Bol. Inst. Esp. Oceanogr. 15 (1-4). 1999: 123-132 **BOLETÍN** INSTITUTO ESPAÑOL DE OCEANOGRAFÍA
ISSN: 0074-0195

Morphology and characterisation of the relict facies on the internal continental shelf in the Gulf of Cadiz, between Ayamonte and Huelva (southern Iberian Peninsula)

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Received October 1997. Accepted April 1998.

ABSTRACT

The objectives of the present paper are the determination of the morphologic characteristics of the superficial Quaternary relict facies on the internal continental shelf in the Gulf of Cadiz, between Ayamonte and Huelva (southern Spain), their characterisation, and their evolution in the final phases of the last eustatic hemicycle. The study area extends from the mouth of the Guadiana River to the mouth of the Tinto-Odiel River, and from the 6 m isobath to the 56 m isobath. High-resolution seismic profiles (3.5 kHz and Geopulse, 175 J), sonographic profiles (SSS, 100 kHz), and bathymetric profiles (Echotrac sounder) were used in this study. Sediment samples were obtained using Van Veen and Shipek drags. Bathymetric, physiographic, lithologic and morphologic analyses were performed to determine the superficial sediment distribution, relict facies distribution, and thickness of the unconsolidated sediment cover.

Analysis of the data obtained indicated that the relict facies beaches and coastal barriers associated with coastal spits located in the ancient outlets of the rivers. Relict facies were grouped into well-differentiated depths, indicating that their position on the continental shelf is influenced by the still-stands and the periods of rapid sea-level changes.

The nature of the outcropping relict facies shows that their final configuration can be related to the shelf construction processes, as well as to the most important Holocene transgressive phases.

Key words: Gulf of Cadiz, continental shelf, Quaternary, geomorphology, relict facies.

RESUMEN

Morfología y caracterización de las facies relictas en la plataforma interna del golfo de Cádiz entre Ayamonte y Huelva (sur de la península Ibérica)

Los objetivos de este trabajo son la determinación de las características morfológicas, la caracterización de las facies relictas cuaternarias superficiales y el estudio de su evolución con relación a las fases finales del último hemiciclo eustático en la plataforma continental interna del golfo de Cádiz, entre Ayamonte y Huelva. El área de estudio abarca desde la desembocadura del río Guadiana hasta la del río Tinto-Odiel y desde los

6 m hasta 56 m de profundidad. Se utilizó gran cantidad de material geofísico, en el que se encuentran perfiles sísmicos de alta resolución (3.5 kHz y Geopulse, 175 J), perfiles sonográficos y perfiles batimétricos, además de muestras de sedimentos obtenidas con dragas Van Veen y Shipek. Con esta información se han realizado análisis batimétricos, fisiográficos, litológicos y morfológicos, además de determinar la distribución de los sedimentos superficiales y de las facies relictas y de cuantificar la potencia de la cobertera sedimentaria.

Con todos los datos obtenidos se ha determinado que las facies relictas son interpretadas como playas y cordones litorales asociados a flechas litorales situadas en las antiguas desembocaduras de los ríos. Las formas descritas están agrupadas en zonaciones batimétricas bien diferenciadas, lo que indica que su posición en la plataforma continental está influida por las paradas y etapas de movimiento rápido del nivel del mar.

Las características de las facies relictas aflorantes indican que su configuración final puede estar relacionada con los procesos de edificación de la plataforma a partir de las mayores fases transgresivas holocenas.

Palabras clave: *Golfo de Cádiz, plataforma continental, cuaternario, geomorfología, facies relictas.*

INTRODUCTION

Relict facies are one of a large number of bodies of depositional and erosional genesis, including morphologic deposits associated with beaches, lagoons and dunes, as well as with other units subject to erosional processes, such as erosional surfaces, terraces, ruts, channels and other minor physiographic elements associated with older coastlines.

The general objectives of the present paper are the determination of the morphologic characteristics of the superficial Quaternary relict facies, their characterisation, and their evolution in the final phases of the last eustatic hemicycle. This study includes: 1) description of the different physiographic domains; 2) distribution and thickness of the sedimentary cover; 3) characterisation and distribution of the different superficial morphologic types; and 4) distribution and characteristics of the relict facies.

The study area is the internal continental shelf of the Gulf of Cadiz, between Ayamonte and Huelva (southern Spain) (figure 1). It is bounded by the parallels 36° 55' N and 37° 15' N and the meridians 6° 50' W and 7° 25' W. It extends from the mouth of the Guadiana River to the mouth of the Tinto-Odiel River, from west to east, and from the 6 m isobath to the 56 m isobath, from north to south. From a geological point of view, the study area is located in the western extreme of the depression of the Guadalquivir River. Most of the inner shelf of this Atlantic sector, between 20-30 m, is covered by an unconsolidated siliciclastic sedimentary cover (Rey y Medialdea, 1989). The thickness of this unit increases from 5-10 m near the present coast to 20-30 m in the south (present shelf). All these siliciclastic deposits overlay an erosional surface (–40 to –30 m) cut into Pliocene and Pleistocene rocks (Rodríguez-Vidal, Cáceres and Rodríguez-Ramírez, 1992).

