
The influence of coastal processes on inner shelf sediment distribution: The Eastern Algarve Shelf (Southern Portugal)

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| A B S T R A C T |

This study examines sediment distribution patterns in the Southeastern Algarve inner shelf (southern Portugal), an area characterized by marked variations in its coastal environment and low continental supply of sediments. The specific goals of this study were to identify the principal sediment sources and the factors influencing sediment transport paths and deposition. A total of 199 samples, collected along the shelf from the Guadiana River mouth to Olhos de Água, were analyzed. Grain-size distribution and parameters were measured for all the samples. Terrigenous and biogenic components of sand were identified in 38 samples, and results analyzed using multivariate non-linear multidimension scaling (MDS) and cluster analysis. Patterns of sediment distribution in this area of the inner shelf vary according to water depth and exhibit significant longshore variation, related mainly to coastal processes (littoral drift and storm currents) and to a lower degree to sediment sources. Sand is dominant at all depths, reflecting the influence of littoral drift in the supply and redistribution of shelf sediments. Fine and gravel-sized deposits are significant in specific areas and are usually associated with changes in sediment composition. Five sectors have been identified according to sedimentary dynamics. The results, based on geostatistical and multivariate analysis, have allowed detailed sediment distribution maps to be generated, which represent an update of the existing cartography and serve as a tool for the management of coastal and marine resources. They have been furthermore compared with inner shelf sediment dynamics in other regions worldwide, to distinguish between specific regional responses to forcing mechanisms and processes that are more generalized within this type of shelf environments. In this context, the results obtained in the Algarve study area are of great interest for the understanding of sediment dynamics of sand dominated inner shelves with reduced continental supply.

KEYWORDS | Inner shelf. Dynamics. Littoral zone. Sediment analysis. Geostatistics. Southeastern Algarve.

from this region of Southern Europe with other regions worldwide, in order to contribute to the general knowledge on inner shelf sedimentary dynamics, as these areas stand as an important transition domain controlling the balance between continental and marine environments. The only published sediment map of the continental shelf of this area was completed more than 20 years ago (Moita, 1986) it was therefore necessary to characterize the inner shelf sediments in detail, creating new and more detailed sediment maps for the area. Our study involved the construction of new maps of sedimentological variables for this region, using non-linear geostatistical techniques. This work also compares the results from the Eastern Algarve inner shelf with other regions worldwide, in order to contribute to the general knowledge on inner shelf sedimentary dynamics, as these areas stand as an important transition domain controlling the balance between continental and marine environments.

REGIONAL SETTING

The study area is located in the south of Portugal, and comprises the inner continental shelf and adjacent coastal zone extending from Olhos de Água, in the west, to the Guadiana estuary, in the east (Fig.1).

The western part of the study area, from Olhos de Água to the Ancão Peninsula (Ria Formosa), is characterized by sandy beaches bordered by a soft cliff carved in Plio-Quaternary red sands and silts. These sediments are easily eroded by marine and subaerial processes, with the resulting material being incorporated in the littoral drift and contributing to the establishment of beach systems in the area (Dias, 1988). There is almost no direct fluvial contribution into this area of the Algarve coast, although the small discharges of Quarteira Stream (at the western limit of the study area) may have contributed with some sediment to the inner shelf in the past. At present, this stream does not connect with the sea, since its mouth drains to the Vilamoura Marina and any material transported there is dredged.

The Ria Formosa (Fig. 2) extends for about 55km between two limiting peninsulas –Ancão Peninsula to the west and Cacela Peninsula to the east –and includes five islands (Barreta, Culatra, Armona, Tavira and Cabanas) separated by six inlets (Ancão, Faro-Olhão, Armona, Fuzeta, Tavira and Lacém). The barrier-island system reaches its most seaward position, *circa* 6km, at Cape Sta. Maria, located in Barreta Island. This location divides the two flanks of the barrier system: the western flank with a NW-SE orientation and the eastern flank with a NE-SW

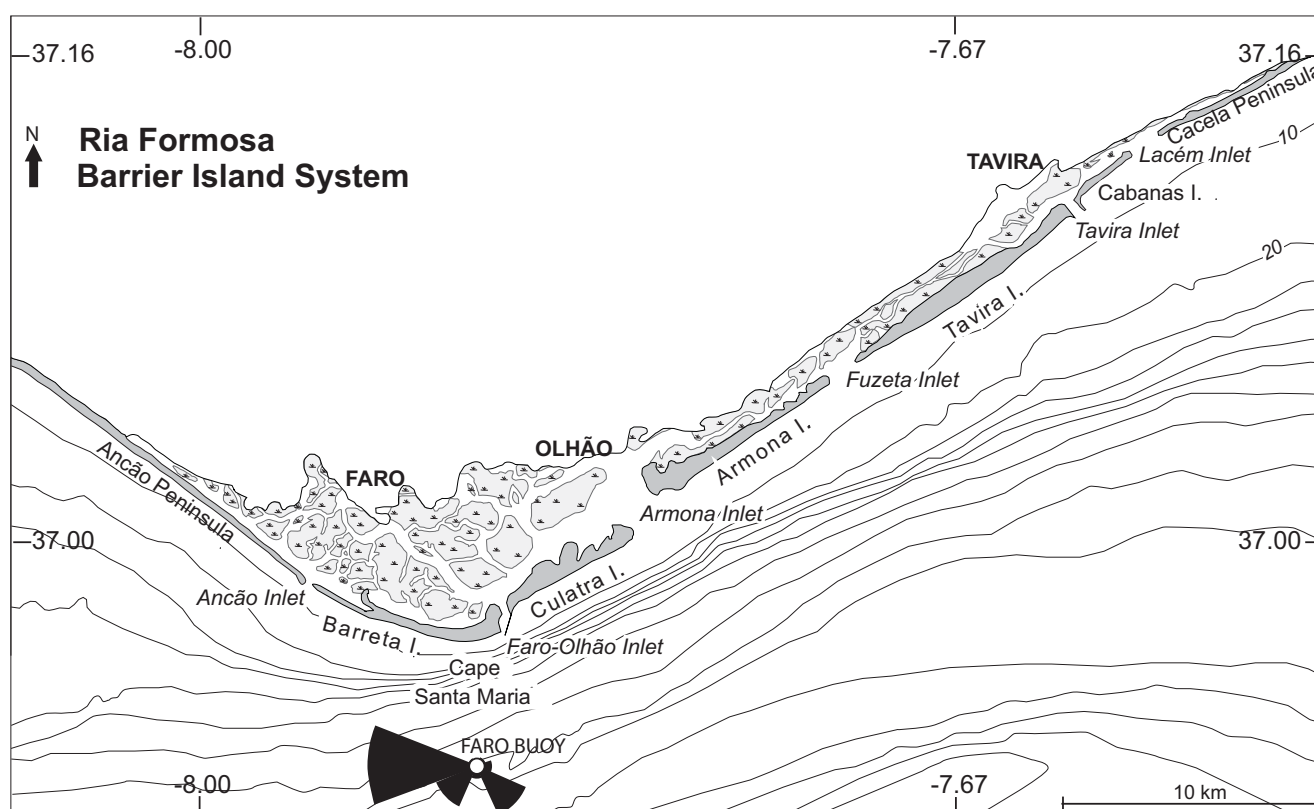


FIGURE 2 | The Ria Formosa Barrier-Island System.

