

Sediment Dispersal Patterns on the Northern Gulf of Cadiz Shelf: Which Areas are Influenced by Anthropogenic Sand Starvation?

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ABSTRACT

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Sediment supply to the northern Gulf of Cadiz shelf has been strongly altered during the second half of the 20th century through anthropogenic activity, with an increasing effect on coastlines and the shelf, and ecological as well as economic repercussions.

The sand-sized fraction of 470 surface sediments collected with grab samplers during a number of field surveys carried out between 1999-2001 were used to analyze coarse-grained sediment types and distribution mechanisms on the northern Gulf of Cadiz shelf. The results show that sand on the northern Gulf of Cadiz inner shelf is dominated by quartz particles, making up as much as 80% of the fraction. The area around the Guadiana Estuary mouth down to a maximum depth of 20 m, reaching approximately 5 km to the west and 30 km to the east of the Guadiana, shows a fan containing up to 40% of terrigenous particles other than quartz (19% of which are remains of metashists and greywackes occurring in the Guadiana River basin), and quartz grains with fresh unused broken surfaces and edges. While data from terrigenous particles indicates the short-term influence of the Guadiana River on the shelf, and thus areas most affected by immediate anthropogenic sand starvation, the larger area influenced by 'fresh' quartz grains points to the long-term influence of the river.

ADDITIONAL INDEX WORDS: *Guadiana river, shelf, Gulf of Cadiz, sediment supply, sand budget.*

INTRODUCTION

Sediment supply to the northern Gulf of Cadiz (SW Iberia) shelf coastline and inner shelf has been strongly altered during the second half of the 20th century. Nearshore westward sediment supply through littoral drift has been inhibited through the construction of several jetties along the coastline, for instance bordering the Faro-Olhão Inlet, and the mouth of the Guadiana Estuary (e.g. GONZALEZ *et al.*, 2001). Additionally, sediment supply to the shelf from the southwestern Iberian Hinterland - particularly coarse-grained sediment has been increasingly cut-off through the construction of a large number of dams since the 1950ies. These anthropogenic alterations are thought to have an increasing effect on both coastlines, leading to locally pronounced erosion, and the shelf, with ecological as well as economic repercussions (e.g. for tourism, and fish stocks). This paper aims at defining areas of the inner shelf in the vicinity of the Guadiana River affected by anthropogenic sand-starvation, both in the long- and the short term.

METHODS

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

Sediment samples were washed several times using increasing amounts of hydrogen peroxide (10, 30, 80, and 130 volumes per liter) 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 ϕ (63 μ 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 determined by drying the sediments and separating them in ϕ 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 PETTICHOHN, 1938).

The components of the sand fraction (-1 to 4 ϕ) were quantified by counting 100 grains in each fraction using a binocular microscope. 35 randomly selected samples in the immediate study area were re-counted for control of the results.

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 metashists 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 sandy aggregates containing silt- to very fine sand-sized particles, and fine-grained mica, giving them a rough surface and 'peppery' appearance.

100 quartz grains in the 1-2 ϕ as well as the 2-3 ϕ fraction of samples containing more than 2% quartz were analyzed for morphoscopic groups (*sensu* CAILLEUX, 1942), dividing the grains into not used (NU; 'non usés'), blunt-shining (EL; 'emoussés-luisants', usually associated with transport in water), and round-matt (RM; 'ronds-mats' associated with eolian transport).