Oceanic circulation in the Gulf of Cadiz is controlled by water exchange in the Strait of Gibraltar. North Atlantic Superficial Water (NASW), which flows to the southeast, is the main current affecting the continental shelf (Ochoa and Bray, 1991). Mediterranean water flows in a northwesterly direction, following the contour of the slope under the action of the Coriolis force. It is subdivided into different branches dwhich spread seaward following the complex submarine physiography of the continental slope, with its different submarine valleys (Zenk, 1975; Ambar, Howe and Abdullah, 1976).

MATERIALS AND METHODS

The present study is based on the analysis of data obtained during the first Marine Geophysics Campaign on the Coast of Huelva sponsored by Spain's Ministry of Environmental Affairs during September and October of 1994. The data included 1 933 km of high-resolution seismic profiles (sub-bottom profiler, 3.5 kHz and Geopulse, 175 J), sonographic profiles (SSS, 100 kHz), bathymetric profiles (Echotrac sounder), and 3 395 superficial samples taken by Shipek and Van Veen drags, with which a superficial sediments map was produced.

In the study, 852.6 km of bathymetric profiles were used for the morphologic analysis, and 25 samples of consolidated material were examined for a visual description (figure 1, table I).

Two hundred and thirty bathymetric determinations of the superficial relict facies were identified in bathymetric and sonographic profiles. The depth was measured in the proximal part landward of each relict morphologic body.

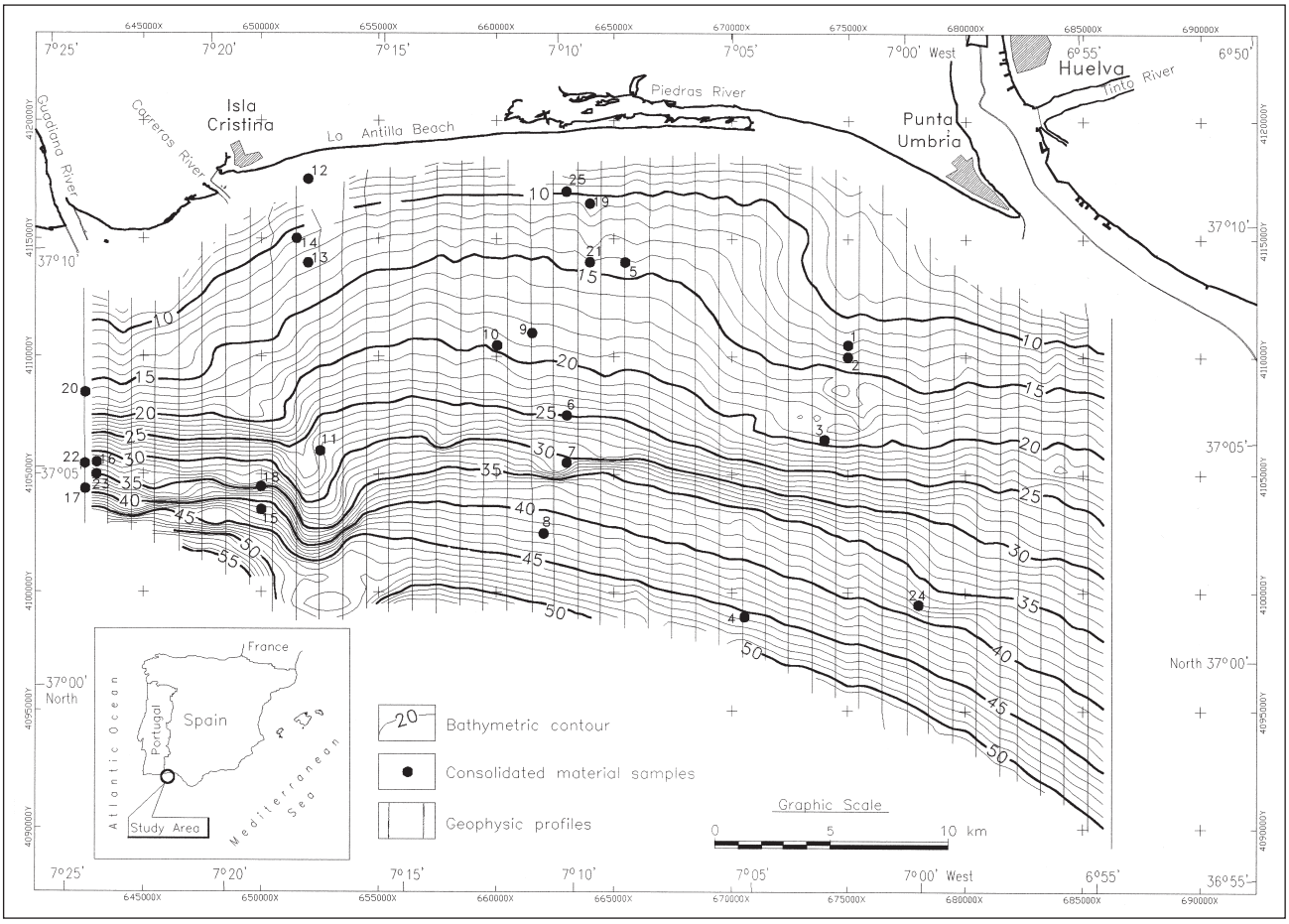

Figure 1. Geographical setting and bathymetry of the study area, with seismic reflection profiles and samples location

The bathymetric map was generated as a digital ground model (DGM) using the SURFER program. Depths in the study zone vary from 5-55 m, and it can be split into a series of sectors of similar bathymetric and physiographic characteristics.

