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Intertidal foraminifera in the Mira estuary, SW Portugal, and their use as sea-level proxies

Foraminíferos intermareales en el estuario de Mira, SO Portugal, y su aplicabilidad como indicadores del nivel marino

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ABSTRACT

Para evaluar la respuesta cuantitativa de los foraminíferos con en relación con los niveles maréales del estuario de Mira, se han desarrollado una serie de funciones de transferencia basadas en un matriz de datos compuesta por 29 muestras y 95 especies obtenidas en tres transeptos. La relación entre los resultados obtenidos e inferidos indica el óptimo funcionamiento de las funciones de transferencia (r^2_{jack} = 0.87), lo cual implica que reconstrucciones de gran precisión (error: ± 12 cm) de los cambios recientes en el nivel marino son posibles. Por otro lado, es importante estudiar el posible efecto de la relación no lineal entre las mareas y la elevación de las muestras en los errores de reconstrucción.

Key words: *Foraminíferos bentónicos, marismas, función de transferencia, Portugal suroeste*

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Introduction

Under the present scenario of rapid sea-level rise as result of the global warming (Solomon *et al.*, 2007), it is desirable to provide new high-resolution sea-level curves geographically distributed to supplement existing instrumental data sets and, importantly, extend these data sets back in time in order to accurately resolve the timing of the sea-level acceleration and the source of the present sea-level rise. Moreover, pre-20th century instrumental records are sparse and geographically very limited to resolve when the global sea-level acceleration started (Jevrejeva *et al.*, 2006).

Several proxies have been used as sea-level indicators, such as diatoms (Gehrels *et al.*, 2001), or testate amoebae (Gehrels *et al.*, 2006). However, salt-marsh foraminifera are considered the most accurate proxies for elevation and able to predict elevations to within ±0.05 m or better (Southall *et al.*, 2006). In fact, since their introduction by Guilbault *et al.* (1996), foraminifera-based transfer functions have become a widely use tool in high-resolution sea-level reconstructions (Horton *et al.*, 1999; Gehrels, 2000; Southall *et al.*, 2006; Leorri *et al.*, 2008) providing quantitative reconstructions with their associated errors.

In this paper, we present new transfer function models developed from the modern distributions of foraminifera recorded from three transects sampled in the Mira estuary, southwest Portugal (Fig. 1). This area was selected based on the existence of two of the longest tide-gauge records from Europe, Cascais and Lagos (Fig. 1), that will be used in the future to assess the foraminifera-based sea-level reconstruction. We describe the development of these transfer functions in order to provide the first quantitative assessment of the potential of intertidal foraminifera for relative sea-level studies in this region and compare the performance of transfer-function models based on both standardized elevation and flooding duration.

Study area

Three profiles including salt-marsh and tidal-flat sub-environments from the Mira estuary, located in the Alentejo coast of Portugal (Fig. 1; T1 to T3), have been sampled. The river channel and estuarine basin are limited by steep slopes cut in Carboniferous flysch with a mesotidal range (2 m neap tide-3.5 m spring tide). The estuary mean depth varies between 5 m and 10 m in the lower and medium zones and less than 3 m in the upper reaches, although the channel deepens and widens close to the mouth, reaching 9 m depth (Alday *et al.*, 2006). This estuary presents the largest extension of salt marshes in the SW coast of Portugal and it is designated as an Special Protection Area (Directive 79/409/CEE) and Site of

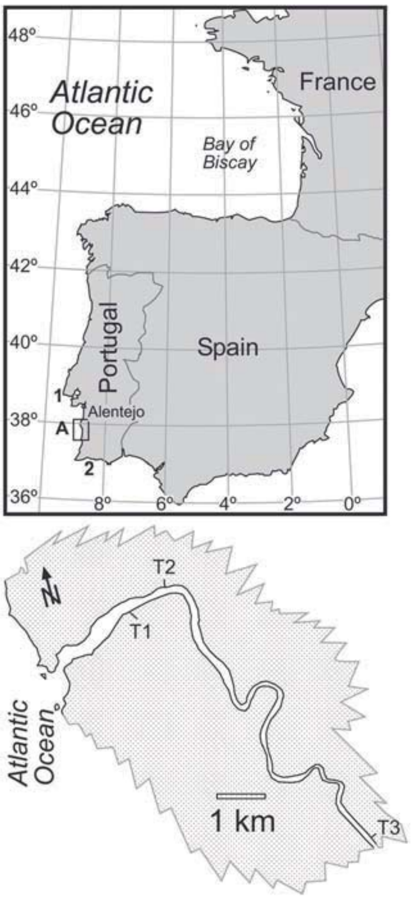

Fig. 1.- Geographical location of the study area. Location of the most relevant tide gauges is also indicated. Key: 1- Cascais; 2- Lagos; A- Mira estuary; T1-T3: Transects.