orientation. The western flank typically has only one small migrating tidal inlet, Ancão Inlet (Fig. 2). The eastern flank has five inlets (Fig. 2), although this number has varied over time. Two inlets were artificially opened and stabilised with jetties, the Faro-Olhão Inlet progressively from 1929 to 1955 (Esaguy, 1986) and the Tavira Inlet progressively from 1927 to 1985 (Esaguy, 1987). The barrier system is extremely dynamic and recent island dynamics have been related variously to tidal inlet evolution (*e.g.*, Weinholtz, 1964; Esaguy, 1984; Vila-Concejo *et al.*, 2004; Pacheco *et al.*, 2008), shoreline evolution (*e.g.*, Ferreira *et al.*, 2006), longshore drift (*e.g.*, Ciavola *et al.*, 1997), overwash processes (*e.g.*, Matias *et al.*, 2008), dune formation (*e.g.*, Gomes *et al.*, 1994) and backbarrier processes (*e.g.*, Carrasco *et al.*, 2008). The evolution of the barrier islands is characterized in general terms by a marked migration of the inlets from W to E, which generates erosion of the islands' western sectors and accumulation on the eastern sectors (Pilkey *et al.*, 1989). Hydrodynamic conditions indicate a division within the Ria Formosa barrier island system into two quasi-independent sub-embayments, which conditions the long term migration patterns of the barrier island multi-inlet system: the western including Ancão, Faro-Olhão and Armona inlets, and the eastern including Fuzeta, Tavira and Lacém inlets (Vila-Concejo *et al.*, 2002). Each sub-embayment operates as an autonomous tidal inlet system with minimal interaction with the rest of the Ria Formosa system, characterized by specific tidal conditions and flow velocities through the inlet (Salles *et al.*, 2005).

From Cacela to the Guadiana Estuary (eastern part of the study area, Fig. 1) an extensive sandy shore has developed. It has experienced strong accumulation during the last few decades, partly induced by the construction of the Guadiana River mouth jetty which inhibits littoral drift transport further east (Gonzalez *et al.*, 2001). The Guadiana River estuary is a fluvial-marine system dominated by a meso-tidal regime, which shows an advanced state of sediment infilling (Morales *et al.*, 2006). At present it is in a prograding phase, with tidal sedimentation in the shallowest areas of the estuary generating fluvial delta construction, while the bypassing of sediment towards the coast occurs in the deepest channel (Morales *et al.*, 2006). Flood episodes play a major role in sediment supply (both fine and coarse grained) from the Guadiana estuary to the adjacent continental shelf (Portela, 2006). In the last few decades sediment transport within the Guadiana estuary to the coastal area has undergone significant changes, mainly due to construction of dams in the river basin. This has reduced by 70% the amount of fines reaching the shelf, and by 60% the amount of coarse material (Portela, 2006). The closing of the Alqueva Dam in 2002, which generated the largest artificial lake in Europe, is likely substantially modifying the water and sediment fluvial fluxes. The dam controls 82% of the watershed area (Portela, 2006) and has

a major impact on sediment transfer from the river basin to the adjacent coastal and shelf systems. Its presence seems to have reduced sediment supply to the coast, as suggested by the near-absence of transient flooding in the estuary since 2002 (Wolanski *et al.*, 2006).

The hydrodynamic regime in the study area is characterized by semi-diurnal tides with average ranges of 1.3m and 2.8m for neap and spring tides, respectively, although maximum ranges of 3.5m can be reached during the latter. Wave climate is moderate to high (Ciavola *et al.*, 1997), with an average offshore significant wave height of 0.92m (Costa *et al.*, 2001). Incident waves from the W-SW are dominant, representing 71% of occurrences (Costa *et al.*, 2001) and generating an eastward directed longshore transport. "Levante" conditions (short period waves generated by SE Mediterranean wind) represent 23% of the total occurrences (Costa *et al.*, 2001). Storm events in the area have been defined as events with offshore significant wave heights greater than 3m (Pessanha and Pires, 1981). The establishment of return periods for the main incident wave directions indicates that SW storms are more energetic than SE storms for the same return period (Pires, 1998). The cusped shape of this section of the Algarve coast generates two different areas in terms of exposure to wave action (Figs. 1, 2). The western area (Olhos de Água until Garrão, Ancão Peninsula and Barreta Island) is more energetic because it is directly exposed to the dominant wave conditions (W-SW). In contrast, the eastern area (from Culatra Island to the Guadiana River mouth) is relatively protected from the more energetic waves but is exposed to "Levante" waves.

The Algarve Continental Shelf has a diverse physiography, characterized in general by the narrow width and relatively shallow depths (110 to 150m) of the shelf break (Vannev and Mougenot, 1981). These are very distinctive characteristics from other shelves located in areas nearby, and also from the general trends of continental shelves worldwide, which generally present greater widths and much lower slope values (Roque, 1998). In the western part of the study area, the shelf width reaches more than 20km near Albufeira, and bathymetric contours are generally parallel to the coast. In the central part (including around Cape Sta. Maria) the shelf narrows to *ca.* 5km wide (Roque, 1998) and the shelf break direction inflects abruptly to NE. In the eastern part of the study area, the shelf widens to reach 24km near the Guadiana River mouth (Moita, 1986). Its slope is variable, with the steepest section (20‰) lying close to Cape Sta. Maria, and from there decreasing both eastward and westward to *ca.* 5‰ in the vicinity of the Guadiana River mouth and Albufeira (Andrade, 1990). The inner shelf, from the shoreline down to 30m depth, follows these same general morphologic trends, although its slope is less steep.

The mean slope values of the inner shelf range from *ca.* 2.6‰ to 4‰, and may locally reach *ca.* 8.4‰ (Roque, 1998). Previous studies have also identified specific morphological features in the upper Algarve margin, namely the infra-littoral prograding wedges (IPW), which occupy a transitional position between the onshore and offshore depositional environments (Hernández-Molina *et al.*, 2000). They are strongly dependant on the rate of sediment supply (Roque, 1998) and have been generated by seaward transport of sediments (Hernández-Molina *et al.*, 2000; Lobo *et al.*, 2004). According to these authors, in the study area, the Faro-Tavira Prograding Wedge extends from 10-15m to *ca.* 25-50m water depth.

