1 Marsh benthic Foraminifera response to estuarine hydrological balance
2 driven by climate variability over the last 2000 years (Minho estuary,
3 NW Portugal).

4
5 João Moreno^{a,i}, Francisco Fatela^a, Eduardo Leorri^b, José M. De la Rosa^c, Inês Pereira^{d,ii}
6 M. Fátima Araújo^d, M. Conceição Freitas^a, D. Reide Corbett^b, Ana Medeiros^d

7
8
9 ^a Universidade de Lisboa, Faculdade de Ciências, Centro de Geologia, Departamento de Geologia,
10 Campo Grande, 1749-016, Lisboa, Portugal.

11 ^b East Carolina University, Department of Geological Sciences, Greenville, NC 27858-4353, USA.

12 ^c Instituto de Recursos Naturales y Agrobiología de Sevilla. Av. Reina Mercedes 10, 41012, Sevilla,
13 España.

14 ^d Universidade de Lisboa, Instituto Superior Técnico, Centro de Ciências e Tecnologias Nucleares,
15 Estrada Nacional 10, km 139,7, 2695-066 Bobadela LRS, Portugal.

16

ⁱ Corresponding author: fax no: (+351) 21 750 01 19; e-mail address: jcmoreno@fc.ul.pt

ⁱⁱ Present address: LIRIO - Pólo de Estremoz da Universidade de Évora, Convento das Maltezas, 7100-513 Estremoz

17 **Abstract**

18 A high-resolution study of a marsh sedimentary sequence from the Minho estuary
19 provides a new palaeoenvironmental reconstruction from NW Iberian based on
20 geological proxies supported by historical and instrumental climatic records. A low
21 salinity tidal flat, dominated by *Trochamminita salsa*, *Haplophragmoides* spp. and
22 *Cribrostomoides* spp., prevailed from AD 140-1360 (Roman Warm Period, Dark Ages,
23 Medieval Climatic Anomaly). This sheltered environment was affected by high
24 hydrodynamic episodes, marked by the increase in silt/clay ratio, decrease of organic
25 matter, and poor and weakly preserved foraminiferal assemblages, suggesting
26 enhanced river runoff. The establishment of low marsh began at AD 1380. This low
27 salinity environment, marked by colder and wet conditions, persisted from AD 1410–
28 1770 (Little Ice Age), when foraminiferal density increased significantly.
29 *Haplophragmoides manilaensis* and *Trochamminita salsa* marks the transition from low
30 to high marsh AD 1730. Since AD 1780 the abundances of salt marsh species
31 (*Jadammina macrescens*, *Trochammina inflata*) increased accompanied by a decrease
32 in foraminiferal density, reflecting climate instability, when droughts alternate with
33 severe floods. SW Europe marsh foraminifera respond to the hydrological balance,
34 controlled by climatic variability modes (e.g. NAO) and solar activity, thus contributing to
35 the understanding of NE Atlantic climate dynamics.

36

37 **Keywords:** Marsh foraminifera; hydrological balance; palaeoenvironmental
38 reconstruction; Climate variability; RWP to Present; Minho estuary; NW Iberian region.

39

40 **Introduction**

41 Tidal marshes are dynamic ecosystems, considered as critical transition zones between
42 adjacent terrestrial and marine environments within the estuarine landscape. These
43 environments have been the source of considerable benefits, both social and economic.
44 The human impact on tidal marshes started a long time ago (e.g. drainage and
45 agriculture, grazing, salt pans), and increased in modern times (dredging, harbours,
46 heavy industries, communication routes and urban settlement, agriculture, sewages and
47 industrial effluents). Identifying past environmental changes that influenced the
48 estuarine margins, whether triggered by natural internal processes (e.g., sediment
49 supply), external forcing (e.g., solar irradiance, volcanic aerosols, atmospheric
50 circulation patterns) or by persistent human impact (e.g., anthropogenic induced climate
51 warming), is essential to understand global and regional climatic variability and the
52 relationship between climate and sea level during the last two millennia.

53 Since the pioneering works of Phleger (1965) and Scott and Medioli (1978, 1980), tidal
54 marsh foraminiferal assemblages have been used as palaeoenvironmental proxies and
55 sea-level indicators in Holocene intertidal deposits (e.g., Gehrels, 1994; Hayward et al.,
56 1999; Horton, 1999; Scott et al., 2001; Gehrels and Newman, 2004; Horton and
57 Edwards, 2005; Fatela et al., 2009; Leorri et al., 2010a, 2011). The distribution of
58 foraminiferal species across tidal marshes around the world exhibits a vertical zonation
59 with respect to the tidal frame that depends on abiotic and biotic factors and allows the
60 recognition of foraminiferal assemblage characteristics of a narrow zone (high marsh)
61 between mean high water (MHW) and mean high water spring (MHWS). They also
62 provide an efficient method to reconstruct water circulation patterns in estuaries and the
63 interplay between marine and freshwater inflow (e.g. Hayward et al., 1999; Leorri and
64 Cearreta, 2009a). The study of modern foraminiferal patterns can be used to interpret

65 fossil brackish foraminiferal faunas and they are of special relevance to recent methods
66 of determining rates of Quaternary changes in sea level, climate and geohistory (e.g.
67 Hayward et al., 1999; Hippensteel et al., 2005; Alday et al., 2006; Drago et al., 2006;
68 Horton and Murray, 2006; Horton and Culver, 2008; Leorri and Cearreta, 2009b, Leorri
69 et al., 2013).

70 In the present work, foraminiferal data are combined with both descriptive documental
71 records and instrument-based observations (i.e. meteorological and hydrological) to
72 improve the understanding of climate variability in the NW of Portugal over the last
73 2,000 years. Further comparison with historical climatic information from the Iberian
74 Peninsula (e.g., Font Tullot, 1988; Benito et al., 1996, 2008, 2010; Bernardéz et al.,
75 2008a; Martín-Chivelet et al., 2011) and palaeoclimatic reconstructions from offshore
76 Atlantic Iberian margin (Lebreiro et al., 2006; Rodrigues et al., 2009; Abrantes et al.,
77 2011) was made to recognize and characterize the potential of marsh foraminiferal
78 assemblages as a proxy for major shifts in climate. Notwithstanding the uncertainties
79 inherent to the dating methods, especially sub-centennial scale chronologies based on
80 radiocarbon dating, foraminiferal changes over the last two millennia might reflect
81 climatic changes such as Roman Warm Period (RWP), Dark Ages (DA), Medieval
82 Climatic Anomaly (MCA), Little Ice Age (LIA), the Solar activity cycles (maxima and
83 minima), the present warming pulse, as well as extreme climatic events.

