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# Geomorphology of the Eastern Algarve proximal continental margin (South Portugal, SW Iberia Peninsula): sedimentary dynamics and its relationship with the last asymmetrical eustatic cycle

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## Resumo

***Palavras-chave*:** geomorfologia, margem continental proximal, Plistocénico Superior-Holocénico, variações do nível do mar, Algarve Oriental.

Quatro categorias morfológicas foram reconhecidas em dados de reflexão sísmica de alta resolução na margem continental proximal do Algarve Oriental (Sul de Portugal): deposicionais (prisma litoral, prodelta, cobertura sedimentar de plataforma e acumulação de talude), erosivas (paleocanais, terraços submarinos, superfície transgressiva e superfície erosiva no talude), gravíticas (deslizamentos e slumps) e neotectónicas (escarpa). Estas morfologias foram geradas no Plistocénico Superior-Holocénico em consequência da relação complexa entre vários factores, designadamente, a taxa de acarreio sedimentar, as condições oceanográficas, a actividade neotectónica e as variações eustáticas durante o último ciclo eustático, desde o baixo nível do mar ao presente alto nível do mar. As variações do nível do mar durante o Plistocénico Superior-Holocénico foram o principal factor controlador e modelador do desenvolvimento das morfologias deposicionais e erosivas.

## Abstract

***Key-words*:** geomorphology, proximal continental margin, Late Pleistocene-Holocene, sea-level changes, Eastern Algarve

Four morphological categories were recognised using high-resolution seismic data on the Eastern Algarve proximal continental margin (South Portugal): depositional (littoral prism, prodelta, shelf sedimentary cover and slope accumulation), erosive (palaeo-channels, submarine terraces, transgressive surface and erosive surface over the slope), gravity (slides and slumps), and neotectonic (submarine scarp). These morphologies were generated during the Late Pleistocene-Holocene, as a result of the interplay between several factors, namely, the rate of sedimentary supply, the oceanographic conditions, the neotectonic activity and the sea-level changes from the last lowstand to the present highstand related with the last eustatic cycle. The Late Quaternary sea-level changes have been the main control and modelling factor for the development of most depositional and erosional morphologies.

## 1. Introduction

During the last decades the systematic acquisition of multibeam bathymetry, side-scan sonar, high and very-high resolution seismic reflection data at continental margins revealed the existence of a complex morphology. These methods allowed the improvement of the knowledge of the geomorphology of the continental margins in detail and better understanding of how the different morphogenetic processes act.

Although, the multibeam bathymetry is one of the most used and useful types of data in geomorphologic analysis, the use of high and very-high resolution seismic profiles allow the knowledge of the internal structure and geometry of the morphologic features, giving information about how the morphogenetic processes acted and changed through time. Derived from the interpretation of this kind of data several authors (e. g. Hernández-Molina, 1993; Díaz-del-Río & Somoza, 1994; Lobo, 1995; Roque, 1998; Roque *et al.*, 2000, 2002) proposed a morphological classification based on the identification of the main modelling processes. According this classification, the submarine forms can be grouped into four categories: a) depositional morphologies, when sedimentary processes are dominant; b) erosive morphologies, when erosive processes prevail; c) gravity morphologies, when they are associated with gravity-driven mass-fluxes; d) neotectonic morphologies, generated by recent tectonic activity.

The aims of this paper are to present a physiographic and a morphological analysis of the Eastern Algarve proximal continental margin and to propose a morphogenetic evolutionary model correlating the genesis of the identified forms with the Late Pleistocene-Holocene climate and sea-level changes.

## 2. Study area framework

The study area is located in the southern Portugal and corresponds to the Eastern Algarve proximal continental margin off Quarteira (western area) and the Guadiana river mouth (eastern area). It covers about 2 240 km$^2$ and is comprised between 37º 08' N and 36º 53' N and 8º 05' W and 7º 19' W (fig. 1). It forms, together with the adjacent Spanish area, the northern border of the Gulf of Cadiz.

### 2.1. *Geological setting*

The stratigraphic and tectonic framework of the South Portuguese continental margin have been investigated in the past decades by several authors, e. g. Baldy (1977), Baldy *et al.* (1977), Mougenot *et al.* (1979), Mougenot (1988), Terrinha (1998), Lopes (2002a), Lopes (2002b), Lopes *et al.* (2006), Roque *et al.* (2006), Matias (2007), Roque (2007), using seismic reflection methods, gravity and piston cores and oil-drills. The Meso-Cenozoic stratigraphic record of Algarve continental margin spans from the Triassic to Quaternary times, with a regional unconformity between the Late Cretaceous and the Paleogene or Miocene. A correlative hiatus/unconformity is also recognized onshore Algarve Basin between the Cenomanian and the early/middle Miocene (Pais *et al.*, 2000; Cachão & Silva, 2000). The oldest Neogene deposits drilled in offshore Algarve Basin consists of Burdigalian limestones (Roque, 2007), followed by middle-late Miocene calci- and silici-clastic sequences composed of sand, silt and mud, and developed on the continental shelf and slope. In the continental shelf, the Pliocene-Quaternary sequences consist of alternating sand and mud layers showing a progradational organization of the strata. On the continental slope, Pliocene pelagic carbonate mud is overlain by Pleistocene silty-mud (Baldy, 1977; Mougenot *et al.*, 1979; Mougenot, 1988). Holocene deposits are made up by sand and mud (Moita, 1986).

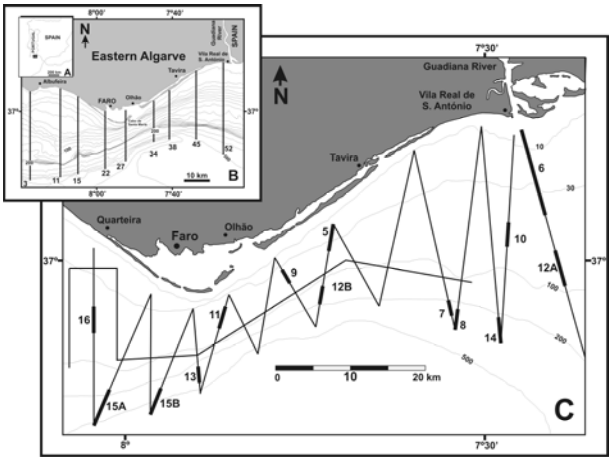

**Fig. 1** – Location of the study area at the Eastern Algarve proximal continental margin (A) and the location of the batimetric profiles shown in Fig. 3 (B) and position of the studied seismic profiles (C). Labels on seismic profiles correspond to numbers of figures in which they are shown.

The main structural features present in the Algarve margin are major fault systems trending NE-SW to E-W, N-S and NW-SE. One of the most important faults is the Quarteira fault that trends NW-SE and separates the eastern and western parts of the Algarve margin (Díaz-del-Rio *et al.*, 1997; Terrinha, 1998; Maestro *et al.*, 1998; Vázquez *et al.*, 1998, Terrinha *et al.*, 2002). Evidences of recent tectonic activity are ancient beaches located at several meters above the present sea-level, normal and reverse faults trending respectively ENE-WSW to NNW-SSE and E-W or N-S and flexures identified onshore or in the continental shelf (Dias & Cabral, 1995a, 1995b, 1995c, 1997a, 1997b; Carrilho *et al.*, 2005). More recent work on the deepest realm of the Gulf of Cadiz have produced images and maps of present day fault activity, mainly along NE-SW thrusts (e.g. Gràcia *et al.*, 2003; Terrinha *et al.*, 2003; Medialdea *et al.*, 2004; Zitellini *et al.*, 2004) and new models of the SW Iberia-NW Africa were also proposed (Gutscher *et al.*, 2002; Zitellini *et al.*, 2009)

The first detailed physiographic and morphologic studies of Southern Portuguese continental shelf were carried out by Mougenot & Vanney (1980) and Vanney & Mougenot (1981), based on medium resolution seismic profiles interpretation and detailed analysis of single beam bathymetry. These authors identified several forms and classified them in four surface categories based on the geometric relationship between the seafloor slope and the structure and age of the sedimentary units: accumulation surfaces, prograding surfaces, erosive surfaces and structural surfaces. Mougenot & Vanney (1980) and Vanney & Mougenot (1981) recognized in the Eastern Algarve continental shelf only the first two morphological categories, respectively, a widespread deltaic front associated with the Guadiana River and a prograding wedge. This reduced number of forms that were identified by these authors is the result of the low resolution of the seismic profiles used in their studies.

### 2.2. *Oceanographic conditions*

The coast of the Algarve is characterized by wave-regime less than 1 m wave height and by a less than 5 seconds mean period (Instituto Hidrográfico, 1994) and is a mesotidal type of coast with an average tidal range of 2 m (Moita, 1986; Morales-González, 1995a, 1995b, 1997; Dabrio *et al.*, 1996). Storm-waves and daily winds that blow from the southwest induce a prominent littoral drift towards east. This current flows parallel to the shoreline with a speed less than 25 cm/s (Moita, 1986).

Among the water masses involved in the oceanic circulation dynamics in the Gulf of Cadiz, the Atlantic Surface Water (ASW) and the Mediterranean Outflow Water (MOW) are the main water masses that control the present-day sedimentary dynamics in the Algarve proximal margin (Caralp, 1988, 1992; Ochoa & Bray, 1991). This oceanic circulation is mainly driven by density difference between the water masses of Atlantic and Mediterranean origin that flow on either side of the Strait of Gibraltar (Tomczak & Godfrey, 1994; Baringer & Price, 1999). The ASW is a water mass, isohaline of about 36.4‰, that flows southeastwards across the Gulf of Cadiz above 100 m depth (Ambar & Howe, 1979; Nelson *et al.*, 1993, 1999). The MOW is a warm and saline water mass, characterised by temperatures of about 13º C and salinity higher than 36.5‰. It spreads westwards out from the Strait of Gibraltar as a high velocity and density-driven bottom current (Tomczak & Godfery, 1994; Baringer & Price, 1999), at water depths between 500 and 1500 m (Madelain, 1970; Mélières, 1974; Ambar & Howe, 1979; Ambar, 1982; Caralp, 1988, 1992; Ochoa & Bray, 1991). The more superficial branch of this undercurrent flows parallel to the northern Gulf of Cadiz continental slope contour between 500 and 900 m depth. The influence of the MOW on the sedimentary dynamic over the Gulf of Cadiz continental slope is shown by development of sand bedforms of several scales like dunes and ripples and by the build-up of a thick sandy contourite body named Faro-Albufeira Drift (Kenyon & Belderson, 1973; Vanney & Mougenot, 1981; Faugères *et al.*, 1984; Gonthier *et al.*, 1984; Mougenot, 1988; Nelson *et al.*, 1993, 1999). The MOW has also an erosive action on the northern side of this contourite drift, contributing to the narrowing of the Algarve continental slope off Faro and Albufeira.

### 2.3. *Distribution and dynamics of superficial sediments*

The distribution of the superficial sediments in the Eastern Algarve continental shelf and on the upper slope shows some characteristics that distinguish it from the others sectors of the Portuguese shelf (Moita, 1986), namely: a) the presence of a great variety of sedimentary types and size classes; b) the predominance of bioclastic sand and gravel, showing in this way the deficiency of fluvial input into the shelf; c) high silty-mud content pointing to lower energetic levels.

