Environmental constraints of foraminiferal assemblages distribution across a brackish tidal marsh (Caminha, NW Portugal)

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ABSTRACT

Foraminiferal living assemblages from a brackish tidal marsh were studied across three sampling transects, under Spring and Autumn conditions. Foraminiferal analysis was also extended to the dead assemblages of Spring samples. Altimetric control of each sampling point was acquired through the connection to the national datum by GPS differential positioning combined with a regional geoid model. The influence of the geochemical characteristics on the assemblages including chemical composition of the estuarine and marsh surface sediments, in addition to salinity, pH and calcite saturation of estuarine and marsh interstitial waters was evaluated.

A high affinity was found between Spring and Autumn living assemblages, probably related to the low number of representative species. The affinity also found between living and dead assemblage was seen as a consequence of low pH and calcite undersaturation that prevent the accumulation effect of several generations of foraminifera.

Salinity appears as a clear constraint to the foraminiferal assemblages composition that is enhanced by calcite undersaturation in brackish marshes interstitial waters and sediments. Generally abundant marsh species like *Trochammina inflata*, *Jadammina macrescens* and the calcareous foraminifera are limited to an episodic presence.

Foraminiferal assemblages distribution across brackish tidal marsh can be assumed as an elevation proxy. The high marsh IB sub-zone is dominated by *Haplophragmoides* sp. and *Haplophragmoides manilaensis*. Low marsh zone II is characterised by the dominance of *Miliammina fusca* but can be subdivided in an IIA upper part, where is followed by *Pseudothurammina limnetis*, and in a IIB lower part defined by a subsidiary presence of *Psammosphaera* sp.

Haplophragmoides manilaensis dominance between 1.55 m and 1.67 m, at living as well as dead assemblages, suggests this species as a potential sea-level indicator for the brackish tidal marshes.

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1. Introduction

The studies of foraminiferal biocoenosis from tidal marshes undertaken in the last decades led to significant advances in the understanding of their ecology in the sea-shore domain (e.g. Phleger and Walton, 1950; Murray, 1971; Pujos, 1971, 1976; Carbonel and Pujos, 1974; Scott and Medioli, 1980; Debenay et al., 1987, 2000, 2002; Cearreta, 1988a,b; Pascual, 1990; Scott and Leckie, 1990; Hayward and Hollis, 1994; De Rijk, 1995; De Rijk and Troelstra, 1997; Alejo et al., 1999; Alve and Murray, 1999; Murray et al., 2000; Sen Gupta, 2002; Diz et al., 2004).

Besides the information about the present day coastal foraminiferal distribution, and its relationship with productivity, marine influence and tidal conditions, this knowledge became fundamental to palaeoecological interpretation (e.g. Hayward et al., 1999; Horton et al., 1999; Diz et al., 2000, 2002; Cearreta et al., 2002a, 2007; Horton and Edwards, 2006). It gives also applicable data in assessing anthropogenic environmental impact, therefore enhancing the social

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relevance of foraminiferal research (e.g. Alve, 1995; Armynot du Châtelet et al., 2004; Cearreta et al., 2000, 2002b,c, 2008).

Tidal marshes are often the most important accumulation environment in estuarine systems. Their importance as archives of recent environmental changes is largely recognised, and marsh foraminifera proved to be a crucial proxy in studies of post-glacial sea-level rise.

In this paper we present a seasonal study of environmental constraints and foraminiferal assemblages present in the brackish tidal marsh of Caminha (NW Portugal). The vertical zonation found on foraminiferal biocenosis is analysed using an ecological approach that includes physical and chemical parameters of estuarine and marsh interstitial waters, sediment chemistry, elevation data and tidal dynamics, evaluated at both the regional and local scales.

This study contributes to fill the need of extending the knowledge about foraminiferal assemblages distribution at brackish environments as indicated previously by several authors (e.g. Horton and Murray, 2007). It is expected that the relations found and discussed here may be of use to support the palaeoenvironmental interpretation of Holocene sediments accumulated in this location and elsewhere.

2. Regional setting

The Minho River is located in northern Portugal (Fig. 1). It defines the political border with Spain along 77 km, just before reaching the Atlantic, joining the Portuguese region of Minho and the Spanish region of Galicia. The Minho watershed develops in rocks of igneous and metamorphic nature and drains the rainiest region of Portugal, with an average annual precipitation of 1300 mm (exceptionally reaching 2700 mm — Bettencourt et al., 2003). The yearly average fluvial discharge is about 300 m^3/s and the winter peak discharge (December to March) usually exceeds 1000 m^3/s; the flood having a 100 years recurrence interval recorded 6100 m^3/s (Bettencourt et al., 2003).

The Minho river outlets in the sea through a barred estuary trending NNE–SSW. It presents a semi-diurnal high-mesotidal regime and the range of the astronomical tide varies between 2 m, during neap waters, and almost 4 m, in spring tides. The high-water astronomic tidal levels are often incremented by storm surges (Taborda and Dias, 1991). The dynamic tide is felt up to 40 km upstream, due to the tidal regime and to both the smoothness and low
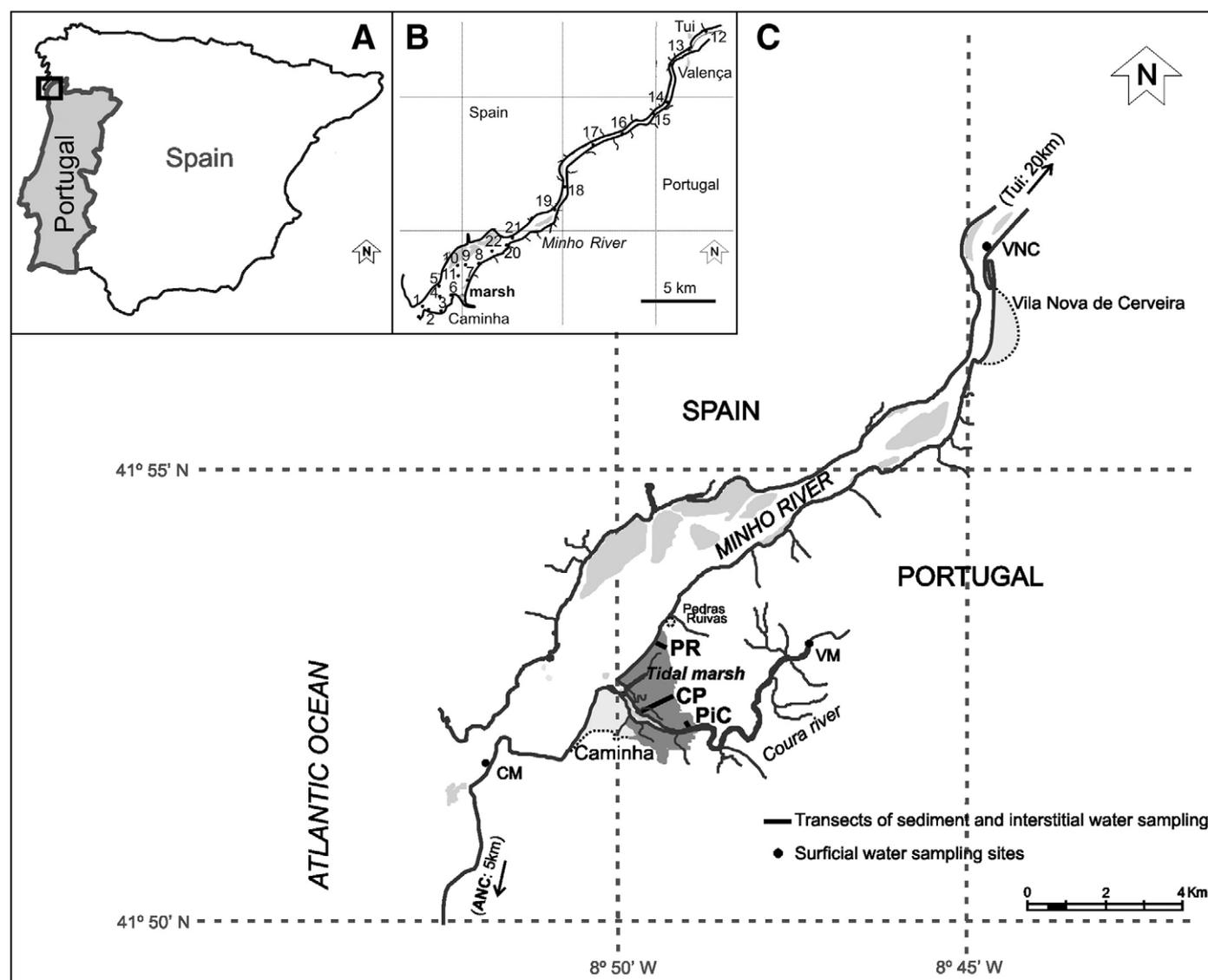

Fig. 1. A — Location of study area in Portugal. B — Location of Minho estuary bottom sediment samples analysed for geochemistry. C — Minho estuary and Coura tributary. Dark gray area represents the Caminha tidal marsh. Sampling transects PR — Pedras Ruivas, CP — Railway bridge and PiC — Pinelas.

gradient of the Minho's outlet (Alves, 1996). The upstream limit of marine water influence is not consensual in the literature and disparate figures, of 9 to 35 km, have been reported (Bettencourt et al., 2003).

The estuary is very shallow as a result of widespread siltation. Consequently, a significant part of the bottom emerges during low water spring tide, when connection with the sea is restricted to two shallow channels incised in the bottom sediment down to −1 m (south) and −2 m (north) (Alves, 1996).

The Minho estuarine basin provides a small accommodation volume for the tidal prism. The lower estuary section just extends a few kilometres from the mouth and essentially behaves as "partially mixed" (Brown et al., 1991).

The widest marsh expansion in the left margin of the Minho estuary, providing an adequate site to investigate the present-day distribution of foraminiferal assemblages, occurs at the confluence with the Coura river (Fig. 1), and is hereafter referred to as the Caminha tidal marsh.

3. Materials and methods

3.1. Minho estuary

A number of vertical profiles of water temperature and salinity were taken along the estuarine axis, in summer conditions, at low- and high-water spring tide, to evaluate the maximum penetration of marine influence. This procedure was repeated under spring conditions, just after the end of the rainy season. These data were obtained using a WTW conductometer LF 191, in sailing upstream.

The surface river, estuarine and marine water has been analysed to provide information about hydrochemical features. Fig. 1 presents the location of sampling sites in the Coura (VM) and Minho (VNC) rivers, and also the sampling locations of seawater close to the estuarine mouth (CM) and 10 km further south (ANC). Sampling was performed in October and repeated in April to search for seasonal trends. The water samples were studied for solubility and equilibrium conditions using the equilibrium speciation and solubility calculation code WATEQ4F (Ball and Nordstrom, 2003). This model was run to determine the saturation index of water regarding the mineral calcite (Moreno et al., 2007).

