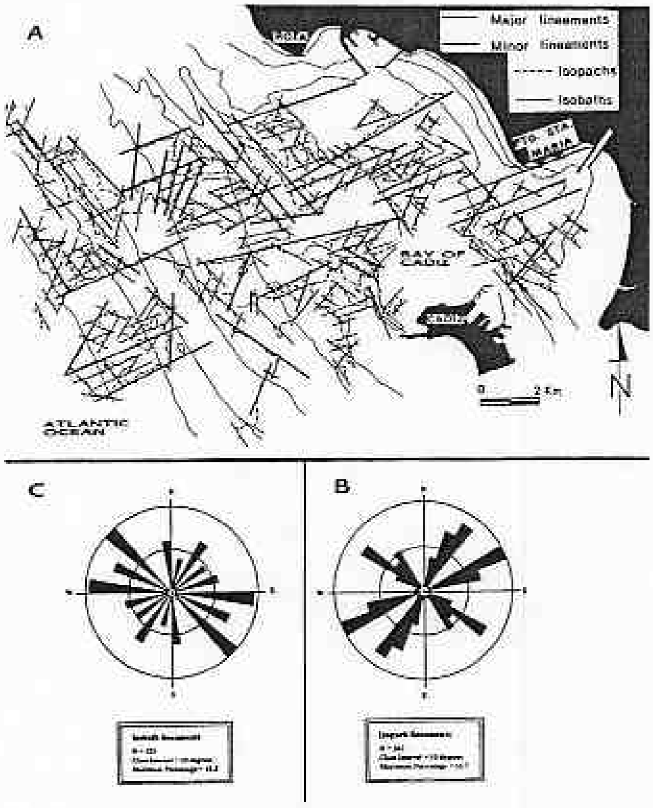

Fig. 6 A) Major and minor lineaments identified in the isopach distribution of the recent marine sediments in Bay of Cadiz. B) Lineaments identified on the isopach distribution map from Fig. 4. C) Prevailing lineament directions measured on isobaths.

The composition and siliciclastic character of the Holocene sedimentary deposits indicates a clear provenance from continental areas, via Guadiana, Guadalquivir and Guadalete rivers, and transported to this coastal zone by an active longshore current. However, the textural characteristics and the high sorting degree of the sand fraction suggest that episodes of low accumulation rates were also frequent, during which pre-existing deposits would have probably experienced some reworking. The outstanding lateral variability of the marine deposits, with alternating bands of sands, muds and muddy sands (Fig. 2), is a consequence of the sedimentary dynamics and the hydrodynamic processes, which include tidal flows and relaxation flows generated during storms. These flows spread out mainly towards the bay mouth and the bands are oriented to the West and SW, marking the sediment transport paths over the seabed. These bands follow structural directions, in coincidence with the orientation of bathymetric and physiographic lineaments.

Basal gravels and overlying sands present important lateral variations of their textural characteristics, from gravels and sands in the Eastern zone, where sublittoral environments prevail, to fine sands and muds towards the shelf. In the transitional zone to the continental shelf adjacent to the Bay of Cadiz, several sedimentological and geophysical studies [15, 17, 18] have revealed the existence of a gross mud wedge, interpreted as a prograding prodeltaic unit associated with the Guadalquivir River mouth.

Analysis of the seismic profiles indicates that the distribution and thickness of the deposits are strongly conditioned by an old relief (Fig. 3 & 5). This previous topography is the result of a complex eustatic evolution during the Quaternary. The most important depocenters, between 10 and 25 m thick, are located over structural depressions that commonly show a plan V shape, suggesting that the marine sediments may infill previous fluvial channels, inherited from subaerial exposition episodes during the last cold phases of the Late Pleistocene. The lateral migration of a unique channel, like the Guadalete River, could have produced this distribution of palaeochannels. Llave *et al.* [23] identified a palaeochannel near Cadiz city, infilled by fluvial deposits and supposed to have an age of between 20 and 18 ka B.P. Several buried flat surfaces associated to infilled palaeochannels can be recognised on the pre-Holocene substratum in some cross sections (Fig. 5B and E). Their perched disposition in relation to the ancient thalwegs suggests that they could form part of a sequence of stepped fluvial terraces, overlaid by the Holocene marine deposits. Other sites (Fig. 5D) seem to draw buried palaeo-scarpments, probably associated to ancient coastlines elaborated during sea level lowstand episodes. New drilling data should be needed in order to confirm the fluvial and/or coastal origin of these buried forms, the real nature of the rocky substratum in all these points and the distribution of ancient palaeochannels.

During the Late Pleistocene the landscape of the zone was characterised by an alluvial plain with several channels and palaeochannels cutting into a moderately tectonised geological substratum of rocks of low strength. As an evidence of this, the isopach lines and depocenters appear oriented following well defined directions that can also be recognised in the surrounding continental, coastal and deep marine areas in the form of faults [12], joints [11, 14], physiographic lineaments and bathymetric lines [33].