The main sources of sediments into the continental shelf of Algarve are cliffs erosion and rivers input, mainly Guadiana River (Andrade, 1990; Marques, 1991). Both processes are responsible by an annual transport into the shelf of about 8.7 x 10 5 $m^3$ of coarse-grained sediments and 7.4 $x10^6$ $m^3$ of fine-grained sediments (Magalhães, 2001). The sands that reach the continental shelf are reworked and remobilized by eastwards longshore currents. Only the fine particles that are transported in suspension are deposited in the shelf. Magalhães (2001) estimated that only 14% of the fine-grained sediments that reach the shelf are in fact deposited there, since the other 86% are transferred to greater depths. Slope sedimentation is controlled by suspension transport, mass gravitational processes and at greater depths by the MOW.

The spatial distribution of the recent deposits shows a general east-west trend almost parallel to the coastline, controlled by the eastwards active littoral drift and the action of the ASW circulation (Moita, 1986). Five main types of surperficial deposits are recognised in the Eastern Algarve continental shelf and slope by Moita (1986) and Magalhães (2001), based on the textural characteristics, composition and physiographic distribution: a) littoral sands; b) middle-shelf sands and gravel; c) middle-shelf muds; d) outer shelf and shelf edge sands and gravel; e) upper slope muds.

The littoral domain is covered by littoral sands that trend parallel to the shoreline and reach about 30 m water depths (Moita, 1986), consisting of a modern deposit constantly winnowing and reworking by the action of waves and currents. These coastal deposits correspond to quartz medium-to-fine sands and in minor extent to biogenic gravel with almost 70% of its terrigenous component originated both by cliffs erosion and wave-currents destruction of ancient littoral sand-bodies (Magalhães, 2001).

The inner continental shelf is cover by quartz-bioclastic sands, which shows large grain-size variability. The presence of mud in the easternmost part of the inner-middle shelf is related to the presence of Guadiana River prodelta deposits.

The middle continental shelf is covered by coarse to medium grained bioclastic sandy deposits, which occur at several water depths. Their grain-size is not in equilibrium with the present-day hydrodynamic conditions, and so they are classified as marine relic-palimpsest deposits (Moita, 1986; Magalhães, 2001). The others sectors of the middle-shelf, are cover by mud and sandy-mud.

In the outer continental shelf and shelf edge bioclastic coarse-grained sands and gravel occur. They are classified by Moita (1986) and Magalhães (2001) as relict deposits, however, with a small modern component of foraminifera and muddy sediments.

The continental slope is covered by modern hemipelagic deposits composed of fine-grained sand, sandy-mud and rich-montmorillonite mud (Moita, 1986). Rare bioclastic gravel deposits are present in some places, corresponding to relic-palimpsest sediments (Magalhães, 2001).

## 3. Data set and methods

The bathymetric map of Faro produced by Vanney & Mougenot (1981), based on single beam data, was used for physiographic analysis and 56 N-S bathymetric profiles were made (fig. 1B). Morphological analysis was achieved by means of seismic stratigraphy interpretation of 417 km of high and very high-resolution seismic profiles (fig. 1C). These were acquired during the Spanish-Portuguese oceanographic cruise FADO-9611 onboard the B/O *Francisco Paula Navarro* using a Uniboom system (Geopulse$^{TM}$ 280 J, shot delay of 500 ms, recording scale of 200 ms) and sub-bottom profiler (3.5 kHz, 100 ms recording interval). Positioning was made using a Differential Global Positioning System (DGPS).

Description, classification and mapping of the seafloor morphologies were based on seismic stratigraphy interpretation following the methodology developed by Mitchum *et al*. (1977). A sound velocity of 1500 m/s was used for time-to-depth conversion on the 3.5 kHz profiles and of 1650 m/s on the Geopulse record, providing an estimate of seismic units minimum thickness. A comparative analysis between the morphologies identified in the Eastern Algarve proximal margin and similar features reported around the world and on the Northern Portuguese and Spanish proximal margins (e.g Dias, 1987; Hernández-Molina, 1993; Lobo 1995) was done.

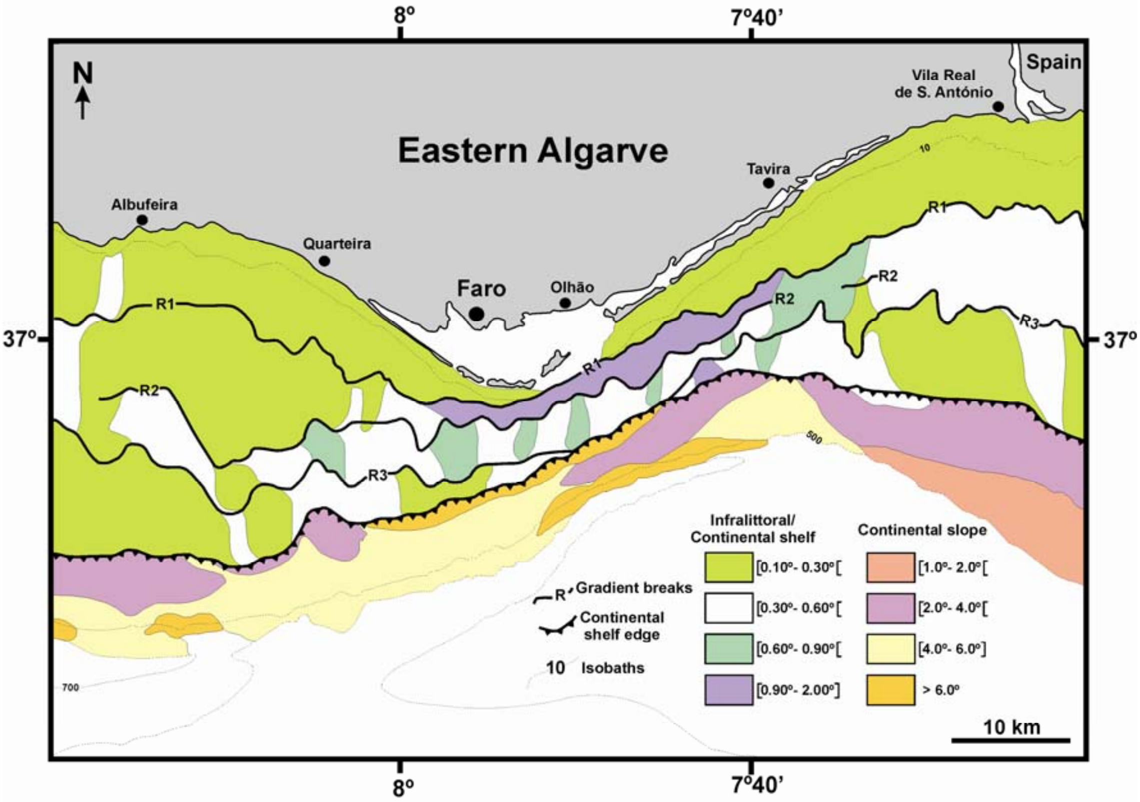

**Fig. 2** – Physiographic domains of the Eastern Algarve proximal margin and gradient breaks.

## 4. Results

### 4.1. *Physiography*

In the Eastern Algarve proximal continental margin four physiographic domains were identified considering gradient values and depth of major gradient breaks (fig. 2; Tab. I): infralittoral, continental shelf, continental shelf edge and continental slope. The infralittoral domain is nearly 8 km wide and extends to about 30-35 m water depth, being characterised by a gentle average gradient of 0.21°. The continental shelf is quite narrow, ranging from 5 km in the western part in front of Faro to its maximum width, around 20 km, off the Guadiana River mouth. The average gradient of the continental shelf is 0.40°, increasing westwards to 0.53°. Three physiographic sub-domains are differentiated, considering the seafloor gradients: the inner shelf, that reaches an average depth of 60 m, with gradients between 0.26° and 0.40°, but reaching locally 0.84°; the middle shelf located at 75-80 m water depth, with an average gradient of 0.50°, although in some zones the values are greater than 0.60°; the outer shelf, located between 90-100 m water depth, with gradients of about 0.30°-0.40°. The continental shelf edge is located at an average depth of -120 m, however it becomes deeper off the Guadiana River where it reaches -140 m. The shelf edge morphology evolves from smooth in the eastern part, off the Guadiana River, to abrupt in the western part off Faro-Tavira sector. The steep continental slope extends to depths of about 500 m in the eastern sector and 700 m in the western sector, showing average gradients of 4.0º, reaching its maximum value of 6.0º off the Faro-Tavira sector.

| ***Physiographic domains and sub-domains*** | ***Slope gradient (º)*** | ***Width (km)*** | ***Depth (m)*** |
|---|---|---|---|
| *Infralittoral* | 0.21 | 8 | 30-35 |
| *Continental shelf* | 0.40-0.53 | 5-20 | 35-100 |
| *Inner continental shelf* | 0.26-0.40 | ------- | 60 |
| *Middle continental shelf* | 0.50-0.60 | ------- | 75-80 |
| *Outer continental shelf* | 0.30-0.40 | ------- | 90-100 |
| *Continental shelf edge* | 3.04 | 2 | 100-140 |
| *Continental slope* | 4 | 10 | 500-700 |

**Table I** – Average slope gradient, width and depth of the physiographic domains and sub-domains of the Eastern Algarve proximal margin.

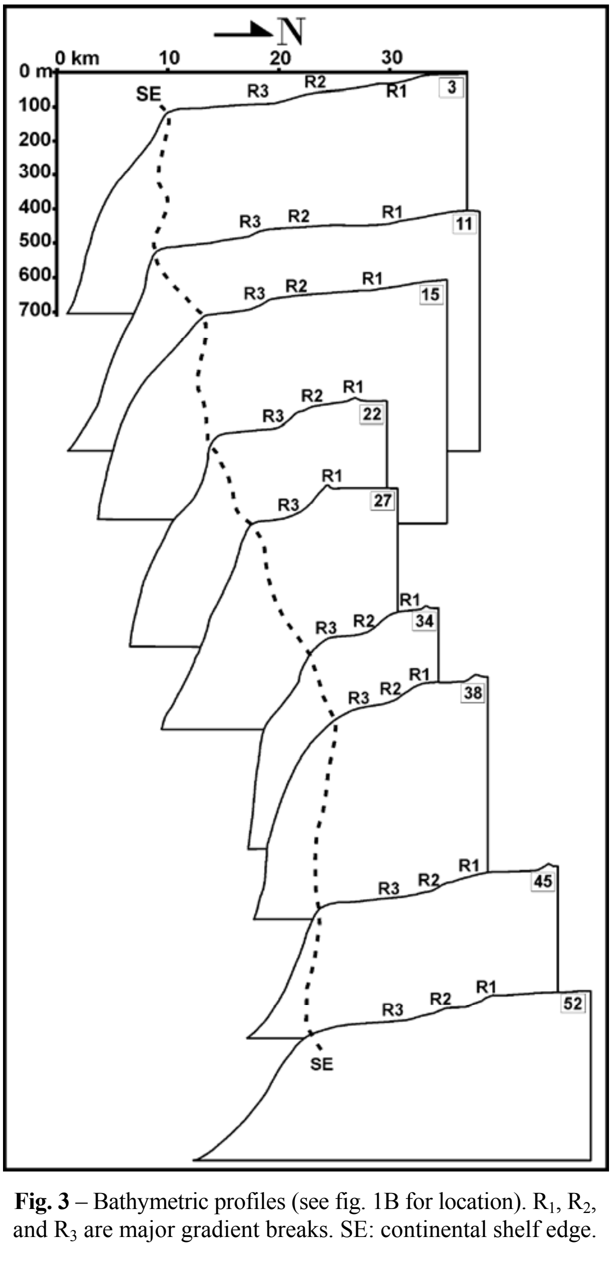

**Fig. 3** – Bathymetric profiles (see fig. 1B for location). $R_1$, $R_2$, and $R_3$ are major gradient breaks. SE: continental shelf edge.