Twenty two bottom sediments from the Minho river were sampled for geochemical analysis in April 2003, using a small van Veen grab sampler. Samples were collected along a transect of 30 km upstream, between the mouth of Minho River (Caminha) and the neighbourhood of the Spanish town of Tui (Fig. 1); synoptic measurement of water salinity and temperature was performed during this sediment sampling. In the laboratory, the bulk sediment was sieved to separate the coarser particles ($\varnothing > 2$ mm) and the undersized fraction was analysed with Energy-Dispersive X-Ray Fluorescence Spectrometry (EDXRF) using a *KEVEX 771* spectrometer. A detailed methodological description of sample preparation, analytical procedures, accuracy and precision of the method may be found in Araújo et al. (1998, 2003).

3.2. Caminha tidal marsh

Twenty four surface sediment samples were collected in April (Spring), and repeated in October 2002 (Autumn), along three cross shore transects: Pedras Ruivas (PR), railway bridge (CP) and Pinelas (PiC), which extend across the marsh, tidal flat and channel environments of both the Minho and Coura estuaries (Fig. 2). An additional high marsh sample (CP7A) was taken in the Autumn, at CP transect in order to improve the characterization of high marsh zone. Sampling was performed during temperate seasons assuming that they are important periods for coastal foraminifera reproduction; this way we expected to obtain a comprehensive characterisation of the

foraminifera assemblages, in spite of the variability of living species proportions along the year (Cearreta, 1988a,b, 1989; Murray and Alve, 2000; Alve and Murray, 2001; Horton and Murray, 2006). Each sample consists of 10 cm^3 of the topmost 1 cm layer of surface sediment that was stored immersed in [1 g/l] alcohol Rose Bengal solution (Lutze, 1964). Sediment was washed through a 63 μm sieve and foraminiferal collection was performed using a micropipette and a wet picking procedure. When possible, 100 individuals were counted in each sample from the living (stained) microfauna, seen that such counting is fully adequate to characterise the low diversity assemblages of tidal marshes (Fatela and Taborda, 2002). Foraminiferal identification followed the Loeblich and Tappan (1988) to generic classification. Dead assemblages from the Spring samples were also studied following the same procedure. Data from the innermost PiC profile are presented and discussed as complementary results of PR and CP transects, given that most of the samples failed to yield the minimum number of individuals required to represent the assemblage.

The Spring and Autumn living foraminiferal assemblages and the Spring dead assemblage were compared using the Index of Affinity (or Similarity), which measures what fraction of the fauna is common to a given pair of samples (Bray and Curtis, 1957; Sanders, 1960; Rogers, 1976; Murray, 1991). The results are expressed as a percentage of affinity, which corresponds to the sum of the lowest percentage of each species occurring in both samples (Sanders, 1960; Murray, 1991). The simplicity of the structure of this index does not affect its reliability and it performs as effectively as more complex methods (Rogers, 1976). Two samples showing an affinity score in excess of 70% are usually considered as very similar (Sanders, 1960). The score characterizing any given pair of samples depends on the number of species common to both samples and an expected minimum value for the index of affinity can be calculated as follows:

$$(S_{min} \times 100 / S_{max}) - 6$$

where S_{min} is the lower species number and S_{max} is the higher species number (Murray, 1991).

When the affinity index determined for a pair of samples is higher than the expected minimum value, it can be considered very similar (Rogers, 1976; Murray, 1991).

Temperature, salinity and pH of sediment pore-water were measured along all three transects, during low water at both Spring and Autumn seasons (Fig. 2). The interstitial water was allowed to seep and accumulate inside perforated PVC tubes previously inserted into the sediment to a depth of 40 cm below the surface, following De Rijk (1995). A few sampling sites in the tidal flat did not supply any interstitial water. In the Pedras Ruivas (PR) transect the salinity and temperature were also measured every 15 min, close to the marsh surface; measurements started just after the beginning of surface submersion and ended at high water slack, unless interrupted for safety reasons. Simultaneous measurement of the temperature and of estuarine water has also been made close to the channel bottom, in high and low water during spring tide. Water parameters were measured using a multiparameter Horiba U-22 probe and a WTW LF 191conductometer.

The hydrochemical features of pore water were also analysed in samples from all transects (Fig. 2) following the same analytical procedures described above for estuarine and sea water.

A number of marsh surface sediment samples for geochemical characterization were also collected in April across PR outer profile (8 samples), CP inner profile (8 samples) and PiC innermost profile (6 samples). A representative fraction of each bulk sediment sample was dried and oven-heated at 450 °C for about 2 h in order to determine the organic matter (loss on ignition — LOI). Further geochemical characterization followed methods and analytical procedures described above.
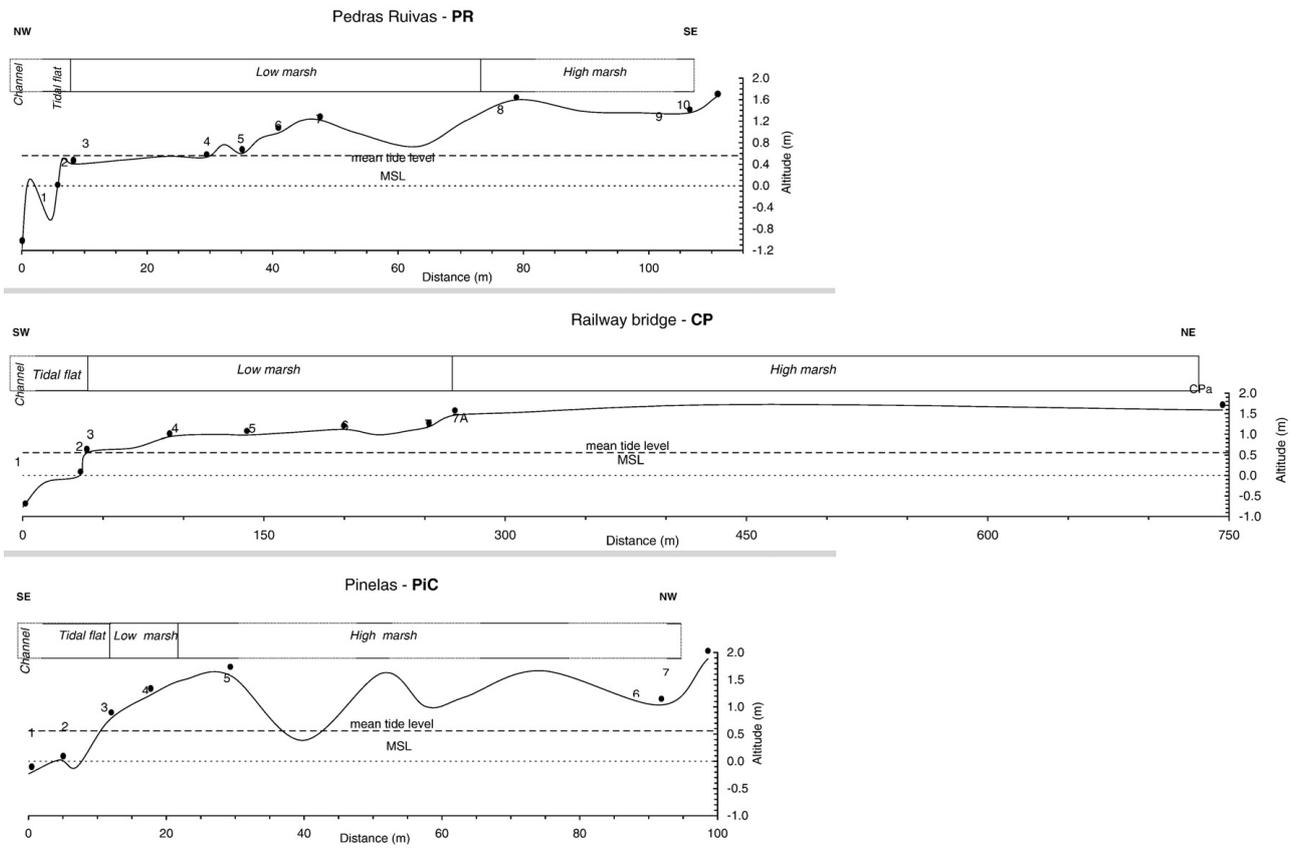
Fig. 2. Sampling and zonation of Caminha tidal marsh transects (ordnance datum: Cascais, Portugal).

The absolute orthometric heights of the marsh transects (Fig. 2), tidal elevation and sampling location have been obtained in the field using a Zeiss Elta R55 total station from a previously selected bench mark; these marks were connected to the national altimetric datum, using a differential GPS equipment and method in combination with a regional geoid model (Catalão, 2006), and linked to local chart datum. This datum — HZ (Hydrographic Zero) lies 2 m below the mean sea level of Cascais 1938 in most hydrographic Portuguese ports. The altimetry data obtained in the field were linked with tidal elevations yielded for each site by the FCUL astronomical tide prediction model (Antunes, 2007). This model uses the harmonic constituents published by the French Navy (SHOM, 1982), to generate a series of water heights at every 10 min for the period of an entire year and retains all successive high and low waters 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 waters 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 inside the Minho 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 the main closest port, and a transfer model was constructed to account for these differences.

4. Results

4.1. Environmental parameters

The salt wedge, as defined by the 35‰ salinity contours, penetrated 4 km upstream at high-water spring slack and the halocline could not be followed for more than 10 km, in the summer. Synoptic salinity values measured in the lower estuary, close to the bottom at low water spring slack, ranged from 0‰ to 2‰. The bottom morphology and regional climatic conditions prevent the extensive penetration of the salt wedge into the estuary and lead to a complete flush-out of marine water with the ebb in each tidal cycle (Moreno et al., 2005c).

The lower estuary is submitted to extreme variations in salinity twice a day (Moreno et al., 2005c) and measurements taken across the PR outer profile, during the submersion period, show that this ecological stress factor is also present on the tidal marsh. Since the moment of arrival of estuarine water at each sampling point until complete flooding of the marsh, salinity values measured close to the sediment–water interface ranged from 1‰ to 32‰ in the tidal flat, 3‰ to 32‰ in the low marsh and 7‰ to 23‰ in the high marsh. Salinity stress is considerably smoothed inside the marsh sediment: the measured values of salinity in interstitial water ranged between 5‰ and 16‰ in the low marsh and between 2‰ and 8‰ in the high marsh. In Autumn conditions, the interstitial waters showed higher salinity and a narrower range of variation, notably in the high marsh: 9‰ to 11‰ (Moreno et al., 2006; Fatela et al., 2007); measurements of pore-water salinity at the very upper limit of high marsh yielded values in the range 2‰ (Spring) to 9‰ (Autumn).

The pH values of the Minho lower estuary water range between 8.3 and 7.9, and the variations in pH are governed by marine water. The water of the Coura lower estuary is more acid, yielding pH values of 6.3 during high water slack (salinity = 28.8‰) and 5.8 during low water slack (salinity = 0.3‰), both values measured at the confluence with the Minho river, and under the same Summer spring tide conditions (Moreno et al., 2005c).