84

85 **Study area**

86 The Minho River runs through the NW of Portugal (Fig. 1), defining 77 km of the political
87 border with Spain, just before reaching the Atlantic Ocean near the ancient fortress
88 town of Caminha. It drains a carbonate depleted Variscan basement across the rainiest

89 area of Portugal, with an average annual precipitation of 1780 mm (maxima 3470 mm;
90 <http://snirh.pt>). The annual average fluvial discharge is approximately 300 m³/s and the
91 winter peak discharge (December to March) generally exceeds 1000 m³/s; the 100-year
92 flood recorded 6100 m³/s (Bettencourt et al., 2003). In spite of the construction of
93 several dams since AD 1951, a correlation between river flow and precipitation of
94 R=0.85 (Fatela et al., 2013) to R=0.88 (Gómez-Gesteira et al., 2011) was found in
95 Minho, as well as a correlation between winter precipitation and NAO index of R=0.70
96 (Fatela et al., 2013).

97 *[Fig. 1.]*

98 The Minho estuary presents a semi-diurnal high-mesotidal regime where astronomical
99 tides range between 2 m and almost 4 m under neap or spring waters, respectively.
100 However, tidal levels are often amplified by storm surges (Taborda and Dias, 1991).
101 The dynamic tide is felt up to 40 km upstream (Alves, 1996). The upstream limit of
102 marine water is recorded up to 6-9 km (Fatela et al., 2009). This estuary is shallow, as a
103 result of widespread siltation, and semi-enclosed by a mouth bar, exposing a
104 considerable part of the bottom during low water spring tide. The lower estuary extends
105 a few kilometres from the mouth and behaves as “partially mixed” (Brown et al., 1991;
106 Moreno et al., 2005c). The most extensive marsh development occurs in the south bank
107 of the Minho estuary, at the confluence with the Coura River (hereafter referred to as
108 the Caminha tidal marsh), providing an adequate site to investigate the current and past
109 distribution of foraminiferal assemblages (Fig. 1).

110

111 **Surface foraminiferal distribution at Caminha marsh.**

Several studies related to the living and dead marsh foraminiferal assemblage zonation and their environmental constraints (Moreno et al., 2005a, 2005b, 2005c, 2006, 2007; Fatela et al., 2007, 2009) and Holocene sea-level changes (Leorri et al., 2010a, 2011; Leorri et al., 2013) have been carried out. The main control to the general composition of the foraminiferal assemblages is salinity and submersion time (e.g., Fatela et al., 2009). However, these assemblages are also controlled by calcite undersaturation in these brackish marshes and tidal flats, where marine water is the major source of carbonates (Moreno et al., 2007; Valente et al., 2009). While with each tidal cycle salinity present large changes, foraminifera live infaunally (i.e., inhabit the sediment) and the controls are exerted by interstitial pore water that buffer these drastic changes (Fatela et al., 2009). The particular conditions (e.g., undersaturation in calcite, low pore-water pH) of the interstitial water have lead to foraminiferal assemblages strongly dominated by robust agglutinated foraminifera, since calcareous foraminifera dissolve and most fragile marsh agglutinated tests disaggregate in response to these geochemical condition.

Low salinity conditions limit the elevation at which foraminiferal assemblages can be found. In fact, in this region the typical highest high marsh zone is absent and it is instead colonized by terrestrial vegetation. A pronounced dilution of marine water, caused by plentiful rain, in conjunction with the morphology of the estuary, limits the tidal salt wedge penetration landwards and residence time of marine waters within the estuarine space.

Following the tidal marsh foraminiferal zonation previously defined by the seminal work of Scott and Medioli (1980) a study of forty-eight surface sediment samples (from the Spring and Fall of 2002; Fatela et al., 2009), shows that Caminha assemblages from the high marsh IB sub-zone, between mean high waters (MHW) and mean high waters

spring (MHWS), are dominated by *Haplophragmoides* sp. and *Haplophragmoides manilaensis* Andersen, 1953, together with *Pseudothurammia limnetis* (Scott and Mediolì, 1980) as a co-dominant species in the living assemblage. The low marsh zone II is characterized by the dominance of *Miliammina fusca* (Brady, 1870). This zone may be subdivided into a IIA upper subzone, between MHW and mean high waters neap (MHWN), where *M. fusca* is accompanied by secondary species *P. limnetis*, and a lower subzone IIB defined by *M. fusca* and secondary *Psammospaera* sp. This subzone is located between MHWN and the mean tide level (MtL, i.e., mean water level inside the estuary). *Haplophragmoides manilaensis* characterises the elevation range between MHW and MHWs (0.99 m to 1.11 m above Minho estuarine MtL). It is the most abundant in both the living (stained) and dead assemblages. Because of its dominance and limited vertical range, *H. manilaensis* is an important sea level and low salinity high marsh indicator (Fatela et al., 2009).

A new set of eighteen surface samples was collected in May 2010 to improve the understanding of the Caminha high marsh assemblage (Fatela et al., 2013).

Correspondence Analysis (CA) integrating dead benthic foraminiferal results from both the 2002 and 2010 samples resulted in 3 defined groups according to foraminiferal assemblage distribution across the tidal marsh zonation, with a significant correlation with submersion time (Fatela et al., 2013). However, a difference is evident between the two sampling periods when the dominant salt marshes species are evaluated; for instance *Trochammina inflata* (Montagu, 1808) and *Jadammina macrescens* (Brady, 1980) were absent in 2002, but are common in 2010. This decline of lower salinity species (*Haplophragmoides* sp., *H. manilaensis*, *H. wilberti* and *P. limnetis*) abundances is seen as a direct consequence of the salinity increase of the interstitial water in the marsh which reflects a decrease in the regional precipitation regime during the 8 years

that separate the samplings (Fatela et al., 2013). This observation points out that the records of benthic foraminifera from Caminha high marsh represent an important proxy for high-resolution studies of climate variability (Fatela et al., 2013).

