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Factors influencing recent benthic foraminifera distribution on the Guadiana shelf (Southwestern Iberia)[☆]

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Abstract

Benthic foraminiferal assemblages in 24 sediment surface samples collected at water depths ranging from 9 to 103 m on the continental shelf off Guadiana River were analysed, leading to the identification of a total of 270 species. Cluster analyses performed on species with a relative abundance higher than 5% led to the identification of four assemblages. The shallowest assemblage, down to 12 m water depth, is represented by *Ammonia beccarii*, *Asterigerinata mamila*, *Eggerelloides scaber*, *Mississipina concentrica*, *Planorbulina mediterraneensis*, *Elphidium crispum* and *Quinqueloculina laevigata*. A second assemblage between 12 and 40 m water depth is characterised by *Bulimina elongata*, *Cribronion gerthi* and *Nonion fabum*. The assemblage between 40 and 95 m water depth is characterised by *Bolivina dilatata*, *Epistominella vitrea*, *Bulimina aculeata*, *Bolivina ordinaria*, *Spiroloxostoma croarae* and *Nonionella iridea*. Finally, below a depth of 95 m on the upper outer shelf, an assemblage exists characterised by *Brizalina spathulata*, *Bulimina marginata*, *Cassidulina minuta*, *Brizalina subaenariensis*, *Cassidulina laevigata* and *Uvigerina peregrina*.

The spatial distribution of assemblages is closely associated with sea-bottom sedimentary environments and bathymetry. The number of benthic foraminiferal tests, and the distribution of several nearshore species within the two shallowest assemblages are clearly influenced by the outflow of the Guadiana Estuary and by local hydrodynamic conditions. The deeper water assemblages, on the other hand, were found to be more related to low levels of tidal energy, low oxygen environments associated to fine-grained sediments, and cold-water filaments related to seasonal upwelling.

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1. Introduction

The Guadiana River basin is one of the largest on the Iberian Peninsula, and together with the Guadalquivir River the most important sediment supplier to the Gulf of Cadiz. In the past 50 years, a series of human interventions have resulted in the

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reduction of average river discharge, affecting mainly the magnitude and frequency of flood events in the river basins, resulting in large-scale changes in the coastline and margins of the Guadiana Estuary, and altering the amount and type of sediment exported to the continental shelf (Gonzalez et al., 2001). Thus, as sedimentation patterns are altered, the effect of these interventions will ultimately also lead to an alteration of other environmental parameters on the shelf. This situation has been further aggravated by the inauguration of the Alqueva dam in February 2002, creating the largest artificial lake in Western Europe, and almost doubling the amount of water stored in dam lakes in the Guadiana River basin (Gonzalez et al., 2001).

A wide range of physical, chemical and biological parameters, such as temperature, salinity, depth, sediment, oxygen, food, toxic substances, as well as biological interactions, influence the distribution of (benthic) Foraminifera (e.g. Colom, 1974; Murray, 1991b; Jorissen, 1999), making them useful tools for ecological and environmental interpretations (e.g. Haunold et al., 1997). As variations in environmental parameters separate adjacent habitats, making particular microhabitats attractive for some *taxa*, but uninhabitable for others (Jorissen, 1999), associations of benthic Foraminifera can be used as indirect indicators for modifications of environmental parameters.

Consequently, the study of these assemblages will not only allow to define present habitats and parameters associated with them, but will also, for instance through the study of sedimentary successions, allow the reconstruction of the past evolution of the shelf, and the parameters that at the time influenced the environment. Furthermore, future variations of the present assemblages will help to understand and localise the impact of anthropogenic activity, occurring not only in the Guadiana River basin, but also on the adjacent shelf and the increasingly populated adjacent coastal regions of the Algarve (southern Portugal) and Andalucía (southwestern Spain).

At present there is only a limited number of studies dealing with the superficial distribution of benthic Foraminifera in the northern Gulf of Cadiz. After the initial publication by Galhano (1963) of the first systematic study on Foraminifera of the

Algarve shelf in the Western Gulf of Cadiz, it was only from the 1990s onwards that further significant research in the area was carried out (e.g. Levy et al., 1993, 1995; Muñoz et al., 1996; González-Regalado et al., 2001; Schönfeld, 2002). With few exceptions (e.g. Muñoz et al., 1996), most of these studies were of a wider regional character with large-spaced sampling grids.

Therefore, the main aims of the present study on the shelf off Guadiana River mouth are to (1) characterise the population of benthic Foraminifera in surface sediments, establishing a relationship of identified benthic foraminiferal assemblages with depth and sediment, focussing on the most abundant assemblages and their spatial distribution; (2) analyse how the river influences this distribution; (3) integrate this information with data on the geomorphological and hydrodynamic setting of the shelf; and (4) identify other possible influencing environmental parameters.

2. Study area

The study area is located in the northern margin of the Gulf of Cadiz (Southwestern Iberian Peninsula), between 9 and 103 m water depth (Fig. 1).

2.1. Wave regime and littoral drift

The Guadiana Estuary system is semidiurnal mesotidal, with a mean tidal range of 2.0 m, ranging between maximum values of 3.8 m and a minimum of 0.5 m (Instituto Hidrográfico, 1998). The tidal wave moves from east to west along the coast, producing minor currents in the range of 0.3–0.4 m/s (Morales, 1997). The region is characterised by waves of low to medium energy, including both Atlantic swell waves and local sea waves. Southwesterly waves prevail with approximately 50% of occurrences from the west. They are less energetic than the southeasterly ones, which make up about 25% of occurrences (Costa, 1994).

The average significant offshore wave height is about 0.9 m (maximum values of 4.9 m and minimum of 0.14 m), with an average period of 4.6 s, and peak average periods of 8 s (Costa, 1994). Under these conditions, sediment grains with a diameter of

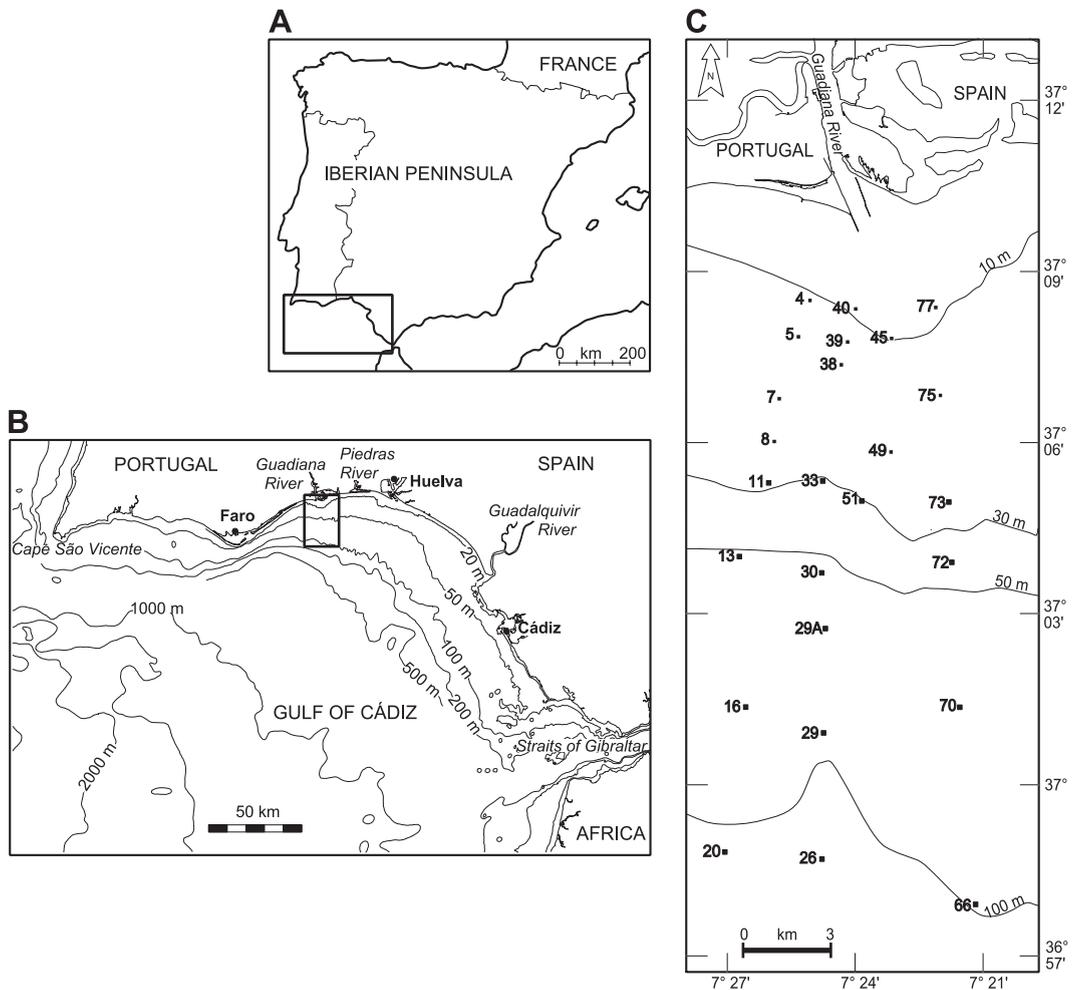


Fig. 1. (A) Location map; (B) location of Gulf of Cadiz; (C) geographic setting of the studied samples.

2 mm (very coarse sand) will be remobilised down to a depth of about 5 m during fair-weather conditions, and 30 m during storms, while grains with a diameter of 32 μm (coarse silt) will be remobilised down to 10–15 m under fair-weather conditions, and 45–50 m during storms (e.g. Komar and Miller, 1973, 1975). The prevailing onshore wave conditions will produce a net annual littoral drift from W to E, estimated between 100,000 and 300,000 m^3/year (Gonzalez et al., 2001).

The Guadiana River water discharge is marked by strong seasonal changes, with floods occurring during the winter months from December to March, and

droughts affecting the river basin during summer months. According to Morales (1995, 1997), the total estimated sediment supply from the river basin to the shelf lies in the range of $57.90 \times 10^4 \text{ m}^3/\text{year}$ for the average suspended load and $43.96 \times 10^4 \text{ m}^3/\text{year}$ for bed load between 1946 and 1990.