REGIONAL SETTING

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 3 000 m³/s and more, while the summers bring extremely low levels of runoff, usually in the range of 10 m³/s, in some years drying off completely. The ratio between minimum and maximum runoff during the period between 1946/47 and 1998/99 was of more than 77. During this period the mean annual river volume was of 4.4 km³, corresponding to a mean river discharge of 139 m³/s. The minimum and maximum annual

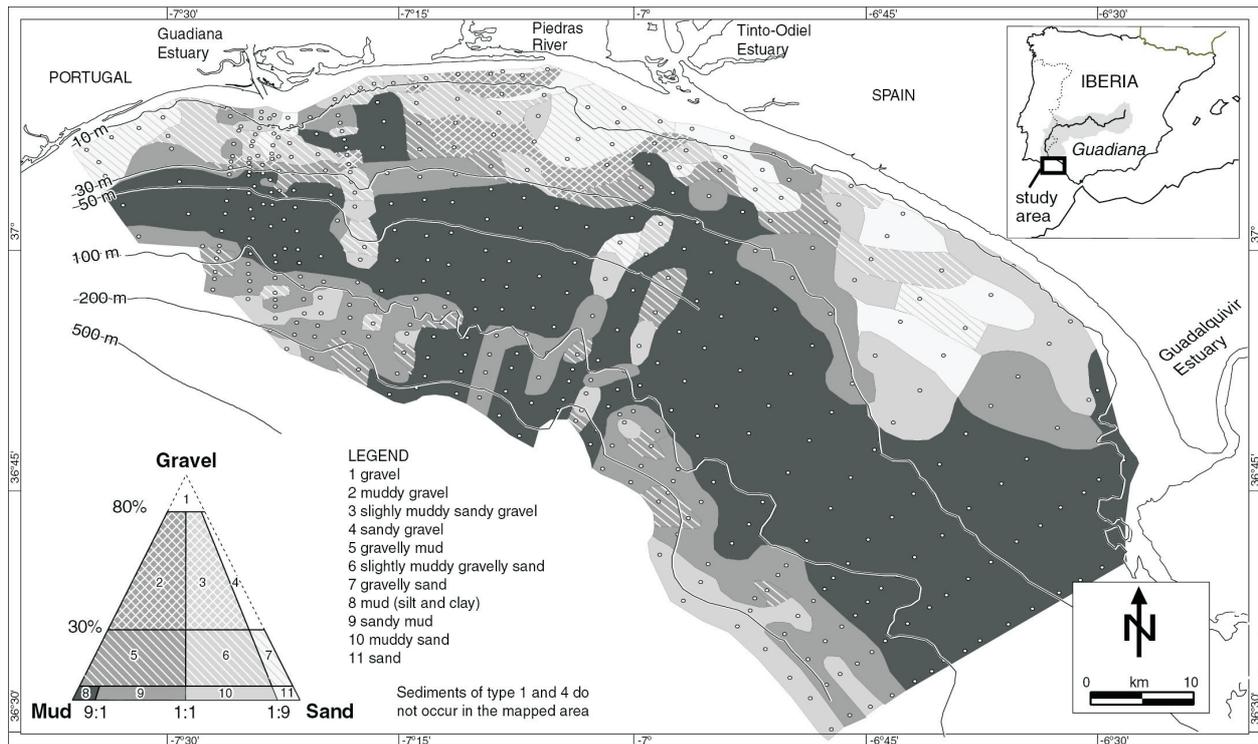


Figure 1. Sediment distribution on the northern Gulf of Cadiz Shelf. The dots represent sampling stations

values for the same time period were of 0.18 km^3 and 13.9 km^3 , respectively, corresponding to a variation in river discharge between $5.6 \text{ m}^3/\text{s}$ 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 carrying an estimated 100 000 and 300 000 m^3/yr of mostly sandy sediment 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.

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 PIREZ, 1998) and periods of $T=10\text{s}$.

RESULTS

The sediment distribution of the northern Gulf of Cadiz is summarized on Figure 1. The inner shelf down to 25 m consists mostly of quartzitic sand bodies, with up to 80% of sand-sized quartz grains, and varying amounts of (biogenic) gravel. Exceptions are areas immediately to the east of the Guadiana Estuary and an approximately 60 km^2 large pro-deltaic mud patch between the Guadiana Estuary and the Piedras River, where bioclasts - mostly mollusk, gastropod, echinoid, foraminifera, and tube-worm fragments - dominate, with up to 90% of particles. The area around the Guadiana Estuary mouth down to a maximum depth of 20 m shows a fan containing up to 40% of terrigenous particles other than quartz.