Fig. 1.- Localización geográfica del área de estudio. La localización de los mareógrafos más relevates también está indicado. Clave: 1- Cascais; 2- Lagos; A- Estuario de Mira; T1-T3: Transeptos.

Community Importance (Directive 92/43/CEE).

Materials and methods

We sampled the uppermost centimetre of the surface sediment along three transects that followed the elevational gradient of the marshes, collecting 29 sediment samples for micropalaeontological analysis (years 2005-2006). Samples height was surveyed using GPS and total station and is presented relative to the hydrographical chart datum of Sines, positioned 2.00 m below the mean sea level at Cascais on 1938.

The height of the surface samples must be standardized to a common datum since the mean tidal range for the different salt marshes varies between 1.81 m and 1.92 m. Two methods were used: height normalization and flooding duration normalization.

The height normalization method follows Leorri *et al.* (2008). In this method, elevations are expressed as a standardized water level index (SWLI):

$$SWLI_n=100(h_n-h_{MTL})/(h_{MHHW}-h_{MTL})+100$$

where $SWLI_n$ is the standardized water level index for sample n, h_n the elevation of sample n (m above local datum), h_{MTL} the mean tide level elevation (m above local datum), h_{MHHW} the mean higher high water elevation (m above local ordnance datum). This produces a standardized water level index (SWLI) for each modern sample, with 100 representing mean tide level (MTL) and 200 for mean highest high water (MHHW).

The duration of the marshes flooding was computed using the FCUL astronomical tide prediction model (Antunes, 2008) and results are presented in table I. This model uses the harmonic constituents published by the French Navy (SHOM, 1982) adjusted to local changes in phase and amplitude determined by observations. A series of water heights, at every 10 min, was generated for the period of a year retaining all successive high- and low-water slacks. This series was further processed to compute the annual frequencies of residence of the water level at each 10 cm-elevation interval above chart datum, and added to yield absolute and relative submersion times for each location as a function of ground elevation. The succession of high- and low-water elevations was used to estimate average values, which can be further processed to determine mean high and low water springs and neaps. In addition, tidal elevations have been measured continuously inside the estuary, in spring and neap conditions, using a LevelTroll 500 pressure transducer. Such measurements have been used to evaluate differences in phase and amplitude between measured and reference tides in Sines (the tide reference model), and a transfer model was constructed to account for these differences.

Micropalaeontological samples were sieved through a 63-micron mesh and washed to remove clay and silt material, and all the remaining residue was analysed. Samples were previously stained using rose Bengal (Walton, 1952) in order to identify specimens considered to be alive at the time of collection. Here, we will use the death assemblages (unstained) since they represent a time-averaged accumulation of foraminiferal tests and they are considered to be a better analogue for reconstructing former sea levels (Horton, 1999).

We selected three transects representing different estuarine areas to avoid the intercorrelation of both elevation and salinity and possible spatial autocorrelation (the tendency of sites close to each other to resemble one another more than randomly selected sites) in the training set. Additionally, combined training sets from various sites provide a more realistic analogue data for fossil assemblages, rather than local data sets (Gehrels *et al.*, 2001). Statistical analysis was performed using C2 (Juggins, 2004). We used «Partial Least Squares» (PLS) regression for all the data sets. The root-mean square of the error of prediction (RMSEP) indicate the systematic differences in prediction errors, whereas the r^2 measures the strength of the relationship of observed *versus* predicted values.

Two data set were build up using standardized data (percentage), one comprising both marsh and tidal-flat samples (intertidal data set) and other restricted to samples above mean low high water (MLHW data set). One additional data set was developed using concentration data (foraminiferal abundances in 10 cm^3 of sediment) of samples above MLHW.