2.2. Oceanographic influencing factors

The studied area is influenced by the North Atlantic Surface Water (NASW), a strong southeasterly inflow over the continental shelf that intensifies towards the Straits of Gibraltar and which occurs

within the upper 300 m of the water column (Ambar and Howe, 1979; Fiúza, 1982; Caralp, 1992). Several authors postulate a periodic influence of cold-water filaments (Vargas et al., 2003; Sánchez and Relvas, 2003; Lobo et al., in press). These filaments can reach the middle shelf in the northern Gulf of Cadiz and are possibly related to seasonal upwelling, although this is still a matter of some debate (in contrast to the area to the west of the study area, near Cape St. Vincent, where upwelling is well documented; e.g. Fiúza, 1982, 1983; Vargas et al., 2003).

2.3. Shelf bathymetry

The northern Gulf of Cadiz shelf width increases towards east while the mean slope decreases. The shelf has a minimum width of 5 km off Faro (Portugal), increases to 20–25 km off the Guadiana River and attains a maximum width of more than 30 km close to the Guadalquivir River mouth. Accordingly, the mean slope of the Portuguese shelf is 0.5° , decreasing to slopes of less than 0.3° on the Spanish shelf. The mean Guadiana shelf slope is 0.32° (Roque, 1998; Lobo et al., 2001).

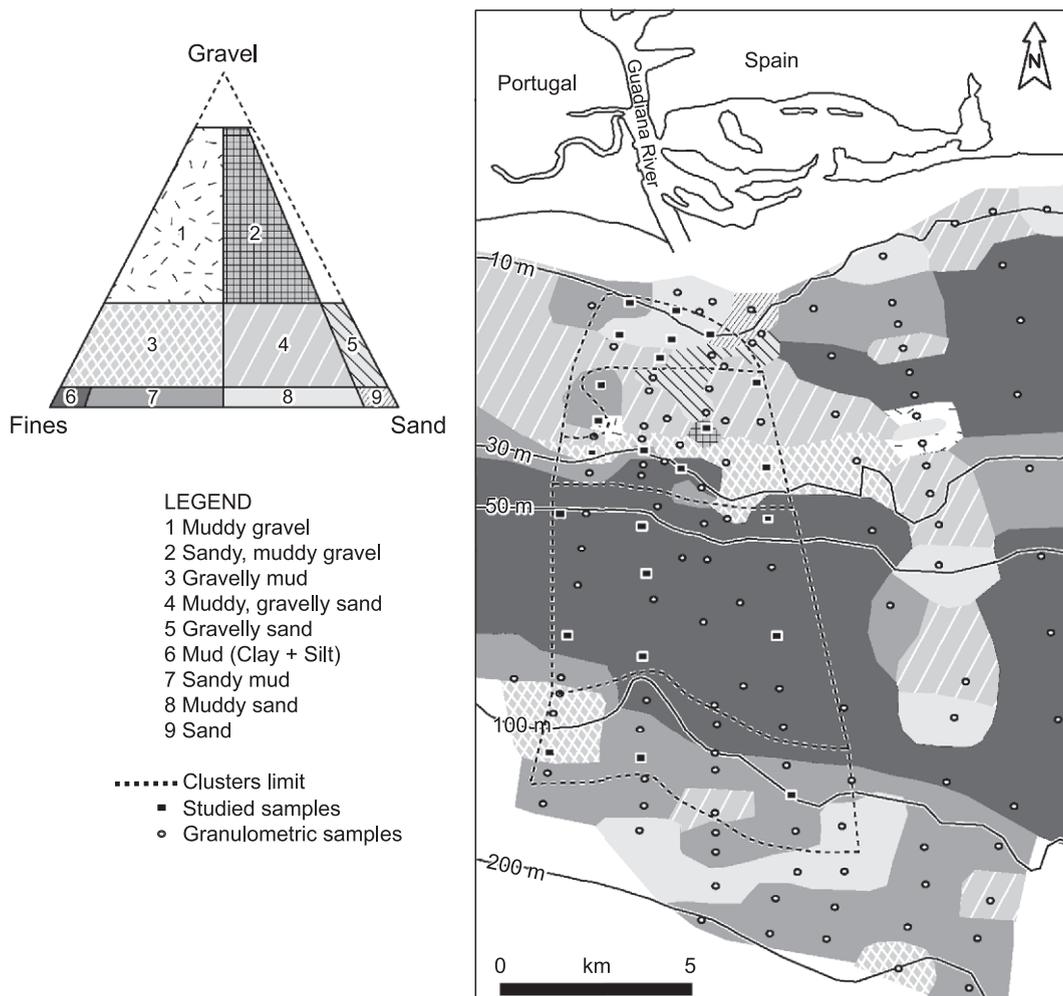


Fig. 2. Sediment composition on the Guadiana Shelf based on 470 samples after González et al. (2003).

The shelf break lies at varying water depths in concordance with width and sea floor gradients changes. Off the Guadiana River it is located at 140–150 m water depth (Baldy, 1977; Vanney and Mougnot, 1981).

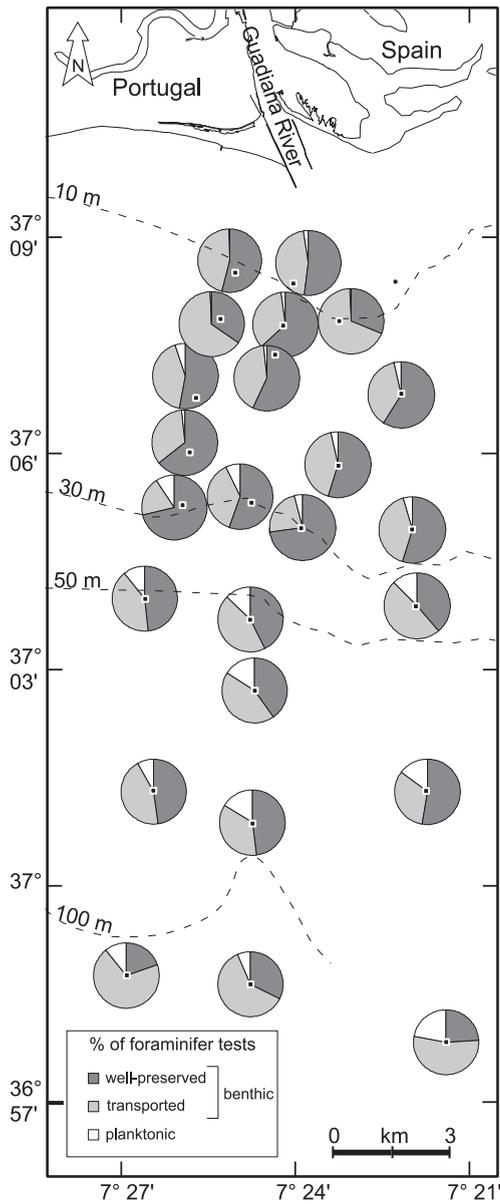


Fig. 3. Percentage distribution of well-preserved and transported benthic as well as planktonic foraminifer tests on the continental shelf off Guadiana River.

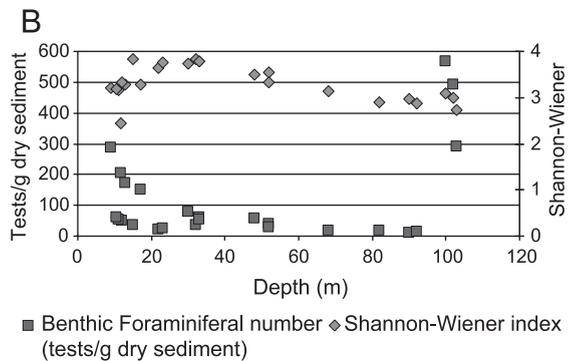
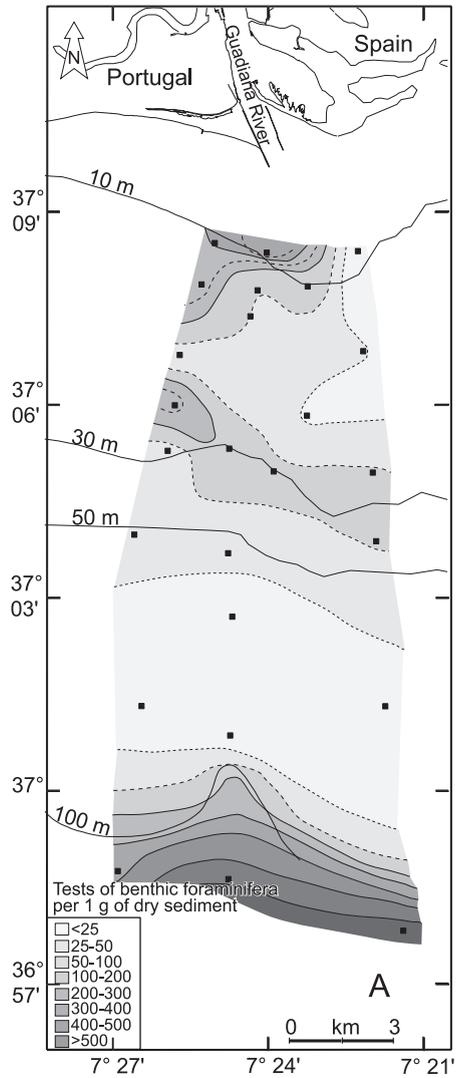


Fig. 4. (A) Distribution of benthic Foraminifera tests (specimens/g dry sediment) in the analysed area; (B) variation of the density and Shannon–Wiener index values with depth.