In the Eastern Algarve continental shelf, three major gradient breaks (excluding the shelf edge) can be recognized at an average water depth of 30 m ($R_1$), 60 m ($R_2$), and 90 m ($R_3$) (fig. 3). The gradient break $R_1$ is the littoral boundary. The gradient break $R_2$ is located in the deepest parts of the inner-shelf and in the medium-shelf domains. The gradient break $R_3$ coincides with the inner edge of the outer shelf. A localized break of gradient is recognised off Faro-Olhão sector at about 10 m water depth probably related to sand ridges of the Ria Formosa barrier islands system (Moita, 1986; Andrade, 1990). The gradient breaks $R_1$, $R_2$, and $R_3$ are probably related to wave erosion at previous sea-level positions. The major gradient breaks are located at similar depths as those reported by Dias (1987) in the North Portuguese continental margin. This author identified gradient breaks at depths of 30-40 m ($R_a$), 50-90 m ($R_b$), 90-115 ($R_c$), and 125-145 m ($R_d$). The latter is unidentified in the Eastern Algarve proximal continental margin probably due to bottom-currents erosion.

## 4.2. *Characterisation and mapping of seafloor morphologies*

The morphologies identified in the Eastern Algarve proximal continental margin are included into four morphogenetic categories: depositional, erosive, gravity and neotectonic.

### 4.2.1. Depositional morphologies

#### *4.2.1.1. Littoral prism*

Two littoral prims have been identified, modern and ancient. The modern Faro-Tavira littoral prism is a large sedimentary body that extends for more than 40 km parallel to the coastline offshore Quarteira-Tavira showing a prograding wedge geometry with a shoreward gentle slope (1.5º) and a seaward steep slope (5.0º) (fig. 4). Its edge is located at water depths ranging from about 40 m in the eastern to 35 m in the western (fig. 5). The lower boundary of the littoral prism is a gentle seaward downlap surface, with gradients of 0.7º to 1.0º, characterised by high amplitude and lateral continuity and its upper boundary is a toplap surface, corresponding to the present day sea-floor. The internal reflection pattern shows, in its proximal part, an aggradational configuration with sub-horizontal reflectors progressively steeper seaward, defining a progradational sigmoidal-oblique configuration (fig. 5). This configuration is typical of high-energy wave-dominated environment (Sangree & Widmier, 1977), associated with significant supply of coarse-grained sediments. This assumption is corroborated by the high-reflectivity acoustic response on 3.5 kHz seismic profiles pointing to a coarse-to-medium grain-size deposit and by the presence off Faro-Tavira area of a coarse-litho-bioclastic sand body between 10 and 30 m water depth (Moita, 1986). It can be correlated with the "littoral sands deposits" described by Moita (1986) and Magalhães (2001). The major development of this littoral prism is in central area (Faro-Tavira sector), where it reaches a maximum thickness of about 20 m off Tavira and decreases westwards to a minimum of 12 m. The seismic profiles show that this littoral prism is an isolated sedimentary body unrelated to deltaic deposits as have been suggested previously by Vanney & Mougenot (1981).

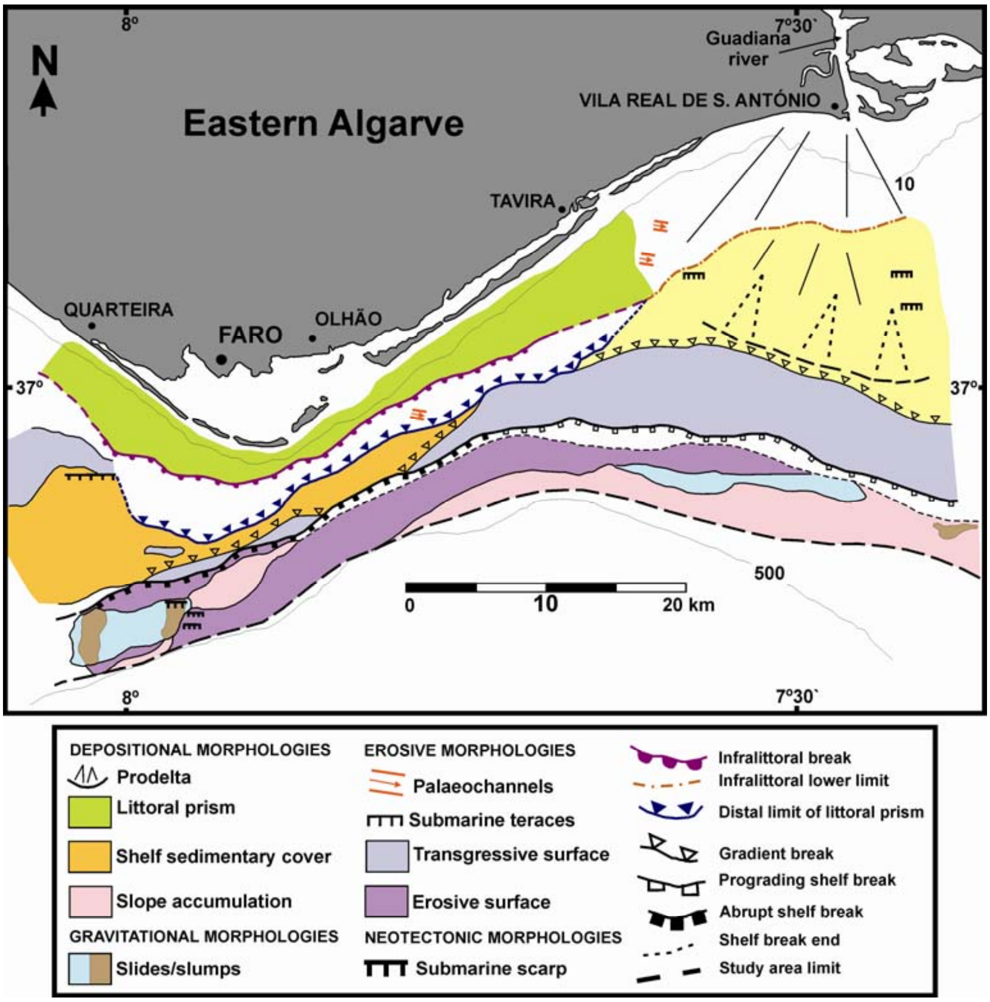

**Fig. 4** – Geomorphological map of the Eastern Algarve proximal continental margin.

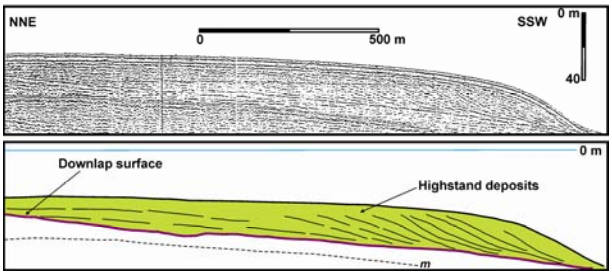

**Fig. 5** – Depositional morphology: littoral prism. It shows a sigmoidal-oblique progradational wedge configuration and its basal boundary is a downlap surface. The Geopulse profile location is shown in fig. 1.

The Faro-Tavira littoral prism shows similar acoustic response and facies architecture to progradational sedimentary bodies reported in Spanish Atlantic and Mediterranean areas, named “Infralittoral Prograding Wedge” by Hernández-Molina *et al.* (1995, 1998, 2000a).

The ancient littoral prism is identified off Quarteira at about 70 m water depth.

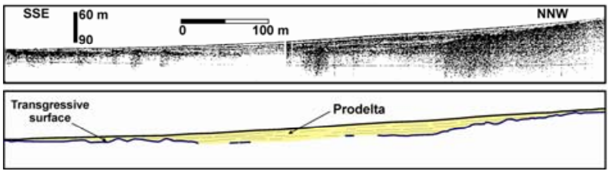

**Fig. 6** – Depositional morphology: prodelta. It shows stratified seismic facies characterised by parallel and continuous reflectors that become gently inclined seaward defining bottomset facies. The 3.5 kHz profile location is shown in fig. 1.

#### *4.2.1.2. Prodelta*

The deltaic morphology is represented by the Guadiana prodelta. It extends over than 25 km parallel to the coast on its Portuguese part, from Tavira to its mouth in the Portuguese-Spanish border (fig. 4), and offshore it reaches about 95 m water depth. The prodelta is below the effective depth of wave erosion and shows a smooth surface with average gradients of about 0.40º decreasing seaward. The sector of the continental shelf where the Guadiana prodelta developed is characterized by small gradients (about 0.30º- 0.40º) and by the absence of any submarine relief.

The 3.5 kHz records display a prodelta seismic unit that overlies the basal transgressive deposits (fig. 6) (Roque, 1998; Roque *et al.*, 1998). Seismic unit presents transparent or stratified seismic facies characterised by parallel, sub-horizontal continuous reflectors that become gently inclined basinward defining bottomset terminations (fig. 6). These seismic facies suggest a low-energy regime (Sangree & Widmier, 1977) and thus a mud-rich prodeltaic deposit containing little to negligible sand fraction. The presence of these prodeltaic muds that are in equilibrium with the present-day hydrodynamic regime is recognised by Moita (1986) and Magalhães (2001). Guadian prodelta reaches 15 m of maximum thickness (Roque, 1998; Roque *et al.*, 2000).

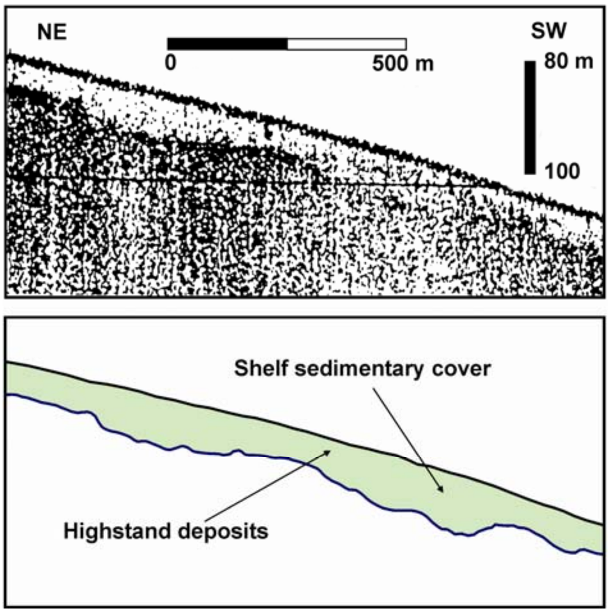

**Fig. 7** – Depositional morphology: shelf sedimentary cover. This morphological type shows transparent seismic facies, which are typical of acoustic response of fine-grained deposits. The 3.5 kHz profile location is shown in fig. 1.