Materials and Methods

The Caminha high marsh sediment core FCPw1 was collected with a manual auger sampler (5 replicated cores, one meter long each) at 1.55 m above mean sea level (41° 52' 37" N and 8° 49' 28" W; Fig. 1), and transferred to a half PVC pipe and wrapped with cling film to protect it during transport and minimize desiccation.

Foraminifera

In the laboratory, the core was carefully sliced into 1cm intervals and 56 samples (ca. 25 cm³) were analysed for foraminiferal purposes. Samples were taken every centimetre to a depth of 30 cm, below which samples were collected every other cm down to 50 cm depth and alternating 2 cm from 50 cm to the core bottom. Each sample corresponds to a circular slice of sediment with a volume of ca. 25 cm³. Samples were wet sieved through to remove clay and silt material (63 µm mesh). At least 100 individuals were wet picked with a micropipette in each sample, a number fully adequate to characterize the low diversity assemblages of tidal marshes (Fatela and Taborda, 2002). When the number of specimens was too low, the trichloroethylene (density=1.46 g/cm³) flotation procedure was used to separate foraminiferal tests from sand particles (Murray, 2006). All specimens contained in that fraction were picked.

Foraminiferal identification followed Loeblich and Tappan (1988) to generic classification and several published papers regarding tidal marsh foraminifera for

specific classification (e.g. Murray, 1971; Scott and Medioli, 1978, 1980; Hayward et al., 1999; Debenay et al., 2002). The specimens picked per sample were archived in a micropalaeontological Plummer cell slide.

Sedimentology and Geochemistry

Two replicate cores were sliced every centimetre for geochemical and sedimentological purposes. All samples were frozen and then freeze-dried prior to the analyses. Organic matter (OM) content was determined by loss on ignition methodology (LOI), using a 2 g of bulk sediment dried and oven-heated at a temperature range of 490-510 °C, for about 2 hours. Sediment pH was determined using the electrometric method (Head, 1980) with an inoLab WTW series pH730 model. Wet sieving was used to separate and determine the ratio of coarse (>63 µm): fine (<63 µm) particles and the silt and clay fractions were determined using a Malvern laser particle analyzer and Mastersize2000 software. Selected samples of one of the replicates were sieved to remove the coarser particles larger than 2 mm. The remaining material (<2 mm) was dried, ground in an agate mill, and a portion was homogenized and compacted into pressed pellets for analysis by Energy-Dispersive X-Ray Fluorescence Spectrometry (EDXRF) using a KEVEX 771 spectrometer. Spectral data were acquired for the quantification of Al, Si, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, Br, Rb, Sr, Zr, and Pb. A detailed description on the sample preparation, analytical conditions, detection limits and the accuracy and precision of the overall procedure have been published elsewhere (Araújo et al., 1998, 2003). In this multi-proxy analysis, special focus was made on the elements recognized as proxies of marine and continental inputs.

Chronology

The upper section of the core was dated via ^{210}Pb measured by alpha spectroscopy following the methodology of Nittrouer et al. (1979). In this approach, unsupported ^{210}Pb ($^{210}\text{Pb}_{\text{Excess}}$) is determined as the difference of ^{210}Pb activity versus ^{226}Ra , assumed to be in equilibrium at depth within the core (Nittrouer et al., 1979). ^{137}Cs (Smith, 2001) and total Pb activities (Leorri et al., 2008; Leorri and Cearreta, 2009b) were used to support the ^{210}Pb derived chronology based on the constant rate of supply model (CRS; Appleby and Oldfield, 1978), as it has been shown to be the most suitable for the region (Leorri et al., 2010b). The radionuclide ^{137}Cs was determined by its gamma emissions at 662 KeV (Appendix A). Samples were counted for 24h to the depth of limit of measurable fallout ^{210}Pb or ^{137}Cs , i.e., until activity concentrations of both radionuclides dropped below the minimum detectable activity (Leorri et al., 2010b). Six additional samples (40-41 cm, 44-45 cm, 63-64 cm, 66-67 cm, 81-82 cm and 90-91 cm depth) were analysed for radiocarbon content (total organic) at Beta Analytic Inc. (USA) (Table 1) to extend the chronology downcore (Fig. 2). The interpolation of the data has been performed using a Bayesian age-depth model (Bchron 3.2; Haslett and Parnell, 2008; Parnell et al., 2008) to provide age and associated errors to the environmental reconstructions. The lowermost 10 cm (91-100 cm depth) have been extrapolated by linear regression from the Bchron calculation between 81 and 91 cm depth. This section has to be considered carefully as errors cannot be calculated. The obtained calendar ages are presented in years of *Anno Domini* (AD).

[Table 1.]

[Fig. 2.]

Historical records

The last two millennia comprise five well-known climatic historical periods: 1) Roman Warm Period (RWP, AD 0-400; e.g., Lamb, 1985); 2) Dark Ages Cold Period (DA, AD

400-700; e.g., Keigwin and Pickart, 1999); 3) Medieval Climatic Anomaly (MCA, AD 900-1300; e.g., Stine, 1994; Mann et al. 2009; Trouet et al., 2009; Cook et al., 2010; Graham et al., 2011); 4) Little Ice Age (LIA, AD 1350-1900; e.g., Bradley and Jones, 1993) and 5) 20th century warming (present warm period - PWP), as recorded by instrumental temperature measurements over the last two centuries. These climate changes were also recognized by several authors that have studied the variability of the climatic conditions in Northern Iberian Peninsula during the late Holocene until present using proxies like organic and inorganic geochemistry, sedimentology and micropalaeontology (e.g., Martínez-Cortizas et al., 1999; Luque and Juliá, 2002; Desprat et al., 2003; Pla and Catalan, 2005; Lebreiro et al., 2006; Burdloff et al., 2008; Martín-Chivelet et al., 2011; González-Álvarez, 2013). In addition, several extreme local climatic events, like strong flooding episodes, are documented (e.g., Marquina, 1949; Benito et al., 1996, 2008; Abrantes et al., 2011). These events have typically occurred at times of transition between climatic periods (e.g., AD 500-600, AD 1100-1200, AD 1450-1600). For example, alternating periods of intensive precipitation and thunderstorms with severe droughts were common during the 18th and 19th centuries as recorded in Portugal (e.g., Marques, 2001; Do Ó and Roxo, 2008; Pfister et al., 2010) and several localities from Southern and Northern Spain (e.g., Riera et al., 2004; Llasat et al., 2005; Vicente-Serrano and Cuadrat, 2007; Benito et al., 2008, 2010; Domínguez-Castro et al., 2008; Gil-Garcia et al., 2008; Martin-Puertas et al., 2008).