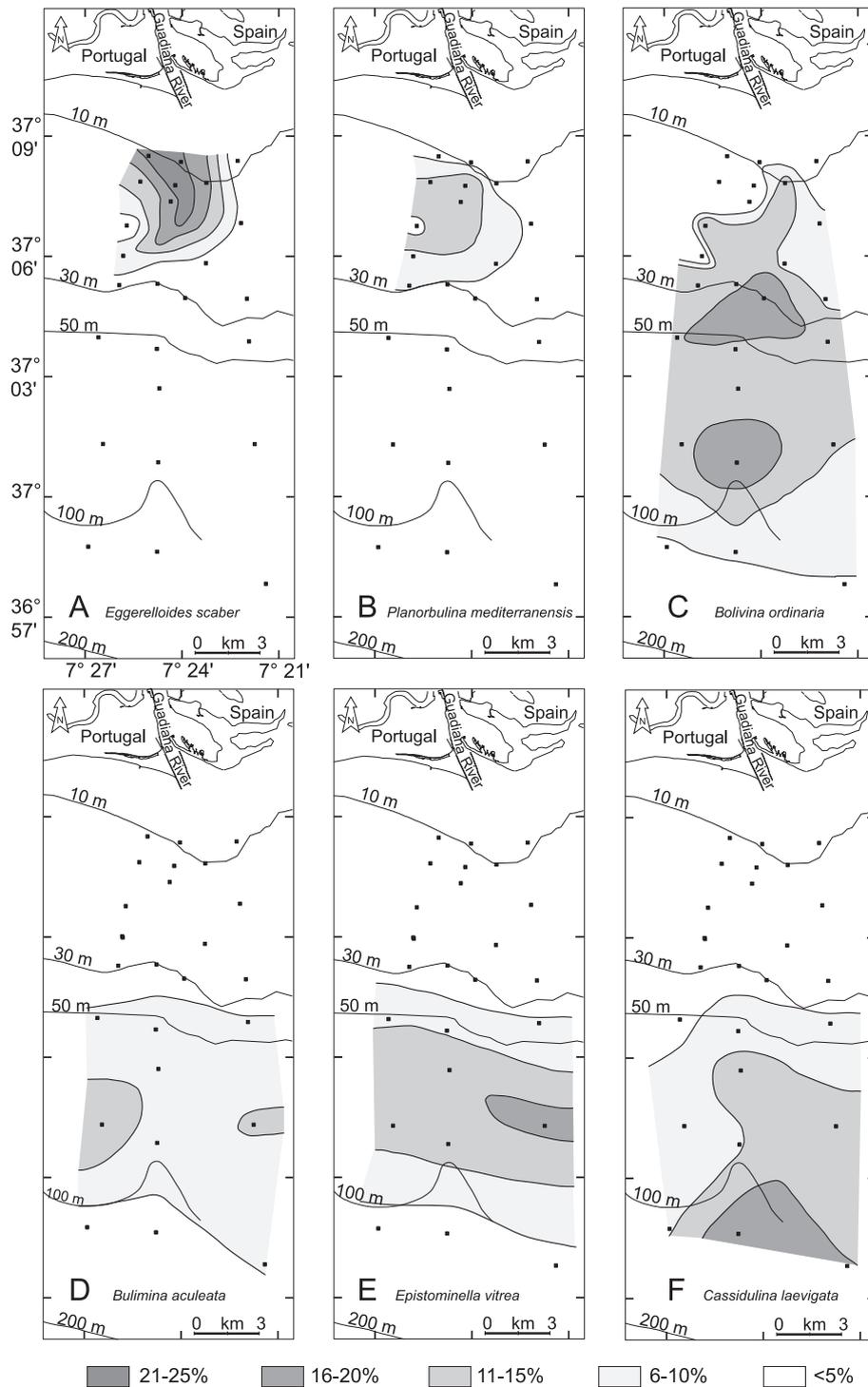


Fig. 5. Distribution of dominant and common species (total assemblage) in the study area as percentage of total Foraminifera population. (A) *Eggerelloides scaber*; (B) *Planorbulina mediterraneensis*; (C) *Bolivina ordinaria*; (D) *Bulimina aculeata*; (E) *Epistominella vitrea*; (F) *Cassidulina laevigata*.

2.4. Sediment cover

Fig. 2 shows the surface sediment distribution on the shelf off the Guadiana Estuary. The figure is adapted from a more extended map of González et al. (2003) based on 470 samples retrieved from the seafloor between January 1999 and November 2001. A belt of sandy deposits containing varying amounts of gravel and showing large variation in components (quartz, a variety of other terrigenous components,

shells and echinoderm fragments) dominates the northern Gulf of Cadiz shelf down to a water depth of approximately 30 m (Fig. 2). To the west of the Guadiana Estuary sediments consist mostly of fine to medium sands, with mean grain sizes between around 250 and 125 μm .

To the east of the Guadiana Estuary mouth, between the Guadiana delta and the Piedras River, several patches of sandy mud and mud define prodeltaic deposits of the Guadiana, forming an oblong

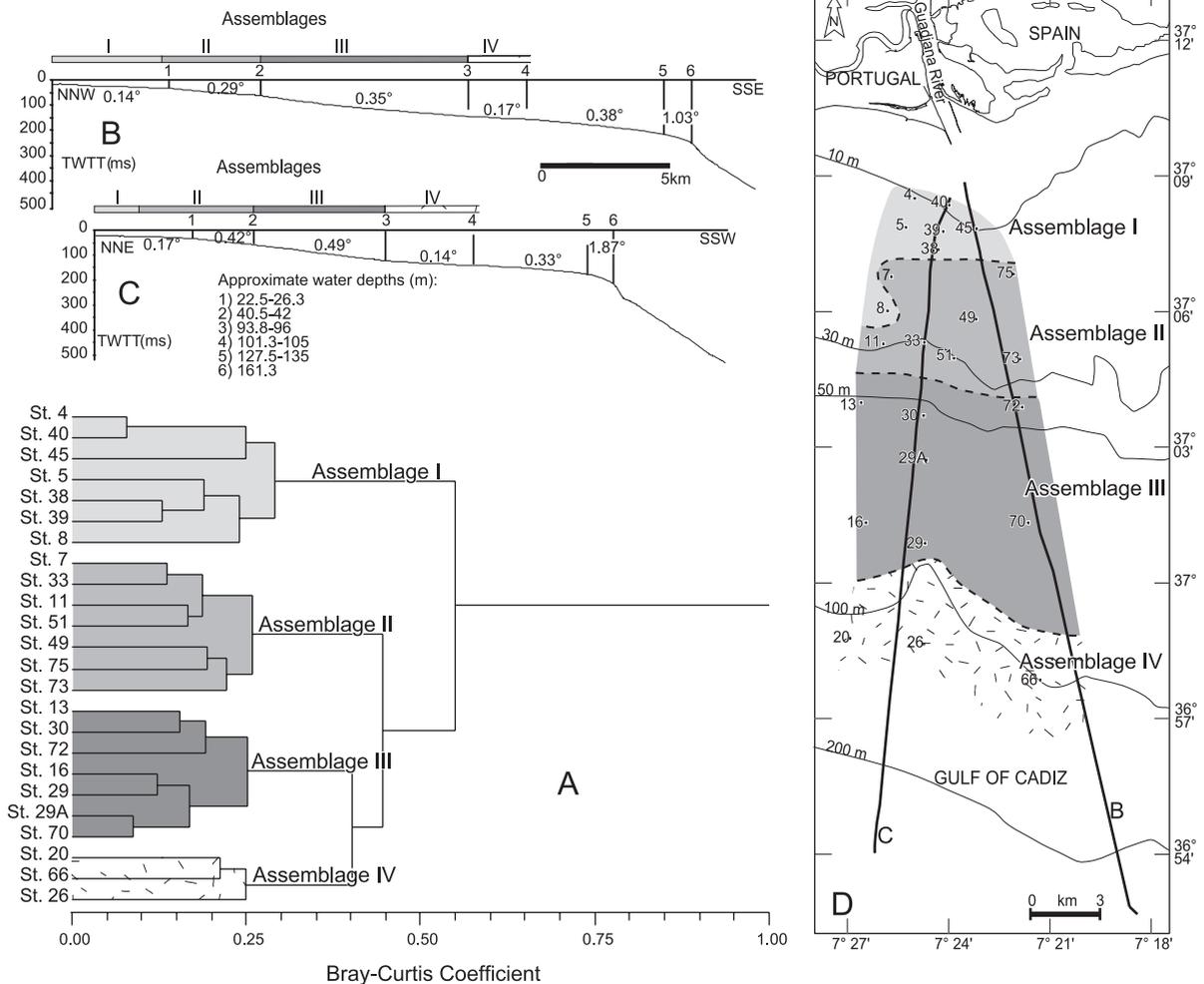


Fig. 6. Dendrogram of Q-mode cluster analysis of the stations based on the total abundance higher than 5%. (A) Total of four assemblages are recognized; (B, C) cross-shelf sections of the study area, focusing on shelf physiographic zonation. Shelf sectors have been differentiated according to seafloor gradient changes; the location of these cross-shelf sections is shown in D. (D) Distribution of the four assemblages across the shelf.

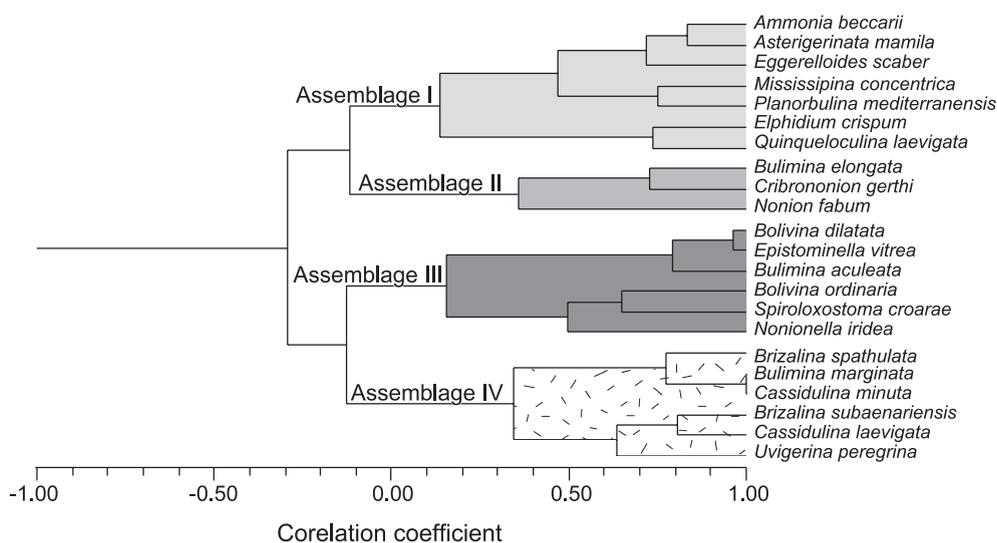


Fig. 7. Dendrogram of R-mode cluster analysis of the species based on the total abundance higher than 5%. Four assemblages are recognized.

mud patch with an area of approximately 60 km², and consisting of very fine-grained material with mean grain sizes of up to 4 µm.