Other determinations were made concerning the superficial Quaternary units. Some of these were established from the seismic record analysis obtained during the aforesaid cruise, the others using high-resolution seismic profiles obtained on the continental shelf of the Gulf of Cadiz (figure 1) (Golca-93 IEO-campaign). The high vertical resolution (0.5-1 m) enables the seismic facies to be distinguished with high resolution.

RESULTS

Bathymetry and physiography

The impossibility of carrying out bathymetric profiles near the coast (6 m) means that the only information available is from the infralittoral part. This domain can be differentiated into four zones with different slops (figures 1, 2 and 3), the two shallower ones with smaller and more horizontal slopes than the deeper ones: a) to a depth of 8 m; b) from 8-20 m; c) from 20-40 m; d) from 40-55 m.

Zone a) has a mean width of 2 000 m, with a slope that ranges from 0.21-0.40 %. This subzone is parallel to the coast, and is always present, except off Isla Cristina and between the mouth of the Piedras River and Punta Umbría.

Zone b) has a mean width of 6 000 m, reaching 9 000 m in width off Punta Umbría. Its mean slope varies between 0.01-0.20 %. This subzone is not present in the western part of the study area, off the Guadiana River. There is an area of some 5 000 metres in length by 3 000 in width off Punta Umbría, where the slope gradient is not greater than 0 %, and which becomes negative in some sectors of reduced area. A negative slope gradient means that the slope is towards land.

Table I. Relationships between the samples obtained and their visual descriptions

Sample number	Visual description
1	Sand of fine grain without shells, well-cemented
2	Sand of rounded quartz grain without shells, well-cemented
3	Sand of rounded quartz grain without shells, well-cemented
4	Very rounded large boulders
5	Very well-selected fine sands, without biogenic remains
6	Shells and other biogenic remains
7	Pieces of reefs
8	Well-selected fine quartz grain cemented by a white matrix
9	Gravel, 2 mm in diameter, with cemented remains of shells and polychate pipes
10	Calcareous pipes without shells, cemented by very fine grains
11	Sand with pipes, shells very-well cemented
12	Sand, very well cemented, without biogenic remains
13	Rounded, fine-grain sand and slightly cemented shells
14	Very fine and very well-selected sand without biogenic remains
15	Quartz grain with some shell fragments
16	A conglomerate of biogenic remains (pipes, shells, algae, etc.)
17	Boulders from 2-4 mm, cemented with a matrix without shells
18	Grains, 1 mm in diameter, with some pipes, shells and equinoderms
19	Very well-cemented sand with very selected grains
20	Pieces of coral, with large fluvial boulders
21	Pipes, shells and some quartz grains
22	Pieces of shell and fine, cemented sand
23	Pieces of shells and equinoderms, rounded small grains, and some very rounded small boulders
24	Sand with slightly cemented shell remains
25	Large pieces of coral and shell remains

Zone c) has a mean slope that ranges from 0.21-0.40 % and a mean width of 6 km. It is possible to differentiate several sections: a western section with marked slope changes, the slope varying from 0.41-0.80 %, that extends from the mouth of the Guadiana to the east, off Isla Cristina (figure 2); a central section, where the slope ranges from 0.21-0.40 %, and within which some areas having a longitudinal subparallel position with respect to that coast show higher values; and an eastern section, with lower slope values, ranging from 0.01-0.20 %.

Zone d), with a mean width of 4 km, has the highest slope values (greater than 0.81 %) in the study area (figure 2). This zone is not clearly differentiated in the easternmost part, as shown by the bathymetric profiles (figure 3).

Regarding the development of the bathymetric profiles analysed, figure 3 shows that the eastern profiles present a gentle surface with progressive slope changes, in contrast to the profiles of the western zone, where the slope changes are sharper, a very marked stepping being produced in the deepest zones.

Morphologic types

From the genetic point of view, the Quaternary morphologic elements of the Huelva continental shelf are associated with river contributions from the adjacent emerged margin, with oceanographic conditions, and with the evolution of the continental shelf during the sea level's regressive and transgressive episodes in the late Quaternary.

From the genetic point of view, the different morphologic types detected in the study zone can be split into two broad groups: depositional morphologies and erosional morphologies.

Prodeltas, sand ridges and small wedges form the depositional morphologies, while the erosional morphologies are relict deposits modified by present-day erosion/sedimentation conditions, and include erosional surfaces, morphologic scarps, and depressions.

Depositional morphologies

- Prodeltas: two prodeltas are described in the study area–one in related to the mouth of the Guadiana River, and the other to the mouth of the Tinto-Odiel River. Both prodeltas extend some 10 km seawards to the 20 m isobath.
- Sand ridges: sand ridges are convex bodies of sandy materials (Catafau *et al.,* 1990). These bodies present an asymmetrical development, with the most abrupt edge normally facing seaward. There is a sand ridge located in the western zone of the study area, in front of the

