

# Sedimentological and paleoenvironmental characterisation of transgressive sediments on the Guadiana Shelf (Northern Gulf of Cadiz, SW Iberia)

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## Abstract

During the transgression following the Last Glacial Maximum, four backstepping parasequences were deposited on the northern Gulf of Cádiz shelf (SW Iberia). In contrast to other areas on the shelf, these transgressive deposits are at, or very close to, the surface to the southeast of the Guadiana Estuary mouth. This is particularly true for transgressive parasequence  $T_C$ , possibly associated with the Younger Dryas event, and the youngest parasequence  $T_D$ , probably linked to a slow-down in sea-level rise at around 8.2 ka BP, both of which form a sandy transgressive bulge on the upper middle shelf.

The older and more distal parasequence  $T_C$  is characterised on seismic records by convex low-angle sigmoidal clinoforms, and contains high amounts of quartz and bioclasts. In contrast, the younger and more proximal parasequence  $T_D$  shows relatively steep concave prograding clinoforms, and contains high amounts of quartz and other terrigenous components, but comparatively low amounts of bioclasts. Furthermore, the difference in age between both parasequences is clearly marked by a difference in the content of glauconite.

The results indicate that sediments found in parasequence  $T_C$  are associated with deposition related to storm events, with frequent reworking of components, and the more proximal and younger sediments in  $T_D$  are the result of rapid sediment accumulation related to floods in the Guadiana River basin, possibly during the transition from a dry cold period to a warmer more humid period, when vegetation cover was lowest and flood frequency increased.

Additionally, accumulations of terrigenous components directly associated with the Guadiana River basin found on the outer shelf indicate that, at least during the beginning of the transgression, overflow channels active during large-scale flood events may have spilled material to an area located immediately to the south of the Guadiana Estuary mouth.

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## 1. Introduction

High-quality paleoceanographic reconstructions based on sequences preserved in shallow marine environments are essential to understand past climatic and oceanographic change. In this context, sediments deposited in transgressive parasequences during periods of fast sea-level rise are a crucial link between lowstand and highstand systems tracts, reflecting times of rapid environmental change (e.g. Trincardi et al., 1996; Scourse and Austin, 2002). The study of such bodies is thus particularly interesting in context of environmental conditions during possible future periods of rapidly

changing environmental conditions, for instance during periods of sea-level rise related to the greenhouse effect.

However, transgressive parasequences deposited during periods of fast and high-amplitude sea-level variations, such as the Quaternary, are elusive. They correspond to times of rapid landward translation of facies belts, leaving the continental shelf starved of sediment, so that condensed successions are deposited (e.g. Miall, 1997). Subsequently, these relatively thin veneers of sediment are covered on siliciclastic shelves by often thick successions of highstand deposits, characterised by prograding wedges of sandy sediments on the inner shelf and muddy deposits on the middle, and to some extent also on the outer shelf. Additionally, the preservation potential of transgressive deposits is low. They are preserved in significant quantities (i.e. more than just a 'veneer' of sediment) on continental

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shelves only in areas with very particular physiographic and sedimentary settings, usually areas with high subsidence and/or high sediment supply (e.g. Penland et al., 1988; Corregiari et al., 1996; Tortora, 1996; Carey et al., 1998; Yoo et al., 2002; Park et al., 2003).

On the Guadiana shelf (northern Gulf of Cadiz, SW Iberia) the surfaces of two post-glacial transgressive parasequences are exposed across the middle shelf and outer inner shelf. Their internal architecture has previously been identified and described by Lobo et al. (2001). These authors relate both parasequences (called by these authors  $T_C$  and  $T_D$ ), forming part of a group of a total of four transgressive parasequences, as probably having originated during periods of slower sea-level rise or even short periods of stagnant sea level, allowing a stabilisation of the coastline position.

It is the aim of this study, using sedimentological data from surface samples, to investigate the sedimentary composition of the sand-sized grain fraction, and to attempt a paleoenvironmental interpretation of these exposed transgressive parasequences. Possible causes for the exposure of these sediments in an area otherwise covered by up to 14 m of highstand mud will be discussed.

## 2. Material and methods

Bathymetric information used in this study was compiled from Fernández-Salas et al. (1999), Instituto Hidrográfico (1998), Instituto Hidrográfico de la Marina (1990), our bathymetric survey carried out in October 2002 to map the location of submerged terraces using a JMC Model F-840 Recording Echo Sounder, and data related to the depth of sampled locations.

A total of 471 surficial sediment samples were collected in the northern Gulf of Cadiz shelf between January 1999 and November 2001 on board the Portuguese vessel *NRP Andromeda* using a Smith McIntyre grab sampler. About 100 of these samples are directly relevant to this paper. However, data from samples outside the study area were used for the extrapolation of results.

Sediment samples were washed several times using increasing amounts of hydrogen peroxide (10, 30, 80, and 130 vol/l) in order to eliminate all organic matter. Coarse sediments (i.e. sands and gravels) were separated from the fine-grained fraction (silt and clay) by wet sieving using a  $4\phi$  (63  $\mu\text{m}$ ) sieve. The grain size analysis of the fine-grained fraction was carried out using the pipette method. The grain size distribution of the coarse fraction was determined by drying the sediments and separating them in  $\phi$  intervals by dry sieving using a sieve rack.

The sediment type in terms of its dominant grain size components (gravel, sand, mud) was determined using

the classification of Folk (1954). Descriptive grain size parameters were calculated using the method of moments (e.g. Krumbein and Pettijohn, 1938). All grain sizes in this paper will be given in the  $\phi$  scale of Krumbein (1934).

The components of the sand fraction ( $-1$  to  $4\phi$ ) were quantified by counting 100 grains in each fraction using a binocular microscope. Thirty-five randomly selected samples in the immediate study area were re-counted for control of the results. Furthermore, several samples of diagnostic importance were additionally re-counted by one of the co-authors.

The grains were classified visually as quartz, feldspar (where possible), mica, terrigenous carbonates (where possible), other terrigenous grains, aggregates, grains containing glauconite, foraminifera, molluscs, and other bioclasts. Additionally, grains from Paleozoic metachists and greywackes—which are widespread within the lower Guadiana River basin (e.g. Oliveira et al., 1979; Oliveira, 1983)—were counted as a separate component. These grains are easily identified under the binocular, usually as clasts containing silt to very fine sand-sized particles, and fine-grained mica, giving them a rough surface and ‘peppery’ appearance.

A total of 100 quartz grains in the  $1-2\phi$  as well as the  $2-3\phi$  fraction of samples containing more than 2% quartz were analysed for morphoscopic groups (*sensu* Cailleux, 1942). Grains were divided into not used (‘non-usés’), blunt-shining (‘emoussés-luisants’, usually associated with transport in water), and round-matt (‘ronds-mats’ associated with eolian transport).

The high-resolution seismic profiles shown in this paper were obtained with a Uniboom system (Geopulse<sup>TM</sup>: 280 Jul, shot delay of 500 ms, recording scale of 200 ms) and a Differential Global Positioning System during the GOLCA 93, FADO 9611, and WADIANA 2000 surveys.

## 3. Regional setting

The study area is located in the northern margin of the Gulf of Cadiz (south-western Iberian Peninsula), on the continental shelf off the Guadiana River (Fig. 1).