Around 30 m water depth a transition zone occurs characterised by muddy sediments containing some gravel off the Guadiana, and featuring mostly mixtures of clay, silt and sand further west and east. Locally the sediment can be quite coarse, with mean grain sizes being as high as 500 µm.

Water depths between 50 and 100 m are characterised by an extensive mud belt, consisting of very fine-grained clayey material. Mean grain sizes are consistently below 8 µm, and lie locally below 4 µm. This broad mud belt is only interrupted to the east of the Guadiana by a cross-shore strip of quartzitic sands and gravelly sands, where mean grain sizes are around 125 µm.

Below 100 m, sediments are generally dominated by sandy and silty clay with mean grain sizes between 63 and 31 µm. These are interrupted locally by large

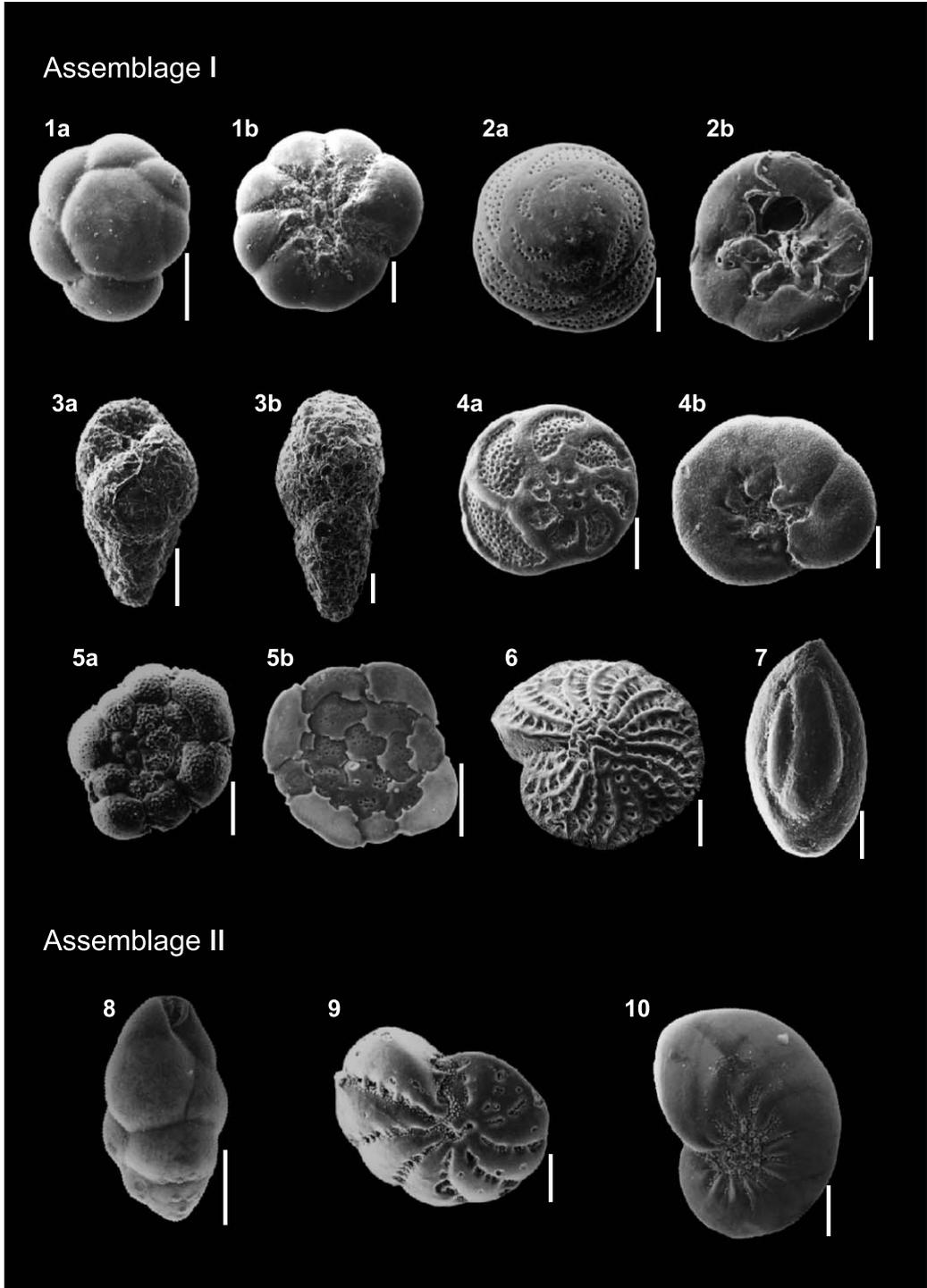
patches of bioclastic sand and gravelly sand in the vicinity of the shelf edge. Here, the mean grain size lies between 250 and 125 µm. The great bulk of sandy sediments here consist of Foraminifera and Molluscs, containing varying amounts of Glauconite. Quartz only occurs rarely in this section of the shelf.

3. Material and methods

A total of 88 surface sediment samples were collected from water depths between 9 and 123 m on the Guadiana Shelf in November 2000 using a Smyth McIntyre grab sampler, 25 of which were selected to study the benthic foraminiferal assemblages (Fig. 1C). Two aliquots from each sample were taken to carry out an analysis of benthic Foraminifera and grain size.

The aliquot from each sample for the analysis of benthic Foraminifera was dried in an oven at 60 °C.

Plate 1. Assemblage I. (1a) *Ammonia beccarii* (Linné) var. *tepida* (Cushman 1926), dorsal side, scale bar=100 µm. (1b) *Ammonia beccarii* (Linné) var. *tepida* (Cushman 1926), ventral side, scale bar=100 µm. (2a) *Asterigerinata mamila* (Williamson 1858), dorsal side, scale bar=50 µm. (2b) *Asterigerinata mamila* (Williamson 1858), ventral side, scale bar=50 µm. (3a) *Eggerelloides scaber* (Williamson 1858), side view, scale bar=100 µm. (3b) *Eggerelloides scaber* (Williamson 1858), side view, scale bar=100 µm. (4a) *Mississippina concentrica* (Parker and Jones, 1864), dorsal side, scale bar=100 µm. (4b) *Mississippina concentrica* (Parker and Jones, 1864), ventral side, scale bar=100 µm. (5a) *Planorbulina mediterranensis* d'Orbigny 1826, dorsal side, scale bar=100 µm. (5b) *Planorbulina mediterranensis* d'Orbigny 1826, ventral side, scale bar=100 µm. (6) *Elphidium crispum* (Linné 1758), scale bar=100 µm. (7) *Quinqueloculina laevigata* d'Orbigny 1839, scale bar=50 µm. Assemblage II. (8) *Bulimina elongata* d'Orbigny 1846, scale bar=150 µm. (9) *Cribrononion gerthi* (van Voorthuysen 1957), scale bar=50 µm. (10) *Nonion fabum* (Fichtel and Moll 1798), scale bar=100 µm (Photographs by Violante Gomes).



Subsequently, the samples were weighed and wet-sieved using 63- and 500- μm sieves. The sediment retained in each sieve was dried at 60 °C and weighed.

The material larger than 63 μm was separated and analysed using a binocular microscope, retrieving at least 300 benthic Foraminifera with well-preserved tests from each sample. All benthic Foraminifera with broken tests as well as fragments and old tests (test with yellow/brown halls, sometimes could be re-crystallised, worn down, filled by sediments or Glauconite) were interpreted as transported. These tests were collected and counted. The total number of planktonic Foraminifera tests in each sample was counted.

Benthic Foraminifera were identified and counted according to Boltovskoy et al. (1980), Ellis and Messina (1940–1978), Levy et al. (1995) and Jones (1994). The relative abundance of specimens (calculated for each sample considering the total analysed microfauna) was defined using the limits of Fatela (1994): dominant (>20%), common (10–20%), accessory (5–10%) and rare or accidental (1–5%). The Shannon–Weaver, $H(S)$, diversity index was calculated using:

$$H(S) = - \sum_{i=1}^S p_i \ln p_i$$

where S is the number of species and p_i the proportion of the i th species (Murray, 1991a).

Only species with at least one occurrence of abundance in the analysed samples larger than 5% were considered to build a matrix of data for the Q- and R-mode cluster analyses. Samples were grouped according to their degree of similarity using the Bray–Curtis coefficient for Q-mode and the correlation coefficient for R-mode. Results were amalgamated using the clustering method unweighted pair-group method (UPGMA), using the program NTSYSpc 2.0 (Rohlf, 1994).

For grain size analysis, the organic matter was removed using 10, 30, 80 and 130 volumes per litre of hydrogen peroxide. Subsequently, the fine- and coarse-grained fractions were separated using a 63- μm sieve. Grain size analysis of the fine-grained fraction (<63 μm) was performed by applying the pipette method and separated in phi intervals. The coarse fraction (>63 μm) was separated by dry sieving in half-phi intervals.