The Minho watershed drains an area of carbonate-depleted rocks, and seawater is the main source of calcium carbonate in estuarine water and sediments (Moreno et al., 2007). The small distance allowed

to penetration of marine water inside the estuary favours under-saturation in calcite of estuarine subtidal and marsh environments, with exception to the estuarine mouth (Moreno et al., 2005c, 2007).

The minimum, maximum and average values on the elemental composition (Si, Al, K, Fe, Mg, Ti, Ca, Zr, Mn, Rb, Sr, Zn, Cr, Pb, Ni and Cu) of surface sediments (22 samples) along the river main channel are listed in Appendix A. Reference values for the standard "average shale" (Salomons and Förstner, 1984) are also presented. The enrichment in Si and the depletion in Al and transition elements of Minho sediments, relative to "average shale", result from the prevalence of a coarser grain sediment fraction. Low Ca and Sr concentrations in river sediments indicate the lithogenic influence of the drainage basin (granitic) in river load sediment composition and also a rather restricted marine influence (Moreno et al., 2005a; Araújo et al., 2002). The high Zr concentrations are also a consequence of weathering of the rocks derived material, mainly granites enriched in zircon.

Sedimentological features, including fine grain size fraction and organic matter contents, and the elemental distribution along each salt marsh sediment transect are displayed in Fig. 3.

An increase in Cr, Mn, Fe, Ni, Cu and Zn is found across the marsh, in agreement with the variation in the <63 μm size-fraction and content in organic matter (Moreno et al., 2005a,b). All elements exhibit higher concentrations in the high-marsh at the PR outer profile and also within slightly depressed zones in low marsh of CP and PiC inner transects, where the sediment/metal entrapping effects typical of marshes are enhanced. Higher Mn concentrations were found in the high marsh in Pr and CP transects. The results also show that the heavy metals Cr, Ni, Cu and Zn closely associate with Mn and Fe, which have a high binding capacity for metals, indicating the trace metal presence as coatings on Mn and Fe oxides. The strong Mn enrichment observed in those sediments seems to induce Ni
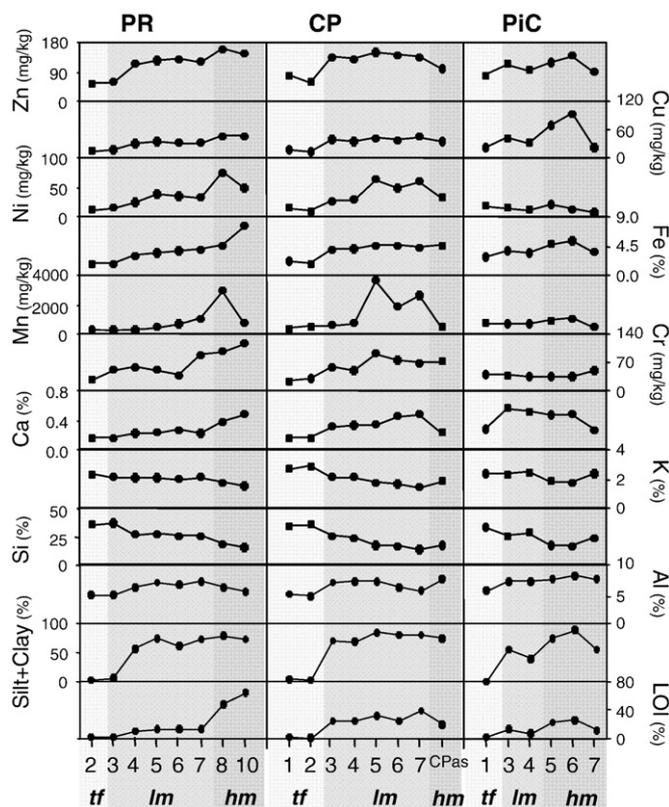
Fig. 3. Textural characteristics and geochemical contents across the Pedras Ruivas (PR), Railway bridge (CP) and Pinelas (PiC) transects; *tf* — tidal flat, *lm* — low marsh, *hm* — high marsh.

Pedras Ruivas - PR transect

Railway bridge - CP transect
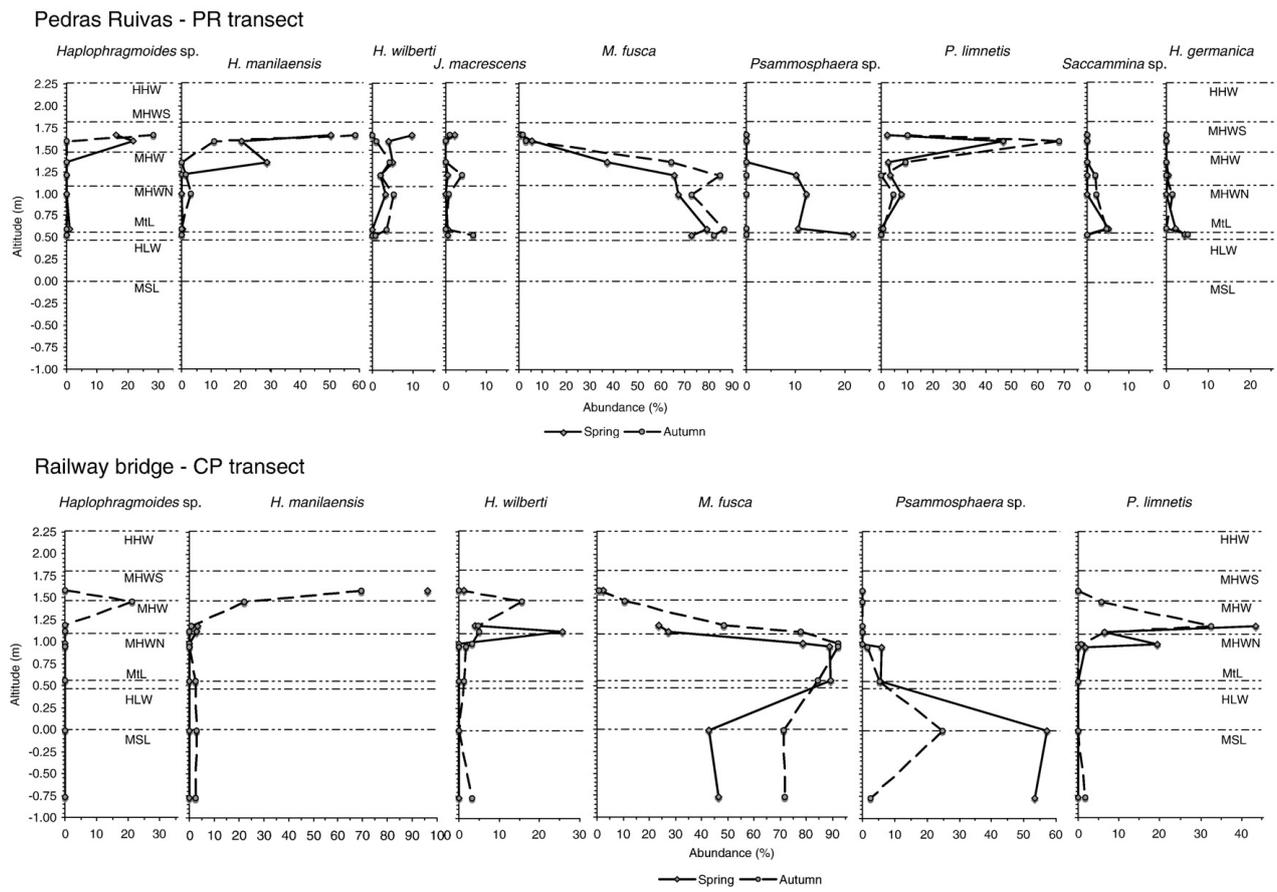
Fig. 4. Spring and Autumn relative abundances (%) of the dominant living benthic foraminiferal species from PR and CP transects. MSL — Mean Sea Level (ordnance datum of Cascais, Portugal). Tidal reference levels inside Minho estuary: HLW — highest low water; MtL — mean tide level; MHWN — mean high waters neap; MHW — mean high waters; MHWS — mean high waters spring; HHW — highest high waters.

contents that could be responsible for biological stress (Long et al., 1995).

4.2. Foraminiferal assemblages

4.2.1. Living assemblages

Foraminiferal assemblages from the brackish tidal marsh are dominated by six main species: *Miliammina fusca*, *Haplophragmoides* sp., *Haplophragmoides manilaensis*, *Haplophragmoides wilberti*, *Pseudothurammina limnetis* and *Psammosphaera* sp. (Fig. 4).

Considering all species that reach 5% of the assemblage in at least one sample, where 100 individuals were counted, the presence of *Tiphotrocha comprimata* (PR9, Spring and Autumn), *Jadammina macrescens* and *Haynesina germanica* (PR4, Autumn) and *Saccammina* sp. (PR5, Spring) must be also reported. Nevertheless their presence is not considered consistently significant.

The distribution of species across the brackish marsh transects shows a heterogeneous pattern. The distribution of the main foraminiferal species indicates vertical (altitude) zonation, a feature also recognised in vascular plant and diatom populations across salt marsh environments (e.g. Phleger and Walton, 1950; Phleger and Bradshaw, 1966; Murray, 1971, 1991; Scott and Medioli, 1980; Gehrels, 1994; Hayward et al., 1999, 2004; Horton and Edwards, 2000, 2006; Gehrels et al., 2001; Davis and FitzGerald, 2004; Leorri et al., 2008).

The Caminha high marsh zone is dominated by the *H. manilaensis* (20% to 96%) association, which can also include *Haplophragmoides* sp. (up to 28%) and a strong presence of *P. limnetis* (up to 68%) as recorded at PR8 (Moreno et al., 2006). This association ranges in elevation between mean high water (MHW) and mean high-water spring (MHWS) (Fig. 4).

A *M. fusca* (24% to 92%) association dominates the brackish low-marsh, and these are essentially bounded by the mean tide level (MtL) and mean high waters (MHW). *Haplophragmoides wilberti* (up to 26%) and *P. limnetis* (up to 44%) may contribute to the low marsh association, essentially above the mean high waters neap (MHWN), and are replaced by *Psammosphaera* sp. (up to 22%) below this elevation threshold (Fig. 4).

The tidal flat environment yielded no significant or consistent foraminifera associations in the cases of the outer PR profile and innermost PiC profile. However, in the CP inner profile an assemblage characterized by *M. fusca* (43% to 71%) and *Psammosphaera* sp. (up to 57%) extends below the marsh zone along the tidal flat and channel (Fig. 4).

Diversity of living assemblages from Caminha tidal marsh exhibits low index values, in agreement with observations reported elsewhere in many marginal environments. Shannon H(s) scores (Hayek and Buzas, 1997) range between 0.30 and 1.85, in the CP inner profile. The high marsh exhibits the highest H(s) values, namely between the MHWN and MHW elevations (Fig. 5).