*4.2.1.3. Continental shelf sedimentary cover*

The continental shelf sedimentary cover is generated by a thin deposit (<10 m thick) that smoothes the sea-floor topography and its surface present a gentle seaward dipping gradient (fig. 7). It covers the underlying erosive irregularities. This morphology exhibits layered seismic facies with sub-horizontal reflectors showing weak reflectivity and lateral continuity or transparent seismic facies, especially in the 3.5 kHz seismic profiles, suggesting fine-grained sediment. The continental shelf sedimentary cover morphology is present over a large area, in both eastern and western sectors of the study area. It occurs mainly in the middle shelf, but also extends to the outer shelf in some areas, becoming thinner towards the shelf edge. However, between Faro and Tavira, where the continental shelf is narrower, the continental shelf sedimentary cover shows little to no development (fig. 4). This morphology can be related to the "middle-shelf muds deposits" described by Moita (1986) and Magalhães (2001). These are modern deposits formed by the suspended-load sediments delivered mostly by Guadiana River.

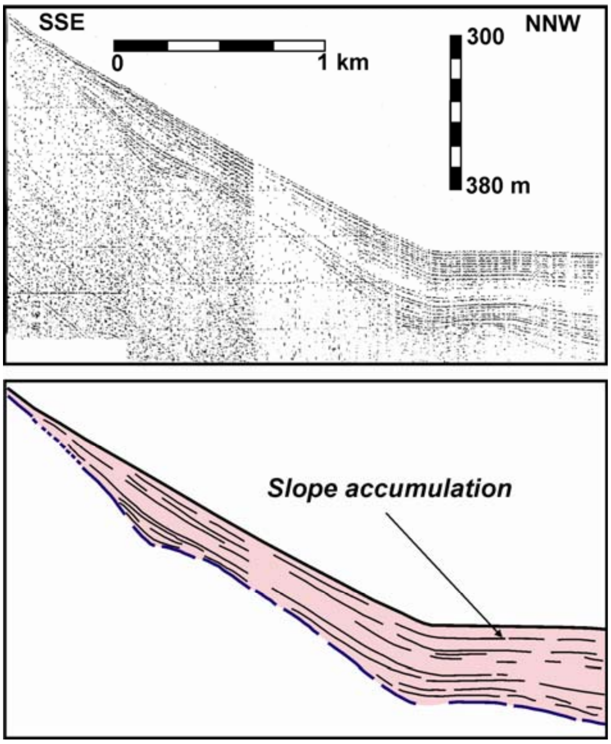

**Fig. 8** – Depositional morphology: slope accumulation. This morphological type constitutes a laterally stratified seismic unit prograding divergently on the upper slope and becoming parallel basinwards. The Geopulse profile location is shown in fig. 1.

*4.2.1.4. Continental slope accumulation*

The continental slope accumulation gives smooth convex-concave topography to sea-floor and it is related to prograding deposits (fig. 8). The seismic facies shows reflectors with strong reflectivity and high lateral continuity. This constitutes a laterally stratified seismic unit prograding divergently on the upper slope and becoming parallel basinward (fig. 8). On the shelf-edge and proximal parts of the upper continental slope the strong acoustic response results from the presence of sandy shelf-edge prograding wedges. The continental slope accumulation is best developed on the eastern sector, off Guadiana River, where it reaches the maximum thickness of 65 m. The continental slope area covered by this feature is about 4 km wide in the eastern sector decreasing towards Faro where it occurs only in small areas, some of them having only 0.5 km width (fig. 4).

### 4.2.2. Erosive morphologies

*4.2.2.1. Palaeo-channels*

A few number of palaeo-channels are identified in the Eastern Algarve continental shelf (fig. 4). Towards the east (off Tavira) they are found below 35 m water depth, trending approximately NW-SE. Towards the west (Faro-Olhão), they are found at about 80 m water depth and trend NE-SW. The maximum depth of the thalweg is located at about 114 m below present-day sea-level and the maximum depth incision of the palaeo-channels is around 40-50 m. These features that are identified on high-resolution seismic profiles are not present-day morphologies, as do not have topographic expression on the sea-floor. They are ancient fluvial channels filled with sediments and therefore they could be classified as relic forms. However, they preserve the ancient fluvial morphology, corresponding to "V"-shape depressions with steep erosive walls. In some cases the palaeo-channels walls are affected by faults (fig. 9). These erosive morphologies contain a sedimentary infill characterised by chaotic reflectors with low reflectivity. They are truncated at the top by an erosive surface, the transgressive surface, which is the lower boundary of overlying transgressive deposits (fig. 18) (Roque, 1998; Roque *et al*., 1998).

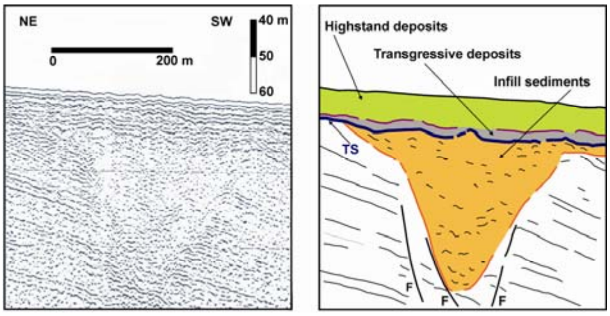

**Fig. 9** – Erosive morphology: paleo-channel. Its walls are bounded by faults and it is filled with sediments showing hummocky and chaotic seismic facies. It is truncated on its top by the transgressive surface, which is covered by transgressive deposits. The Geopulse profile location is shown in fig. 1.

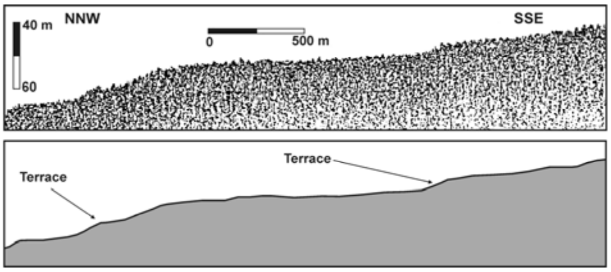

**Fig. 10** – Erosive morphology: submarine terraces. They correspond to small scarp features with the steep face seawards. The 3.5 kHz profile location is shown in fig. 1.

### *4.2.2.2. Submarine terraces*

The submarine terraces are identified on the continental shelf as small scarp features only a few meters high and trend nearly parallel to the bathymetric contours and show steep seaward slopes and gentle landward gradients (fig. 4 and fig. 10). They were recognised on the inner and middle continental shelf between 50 and 84 m water depth and can be grouped in five sets, respectively: $T_1$ at 50 m, $T_2$ at 58 m, $T_3$ at 64-68 m, $T_4$ at 72 m, and finally $T_5$ at 84 m (Tab. II). The occurrence of identical morphologies, found at similar water depths in other Iberian continental shelves, has been reported by several authors, namely, in the northern Portuguese continental shelf (Musellec, 1974; Dias, 1987), in the south-west Portuguese shelf (Baldy, 1977; Gierloff-Ermen *et al*., 1979), in the Gulf of Cadiz (Lobo, 1995; Lobo *et al*., 2001), and in the Alboran Sea (Hernández-Molina, 1993; Hernández-Molina *et al*., 1994b, 1996a). Fleming (1972) reported the presence of submarine terraces in Gibraltar area and along the Mediterranean. All terraces recognised in those shelves can be included in five sets raging from 45 to 84 m water depth: $T_a$ between 45 and 52 m; $T_b$ between 55 and 60 m; $T_c$ between 65 and 68 m; $T_d$ between 70 and 75 m; $T_e$ between 80 and 84 m (Tab. II). Among all these groups, the terraces placed between 65 and 68 m depth ($T_c$) have been reported in all the shelves. This suggests the occurrence of at least a regional episode of wave-cutting terraces.

| *Continental shelves* | $T_a$ | $T_b$ | $T_c$ | $T_d$ | $T_e$ |
|---|---|---|---|---|---|
| **Northern Portuguese shelf** *(Musellec, 1974)* | - | - | 65 | - | 80 |
| **Northern Portuguese shelf** *(Dias, 1987)* | 45 | 60 | 65 | - | - |
| **South-west Portuguese shelf** *(Baldy, 1977)* | 45<br>- | -<br>- | 65<br>67 | -<br>- | -<br>- |
| **South-west Portuguese shelf** *(Gierloff-Ermen* et al., *1979)* | - | - | 67 | - | 82 |
| **Gulf of Cadiz** *(Lobo, 1995)* | -<br>- | -<br>- | 65<br>68 | 73<br>- | -<br>- |
| **Gulf of Cadiz** *(Lobo* et al., *2001)* | 49 | - | - | 71 | - |
| **Alboran Sea** *(Hernández-Molina* et al., *1996)* | 47<br>50<br>- | 55<br>60<br>- | 65<br>-<br>- | 70<br>73<br>75 | 80<br>-<br>- |
| **Mediterranean Sea *(a)*** *(Flemming, 1972)* | - | 55 | - | - | - |
| **Mediterranean Sea *(b)*** *(Flemming, 1972)* | 46<br>52 | -<br>- | 67<br>- | 72<br>- | 79<br>- |
| **Algarve Shelf** *(Roque, 1998)* | **$T_1$**<br>**50**<br>**-** | **$T_2$**<br>**58**<br>**-** | **$T_3$**<br>**64**<br>**68** | **$T_4$**<br>**72**<br>**-** | **$T_5$**<br>**84**<br>**-** |

**Table II** – Correlation between the groups of submarine terraces identified in the Eastern Algarve continental shelf ($T_1$ to $T_5$), and similar features reported in others Iberian and Mediterranean shelves. All of these submarine terraces can be grouped in five sets considering their water depth ($T_a$ to $T_e$). The terraces located at 64-68 m water depth (group $T_c$) are the best represented in all the shelves. (a) major features; (b) small features.

In the Eastern Algarve continental shelf some terraces are fossil morphologies since at present they are covered by sediments and do not have any topographic expression on the sea-floor (fig. 11). These older terraces, recognised at water depths below 80 m, can be laterally correlated with aggradational and progradational deposits, which show a sheet-like or lobate external shapes and their internal configuration can be parallel or slightly sigmoidal showing onlap landward terminations and downlap seaward (fig. 11). The deepest terraces (72 and 84 m depth) are located off the Quarteira-Faro sector (western area), while the shallowest (50 m depth) occur in the easternmost Tavira-Guadiana sector. This could occur because in the former sector the shallow terraces are presently buried by the littoral prism deposits.

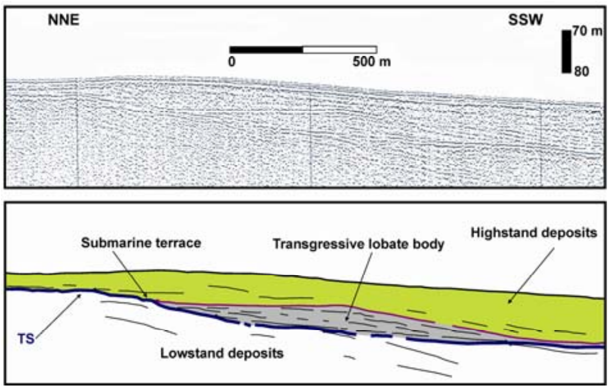

**Fig. 11** – Erosive morphology: submarine terrace and associated lobate body showing the onlap of the reflectors landward. It corresponds to a parasequence of the transgressive system tract (TST). The Geopulse profile location is shown in fig. 1.