Sediments of the Algarve inner shelf have been the focus of some previous studies. Moita (1986) characterized the inner shelf as a place for deposition of sands with variable grain-size distribution, which reflects different origins for this material. There is a modern component related to coastal erosion which produces fresh sediments to be integrated in inner shelf deposits, and an older component generated in other deposits of the shelf itself (Moita, 1986). In the Plio-Quaternary soft cliff coast in the western part of the study area, a cliff retreat data set (1958-1991) between Quarteira and Vale do Lobo indicates mean retreat rates of 0.7-3.5m/year east of Quarteira, and 0.6-2m/year around Vale do Lobo (Correia *et al.*, 1996). The construction of the Vilamoura jetties and of the Quarteira groyne in the early 1970's seems to have led to an interruption of the littoral drift to the east, and a consequent substantial increase in the rates of cliff retreat in the area (Correia *et al.*, 1996). The amount of sediment supplied from cliff erosion along this coastal stretch to the littoral system has been estimated by Correia *et al.* (1997) at *ca.* 36,400m³/year for the period 1983-1991. Sediments eroded from the cliffs between Olhos de Água and Ancão Peninsula present a high degree of textural compatibility with the sand deposits that form the Ria Formosa beach systems (Andrade, 1990), revealing a close dependence of these systems on the eastward littoral drift that relocates cliff-derived sediment along the coast. On that basis, cliff erosion has been identified as the most important source of sediment to the downdrift Ria Formosa barrier island system (Dias, 1988; Pilkey *et al.*, 1989; Andrade, 1990). The shelf area adjacent to the Ria Formosa barrier-islands has been identified as a depositary domain of sediments eroded from the barrier-islands, and not as a sediment source to the barrier system (Andrade, 1990). The depth of closure, which controls sediment exchange between the coastal system and the inner shelf, has been estimated at about 6m to 10m for this area (Andrade, 1990; Dolbeth *et al.*, 2007), although it may vary locally. Sedimentary distribution patterns in the continental shelf above 300m water depth, including the inner shelf domain, indicate dominant eastward transport of sediments under the

influence of southeastward Atlantic inflow currents (Nelson *et al.*, 1999). In the Guadiana shelf area, sediments located down to *ca.* 10m water depth are fine to medium sands whereas from 10m to 30m water depth they correspond to coarse sands (Moita, 1986; Gonzalez *et al.*, 2004). The Guadiana River is the main regional sediment source to the adjacent shelf (Gonzalez *et al.*, 2004), with sediment supply from the river basin being higher in suspended load than bed load (Morales, 1997). Littoral drift constitutes the second regional source of sediments in the Guadiana shelf area, corresponding mainly to sand (Gonzalez *et al.*, 2004).

MATERIAL AND METHODS

Sediment Analysis

To study the distribution of superficial sediments in the Algarve inner shelf, 199 samples were collected with a Petit Ponar grab from near the Guadiana River mouth (east of Cape Sta. Maria) to Olhos de Água (to the west). Samples were taken from 92 transects set perpendicular to the coast between 3m and 16m water depth (Fig. 1). All samples were collected during the bivalve surveys carried out by Portuguese Institute of Sea and Fisheries Research/National Institute of Biological Resources (INRB/IPIMAR) on board the Research Vessel Tellina, in October/November of 2005.

Grain-size analysis was performed first by wet separation of the coarse (sand and gravel) and fine (silt and clay) fractions using a 63µm sieve. The coarse fraction was analyzed by dry sieving and the fine fraction using the pipette method. Grain-size determination was made according to phi (Φ) scale intervals after Krumbein (1934), and sediment typology in terms of its dominant grain-size components (gravel, sand, mud) followed the classification of Folk (1954). Granulometric parameters were established using the Grain Size Distribution and Statistics program (Blott, 2000), and sediment description according to the mean and sorting coefficient was established using the Folk and Ward (1957) classification.

To determine the main sedimentary components, sand fraction analysis was performed on 38 samples considered representative of the study area (Fig. 1). Each phi class of the sand fraction was analyzed under a binocular microscope and 100 grains were counted and identified. Terrigenous grains were classified as quartz, mica, other terrigenous and aggregates. Bioclasts were separated into molluscs and other bioclasts. The distribution of the relative abundance of each component in the inner shelf was subsequently computed. The sand fraction results were analyzed via multivariate analysis, using non-linear multidimension scaling and cluster analysis.

Geostatistical analysis

Based on the results of sediment grain-size analysis, maps of the textural parameters were generated. To create continuous maps of the sediment, it was necessary to model and interpolate (predict) the point samples taken over the area. Verfaillie *et al.* (2006) found that universal kriging, using depth (bathymetry) as a linear function of sediment grain-size, was the best interpolation method to create sediment maps. That approach was used in the current study.

The fundamentals of geostatistics, with an emphasis on the non-linear methods employed in this study, are explained in detail in several publications (*e.g.*, Cressie, 1991; Diggle *et al.*, 2003; Bivand *et al.*, 2008). The approach used can be viewed as a Generalised Linear Model (McCullagh and Nelder, 1989) in a spatial context (Diggle *et al.*, 2003) or as a generalization of universal kriging to non-Gaussian data (Cressie, 1991). The procedure applied to fit this method was to model the autocorrelation function $\gamma(h)$ of the spatial process $S(x)$ taking into account the explanatory variables $f(x)$. The range of the semivariogram is interpreted as the distance beyond which no effects of spatial covariance exist among the samples (Maynou *et al.*, 1998).

In this study, we used sediment characteristics (grain-size and sorting coefficient) as dependent Z_i variables. As explanatory variables $f_k(x)$ we used a linear trend with depth. The autocorrelation function $\gamma(h)$ of the spatial process $S(x)$ was fitted by weighted least squares, as recommended by Cressie (1991) for Gaussian random processes.

All analyses were conducted using the software package R (R_Development_Core_Team, 2008), and the libraries 'gstat' (Pebesma, 2004) and 'vegan' (Oksanen *et al.*, 2008).

RESULTS

Grain size distribution

Grain-size analysis performed on superficial sediments of the Algarve inner shelf between the Guadiana River Mouth and Olhos de Água revealed a clear dominance of sandy sediments (Fig. 3). Sand usually dominates sediments at all depths of the inner shelf with abundances consistently above 80%, except around 10m water depth near the Guadiana river mouth where it comprises 20-70% of total sediment (Fig. 4A).