The middle shelf is covered almost in its entirety by mud and muddy sand, interpreted as distal pro-deltaic bodies derived from the river systems since the last post-glacial sea-level rise. Several cross-shelf strips containing various amounts of sandy

and gravel cross the middle shelf south of the Guadiana and Tinto-Odiel Rivers. These deposits are related to transgressive sand outcropping at the sea-bottom off the Guadiana River (GONZALEZ *et al.*, in press). The outer shelf is covered by a variety of mostly sandy and gravelly patches, many of which are thought to be transgressive in origin (e.g. NELSON *et al.*, 1999; GONZALEZ *et al.*, in press).

A morphoscopic analysis of quartz grains shows that NU (not-used) grains with mostly fresh, unused broken surfaces and edges, occur mostly predominantly in the vicinity of the Guadiana Estuary, the highest concentrations coinciding more or less with the area covered by terrigenous particles other than quartz reaching approximately 5 km towards west and 30 km towards east along the coast (Figure 2). Additionally, fresh Quartz grains (of NU, but also EL type) are distributed across the shelf to a depth of up to 50 m (with decreasing influence below 20 m water depth) both in a south-southwesterly and a broad south-easterly direction. Both areas are separated by strip of seafloor at the outer boundary of inner shelf off the Guadiana River mouth where older (Pleistocene) sediments crop out. NU grains also occur in larger relative quantities on the middle and outer shelf, and on the easternmost edge of the study area (here associated with the mouth of the Guadalquivir Estuary. Eastwards of the Piedras River grains of EL type (associated with transport in water), with shiny, polished surfaces and round edges dominate. Several areas, particularly off the main river mouths show large accumulations of RM grains (usually associated with eolian transport), with well-rounded surfaces and covered by a matt, ferruginous patina. It is likely that these last grains are linked with fluvial contributions to the area during the Pleistocene (e.g. MORENO *et al.*, 2002).

Figure 3 shows the distribution of metashist and greywacke particles on the inner shelf. Our analysis indicates that these sediments are exported to the inner shelf almost exclusively by the Guadiana River, and do not occur elsewhere on the inner shelf of the northern Gulf of Cadiz in significant ($>2\%$) quantities, although these sediments do crop out in other regional river basins (e.g. PIEDRAS, or TINTO-ODIEL RIVERS).

The occurrence of metashist and greywacke is very similar to that of NU-dominated quartz provinces in the vicinity of the Guadiana Estuary, although smaller in size. Along the coast these grains constitute more than 5% of sand to about 5 km west