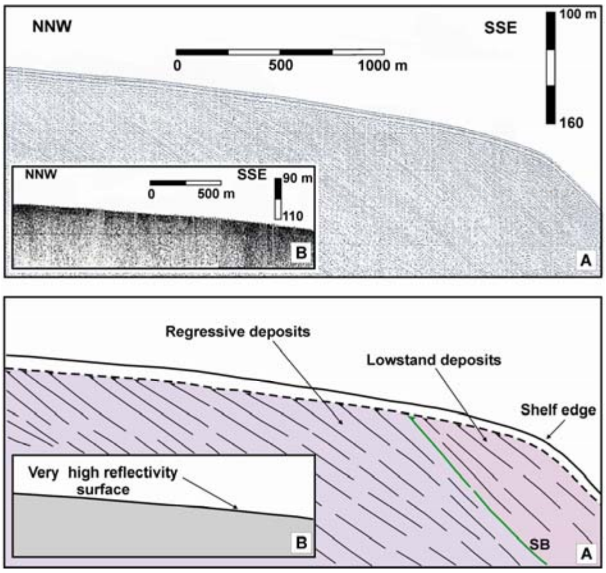

**Fig. 12** – Erosive morphology: transgressive surface. It is characterised by the truncation of the underlying reflectors (A) and by a strong acoustic response in the 3.5 kHz profile (B) The Geopulse and 3.5 kHz profiles location is shown in fig. 1.

### *4.2.2.3. Transgressive surface*

The transgressive surface is an almost flat and rough erosive surface gently dipping seaward. It occurs in the outer continental shelf at an average water depth of 90-100 m and extends to the continental shelf edge. This surface truncates the underlying reflectors and is well identified in the 3.5 kHz seismic profiles because it shows a very high reflectivity (fig. 12). This strong acoustic response could suggest the presence either of coarse-grained sediments or small irregularities across the outer shelf surface. In fact, the outer shelf is covered by the "outer shelf sand and gravel deposits" recognised by Moita (1986) and Magalhães (2001). The partial lithification of the transgressive surface (Hernández-Molina, 1993) could be also another explanation for its high reflectivity.

Like most of the morphologies identified in the study area, the transgressive surface is best developed in the eastern sector (Tavira-Guadiana area), where it is 6 km wide, decreasing towards the west and reaching its minimum width offshore Faro (fig. 4).

The transgressive surface is the lower boundary of the transgressive deposits that constitute aggradational and backstepping parasequences of the transgressive systems tract (TST) identified in the Eastern Algarve continental shelf (Roque, 1998; Roque *et al.*, 1998) (fig. 18), which of them bounded by ravinement surfaces. The transgressive surface is an erosive surface that represents the first main event of marine flooding across the shelf after the lowstand stage (Van Wagoner *et al.*, 1988; Haq, 1991; Vail *et al.*, 1991). The ravinement surface is a surface formed by transgressive erosion during landward shoreface retreat (Nummedal & Swift, 1987; Suter *et al.*, 1987; Swift & Thorne, 1991; Thorne & Swift, 1991).

### *4.2.2.4. Erosive surface over the continental slope*

The erosive surface over the continental slope is a steep seaward dipping rough surface due to the presence of small depressions (fig. 13). It is represented all over the slope, affecting an area that becomes wider westwards (fig. 4).

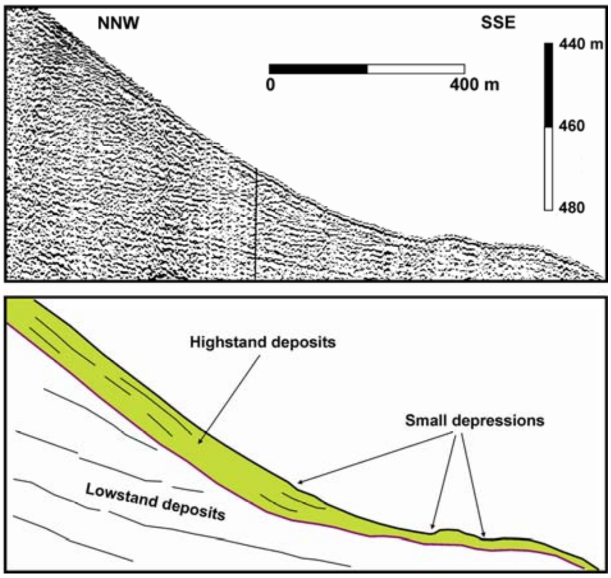

**Fig. 13** – Erosive morphology: erosive surface over the continental slope. Small depressions incise the upper continental slope. The Geopulse profile location is shown in fig. 1.

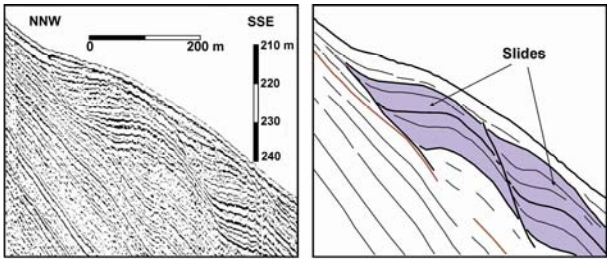

**Fig. 14** – Gravity morphology: slides. Blocks of internally undisturbed sediments are bounded by slide-faults. The internal reflectors showing high amplitude and continuity defining parallel, stratified seismic facies. The Geopulse profile location is shown in fig. 1.

### 4.2.3. Gravity morphologies

*4.2.3.1. Slides and slumps*

The slides recognised on the upper slope of the easternmost sector are bounded by offshore dipping slide-faults that individualise almost underformed blocks (fig. 14). The reflectors within these sediment blocks show high amplitude and continuity defining parallel, stratified seismic facies. The planar faults that bound these blocks could have been generated by liquefaction or plastic flow of soft layers beneath a more competent upper sediment layer (Hart, 1993). These slides affect the upper tens of meters of most recent sediments corresponding to transgressive and highstand deposits (Roque, 1998). This suggests that slope mass-failure processes are still active in this sector of the upper slope. The spatial distribution of slumps is also restricted to the upper slope, where they disturb mainly the lowstand deposits of Late Pleistocene age (Roque, 1998). They are well represented in the sector Tavira-Guadiana River as large slumped masses of sediments and as single rotational sumps in the sector Faro-Quarteira (fig. 15A). A single rotational slump mass is identified off Faro at about 198 m water depth and it reaches about 40 m thickness. Acoustically, this slump presents weak or discontinuous reflectors, defining chaotic or wavy seismic facies. A concave-downslope spoon-shaped depression is recognised between the shelf-edge and the slump. It represents a relic of the ancient slump scar, whose presence is also inferred upslope of the slump by the onlapping of parallel and stratified reflectors onto the shelf-break. At present the slump is covered by recent deposits that reach about 12.5 m maximum thickness. Figure 15B shows an example of escarpments and related slumped deposits located at their toes. These scarps seem to be formed only by downslope displacement of sediments, as a tectonic origin for them is not evident.

Slumped zones are also recognised west of Faro. However, these slumps do not have morphological expression on the sea-floor, because they are completely covered by more recent transgressive and highstand deposits (Roque, 1998).

### 4.2.4. Neotectonic morphologies

*4.2.4.1. Submarine scarp*

A submarine tectonic scarp (< 10 m high) is recognized in middle-continental shelf offshore Quarteira at about 50 m water depth (fig. 4 and fig. 16). It is related to a northwards dipping reverse fault trending nearly W-E to WNW-ESE that cuts the transgressive surface (TS) and the transgressive deposits (Roque, 1998) and offsets the sea-floor. Several other active faults affect these deposits, mainly off Faro and Tavira, however they are blind-faults that do not reach the sea-floor surface. Another submarine scarp associated with sediment slides and slumps is identified on the upper continental slope offshore Faro at more than 300 m water depth (fig. 4).

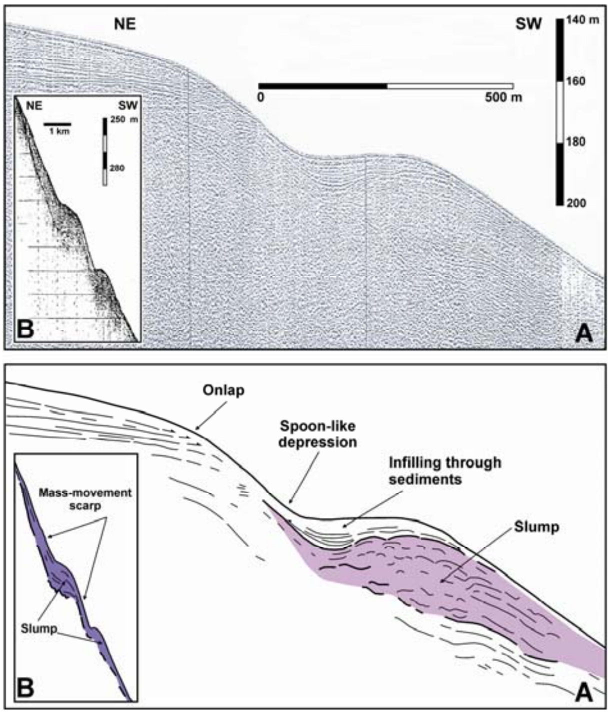

**Fig. 15** – Gravity morphology: slumps. This morphology shows weak or discontinuous reflectors, defining chaotic or wavy seismic facies. (A) Rotational slump. (B) Mass-movement scarps and related slumps. The Geopulse and 3.5 kHz profiles location is shown in fig. 1.

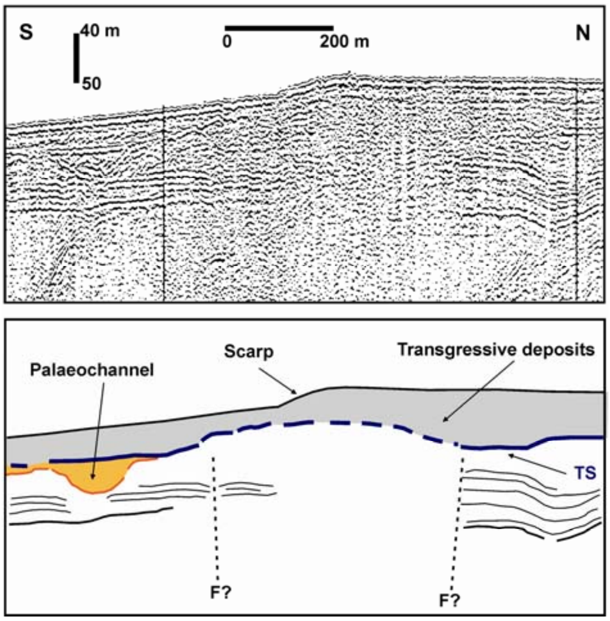

**Fig. 16** – Possible neotectonic morphology: submarine scarp. The Geopulse profile location is shown in fig. 1.

## 5. Morphogenetic factors

The development and evolution of the physiographical and morphological features identified in the Eastern Algarve proximal continental margin are the result of a complex interplay of several factors, such as the sedimentary architecture of underlying Quaternary deposits, the present-day depositional dynamics, the neotectonic activity, the coastal hydrodynamic regime and the pattern of oceanic circulation, and finally the Late-Quaternary sea-level changes (fig. 17).