Density or standing crop values (Murray, 1991) of living assemblage tend to be higher in Autumn. These values range between 12 foraminifera/cm³ in Spring, and 312 foraminifera/cm³ in Autumn assemblage, both results being yielded by the CP inner profile. The highest density values were found between MtL and MHW levels, in the low marsh zone (Fig. 5).

4.2.2. Dead assemblages

M. fusca, *Haplophragmoides* sp., *H. manilaensis*, *H. wilberti*, *P. limnetis* and *Psammosphaera* sp. are also the main species found in dead assemblages of the Caminha tidal marsh. Only *Paratrochammina* sp. joins this group at a significant level and even so, it occurred only in the CP6 sampling point (5.4%).

The proportion of main species in dead assemblages tends to be similar to those found in living assemblages, namely *M. fusca* and *Haplophragmoides* genera representatives. *P. limnetis* and *Psammo-*
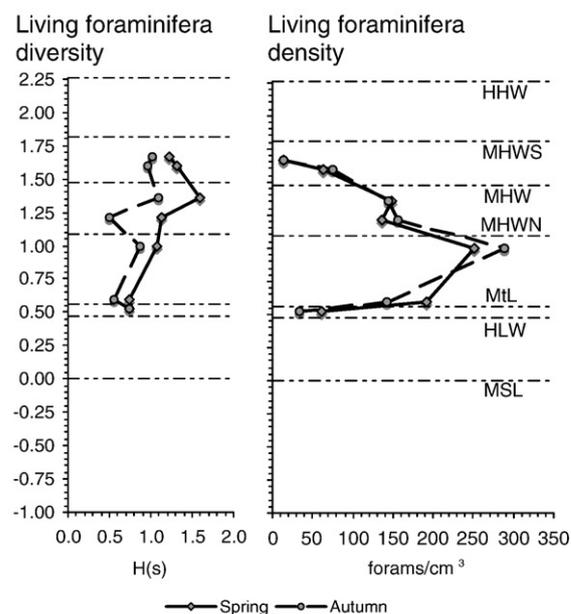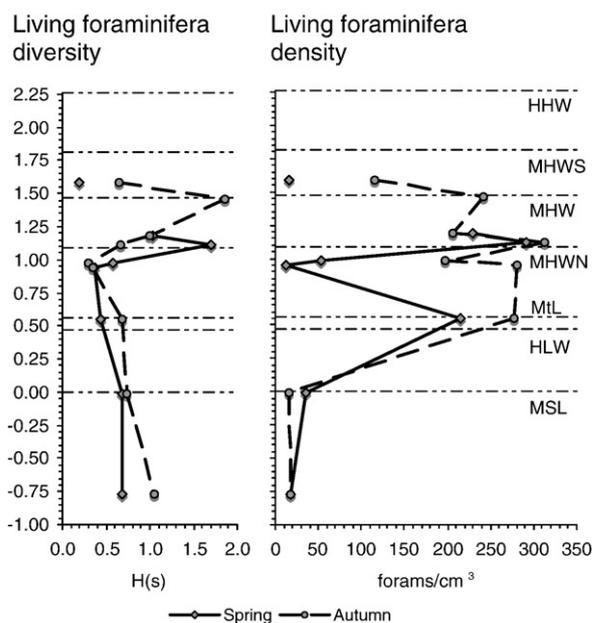
Fig. 5. Diversity and density of Spring and Autumn living benthic foraminiferal assemblages from PR and CP transects. MSL — Mean Sea Level (ordnance datum of Cascais, Portugal). Tidal reference levels inside Minho estuary: HLW — highest low water; MtL — mean tide level; MHWN — mean high waters neap; MHW — mean high waters; MHWS — mean high waters spring; HHW — highest high waters.

sphaera sp. are significant in dead assemblages but their proportions are lower than in the living assemblage, namely in the PR profile.

The distribution of dead assemblages exhibits the same zonation described for the living foraminiferal populations across the marsh transects (Fig. 6). The high marsh zone is also dominated by a *H. manilaensis* (33% to 55%) association, which includes *Haplophragmoides* sp. (14% to 35%) and *P. limnetis* (8% to 13%) at the outer PR profile. The *M. fusca* (41% to 89%) association dominates the brackish low-marsh, together with *H. wilberti* (up to 19%) and *P. limnetis* (up to 28%) above the MHWN, the latter species being replaced by *Psammosphaera* sp. (up to 6%) below this elevation.

Pedras Ruivas - PR transect
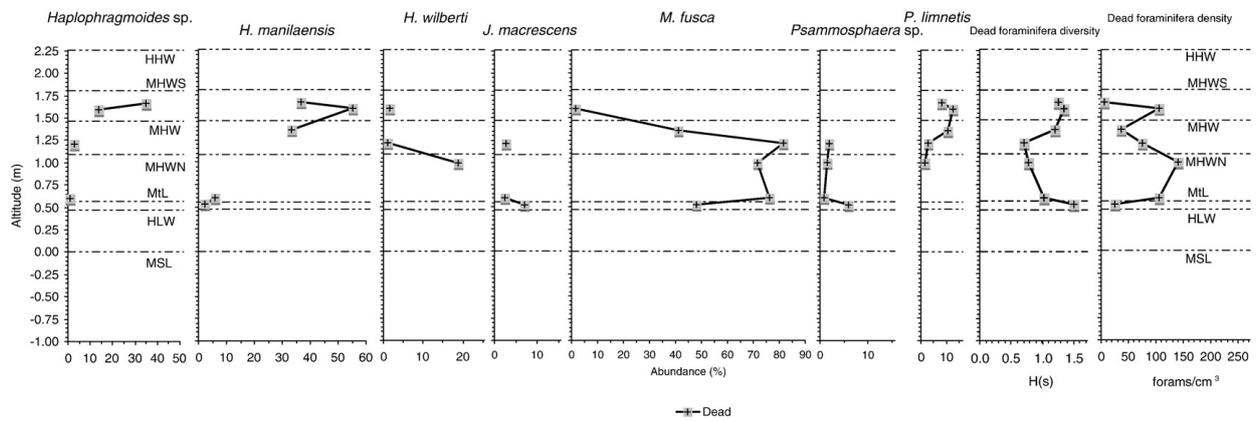
Railway bridge - CP transect
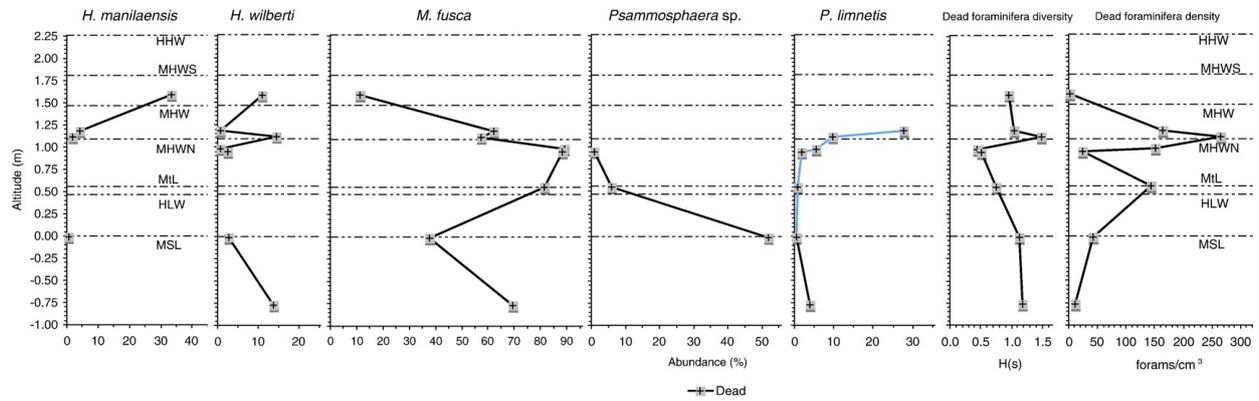
Fig. 6. Relative abundances (%) of the dominant dead benthic foraminiferal species from PR and CP transects; diversity and density of dead assemblages. MSL — Mean Sea Level (ordnance datum of Cascais, Portugal). Tidal reference levels inside Minho estuary: HLW — highest low water; MtL — mean tide level; MHWN — mean high waters neap; MHW — mean high waters; MHWS — mean high waters spring; HHW — highest high waters.

Table 1
Affinity index of Pedras Ruivas (PR) transect between Spring and Autumn living foraminiferal assemblages and living and dead foraminiferal assemblages

| Sampling points	Spring/Autumn: living			Dead/Living (Spring)			Dead/Living (Autumn)		
	AffinV	ExMnV	AFFi	AffinV	ExMnV	AFFi	AffinV	ExMnV	AFFi
PR10	70.4	65.4	VH	55.1	51.1	VH	80.9	74.0	VH
PR8	61.8	94.0	l/n	49.0	56.5	l/n	79.0	74.0	VH
PR9	49.9	49.6	VH	73.7	49.6	VH	n/d	n/d	n/d
PR7	68.7	54.0	VH	71.5	74.0	VH	92.1	94.0	VH
PR6	75.1	94.0	VH	74.3	69.0	VH	81.0	81.5	VH
PR5	83.6	65.4	VH	84.2	57.6	VH	87.4	94.0	VH
PR4	78.3	56.5	VH	57.0	49.6	VH	84.2	44.0	VH
PR3	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
PR2	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
PR1	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d

AffinV — calculated value of Affinity index (%); ExMnV — calculated expected minimum value (%); AFFi — affinity assessment; VH — very high affinity; l/n — low or no affinity; n/d — no data.

Again, the significant presence of dead foraminiferal assemblage tests in the tidal flat zone is limited to the CP inner profile, where *M. fusca* (38% to 70%), *Psammosphaera* sp. (up to 52%) and *H. wilberti* (up to 14%) extend below the marsh zone (Fig. 6).

The Diversity index of dead assemblages tends to be lower than in the living assemblages across both the high and the low marsh zones. Values of the H(s) index range from 0.40 to 1.50 within the MtL – MHWS elevation interval. Nevertheless, the dead assemblage from tidal flat CP profile yielded a slight increase of the diversity index values (1.10 to 1.20), when compared with the score of the living assemblage (0.68 to 1.05; Fig. 6).

The foraminiferal density found in dead assemblages (1 to 265 foraminifera/cm^3) is lower than in living assemblages. Higher density values (25 to 265 foraminifera/cm^3) occur along the low marsh zone, following a trend similar to the one found in living assemblages.

In general, values of both density and diversity of dead assemblages across the marsh transects are lower than in the case of living assemblages. Only a few exceptions to this general rule were found, namely in the values of the diversity index characterising the upper and lower limits of the brackish marsh.

4.3. Assemblages affinity

The assessment of the Index of Affinity (Bray and Curtis, 1957; Sanders, 1960; Rogers, 1976; Murray, 1991) from the Caminha brackish tidal marsh data indicates strong resemblance between Spring and Autumn assemblages and also between living and dead assemblages.