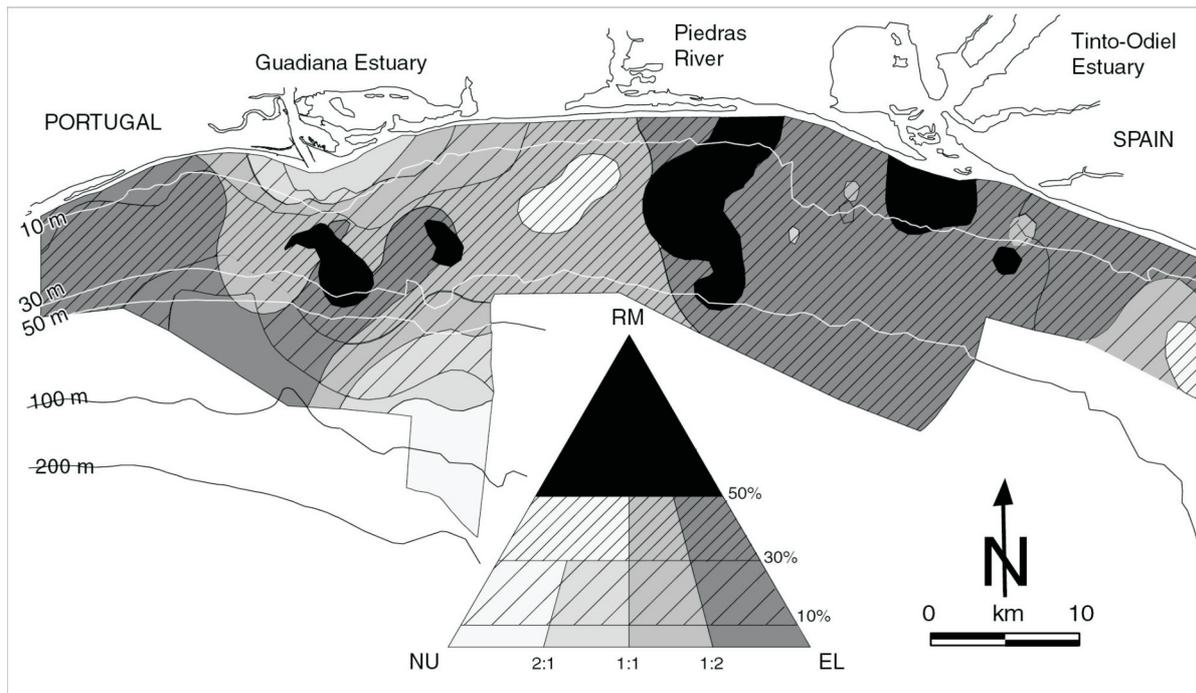


Figure 2. Distribution of quartz types (*sensu* CALLEUX, 1942) across the northern Gulf of Cadiz inner shelf.

and 10 km east of the Guadiana Estuary mouth, peaking at about 18-20% immediately in front of the Guadiana Estuary mouth. The quantity of grains falls below 5% at water depths greater than 5-7 m and peters out between 10-15 m (Figure 3).

DISCUSSION AND CONCLUSIONS

Under recent European legislation (EUROPEAN PARLIAMENT, 2000) coastal areas adjacent to river basins are included into these river basins, to form a larger unit denominated River Basin Districts, in this way recognizing the immense importance of river basins to their adjacent coastal areas. Simultaneously the document calls for a definition of the characteristics of such river basin districts, raising the important

question on how exactly to define a coastal area influenced by a river basin.

Although the above mentioned legal document focuses primarily on the quality of water and the removal of pollutants from the hydrologic system, it also gives some importance to hydromorphological quality elements (depth variations, structure and substrate of the coastal bed) in riverine, estuarine and coastal areas.

It has long been known that one of the effects of anthropic activity (e.g. building of dams) is the reduction of sediment export from river basins to adjacent coastal areas (e.g. NORRIS, 1964; BOWEN and INMAN, 1966; BROWLY and BROWN, 1978; COLLINS and EVANS, 1986; HART and LONG, 1990; RUBIN *et al.*, 1994; STANLEY *et al.*, 1998; CARRIQUIRY and SÁNCHEZ,