Patterns of sediment distribution in the inner shelf are related to water depth and exhibit significant longshore

variation in the study area (Fig. 4A). Fines accumulate in the vicinity of the Guadiana River mouth but are almost absent to the west of Manta Rota. Also, their abundance shows a clear increasing trend towards deeper environments of the inner shelf. In the vicinity of the Guadiana mouth, between 0 and 5m water depth, fines constitute only up to 7% of total sediments. From 5 to 10m water depth, they comprise between *ca.* 15 and 40%, and up to 15m water depth nearly 70%. Gravel-sized sediments also show important spatial variations. They are almost absent between 0 and 5m water depth, except near Olhos de Água (*ca.* 20%), Culatra Island, from Manta Rota to the Guadiana mouth (*ca.* 15%), and close to the Guadiana River mouth (up to 40%). From 5 to 10m water depth, gravel is present between the Guadiana shelf and the area near Fuzeta Inlet (5-25%) and close to Olhos de Água (*ca.* 20%). In deeper areas (10-15m) it represents a significant part of sediments, *ca.* 10-30% between the Guadiana shelf area and near Fuzeta Inlet, and *ca.* 10-20% between Olhos de Água and off Quarteira Stream.

The distribution of sediment mean grain-size along the study area (Fig. 5) shows a strong dominance of fine and very fine sands ($2\Phi-4\Phi$), and silt ($> 4\Phi$) in the Guadiana shelf. Mean grain-size tendencies are clearly different in the Ria Formosa shelf area. The eastern flank contains mainly coarse ($0\Phi-1\Phi$) and medium ($1\Phi-2\Phi$) sands, whilst the western flank presents mostly fine ($2\Phi-3\Phi$) and medium sands. Almost exclusively coarse-grained (mean) sands are found in the vicinity of Olhos de Água area. Mean grain-size also varies according to water depth (Fig. 5). Around

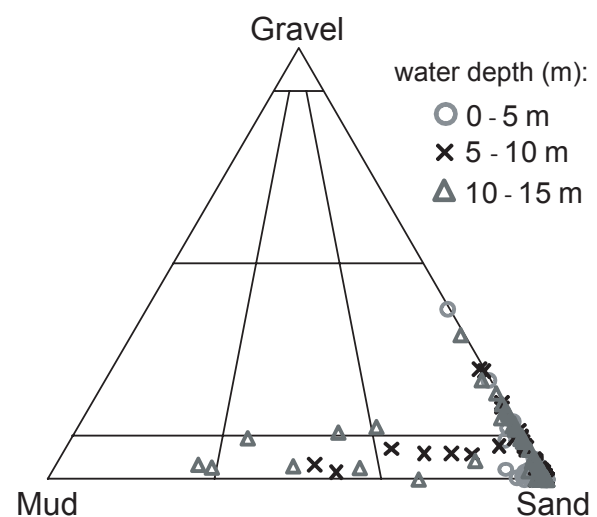


FIGURE 3 | Classification of the Algarve inner shelf sediments according to the Folk diagram (1954).

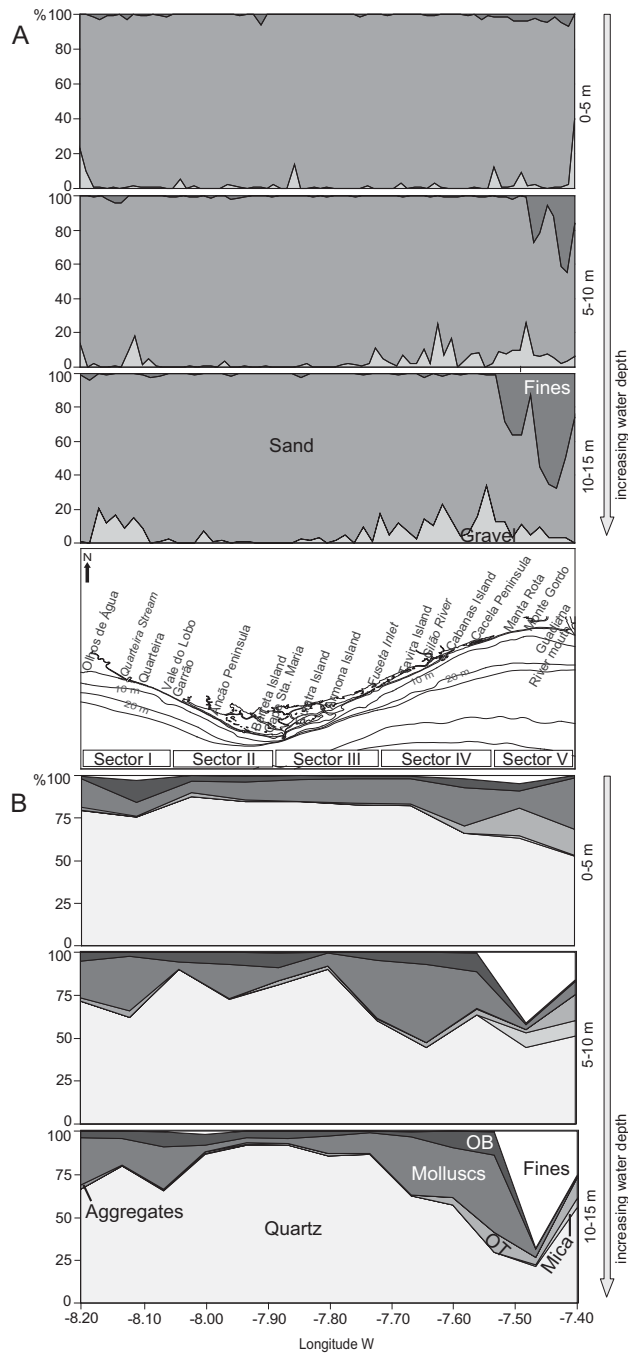


FIGURE 4 | Grain-size and sand composition distributional patterns in the Southeastern Algarve inner shelf. A) Sediment type (Folk, 1954); B) Sand terrigenous and biogenic components (OT: other terrigenous; OB: other bioclasts).

the Guadiana River mouth, sediments correspond mostly to fine and very fine sands up to *ca.* 10m water depth, and to coarse silt below 10m water depth. Fine sands appear down to 5m water depth between Monte Gordo and Manta Rota, and also in the Ria Formosa eastern flank as restricted deposits between Cabanas and Cacela,

and close to Tavira Island west of the Gilão River. A significant deposit of fine sand occupies the inner shelf down to 15m to the east of the Armona Inlet. Coarse sands occur as restricted deposits below 5-10m water depth, from Manta Rota to the west end of Cacela Peninsula, and along Tavira Island. In the western part of the study area, fine and medium sand deposits alternate along the coast. Fine sand deposits are dominant in the area of Cape Sta. Maria, along the Ancão Peninsula, and to the east of Quarteira Stream.