Results and Discussion

The Mira data set contains 95 species of foraminifera, although only 37 have an abundance of at least 2% in a single sample. Two samples presented less than 10 individuals and they have been removed from the data sets. The most abundant species are *Jadammina macrescens* (mean value and range: 46%, 0-100%) and *Trochammina inflata* (12%, 0-37%) together with *Haynesina germanica* (7%, 0-35%). *Bolivina pseudoplicata, Quinqueloculina* spp., *Reophax moniliformis, Miliammina fusca* and *Bolivina* spp. are also significant (mean abundance values between 2 and 5%). The rest of the species present mean abundance values below 2%. The composition of the death assemblage presented here is broadly comparable to those from other areas in the North Atlantic. In fact, despite the variety of environmental parameters that can affect foraminiferal zonations, marsh surface foraminiferal distributions are roughly similar in all temperate areas and follow the vertical zonation concept proposed by Scott and Medioli (1978). *Jadammina macrescens* and *T. inflata* dominate the assemblages that characterize the highest tidal levels. At mid-tidal elevations calcareous species become more abundant, although their presence depends on the availability of calcium carbonate in the environment.

Preliminary analysis demonstrated that PLS method performed best in terms of maximum bias, r^2 and a smaller RMSEP. The PLS transfer function produces results for five components. The final models were selected based on low RMSEP, low maximum bias, high squared correlation (r^2) of observed versus predicted values, and the smallest number of «useful» components. Model S1 corresponds to the unscreened data set with SWLI (for the 29 samples and 95 species) and produced a moderate performance (r^2_{jack} = 0.82, RMSEP = 23.8; Table I). However, samples below MLHW are considered less suitable for sea-level studies (Woodroffe, 2009). We have explored, therefore, possible models that reconstruct palaeomarsh surface elevation based on samples above MLHW. Model S2 uses samples above MLHW with SWLI and Model FD2 uses samples above MLHW with % flooding duration. Additionally, in Model FD2 flooding duration has been root squared transformed (SQRT) following Gehrels (2000). The overall effect of this process is to evenly distribute the samples along the gradient since they tend to be concentrated in the highest elevations. Finally, Model S3 is a modified version of Model S2 but uses concentration data instead on percent data. Models S2, S3 and FD2 perform very strongly (component 2; r^2_{jack}= 0.88; RMSEP = 9.6; r^2_{jack}= 0.87; RMSEP = 9.6 and r^2_{jack}= 0.89; RMSEP = 0.52 %, respectively; Fig. 2; Table I).

Both models, S2 and S3, performed very strongly and identically which most probably implies that the standardization of the data set does not create any distortion in the ecologic response patterns of the taxa within the data set (Mekik and Loubere, 1999). From an ecological point of view, foraminifera are controlled by subaerial exposure, hence, by flooding duration. The relation between height and flooding duration is non-linear, particularly for the upper marsh surface and, therefore, the time of subaerial exposure is very sensitive to small changes in height. This normalization has been recommended as the best option because it produces smaller standard errors for the indicative meaning of foraminiferal assemblages than normalization according to height (Gehrels, 2000).

The standard error for Models S2 and S3 can be easily calculated following back transformation of the SWLI values. These models have a precision of ca. ±0.12 m for the study area (ranges between ±0.119 m and ±0.124 m). The margin of error for Model FD2 is 0,52 %, however, when standard error for flooding duration are expressed as height, the error becomes variable because the relationship between flooding duration and height is non-linear. The largest error would occur in the highest part of the marsh where flooding duration increases with decreasing height very slowly (Gehrels, 2000) and can be as large as ±0.18 m, significantly larger than the RMSEP predicted by Model S2 that assigned an error of ±0.12 m. Similar results were reported by Gehrels (2000).

The precision of the transfer functions obtained here is comparable to other foraminifera-based transfer functions developed from the northern Atlantic Ocean. The only salt-marsh based sea-level reconstruction that has been attempted so far in the SW European Atlantic coast reported an error of ±0.11 m (Leorri *et al.*, 2008). Other foraminiferal transfer functions from the northestern Atlantic Ocean have reported errors ranging from ±0.12 m to ±0.29 m, while on the northwestern Atlantic Ocean, reported errors ranged from ±0.18 m to ±0.25 m (see Leorri *et al.*, 2008 for a review).

