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Research paper

Ecological zonation of benthic foraminifera in the lower Guadiana Estuary (southeastern Portugal)

Camacho Sarita [a,*], Moura Delminda [a], Connor Simon [a,b], Scott David [c], Boski Tomasz [a]

[a] CIMA, Faculdade de Ciências e Tecnologia, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
[b] School of Geography and Environmental Science, Faculty of Arts, Monash University, Clayton 3800, Australia
[c] Centre for Environmental and Marine Geology, Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia B3H 4J1, Canada

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ABSTRACT

The present study analyzes the spatial distribution and seasonal distribution of live benthic foraminiferal communities in the estuary of Guadiana, the fourth largest river on the Iberian Peninsula, and establishes, through statistical analysis, their relationships with a series of environmental parameters. Forty-four superficial sediment samples were collected along distance-to-sea and elevation gradients in the winter and summer of 2010. Fifty-three foraminifera species were identified along the intertidal margins of the estuary. Foraminiferal distribution reflected seasonal variation of environmental factors, whose relative importance varied according to species tolerances. Elevation in relation to mean sea level appeared to be the most important parameter controlling foraminiferal distribution, probably because it combines the effects of a series of other variables (i.e. organic matter, sediment texture, pH and temperature). In the highest marsh areas, where environmental conditions approach survival thresholds, only some agglutinated species are able to survive. In the lower intertidal zone, where subaerial exposure is diminished and environmental conditions are generally less variable, more diverse faunas, mainly composed of calcareous species, prevail. During winter, when fluvial discharge peaks, agglutinated species represent more than 80% of the total individuals. In summer, when marine conditions prevail, calcareous species become more competitive, increase their densities and expand into higher marsh zones and estuarine upper reaches.

In the estuary, three different foraminiferal assemblages are distinguished: i) *Miliammina fusca* assemblage, which dominates in unvegetated areas of the lower marsh and tidal flats of the mid-upper estuary; ii) *Jadammina macrescens* assemblage, which dominates in the highest marsh areas in the lower estuary; and iii) *Ammonia aberdoveyensis* assemblage, which dominates the areas of low marsh and tidal flats of the lower estuary.

1. Introduction

Foraminifera are single celled eukaryote organisms that occupy a great diversity of habitats, from the deepest oceanic environments to the upper limits of the tidal zones in coastal wetlands. Most foraminifera possess a hard test which, after death, remains in the sediment where it may eventually fossilize. This particular character brings some advantages compared to many other environmental proxies because foraminifera leave a permanent record in sedimentary sequences, enabling the reconstruction of the environmental history of a site in the absence of the original physico-chemical baseline data (Scott et al., 2001). In estuaries, foraminifera may serve as bioindicators of great interest as they have short life cycles and react quickly to changes (Debenay et al., 2000). Being small and abundant, foraminifera are found in great quantities in small sediment volumes, enabling statistically reliable and economically attractive studies (Scott et al., 2001).

Most ecological studies of foraminifera have been carried out with the aim of providing a contemporary database with which fossil foraminifera can be compared and interpreted (e.g. Wang et al., 1985; Thomas and Varekamp, 1991; Cearreta, 1998; Duleba et al., 1999; Edwards and Horton, 2000; Li et al., 2000). Saltmarsh foraminifera, in particular, are useful tools for Holocene sea-level reconstructions (Scott and Medioli, 1978, 1980a; Horton and Edwards, 2006). Statistical studies, based on the distribution of benthic foraminifera in marine and estuarine environments, have also shown that these organisms can be successfully used to identify various ecological provinces, to detect environmental stress conditions and to monitor pollution (Albani et al., 2001). Nevertheless, before using foraminiferal assemblages as stress and pollution indicators in transitional environments, a precise understanding of their response to environmental variables is necessary in order to distinguish between anthropogenic stress and natural environment changes (Debenay et al., 2000). This requirement is particularly critical in estuaries and coastal lagoons that are subject to a complex interaction

* Corresponding author. Tel.: +351 919 741 802.
E-mail addresses: scamacho@ualg.pt (C. Sarita), dmoura@ualg.pt (M. Delminda), Simon.Connor@monash.edu (C. Simon), dbscott@dal.ca (S. David), tboski@ualg.pt (B. Tomasz).