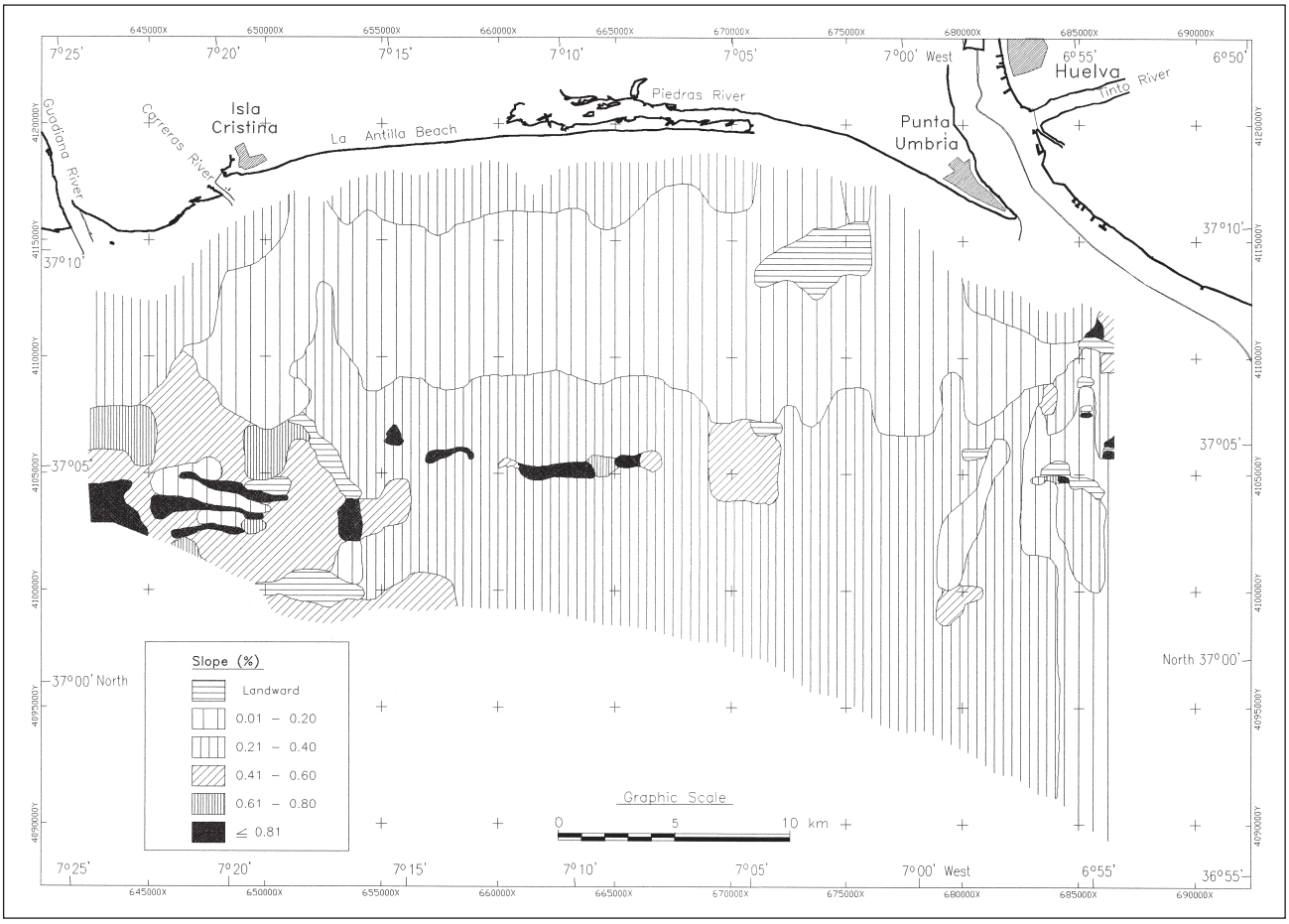

Figure 2. Map of the superficial distribution of slope for the study area

mouth of the Guadiana River. It is about 7 km long and 5 km wide, with bathymetric depth limits of 20-50 m. Its genesis can be related to sediment contributions from the Guadiana River when the sea level was lower than at present.

- Small wedges: these features are deposits covering the relief and the irregularities of the rocky consolidated bottom. Their morphology is on a smaller scale, with a width of 1 km and a length ranging from 2-5 km. They are located in the southwest sector of the study area. Their genesis is related with the dam effect of the rocky outcropping, making sedimentation of the materials possible.

Erosional morphologies

- Erosional surfaces: horizontal or under-horizontal erosion areas composed by relict sandy facies. Most are located at between 15-35 m throughout the area, from west to east. They can reach about 10 km in length and 4 km in width. Their genesis is related to the erosion produced by wave action on the coastline over not-easily-eroded material, during the continuous sea-level changes.
- Morphologic scarps: positive reliefs of variable area that belong to the relict sandy facies. There are two types. The first presents a strong middle slope, with abrupt slope changes at both ends. The scarps have a continuity of up to 5 km, and can be even 5 m height in unevenness, above all in the southwestern sector. Their genesis can be related to the long-term sea-level stabilisation stages that produced these cliffs, or to the neotectonic processes of block movements producing the stepping of these scarps. The second scarp type is small, of irregular distribution, and on a scale of metres.