Solar activity cycles (maxima and minima) are based on Versteegh (2005), Usoskin et al. (2007), Scafetta (2012) and Steinhilber et al. (2012). Precipitation data were compiled from the monthly records of meteorological stations from the Minho region since 1930. The available data from the Portuguese sectors of Minho and Lima basins were merged in order to obtain the longest and the most representative record of the

area (<http://snirh.pt>). This series of precipitation data from 1932 to 2010 was used to compute the SPI (McKee et al., 1993; Moreira et al., 2012) with a freeware program (SPI_SL_6.exe) available at the National Drought Mitigation Center of the University of Nebraska-Lincoln (<http://drought.unl.edu>). The SPI allows the identification of drought events and classifies their severity according to defined drought classes. The wide use of this index comes from its reliability and relatively easy comparison between different locations and climates (<http://drought.unl.edu>). Moreira et al. (2012) determined the SPI from Porto (Serra do Pilar: 41° 08' 19.20" N – 08° 36' 09.68" W), ca. 80 km south of Caminha, based on the precipitation record from 1863 to 2007. Considering the good correlation ($R=0.85$) between SPI from Minho region and Porto, the latter was used as representative of severe and extreme droughts that occurred in NW Portugal. In this work, the SPI12 month period was used because it reflects long-term precipitation patterns and identifies dryer periods of long duration with impact in the hydrological regime (e.g. McKee et al., 1993; Moreira et al., 2012; <http://drought.unl.edu>). The identification of the severe and extreme drought periods between 2007 and 2010 in NW Portugal was completed with the on-line SPI data provided by the Instituto Português do Mar e da Atmosfera (<http://www.ipma.pt>).

Results

Based on foraminiferal assemblages (defined in terms of species presence, abundance, dominance and density – number of foraminifera per cm^3 ; Appendix B), the Caminha marsh core (FCPw1) can be divided into six different Foraminiferal Assemblage Zones (FAZ VI to I; Table 2). This division is also supported in sedimentological and geochemical data (Table 2, Appendix C).

[Table 2]

FAZ VI (100 cm to 46 cm depth) ranges from AD 140 to 1380, encompassing the RWP, DA cold period and the MCA. The foraminiferal assemblages are scarce (average 3 tests/cm³), often exhibiting poorly preserved tests and low diversity (average 3 species/sample). Assemblages are composed primarily by the upstream low salinity species *Trochammina salsa/irregularis* Cushman and Bronnimann, 1948, followed by *Cribr stomoides* spp. and *Haplopragmoides* spp. (Table 2). *Jadammina macrescens* is also present (7%) at AD 1070.

Sediment is essentially mud (average 97%) and the OM content ranges between 6-13%; the pH values are generally low, exhibiting an average of 4.8 (Table 2; Appendix C); the higher concentration of Zr is recorded in this FAZ (average 213 ppm; Appendix C). In this zone, some intervals barren of foraminifera tend to be related with higher silt/clay ratio (Appendix B and C), namely at AD 190, AD 800, AD 1140, 1270 and two in the interval AD 1310–1340.

FAZ V (46 cm to 29 cm depth) ranges from AD 1380 to AD 1690 and is included within the LIA period. This unit records a strong increase in the density of the assemblages (average 260 tests/cm³), but low species richness remains (average 5 species/sample). The low salinity species still dominate (82-95%), namely *T. salsa/irregularis* and *M. fusca*, with minor presence of *Haplopragmoides* spp., *Cribr stomoides* sp., *H. manilaensis* and *P. limnetis*. Salt marsh species *Tiphotrocha comprimata* (Cushman and Bronnimann, 1948), *Paratrochammina guaratibaensis* (Brönnimann, 1986), *Polysaccammina ipohalina* Scott, 1976, and *Siphotrochammina lobata* Saunders, 1957 join *J. macrescens*, and *T. inflata* (Table 2; Appendix B).

Concomitant with FAZ V, mud percentage decreases (average 91%) while OM content (12% to 24%) and pH values (average 6.1; Table 2) increase; the average concentration of Zr falls in this zone to 161 ppm, whereas Br exhibits an opposite trend rising from an average content of 148 ppm (FAZ VI) to 483 ppm (FAZ V; Appendix C).

The FAZ IV (29 cm to 20 cm depth) spans from AD 1690 to AD 1780 (LIA). Foraminifera in this unit are still abundant (average 244 tests/cm³). The assemblages have low diversity (average 6 species/sample) and they are still dominated by low salinity species (84-95%), *T. salsa/irregularis*, *H. manilaensis* and *M. fusca*, along with secondary species *Cribr stomoides* sp., *H. wilberti* and *P. limnetis* (Table 2). Salt marsh foraminifera, *T. comprimata*, *J. macrescens*, *T. inflata*, *P. guaratibaensis* and *P. ipohalina*, are also found. The increasing trend of OM towards the top of the core is significant, reaching 25-38% in this FAZ (Table 2). Likewise, the sediment texture continues the tendency of coarsening towards the top of the core (average mud percentage 86%), but the coarse fraction is mainly represented by plant debris. Br presents its highest content, with 1300 ppm (average 927 ppm), and the concentration of Zr continues falling in this FAZ (average 143 ppm; Appendix C).

FAZ III (20 cm to 10 cm depth) extends between AD 1780 and AD 1900 (LIA). Low foraminiferal diversity (8 species/sample) prevails and density exhibits a significant drop (average 79 tests/cm³). Low salinity species (*H. manilaensis*, *T. salsa/irregularis*, *M. fusca* and *Haplopragmoides* spp.) dominate (average 57%), but in this FAZ the “normal” salinity species (*J. macrescens*, *T. inflata* and *T. comprimata*) become a significant part of the assemblages (average 35%). Minor species are represented in this FAZ by *Cribr stomoides* spp., *H. wilberti*, *P. guaratibaensis*, *P. ipohalina* and *P. limnetis* (Table 2). The OM content remains high (average 33%) and the average mud content decreases to 79% (Table 2). Br stills exhibits high concentration (average 605 ppm).