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of numerous physico-chemical natural parameters, each presenting spatial and temporal variability, and because these environments are often exposed to various human impacts such as chemicals, including industrial pollutants and agricultural pesticides (Debenay, 1995, 2000; Debenay et al., 2000).

Explaining foraminiferal distribution patterns thus requires consideration of a broad range of environmental factors (Murray, 2001). Among the many parameters studied in marginal environments, elevation, which controls the time of subaerial exposure between tidal cycles, is widely regarded as the principal factor controlling foraminiferal distribution (Scott and Medioli, 1978; Thomas and Varekamp, 1991; Nydick et al., 1995; Horton et al., 1999; Gehrels, 2000; González et al., 2000; Horton and Murray, 2007).

Other parameters, such as presence or absence of vegetation, desiccation, porewater salinity and pH have also been identified as important ecological controls on marsh foraminifera (Murray, 2006). In the Great Marshes of Massachusetts, De Rijk (1995) and De Rijk and Troelstra (1997) found that foraminifera distribution was controlled mainly by spatial and temporal changes in a series of environmental variables, particularly salinity, leading them to conclude that there is no single model relating foraminifera to elevation, that can be applied worldwide. Likewise, Goldstein and Watkins (1998), in a study of the saltmarsh of St. Catherine's Island, Georgia, found significant differences in the foraminiferal distribution patterns compared to those described by Scott and Medioli (1978, 1980a, 1986), which they explained by differences in geographical setting, including differences in saltmarsh physiography. In the mangrove swamps of French Guiana, elevation was found to have only minor influence on the distribution of foraminiferal assemblages (Debenay et al., 2004).

Species will be able to survive and potentially prosper as long as conditions remain within their tolerance limits. Once conditions move beyond the tolerance limits for any limiting factor, the species is likely to disappear (Murray, 2003). Summarizing, in estuaries, a great diversity of stress factors disturbs the living communities and causes significant temporal and spatial variability in the assemblages of benthic microfauna. As a result, the composition of benthic foraminiferal assemblages reflects the complex interaction between biotic and abiotic parameters and their multiple changes in space and time (Debenay et al., 2000).

In Portugal, baseline studies in the more pristine coastal ecosystems are rare and the use of foraminifera as indicators of environmental status has hitherto been relatively uncommon. In order to reverse this trend, the present work aims to identify the spatial–seasonal variation in the distribution of living benthic foraminiferal assemblages in the Guadiana Estuary and to investigate their relationships with environmental parameters; this is expected to improve the possible use of benthic foraminifera as bioindicators, provide baseline data for future inferences of environmental quality in the Guadiana, and to provide a modern analog dataset for reliable paleoenvironmental interpretations on local and regional scales.

2. Study area

The Guadiana River rises in the Ruidera Lakes in Spain, at 1700 m altitude, and runs 810 km south until reaching the Gulf of Cadiz and the Atlantic Ocean, between the Portuguese town of Vila Real de Santo António and the Spanish town of Ayamonte (Fig. 1). Located between 37° and 40°N and between 2° and 8°W, its catchment area covers approximately 66 900 km^2 (Brandão and Rodrigues, 2000). The Guadiana Estuary makes part of one of the most important mesotidal fluvio-marine systems of the south-western Iberian Peninsula (Morales, 1997; Morales et al., 2006). The mean tidal range at the river mouth is approximately 2 m, reaching 3.4 m during spring tides (Instituto Hidrográfico, 2011) and the tidal influence extends approximately 44 km upstream (Oliveira et al., 2006). The estuary is funnel-shaped and filled with post-glacial sediments (Boski et al., 2006). Currently, it is in advanced state of sediment infilling, with the formation of a flood delta at its mouth caused by the interaction of coastal sedimentation processes and a relatively stable sea level (Morales et al., 2006). Its basin has Mediterranean climate characteristics, with hot, dry summers, and rainy cooler winters.