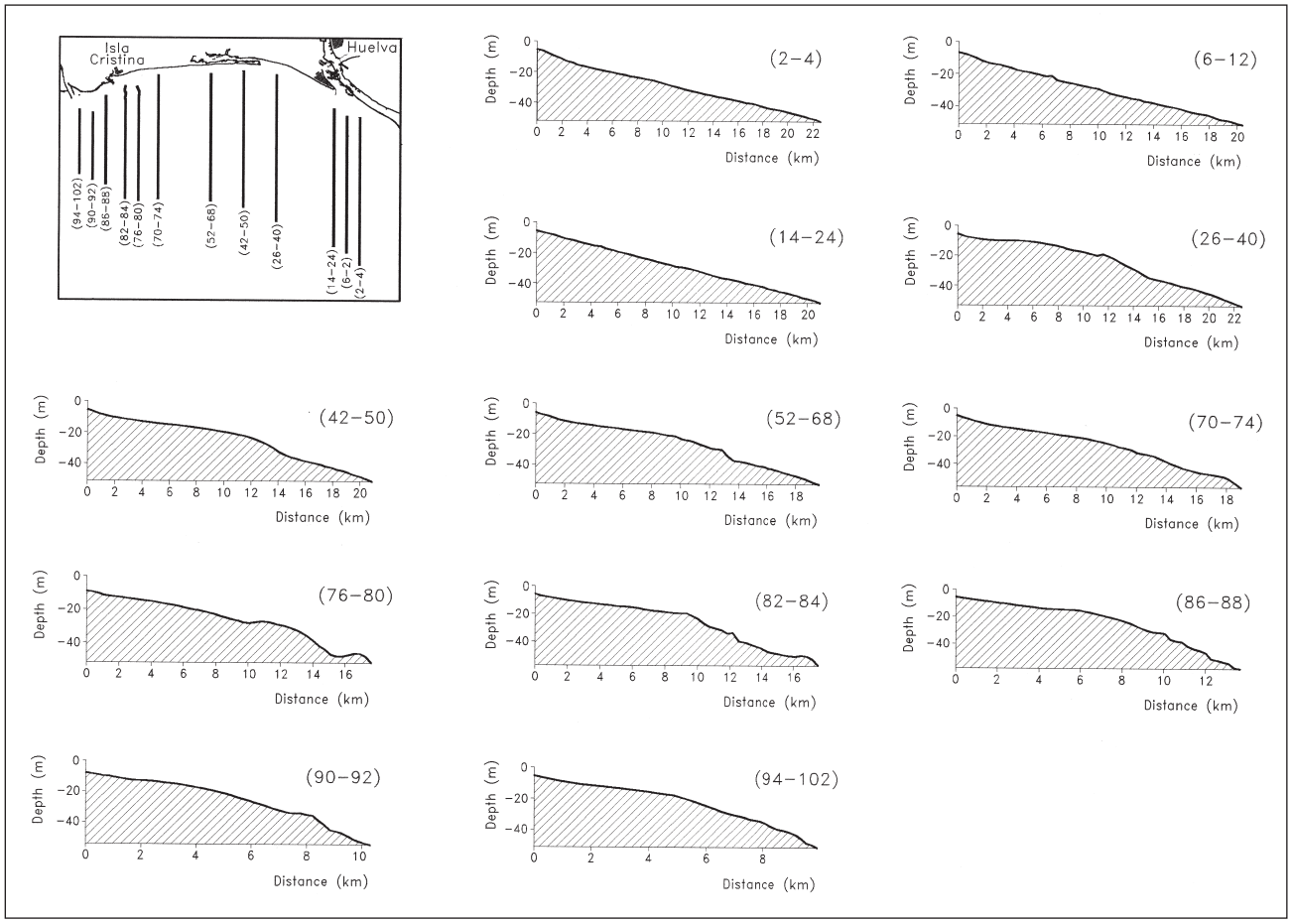

Figure 3. Model profiles identified in the study area. The ranges of the profiles of the different bathymetric types and the ap proximate position in each one of the groups are indicated

- Depressions are small, negative morphologies, and are presented locally, mainly at depths greater than 20 m, in rocky zones behind small rock ridges. Their scale is of metres.

Superficial sediments distribution

The internal continental shelf bottom between Ayamonte and Huelva comprises sands, muds and rocks, with some sporadic small areas of gravel (figure 4) and very rounded boulder accumulations.

Sands are restricted to the shallowest zones, of less than 25 m in depth, except close to the mouth of the Guadiana, where they are substituted by muds, to 10 m in depth. In this same zone, the sands extend to a depth of 56 m, forming a sand ridge.

The fine deposits (muds) appear generally at depths of more than 25 m, except in the eastern sector near the mouth of the Guadiana, where they are deposited at shallower depths.

Thickness of the unconsolidated sediment cover

Different depocentres can be identified in the unconsolidated sediments of the study area. The mean sedimentary thickness of sand is about 5 m, though in the western sector it reaches 20 m. Two important depocentres are differentiated in the sandy facies (figure 4): one between 15-16 m in depth, with a sedimentary thickness of 10 m, off the mouth of the River Piedras, and the other, larger one, between depths of 30-56 m, with a sedimentary thickness of more than 20 m, off Isla Cristina.

Muds have a sedimentary thickness ranging from 5-10 m, but which can reach 15 m in the deepest zone of the study area, near the mouth of the Piedras River (figure 4). Several depocentres can be differentiated in the muddy sediments, the most important being those with a sedimentary thickness of 10 m, located in front of the mouth of the Tinto-Odiel between depths of 22-26 m, and those

with a sedimentary thickness of 15 m located opposite of the mouth of the River Carreras between 20 and 22 m in depth and in front of the Piedras, at depths greater than 45 m.