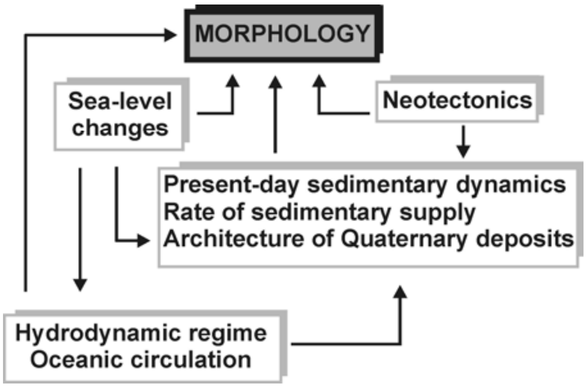

**Fig. 17** – Relationship between the morphogenetic factors that have controlled the development of the different morphologies identified in the Eastern Algarve proximal continental margin.

## 5.1. *Depositional morphologies*

### 5.1.1. Littoral prism

The littoral prism was first described by Vanney & Mougenot (1981) as a deltaic front located offshore Faro, covering all over the continental shelf and extending eastwards nearly to Guadiana River prodelta. However, the seismic profiles used in our work show that the littoral prism is an isolated sedimentary body unrelated to deltaic deposits.

According to Hernández-Molina *et al.* (2000a) littoral prisms are progradational bodies build up on the infra-littoral and inner shelves of clastic wave-dominated coasts by the action of storm-generated currents. Although storms are episodic, the down-welling currents and storm-waves remobilize littoral coarse-grained material and transported it seaward into the more distal parts of the infralittoral domain where it is deposited. The degree of development presented by those littoral prisms reflects the balance between the rate of sedimentary supply and the erosive processes activity (Hernández-Molina 1993; Hernández-Molina *et al.*, 1998).

The morphology shown by the Faro-Tavira littoral prism is related to the average water depth level that is affected by storm currents and waves. In the Eastern Algarve the average water depth of remobilization of coarse-medium sands during a storm is deeper off Tavira and it becomes shallower towards Faro (Magalhães, 2001). This is testified by the location of the littoral prism edge at –40 m off Tavira and –35 m off Faro, respectively. These depths correspond to the mean level of the storm wave base on these sectors. The deeper level of sand remobilization off Tavira and the contribution of sediment delivered by the Guadiana River (Moita, 1986), could explain why the littoral prism reaches its maximum thickness in this sector.

### 5.1.2. Prodelta

Prodelta development depends mainly on the rate of sedimentary supply and oceanographic conditions, such as wave regime, tides, and currents. The small thickness and lateral extension shown by the Guadiana prodelta was previously reported by Vanney & Mougenot (1981), and is more evident when compared with the nearby Spanish rivers, like for instance, the Guadalquivir prodelta (Morales-González, 1995a, 1995b, 1997; Lobo, 1995). In fact, the Guadiana prodelta reaches only 15 m of maximum thickness (Roque, 1998; Roque *et al.*, 2000), what could be explained in part by the little load of sediments delivered by this river, just about 57.90x10$^4$ m$^3$/yr (Morales-González, 1995a). Furthermore, the majority of Guadiana's load of sediments is trapped in the marine part of its estuary promoting the development of a wave-dominated deltaic environment (Borrego *et al.*, 1995). Thus, just a small amount of sediment reach the littoral where part of it is transported eastwards by the littoral drift and currents, and only the suspended load that escapes to this circulation either feed the prodelta or migrates towards the shelf being deposited as continental shelf sedimentary cover.

The sector of the continental shelf where the Guadiana River prodelta is developed is characterized by small gradients (about 0.3º- 0.4º) and by the absence of any submarine relief. Such conditions favoured the formation of this prodelta.

The sea-level position is also an important controlling factor to take in consideration because prodeltas development is favoured during highstand stages (Bellotti *et al.*, 1994; Hernández-Molina *et al.*, 1994a, 2000b). In fact, many rivers have a prodelta that advances seawards across the adjacent continental shelf like the Ebro (Díaz *et al.*, 1990), the Rhône (Gensous, 1994), the Tiber (Belloti *et al.*, 1994) and the Guadalquivir (Lobo, 1995). During the Late Holocene after the decrease of sea-level rise rate reached in South Portugal at about 6.0-5.0 ky BP (Moura *et al.*, 2000; Magalhães, 2001), the deltaic complex of Guadiana River began to progradate across the shelf and thereby developing the prodelta. Southern Spanish Rivers (e.g. Guadalquivir) show a similar evolution (Díaz *et al.*, 1990; Borrego *et al.*, 1995; Somoza *et al.*, 1998; Dabrio *et al.*, 2000).

### 5.1.3. Continental shelf sedimentary cover

The main factor controlling the formation of the continental shelf sedimentary cover is the volume of suspended-load sediments delivered mostly by Guadiana River.

### 5.1.4. Continental slope accumulation

The continental slope accumulation corresponds to shelf-edge prograding lowstand deposits formed during the last Glacial (Roque, 1998; Roque *et al.*, 1998) and consisting of "shelf edge sands and gravel deposits" (Moita, 1986; Magalhães, 2001). However, on the more distal parts of the continental slope, low amplitude stratified and transparent facies denote the existence of fine-grained deposits. These seismic facies are typical of hemipelagic deposits and can be correlated to the "upper slope mud deposits" (Moita, 1986; Magalhães, 2001).

## 5.2. *Erosive morphologies*

### 5.2.1. Palaeo-channels

The formation of fluvial channels on the continental shelf has been related to lowstand sea-level stages when the shelf was exposed to sub-aerial conditions (e.g. Vanney, 1977). The Southern Spanish Rivers as Odiel, Tinto and Guadalete excavated valleys during the last sea-level fall (Dabrio *et al*., 2000). Similar features were described in others continental shelves, such as in the Rhône continental shelf (Gensous & Tesson, 1996), Lousiana continental shelf (Suter *et al*., 1987), Beaufort Sea (Héquette & Hill, 1990), Sendai Japan (Saito, 1991), Adriatic Sea (Trincardi *et al*., 1994) and California coast (Burger *et al*., 2001). The formation of the palaeo-channels identified in the Eastern Algarve continental shelf can be related to the sea-level drop during the Last Glacial because they are incised on forced regressive prograding wedges and older lowstand deposits, and are bounded at top by the trangressive surface.

### 5.2.2. Submarine terraces

Submarine terraces are morphologies generated by wave action during still-stands of the last post-glacial sea-level rise when the sea-level was lower than present-day (Hernández-Molina *et al*., 1996a; Roque, 1998; Roque *et al*., 1998). Submarine terraces have been reported from continental shelves throughout the world, as far from the study area, as Israel (Mart & Belknap, 1991) or India (Wagle *et al*., 1994).

In the Eastern Algarve continental shelf some terraces are fossil morphologies since they are covered by sediments and do not have any topographic expression on the sea-floor (fig. 11) and they can be only recognized using seismic reflection methods. These older terraces, identified at water depths below 80 m, can be laterally correlated with aggradational and progradational deposits, which show a sheet-like or lobate shapes, with parallel or slightly sigmoidal internal configuration, showing onlap terminations landward and downlap seaward. These bodies correspond to transgressive coastal deposits (fig. 18), formed during the post-glacial rise of sea-level (Roque, 1998; Roque *et al*., 1998). In the Spanish continental shelves a similar relationship between terraces and transgressive depositional bodies was already documented by Hernández-Molina *et al*. (1994a; 1996a) and Lobo *et al*. (2001) (fig. 18). This association between terraces and sedimentary bodies shows that two kinds of processes were involved in their genesis: first an erosive phase that shaped the terrace by wave-cutting, followed by the deposition of the aggradational or progradational bodies. This association also suggests that the general post-glacial rise of sea-level was punctuated by short still-stands that allowed the development of minor terraces and small sedimentary bodies.

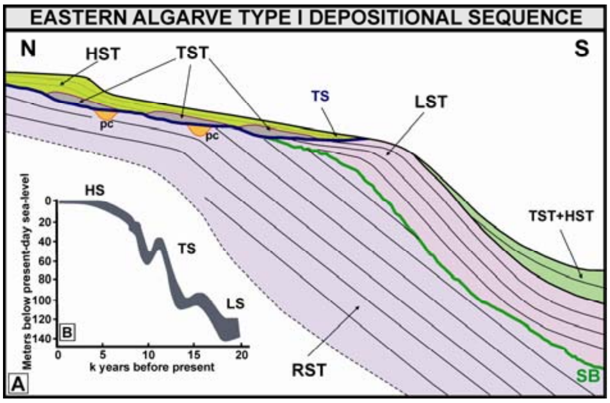

**Fig. 18** – (A) Schematic drawing of Eastern Algarve 5th-order type I depositional sequence architecture. (B) Eustatic curve proposed by Dias (1987) for the North Portuguese continental shelf since the glacial maximum (20-18 ky) until the present. The depositional sequence is composed of: forced regressive systems tract (RST); lowstand systems tract (LST); transgressive systems tract (TST) and highstand systems tract (HST). SB: Sequence boundary; TS: transgressive surface; pc: palaeochannels (See the text for more details).

### 5.2.3. Transgressive surface

The preservation and exposition of the transgressive surface depends of the rate sea-level rise, subsidence rate, rate of sedimentary supply and width of the continental shelf. A rapid subsidence conjugated with a relatively rapid sea-level rise could contribute both for the good preservation of the transgressive surface. Its preservation could also occur when the continental shelf is narrow and the sedimentary supply is low. These conditions seem to have been the prevailing ones in the Algarve continental shelf during the late post-glacial sea-level rise.

The "outer shelf sand and gravel deposits" (Moita, 1986; Magalhães, 2001) can be associated with the transgressive surface, and are interpreted as relic sediments deposited during the post-glacial sea-level rise because they show characteristics of high-energy environment, which are in disagreement with the present-day hydrodynamic system.

### 5.2.4. Erosive surface over the continental slope

The erosive surface over the continental slope probably results from erosive action of the more superficial branch of the MOW that flows parallel to the continental slope at 500-900 m water depth, creating small depressions at the top of the deposits (Llave *et al*., 2002).

## 5.3. *Gravity morphologies*

### 5.3.1. Slides and slumps

Driven by gravity, slumping and sliding are the most common processes of downslope mass sediment transport. They can be triggered by several mechanisms, that include: gas generation in the sediments; seismic activity; high sedimentation rate at the shelf break and on the upper slope, particularly where gradients are steeper; gas hydrate decomposition within the sediment due to the variation of the depth of its stability field boundary; bottom-water movements near the shelf break (e.g. Knebel & Carson, 1979; Prior *et al.*, 1982; Chough *et al.*, 1991; Masson *et al.*, 1996; Mulder & Cochonat, 1996).

Among the variety of factors suggested above, the most likely triggering mechanism for the development of slides and slumps on the Eastern Algarve continental slope is sediment loading associated with high slope gradients that reach up to 6º. Another triggerering mechanism that could be taken in consideration, however with precaution, are earthquakes events. In fact, the Algarve margin has moderated seismicity, especially concentrated offshore Faro-Tavira area and various active structures have been identified in the continental shelf and slope (Maestro *et al.*, 1998, Zitellini *et al.*, 2004).

### 5.4. *Neotectonic morphologies*

#### 5.4.1. Submarine scarp

Recent tectonic activity is recorded by submarine scarps associated with W-E to WNW-ESE reverse faults.