4. Results

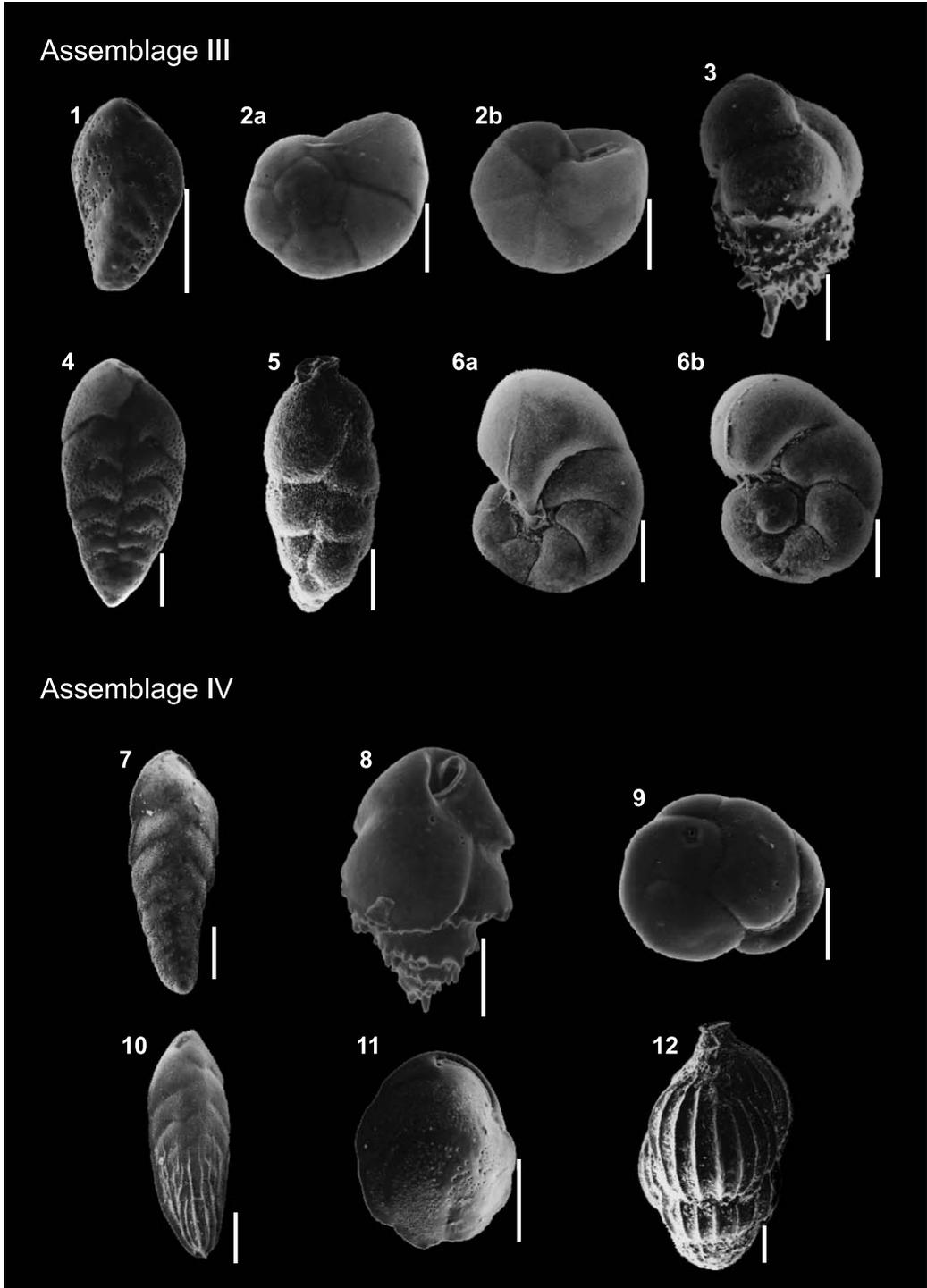
4.1. Identified benthic foraminifera populations

A total of 270 benthic Foraminifera species and 56 genera left on open classification were identified of which 22 species showed a relative abundance larger than 5% in at least one sample (Appendix A which is found on the online version of this paper).

Fig. 3 shows the distribution of identified well-preserved and transported (broken as well as fragments and old tests) benthic and planktonic Foraminifera across the shelf. In general, well-preserved benthic Foraminifera tests dominated all samples (Appendix B). Transported benthic Foraminifera tests only show higher percentages in some samples located between 10–13 m and around 100 m water depth. Samples collected around 100 m include between 16% and 38% of the total assemblage of old tests containing Glauconite (Appendix A). The percentage of planktonic Foraminifera is lower than 2.5% at water depths lower than 30 m, and increases seaward (Appendix A).

The benthic foraminiferal number (specimens/g dry sediment) and the Shannon–Weaver index are related to bathymetry (Appendix B, Fig. 4). In general, the benthic foraminiferal number is inversely related with water depth, although the highest values (568 tests of benthic foraminifers/g) are found at a water depth of around 100 m. Furthermore, lower numbers of speci-

Plate 2. Assemblage III. (1) *Bolivina dilatata* Reuss 1850, scale bar=100 μm . (2a) *Epistominella vitrea* Parker 1953, dorsal side, scale bar=100 μm . (2b) *Epistominella vitrea* Parker 1953, ventral side, scale bar=50 μm . (3) *Bulimina aculeata* d'Orbigny 1826, scale bar=100 μm . (4) *Bolivina ordinaria* Phleger and Parker 1952, scale bar=100 μm . (5) *Spiroloxostoma croarae* Conato 1964, scale bar=50 μm . (6a) *Nonionella iridea* Heron-Allen and Earland 1932, ventral side, scale bar=50 μm . (6b) *Nonionella iridea* Heron-Allen and Earland 1932, dorsal side, scale bar=50 μm . Assemblage IV. (7) *Brizalina spathulata* (Williamson 1858), scale bar=100 μm . (8) *Bulimina marginata* d'Orbigny 1826, scale bar=100 μm . (9) *Cassidulina minuta* Cushman 1933, scale bar=50 μm . (10) *Brizalina subaenariensis* (Cushman 1922), scale bar=100 μm . (11) *Cassidulina laevigata* d'Orbigny 1826, scale bar=150 μm . (12) *Uvigerina peregrina* Cushman 1923, scale bar=50 μm (Photographs by Violante Gomes).



mens occur to the east of the study area in shallow water (Fig. 4A). The Shannon–Weaver index ranges between 2.4 and 3.8, with highest values between 20 and 30 m water depth (Fig. 4B).

Considering the total number of species and the total assemblages identified in the study area, only *Eggerelloides scaber* can be considered to be a dominant species, whereas *Cassidulina laevigata* (including var. *carinata*), *Bolivina ordinaria*, *Bulimina aculeata*, *Epistominella vitrea* and *Planorbulina mediterranensis* are considered common species. The following species are classified as accessory species: *Ammonia beccarii*, *Asterigerinata mamila*, *Bolivina dilatata*, *Brizalina*

spatulata, *Brizalina subaenariensis*, *Bulimina elongata*, *Bulimina marginata*, *Cassidulina minuta*, *Cribronion gerthi*, *Elphidium crispum*, *Mississippina concentrica*, *Nonion fabum*, *Nonionella iridea*, *Quinqueloculina laevigata*, *Spiroloxostoma croarae* and *Uvigerina peregrina* (see Appendix C for taxonomic concept used). All other species occur in relative abundances lower than 5%, and are considered to be rare or accidental species (Appendix A).

Dominant, common and accessory species are represented in more than 50% of the samples, with the exception of *Bulimina marginata* and *Uvigerina peregrina*, which are present in 20–50% of the samples.

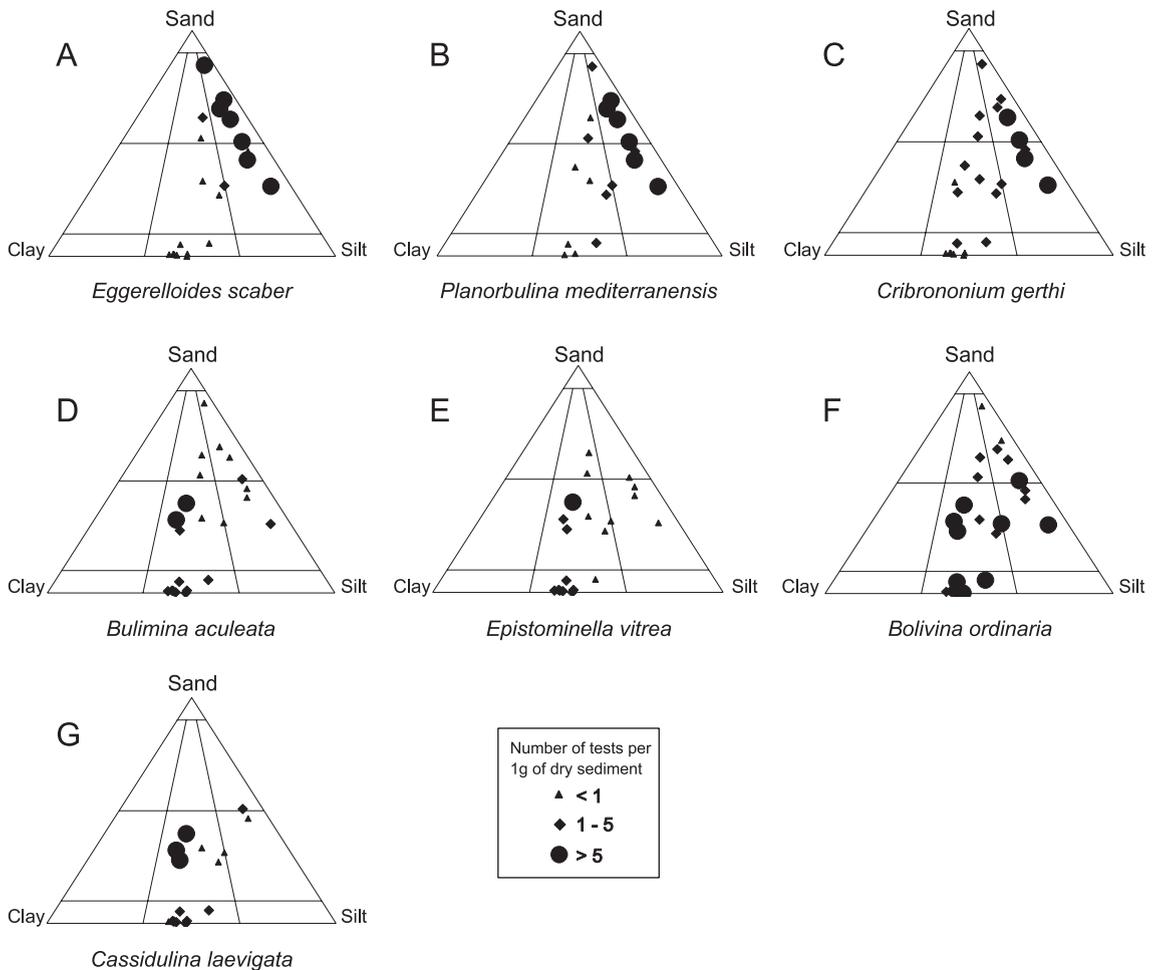


Fig. 8. Ternary clay–silt–sand diagrams of benthic foraminiferal number (specimens/g) of the most abundant species. Sediment subdivisions are according to Folk (1954). (A) *Eggerelloides scaber*; (B) *Planorbulina mediterranensis*; (C) *Cribronion gerthi*; (D) *Bulimina aculeata*; (E) *Epistominella vitrea*; (F) *Bolivina ordinaria*; (G) *Cassidulina laevigata*.