FAZ II (10 cm to 4 cm depth) spans from AD 1900 to 1985 (PWP). Foraminiferal assemblages reach the highest number of species (9), but have similarly low diversity and exhibit a consistent density increase, with an average of 168 tests/cm³. Low salinity species represent 58% (average) of the assemblages and “normal” salinity species 37% (average; Table 2). This FAZ records the only interval (8-9 cm; AD 1934) where “normal” salinity species became dominant (59%), marked by the acme of *T. inflata*. Mud percentage and Zr sediment content present the same trend as in the previous FAZ III, while OM and Br content increase, the latter achieving the average of 919 ppm (Table 2; Appendix C).

FAZ I (4 cm to 0 cm depth), from AD 1985 to 2010, show that diversity of foraminiferal assemblages still low until present (maximum 11 species) but their density increases to an average of 253 tests/cm³ (Table 2). The lower faunal densities occur between AD 1995 (22 tests/cm³) and AD 2002 (99 tests/cm³). In this FAZ, the high marsh foraminiferal assemblages are dominated by the low salinity species *H. manilaensis*, *Haplophragmoides* spp., *M. fusca* and *T. salsa/irregularis*, representing 77% to 88% of the assemblage, with *Cribrostomoides* spp., *H. wilberti* and *P. limnetis* as minor representatives as well as the “normal” salinity marsh species *T. comprimata*, *J. macrescens*, *P. guaratibaensis*. *Trochammina inflata* is the most representative of this group (average 7%; Table 2), reaching the highest percentages at the uppermost sample (AD 2010), although its presence is significantly reduced from FAZ II to FAZ I. The coarsening upwards trend is clear in FAZ I (average 63% mud), as well as the increase of OM content (average of 53%), reflecting the observed increase of marsh plant debris. Zr and Br trends change, with the gradual decrease of Zr from the bottom to the top of the core (average 115 ppm) and the Br content increasing to an average of 1120 ppm (Appendix C).

355

356 **Discussion**

357 The sediment texture of core FCPw1 and the OM content (Table 2) indicate the
358 development of a tidal flat (FAZ VI) that lasted over 1200 years (AD 140–1380). During
359 this period, foraminiferal assemblages present low density, with a dominance of few low
360 salinity species (Fig. 3). However these originally scarce assemblages, like in the tidal
361 flats modern analogues (Fatela et al., 2009), are often poorly preserved, suggesting a
362 diagenetic alteration, probably related to the low values of sediment pH (Table 2) that
363 seem to reflect a strong fluvial influence. In fact, minimum pH values of 4.33 have been
364 recently measured in the Coura river waters (Moreno et al., 2005). Alternatively,
365 foraminifera are absent from this depositional setting probably due to low salinity. These
366 low abundances tend to be correlated with higher silt/clay ratio (Fig. 4). Silt/clay ratio
367 could be used as a proxy of hydrodynamic energy, where higher silt content could be
368 associated to periods of rainfall/flood intensification, mainly at AD 140-190, AD 320 and
369 AD 800, AD 1140, AD 1270 and AD 1310-1340. Desprat et al. (2003) identified the
370 development of temperate vegetation during Roman colonization in Galicia (RWP,
371 peaking at AD 150), suggesting that this period presented humid conditions. Moreover
372 the palaeotemperature records from speleothem materials located in the North of Spain
373 (Martín-Chivelet et al., 2011) show some marked negative anomalies for the late RWP
374 period, namely AD 90 and AD 250 (Fig. 3).

375 *[Fig. 3]*

376 *[Fig. 4]*

377 The combined effect of high precipitation and changes in land use (e.g., deforestation
378 and farming, associated with the mining exploitation, intensified soil erosion) carried out

by Romans in NW Iberia, and more specifically in the Minho river catchment area, led to a higher loading of terrestrial-derived sediments transported to the shelf by the rivers. A significant increase in river borne detrital material in sediments to the W Iberian shelf is broadly recognized during the RWP (e.g., Lebreiro et al., 2006: 50 BC; Bernardéz et al., 2008a, b: 50 BC – AD 250; Abrantes et al., 2005; Rodrigues et al., 2009; Mohamed et al., 2010: AD 0-550). Foraminiferal data suggests increased fluvial influence at AD 230-280 as indicated by low salinity species (*T. salsa/irregularis* and *M. fusca*) and the low density. This contrasts with a previous study devoted to the identification of OM sources by using lipid biomarkers analysis (de la Rosa et al., 2012) performed at the same location that pointed to an increase contribution of marine phytoplankton to the organic pool at that time. This disagreement can be explained by the complex processes that control salt marsh settings. For instance, while increase river flow might provide the ecological framework, more frequent or intense storms (recorded between AD 50-300; Behre, 2007) could deposit marine phytoplankton, leaving a geochemical signal but without modifying the brackish conditions. Overwash deposits found at AD 180-310 40 km south of the Minho estuary (Granja, 1999) supports this hypothesis.

The uppermost FAZ VI (AD 1080 to AD 1380) is coeval with the later part of the MCA and the transition to the LIA. The new climatic conditions are reflected in the core sediments in four episodes of very low abundance and poorly preserved foraminifera. The first occurrence at AD 1140 is coeval with a maximum in carbon isotopic composition ($\delta^{13}\text{C}$; De la Rosa et al., 2012; Appendix D) and organic carbon to total nitrogen ratio (Corg/N), indicating a major input from terrestrial plants at AD 1140-1160 (Appendix D). This is further supported by the, lipid content, average chain length of *n*-alkanes (ACL) and terrigenous/ aquatic ratio of *n*-alkanes (TAR) values that also suggest an increase in the continental discharges at that time, which is contemporary

with major river flood events reported for the same period in this area (De la Rosa et al., 2012). This event could be related with the Oört Solar Minimum (AD 1040-1080), if the date uncertainties are considered. The following episodes occurred at AD 1270, AD 1310 and AD 1340 (Fig. 3), might be related to the Wolf Solar Minimum (AD 1280–1350). Historical records of the 12th and 13th centuries confirm that the Atlantic Iberian region experienced severe winter floods in the years of AD 1102, 1168, 1178, 1181, 1201, 1203, 1207, 1258, 1264 and 1310 (Font Tullot, 1988; Benito et al., 2008).