### 3.1. Shelf physiography

The Guadiana shelf lies in a transition zone between the narrow and relatively steep Portuguese shelf, with a width of 5 km between Cape Santa Maria and Tavira and a slope of  $0.5^\circ$ , and the north-eastern corner of the Gulf of Cadiz where the shelf is more than 30 km wide off the Guadalquivir River mouth, with slopes of less than  $0.2^\circ$  (Lobo et al., 2001). The shelf break lies at varying water depths, being at 140–150 m water depth

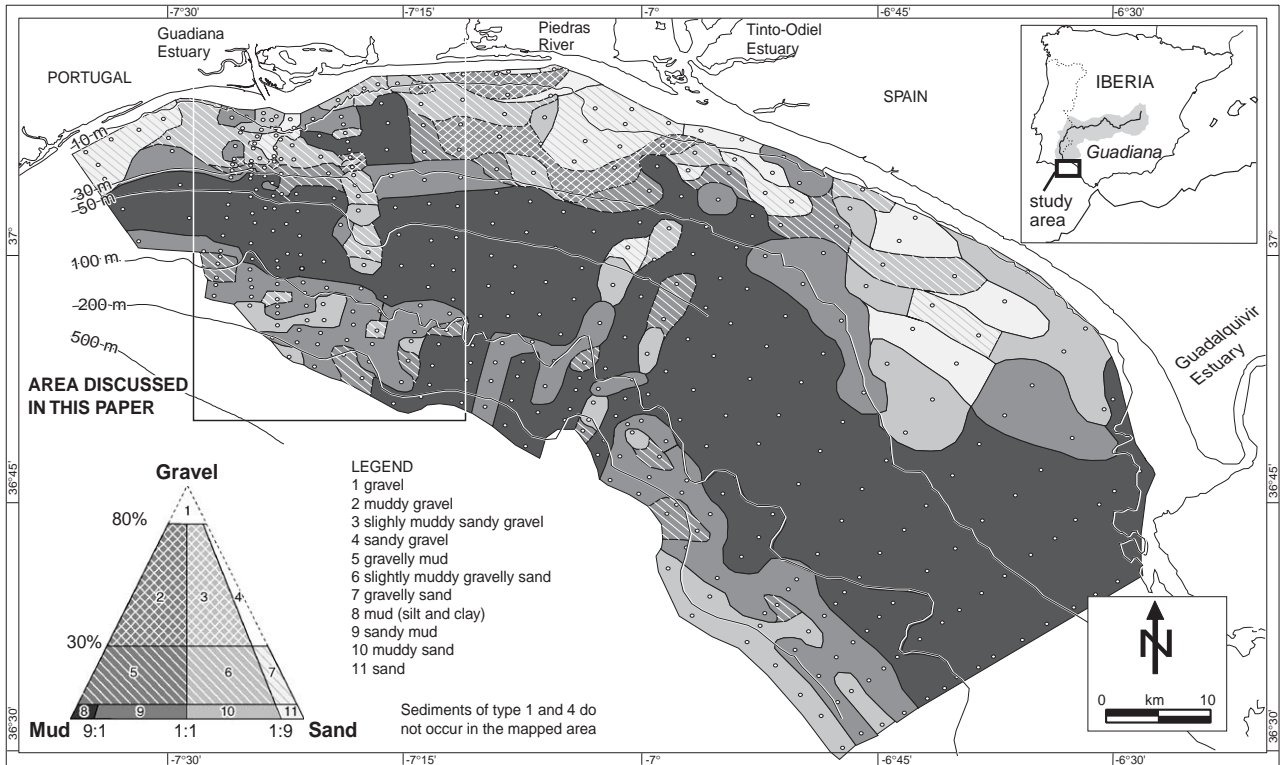


Fig. 1. Distribution of shelf sediments in the northern Gulf of Cadiz. The sediment nomenclature used is according to Folk (1954).

off the Guadiana River (Baldy, 1977; Vanney and Mougnot, 1981).

### 3.2. Sediment cover

Sandy deposits dominate the shelf down to a depth of approximately 25 m, particularly in near-shore zones (Fig. 1; cf. Moita, 1986; Fernández-Salas et al., 1999). A prodeltaic wedge of the Guadiana Estuary (Fig. 2) consists of several patches of sandy mud and mud forming an oblong mud patch with an area of roughly 60 km<sup>2</sup> (Fig. 1; cf. Fernández-Salas et al., 1999).

The outer infralittoral between 25 and 30 m consists of sands and sandy mud. Additionally, this area features a series of rocky outcrops of reduced extent, and probably of Holocene age (Rey and Medialdea, 1989; Fernández-Salas et al., 1999), containing varying amounts of terrigenous gravel.

The middle shelf is characterised by an extensive mud belt, consisting of very fine-grained clayey material (Fig. 1; cf. Nelson et al., 1999). The surface of the outer infralittoral ridge and the upper middle shelf transgressive wedge (Fig. 2), cutting from north to south through the muddy highstand middle shelf deposits, is composed of muddy gravelly sands and muddy sands (Fig. 1).

On the outer shelf below 100 m sediments are generally dominated by sandy and silty clay. These are interrupted locally by large patches of sand and gravelly sand in the vicinity of the shelf edge.

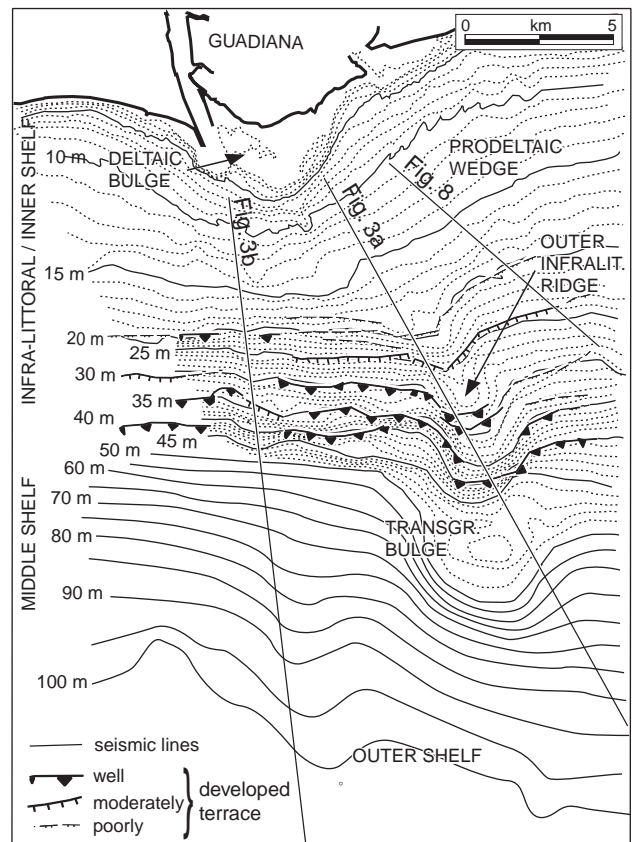


Fig. 2. Physiography and morphology of the Guadiana shelf. The lines mark the location of seismic records shown in this paper.

### 3.3. Sediment supply

Sediment is supplied to the Guadiana shelf from two main sources. The largest regional sediment source is the Guadiana River. The Guadiana river discharge experiences large variations, with winter months from December to March usually being marked by floods, where discharge levels can reach  $3000\text{ m}^3/\text{s}$  and more, while the summers bring extremely low levels of runoff, usually in the range of  $10\text{ m}^3/\text{s}$ , in some years drying off completely. The ratio between minimum and maximum runoff during the period between 1946/47 and 1998/99 was more than 77. During this period the mean annual river volume was  $4.4\text{ km}^3$ , corresponding to a mean river discharge of  $139\text{ m}^3/\text{s}$ . The minimum and maximum annual values for the same time period were 0.18 and  $13.9\text{ km}^3$ , respectively, corresponding to a variation in river discharge between 5.6 and  $436\text{ m}^3/\text{s}$ . This has led to an estimated sediment supply from the river basin to the shelf in the range of  $57.90 \times 10^4\text{ m}^3/\text{yr}$  for the average suspended load and  $43.96 \times 10^4\text{ m}^3/\text{yr}$  for bedload between 1946 and 1990 (Morales, 1997).