During the postglacial transgression the palaeoenvironmental evolution of the Bay was characterised by a progressive transition to coastal and marine environments. The basal gravels are a product of the erosion of the Plio-Pleistocene conglomeratic substratum and could be interpreted as old fluvial deposits of the Guadalete River or, in some points, as high-energy coastal sediments associated with past rocky cliff toes. The sandy levels overlaying the gravels were deposited in medium-energy beach environments, probably during an intermediate episode of sea level stabilisation. The Guadalete River mouth retreated landwards until the maximum flooding of the Late Holocene highstand (ca. 6.500 years BP), when the river mouth transformed into a tidal estuary [9] partially closed by a littoral spit. As a consequence, the fluvial supply to the continental shelf was considerably reduced and the Bay of Cadiz and inner continental shelf sands have since been covered by finer deposits, such as muddy sands and muds, characteristic of a marine environment slightly affected by wave action.

The bathymetric lines follow a prevailing NW-SE orientation, parallel to the coastline and continental margin direction. Another prevalent bathymetric direction is E-W, parallel to several straight coastal segments, which regionally give the Cadiz coast a stepped outline (Fig. 7A). These E-W elements are responsible for the presence of wide bays opened to the South and SW in the South-Atlantic spanish coast and for several submarine valleys present on the adjacent continental shelf and slope. Regarding isopach lineaments (Fig. 6A & B), the NW-SE direction controls the location and extension of the thicker depocenters and is parallel to the dominant bathymetric lines, regional coastline and continental margin orientations. The other two prevalent families (NNE-SSW and ENE-WSW) control the location and plan form of other minor depocenters and broadly coincide with secondary bathymetric lineaments. All these prevailing directions coincide with the main fault systems observable in pre-Holocene materials outcropping in neighbouring coastal and continental areas [3, 5, 7, 12, 14, 34].

A comparison has been made between these directions and other regional data on joint systems and faults, both affecting the Plio-Pleistocene conglomeratic unit and other Quaternary materials, and measured in coastal areas of the Bay of Cadiz. Joints show a prevalent ESE-WNW to E-W family (Fig. 7A),

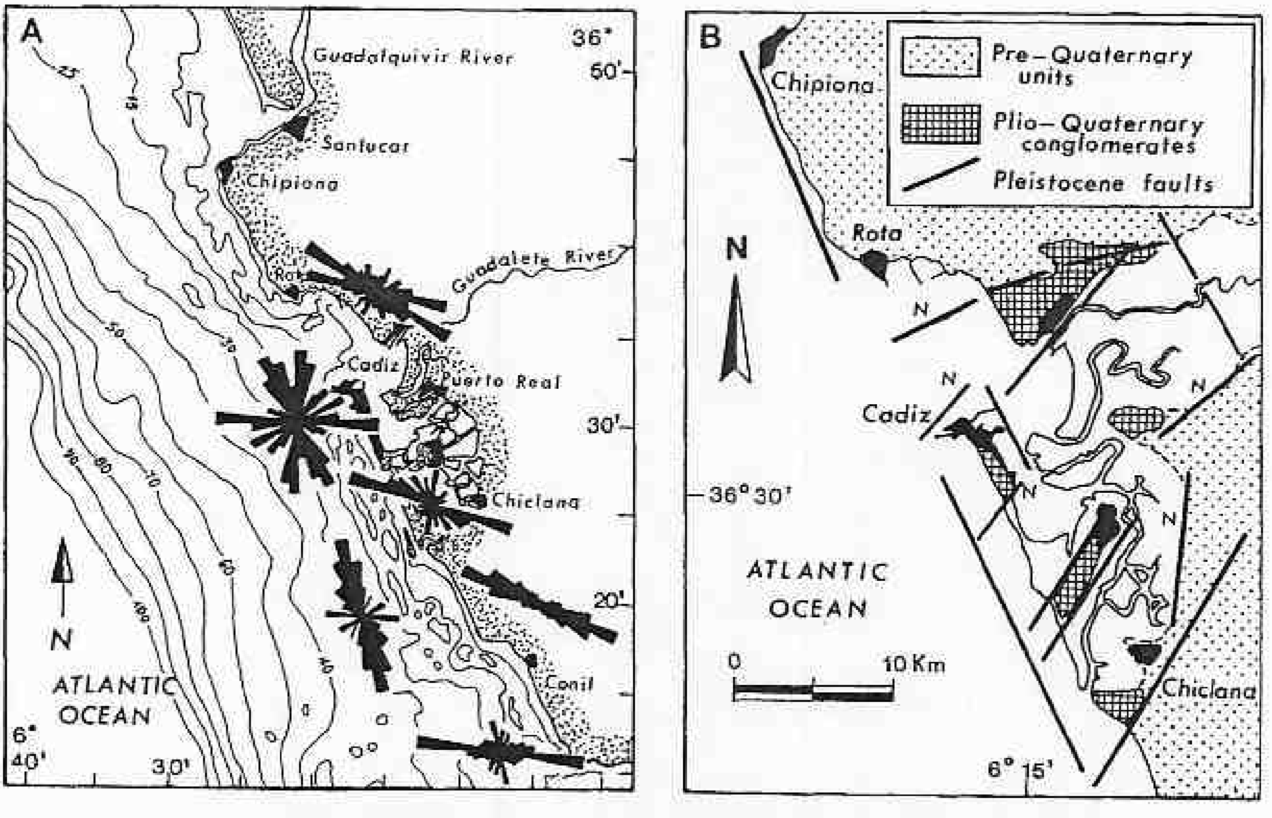

Fig. 7 A: Prevailing joint directions affecting Plio-Quaternary and Pleistocene units outcropping in the coastal zone [modified from 14]; B: Main Quaternary faults that control the coastal morphology in the Bay of Cadiz and surrounding areas [modified from 12]. Letters "N" indicate tectonic accidents deduced in the present work.