Sediment cores from the shelf Douro Mud Patch allowed the recognition of abnormal precipitation events resulting in fluvial flooding recorded at AD 1100-1200, coeval with well-marked sea surface temperatures (SST) decreases, shifts in solar activity and more persistent NAO negative phases (Abrantes et al., 2011). Low salinity foraminiferal assemblages are only well preserved between AD 1190 and AD 1230, in a period that corresponds to the Medieval Solar Maximum (AD 1100-1250).

In summary, FAZ VI records a prevailing fluvial contribution, leading to a low salinity environment in spite of the proximity to the river mouth (ca. 3.5 km). If stronger marine input existed, namely at RWP and MCA, it did not last long enough in order to change the environmental conditions of the tidal flats in this sector of the estuary.

Above the tidal flat represented by FAZ VI, a tidal marsh develops (FAZ V) still under low salinity conditions from AD 1380 to 1690, where foraminiferal assemblages exhibit low diversity but significantly higher density. This suggests that sedimentation rates are large enough to gain elevation in relation to the tidal frame. Salt marsh species *T. comprimata* tend to increase towards the top of this section (36-29 cm depth) after AD 1610 (4-6%; Fig. 3), suggesting that the low marsh environment was already installed, growing from the lower IIB zone (between MtL and MHWN) to IIA zone (between MHWN and MHW) and marking the increase of the marsh palaeoelevation. This

important step in Caminha marsh evolution was accompanied by a significant increase in OM and Br content followed by the opposite trend in Zr concentration (Fig. 4; Appendix C). Positive correlations between Br and OM contents in soils and marine sediments were documented at least since the 1970s (e.g., Yamada, 1968; Price et al., 1970). More recent studies have shown that Br cycling in marine and terrestrial ecosystems is strongly influenced by OM (e.g., Leri et al., 2010; Leri and Myneni, 2012). According to these authors the relative ease of natural Br oxidation seems to promote its biogeochemical transformation from inorganic to organic forms, conducting to the incorporation into OM through enzymatic processes related to plant litter decay. Salt marshes are areas of high primary productivity and OM accumulation, thus presenting relatively high amounts of Br, supplied by seawater inundation, in both sediment and flora (Rhew et al, 2002). Considered together, the density of foraminiferal assemblages, the OM and Br data suggest the development of a vegetated low marsh. The up-core lowering of Zr content, observed from the base of FAZ V (Appendix C), provide another evidence of an energy drop caused by the development of vegetation on the marsh surface and consequent flat energy gradients. In fact, heavy minerals like zircon require strong hydrodynamic forces for mobilization and transport and serve as a geochemical proxy of depositional energy (e.g., Dellwig et al., 2000; Kolditz et al., 2012). The accumulation of plant debris and particulate OM, following development of the low marsh, directly contributes to the increase in sediment coarse particles, preventing the use of silt/clay ratio as a runoff proxy after AD 1380. Geochemical data also record the more depleted values of $\delta^{13}\text{C}$ accompanied by high $\text{C}_{\text{org}}/\text{N}$ ratios, suggesting a maximum of terrestrial contribution and lipid biomarkers ($\text{C}_{31}/\text{C}_{27\text{al}}$, CPI^{ole} and ACL_{al}) indicate that grass vegetation prevails (De la Rosa et al., 2012; Appendix D) during this FAZ.

After the former phase of uncovered tidal flats conditions, FAZ V marks an important step with the onset of a vegetated low marsh surface after AD 1380, despite the persistent high rainfall, fluvial runoff and intense floods recorded during the LIA (e.g., Benito, 2006; Benito et al., 2008; Bernárdez et al., 2008a; Burdloff et al., 2008; Abrantes et al., 2011; González-Álvarez, 2013; Appendix E). Halophytic plants buffer the energy in the system trapping sediment, which increases the marsh vertical elevation.

However, other factors such as deforestation, agriculture and mining play a significant role in sedimentation rates. These factors were exacerbated since the Roman times, which associated with low energetic conditions, lead to the siltation of tide-dominated estuaries (Poirier et al., 2011). This fill up of the Portuguese coastal systems has been reported in many other locations, namely in *Caminha* at AD 1541, 1575 and 1582 (Granja, 1990, 2007; Granja and Carvalho, 1992). For instance, in the Royal Courts of *Évora* (AD 1436), the ship-owners from *Viana do Castelo*, *Ponte de Lima* and *Vila do Conde*, stated that they were already silted, preventing the access of larger ships. In fact, the forests depletion in northern Portuguese hinterland attained a critical point that necessitated the import of timber from the North of Spain, France, England and Flanders, in order to supply the growing shipbuilding industry (Devy-Vareta, 1986). This was also a period of increased formation of transgressive dune fields. A generalized phase of intense aeolian activity is also distinguished along the Portuguese coast, marked by dune development and enhancement of westerly winds and storminess throughout the LIA, compatible with prolonged negative phases of the NAO (e.g., Clarke and Rendell, 2006; Clemmensen et al., 2009; Costas et al. 2012).

The transition between FAZ V and FAZ IV is marked by the species *T. comprimata* and *P. ipohalina* (AD 1690–1730) and *J. macrescens*, *H. wilberti*, *P. limnetis* and *T. inflata* at the top of FAZ IV (AD 1770). This distribution suggests a gradual evolution from low

marsh zone IIA to high marsh zone IB (between MHW and MHWS). It still portrays a markedly low salinity environment, but the presence (even in low percentage) of these salt marsh species suggests increasing salinity in the area, that might be related to sea-level changes.

The transition from low to high marsh occurs mostly during the Maunder Solar Minimum (AD 1645-1715). The grain size and OM content is still increasing in this FAZ, Br presents its highest content and foraminiferal density remains high, probably reflecting a denser marsh plant cover. During this period, there was a wet phase recorded in Galician continental vegetation (Schellekens et al., 2011), concomitant with the coldest phase of the LIA in Europe that peaked around AD 1700 (e.g., Luterbacher et al., 2001; Desprat et al., 2003; Lockwood et al., 2010; Lockwood, 2012).