The second regional sediment source is the littoral drift. Prevailing onshore wave conditions along the coastline produce an eastward net annual littoral drift estimated to be between 100,000 and  $300,000\text{ m}^3$  of mostly sandy sediment per year, carrying sediments from the southern Portuguese coast towards the eastern portion of the Gulf of Cadiz (Gonzalez et al., 2001). While some of these sand- and gravel-sized sediments are trapped in the Guadiana estuarine system as they pass the river mouth, most sediment bypasses the Guadiana mouth and remains within the inner shelf.

### 3.4. Wave regime

The most frequent wave conditions in the vicinity of the Guadiana shelf show wave heights of around  $H=1\text{ m}$  and periods of  $T=8\text{ s}$  (Costa, 1994). Storms will typically feature wave heights of  $H=3\text{ m}$  with periods of  $T=8\text{ s}$ , while exceptional storms from SW with a return period of 10 years have estimated heights of  $H=6.5\text{ m}$  (height deduced from Pires, 1998) and periods of  $T=10\text{ s}$ .

## 4. Results

### 4.1. Bathymetry and physiography

To better understand the morphological features of the Guadiana shelf, an attempt was made to construct a high-resolution bathymetric chart using available data. The Guadiana Estuary mouth is characterised by a 2–3 km broad sandy deltaic bulge, stretching 6.5 km eastwards from the Guadiana mouth (Fig. 2). The

narrow and relatively steep front of this bulge is well defined and has its limit at around 5–10 m water depth. The bulge merges in an east- and south-eastward direction into a prodeltaic wedge, characterised by recent fine-grained sedimentation (Figs. 2 and 3a).

Both morphological units rest on an about 10–15 km wide infralittoral (*sensu* Hernández-Molina et al., 2000), the lower limit of which is located at about 45–50 m water depth. In particular, the outer infralittoral has a very complex morphology, and is cut in many locations by steep, and even sub-vertical terraces (Fig. 2; cf. Fernández-Salas et al., 1999).

Between approximately 10–20 km SSE of the Guadiana River mouth, and in water depths of 20–50 m, a short, narrow ridge is developed on the edge of the infralittoral, reaching a maximum elevation above the surrounding sea-floor of about 10 m at a water depth of 40 m. At the base of this ridge a 4–5 km broad fan-shaped bulge extends about 4 km into the middle shelf between water depths of 50–70 m. The top of this bulge is nearly flat, and parts of it may even slope against the general trend of the morphology (cf. Fernández-Salas et al., 1999).

The middle shelf, here defined morphologically, is located at a depth between 50 and 90 m water depth with slopes of  $0.35^\circ$ – $0.49^\circ$ . The upper portion of the relatively narrow outer shelf is characterised by more gentle slopes of  $0.14^\circ$ – $0.17^\circ$ .

### 4.2. Post-glacial stratigraphy

The stratigraphic framework for this continental shelf has been summarised in a series of publications (e.g. Somoza et al., 1997; Nelson et al., 1999; Hernández-Molina et al., 2000; Lobo et al., 2001, 2002, in press). Sediments deposited after the last glacial maximum on the Guadiana shelf feature both transgressive (TST) and highstand (HST) system tracts (Lobo et al., 2001).

The post-glacial transgressive deposits are constituted by four backstepping parasequences (Lobo et al., 2001), downlapped by shelf prograding subaqueous deltaic and pro-deltaic facies of the Holocene HST (Maldonado and Nelson, 1999; Rodero et al., 1999). These backstepping transgressive deposits ( $T_A$  to  $T_D$ , from oldest to youngest) are exposed on the Guadiana shelf in the area of the transgressive bulge, and on the middle shelf to the south of it (Figs. 2 and 3a). Two older transgressive deposits  $T_A$  and  $T_B$  occur on the outer middle and outer shelf. These transgressive deposits are buried underneath highstand deposits on most of the other parts of the northern Gulf of Cádiz (Lobo et al., 2001).

High-resolution seismic profiles discussed in detail in Lobo et al. (2001) show that transgressive parasequence  $T_C$ , located on the middle shelf and the outer portion of the transgressive bulge, is dominated by a convex low

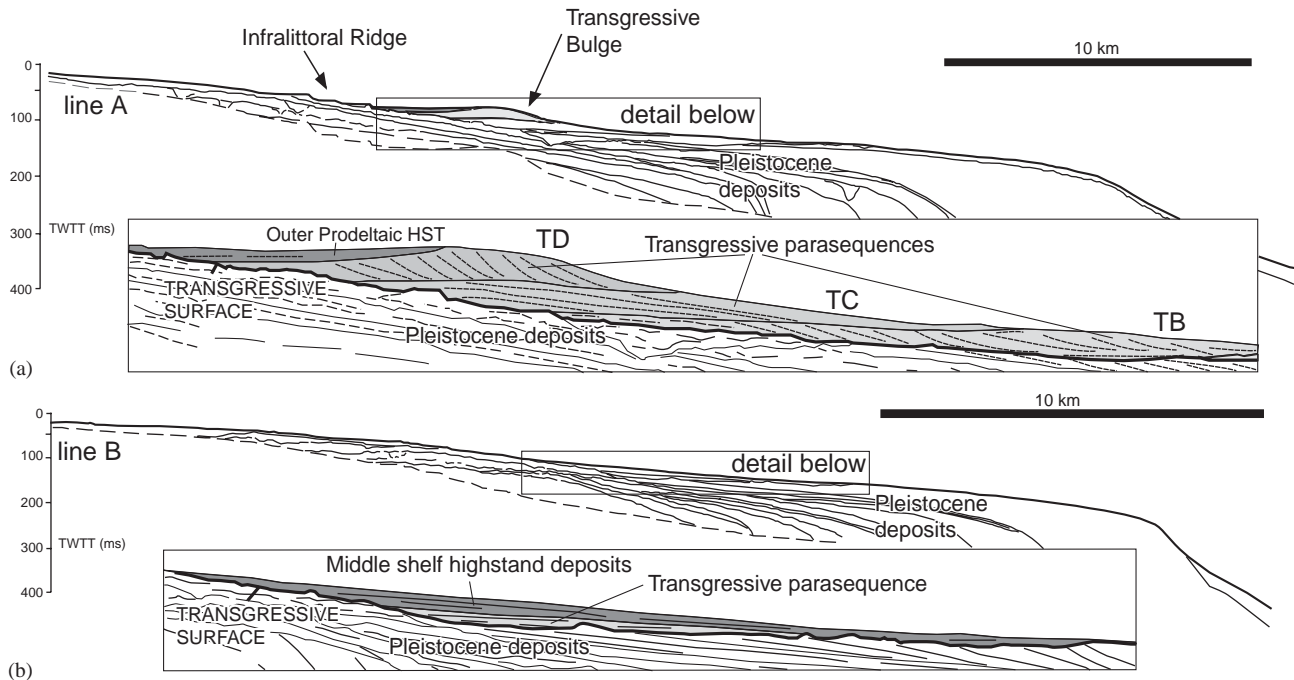


Fig. 3. Seismic sections in the vicinity of both analysed transects. The location of the sections is shown on Fig. 2.

angle sigmoidal configuration (Fig. 3a). The more proximal and younger parasequence  $T_D$ , making up the bulk of the transgressive bulge, contains comparatively steep concave upward prograding clinoforms attributed to a tangential-oblique configuration (Fig. 3a). Both parasequences are separated by a well-defined (erosional) horizon, locally forming a thin lenticular body with horizontal aggradational reflectors between both parasequences. Elsewhere on the middle shelf to the south of the Guadiana Estuary mouth these deposits are less well developed, and covered by highstand mud deposits with a thickness of approximately 8–14 m (12–20 ms TWTT on seismic records) (Fig. 3b).