The presence of fine sediments in front of Isla Cristina (figure 4) is related to the deposits of the Guadiana prodelta, which are transported toward deeper zones (> 30 m) and afterwards distributed by the bottom currents throughout the platform. The disconnection of these muds from the mouth of the Guadiana can be related to the strong eastward coastal current, which washes off the muddy fraction and transports it away from the zone, preventing mud deposits alogn the whole coast.

Relict facies

Distribution and depths

The relict facies present in the study area are characterised by good lateral continuity. Where this is not so, the relict facies are covered by recent sedimentary deposits originated from the sedimentary contributions of the Guadiana, Piedras and Tinto-Odiel Rivers, which cover them without allowing outcropping of the relict material. The direction of the outcropping relict facies is generally parallel to the present coast (figure 4).

Relict facies appear frequently at the following depths, in metres: 9, 10, 12, 16, 18, 19, 20, 22, 23, 24, 28, 31, 33 and 34 (figures 5 and 6). However, they have also been detected at depths from 6-53 m. Figure 5 shows that the highest concentration of the relict facies is located between 12-31 m. This can also be observed in figure 4, showing the superficial distribution of these morphologies.

According to the data shown in figures 4, 5 and 6, four categories of relict facies can be established. These groupings depend on the depth range at which relict facies are found:

I) all relict facies up to 14 m; II) from 14-30/31 m; III) from 30/31-37 m; IV) from 37-56 m.

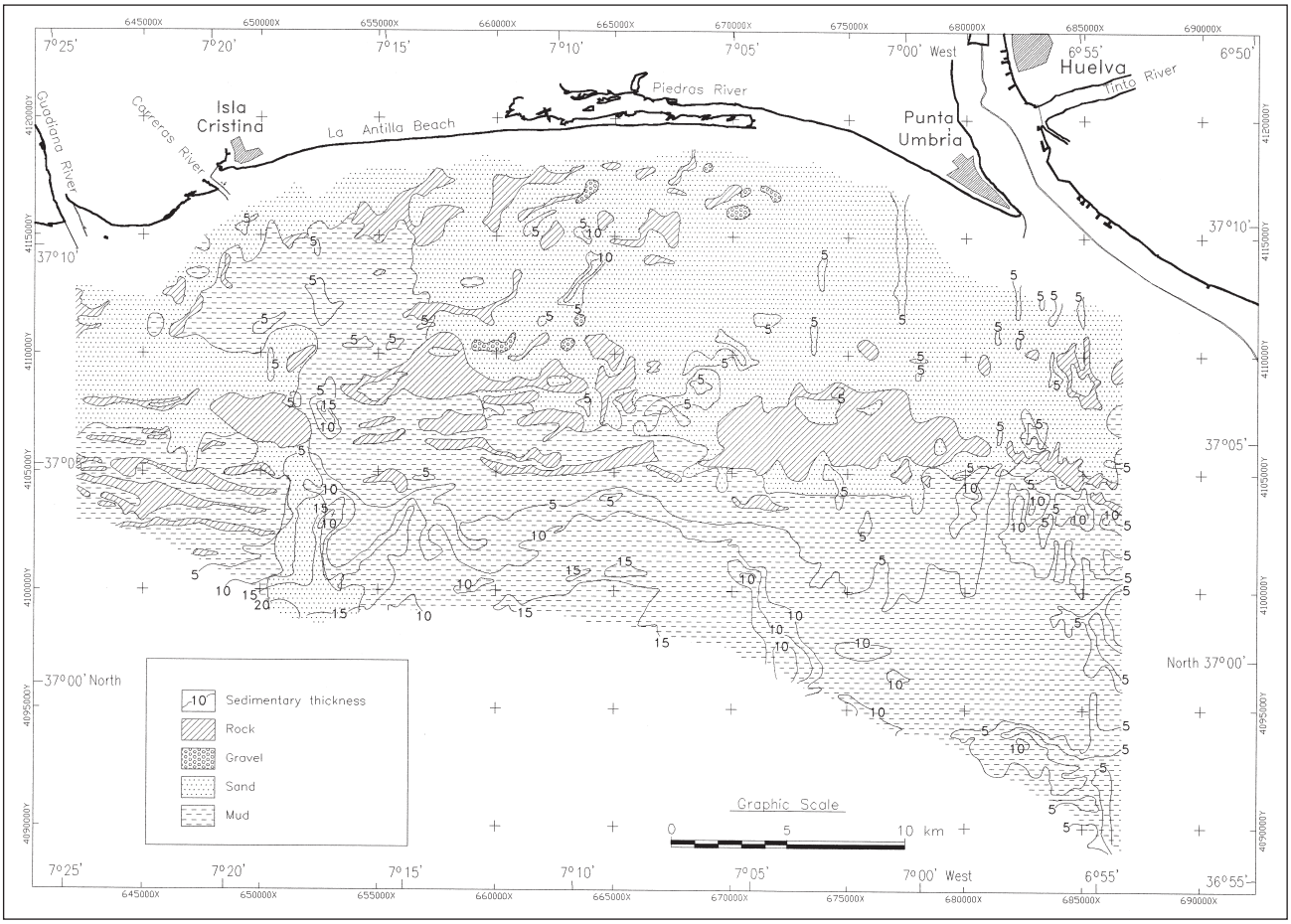

Figure 4. Superficial distribution of the different sediment types identified in the study area. Unconsolidated sediment isopachs are indicated