These results suggest the existence of very high affinity between Spring and Autumn biocoenoses and living and dead assemblages when foraminiferal microfaunas are both compared across the tidal flat and low marsh zones (Tables 1 and 2). In the cases where the index of affinity is lower than 70%, its score is usually higher than the expected minimum value. A few exceptions exist close to the upper limit of the low marsh zone (CP 6 and 7) and in the high marsh zone (PR 8 and CPas).

5. Discussion

The study of foraminiferal microfauna distribution across a brackish tidal marsh presented here yielded a number of results deserving further comments and discussion, namely: a) which species increase in proportion in the brackish environments and dominate the assemblages of tidal marsh zones; b) the absence of marine allochthonous species and the rarity of intertidal carbonated foraminifera; c) the affinity found between living Spring and Autumn assemblages and dead assemblage.

A brackish foraminiferal assemblage was found in the Caminha tidal marsh, composed essentially by *Haplophragmoides* sp., *H. manilaensis*, *H. wilberti*, *M. fusca*, *P. limnetis*, *Psammosphaera* sp., followed in abundance *T. comprimata*, *J. macrescens*, *H. germanica* and *Saccammina* sp., which can be episodically significant, and this is in general agreement with findings in similar environments reported by other authors (e.g. Murray, 1991; De Rijk, 1995; De Rijk and Troelstra, 1997; Hayward et al., 1999, 2004; Sen Gupta, 2002; Debenay et al., 2002; Moreno et al., 2006).

When present, *H. germanica* always exhibits very thin tests that frequently show features typical of destruction, or complete lack, of the carbonate layer (Moreno et al., 2007). This shows that calcareous foraminifera in this environment just found the minimum conditions to settle and survive, but they were not able to reach a successful reproduction and cannot compete within assemblage to achieve widespread colonization of this brackish tidal marsh (Murray, 2003).

The marine forms like *Quinqueloculina* spp., *Bolivina* spp. and *Cibicides* spp., which are frequently reported as allochthonous in marsh assemblages (e.g. Cearreta, 1988b; Murray, 1991) are completely absent in the Caminha tidal marsh. Nevertheless, allochthonous marine species do occur in significant proportions in the marsh assemblages of neighbour estuaries, like in the Lima tidal marsh, which is located just 20 km south (Fatela et al., 2007).

The distribution of estuarine subtidal foraminifera is limited to the muddy substrata and clearly reflects the ecological constraints of a strong salinity gradient (Scott and Medioli, 1980; Hayward et al., 1999, 2004). An assemblage dominated by *Bolivina* spp. and *Reophax nodulosus* was found confined to the Minho river mouth; these are replaced in importance by *J. macrescens*, *H. wilberti* and *T. inflata* 4 km upstream whereas *H. manilaensis* and *M. fusca* become dominating species 7.5 km away from the estuary mouth; finally, an assemblage strongly dominated by M. *fusca*, followed by *Psammosphaera* sp., was found at the confluence with the Coura river (Fatela et al., 2003; Moreno et al., 2005c).

The odd composition of the brackish marsh assemblage reported here, must be assessed within the context of the governing ecological conditions in this estuary, where marine water is totally flushed out during each ebb cycle (Moreno et al., 2005c), therefore limiting the efficient transport of (allochthonous) shelf species to the river mouth (Fatela et al., 2003) or lower estuarine intertidal zones (Murray, 2003). Besides brackish preferences, these foraminiferal species reveal strong eurihalyne characteristics.

The undersaturation in calcite of estuarine and marsh interstitial waters and sediments, associated with the low values of pH measured in the field (Moreno et al., 2005c, 2006, 2007) further limit the distribution and the proportion of calcareous foraminifera in both the subtidal and marsh environments. This reflects the pattern of the marine influence inside the estuary, and explains why the abundance

Table 2
Affinity index of Railway bridge (CP) transect between Spring and Autumn living foraminiferal assemblages and living and dead foraminiferal assemblages

Sampling points	Spring/Autumn: living			Dead/Living (Spring)			Dead/Living (Autumn)		
	AffinV	ExMnV	AFFi	AffinV	ExMnV	AFFi	AffinV	ExMnV	AFFi
Cpas	70.6	94.0	VH	37.2	94.0	l/n	30.4	94.0	l/n
CP7	61.6	77.3	l/n	56.8	65.4	l/n	55.4	94.0	l/n
CP6	42.2	54.0	l/n	55.3	70.9	l/n	84.5	40.2	VH
CP5	79.5	54.0	VH	84.2	54.0	VH	93.3	94.0	VH
CP4	90.5	94.0	VH	91.8	44.0	VH	92.8	44.0	VH
CP3	89.9	71.8	VH	87.3	94.0	l/n	87.3	71.8	VH
CP2	67.7	44.0	VH	89.5	9.4	VH	77.5	24.8	VH
CP1	49.1	16.2	VH	46.6	10.7	VH	75.1	69.0	VH

AffinV — calculated value of Affinity index (%); ExMnV — calculated expected minimum value (%); AFFi — affinity assessment; VH — very high affinity; l/n — low or no affinity; n/d — no data.

and H(s) diversity index of dead assemblages is in general lower than in living assemblages (Figs. 5 and 6). The accumulation effect of several generations of foraminifera in the dead assemblage over the time, reported elsewhere by Horton et al. (1999) and Horton and Murray (2006, 2007) may be almost absent in this (and other similar) brackish tidal marshes. In addition, the high proportion of some agglutinated species, found in the marsh assemblages may result from the local geochemical conditions, which induce both dissolution of calcareous marsh species and cement destruction of the fragile marsh agglutinated species (Martin, 2002; Murray, 2003; Moreno et al., 2007). The dead assemblages found in this brackish marsh represent a record centred in the dominant and subsidiary foraminiferal species, where taphonomic processes eliminate the rare and episodically significant species, and probably also a part of the main species tests.

A residual presence of *H. germanica*, *Cibicides* sp. and some agglutinated tests is kept within the dead associations below the MtL, allowing raising H(s) to values slightly higher than in the living assemblage. However, this increase has no correspondence in dead assemblage density.

The extensive influence of freshwater during low tide submits the lower estuary to an extreme salinity range twice a day (Moreno et al., 2005c). Salinity measurements performed across the PR outer profile during flooding of the intertidal domain, show that such ecological pressure is significantly reduced in the marsh zone. The salinity of interstitial water in marsh sediment reflects the protection offered, in some way, by the marsh biotope to the foraminiferal assemblages against the extreme variations of the estuarine environment, dumping this effect and allowing the development of a brackish association.

The distribution of foraminiferal assemblages across the Caminha brackish marsh is neither homogeneous nor random. A zonation pattern is present (Moreno et al., 2005c, 2006) which agrees with the main marsh zones usually referred to and commonly related with distribution of vegetation or diatoms (e.g. Phleger and Bradshaw, 1966; Scott and Medioli, 1980; Horton and Edwards, 2000; Gehrels et al., 2001). Elevation is assumed as the most important factor governing this distribution, but it should not be seen as an ecological factor by itself but as a constraint to other ecological controls of marsh foraminifera, like salinity and pH of interstitial waters, vegetation presence and time of submersion (Murray, 2006). De Rijk (1995) and De Rijk and Troelstra (1997) pointed out the importance of salinity of sediment interstitial water in controlling the distribution of foraminifera in the Great Marshes (Massachusetts), but in most cases this does not seem to be the main zonation factor. In fact, a strong correlation is usually reported in a large number of examples between the distribution of marsh foraminifera assemblages and time of submersion. Considering that time of submersion is a function of elevation, the distribution of marsh foraminiferal assemblages appears to be related with tidal level references and can be used as a sea-level proxy (e.g. Scott and Medioli, 1980; Williams, 1994; Gehrels, 1994; Horton et al., 1999; Horton and Edwards, 2000, 2006; Gehrels et al., 2001).

In a two-stepped approach, we can first consider that salinity is the factor constraining the general composition of marsh assemblages, as suggested by the replacement of the usually salt marsh dominant *T. inflata* and *J. macrescens* species by the brackish assemblage found in the Caminha tidal marsh. As discussed above, water undersaturation in calcium carbonate favours the environmental conditions promoting the permanence of a brackish marsh assemblage cleaned out of allochthonous species (e.g. *Quinqueloculina* spp., *Bolivina* spp.) and almost barren of euryhaline species like *H. germanica* and *A. beccarii*. Besides, the distribution of brackish foraminiferal assemblage suggests a pattern according with marsh zonation or elevation.

The brackish high marsh is a *Haplophragmoides*-rich zone (Fig. 7), where *Haplophragmoides* sp. is a dominant species (abundance always>10%: Murray, 2007), between 1.46 m and 1.67 m, the highest sampled altitude. *Haplophragmoides manilaensis* is also dominant

between 1.36 m and 1.67 m, extending its presence, though in small proportion, to the upper part of the Caminha low marsh. *Haplophragmoides wilberti*, that is dominant in brackish high marshes from New Zealand (Hayward et al., 1999, 2004), shows always a subsidiary presence in the high marsh zone of Caminha, and again extends to the upper part of low marsh, above 1.12 m (or 0.99 m in the dead assemblage). *Pseudothurammina limnetis* may be co-dominant at the lower part of high marsh but keeps a significant presence in the low marsh, above 0.98 m.

The brackish low marsh studied here, is essentially a *Miliammina fusca* zone, considering its strong dominance between the altitude of 0.52 m and 1.22 m and the subsidiary species allow its further division: *Haplophragmoides manilaensis* and *P. limnetis* define an upper low marsh domain between MHW (1.47 m) and 0.98 m, and *Psammosphaera* sp. a lower low marsh domain, between 0.52 m and 1.22 m (Fig. 7).

Dominancy of *M. fusca* and *Psammosphaera* sp. in the tidal flat is limited to the inner CP profile, but this could be a local feature, an artefact of erosion of the low marsh fringe, as observed to happen in this location. Furthermore the episodic record of these species in the subtidal estuarine domain may indicate an *in situ* origin but does not allow the definition of a specific tidal flat foraminiferal zone. It is worth to note that this extension of *M. fusca* dominance throughout the lower intertidal and subtidal zones seems characteristic of low salinity estuaries (Hayward et al., 2004).