Large approximately NW–SE oriented paleochannels are located on the inner shelf, eroding older Pleistocene units (Fig. 4; see Fig. 2 for location), and buried by prodeltaic highstand sediments. These channels show a complex, polycyclic internal architecture, and it is probable that they constituted ancient courses of the Guadiana River also active during the transgression. However, Lobo et al. (2001) point out that from the analysis of seismic profiles alone it is not possible to find a direct correlation between the channels and the transgressive seismic units.

Significant highstand deposits outside the middle shelf are found off the Guadiana Estuary mouth, where they form the deltaic bulge and prodeltaic wedge, and in adjacent coastal areas down to a depth of 5–10 m. Additionally, a wedge of outer prodeltaic highstand sediments is found overlying the transgressive parasequence  $T_D$ . Elsewhere, particularly on the

outer infralittoral, seismic sections show ancient Pleistocene deposits at or very close to the modern seafloor.

#### 4.3. Mean grain size

Most sediment down to a water depth of 10 m was found to have a mean grain size of around  $2-3\phi$  in the immediate vicinity of the Guadiana Estuary. Both westwards, and towards the Piedras River system mean grain sizes along the coast increase (Fig. 5). The infralittoral at a depth of around 25 m shows several coarse-grained patches with mean grain sizes between  $-1$  and  $1\phi$  more or less coinciding with the location of rocky outcrops.

Sediments on the middle shelf mud belt are significantly finer, with mean grain sizes consistently above  $8\phi$  west of the Guadiana, and slightly coarser ( $6-8\phi$ ) to the east (Fig. 5). The transgressive ridge shows a fining of sediments with increasing water depth, with mean grain sizes around  $0-1\phi$  at 30 m, and  $4-5\phi$  at 50–60 m. The outer shelf shows a mixture of signatures, with fine-grained sediments prevailing in the eastern portion, and relatively coarser sediments occurring to the west in the area located immediately south of the Guadiana Estuary mouth.

#### 4.4. Distribution patterns of key components

The distribution of quartz (all fractions; Fig. 6a) shows that the highest concentrations occur mainly in

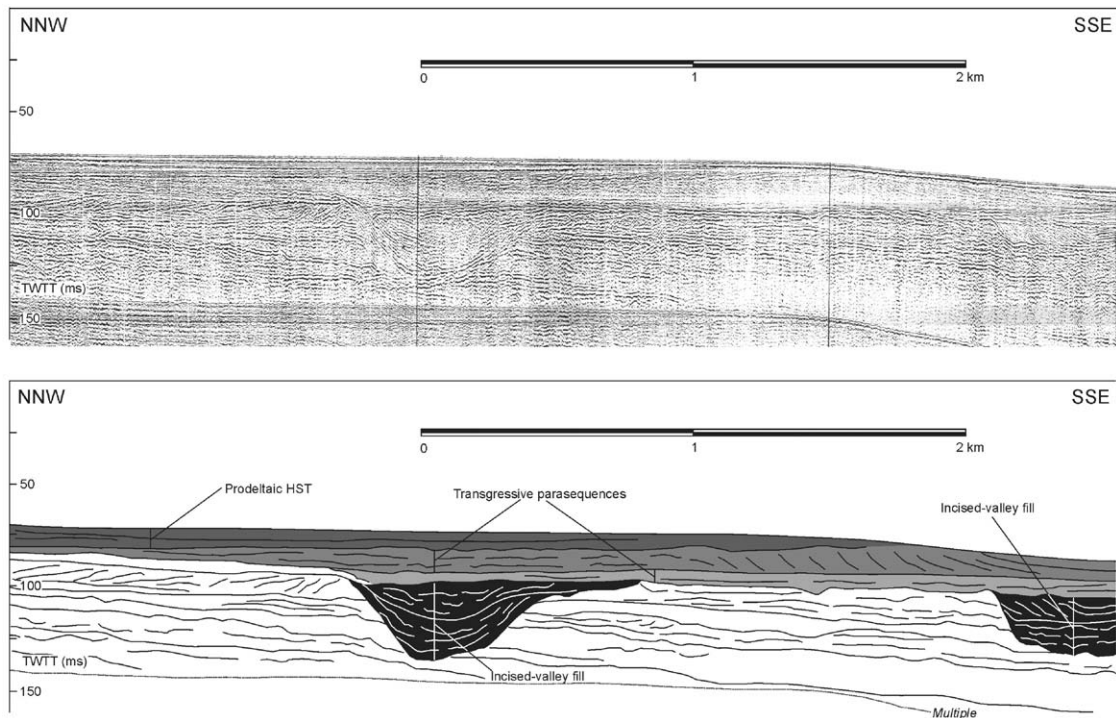


Fig. 4. Large channel with complex infill patterns eroding the Pleistocene underground. The location of the section is shown on Fig. 2.

the prodeltaic area, both to the south of the deltaic bulge and the east, near the coast. High percentages of quartz can also be found at around 30 m water depth, parallel to the upper edge of the outer infralittoral. Amounts of quartz remain relatively high along the infralittoral ridge and the transgressive bulge, but show a southward decreasing trend. A further concentration of quartz can be found south of the transgressive bulge on the upper shelf edge.

The high percentages of quartz at the outer infralittoral are related to the distribution of quartz within the very coarse grained sand fraction, where quartz makes up to 70% of all grains (Fig. 6b). Furthermore, very coarse-grained quartz also occurs in a large, diffuse patch on the outer shelf to the south of the Guadiana Estuary mouth. This patch is not, however, found to the south of the transgressive deposits (Fig. 6b).

Terrigenous components (other than quartz) are in general found on the infralittoral, particularly on the deltaic bulge of the Guadiana, where concentrations can be as high as 40% (Fig. 6c). The transgressive bulge shows a local depocentre with up to 8% terrigenous components associated with the surface of transgressive parasequence  $T_D$ , between water depth of 45 and 65 m. Additionally, two depocentres can be found to the south of the Guadiana Estuary mouth, one at the outer edge of the infralittoral, at water depths of 30–50 m, and one on the outer shelf at water depths of 95–120 m,

both with as much as 10% of terrigenous components (Fig. 6c).

All the above-mentioned depocentres containing terrigenous material other than quartz also contain between 2% and 4% of Paleozoic metaschists and greywacke. In all of the analysed samples across the northern Gulf of Cadiz shelf these very particular components were only found in the area directly related to the Guadiana River basin, and, in much smaller concentrations (rarely more than 1%), further to the west.

To the east of the position of the infralittoral ridge the percentages of quartz and terrigenous components decrease significantly on the entire shelf, and only increase near the Piedras River mouth. This decrease in terrigenous components is linked with an increase in bioclastic sand-sized components (molluscs and echinoderms). Furthermore, it also coincides with the depocentre of fine-grained prodeltaic wedge sediments.

Fig. 6d shows the distribution of glauconite on the Guadiana shelf. The percentage of glauconite is highest on the outer shelf, with maxima both to the south of the Guadiana Estuary mouth, and to the south of the transgressive bulge, where the main depocentre is located, with as much as 16% glauconitic grains. This amount of glauconite decreases along the transgressive bulge northwards. There is about half as much (ca. 5%) glauconite on transgressive deposit  $T_D$  as on  $T_C$  (ca. 10%).