The distribution of the total assemblage of dominant and common species on the Guadiana Shelf shows the following patterns (Fig. 5):

Eggerelloides scaber and *Planorbulina mediterraneensis* occur in highest percentages in water depths shallower than 30 m (Fig. 5A,B). Maximum percentage values of these species (23.58 and 12.59%, respectively) occur between 10 and 13 m water depth. Below 30 m their relative abundance drops below 5%, only very rarely occurring in the deepest analysed samples.

Bolivina ordinaria, *Bulimina aculeata* and *Epistominella vitrea* display the highest percentages between 30 and 100 m water depth (Fig. 5C–E). *B. ordinaria* was found in all analysed samples showing a bimodal distribution with peak values higher than 17% at water depths around 30 as well as 90 m (Fig. 5C). *B. aculeata* and *E. vitrea* are the most common species between 65 and 90 m with maximum percentages of 14 and 17%, respectively. In both cases, these values decrease both in a landward and seaward direction reaching values lower than 1% in shallow water (Fig. 5D,E).

The occurrence of *Cassidulina laevigata* is directly related to water depth, as percentage values increase seaward, attaining a maximum value of 18% at 102 m water depth, whereas values lower than 1% occur in shallow water (Fig. 5F).

4.2. Cluster analysis

Q-mode cluster analysis, applied to stations containing species with relative abundances higher than 5%, distinguished four assemblages (Fig. 6A). A comparison of the distribution of these assemblages with the physiographic zonation of the shelf (e.g. Fig. 6B,C) shows that the distribution of assemblages seems to be associated with bathymetry and possibly shelf morphology. Assemblage I occurs at water depths of up to around 12 m, with the exception of station 8 situated at 17 m water depth, assemblage II can be found between 12 and 40 m, assemblage III between 44 and 95 m, and assemblage IV dominates at water depths generally below 95 m (Fig. 6D).

R-mode cluster analysis groups species into four assemblages (Fig. 7): assemblage I with the species *Ammonia beccarii*, *Asterigerinata mamila*, *Eggerelloides scaber*, *Mississippina concentrica*, *Planorbulina mediterraneensis*, *Elphidium crispum* and

Quinqueloculina laevigata (Plate 1, Figs. 1–7); assemblage II with *Bulimina elongata*, *Cribronion gerthi* and *Nonion fabum* (Plate 1, Figs. 8–10); assemblage III with *Bolivina dilatata*, *Epistominella vitrea*, *Bulimina aculeata*, *Bolivina ordinaria*, *Spiroloxostoma croarae* and *Nonionella iridea* (Plate 2, Figs. 1–6); and assemblage IV with *Brizalina spathulata*, *Bulimina marginata*, *Cassidulina minuta*, *Brizalina subaenariensis*, *Cassidulina laevigata* and *Uvigerina peregrina* (Plate 2, Figs. 7–12).

4.3. Relationship of identified species with sediment type

The percentage of gravel, sand, silt and clay of the analysed samples can be found in Appendix B. Fig. 8 shows the number of benthic foraminiferal tests (specimens/g dry sediment) of high abundance species versus sediment type, using ternary clay–silt–sand diagrams with divisions according to Folk (1954). *Eggerelloides scaber*, *Planorbulina mediterraneensis* and *Cribronion gerthi* all show highest number of tests in sediments dominated by sand and silt (Fig. 8A–C). *Bulimina aculeata*, *Epistominella vitrea* and *Cassidulina laevigata* show highest number of tests in samples characterised by mixed sand, silt and clay, although some samples of similar composition show low number of foraminiferal tests (Fig. 8D,E,G). *Bolivina ordinaria* shows a moderate correspondence with sandy and clayey silt, or with sand, silt and clay mixtures (Fig. 8F).

5. Discussion

The benthic foraminiferal fauna from the continental shelf off Guadiana River is very diverse. The values of Shannon–Wiener index are higher in the lower limit than those obtained by Redois and Debenay (1999) (between 1.8 and 3.7) on the Senegalese continental shelf and by Martins and Carapito (1999) (between 1.94 and 3.65) on the north continental shelf of Portugal (Aveiro). According to Murray (1991a), the values obtained of Shannon–Wiener index indicate a normal marine shelf environment. The number of benthic foraminifera found per gram sediment is similar to that obtained by Fatela (1989) in the NW of Portugal for similar depths, however, is

lower than the values obtained by Levy et al. (1995) that ranged between 1600 and 28,000 individuals/g sediment in a study covering the entire continental shelf of Portugal. Most identified species are similar to those characterising neighbouring shelf areas of the eastern Atlantic such as the northeastern Gulf of Cadiz (e.g. Villanueva Guimerans, 2000, 2001; Villanueva Guimerans and Sánchez Ariza, 1996; Villanueva Guimerans and Canudo Sanagustín, 1999; Villanueva Guimerans et al., 1999a,b) the western coast of Portugal (e.g. Levy et al., 1993, 1995; Martins, 1997; Ubaldo and Otero, 1978; Schönfeld, 1997), the coast of Morocco (Mathieu, 1986) and the coast of Senegal (Debenay and Redois, 1997a,b; Redois and Debenay, 1999).

However, despite these similarities and the investigation carried out in the northern Gulf of Cadiz (e.g. Levy et al., 1993, 1995; González-Regalado et al., 2001; Schönfeld, 2002), the distribution of shelf species is important for showing large regional and temporal variations, influenced by local environmental parameters (Debenay and Redois, 1997a), making it indispensable to confirm and control existing information for the use of Foraminifera for any detailed environmental study. Furthermore, the sample density presented in this study is higher than that of previous authors, allowing a more refined analysis of cross-shelf variations in Foraminifera distribution.

Q-mode analysis, sediment data and morphology indicate a zonation of the Guadiana shelf into four segments (Fig. 6). This is well supported by R-mode cluster analysis, which distinguishes four different assemblages at identical locations (Fig. 7).

The shallowest foraminiferal assemblage (Fig. 7), corresponding to assemblage I, is composed of species characteristic of littoral environments (e.g. Colom, 1974; Pujos, 1976; Levy et al., 1995; Fatela, 1989; Martins, 1997). The sediments characterising this assemblage are muddy sand, sandy mud and muddy gravelly sand (Fig. 2).

Murray (1991a) found several species of this assemblage associated with muddy sand: *Ammonia beccarii*, *Eggerelloides scaber* and *Elphidium crispum*. Pujos (1976) finds *Asterigerinata mamila* and Villanueva Guimerans and Cervera Currado (1999) *Planorbulina mediterraneensis* in sediments with high sand content. It can be speculated that long-shore transport by littoral drift and tidal currents mix benthic

Foraminifera species that do not necessarily occupy the identical shallow-marine substrates.

Pujos (1976), Colom (1974), Murray (1991a) and Villanueva Guimerans and Cervera Currado (1999) observed that some of the species occurring in this assemblage are associated with vegetated environments. *Eggerelloides scaber* is possibly related to the presence of *Zostera* in the lower part of the Guadiana Estuary (Chícharo et al., 2001). This species has also been found abundant close to areas colonised by *Zostera noltii* in the Array River in France (Redois and Debenay, 1996). Although none of the samples collected in this study showed evidence for dense patches of vegetation, occasional remnants of vegetation were found in several samples.

This shallow Foraminifera assemblage is found in an area of the Guadiana Shelf where silt- to fine-grained sand-sized sediments can be frequently remobilised by waves and tidal currents. It corresponds to the shoreface (e.g. Hernández-Molina et al., 2000) or foreshore domains of other authors (e.g. Reineck and Singh, 1986; Walker and Plint, 1992). However, the inclusion of a deeper lying sample with a similar association of benthic Foraminifera in this assemblage is probably not related with wave energy and bathymetry but with the nature of the sediment, characterised by a mixture of sandy mud and muddy gravel (Fig. 2).

Assemblage II is found between approximately 12 and 40 m water depth. Sediments are generally composed of muddy gravelly sands, gravelly mud, sandy mud and mud (Fig. 2). Benthic foraminifera assemblages are characterised by the species *Bulimina elongata*, *Cribronion gerthi* and *Nonion fabum* (assemblage II, Fig. 7). These species were observed in other areas associated with fine sands and muddy sediments (Pujos, 1976; Debenay and Redois, 1997b; Redois and Debenay, 1999; Villanueva Guimerans, 2000). Authors give a variety of depth ranges in which these species can occur on the Portuguese Shelf, ranging from 0–150 m for *Bulimina elongata* (e.g. Levy et al., 1995), to 30–70 m for *C. gerthi* (Fatela, 1989), or up to 80 m for *Nonion fabum* (Levy et al., 1995; identified by these authors as *Nonion commune*).