The slight enrichment of marsh sediment in Cr, Mn, Fe, Ni, Cu and Zn seems to be dependent on grain size and organic matter contents that, binding trace metals, play an important role in their transport and accumulation. In our study areas, the contents in these elements do not exceed the average values published for non-polluted sediments (Appendix A). A potential biological harmful content in Ni, does not seem to influence the brackish marsh foraminiferal assemblages. Actually, the highest Ni (76 mg/kg) contents measured in sediments at PR8, CP5 and CP7 (Fig. 3) do not seem to have any
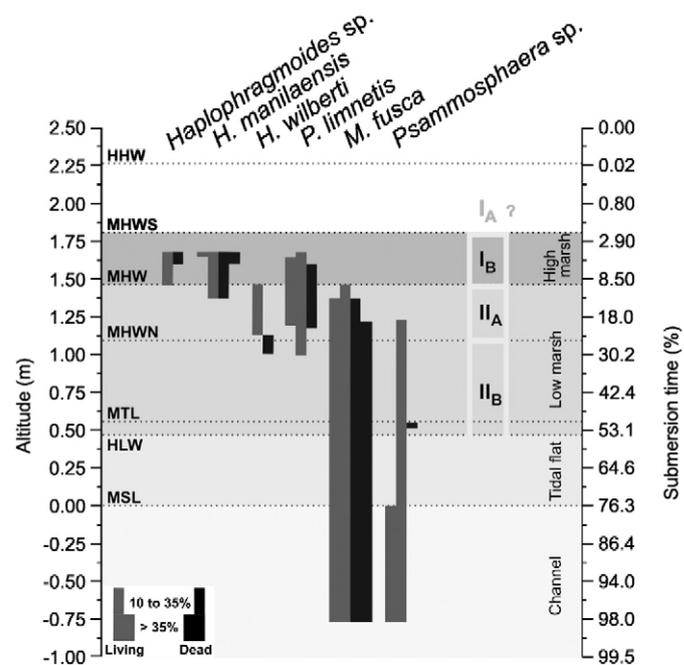

Fig. 7. Vertical distribution of the dominant benthic foraminiferal species and zonation of the brackish Caminha tidal marsh. MSL — Mean Sea Level (ordnance datum of Cascais, Portugal). Tidal reference levels inside Minho estuary: HLW highest low water; MtL — mean tide level; MHWN — mean high waters neap; MHW — mean high waters; MHWS — mean high waters spring; HHW — highest high waters.

noticeable influence on the foraminifera assemblages, as demonstrated by scores of both the H(s) and the standing crop scores (Appendix B). This means that no effects, such as foraminiferal assemblages reduction or particular opportunistic species behaviour, arose in close relation with the potential biological stress induced by Ni. Fixation of heavy metals by Fe and Mn (hydr)oxides of marsh sediments (Moreno et al., 2005a), may reduce their bioavailability and, consequently, any eventual ecological expression of their concentration becomes insignificant when compared with salinity and time of submersion constraints.

The results obtained from the assessment of assemblages affinity indicate that foraminiferal associations of this brackish tidal marsh are very similar when comparing either seasonal biocoenoses and living and dead assemblages. Though we are aware of the limited number of species shared by the assemblages under comparison, we consider that a significant affinity exists between living and dead assemblages and that this resemblance is meaningful for palaeoecological studies.

In previous works (Moreno et al., 2005c, 2006) a spring foraminiferal vertical marsh zonation was suggested for this field area, according with criteria developed by Scott and Medioli (1980). The proposal was based upon both the mean sea level national datum and tidal references extracted from tide-tables published by the Portuguese Navy (IH, 2002), which were derived for ports located in the vicinity of the studied locations and the altitude data obtained in the field for different zones were matched against those tidal-borne elevation thresholds.

Under the scope of this study, we performed tidal measurements inside the Minho estuary, close to the PR outer profile, which clearly show that the local mean tide level (MtL) rests 0.56 m above the mean sea level (MSL) reported in tide-tables and characteristic of port gauges located further seaward. Such observations and the data pertaining living Autumn and dead foraminiferal assemblages allow the suggestion of a more reliable vertical zonation of the studied brackish marsh.

The lower limit of low marsh, assumed in coincidence with the lowest presence of vascular plants (e.g. Davis and FitzGerald, 2004), comes out in this case related with the highest low water level (HLW), above 0.47 m. The mean high water level (MHW) was computed at 1.47 m and the highest high water level (HHW) at 2.26 m and these elevations define the boundaries of the high marsh.

The highest sampling points used in this study were defined at the limit between marsh and terrestrial plants, and yet this limit stands in all cases below the local HHW line: the outer profile PR10 marks 1.67 m at the inner limit, the CPas inner profile marks 1.59 m and the innermost profile PiC7 marks 1.89 m. In this case, the short yearly time of submersion characterizing this ribbon (PR10<4%, CPas<6% and PiC7<1.5%), the low salinity of interstitial waters and the frequent washing and soaking of the sediment by abundant rain, added by dilution of marine water, concur to allow some terrestrial plants (*Fraxinus* trees at PR10, for instance) to succeed in colonizing a zone that otherwise would be a typical high marsh domain with halophyte species. Consequently, the outer limit of brackish tidal marsh is, in this case, forced down close to the mean high water spring (MHWS) level. In fact, marsh vegetation provides a useful broad picture of the upper intertidal zone, within which the marsh domains develops, but does not provide a reliable definition of its limits (e.g. McKee and Patrick, 1988; Landin, 1990; Gehrels, 1994).

In such brackish marsh context, the faunal high marsh zone IA is absent (Scott and Medioli, 1980). The faunal zone I appear restricted to a IB sub-zone, confined between MHW and MHWS, dominated by *Haplophragmoides* sp. and *H. manilaensis*, but where *P. limnetis* may be co-dominant in the living assemblage (Fig. 7). The low marsh zone II is clearly dominated by *M. fusca* and can be subdivided in an IIA upper subzone, bracketed by MHW and MHWN, where this species is followed by *P. limnetis*, and in a IIB lower subzone, within the interval of MHWN and HLW, and characterized by a subsidiary presence of *Psammosphaera* sp. (Fig. 7).

In addition to, and in consequence of, this marsh zonation, the strong dominance of *H. manilaensis* between 1.55 m and 1.67 m (or 0.99 m and 1.11 m above local MtL inside the estuary) found in both the living and dead assemblages, leads us to consider that this species may replace *T. inflata* as a sea-level indicator (Gehrels, 1994) at the brackish tidal marshes.

6. Conclusions

The results presented and discussed above were obtained from the Caminha tidal marsh and contribute to extend and refine our present-day knowledge on the distribution of foraminiferal assemblages in brackish intertidal environments.

Salinity is a main constraint to general composition of the foraminiferal assemblages, but its effect may be enhanced by calcite undersaturation in brackish marshes, where marine water is the main source of carbonates. No other geochemical influence was detected, even though a heavy metals increment was measured in marsh sediments.

The high range of salinity values recorded over each tidal cycle in both estuarine and marsh flooding waters, is substantially buffered inside marsh sediment where interstitial water indicated a much more stable environment. Here, undersaturation in calcite and low pH values of interstitial water limit the episodic presence of calcareous foraminifera to unrepresentative proportions in the foraminiferal assemblages of brackish marsh. In addition, the accumulation effect of several generations of foraminifera in dead assemblages over the time is prevented by these geochemical conditions that, instead, lead to the concentration of the agglutinated main species due to dissolution of calcareous marsh species and cement destruction of the most fragile marsh agglutinated species. This fact can also explain the absence of marked seasonal differences in biocoenoses and the high affinity found between living and dead assemblages in the brackish marsh assemblages.

Another low salinity constraint comes out from tidal measurements inside the estuary that revealed the absence of a typical highest high marsh zone, which is instead colonized by terrestrial vegetation. The lowering of marsh limits may be explained by the pronounced dilution of marine water, promoted by abundant rain, limited salt-wedge penetration and residence within the estuarine space.

The decrease in time of submersion with increasing elevation across the intertidal zone governs the distribution of foraminiferal assemblages and these may be assumed as elevation proxies across brackish tidal marsh. According to the tidal marsh zonation defined by Scott and Medioli (1980), the IB sub-zone, between MHW and MHWS, is dominated by *Haplophragmoides* sp., with *H. manilaensis*. *Pseudothurammina limnetis* eventually adding up to the living assemblage as a co-dominant species. The low marsh zone II is characterised by the dominance of *M. fusca* and it may be subdivided in an IIA upper subzone, between MHW and MHWN, where this species is followed by *P. limnetis*, and in a IIB lower subzone defined by a subsidiary presence of *Psammosphaera* sp. between the levels of MHWN and MtL.

The *Haplophragmoides manilaensis* dominance characterizing the elevation range of 1.55 m to 1.67 m (0.99 m to 1.11 m above estuarine MtL), which stands in both the living and dead assemblages, suggests this species as a potential sea-level indicator in the brackish tidal marshes.

Appendix A. Elemental composition of surface sediments collected at Minho estuary

Elements	Minho estuary (N=22)				Minho lower estuary (N=14)				Average shale*
	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD	
Mg (%)	0.5	0.4	0.7	0.1	0.5	0.4	0.7	0.1	1.5
Al (%)	5.9	4.2	7.7	1.0	5.6	4.2	7.7	1.0	8
Si (%)	35.3	29.4	39.8	2.7	35.8	29.4	39.8	2.9	27.3
K (%)	2.4	2.0	2.9	0.3	2.4	2.1	2.9	0.3	2.7
Ca (%)	0.2	0.1	0.9	0.2	0.2	0.1	0.9	0.2	2.2
Ti (%)	0.3	0.1	0.5	0.1	0.3	0.1	0.4	0.1	0.5
Cr (mg/kg)	41	20	62	11.6	37	20	53	9.3	90
Mn (mg/kg)	302	124	500	87.6	276	124	399	80.4	850
Fe (%)	2.3	1.0	3.5	0.7	2.1	1.0	3.5	0.7	4.7
Ni (mg/kg)	23	9	47	9.8	20	9	43	9.5	68
Cu (mg/kg)	20	9	36	7.2	18	9	32	6.6	45
Zn (mg/kg)	80	32	157	31.3	71	32	157	33.3	95
Rb (mg/kg)	169	147	198	14.7	172	152	198	14.0	n.p.
Sr (mg/kg)	85	62	138	15.1	86	62	138	18.4	140
Zr (mg/kg)	391	117	956	197.6	331	117	721	173.2	160
Pb (mg/kg)	32	12	42	9.5	34	18	42	8.3	20

Main analitycal results from the surface sediments of Minho estuary and Caminha tidal marsh.
Min. — minimum value; Max — Maximum value; SD — standard deviation; n.p. — not published.
* After Salomons and Förstner (1984).