FAZ III to I also correspond to a high marsh depositional environment, recording frequent increments of salt marsh species and low foraminiferal density episodes, under general conditions of low salinity. Such variability of assemblages is associated with the end of the LIA and beginning of the PWP, characterized by alternating wet and dry years, namely dryer winter conditions (e.g., Marques, 2001; Abrantes et al., 2011). This reduced river discharge lead to an increase in the marine influence inside the estuary. The beginning of meteorological instrumental record in the NW of Portugal in AD 1864 (FAZ III) allows a better interpretation of proxy data.

The high marsh (foraminiferal IB zone) recorded at FAZ III, is mostly represented by low salinity assemblages. The species associated with salt marshes are meaningful but with lower percents: *J. macrescens* (12-23%), *T. inflata* (3-22%) and *T. comprimata* (3-13%). The assemblages still have low diversity and density exhibits a significant drop for most of FAZ III (Table 2). The lower density levels, 59 tests/cm³ (AD 1780) and 34 tests/cm³ (AD 1820), tend to be associated with the Dalton Solar Minimum (AD 1790-1820)

transitions. Other low values are recorded throughout this event: 17 tests/cm³ (AD 1850) and 44 tests/cm³ (AD 1890). This disparate record between 17 and 205 test/cm³ suggests a biotic response to more stressful conditions, induced by alternating periods of intense rainfall/floods and droughts. In fact, it was a time of major river floods in northern Portugal, as recorded at Douro basin (e.g., Rodrigues et al., 2003; Araújo, 2005). The record of floods from the Atlantic Iberian rivers (south basins included) also suggests higher flood intensification during the periods AD 1730-1760, AD 1780-1810 and AD 1870-1900 (Marques, 2001; Rodrigues et al., 2003; Benito et al., 2008; Appendix E). This alternating climatic pattern switches the system from essentially fluvial controlled to more marine, with increasing salinity in the high marsh ecosystem as a result of higher evaporation rates and higher inputs of marine water into the estuary.

Alternations in the C/N and $\delta^{13}\text{C}$ values through the 18th and 19th centuries were consistent with fluctuations in the *n*-alkyl parameters. These proxies also document regular intensive rainfall alternating with severe droughts (De la Rosa et al., 2012). Events like storms, cold, persistent rains, wet and cool summers, and droughts, that caused wine harvest delays, crop loss and famines, high prices of cereals, and plagues are documented for the Minho region throughout the 18th century and the beginning of the 19th century, as well as religious services *pro-pluvia* and *pro-serenitate* (Marques, 2001). These historical records therefore corroborate the climatic pattern suggested by geochemical and foraminiferal proxies.

The lowest foraminifera density level recorded in FAZ II (68 tests/cm³) occurs at AD 1900, probably linked to the solar minimum of AD 1900-1920 (Scaffeta, 2012). Major flooding events of the NW Portuguese main rivers are recorded in the transition from the 19th to the 20th century, like in the Douro (e.g., Rodrigues et al., 2003; Araújo, 2005;

Appendix E) and Lima basins: the higher mark of the 20th century Lima river flood, from 1909, may be directly observed on the medieval tower wall of Ponte de Lima.

The analysis of the drought events, based on standardized precipitation index (SPI_12 month) for the series of Porto meteorological stations data (1922-2005), reveals that droughts begun in the mid 1930s, attaining their most significant expression (severe to extreme droughts: $SPI \leq -1.5$) in the 1940s and 1950s (1944/45, 1949, 1953/54 and 1957; Domingos, 2006). Moreira et al. (2012) noted the same severe and extreme droughts until 1956, followed by a period of decrease in drought episodes. Besides its severity, the Palmer Drought Severity Index (PDSI) notes that the duration of these droughts was the most striking of the instrumental record: 1933-1935, 26 months; 1943-1946, 36 months and 1953-1955, 25 months (Pires et al., 2010). The salt marsh species acme (AD 1934) may therefore be the corollary of these dryer conditions (Fig. 5), probably associated with the solar maximum of AD 1940-1950 (Scaffeta, 2012). After AD 1960, the foraminiferal assemblages gradually become dominated by low salinity species (>70%) until AD 1983, during the solar minimum AD 1960-1980. This transition points towards a higher fluvial influence in the lower estuary. In fact, the instrumental precipitation recorded in the Minho region (available since 1934; <http://snirh.pt>) shows persistent positive anomalies from 1955 to 1983 (Fatela et al., 2013) and the SPI_12 of Porto exhibits the lowest drought indices (Fig. 5). Besides the direct effect of this high precipitation, the river flow and seepage inputs are also enhanced over the high marsh zone, creating ecological conditions that lead to a major presence of low salinity species.

[Fig. 5]

The enhanced Br concentration shows a direct relation with OM contents throughout this FAZ (10-4 cm depth; AD 1900 to 1985) with higher values at 4-5 cm depth, AD

1983 (appendix C). The organic geochemical results obtained by De la Rosa et al. (2012) showed a decrease in the terrestrial OM component and an increase of plankton-derived lipid contribution at AD 1960-1985. This was interpreted as a possible enhancement of marine input probably associated with a reduction in the Minho River discharge due to the construction of many major dams or with diagenetic processes induced by the selective degradation of different minerals in sediments affecting, for instance, the Corg/N. While the presence of dams might reduce the relationship between precipitation and runoff, the good correlation between these two parameters (DeCastro et al., 2006; Gómez-Gesteira et al., 2011; Fatela et al., 2013) suggests that this is not the case here. Also, it should be noted that the intense dredging in the Minho lower estuary, mainly between 1960-1990 (Alves, 1996; Delgado, 2011), caused an intense remobilization of sediments. The process of sand extraction also included the wash of these materials leaving the mud fraction (OM included) inside the estuary during rising tides. These anthropic activities likely promoted remobilization, transport and redeposition of the mud fraction, contributing to the intensification of the geochemical marine signal in the tidal marshes. The foraminiferal assemblages highlight that rainfall increased the brackish ecological conditions at the high marsh, in spite of the enhanced marine geochemical records for this time.

Increase fluvial influence is also recorded in FAZ I by the OM proxies (De la Rosa et al., 2012). Foraminiferal assemblages are consistent with the present day high marsh zone IB. This assemblage reflects the modern hydroclimatic balance in the Minho lower estuary, where low salinity species prevail at higher high marsh zones (Fig. 3; Table 2), mostly under brackish/fresh estuarine water. The lowest values of foraminiferal density reflect the precipitation positive anomalies and the intensification of floods events (Fatela et al., 2013).