The sorting coefficient (σ) distribution (Fig. 6) also exhibits different trends east and west of Cape Sta. Maria. To the east of the cape, sediments are clearly less sorted, particularly in the Guadiana shelf where moderately ($0.5\Phi-1\Phi$) and poorly ($1.5\Phi-2\Phi$) sorted sediments dominate. West of the Guadiana River mouth, sorting decreases with water depth, from moderately sorted down to *ca.* 5m, to poorly and very poorly ($> 2\Phi$) sorted below the 5m bathymetric contour. Poorly sorted sediments also occur down to *ca.* 10m water depth between Monte Gordo and Manta Rota, and offshore Cabanas Island. A similar poorly sorted deposit is located around the 10m bathymetric line to the east of the Fuzeta Inlet. The inner shelf around Cape Sta. Maria –from Armona Island to Ancão Peninsula– is characterized mostly by moderately sorted sediments. In the western part of the study area, from Garrão to Olhos de Água, sediments are always moderately sorted at all depths, except off the Quarteira Stream where the sorting coefficient is higher.

Sand fraction analysis

Sand fraction analysis revealed important along-shore variations in the composition of the Algarve inner shelf deposits, as well as with increasing water depth (Fig. 4B). Sediments are dominated by terrigenous particles (mostly quartz) along the study area, making up to 90% of total sediment. Biogenic components are mostly molluscs, which in certain areas (near Manta Rota and Cacela Peninsula) reach almost 50% of total sediment. Both eastern and westernmost sectors, beyond the Ria Formosa system, exhibit higher variability in their sedimentological composition.

Between 0 and 5m water depth (Fig. 4B), in the Guadiana shelf area and extending to Manta Rota, quartz makes up 50-65% of the sediment and other terrigenous comprise up to 15% in the vicinity of the Guadiana River mouth. Along the Ria Formosa barrier-island system, from Cacela to Ancão Peninsula, these shallower sediments are very homogeneous, with quartz constituting 80-90%. Other terrigenous particles are practically absent and bioclasts comprise almost 20%. Further to the west, close to Olhos de Água, there are small percentages of aggregates and molluscs are *ca.* 15%.

From 5 to 10m water depth (Fig. 4B), sand components are more variable along the study area. Between the Guadiana River mouth area and Manta Rota, mica has its highest abundance (*ca.* 10%) and other terrigenous a peak of abundance around 15% just off the Guadiana River mouth. Molluscs increase from *ca.* 5% around the Guadiana River mouth to *ca.* 20% near Manta Rota.

Off the Guadiana River mouth and until Fuzeta Inlet, quartz exhibits its lowest abundance (*ca.* 30%). Along the eastern flank of the Ria Formosa, extending almost to Armona Island, molluscs (35-45%) co-dominate total sediments with quartz (45-60%). Close to Armona Island, quartz increases to 90% and molluscs decrease to 7-8%. The latter become more strongly represented (20-30%)

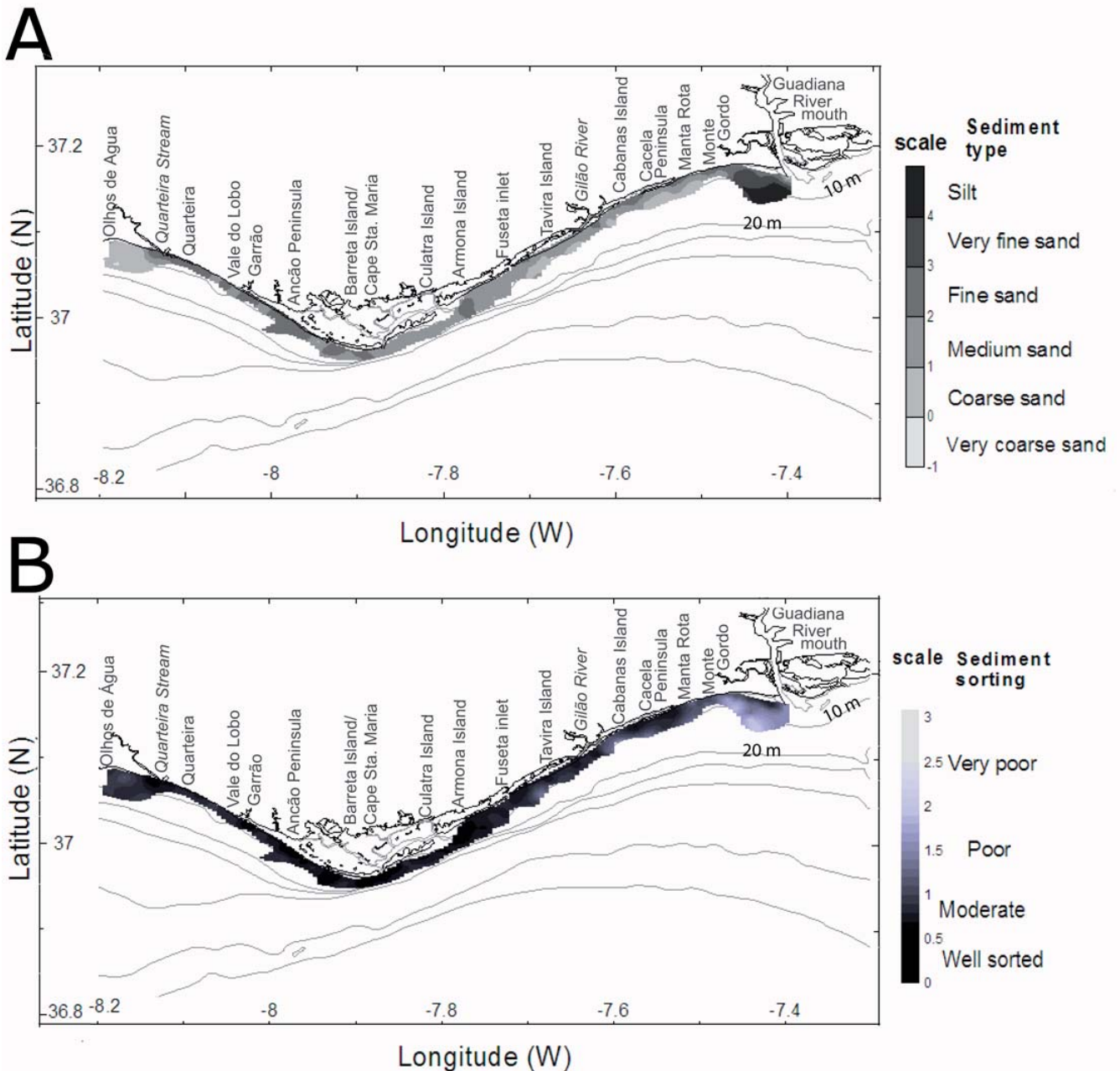


FIGURE 5 | Granulometric parameters (classification of Folk and Ward, 1957) distribution in the Southeastern Algarve inner shelf. The scale is represented in phi (Φ) units. A) Sediment mean grain-size, estimated by universal kriging with depth as a linear covariate; B) Sediment sorting, estimated by universal kriging with depth as a linear covariate.

from the Quarteira Stream to Olhos de Água, as quartz decreases to 60-70% and aggregates are 2-4%.