## 6. Morphogenetic evolution and Late-Quaternary sea-level changes

The Quaternary is characterised by a succession of glacial and interglacial periods and consequent eustatic changes, modulated by Milankovitch cycles of about 100 ky eccentricity, 40 ky obliquity and 20 ky precession. Before the Middle Pleistocene the climatic and eustatic variations were dominated by 40 ky obliquity cycle, but after this period at about 900/920 ky an important change in the general climatic trend occurred. Since then, during the Late Pleistocene-Holocene, the climatic and glacio-eustatic fluctuations have been controlled and modulated mainly by the last 4th -order 100-110 ky eccentricity cycle and also by the 5th -order 22-23 ky precession cycles (Mörner, 1972; Chappel & Shackleton, 1986; Hernández-Molina *et al.*, 1996b). The signature of this cyclicity modification is showed by imposed higher sea-level change amplitudes (around 120-150 m; Lowrie, 1986) and a by strong asymmetry marked by a slow and gradual sea-level fall, a short lowstand, a rapid sea-level rise, and a brief highstand.

The sequence stratigraphy analysis of Late Quaternary deposits carried out in the last few years in the Gulf of Cadiz margin by e.g. Somoza *et al.* (1994), Lobo (1995), Lobo *et al.* (1997), Hernández-Molina *et al.* (2000b) suggests that the asymmetry of the 4th and 5th -order eustatic cycles is expressed on the stratigraphic architecture shown by these deposits.

These authors recognise two major type 1 asymmetrical depositional sequences generated by 4th -order asymmetrical relative sea-level changes. Each sequence can itself be divided into asymmetrical depositional sequences generated by 5th -order asymmetrical sea-level changes. All sequences comprise four systems tracts: forced regressive (RST), lowstand (LST), transgressive (TST) and highstand (HST). The asymmetry is expressed by the great development shown by the forced regressive systems tracts (RST) face to development showed by the others systems tracts together (LST, TST and HST). Furthermore, considering that the Late Quaternary entire cycle of 4th -order eustatic changes is about 130 ky years long and it is composed of four stages (regressive, lowstand, transgressive and highstand), the duration of just only the regressive interval correspond to about 106 ky years of the cycle, so it is clear that this is asymmetrical. Thus, if only the lowstand, transgressive and highstand intervals are taken in to account, they in fact constitute a hemicycle because the long regressive interval is not been considered.

In the Eastern Algarve continental shelf a 5th -order type 1 depositional sequence is identified (Roque, 1998; Roque *et al.*, 1998) and it can be correlated with the more recent 5th -order depositional sequence described in the Spanish sector of the Gulf of Cadiz ("depositional subsequence II4") by Somoza *et al.* (1994), Lobo *et al.* (1997) and Hernández-Molina *et al.* (2000b). It is composed of a forced regressive system tract (RST) deposited from the last interglacial until the beginning of the last glaciation at about 24 ky BP; a lowstand systems tract (LST) deposited during the last glaciation at about 20-18 ky BP; a transgressive system tract (TST) deposited during the post-glacial transgression between 14 and 6.5 ky BP; a highstand system tract (HST) deposited from the last maximum eustatic up to the present (fig.18).

Assuming that these Late Pleistocene-Holocene 5th -order sea-level changes have been the main control and modelling factor, the genesis of Eastern Algarve proximal continental margin morphologies must reflect it. Therefore, in this work and for morphogenetic proposes, we just considered the sea-level changes that occurred since the last Glacial until present-day. Thus, the development of the several morphological features identified in Eastern Algarve during the last 20 ky BP could be related to three major sea-level stages based on seismic-sequence stratigraphy analysis of the Gulf of Cadiz region (Somoza *et al.*, 1994, Hernández-Molina *et al.*,1994b, 1996b, 2000b, 2002; Lobo, 1995; Lobo *et al.*, 1997; Roque, 1998; Roque *et al.*, 1998, 2000, 2002) (fig. 16): *a)* a lowstand stage (between the last eustatic minimum at 20-18 ky BP and the beginning of the post-glacial sea-level rise at 14 ky BP); *b)* a transgressive stage (during the post-glacial sea-level rise until the eustatic maximum at 6.5 ky BP); *c)* a highstand stage (extending until the present time). Considering theses three major sea-level stages the following morphogenetic evolution is proposed (fig. 19):

### 6.1. *Lowstand stage*

During the last glaciation the polar front was located at about 42º N, close to the Iberia Peninsula (Fatela, 1994; Fatela *et al.*, 1994). Under such severe climatic conditions the Last Glacial Maximum was reached at about 20-18 ky BP, when sea-level suffered a major drop of about 120 meters (Duplessy *et al.*, 1981;

Ruddiman & McIntyre, 1981; Dias, 1987). During this time, the Eastern Algarve continental shelf was exposed to sub-aerial erosion and rivers cut down the inner-middle shelf creating *fluvial channels* with thalwegs reaching the lowest water depth of about 114 m below the present sea-level (fig. 19A). Similar features have been reported in others shelves (e.g. Suter *et al*., 1987; Héquette & Hill, 1990; Saito, 1991; Hernández-Molina, 1993; Trincardi *et al*., 1994; Tesson *et al*., 1990). These channels started to infill with sediments near the end of this lowstand stage. The paleo-channels are covered by later transgressive deposits and so do not show any morphological expression on the present-day sea-floor. In fact, they are relic morphologies that testify the last sea-level drop below the shelf break and the shelf exposition to subaerial conditions.

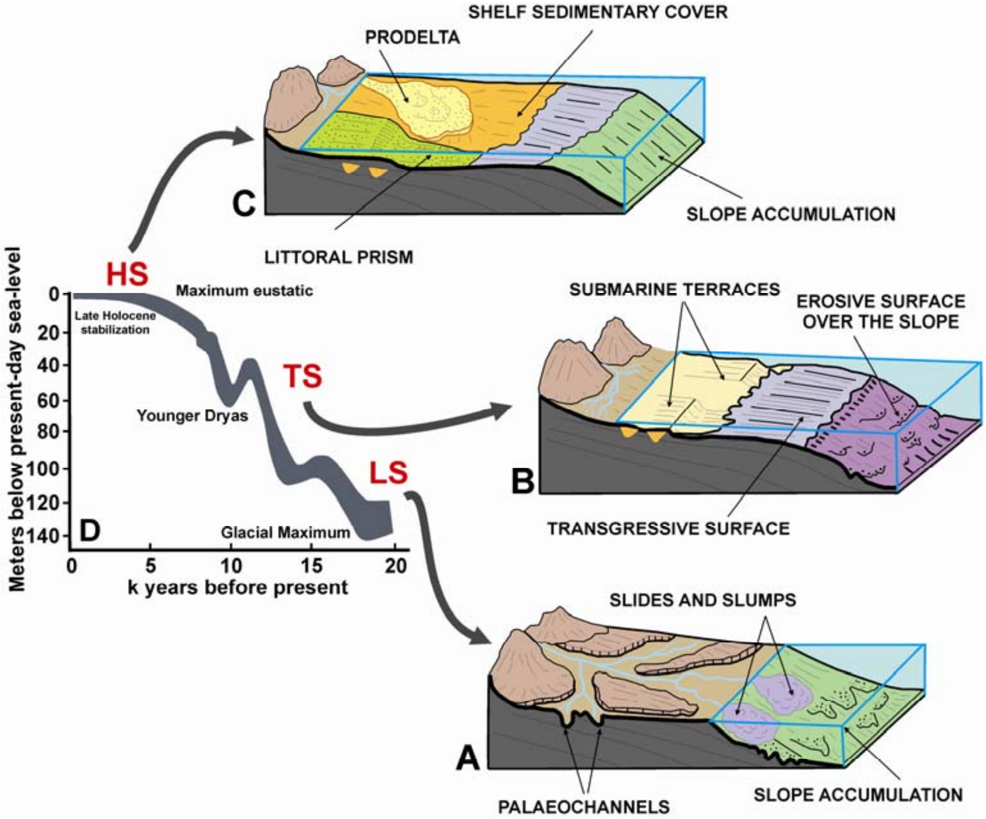

**Fig. 19** – Morphogenetic evolution model and the Late Quaternary sea-level changes. (A): during the last Glacial (lowstand sea-level stage (LS)) the continental shelf was exposed sub-aerially and fluvial channels were incised; slides and slumps were triggered mostly by huge amounts of sediments delivered on the steep continental slope. The distal continental slope was also covered by accumulation of sediments. (B): during the post-glacial sea-level rise (transgressive stage: TS) the action of waves and currents favoured the development of erosive morphologies in the continental shelf, like the transgressive surface and submarine terraces. The erosive effects of the MOW flowing across the upper slope were responsible by the development of the erosive surface over the slope. (C): during the highstand sea-level stage (HS) the present-day oceanographic conditions are the main modelling and depositional factor. Under such conditions the great development of depositional morphologies is shown by the presence, of the littoral prism, prodelta, shelf sedimentary cover and slope accumulation.

During the Last Glacial the coastline was located near the shelf edge and great amounts of sediments were delivered directly there and onto the upper continental slope, contributing to the build up of a shelf-edge prograding wedge, corresponding to the lowstand systems tract (fig. 18) (Roque, 1998; Roque *et al*., 1998). Therefore, this huge sediment influx onto the steep upper slope could have triggered mass-gravitational processes responsible for the formation of *slides and slumps* (fig. 19A), which are common features in the continental shelves during lowstands (e. g. Knebel & Carson, 1979; Pratson & Laine, 1989; Alonso & Maldonado, 1992; Mosher *et al*., 1994; Lobo, 1995; Mulder & Cochonat, 1996). These mass-sliding events could have been produced well after the end of an important progradational phase (Mongardi *et al*., 1994).

## 6.2. *Transgressive stage*

Following this lowstand period, warmer conditions were reached in the Northern Hemisphere and ice-sheets began to melt. Consequently, the sea-level began to rise, although without oscillations in response to minor advances and retreat of the glaciers in continental landmass. Moreover, the deglaciation process had two major melt-water pulses, the first at around 14 ky BP and the later at about 11 ky BP (Bard *et al*., 1987).

Several authors support the idea that the global post-glacial sea-level rise occurred intermittently with small and rapid rises episodes alternating with briefs stillstands or minor falls of sea-level (e. g. Dias, 1987; Hernández-Molina *et al.*, 1994b; Bellotti *et al.*, 1995; Somoza *et al.*, 1998; Dabrio *et al.*, 2000). In the Northern Portuguese continental shelf the sea-level started to rise rapidly and attained -110/-100 m at about 14-13 ky BP, followed by a stillstand (Dias, 1987; Rodrigues *et al.*, 2000; Rodrigues, 2004).

The trend of sea-level rise accelerated between 16 and 12 ka in the Portuguese shelf with estimated rates of 15m/ka (Dias *et al.*, 1997). Data from aeolian dunes and palaeosoils in the Spanish coast of the Gulf of Cadiz (Huelva) suggest an acceleration of the sea level rise between 14 ka and 10.5 ka (Dabrio *et al.*, 2000). During the post-glacial sea-level rise the morphogenesis was dominated by erosive processes, however during brief stillstands the depositional processes become predominant and responsible by the genesis of transgressive parasequences that formed a transgressive system tracts (fig.18). Even so, when we compare the importance of each morphogenetic process during the three stages (lowstand, transgressive and highstand), it is clear that the erosive processes were most important during the transgressive period, although they were not the only ones.