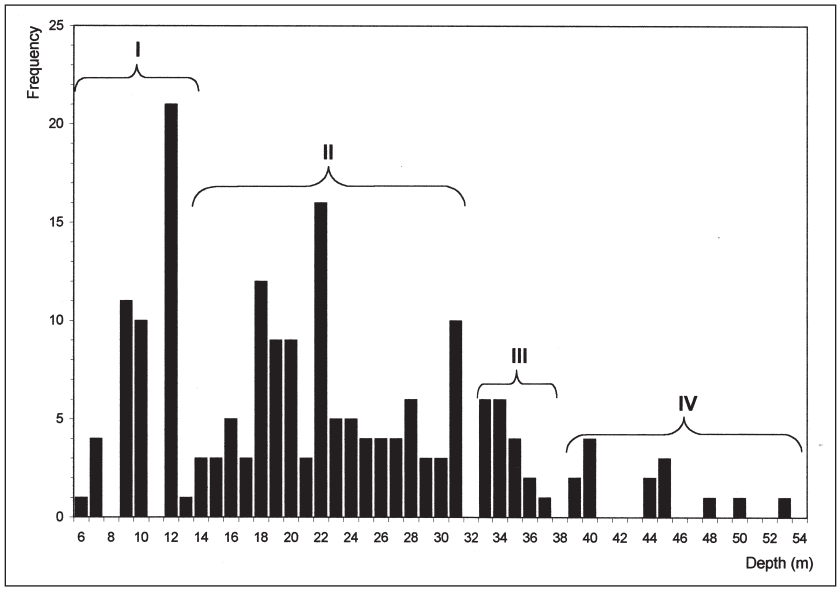

Figure 5. Graph of relict facies frequency and depth. The grouping of the relict facies in restricted depth ranges can be observed

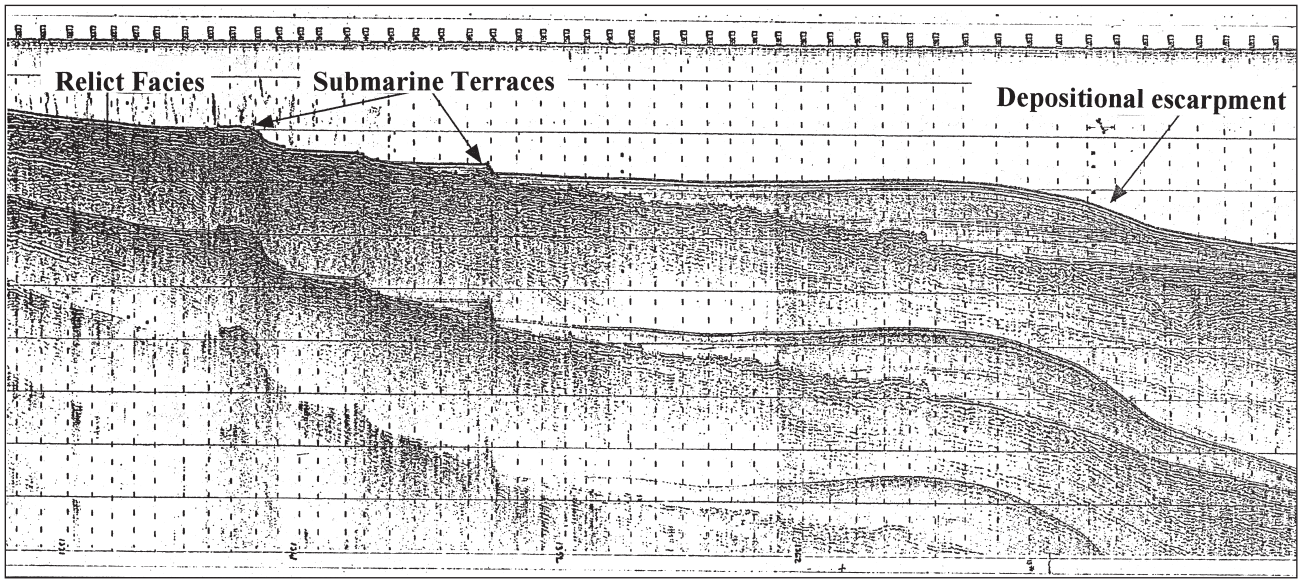

Figure 6. High-resolution seismic reflection profile of Geopulse (Profile A, see figure 1 for location) in which it is possible to differentiate several submarine terraces over groupings of the relict facies in restricted depth ranges

Category I is more frequent in the central zone of the study area, between the mouth of the Piedras River and Isla Cristina. The outcrops are not continuous, and occupy a small area. The outcrops of category II occupy a larger area, being present throughout the study area. The outcrops of categories III and IV are less developed in the north-south direction, but present a great continuity in the east-west direction. The last two categories are restricted to the westernmost zone of the study area.

The reason why category I appears with greater frequency in the shallowest central zone of the study area (figure 4) is the absence of direct contributions from any river. In contrast, in the western and eastern sectors, there are two important river mouths, those of the Guadiana and Piedras, which are responsible for covering the outcropping relict with their deltaic deposits. The deposits of category II present a great lateral continuity, possibly as a result of the erosive effect of the eastward Atlantic flow (NASW) (Melieres, 1974), preventing sedimentation and establishing erosive surfaces. Categories III and IV are restricted to the western sector, possibly because of greater differential ero-

sion in this zone. This differential erosion may be due to tectonic movements that raised the zone, exposing it more to erosion, or the abruptness of the scarp may have prevented its being covered with sufficient sediment originating from the west, so that still it continue present on the bottom of the sea.