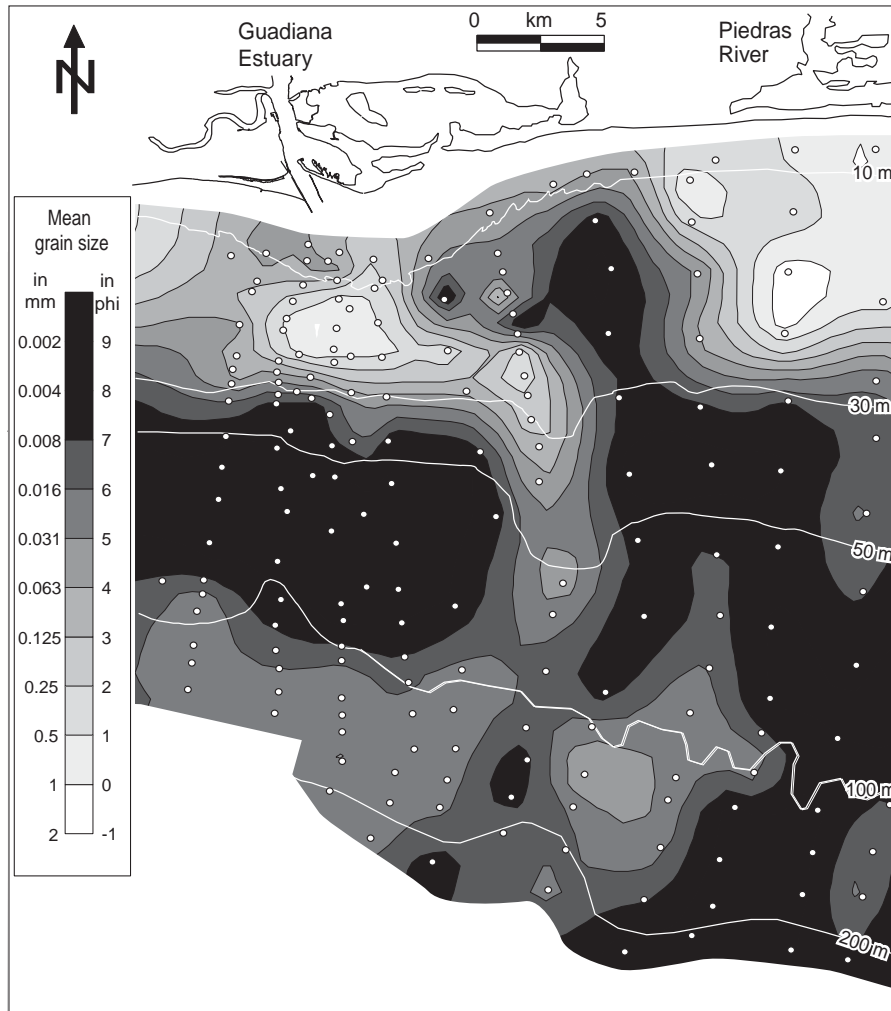


Fig. 5. Mean grain size distribution on the Guadiana shelf.

Glauconite contents on the outer shelf show a strong decrease eastward, to the south of the Piedras River. The values only increase several kilometres further to the east, to the south of the Tinto–Odiel system (not shown on Fig. 6d).

Most of the infralittoral of the Guadiana shelf is dominated by terrigenous components. However, locally bioclasts can form larger accumulations. The infralittoral between the Guadiana Estuary and the Piedras River shows large quantities of molluscs and echinoderm fragments. Autochthonous bryozoans and cold water coral occur in patches on the outer infralittoral, and locally form extensive ‘meadows’, associated with rocky outcrops (some samples retrieved bryozoans still attached to rocks) and terraces.

Most of the sand on the middle and outer shelf is composed of grains of bioclastic origin. Foraminifera dominate, but some samples on the outer shelf feature larger quantities of mollusc remains, in particular in the area of the transgressive bulge and southward. Here, the

amount of biogenous components increases from percentages of 25–35% to about 70%.

#### 4.5. Morphoscopic analysis of the quartz fraction

Fig. 7 shows the distribution of morphoscopic quartz types between the Southern Portuguese coast and the Spanish coastline to the east of the Tinto–Odiel system. Particularly the area to the south and east of the Guadiana Estuary mouth contains larger amounts of NU (not used) and EL (blunt-shining) grains, while both the Piedras and the Tinto–Odiel systems are locally dominated by high contents of RM (round-matt grains). The Guadiana shelf only shows smaller patches of RM grains located on the edge of the infralittoral between the area south of the Guadiana Estuary mouth and the top of the infralittoral ridge. All RM grains showed more or less thick iron-oxide patinas and/or percussion marks, probably related to exposure on the shelf during lowstand conditions. Most of these grains show some