Appendix B. Marsh foraminiferal reference list for those species mentioned in the text

Species		Citation
Haplophragmoides manilaensis Andersen	Plate I, fig. 3	*Haplophragmoides manilaensis* Andersen, 1953: p. 22, pl. 4, fig. 7, 8.
Haplophragmoides wilberti Andersen	Plate I, fig. 4	*Haplophragmoides wilberti* Andersen, 1953: p. 21, pl. 2, figs. 5, 6, pl. 3, figs. 9–16.
Haplophragmoides sp.	Plate I, fig. 2	
Haynesina germanica (Ehrenberg)	Plate I, fig. 1a,b	*Nonionina germanica* Ehrenberg, 1840: p. 23, pl. 2, figs. 1a–g.
		Protelphidium anglicum Murray, 1965: p. 149–150, pl. 25, figs. 1–5, pl. 26, figs. 1–6.
Jadammina macrescens (Brady)		*Trochammina inflata* (Montagu) var. *macrescens* Brady, 1870: p. 290, pl. 11, figs. 5a–c.
	Plate I, fig. 6a,b	*Jadammina polystoma* Bartenstein and Brand, 1938: p. 381, text-figs. 1–3.
		Trochammina macrescens Brady; Phleger and Walton, 1950: p. 281, pl. 2, figs. 6, 7.
		Jadammina macrescens (Brady); Murray, 1971: p. 41, pl. 13, figs. 1–5.
Miliammina fusca (Brady)		*Quinqueloculina fusca* Brady, 1870: p. 286, pl. 11, fig. 2a–c.
	Plate I, fig. 5	*Miliammina fusca* (Brady); Horton and Edwards, 2006: p. 68, pl. 1, figs. 5a, b.
Paratrochammina sp. 1	Plate I, fig. 7	
Paratrochammina sp. 2	Plate II, fig. 1	
Psammosphaera sp.	Plate II, fig. 2	
Pseudothurammina limnetis (Scott and Medioli)		*Thurammina ? limnetis*, Scott and Medioli, 1980: p. 43, pl. 1, figs. 1–3.
	Plate II, fig. 3a,b	*Pseudothurammina limnetis*, (Scott and Medioli); De Rijk, 1995: p. 28, pl. 1, figs. 15, 16.
Saccammina sp.	Plate II, fig. 4a,b	
Tiphotrocha comprimata (Cushman and Bronniman)		*Trochammina comprimata* Cushman and Bronniman, 1948: p. 41, pl. 8, figs. 1–3.
		Tiphotrocha comprimata (Cushman and Bronniman); Horton and Edwards, 2006: p. 69, pl. 2, figs. a–e.
Trochammina inflata (Montagu)		*Nautilus inflatus* Montagu, 1808: p. 81, pl. 18, fig. 3.
	Plate II, fig. 5a,b,c	*Trochammina inflata* (Montagu); Horton and Edwards, 2006: p. 69, pl. 2, figs. 8a–d.
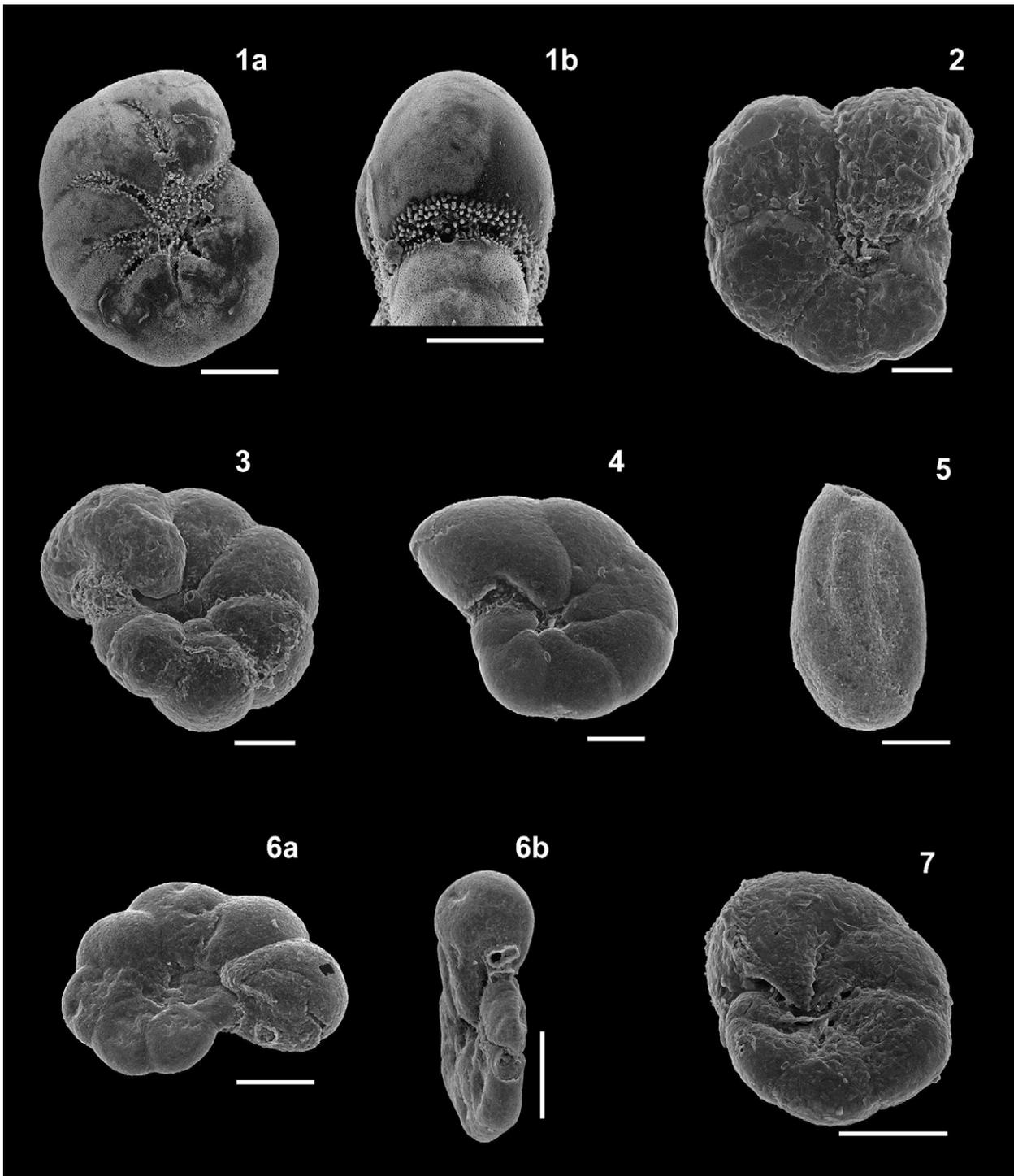
Plate I. Scale bar 100 μm. 1a,b *Haynesina germanica* (Ehrenberg). 2 *Haplophragmoides* sp. 3 *Haplophragmoides manilaensis* Andersen. 4 *Haplophragmoides wilberti* Andersen. 5 *Milliammina fusca* (Brady). 6a,b *Jadammina macrescens* (Brady). 7 *Paratrochammina* sp.1.
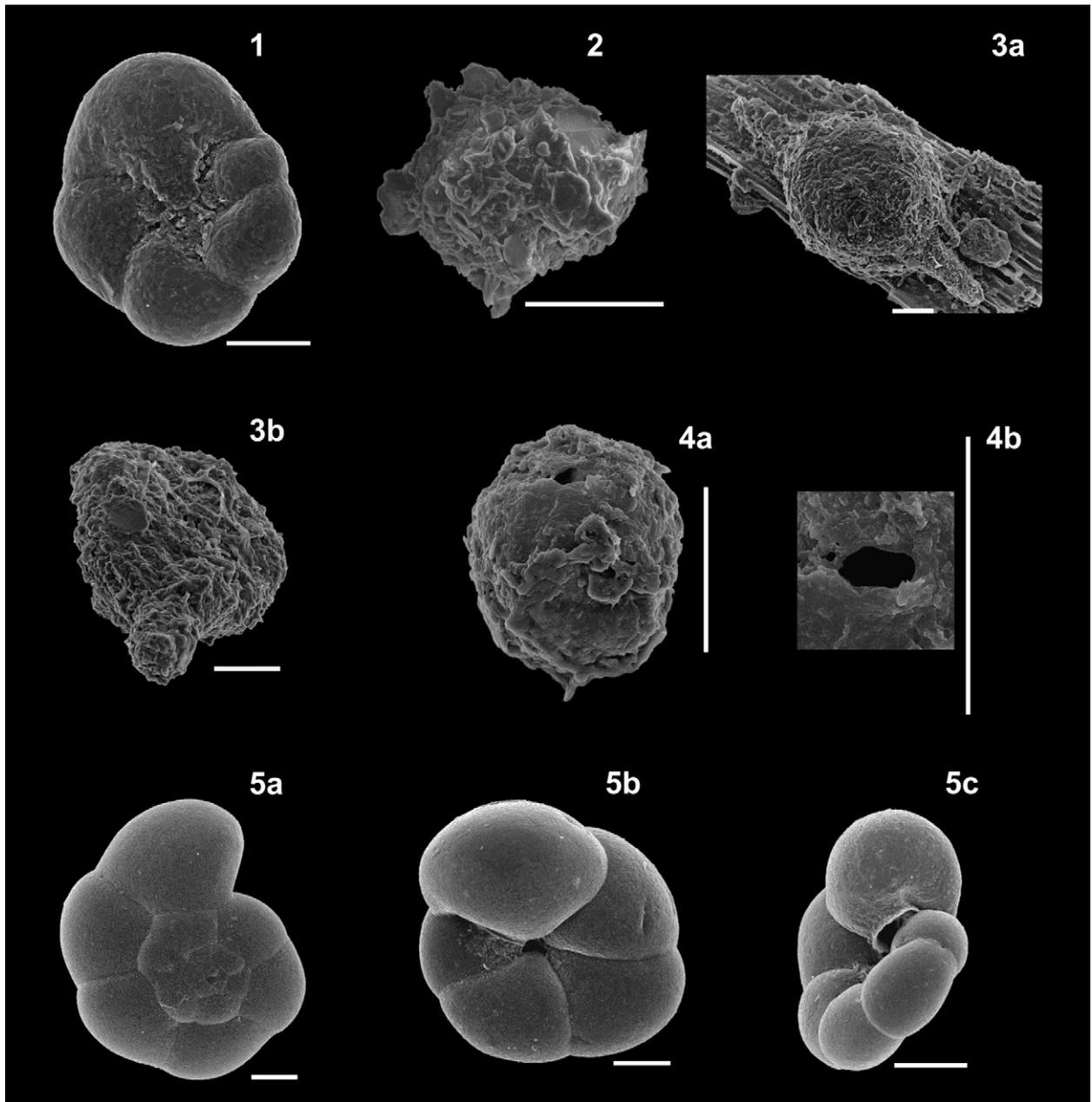
Plate II. Scale bar 100 μm. 1 *Paratrochammina* sp.2. 2 *Psammosphaera* sp. 3a,b *Pseudothurammina limnetis* (Scott and Medioli). 4a,b *Saccammina* sp. 5a,b,c *Trochammina inflata* (Montagu).