In our study area this assemblage is limited to the outer part of the inner shelf. In terms of wave energy this area is only influenced by storm waves. Depending

on the wave height and period, all sediments occurring in this cluster can periodically be remobilised. The lower limit of occurrence of this assemblage coincides with the upper limit of the extensive mid-shelf mud patches, and the area where fine-grained sediments exported from the Guadiana River basin during floods are deposited (Gonzalez et al., 2002).

The fact that this assemblage occurs in an area covered by a mixture of sediments found both in shallower and deeper areas (Fig. 2), and presented the highest Shannon–Weaver index diversity values (between 3.6 and 3.8) (Fig. 4B), indicates that this is a transitional area where coastal associations dominated by assemblage I and the middle shelf mud patch dominated by assemblage III coexist. It is probable that the upper limit of the occurrence of this assemblage is conditioned by the wave regime (specifically the water energy), while its lower limit is dictated by the change of sediment.

Our data indicates an influence of the outflow from the Guadiana Estuary in the distribution of benthic foraminifera in assemblages I and II, leading to an east–west asymmetry in the benthic foraminiferal number (Fig. 4), and possibly controlling the distribution of some of the shallow-marine species (e.g. *Eggerelloides scaber* or *Planorbulina mediterraneensis*; Fig. 5A,B).

This is particularly true during flood events, which can directly affect the shelf down to a depth of 40–50 m (Gonzalez et al., 2002), as both sandy and clayey sediments are flushed out of the estuary, thus fundamentally altering the clay/sand ratio of nearshore sediments. The plume of the Guadiana Estuary during flood events is generally skewed towards SSE, leading to the deposition of fine-grained material on the inter- and infra-littoral east of the Guadiana mouth rather than the west. Consequently, the bulk of exported and remobilised fine-grained sediments end up to the east of the Guadiana Estuary, as evidenced for instance by isopachs of muddy Holocene sediments (e.g. Nelson et al., 1999).

Furthermore, the higher percentage of older and broken tests found in shallow waters (Fig. 3) is evidence for occasional transportation of shells caused by waves and possibly periods of higher river discharges (occurring mainly during the Winter).

Assemblage III is found between 40 and 95 m water depth, and corresponds to an area covered by

large, fine-grained mud deposits (Fig. 2), defining the middle shelf. This area is characterised by the species *Bolivina dilatata*, *Epistominella vitrea*, *Bulimina aculeata*, *Bolivina ordinaria*, *Spiroloxostoma croarae* and *Nonionella iridea*. This is in accordance with Murray (1991b), who found that these genera are characterised as living in muddy sediments and associated with low levels of water energy.

Assemblage IV is found below 95 m, with sediments dominated by bioclastic sandy mud and gravelly mud (Fig. 2). This area corresponds to a transition between middle and outer shelf. This assemblage is characterised by the species *Brizalina spathulata*, *Bulimina marginata*, *Cassidulina minuta*, *Brizalina subaenariensis*, *Cassidulina laevigata* and *Uvigerina peregrina*. These species were also identified by other authors at similar and higher depths in fine sands and muddy sediments (e.g. Colom, 1974; Pujos, 1976; Levy et al., 1995; Debenay and Redois, 1997b; Villanueva Guimerans, 2000, 2001).

Many of the species tolerant to oxygen deficiency are typical of muddy environments (Van der Zwaan et al., 1999) sometimes containing high amounts of organic carbon (Murray, 1991b). Abundances higher than 5% of some genera normally associated with oxygen-deficient environments (e.g. Murray, 1991b; Van der Zwaan et al., 1999; Bernhard and Sen Gupta, 1999) in assemblages III and IV (Fig. 7), such as *Bolivina*, *Brizalina*, *Bulimina*, *Cassidulina* and *Uvigerina*, suggest that these assemblages might be found in oxygen-depleted environments. Species like *Bulimina marginata* and *Brizalina spathulata* were observed by Donnici and Barbero (2002) on the northern Adriatic continental shelf in nutrient-rich zones of clay-rich sediments, subject to periodic anoxia.

The families Bolivinidae and Buliminidae, well represented in assemblages III and IV, are associated with upwelling phenomena (Mathieu, 1986), similar to species like *Brizalina spathulata* and *Cassidulina laevigata* at the continental shelf of Portugal (Levy et al., 1995), Morocco (Mathieu, 1986) and Senegal (Debenay and Redois, 1997a). The presence of those families and species in the deeper assemblages, as well as the observed lower water temperature (lower than 15 °C) in January 2000, suggest that these assemblages could indeed be influenced by upwelling events (or filaments related to upwelling; cf. Sánchez and Relvas, 2003; Lobo et al., in press), that accord-

ing to Vargas et al. (2003) occur in shelf waters in southeastern Iberia during autumn–winter.

Representative species from the Guadiana Estuary, like *Trochammina inflata* and *Jadammina macrecens* (Muñoz et al., 1996), were observed in the samples collected close to the river mouth (Stations 4 and 40) with total abundance lower than 3% (Appendix A), indicating some level of export of tests from the Guadiana Estuary to the nearby shelf. Another species characteristic of estuarine waters observed by Muñoz et al. (1996) was *Ammonia beccarii*. However, this species is commonly found in both estuarine and shelf associations (Murray, 1991a). The total abundance of *A. beccarii* on the shelf (including all observed variants) is near 10% for well-preserved tests and 18% for transported tests in the present study. The high percentage of transported tests is very probably related to an export of individuals from the estuary to the shelf by tidal currents and flood events.

High percentages of transported benthic Foraminifera, mainly of the genus *Elphidium*, normally identified at shallow water depths (e.g. Murray, 1991a,b; Levy et al., 1995) are found at around 100 m water depth. These tests are probably related to sea-level stillstand conditions—allowing the development of a coastal environment at the location of the present upper outer shelf—during the early stages of the post-glacial transgression (e.g. Dias et al., 2000). The fact that they are still exposed on the sea ground points to very low sedimentation rates in this area of the shelf. This is reinforced by the common occurrence of Glauconite in these tests, usually associated with periods of no active sedimentation (e.g. Odin and Matter, 1981).

Levy et al. (1995) suggested a relationship between the different sectors of the Portuguese continental shelf and the depth distribution of benthic Foraminifera species. According to this subdivision the inner shelf is located from the coast to 70 m water depth, the middle shelf between 70 and 110 m, and the outer shelf between 110 and 180 m. González-Regalado et al. (2001) suggested two associations based on the benthic Foraminifera distribution in the Spanish continental shelf in the vicinity of the study area: the inner shelf, up to a depth of 30 m and the middle shelf, between 30 and 100 m. The depth limits proposed by these authors are not equivalent to those observed in this

study. The reason for this might be a wider sampling grid in the area studied by Levy et al. (1995) and very general conclusions of González-Regalado et al. (2001) based on only four samples. However, some of the species identified by Levy et al. (1995) at the inner shelf were also verified in this study by our shallowest associations (assemblages I and II), and species associated by Levy et al. (1995) with the middle shelf were here found in the transitional zone between middle and outer shelf (assemblage IV). Associations composed by some of the observed species, were identified by other authors in Europe and northern Africa (Murray, 1991a). For example, in the northern Adriatic Sea near the Po Delta, Donnici and Barbero (2002) identified a coastal association from 5 to 13.5 m water depth, in which *Ammonia beccarii* reaches its highest frequency, which may contain *Eggerella scabra* (= *E. scaber*, in this study).

Our analysis suggests that *Eggerelloides scaber*, *Planorbulina mediterraneensis* and *Cribronion gerthi*, seem to be strongly linked to sandy/silt sediment mixtures (Fig. 8A–C) and can be found in coastal assemblages (assemblage I) and the inner shelf (assemblage II). This fact might also be strongly linked to the hydrodynamic conditions in the vicinity of the Guadiana Estuary, as already mentioned.

On the other hand, it was not possible to establish relations between single species and the type of sediment in assemblages III and IV. Although *Bulimina aculeata*, *Epistominella vitrea* and *Cassidulina laevigata* had higher number of benthic foraminiferal tests per gram in sediments characterised by sand, silt and clay mixtures, they also showed lower number of specimens per gram in the same type of sediment (Fig. 8D,E,G). Our data did not allow us to establish a clear relationship between number of specimens per gram of *Bolivina ordinaria* and sediment type (Fig. 8G). For these four species, the type of sediment seems not be the dominant factor in determining the number of benthic foraminiferal tests per gram dry sediment.

6. Conclusions

The continental shelf off the Guadiana River shows a very diverse benthic foraminiferal fauna. Most found species are in agreement with those

reported by other authors that have studied the Gulf of Cadiz.

A hierarchical classification of foraminiferal assemblages using Q- and R-mode analyses allowed establishing four assemblages:

Assemblage I is characterised by the species *Ammonia beccarii*, *Asterigerinata mamila*, *Eggerelloides scaber*, *Mississippina concentrica*, *Planorbulina mediterraneensis*, *Elphidium crispum* and *Quinqueloculina laevigata*. This assemblage is found in water depths of up to 12 m, influenced by fair-weather waves, and corresponds to the shoreface or foreshore domains. It is characterised by muddy sand, sandy mud and muddy gravelly sand.

Bulimina elongata, *Cribronion gerthi* and *Nonion fabum* were distinctive for assemblage II. It occurs between the 12 and 40 m water depth, is influenced only by storm waves, and corresponds to the outer inner shelf. The sediments are generally muddy gravelly sands, gravelly mud, sandy mud and mud.

Assemblage III is characterised by the species *Bolivina dilatata*, *Epistominella vitrea*, *Bulimina aculeata*, *Bolivina ordinaria*, *Spiroloxostoma croarae* and *Nonionella iridea*. Water depths for this assemblage ranged from 40 to 95 m. It is associated with low levels of water energy, and corresponds to the middle shelf. It corresponds to an area covered by large, fine-grained mud deposits. This assemblage also shows an increase in the amount of planktonic Foraminifera tests.

Below 95 m water depth, a transitional zone between middle and outer corresponding to assemblage IV is characterised by *Brizalina spathulata*, *Bulimina marginata*, *Cassidulina minuta*, *Brizalina subaenariensis*, *Cassidulina laevigata* and *Uvigerina peregrina* species. The sediments are dominated by bioclastic sandy mud and gravelly mud.