Between 10 and 15m water depth (Fig. 4B), there is also a significant variability in sand composition. Near Manta Rota, sediments contain their lowest quartz content (*ca.* 30%). Mica (5%) and other terrigenous (10%) still appear in the Guadiana River mouth area. Along the eastern flank of the barrier-island system until near the Tavira Inlet, quartz (50-60%) dominates and molluscs comprise 30-45%. Mica and other terrigenous disappear just west the Guadiana River mouth. Around Fuzeta, Cape Sta. Maria and Ancão Peninsula, sediments are very homogeneous, composed by *ca.* 85-90% of quartz and 3-6% of bioclasts. To the west, in the area influenced by the Quarteira Stream, quartz decreases and molluscs increase up to 15-25%. Close to Olhos de Água, sediments are similar but also contain *ca.* 2% aggregates.

Sediments also exhibit specific variability trends in their cross-shore distribution along the study area (Fig. 4B). Down to 5m water depth, they are fairly homogeneous with dominant quartz and significant amounts of molluscs, except for the deposit with higher other terrigenous which occurs near the Guadiana River mouth. The cross-shore variability of the sediments seems to increase with water depth. Deeper areas of the inner shelf usually have higher contents of biogenic components, namely molluscs. In the Guadiana shelf area, variability is particularly high because of increasing contents of other terrigenous and mica particles in the sand fraction, and also of fines. Higher cross-shore variability also characterizes the Quarteira-Olhos de Água area, related to the presence of aggregates.

Hierarchical cluster analysis applied to sand composition separates three main groups of samples with 40% dissimilarity (Fig. 7A). Group A is composed of samples which are clearly dominated by quartz, usually above 80% of total sediment. Group B contains samples with greater percentages of molluscs, and Group C unites samples with greater amounts of fines, mica molluscs and other terrigenous. Cluster results are clearly confirmed in the non-linear multidimensional scaling analysis (Fig. 7B). Geographically, group C is located mainly close to Guadiana River, group A mostly seaward of the Ria Formosa barrier system, and group B close to Quarteira.

DISCUSSION

General trends in the spatial distribution of sediments in the Algarve inner shelf exhibit a marked variation in response to differential exposure to forcing agents along the study area, to the influence of different sediment sources and to the depth gradient, as has been observed

in other inner shelf environments around the world (*e.g.*, Brooks *et al.*, 2003; Crockett and Nittrouer, 2004; Finkl *et al.*, 2007; Garnaud *et al.*, 2003; George *et al.*, 2007; Guillén *et al.*, 2002; James *et al.*, 2008). Geostatistical methods proved to be an effective tool to map the inner shelf sediment variables, as found in few previous studies (Verfaillie *et al.*, 2006).

Both sediment sources and sediment dynamics can be interpreted on the basis of grain-size maps and the distribution of coarse-fraction components, in the context of existing background knowledge of the study area. The three main groups of sediment identified using cluster analysis and validated in the non-linear multidimensional scaling statistical analyses applied to sand composition variability, are related to the three main sources of sediments (Fig. 7). Cluster group/source A is dominated by quartz, which is widespread along the whole study area. It reflects the dominance of littoral drift in sediment redistribution and deposition in the inner shelf environments. Cluster group/source B is characterized by the presence of molluscs. This biogenic source of sediments is associated with cross-shore distribution patterns which determine the concentration of these elements deeper than the depth of closure in certain areas, manifest as coarse-grained deposits. Finally, cluster group/source C is related to the presence of fines, mica and other terrigenous particles, and clearly reflects the influence of the Guadiana River on the characteristics of inner shelf sediments in the easternmost part of the study area. While the first cluster (group/source A) translates the along-shore redistribution of sediments, the other two clusters (group/sources B and C) clearly reveal the significant cross-shelf gradation of sediment grain-size and composition, as observed in other systems such as the West Florida inner shelf (Finkl *et al.*, 2007).

As recorded in other inner shelves (*e.g.*, Crockett and Nittrouer, 2004), sediment distribution patterns in the Algarve shelf are controlled mainly by type and proximity to the sediment sources, and by prevailing coastal conditions (*e.g.*, waves and currents). The three main sediment sources previously described interact with local coastal and near-shore dynamics to allow five sectors of the Algarve inner shelf to be differentiated (Fig. 4), as follows.

Sector I (Olhos de Água - Garrão), in the westernmost part of the study area, ensures sediment supply to the adjacent shelf through soft cliff erosion. Part of this material remains in this sector as less mature sand deposits. A significant amount, however, is incorporated in the littoral drift and redistributed eastward along the coast and adjacent inner shelf. In the Olhos de Água shelf, the increase in gravel content with water depth (Fig. 4A) is related to increasing amounts of mollusc shells (Fig. 4B). The differential accumulation of shell clasts is not

exclusive of the Algarve inner shelf. The mixed carbonate/siliciclastic Florida inner shelf is also characterized by the accumulation of coarser carbonate sediments produced by marine organisms (Brooks *et al.*, 2003). In the shallower zone of the inner shelf (0–5m water depth) off the Quarteira Stream, small amounts of silt-clay material (Figs. 4, 5) are related to minor river discharges. As in Olhos de Água, erosion of the Plio-Quaternary cliffs in the area between Garrão and Quarteira Stream acts as an important source of coarse sediments to this sector of the shelf (Dias and Neal, 1992; Correia *et al.*, 1996). The coarse sediment input generates sediments with poorer sorting than is observed in adjacent eastward sectors (Fig. 6). The presence of aggregate particles (Fig. 4B) is an exclusive characteristic of this sector and reflects the limited transport and abrasion of sediments supplied by cliff erosion. The fact that locally generated terrigenous and biogenic particles remain in the nearby shelf area reflects both the relative ineffectiveness of the sediment redistribution processes and the importance of sediment sources in this sector of the Algarve shelf. Patches of different sediment types found near their source in the inner shelf (*e.g.*, Brooks *et al.*, 2003 and the study area), mean that their distribution owes less to the action of large-scale remobilization processes and is mainly dictated by the sediment source.