In the outer continental shelf the beginning of transgression is represented by the *transgressive surface*, which constitutes the lower boundary of the transgressive deposits (fig.18) (Roque, 1998; Roque *et al.*, 1998) and it marks the first main event of marine flooding across the shelf after the lowstand stage (Van Wagoner *et al.*, 1988; Haq, 1991; Vail *et al.*, 1991) (fig. 19B). The incised fluvial channels that were generated during the previous lowstand stage were completely filled during this transgression, and they are top-bounded by the transgressive surface. The presence of five *submarine terraces* series (fig. 19B) in the Eastern Algarve continental shelf at water depths ranging from 50 to 84 m (Tab. II), suggests the existence of short stillstands during this post-glacial sea-level rise. In the adjacent sectors of the Gulf of Cadiz continental shelf, the bulk of submarine terraces are located at the same range of water depths, between 55 and 80 m (Lobo, 1995).

The submarine terraces could have been associated with the development of transgressive deposits. This association reveals the action of erosion followed by sedimentation. Therefore, some terraces of the Eastern Algarve, for instance those placed below 80 m water depth, are associated with aggradational or backstepping progradational low angle bodies widespread over the continental shelf, which consist in parasequences of the transgressive system tract (fig. 11, fig. 18) (Roque, 1998; Roque *et al.*, 1998). In the Spanish sector, offshore Guadiana river mouth, similar terraces and related depositional bodies have been identified (Lobo, 1995; Lobo *et al.*, 2001). These authors described four seismic units located over the upper slope (seismic unit A) and the middle shelf (seismic units B, C, and D), where they are set out in a progressively landward backstepping pattern. The upper boundary of the seismic units B, C, and D is assumed to be respectively at 82-83, 64-65 and 55 m below sea-level. Only these last three seismic units are associated with wave-cut terraces, and which present top surfaces located respectively at the following water depths: 71 m (terrace B), 49 m (terrace C) and 35 m (terrace D). The formation of these seismic units and associated terraces are thought to be linked to periods of reduced sea-level rise or small-scale sea-level stillstands during the post-glacial transgression (Lobo *et al.*, 2001).

The correlation between the Algarve's terraces and those reported on the other Iberian and Mediterranean shelves, is best given by the third group ($T_c$: 65 to 68 m depth) (Tab. II) which is widely represented, suggesting a longer stillstand event. Additionally, the existence of submarine terraces at water depths of 65-70 meters on the nearby Spanish shelf (Lobo, 1995; Lobo *et al.*, 2001) is an indication of the regional character of this episode.

Magalhães (2001) refers the presence of an ancient littoral at 70 meters water depth based on the analysis of sands grain-size and composition. Fragments of beach-rock were also detected offshore Faro and Tavira, and according to the referred author, they could have been formed when sea level was 60 meters below its present level. However, the use of beach-rock as an indicator of ancient littoral environments must be taken with caution because they could correspond to ancient sand-dune systems.

A correlation could be established between the development of all the mentioned morphological features identified in Iberian and Mediterranean regions (e.g. Flemming, 1972) and the climatic-eustatic events that occurred during this post-glacial transgressive stage.

Thus, the formation of $T_c$ group of terraces between 65 to 68 m water depths can be related to a sea-level fall that affected these regions and which could be linked to the Younger Dryas cold climatic event at about 11-10 ky years BP (Bard *et al.*, 1987; Jouzel *et al.*, 1994). This represented an exceptionally cooling period in the Northern Hemisphere, characterised by the last major polar front re-advance towards south and a significant sea-level drop (Rudiman & MacIntyre, 1981). This cold event was probably caused by major oceanographic changes related to a cooling of the Atlantic surface water, triggered by the sudden influx of fresh melt-water from Laurentide ice sheet into North Atlantic that stopped the oceanic circulation (Wells *et al.*, 1996). The onset of the Younger Dryas marks the beginning of the Holocene. Radiocarbon dating of Norwegian lake sediments suggests that the Younger Dryas-Holocene transition took place at about 9750 years BP (or using a calendar year BP scale within the range 11500-11 600 cal years BP) (Gulliksen *et al.*, 1998). After the end of this cold episode the general sea-level rised again (Sierro *et al.*, 1999).

Several authors, as Dias (1987), Rodrigues *et al.* (2000) and Rodrigues (2004) claim that during this cold climatic event the sea-level dropped to about –60 m in the Northern Portuguese shelf. Evidences of this are shown by the presence of coarse-grained sand and gravel deposits named after Dias (1987) the "Middle Shelf Deposits". These deposits occur at 62 m and 55 m water depth, and respective radiocarbon dating give an age of 10 415±120 years BP and 11 120±180 years BP (Dias, 1987). Moreover, the majority of morphologic features recognised by Rodrigues (2004) in the Northern Portuguese continental shelf, as for instance, terraces, gradient breaks, ancient cliffs and ancient sand bars are concentrated at a water depths range between 60 and 40 m, and have been directly observed using a remote operated vehicle system (ROV) (Rodrigues *et al.*, 2000). These forms are well preserved, probably due to the very rapid rise of sea level after the Younger Dryas event. Dias (1987) has also reported the presence of submarine terraces at 65 m water depth. The break of gradient at 60 m water depth ($R_2$ in this work, $R_b$ *in* Dias, 1987) recognised along all the Portuguese shelves could have been formed also during this cold climatic event.

Lobo *et al.* (2001) suggested that the formation of both terraces located at 71 m (TB) and 49 m (TC), and respectively, could have occurred during the Younger Dryas. According to these authors the first terrace represents the beginning of sea-level rise reduction related to this climatic event and the second one its end. However, these authors did not find any terrace or another morphological feature located around 60-65 m water depth as the ones described by Dias (1987) and Rodrigues (2004) as evidences of the Younger Dryas.

The submarine terraces located in the Mediterranean at 46 m, 52 m and 67 m water depth, which appear to have been formed in descending order, were interpreted by Flemming (1972) as indicative of the last sea level fall before the Würm glaciation. However, considering their range depths, we suggest that they are related to the Younger Dryas sea-level drop reported in the Northern Portuguese shelf. During this transgressive stage the action of oceanic undercurrents imprinted the slope cutting small depressions, shaping an irregular surface (the *erosive surface over the continental slope*) located at a few hundred meters water depth (fig. 19B). The MOW present-day circulation pattern was already established at this time, and thus, it could also be responsible by the development of erosive features on the continental slope (Llave *et al.*, 2002).

### 6.3. *Highstand stage*

The Holocene is a period characterised by a general sea-level rise that reached its maximum position in south Iberia at about 6.5 $^{14}$C ky BP, then the rate of eustatic rise decreased drastically (Zazo *et al.*, 1994; Dabrio *et al.*, 1996, 2000). In Iberia, at the beginning of Holocene the sea level was at –30/–35 m in the continental shelves (Dias *et al.*, 1997; Hernández-Molina *et al.*, 1994b). A smaller episode of sea-level rise occurred between ca. 3000 and 2750 $^{14}$C yr BP (Dabrio *et al.*, 2000). These fluctuations of sea-level are reflected on the coastal morphology changes of this region during this time. Two phases of major progradation are identified in spit-bar systems in Southern Spain by the referred authors: the first one between 6450-3000 yr BP, and a second one from 2750 C yr BP to present. During the latter, the processes of coastal progradation prevailed over aggradation (Dabrio *et al.*, 2000).

However, Moura *et al.* (2000) and Magalhães (2001) suggest that in South Portugal the rate of sea-level rise decreased drastically after 6.2 ky BP and at about 5.0 ky BP the sea-level approached the present-day level and stabilized.

Under such highstand conditions new hydrodynamic regime and depositional dynamics were established over the Eastern Algarve continental shelf and upper slope. Since this time the depositional processes have been dominant. In the inner-middle continental shelf the previous transgressive surface and transgressive deposits were covered almost entirely by highstand deposits, except on the outer shelf, where the "outer shelf sand and gravel deposits" (Moita, 1986; Magalhães, 2001) are the remnants of the post-glacial sea-level rise event. The development of depositional forms has been favoured and these forms are represented in all physiographic domains, from the littoral to the continental slope. The *littoral prism* is one of the main morphologies that are present in this area (fig. 19C). The Faro-Tavira littoral prism can be correlated with an individualised sand body located at water depth between 10 and 30 m, which was interpreted by Moita (1986) as an ancient transgressive coastal body formed during the Holocene.

The first marine influence in the estuaries of South Iberia took place at about 10 ky BP, and more open marine conditions were reached during the maximum eustatic (Dabrio *et al.*, 2000). Between 6.5 and 4.0 ky BP the evolution of estuaries is closely related to the decrease of the rate of sea-level rise. During this period the rate of fluvial input to estuaries surpassed the rate of sea-level rise, favouring the accumulation of spit-bars and formation of tidal flats (Borja *et al.*, 1999).

Under such conditions, the Guadiana River's *prodelta* started its progradation across the shelf over the older transgressive deposits (TST) (fig. 18 and fig. 19C). Great amount of sediments are trapped in the estuary of this river and only a small part reaches the sea. There, the present-day hydrodynamic conditions are responsible by the transport and re-distribution into the continental shelf of the sediments that are delivered by Guadiana River. An active eastward moving littoral drift incorporates part of the sediments, and only some of the fine-grained sediments are transported in suspension, feeding the adjacent shelf, covering its irregularities, smoothing the topography, and creating the *shelf sedimentary cover*. Part of these sediments migrate seaward reaching the upper slope where contribute to the development of the *slope accumulation*, that on more distal parts is made up of hemipelagic sediments (Moita, 1986; Magalhães, 2001) (fig. 19C). All these depositional morphologies can be correlated with the highstand systems tract of the Eastern Algarve type I depositional sequence (fig. 18) (Roque, 1998; Roque *et al.*, 1998).

## 7. Conclusions

The interpretation of high and very high-resolution seismic profiles allowed the identification of eleven morphological types grouped in four morphogenetic categories: *depositional* (littoral prism, prodelta, continental shelf sedimentary cover, continental slope accumulation), *erosive* (palaeochannels, terraces, transgressive surface, erosive surface over the continental slope), *gravity* (slides, slumps) and *neotectonic* (scarp).

Morphologies mapping shows that they occur in the littoral (littoral prism), continental shelf (prodelta, continental shelf sedimentary cover; palaeo-channels, terraces, transgressive surface) and on the continental slope (continental slope accumulation, erosive surface over the continental slope, slides, slumps, scarp).

The most represented morphologies are depositional and erosive, suggesting that sedimentary processes have been the most active ones shaping the Eastern Algarve proximal margin.

Late Pleistocene-Holocene sea-level changes can be pointed as the main control and modelling factor and a three stages morphogenetic model is proposed:

1 - During the *lowstand stage* (between the last eustatic minimum at 20-18 ky BP and the beginning of the post-glacial transgression at 14 ky BP) the erosive processes dominated in the exposed continental shelf, as testified by palaeo-channels filled with sediments. The huge amount of coastal sediment influx on the shelf-edge and upper slope triggered mass-gravitational processes as slides and slumps.

2 - During the *transgressive stage* (from 14 ky BP to the maximum eustatic at 6.5ky BP) the erosive processes shaped the transgressive surface, submarine terraces and erosive surface over the continental slope. The first main event of marine flooding across the shelf after the lowstand created the transgressive surface. The formation of terraces occurred during sea-level stillstands and they were preserved by the rapid eustatic rise that follows. The action of oceanic bottom-currents as the MOW formed the erosive surface over the continental slope.

3 - During the *highstand stage* (between the maximum eustatic and present) the prevailing hydrodynamic regime and sedimentary dynamics favoured the depositional processes and the development of the littoral prism, prodelta of the Guadiana River, continental shelf sedimentary cover and the continental slope accumulation.

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