parallel to the short segments that step the regional NW-SE coastline strike. Joints with a NW-SE direction, although not well represented on a regional scale, locally predominate at some locations (Fig. 7A, [11]). Parallel tectolineaments have been identified on land through the analysis of satellite images and topographic maps [14].

The distribution of regional tectonic stress directions in SW Iberia during the Quaternary shows a prevailing NNW-SSE to N-S compression [30]. At a regional scale, this tectonic activity has produced three main strike-slip fault families [7]: NW-SE and ENE-WSW, both with dextral movement, and a third family NNE-SSW with a prevalent sinistral motion. In the Bay of Cadiz two main families of conjugated strike-slip faults affecting Middle Pleistocene fluvial deposits have been identified [12]: dextral NW-SE and sinistral NE-SW (Fig. 7B). The ENE-WSW family only appears to the North, delimiting the northern portion of the bay and affecting Plio-Pleistocene conglomerates [35]. In the continental shelf beneath the Bay of Cadiz, the NE-SW and NNW-SSE faulting directions have been also recognised affecting Quaternary deposits [27]. In the northern part of the Bay, Vazquez et al. [33] identified two faulting systems by seismic reflection techniques, running NE-SW and ESE-WNW. The first system appears in the submerged zone as a prolongation of the Guadalete River mouth fault (figure 7B, [12]) and affects the Late Pleistocene sedimentary infill of fluvial palaeochannels, indicating a very recent tectonic activity. The ESE-WNW direction is equivalent to one of the prevailing joint families affecting the Plio-Pleistocene unit.

The present study reveals the existence of several lineament families that control the broad sea bottom morphology (NW-SE and E-W) and the geometry and distribution of Holocene sedimentary depocenters (NE-SW, ENE-WSW and NW-SE to NNW-SSE). All of them clearly coincide with the most important neotectonic lines recognised in continental areas, both at local and at regional scales. In the mainland these lines correspond to faults active at least during the Middle-Late Pleistocene. The most frequent lineament family is the ENE-WSW one (Fig. 6), suggesting the prolongation of the main ENE-WSW fault that limits the North of the Bay of Cadiz (Fig. 7B) towards the shelf. The movement of all these faults generated a readjustment of blocks [12] that could explain local relative sea level fluctuations.

In summary, the present coastline and seabed morphology in the Bay of Cadiz is the final result of the neotectonic activity of faults and joints. The active faults produced a series of raised and sunken blocks and an alternating distribution of headlands and bays. At the same time, this tectonic activity conditioned the sedimentary deposit thickness, the location of structural highs and lows and the spatial distribution of sedimentary traps in zones of converging faults. Morphostructural control on the current sedimentary dynamics is exerted through the selective location of river mouths and on the submerged physiography, which conditions wave refraction processes, tidal current directions and sediment transport paths.

6. Conclusions

The analysis of the Late Quaternary sedimentary cover of the Bay of Cadiz sea bottom has revealed the complexity of factors influencing the distribution of marine sediments in tectonically active regions. The nature of the deposits indicates a prevailing terrigenous sedimentation, conditioned by the fluctuating sediment supply from the continent. A certain cyclical pattern has been recognised in the sedimentary history of the Bay, with alternating periods of high and low sedimentation rates.

The historical distribution of depositional environments (continental, coastal and marine) and the associated efficiency of the sedimentary processes were highly controlled by the fluctuating sea level during the Late Quaternary. The coastline advance during the Upper Pleistocene lowstand led to the accumulation of fluvial deposits and the development of an alluvial plain in the Bay of Cadiz area. The Holocene transgression produced the marine flooding of this embayment and its transformation into an open marine bay.

The recent sedimentary infilling on the Bay of Cadiz seabed presents a remarkable structural control. Location of the main depocenters and even the distribution of isopachs, follow lines parallel to the main structural directions of recent faults and fractures recognised in both marine and continental surrounding areas. These structures condition the distribution and orientation of sediment thickness and play an important role in the depocenter location, since they occupy previous fluvial channels incised following very marked morphostructural lines.

Many factors associated to the currently active sedimentary dynamics, e.g. coastal and seabed physiography, water depth, distribution of depositional environments, wave refraction processes, distribution of water flows, are absolutely controlled by the morphostructures of the rocky substratum. The Bay of Cadiz thus constitutes a good example of how Quaternary tectonics can influence the sedimentary evolution and dynamics in coastal and shallow marine areas.

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