Sector II (Garrão-Cape Sta. Maria) is characterized by homogeneous deposits of moderately sorted fine sand (Figs. 5, 6), with low compositional variability (Fig. 4B). This homogeneity is related to the absence of streams, rivers, cliffs, outcrops or other external sources. Sand components also show low variability (Fig. 4B). No important fluvial systems exist in this sector, and consequently there is almost no contribution of other terrigenous particles. Littoral drift is the main sediment source to this sector of the inner shelf and quartz dominates sediments. Sediments are mainly driven from sector I to sector II by longshore drift, and then redistributed by waves and currents. The wave climate and current patterns do not exhibit any marked variations throughout the sector but their interaction with seabed gradients controls the cross-shore sediment characteristics in the inner shelf. This is a common depositional mechanism that can be seen in the Tasmania shelf (James *et al.*, 2008), the Northern California shelf (Crockett and Nittrouer, 2004), the Florida shelf (Brooks *et al.*, 2003) or the Ebro delta shelf in Northeast Spain (Guillén *et al.*, 2002). This sector of the Algarve inner shelf is located on the high-energy western flank (Vila-Concejo *et al.*, 2006) of the Ria Formosa barrier island system, where W-SW swell waves dominate the wave climate. Greater amounts of bioclasts, mainly molluscs, appear in the Garrão area deeper than 10–15m water depth. At these depths, deeper than the local depth of closure (around 10–11m) (Ferreira, 2000; Dolbeth *et al.*, 2007), bioclasts are related to in-situ living molluscs

that colonise these less hydrodynamic areas, rather than to shells transported offshore from shallower highly energetic areas.

Sector III (Cape Sta. Maria-Fuzeta Inlet) also presents very homogeneous sediments, almost entirely composed of moderately sorted sands (Fig. 4A, 6) in which quartz dominates the sedimentological composition (Fig. 4B). The pattern of sediment distribution is similar to that observed in Sector II, revealing some continuity of sediment supply, but sands are clearly coarser (Fig. 5). This is rather counterintuitive since the western flank of the Ria Formosa system is more exposed to the dominant more energetic waves. The presence of molluscs on the eastern side of Cape Sta. Maria (Fig. 4B) is responsible for the increase in mean grain-size, as observed in limited areas of Sector I. Bioclasts are slightly more abundant than in Sector II because the more energetic western flank does not favour preservation of the shells at shallow depths.

Sector IV (Fuzeta Inlet-Manta Rota) includes a part of the barrier-island system and the coastal area located immediately eastwards. Sand dominates sediments down to 5m water depth. In deeper areas of the inner shelf, gravel-sized sediments become important (Fig. 4A, 5), associated with large amounts of mollusc shells (Fig. 4B), as pointed out in earlier studies (Rufino *et al.*, 2008). The coarser grain-size of these deposits is not indicative of high hydrodynamic levels, but inversely their biogenic nature suggests an environment with low hydrodynamic conditions that allows fragile elements (*e.g.* carbonate mollusc shells) to be preserved and deposited in the shelf. Due to its general orientation, this part of the Algarve coast is sheltered from the dominant W-SW waves and more energetic storms. On the other hand, this sector of the shelf is located downdrift of the two largest inlets of the Ria Formosa system (Faro-Olhão and Armona inlets). In other inner shelves located close to barrier-island systems (*e.g.*, Finkl *et al.*, 2007), the large sand bodies that accumulate due to important ebb-tidal forces near the inlets are poor sediment bypassers and inversely act as permanent sinks of littoral drift transported sediments. The same process seems to occur in this part of the Algarve inner shelf, where the most important Ria Formosa inlets are responsible for significant sediment trapping and consequent restraint of the amount of sand reaching the easternmost sectors (Vila-Concejo *et al.*, 2004). This explains the lower supply of terrigenous particles by littoral drift (*e.g.*, quartz particles) and the relative increase of autochthonous biogenic particles. Due to lower energy levels, the depth of closure in this sector (around 6–10m water depth; Andrade, 1990) is shallower than in the western sectors. At greater depths, storm waves no longer have influence on bottom sediments. Hence, the less energetic environment allows shells to be preserved as coarser particles in the sediment, as observed in this section of the Algarve inner shelf (Rufino *et al.*, 2008).

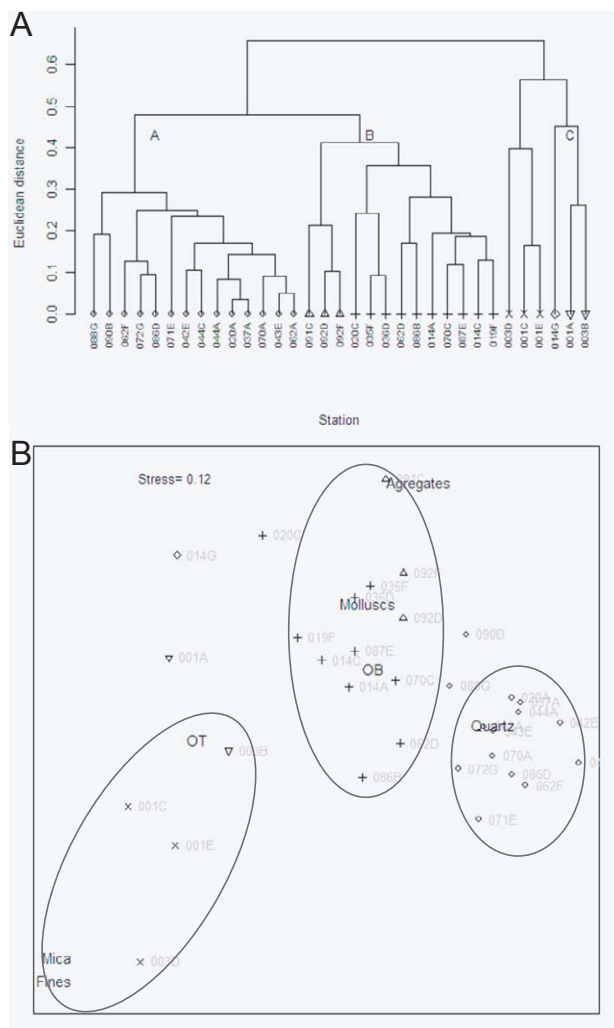


FIGURE 6 | Application of Cluster A) and non metric multidimension scaling B) analyses of sand compositional results, and identification of sedimentary components cluster groups (OT: other terrigenous; OB: other bioclasts).