During the winter sampling in February–March 2010, high precipitation was observed, leading to high fluvial discharge, especially in March, when maximum discharge values of approximately 2100 m^3 s^{-1} were registered. The summer was typically dry, with no rain and low, regular, discharges (mean Q = 52 m^3 s^{-1}) (SNIRH, 2012).

The Guadiana Estuary represents a rich area in terms of ecological interest, noteworthy for its endemism and halophytic saltmarsh communities. The Lower Guadiana River is listed as a Wetland of International Importance (Ramsar, Scientific and Technical Review Panel, 2013), is included in the Natura 2000 Network and its extensive marshlands were declared a Nature Reserve in 1975 (Instituto da Conservação da Natureza e Biodiversidade, 2007). Nevertheless, a number of environmental impacts have been reported in recent years (Morais, 2008; Guimarães et al., 2012), resulting mainly from untreated waste water discharge, agriculture and damming. The morphology of the estuary itself has been changed dramatically due to the building of hard engineering structures (dams and jetties) strongly conditioning the natural exchange between continent and sea.

3. Material and methods

3.1. Sampling strategy

In 2010, forty-nine surface sediment samples were collected for benthic foraminifera analysis during two field campaigns in the two most contrasting seasons, winter (February and March) and summer (August). The sampling extended over 27 km, from Laranjeiras village to the mouth of the river Guadiana (Lagoa site — LG) (geographic coordinates for all samples are presented in Table A.1, Appendix A). In total, eleven sites were sampled, the majority located on the Portuguese side of the river (Fig. 1). In the middle estuary and upper estuary, only one sample per site was collected due to the absence of saltmarsh zonation. In the lower estuary, where the environmental zonation is well-defined due to the stronger effect of the tidal range, several samples were collected along elevational profiles at each site, usually perpendicular to the main river channel. Transects were placed according to the vertical zonation of halophytic vegetation, with the aim of sampling the distinct saltmarsh zones and the unvegetated tidal mud-flats (Fig. 2). At the eleven different sites, five individual samples and six transects were collected, resulting in a total of 49 samples (24 in winter and 25 in summer). Site PI1, approximately 8 km upstream from the estuary's mouth, was only sampled in summer due to technical problems. Detailed topographic profiles were produced using a differential Global Positioning System (d-GPS), a Trimble 5800 mobile unit, and a Nikon DTM 310 Total Station. Elevation values were measured in relation to mean sea level (MSL), which is the adopted mean value for water level derived from a series of tide gauge observations of variable duration (Instituto Hidrográfico, 2011) (Fig. 2). The elevation (intertidal) gradient was divided in: 1) upper marsh zone (samples collected at 1–2 m above MSL, mainly high marsh vegetation), 2) lower marsh zone (0–1 m above MSL, mainly mid-low marsh vegetation), and 3) mud zone (−1–0 m in relation to MSL, mainly unvegetated tidal mud-flats). The distance-to-sea gradient was divided into lower estuary, middle estuary and upper estuary (Fig. 1) according to Boski et al. (2006).

At each sampling point, two pseudoreplicates were collected (replicates at the same site, thus not statistically independent) (Hurlbert, 1984) with the aim of neutralizing the effects of patchiness (Fatela and Taborda, 2002; Debenay et al., 2006; Armynot du Châtelet et al., 2009), or non-uniform distribution of benthic communities (Underwood and Chapman, 2005; Morvan et al., 2006; Murray, 2006). In nature, most of the populations exhibit varying degrees of patchiness in response to biotic and/or abiotic factors, promoted by both natural and anthropogenic