Appendix C. Living foraminiferal assemblages data from Caminha tidal marsh

PEDRAS RUIVAS_PR transect

Site	Altitude_m	T. subm_%	Haplophragmoides sp.		H. manilaensis		H. wilberti		J. macrescens		M. fusca		Psammosphaera sp.	
PR10	1.67	4.2	16.0	28.4	50.4	58.7	9.9	0.0	2.3	0.9	0.8	1.8	0.0	0.0
PR8	1.60	5.7	21.8	0.0	20.2	11.0	4.0	1.0	0.0	0.0	5.6	3.0	0.0	0.0
PR9	1.36	13.5	0.0	0.0	28.8	0.0	5.1	4.2	0.0	0.0	37.2	64.4	0.0	0.0
PR7	1.21	19.8	0.0	0.0	0.0	1.4	2.0	2.0	0.5	4.1	65.5	85.0	10.2	0.0
PR6	0.99	30.7	0.0	0.0	0.0	3.0	3.4	5.3	0.0	0.8	67.2	72.9	12.2	0.0
PR5	0.60	48.9	0.9	0.0	0.5	0.0	0.0	3.6	0.5	0.0	79.1	86.4	10.5	0.0
PR4	0.53	51.8	0.0	0.0	0.0	0.0	0.0	0.8	0.5	6.7	72.9	82.4	21.7	0.0
PR3	0.40	57.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	0.0	0.0
PR2	-0.03	77.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PR1	-1.18	100.0	0.0	0.0	0.0	0.0	5.8	0.0	0.0	0.0	51.9	33.3	36.5	66.7
			Spring	Autumn	n/d	no data								

Railway bridge_CP transect

Site	Altitude_m	T. subm_%	Haplophragmoides sp.		H. manilaensis		H. wilberti		J. macrescens		M. fusca		Psammosphaera sp.	
CPas	1.59	6.0	0.0	0.0	96.1	69.6	1.3	0.0	0.0	0.0	2.6	1.0	0.0	0.0
CP7a	1.46	9.9	n/d	21.4	n/d	22.1	n/d	15.7	n/d	0.0	n/d	10.7	n/d	0.0
CP7	1.19	20.7	0.0	0.0	3.6	0.9	4.1	4.7	0.0	0.0	23.9	48.6	0.0	0.0
CP6	1.12	23.9	0.0	0.0	2.7	0.0	25.7	5.0	0.0	0.0	27.3	78.0	0.0	0.0
CP5	0.98	31.2	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	78.6	92.4	0.0	0.0
CP4	0.95	32.8	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	88.8	92.4	6.0	1.7
CP3	0.56	50.5	0.0	0.0	0.0	2.7	0.0	1.3	0.5	0.0	89.5	84.6	5.5	5.4
CP2	-0.01	76.8	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	43.0	71.3	57.0	24.8
CP1	-0.77	98.1	0.0	0.0	0.0	2.5	0.0	3.3	0.0	0.0	46.6	71.9	53.4	2.5
			Spring	Autumn										

Pinelas_PiC transect

Site	Altitude_m	T. subm_%	Haplophragmoides sp.		H. manilaensis		H. wilberti		J. macrescens		M. fusca		Psammosphaera sp.	
PiC7	1.89	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PiC5	1.57	6.6	0.0	0.0	50.0	0.0	0.0	0.0	0.0	0.0	13.2	0.0	14.9	0.0
PiC4	1.23	18.9	0.0	100.0	8.2	0.0	0.0	0.0	0.0	0.0	20.4	0.0	53.1	0.0
PiC6	1.04	28.0	0.0	0.0	26.4	7.4	5.7	4.1	0.0	0.0	32.1	47.1	0.0	0.0
PiC3	0.76	42.0	0.0	0.0	7.2	4.3	0.0	0.0	0.0	0.0	44.3	84.6	26.8	0.9
PiC2	0.03	75.0	0.0	0.0	0.0	11.1	0.0	0.0	0.0	0.0	100.0	77.8	0.0	0.0
PiC1	-0.23	85.7	0.0	0.0	0.0	16.7	0.0	0.0	0.0	0.0	22.2	76.7	77.8	0.0
			Spring	Autumn										

PEDRAS RUIVAS_PR transect

Site	P. limnetis		T. comprimata		Saccammina sp.		H. germanica		Total number_N		Foram/cm^3		Diversity _ H(s)		No. of species _ S	
PR10	2.3	10.1	1.5	0.0	0.0	0.0	0.0	0.0	**131**	**109**	13	14	1.21	1.02	7	5
PR8	46.8	68.0	0.0	0.0	0.0	0.0	0.0	0.0	**124**	**100**	63	75	1.31	0.96	5	5
PR9	2.6	9.3	16.0	5.9	0.0	0.0	0.0	0.0	**156**	**118**	149	144	1.60	1.10	9	5
PR7	3.6	0.0	1.0	0.7	0.0	2.0	0.5	0.0	**197**	**147**	136	157	1.13	0.50	11	6
PR6	8.0	4.5	0.0	1.5	0.0	2.3	0.0	1.5	**238**	**133**	250	290	1.08	0.87	8	8
PR5	0.0	0.9	0.0	0.0	5.0	4.5	2.3	0.0	**220**	**110**	193	142	0.75	0.55	7	5
PR4	0.0	0.0	0.0	0.0	0.0	0.0	4.3	5.0	**207**	**119**	61	33	0.75	0.75	5	8
PR3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2	1	0.4	3	0.00	0.00	1	1
PR2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.00	0.00	0	0
PR1	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52	3	8	3	0.95	0.64	9	2
	Spring	Autumn									n/d	no data				

Railway bridge_CP transect

Site	P. limnetis		T. comprimata		Saccammina sp.		H. germanica		Total number_N		Foram/cm^3		Diversity _ H(s)		No. of species _ S	
CPas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**152**	**102**	16	116	0.19	0.66	3	3
CP7a	n/d	5.7	n/d	0.0	n/d	0.0	n/d	0.0	n/d	**140**	n/d	242	n/d	1.85	n/d	7
CP7	43.7	32.7	0.0	1.0	0.0	0.9	0.0	0.0	**197**	**107**	230	206	1.04	1.00	5	6
CP6	6.6	6.4	3.3	2.8	0.0	0.7	0.0	0.0	**183**	**141**	292	312	1.71	0.67	10	6
CP5	19.4	0.8	0.0	0.0	0.0	0.8	0.0	0.0	**103**	**119**	54	197	0.58	0.30	3	5
CP4	1.7	0.0	0.0	0.0	0.0	4.2	0.0	0.0	**116**	**118**	12	281	0.37	0.35	4	4
CP3	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	**200**	**149**	215	277	0.44	0.68	9	7
CP2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**149**	**101**	35	16	0.68	0.74	2	4
CP1	0.0	1.7	0.0	1.7	0.0	0.0	0.0	0.8	**176**	**121**	18	18	0.69	1.05	2	9
	Spring	Autumn														

Pinelas_PiC transect

Site	P. limnetis		T. comprimata		Saccammina sp.		H. germanica		Total number_N		Foram/cm^3		Diversity _ H(s)		No. of species _ S	
PiC7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.00	0.00	0	0
PiC5	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	114	0	65	0	1.27	0.00	5	0
PiC4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49	1	17	1	1.18	0.00	4	1
PiC6	1.9	1.7	5.7	9.1	0.0	0.0	0.0	0.0	53	121	11	46	1.58	1.44	7	9
PiC3	2.1	0.0	0.0	0.0	0.0	1.7	0.0	0.0	97	117	12	152	1.30	0.62	5	6
PiC2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	9	0.3	6	0.00	0.68	1	3
PiC1	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	9	30	1	3	0.53	0.73	2	4
	Spring	Autumn														

Appendix D. Dead foraminiferal assemblages data from Caminha tidal marsh

Site	Altitude_m	T. subm_%	Haplophragmoides sp.	H. manilaensis	H. wilberti	J. macrescens	M. fusca	Paratrochammina sp.	Psammosphaera sp.	P. limnetis	Total number_N	Foram/cm³	Diversity_H(s)	No. of species_S
PEDRAS RUIVAS_PR transect														
PR10	1.67	4.2	34.7	36.7	0.0	0.0	0.0	0.0	0.0	8.2	49	5	1.26	4
PR8	1.60	5.7	13.5	55.3	1.4	0.0	1.4	0.0	0.0	12.5	208	106	1.35	8
PR9	1.36	13.5	0.0	33.3	0.0	0.0	41.0	0.0	0.0	10.3	39	37	1.20	5
PR7	1.21	19.8	2.8	0.0	0.9	2.8	81.7	0.0	1.8	2.8	109	76	0.70	8
PR6	0.99	30.7	0.0	0.0	18.8	0.0	71.4	0.0	1.5	1.5	133	140	0.77	6
PR5	0.60	48.9	0.8	5.8	0.0	2.5	76.0	0.0	0.8	0.0	121	106	1.03	11
PR4	0.53	51.8	0.0	2.4	0.0	7.1	48.2	0.0	5.9	0.0	85	25	1.50	9
PR3	0.40	57.5	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	2	0	0.00	1
PR2	−0.03	77.6	0.0	0.0	0.0	0.0	80.0	0.0	0.0	0.0	5	1	0.50	2
PR1	−1.18	100.0	1.0	0.0	9.4	0.0	74.0	0.0	0.0	0.0	96	15	0.86	7
Railway bridge_CP transect														
Cpas	1.59	6.0	0.0	33.3	11.1	0.0	11.1	0.0	0.0	0.0	9	1	0.95	3
CP7	1.19	20.7	0.0	4.3	0.7	0.0	62.4	1.4	0.0	27.7	141	164	1.04	7
CP6	1.12	23.9	0.0	1.8	14.5	0.0	57.2	5.4	0.0	9.6	166	265	1.49	13
CP5	0.98	31.2	0.0	0.0	0.7	0.0	89.2	0.3	0.0	5.6	288	151	0.45	5
CP4	0.95	32.8	0.0	0.0	2.6	0.0	88.4	0.9	0.9	1.7	232	23	0.51	8
CP3	0.56	50.5	0.0	0.0		0.0	81.3	0.0	6.0	0.7	134	144	0.75	9
CP2	−0.01	76.8	0.0	0.6	2.8	0.0	37.6	0.0	51.9	0.6	181	42	1.14	13
CP1	−0.77	98.1	0.0	0.0	13.7	0.0	69.6	2.0	0.0	3.9	102	10	1.18	12
Pinelas_PiC transect														
PiC7	1.89	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.00	0
PiC5	1.57	6.6	0.0	59.9	4.8	0.0	23.2	0.0	0.0	0.0	397	225	1.07	5
PiC4	1.23	18.9	0.0	36.0	0.0	0.0	16.0	0.0	12.0	0.0	25	9	1.53	5
PiC6	1.04	28.0	0.0	14.0	13.3	0.0	51.0	0.0	0.0	0.0	300	65	1.45	8
PiC3	0.76	42.0	0.0	31.0	0.0	0.0	50.0	0.0	0.0	0.0	42	5	1.10	4
PiC2	0.03	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.00	0
PiC1	−0.23	85.7	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	3	0.3	0.00	1

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