Sector V (Manta Rota-Guadiana River mouth) is clearly under the influence of discharges from the Guadiana River, which has been identified as the main sediment source to this part of the Algarve continental shelf (Gonzalez *et al.*, 2004). The river discharges correspond mainly to suspended load (Morales, 1997; Portela, 2004). Dominance of schists/greywackes and some types of eruptive rocks in the Guadiana River Basin allow only a very small contribution of sandy sediments to the shelf, which settle mainly in proximal areas of the inner shelf (*e.g.*, Gonzalez *et al.*, 2004). Fine sediments and mica particles are transported in suspension to more distal areas of the inner shelf. Here, the increasing water depth below the depth of closure reduces wave impact over sediments deposited in the sea bed, contributing to a shift in deposition, from coarser sands to fine sediments. The importance of wave

currents in the establishment of shelf sand-mud transitions is relevant as wave-storm activity is the main cause of fine sediment resuspension and deposition in deeper areas of the inner shelf, a depositional pattern also detected in the Adriatic shelf (George *et al.*, 2007) and the shelf off the Ebro River in Spain (Guillén *et al.*, 2002). In addition to wave control, the greater distance to the river mouth and to higher turbulence generated by fluvial discharge currents, contributes furthermore to a less hydrodynamic environment that allows deposition of those particles (Figs. 4, 5). Other terrigenous particles show higher abundances in the sand deposits close to the river mouth down to 5m water depth (Fig. 4B). They reflect the direct influence of river discharges in the area, usually corresponding to heavy minerals from the dismantling of igneous and metamorphic rocks of the river basin. Moreover, the greater abundance of other terrigenous particles accompanies dominant sandy deposition at shallower inner shelf depths (Fig. 4A, 5), because the hydrodynamic conditions do not allow deposition of fine material in the area. Also, proximity to the sediment source allows the system to preserve less stable elements, such as many other terrigenous particles, which would otherwise not resist during long transport paths. Mica particles, also of continental origin and linked to the Guadiana discharges, are transported offshore in suspension with the fines and settle below 10m water depth (Fig. 5B). The Guadiana River discharge gives a specific imprint to deposition on the adjacent inner shelf, as expected since a significant amount of the continental supplied bed and suspended load remains close to its source, similar to what is seen off the Eel River in Northern California (Crockett and Nittrouer, 2004) or in the Bay of the River Seine in France (Garnaud *et al.*, 2003). Fluvial-supplied other terrigenous and marine shells (molluscs) are concentrated at shallower depths (Fig. 4B) just off the river mouth, whilst mica particles and dominant fines are remobilized by wave-storm currents and concentrate in less hydrodynamic deeper areas of the inner shelf (Fig. 4).

CONCLUSIONS

The present study investigated aspects of sediment supply and dispersion in the Eastern Algarve inner shelf. The main goal was to establish sediment paths for this region, and identify differences and similarities with other inner shelf settings to typify these complex environments where marine, continental, and coastal forcing agents interplay. The characterization of modern sediments in this region also constitutes an effort to update the most recent sedimentary cartography of the region, which previously dated back to the 1980s, and thereby the study contributes to present and future coastal management actions (*e.g.*, dredging, beach nourishment). The maps produced successfully portray the continuous distribution

of sediment grain-size and sorting coefficients, and reveal patterns sympathetic to the variation in the forcing agents. In addition, the data obtained in this study provide a base for the analysis of coastal benthic communities that rely on the sediment. The studied area supports an important bivalve dredge fishery, for which management plans are produced on an annual basis by the Portuguese Institute of Sea and Fisheries Research/National Institute of Biological Resources (INRB/IPIMAR).

General trends in the spatial distribution of sediments in the inner shelf exhibit important longshore and cross-shore (depth gradient) variation, as accounted for in other inner shelves worldwide. However, marine/coastal processes seem in general to dominate over the influence of terrestrial sources of sediment, a specific feature that is characteristic of sediment-starved shelves. Nevertheless, the sediment distribution in the Eastern Algarve inner shelf reflects the important imprint of different sediment sources over the dominant action of coastal processes, namely the littoral drift, and the wave and storm-generated currents, in specific areas of the shelf.

There is a close relationship between the grain-size and composition of inner shelf deposits and geological processes occurring in the adjacent coastal area. In the western part of the study area, sediments are supplied to the shelf by cliff erosion, whereas in the eastern part, sediments are mainly supplied by the Guadiana River discharges. However, these sediment sources imprint distinctive characteristics over limited areas of influence, outside of which sediments are dominated by quartz sand transported by longshore drift in the emerged and submerged beach. This small contribution of continental sediments to the coastal zone is responsible for the relative homogeneity of the central part of the studied area. Also, it emphasises the importance of coastal processes in the redistribution of available sand in the beach and ultimately in the inner shelf.

An apparent disagreement between grain-size and hydrodynamic regime was noticed in the comparison of the two flanks of the Ria Formosa barrier system. Results from sediment composition showed that the observed coarsening in the eastern flank is a consequence of the existence and preservation of bioclasts under milder conditions, deeper than the profile depth of closure or in sheltered areas, namely from storm currents. Geostatistical analysis confirmed these trends, which are closely associated with the influence of different sediment sources. On this basis, five sectors can be identified in the Eastern Algarve inner shelf, which reflect specific sedimentary dynamics. Cliffs in the westernmost sector of the study area (Sector I) ensure sediment supply to the adjacent shelf through cliff erosion. Part of this material remains in this sector as

less mature sand deposits, whilst the rest is incorporated in the littoral drift and redistributed eastward along the coast and adjacent inner shelf. In the Ria Formosa barriers, the general configuration of the coast plays a major role in sediment distribution patterns along the shelf, creating two areas differentiated by their degree of exposure to the dominant wave climate: westward and around Cape Sta. Maria (Sector II), and eastward to the Guadiana River mouth (Sectors III-V). Coarser sediments in the eastern area result from the presence of mollusc shells, which are better preserved due to the sheltered position with regard to the SW dominant waves and winter storms. Large amounts of fines found in the area off the Guadiana River mouth are a direct consequence of river discharges (Sector V). They are deposited mainly in areas deeper than *ca.* 5m water depth, which are less affected by hydrodynamics associated with the influence of wave/tidal currents and turbulence generated by the river discharges. The absence of other important regional drainage systems explains the lack of more extensive fine sediment deposits in other parts of the inner shelf.

The sedimentological characterization of this type of inner shelf setting, and the understanding of the mechanisms which rule its depositional dynamics, have been successfully improved by the use of the non-linear multidimensional scaling, which proved to be a very useful tool for the study of these environments.

Overall, the sediment distribution trends observed in the Eastern Algarve inner shelf are constrained by reduced continental sediment supply, and therefore dominated by coastal processes, which in turn control the associated ecosystems. In such inner shelf environment, our data helped demonstrate that littoral drift and nearshore currents during storm events generate sediment redistribution and chiefly control sediment deposition. Local sources of terrestrial input are nonetheless very important in these types of shelves, in the sense that they originate specific inner shelf deposits and set higher variability in sediment distributional patterns. This is crucial both for the establishment of diverse ecosystems and for the use and management of natural resources. Results from characterization of the depositional environment and dynamics of the Eastern Algarve inner shelf will serve as an important management tool for coastal and marine resources on which local and regional development greatly depends.

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