The results obtained here show a strong correlation of the assemblages of agglutinated salt-marsh foraminifera with elevation above mean tidal level and with percentage of flooding duration. Although both methods performed very strongly, the variability of the errors depending on flooding duration have important implications for sea-level reconstructions, specially for those based on training sets with short elevational ranges focused on the highest elevations of the marsh environment. This reflects the non-linear relation between height and flooding duration. In fact, reconstruction of environmental variables based on transfer functions should be done when these variables are either ecologically important determinants in the system (e.g., flooding time) or linearly related to such determinants. This, does not rules out the use of height normalization but it should be considered more carefully. On the other hand, here the use of concentration data or standardized data does not seem to have a significant effect on model performance.

Conclusions

This study confirms the usefulness of salt-marsh foraminifera as sea-level

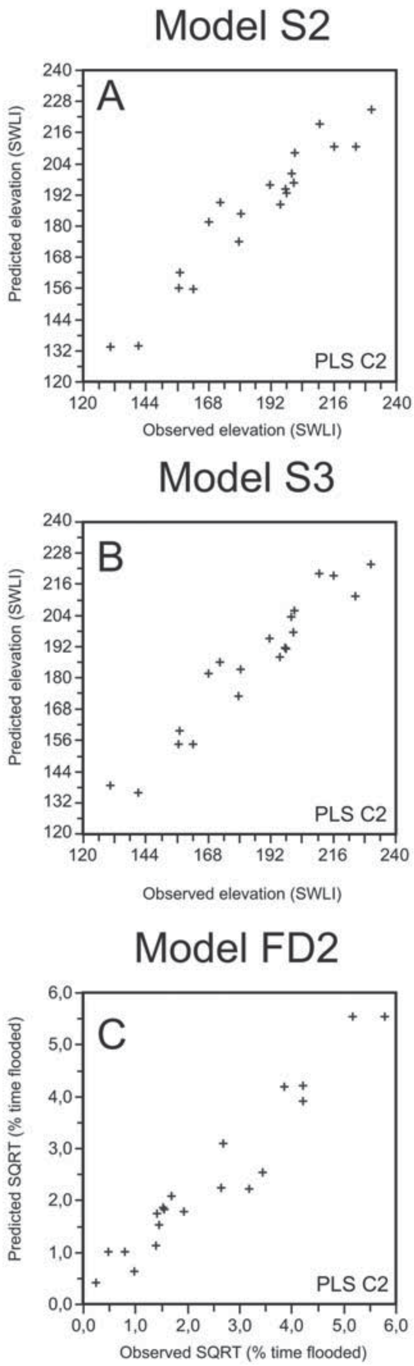

Fig. 2.- Observed and predicted values of the SWLI for Models S2 and S3 (component 2) and observed and predicted values of the % SQRT flooding time for Model FD2 (component 2) of the foraminiferal transfer functions.

Fig. 2.- Valores de SWLI observados y calculados con los Modelos S1 y S2 (componente 2) y los valores observados y calculados del % del tiempo de sumersión (transformado) con el Modelo FD2 (componente 2) de la función de transferencia.

	Model S1 C2	Model S2 C2	Model S3 C2	Model FD2 C2
RMSE	18.65	7.61	7.48	0.42
r^2	0.89	0.92	0.92	0.93
Max_Bias	37.00	9.94	10.14	0.93
r^2_{jack}	0.83	0.88	0.87	0.89
Max_Bias $_{jack}$	48.87	16.12	15.55	1.04
RMSEP $_{jack}$	23.81	9.59	9.60	0.52

Table I.- Statistics summary of the performance of Partial Least Squares (PLS) for the foraminiferal assemblages from the Mira estuary. C2 = component 2.

Tabla I.- Resumen estadístico de los resultados de PLS obtenidos de las asociaciones de foraminíferos del estuario de Mira. C2 = componente 2.

proxies in SW Portugal, where tidal flooding (and, hence, height above local mean tide level) is the main control in the marsh environment. In fact, foraminifera-based transfer functions offer a quantitative and robust methodology to reconstruct former sea levels from salt-marsh sediments. However, the accuracy of the models depends on the composition of the training set, the selection of the regression model, and the selection of the standardization of the elevation for sites with different tidal regimes.

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