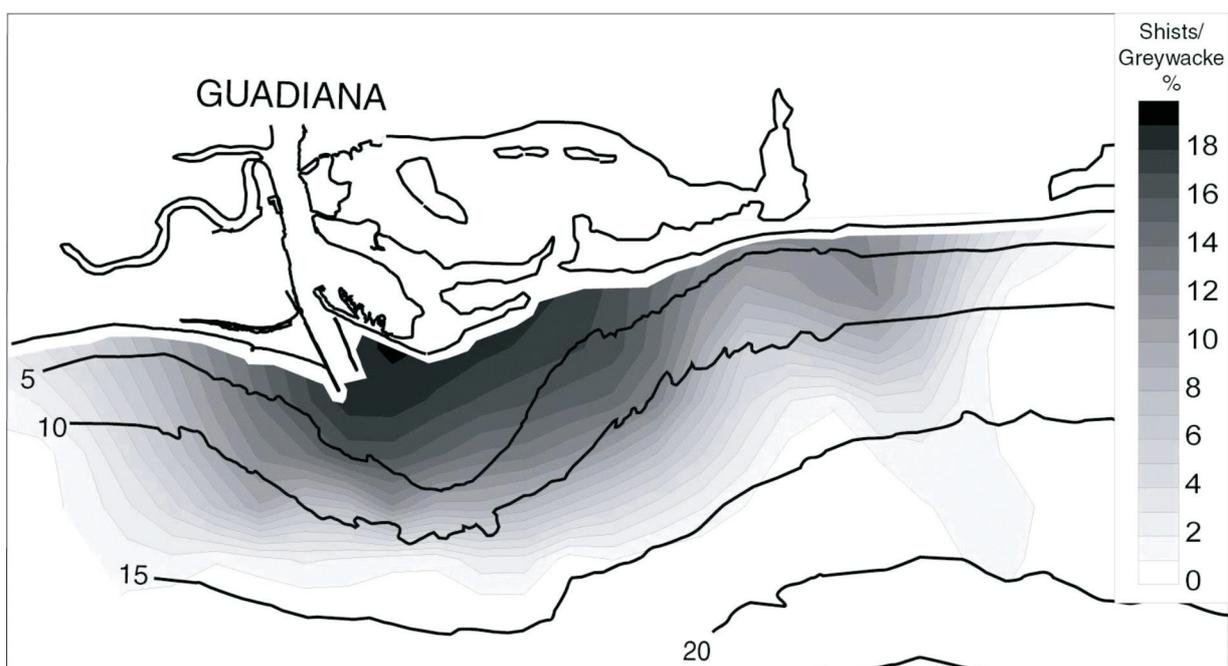


Figure 3. Percentage of metashist and greywacke fragments within sand-sized components in the vicinity of the Guadiana Estuary mouth.

1999). Such a reduction of sediment export to coastal areas is, if it affects existing ecosystems in a significant way, probably illegal considering the new legislation by the European Parliament (2000).

In this context, components that can be attributed to a singular source can be used as a proxy for the influence of a river system on nearshore areas in order to quantify coarse sediment export by river basins, and to analyze the change of this quantity over time, possibly in function of anthropogenic activity.

Although quartz has been used to determine sediment sources and sinks on continental shelves (e.g. PRUSAK and MAZZULLO, 1987), quartzitic particles have a long lifespan and can return during various sea-level cycles into a sedimentary system, making a distinction of past and present hydrodynamic regimes difficult (e.g. GUTIÉRREZ-MAS *et al.*, 2003).

The distribution of quartz types on the northern Gulf of Cadiz inner shelf gives a complex picture (Figure 2). A high concentration of NU (not-used) quartz in the vicinity of the Guadiana Estuary mouth indicate that these quartz grains possibly are directly associated with this river basin.

However, areas at the outer limit of the inner shelf located at water depths between 30-50 m, where large concentrations of NU grains occur, and seemingly under the present-day influence of the Guadiana River basin, may actually represent areas where older deposits crop out, for instance sediment bodies deposited during the last transgression which are known to surface in the area (LOBO *et al.*, 2001; GONZALEZ *et al.*, in press). Despite this, a comparison of quartz grain types (here determined using the simple method of CAILLEUX, 1942) gives useful clues about the long-term export of coarse-grained sediments to the shelf, showing the influence both of the dominant eastward transport of the littoral drift, and on offshore trend in the vicinity of the Guadiana river mouth.

For a definition of the immediate influence of sand exported from the Guadiana river basin, fragments of metashists and greywackes are better candidates, and seem, in this particular case, to be a viable alternative to other particles (for instance heavy minerals). Relatively easily identifiable, these fragile particles don't survive multiple sea-level cycles, and probably don't have a long lifespan (i.e. larger than decadal) within the present day environment. Thus, they can be used in the context of this paper as a proxy defining the short-term export of sediment from the Guadiana.

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