Benthic Foraminifera distribution in the shallowest associations (assemblages I and II) show to be influenced by water exported from the Guadiana River basin to the shelf and by the hydrodynamic conditions, as verified by east–west asymmetry in specimens per gram dry sediment, in the distribution of some shallow-marine species and by the higher percentage of older and broken tests found in these assemblages.

The presence of some genera adapted to sediments rich in organic matter and low oxygen conditions in middle shelf mud patch sediments indicate that this environment is restricted to specialised genera. Finally, the outer shelf Foraminifera associations may be influenced by periodic intrusions of colder waters, possibly related to upwelling.

An association of some species with specific types of sediment could be verified. The species *Eggerelloides scaber*, *Planorbulina mediterraneensis* and *Cribronion gerthi* are related with sandy silt and silty sands. For other species, however, the type of sediment could not be determined as a dominant factor.

Old glauconitic *Elphidium* tests, a genus related to shallow water depth, were found on the outer shelf. They are probably related to lower sea levels at the beginning of the Holocene, and document low sedimentation rates in this area.

The distribution of benthic Foraminifera in the continental shelf off the Guadiana River is strongly influenced by bathymetry and sediment cover. However, other factors, such as hydrodynamics conditions, vegetation cover, salinity, temperature, quantity of oxygen and organic matter, seem to have a relevant importance in the composition of benthic Foraminifera assemblages.

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Appendix B. Depth, location, number of tests (well-preserved, broken, old, fragments, planktonic), Shannon–Weaver index, number of benthic foraminifera per gram dry sediment, number of species and percentages of gravel, sand, silt and clay

Station	Depth (m)	Longitude	Latitude	Number of tests					Shannon–Weaver index	Foraminiferal number (specimens/g)	Species number	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
				Well-preserved	Broken	Old	Fragments	Planktonic							
40	9	–7.39959	37.139529	342	135	133	34	16	3.21	288.02	61	0.20	50.56	42.21	7.03
45	10.5	–7.3861	37.1308527	133	59	226	8	2	3.18	61.54	58	0.85	84.40	11.64	3.11
39	11	–7.40263	37.129826	355	102	52	41	12	3.16	53.34	68	1.71	68.95	25.27	4.08
4	11.8	–7.41672	37.1420863	344	159	93	38	4	2.44	203.01	76	0.15	30.71	62.13	7.01
38	12	–7.40496	37.1230845	334	110	104	29	10	3.34	49.92	76	11.67	65.18	18.11	5.03
77	12	–7.36955	37.1399322			4						1.58	95.83	2.03	0.56
5	13	–7.42103	37.1313513	404	219	500	32	10	3.28	172.02	75	2.87	60.41	30.88	5.84
7	15	–7.42825	37.1131363	443	132	149	67	44	3.84	35.65	91	4.01	46.50	42.80	6.69
8	17	–7.43013	37.1005338	328	145	199	76	14	3.28	152.25	58	2.00	42.49	46.58	8.93
49	22	–7.3864	37.0973875	366	102	144	32	25	3.63	21.97	72	30.66	52.39	9.57	7.37
75	23	–7.36784	37.114072	406	92	144	25	24	3.75	26.02	78	22.06	61.46	9.86	6.62
33	30	–7.41203	37.0889018	334	73	52	102	44	3.73	79.53	85	4.97	31.34	42.36	21.32
11	32	–7.43231	37.0883575	323	34	10	44	43	3.82	36.85	85	10.60	27.10	39.19	23.11
51	33	–7.39739	37.0829592	411	50	15	64	24	3.77	60.31	100	0.36	5.81	52.86	40.97
73	33	–7.36478	37.0826632	335	90	72	89	27	3.79	53.77	88	10.39	33.42	31.18	25.01
72	48	–7.36365	37.0648717	354	226	91	123	114	3.49	58.54	65	1.88	5.11	42.53	50.48
13	52	–7.4433	37.0666495	366	167	79	62	83	3.54	40.25	80	0	0	48.07	51.93
30	52	–7.41246	37.0618375	362	182	92	103	108	3.32	26.99	65	0	1.12	47.90	50.98
29A	68	–7.41109	37.0454507	470	239	147	123	188	3.15	19.28	68	0	0.39	44.50	55.11
70	75	–7.36077	37.0221798	461	151	20	116	129	2.90	18.07	55	0	0.73	43.48	55.79
16	90	–7.44101	37.0223312	388	173	52	132	65	2.97	11.22	53	0	0.77	41.64	57.60
29	92	–7.41181	37.0147195	400	168	68	64	134	2.88	15.42	53	0	0.93	42.97	56.10
66	100	–7.35494	36.9641257	384	138	577	135	355	3.10	567.93	70	0.94	39.55	28.30	31.21
26	102	–7.41249	36.9775512	486	153	383	372	100	2.98	493.60	70	1.31	27.75	31.72	39.23
20	103	–7.44888	36.9796577	379	225	828	282	211	2.73	289.34	65	8.21	32.16	25.44	34.19

Appendix C. List of species used for statistical analysis

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- Ammonia beccarii* (Linné, 1758) (Plate I, 1a–b)
Nautilus beccarii Linné, 1758, p. 710, pl. 1, Fig. 1a–c
- Asterigerinata mamila* (Williamson, 1858) (Plate I, 2a–b)
Rotalina mamilla Williamson, 1858, p. 54, pl. 4, Figs. 109–111
Discorbis mamila (Williamson); Colom, 1974, p. 124, Fig. 21, x–y
- Bolivina dilatata* Reuss, 1850 (Plate II, 1)
Bolivina dilatata Reuss, 1850, p. 381, pl. 48, Fig. 15
- Bolivina ordinaria* Phleger and Parker, 1952 new name (Plate II, 4)
Bolivina ordinaria Phleger and Parker, 1952, p. 14, pl. 7, Figs. 4, 5a, b, 6
- Brizalina spathulata* (Williamson, 1858) (Plate II, 7)
Textularia variabilis Williamson var. *spathulata* Williamson 1858, p. 76, pl. 6, Figs. 164–165
- Brizalina subaenariensis* (Cushman, 1922) (Plate II, 10)
Bolivina subaenariensis Cushman, 1922, p. 46, pl. 7, Fig. 6
- Bulimina aculeata* d'Orbigny, 1826 (Plate II, 3)
Bulimina aculeata d'Orbigny, 1826, p. 269, pl. 11, Fig. 128
- Bulimina elongata* d'Orbigny, 1846 (Plate I, 8)
Bulimina elongata d'Orbigny, 1846, p. 187, pl. 11, Figs. 19–20
- Bulimina marginata* d'Orbigny, 1826 (Plate II, 8)
Bulimina marginata d'Orbigny, 1826, p. 269, pl. 12, Figs. 10–12
- Cassidulina laevigata* d'Orbigny, 1826 (Plate II, 11)
Cassidulina laevigata d'Orbigny, 1826, p. 282, pl. 15, Figs. 4–5
- Cassidulina minuta* Cushman, 1933 (Plate II, 9)
Cassidulina minuta Cushman, 1933, p. 92, pl. 10, Fig. 3
- Cribrononion gerthi* (Van Voorthuysen, 1957) (Plate I, 9)
Elphidium gerthi Van Voorthuysen, 1957, p. 32, pl. 23, Fig. 12 a–b
- Eggerelloides scaber* (Williamson, 1858) (Plate I, 3a–b)
Bulimina scabra Williamson, 1858, p. 65, pl. 5, Figs. 136–137
Eggerella scabra (Williamson); Colom, 1974, p. 93, Fig. 10, b–d
Eggerella scabra (Williamson); Levy et al., 1995, p. 19, pl. 2, Fig. 9
Eggerelloides scabrus (Williamson); Debenay and Redois, 1997, pl. 1, Fig. 6
- Elphidium crispum* (Linné, 1758) (Plate I, 6)
Nautilus crispus Linnaeus, 1758, p. 709
- Epistominella vitrea* Parker, 1953 (Plate II, 2a–b)
Epistominella vitrea Parker, 1953, p. 9, pl. 4, Figs. 34–36, 40–41
- Mississippina concentrica* (Parker and Jones, 1864) (Plate I, 4a–b)
Pulvinulina concentrica Parker and Jones, 1864, p. 470, pl. 48, Fig. 14
- Nonion fabum* (Fichtel and Moll 1798) (Plate I, 10)
Nautilus faba Fichtel and Moll, 1798, p. 103, pl. 19, Figs. a–c
Florilus asterizans (Fichtel and Moll); Ubaldo and Otero, 1978, p. 116, pl. 5, Figs. 14, 15
Nonion commune (d'Orbigny); Levy et al., 1995, p. 46, pl. 11, Fig. 1
Nonion asterizans (Fichtel and Moll); Martins, 1997, p. 283, pl. 11, Fig. 1
- Nonionella iridea* Heron-Allen and Earland, 1932 (Plate II, 6a–b)
Nonionella iridea Heron-Allen and Earland, 1932, p. 438, pl. 16, Figs. 14–16
- Planorbulina mediterraneensis* d'Orbigny, 1826 (Plate I, 5a–b)
Planorbulina mediterraneensis d'Orbigny, 1826, p. 280, pl. 14, Figs. 4–6
- Quinqueloculina laevigata* d'Orbigny 1839 (Plate I, 7)
Quinqueloculina laevigata d'Orbigny, 1839, p. 143, pl. 3, Figs. 31–33
- Spiroloxostoma croarae* Conato, 1964 (Plate II, 5)
Spiroloxostoma croarae Conato, 1964, p. 285, pl. 1, Fig. 6a, a', a"; p. 285, tf. 5.
- Uvigerina peregrina* Cushman, 1923 (Plate II, 12)
Uvigerina peregrina Cushman, 1923, p. 166, pl. 42, Figs. 7–10
Uvigerina sp. 221 Lutze, 1986, p. 38, pl. 4, Figs. 1–4
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