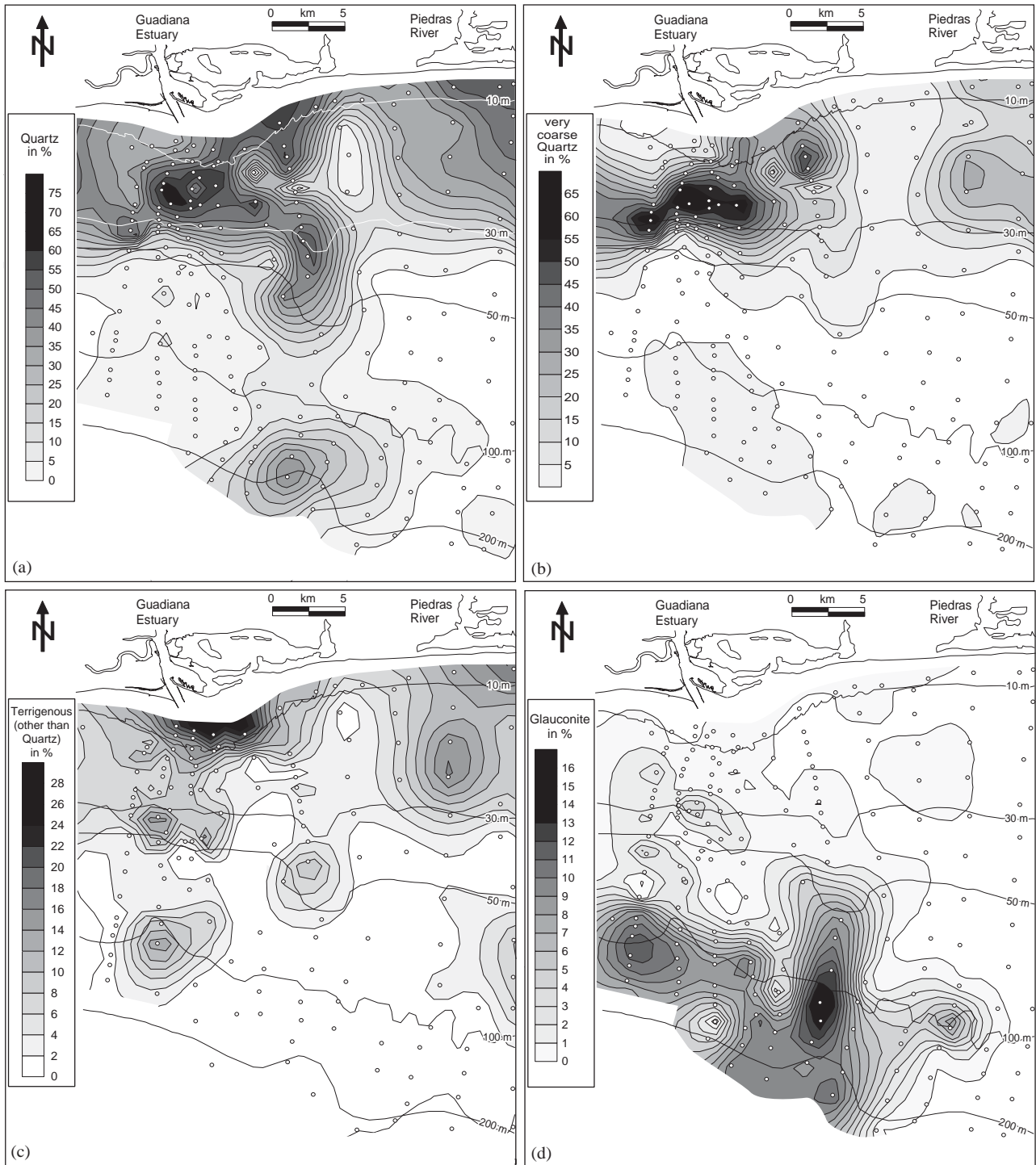


Fig. 6. Distribution of some key components on the Guadiana shelf. (a) quartz; (b) quartz within the very coarse quartz fraction; (c) terrigenous components other than quartz; (d) glauconite.

extent of polish, abrading the patinas and percussion marks, which are interpreted as signs for reworking during the or after the transgression.

Large quantities of NU grains are accumulated on the Guadiana shelf both at the deltaic bulge and south of the transgressive bulge on the outer middle and outer shelf (Fig. 7).

## 5. Discussion

The results discussed in this paper are based on surficial samples, and therefore reflect only the terminal phases of depositional processes that created transgressive parasequences on the Guadiana shelf. Nevertheless, the dataset offers a first insight other than from seismic



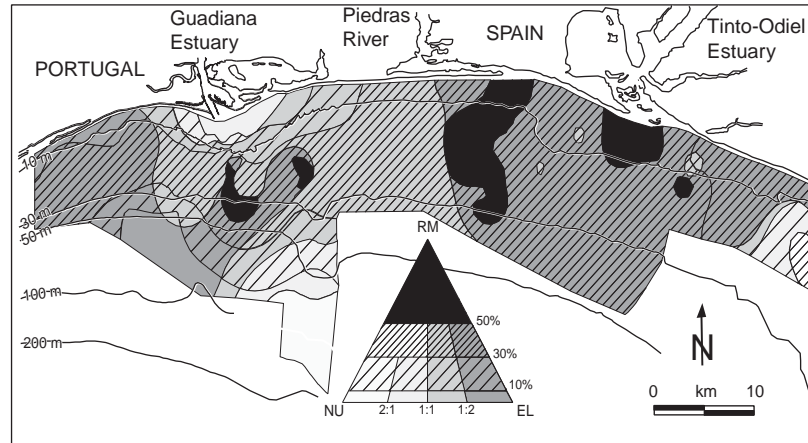


Fig. 7. Distribution of morphoscopic quartz types on the Guadiana shelf.

records into processes active in this area during the last transgression.

So far, dating of the sediments has remained elusive. Consequently, attempts at estimating the timing of the deposition of the parasequences remain speculative. Lobo et al. (2001) proposed a chronostratigraphic framework linking parasequence  $T_C$  to the Younger Dryas Event (e.g. Davies et al., 1992), and  $T_D$  with an event centred at approximately 8.2 ka BP (Bard et al., 1996; Alley et al., 1997). These ages were inferred from a correlation between transgressive seismic units and the estimated depth of submarine terraces, a criterium used by a number of other authors (e.g. Suter et al., 1987; Savoye and Piper, 1993; Hernández-Molina et al., 1994; Chiocci and Orlando, 1996). It is well possible, however, that the sediments are younger, particularly deposits at the top of the parasequences exposed on the sea floor and the subject of this study.

Seismic records indicate that the bulk of transgressive sediments were deposited southeastward of the Guadiana Estuary mouth, forming the transgressive bulge and sediment accumulations to the south of it (cf. Lobo et al., 2001). In this context the transgressive bulge, made up essentially by transgressive parasequence  $T_D$ , can be interpreted either as a detritic fan, or (pro-)deltaic body.

Lobo et al. (2001) interpreted both parasequences  $T_C$  and  $T_D$  as being near-coastal high-energy units. However, both units show a differing internal configuration: while  $T_C$  shows low-angle sigmoidal clinoforms,  $T_D$  is composed of prograding, steep foresets that downlap onto the proximal parts of  $T_C$ , indicating that  $T_C$  was deposited further offshore and under lower energy conditions than  $T_D$ , an assumption supported by the fact that the amount of bioclasts almost doubles between  $T_D$  and  $T_C$ .

Quartz, as well as other terrigenous components, is more frequent within the more proximal parasequence  $T_D$  than the distal, older unit  $T_C$ . Additionally, up to

10% of components of the sediments found in  $T_D$  were terrigenous components (other than quartz) originating from the Guadiana River system, as indicated by remnants of metaschists and greywacke. These and other fragile sediment grains do not survive frequent reworking by waves and currents.

In contrast, such terrigenous grains do not occur within the surface of transgressive parasequence  $T_C$ . They are also lacking further south where older transgressive deposits are exposed on the outer shelf and uppermost continental slope, which contain high amounts of quartz but not other terrigenous components (Figs. 6a and c).

It is probable that the older, more distal parasequence  $T_C$  was created during a longer period of time, allowing for repeated remobilisation of sediments, and thus eliminating more fragile terrigenous components. Such a repeated remobilisation, creating the low-angle clinoforms forming  $T_C$  could be related to storms active in a shallow inner shelf environment (cf. Lobo et al., 2001). Possible sediment sources for the deposits found within  $T_C$  are the littoral drift, material eroded from adjacent coastal (now submerged) terraces, and the Guadiana River.

In contrast, the higher energetic, more proximal (as suggested by the seismic architecture) and younger parasequence  $T_D$  contains quartz as well as other terrigenous components, but relatively few bioclasts. These units could have been created as a result of high-energy flood events in the Guadiana River basin. This is particularly supported by the higher amounts of metashist and greywacke fragments within  $T_D$ . Preliminary results from vibrocores extracted from the top of parasequence  $T_D$ , as well as several more proximal locations, in particular the area of rocky outcrops at the edge of the infralittoral rich in very coarse-grained quartz, show that material eroded from coastal terraces only played a very limited role in contributing sediment

to this area (Gonzalez et al., 2003). Lobo et al. (2001), calculating the volumes of each of the transgressive units, and comparing them to present day sediment supply from the river basin, concluded that sediment supply to the shelf must have been considerably higher than at present.

It is possible that the formation of the transgressive bulge was further enhanced by a dry-humid climate transition. Hillslope erodibility in river valleys is particularly high during the switch from arid to humid climatic periods, when the vegetation cover is at its lowest (e.g. Knox, 1972; Roberts and Barker, 1993; Viles and Goudie, 2003). A series of such climatic changes are well known to have affected the interior of the Iberian Peninsula (e.g. Dorado Valiño et al., 2002), and can lead to an associated increase in the frequency of flood events (e.g. Knox, 1993). Dorado Valiño et al. (2002) point to a pronounced dry-humid transition at around 8 ka BP, which would coincide well with the age of  $T_D$  proposed by Lobo et al. (2001).

The preservation of the transgressive units on the Guadiana shelf was aided by the peculiar paleogeography at the edge of the present day infralittoral, forming a series of terraces and the infralittoral ridge (Fig. 2), which all served to shelter the deposited units on an otherwise exposed and relatively high-energy shelf. Note that on the exposed infralittoral, for instance, no transgressive deposits have been preserved and older Pleistocene units crop out.