Sedimentological characteristics

Although the relict facies present a very varied superficial morphology, when they are outcropping they are characterised by non-deposition surfaces of small slope and of scarce relief. In other circumstances, the relict facies present pronounced relief, with scarps associated with small rock ridges and steps towards both the inward and outward parts of the continental shelf. This is more marked in the western zone of the study area. The relict facies are distributed throughout the continental shelf, with an elongated development and a direction parallel to the coast, so that the bodies appear independent one from the other. These bodies are arranged in step form toward the deepest zones.

Relict facies mainly comprise three different lithologic types, always associated with the cementation of sands and gravel of beach systems, conglomerates of biothermic nature (shell conglomerates and mollusc and bivalve shell and organic concretions), and in other cases, reef concretions partially cemented by calcareous algae and calcareous pipes of worms. This last type of lithology is less frequent, and is found largely in the present shallow-bottom zones. Samples with a high content of rounded and flattened boulders have been obtained close to the relict outcroppings, The composition of these samples corresponded to cemented calcareous sediments. This, together with the nature of the materials forming the relict facies, confirms the relationship between the outcropping undoubtedly with ancient coastlines and associated coastal systems.

Figure 1 and table I show that the materials constituting the relict facies are formed largely by very well-selected and cemented fine sands, without biogenic remains (e.g. samples 1, 5, and 12). This type of sediment occupies the deepest zones of the eastern sector. However, the same type of sand appears in the western zone (samples 21-24), but, in this case, bound to shell remains, echinoderms, and polychaete pipes, together with some small boulders. The same classification includes another zone of different lithology, with depths from 14-31 m, where the sands are azoic and the grains are very rounded (samples 2, 3 and 14), excepting the sediments of the western zone, which have biogenic components (samples 25 and 15). Finally, the shallowest zone is characterised by a high content of biodetritic and biogenic remains, including shell fragments, coral, and polychaete pipes.

Well-selected quartz sands and the isolated accumulations that were also detected in the shallowest zones of the platform come fundamentally from erosion of the coastal deposits and from re-erosion of the accumulations of the relict bodies. Sandy cover, which in the west zone reaches the deepest zones, forming the sandy ridges described above, has been deposited possibly as a consequence of ancient sedimentary contributions of the Guadiana River when the sea level was lower than at present, or forms part of the recent prodelta in one of its greater progradation phases.

DISCUSSION

From a consideration of their morphology, their position with respect to the present coast, and their lithologic nature, relict facies are interpreted as beaches and coastal barriers associated with coastal spits located in the ancient outlets of rivers. They were deposited along the entire ancient coastline during periods of low sea level, and have been eroded by the continuous variations in sea level, forming the extent erosional surfaces.

The forms described are grouped in well-differentiated bathymetric groups. This leads us to deduce that their preservation has depended on several factors: the original topography of the continental shelf and its subaerial exposure, wave energy, the volume of sedimentary contribution, neotectonic activity, and the relative exchange rate of the sea level and its fluctuations (Hernández-Molina *et al.*, 1996). Bathymetric groups indicate the differential behaviour of the sea level obrt time, with longer gaps during the periods when these sedimentary elements were being deposited.

Relict facies of the same nature have been described by Hernández-Molina (1993) for the northwestern coast of the Alborán Sea, and by Gutiérrez-Mas (1992) and Rodríguez-Vidal, Cáceres and

Rodríguez-Ramírez (1992) for the continental shelf of the Gulf of Cadiz.

In terms of the evolution of sedimentary dynamics, the arrangement of the sediments on the continental shelf of Huelva is a consequence of the phenomena affecting the platform during the last sea-level rise. During the Holocene, this rise favoured the accumulation of fine sediments of river origin on the internal continental shelf (Swift and Thorne, 1991), especially in the zones near the mouths of the large rivers (as, in this case, of the Guadiana), while coarser and better-sorted sediments are found in the zones of little sedimentation. The erosion of the coastal deposits and the development of the retrograding bodies took place during the Flandrian transgression (14 000-6 000 years BP) (Aloïsi, 1986; Rodrigues, Magalhaes and Alveirnho Dias, 1992). Thus, the sands of the shallowest zones are considered coastal deposits of high energy, accumulated during the sea-level rise. These sands have not been covered by fine fluvial sediments due to the latter's small contribution, or because the sediments have remained within the estuaries. Highstand system tract has been developed during the last 6 000 years (Aloïsi, 1986; Hernández-Molina *et al.*, 1994). During this period, the prodelta of the Guadiana has developed and been redistributed westward by the currents of the continental shelf. Possibly, ancient sediments have been turned over in the zones of lower sedimentation rate, generating palimpsest-type deposits (Gutiérrez-Mas *et al.,* 1995).

The characteristics of the outcropping relict facies indicate that their final configuration may be related with the construction processes of the platform, as well as with the greater Holocene transgressive phases.

ACKNOWLEDGEMENTS

Our thanks to the Ministerio de Obras Públicas, Transportes y Medio Ambiente for giving us the possibility of accessing the geophysical data off the Huelva coast, and to the CICYT (Comisión Interministerial de Ciencia y Tecnología) Research Project PB-91-0622-C03-03 for enabling us to use the geophysical information of the study area. This study is part of IGCP research project 396 entitled Continental Shelves in the Quaternary.

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