Glauconite appears in significant quantities beginning at the base of  $T_D$ , with a clear jump in glauconitic content from  $T_D$  to  $T_C$ , as well as between  $T_D$  and highstand deposits (Fig. 7d), documenting the higher age of exposed sediments, as authigenic glauconite requires several thousand years for its formation (e.g. Odin and Létolle, 1978). Furthermore, glauconite is well known to be associated with periods of transgression and little deposition or even erosion of sediment (e.g. Rech-Frollo, 1963; McRae, 1972; Van Houten and Purker, 1984; Harris and Whiting, 2000).

The continued exposure of this part of the transgressive units on the middle shelf and outer infralittoral in an area where otherwise up to 14 m of mud have been deposited could be explained by the fact that the morphologic exposure of these sediments on the middle shelf favours erosion of most modern mud. The existing hydrodynamic conditions transport the suspended fine-grained sediment, depending on conditions, either towards west or east (Lobo et al., 2004). Sand, on the other hand, although likely to be put into suspension during major storms, will probably be re-deposited not too far away again at the end of such a storm.

Sedimentological data indicate the possible presence of an older detritic system at the beginning of the transgression, transporting sediment in a southward direction from the present day Guadiana Estuary, with

the depocentre being on the outer shelf and inner continental slope. Although there are only limited amounts of quartz on the outer shelf at this location (Fig. 6a), there are several spots with increased content of terrigenous grains other than quartz to the south of the Guadiana (Fig. 6c). The area also shows the existence of very coarse quartz grains on the outer shelf (Fig. 6b) that may have originated at the edge of the infralittoral, indicating very high-energy transport conditions. Additionally, according to isopach maps shown in Lobo et al. (2001) this part of the outer shelf was a depot centre during the formation of the oldest transgressive unit  $T_A$ .

However, other data, for instance the distribution of morphoscopic quartz groups (Fig. 7) indicates that during the early stages of the transgression the main depocentre was located to the south of the transgressive bulge. Here, unusually high quantities of very fresh quartz grains (type NU) are found. Elsewhere, a similar configuration of quartz grain types (high amounts of NU, few EL and RM) occurs only in the immediate vicinity of the Guadiana Estuary mouth.

At present it is not clear whether a N–S trending Guadiana River system may have existed at the beginning of the transgression. A more probable explanation would be that these deposits represent a speculative ‘overflow’ system of the Guadiana River, only active during large-scale flood events.

## 6. Conclusions

A sedimentological analysis of sediments of transgressive parasequences cropping out on the middle and outer shelf to the SE of the Guadiana Estuary mouth (SW Iberia) showed marked differences between sediments found within the more distal and older parasequence  $T_C$  (attributed to the Younger Dryas) and the more proximal and younger parasequence  $T_D$  (attributed to a slow-down in sea-level rise at around 8.2 ka BP). While  $T_C$  shows a high content in quartz and bioclasts,  $T_D$  is dominated by a mix of quartz and terrigenous components other than quartz, and contains fewer bioclasts. There is a marked difference in glauconite between the sediments of both parasequences.

These differences are in agreement with the general architecture found in seismic records, and are attributed to different depositional mechanisms creating the two parasequences. The data suggests that while the formation of  $T_C$  occurred over a longer period of time, with frequent reworking of grains, ultimately depositing sediments as tempestites in an offshore location,  $T_D$  was deposited much quicker and at a much more proximal location, possibly as detrital fan related to flood events in the paleo-Guadiana River basin.

Furthermore, there is evidence that, at least during the initial stages of the transgression sediments were spilled to a location to the south of the Guadiana River mouth. Outer shelf sediment patches related to the surface of parasequence  $T_A$ , the oldest on the Guadiana shelf, show high concentrations of terrigenous components, as well as some very coarse grained quartz grains that might have originated on the present day infralittoral. These sediments could be related to southward-directed overflow channels active during large-scale flood events.

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### References

- Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: a prominent widespread event 8200 years ago. *Geology* 25/6, 483–486.
- Baldy, P., 1977. Géologie du plateau continental portugaise (au sud du cap de Sines). Thèse de 3ème Cycle, Université Paris VI, 113pp.
- Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., Rougerie, F., 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature* 382, 241–244.
- Cailleux, A., 1942. Les actions éoliennes périglaciaires en europe. *Mémoires de la Société Géologique de France* 46, 1–176.
- Carey, J.S., Sheridan, R.E., Ashley, G.M., 1998. Late Quaternary sequence stratigraphy of a slowly subsiding passive margin. *New Jersey continental shelf. American Association of Petroleum Geologists Bulletin* 82, 773–791.
- Chiocci, F.L., Orlando, L., 1996. Lowstand terraces on Tyrrhenian Sea steep continental slopes. *Marine Geology* 134, 127–143.
- Correggiari, A., Roveri, M., Trincardi, F., 1996. Late Pleistocene and Holocene evolution of the North Adriatic Sea. *Il Quaternario* 9 (2), 697–704.
- Costa, C., 1994. Wind-Wave Climatology of the Portuguese Coast. Final Report of Sub-Project A. NATO PO-WAVES Report 6/94-A, 80pp.
- Davies, T.A., Austin Jr., J.A., Lagoe, M.B., Milliman, J.D., 1992. Late Quaternary sedimentation off New Jersey: New results using 3-D seismic profiles and cores. *Marine Geology* 108, 323–343.
- Dorado Valiño, M., Valdeolillos Rodríguez, A., Ruiz Zapata, M.B., Gil García, M.J., Bustamante Gutiérrez, I.De, 2002. Climatic changes since the Late-glacial/Holocene transition in La Mancha Plain (South-central Iberian Peninsula, Spain) and their incidence on Las Tablas de Daimiel marshlands. *Quaternary International* 93–94, 73–84.
- Fernández-Salas, L.M., Rey, J., Pérez-Vázquez, E., Ramirez, J.L., Hernández-Molina, F.J., Somoza, L., De Andrés, J.R., Lobo, F.J., 1999. Morphology and characterization of the relict facies on the internal continental shelf in the Gulf of Cadiz between Ayamonte and Huelva (Spain). *Boletín del Instituto Español de Oceanografía* 15, 123–132.
- Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Geology* 62/4, 344–359.
- Gonzalez, R., Dias, J.M.A., Ferreira, Ó., 2001. Recent rapid evolution of the Guadiana Estuary (Southern Portugal/Spain). *Journal of Coastal Research Special Issue* 34, 516–527.
- Gonzalez, R., Lobo, F., Mendes, I., Dias, J.M.A., 2003. Possible mechanisms leading to the formation of a thick prograding transgressive wedge at the edge of the inner Guadiana Shelf (SW Iberian Peninsula): preliminary results. *IGCP #437 Final Annual Conference, Otranto/Taranto, Italy, 22–28 September 2003*, 102–105.
- Harris, L.C., Whiting, B.M., 2000. Sequence-stratigraphic significance of Miocene to Pliocene glauconite-rich layers, on- and offshore of the US Mid-Atlantic margin. *Sedimentary Geology* 134 (1–2), 129–147.
- Hernández-Molina, F.J., Somoza, L., Rey, J., Pomar, L., 1994. Late Pleistocene–Holocene sediments on the Spanish continental shelves: model for very high resolution sequence stratigraphy. *Marine Geology* 120, 129–174.
- Hernández-Molina, F.J., Fernández-Salas, L.M., Lobo, F., Somoza, L., Díaz-del-Río, V., Dias, J.M.A., 2000. The infralittoral prograding wedge: a new large-scale progradational sedimentary body in shallow marine environments. *Geo-Marine Letters* 20, 109–117.
- Instituto Hidrográfico, 1998. Portugal Continental—Costa Oeste e Sul; Cabo de São Vicente à Foz do Guadiana. Bathymetric Chart, 1st Edition. Scale 1:150'000, Projection Mercator, International Ellipsoid, European Datum (Potsdam).
- Instituto Hidrográfico de la Marina, 1990. Desembocadura del Rio Guadiana y Ria de Isla Cristina. Bathymetric Chart, 3rd Edition. Scale 1:20'000, Projection Mercator, European Datum (Potsdam).
- Knox, J.C., 1972. Valley alluviation in southwestern Wisconsin. *Annals of the Association of American Geographers* 62, 401–410.
- Knox, J.C., 1993. Large increase in flood magnitude in response to modest changes in climate. *Nature* 361, 430–432.
- Krumbein, W.C., 1934. Size frequency distributions of sediments. *Journal of Sedimentary Petrology* 4, 65–77.
- Krumbein, W.C., Pettijohn, F.J., 1938. *Manual of sedimentary petrology*. Appleton-Century-Crofts, 549pp.
- Lobo, F.J., Hernández-Molina, F.J., Díaz Del Río, V., 2001. The sedimentary record of the post-glacial transgression on the Gulf of Cadiz continental shelf (Southwest Spain). *Marine Geology* 178, 171–195.
- Lobo, F.J., Hernández-Molina, F.J., Somoza, L., Díaz Del Río, V., Dias, J.M.A., 2002. Stratigraphic evidence of an upper Pleistocene TST to HST complex on the Gulf of Cádiz continental shelf (southwest Iberian Peninsula). *Geo-Marine Letters* 22, 95–107.
- Lobo, F.J., Sánchez, R., González, R., Dias, J.M.A., Hernández-Molina, F.J., Fernández-Salas, L.M., Díaz del Río, V., Mendes, I., 2004. Contrasting styles of the holocene highstand sedimentation and sediment dispersal systems in the northern shelf of the Gulf of Cadiz. *Continental Shelf Research* 24 (4–5), 461–482.
- Maldonado, A., Nelson, C.H., 1999. Interaction of tectonic and depositional processes that control the evolution of the Iberian Gulf of Cadiz margin. *Marine Geology* 155, 217–242.
- McRae, S.G., 1972. Glauconite. *Earth Sciences Reviews* 8, 397–440.
- Miall, A.D., 1997. *The Geology of Stratigraphic Sequences*. Springer, Berlin, 433pp.
- Moita, I., 1986. Notícia Explicativa da Carta dos Sedimentos Superficiais da Plataforma. Folha SED 8, Instituto Hidrográfico, 18pp.

- Morales, J.A., 1997. Evolution and facies architecture of the mesotidal Guadiana River delta (SW Spain–Portugal). *Marine Geology* 138, 127–148.
- Nelson, C.H., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., Barber Jr., J.H., 1999. Influence of the Atlantic inflow and Mediterranean outflow currents on Late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. *Marine Geology* 155, 99–129.
- Odin, G.S., Létolle, R., 1978. Les glauconie et aspects voisins ou confondus; signification sédimentologique. *Bulletin de la Société Géologique de France* XX (4), 553–558.
- Oliveira, J.T., 1983. The marine Carboniferous of South Portugal: a stratigraphic and sedimentological approach. In: Sousa, M.J.L., Oliveira, J.T. (Eds.), *The Carboniferous of Portugal*. *Memorias do Serviço Geologico de Portugal* 29, 3–33, Lisbon.
- Oliveira, J.T., Horn, M., Paproth, E.P., 1979. Preliminary note on the stratigraphy of the Baixo Alentejo Flysch Group, Carboniferous of Portugal and on the paleogeographic development compared to corresponding units in Northwest Germany. *Comunicações do Serviço Geologico do Portugal* 65, 151–168, Lisbon.
- Park, S.C., Han, H.S., Yoo, D.G., 2003. Transgressive sand ridges on the mid-shelf of the southern sea of Korea (Korea Strait): formation and development in high-energy environments. *Marine Geology* 193, 1–18.
- Penland, S., Boyd, R., Suter, J.R., 1988. Transgressive depositional systems of the Mississippi Delta Plain: A model for barrier shoreline and shelf sand development. *Journal of Sedimentary Petrology* 58 (6), 932–949.
- Pires, H.O., 1998. Preliminary Report on the Wave Climate at Faro. Project INDIA. Unpublished Report, Instituto de Meteorologia, 37pp.
- Rech-Frollo, M.M., 1963. Les conditions de formation de la glauconite en relation avec le flysch. *Comptes Rendues de la Academie de Sciences de Paris* 257, 3011–3013.
- Rey, J., Medialdea, T., 1989. Morfología y sedimentos recientes del margen continental de Andalucía Occidental El Cuaternario en Andalucía Occidental. *AEQUA Monografias* 1, 133–144.
- Roberts, N., Barker, P., 1993. Landscape stability and biogeomorphic response to past and future climatic shifts in intertropical Africa. In: Thomas, D.S.G., Allison, R.J. (Eds.), *Landscape Sensitivity*. Wiley, Chichester, pp. 65–82.
- Rodero, J., Pallarés, L., Maldonado, A., 1999. Late quaternary seismic facies of the Gulf of Cadiz Spanish margin: depositional processes influenced by sea-level change and tectonic controls. *Marine Geology* 155, 131–156.
- Savoie, B., Piper, D.J.W., 1993. Quaternary sea-level change and sedimentation on the continental shelf and slope off Antibes, French Riviera. *Geo-Marine Letters* 17, 133–139.
- Scourse, J.D., Austin, W.E.N., 2002. Editorial: Quaternary shelf sea paleoceanography: recent developments in Europe. *Marine Geology* 191, 87–94.
- Somoza, L., Hernández-Molina, F.J., De Andrés, J.R., Rey, J., 1997. Continental shelf architecture and sea-level cycles: Late Quaternary high-resolution stratigraphy of the Gulf of Cádiz, Spain. *Geo-Marine Letters* 17, 133–139.
- Suter, J.R., Berryhill Jr., H.L., Penland, S., 1987. Late Quaternary sea-level fluctuations and depositional sequences southwest Louisiana continental shelf. *Society of Economic Paleontologists and Mineralogists Special Publication* 41, 199–222.
- Tortora, P., 1996. Depositional and erosional coastal processes during the last postglacial sea-level rise: an example from the central Tyrrhenian continental shelf (Italy). *Journal of Sedimentary Research* 66 (2), 391–405.
- Trincardi, F., Cattaneo, A., Asioli, A., Corregiari, A., Langone, L., 1996. Stratigraphy of the late-Quaternary deposits in the central Adriatic basin and the record of short-term climatic events. *Memorie dell'Istituto Italiano di Idrobiologia* 55, 39–70.
- Van Houten, F.B., Puruker, M.E., 1984. Glauconitic peloids and chamositic ooids—favorable constraints and problems. *Earth Science Reviews* 20, 211–243.
- Vaney, J.-R., Mougenot, D., 1981. La plate-forme continentale du Portugal et les provinces adjacentes: Analyse géomorphologique. *Memórias dos Serviços Geológicos de Portugal* 28, 86pp.
- Viles, H.A., Goudie, A.S., 2003. Interannual, decadal and multi-decadal scale climatic variability and geomorphology. *Earth-science Reviews* 61, 105–131.
- Yoo, D.G., Lee, C.W., Kim, S.P., Jin, J.H., Kim, J.K., Han, H.C., 2002. Late Quaternary transgressive and highstand systems tracts in the northern East China Sea mid-shelf. *Marine Geology* 187, 313–328.