Brackish conditions have persisted in the Minho estuary at least since 140 AD. The intertidal sedimentary record, highlight two main steps - tidal flat and marsh - where the preservation of proxies information, namely benthic foraminifera, is quite distinct. The tidal flat assemblages are poorly preserved and often absent, in this environment where the hydrogeochemical pattern is marked by a general baseline depleted in calcium carbonate (Moreno et al., 2007; Valente et al., 2009). Even so, it is clear that the residual assemblages are predominantly composed by low salinity species. The sediment accretion leads to the marsh installation after AD 1380 and the development of a plant cover that reduces hydrodynamics energy, acts as a sediment trap and improves the assemblages' preservation. Marsh foraminiferal response firstly reflects the elevation change from tidal flat to high marsh and the hydrological balance inside the estuary.

The hydrological balance is closely connected to climate variability during the last millennia and its dependant on the fluctuations in solar activity (e.g., Shindell et al., 2001; Keller, 2004; Versteegh, 2005; Duhau, 2006; Wanner et al., 2008; Jager and Duhau, 2009; Lean, 2010; Mörner, 2010; Jager and Nieuwenhuijzen, 2013; Usoskin, 2013), which drives the position, migration and stability of atmospheric systems (e.g., Haigh, 2007) and oceanic circulation (e.g., Mörner, 2010). According to Shindell et al. (2001) and Martín-Puertas et al. (2012), the modelling of climate response to periods of low solar activity couple with low NAO index and led to a southward displacement of the westerlies. Therefore, as a response to reduced solar activity, European mid-latitudes experienced colder temperatures and increased humidity. The paleoclimatic records of the Iberian Peninsula continental shelf reveal increased river discharge during periods of NAO-negative (Álvarez et al., 2005; Lebreiro et al., 2006; Bernárdez et al., 2008b; Abrantes et al., 2011; González-Álvarez, 2013) and the instrumental data show good

correlations between negative phases of NAO index and winter precipitation and river flow in NW Iberia, namely in Minho river basin (e.g., Trigo et al., 2004; de Castro et al., 2006; Fatela et al., 2013). The hydrological balance recorded by the Caminha marsh foraminifera and sedimentological proxies is controlled by the atmospherical modes, reflecting the NE Atlantic climate dynamic, namely from LIA to present.

Conclusions

Foraminiferal assemblages reveal the palaeoenvironmental evolution of NW Portugal estuaries, primarily in the intertidal zone. The assemblages, associated with sedimentological and geochemical proxies, provided a detailed reconstruction for the last two millennia. Six Foraminiferal Assemblages Zones (FAZ) have been considered in this period. The tidal flat environment prevailed in the riverbanks of Minho low estuary until the end of the 14th century, when vertical accretion led to the colonization by halophyte plants and the development of a stable low marsh environment. The natural continuity of this process, probably enhanced by anthropogenic activities, resulted in the establishment of the high marsh zone, beginning at about the 18th century. Foraminiferal species and the density of their assemblages revealed to be a fundamental tool to the recognition of the estuarine hydrological balance. Namely between predominantly marine or fluvial conditions as result of wet or dry periods. Estuarine evolution mainly occurred under brackish conditions reflected by the dominance of low salinity species, where the flood events created a drop in the foraminiferal density. The drought periods are marked by an increase in the proportion of salt marsh species that dominated the assemblages during the most severe events recorded in the middle of 20th century. The stronger influence of marine or fluvial conditions inside the estuary over RWP, MCA, LIA and PWP appears closely connected to climate variability (in dependence upon the

fluctuations in solar activity), highlighting the contribution of marsh foraminifera from SW Europe to the understanding of NE Atlantic regional climate evolution.

Acknowledgements

This work is a contribution of the WestLog (PTDC/CTE/105370/2008) project, funded by the Fundação para a Ciência e Tecnologia – FCT, that includes the grants of João Moreno, Inês Pereira and Ana Medeiros. Jose de la Rosa’s participation was funded through the Ciência 2008 framework (FCT) at IST/CTN. It is also a contribution to the IGCP Project 588, Northwest Europe working group of the INQUA Commission on Coastal and Marine Processes and the Geo-Q Zentroa Research Unit (Joaquín Gómez de Llarena Laboratory), Sociedad de Ciencias Aranzadi.

We are grateful to Elsa Moreira (Centro de Matemática e Aplicações, Faculdade de Ciências e Tecnologia - UNL) who kindly provided SPI data series from Porto. We also thank Peter Langdon, Derek Booth and two anonymous reviewers for their comments that improved the final the manuscript.

References

Abrantes, F., Lebreiro, S., Rodrigues, T., Gil, I., Bartels-Jónsdóttir, H., Oliveira, P., Kissel, C., Grimalt, J.O., 2005. Shallow marine sediment cores record climate variability and earthquake activity off Lisbon (Portugal) for the last 2,000 years. *Quaternary Science Reviews* 24, 2477–94.

- 649 Abrantes, F., Rodrigues, T., Montanari, B., Santos, C., Witt, L., Lopes, C., Voelker,
650 A.H.L., 2011. Climate of the last millennium at the southern pole of the North
651 Atlantic Oscillation: an inner-shelf sediment record of flooding and upwelling.
652 *Climate Research* 48, 261–280.
- 653 Alday, M., Cearreta, A., Cachão, M., Freitas, M.C., Andrade, C., Gama, C., 2006.
654 Micropalaeontological record of Holocene estuarine and marine stages in the
655 Corgo do Porto rivulet (Mira River, SW Portugal). *Estuarine, Coastal and Shelf*
656 *Science* 66, 532-543.
- 657 Álvarez, M., Flores, J., Sierro, F., Diz, P., Francés, G., Pelejero, C., Grimalt, J., 2005.
658 Millennial surface water dynamics in the Ría de Vigo during the last 3000 years as
659 revealed by coccoliths and molecular biomarkers. *Palaeogeography,*
660 *Palaeoclimatology, Palaeoecology* 218, 1–13.
- 661 Appleby, P.G., Oldfield, F., 1992. Application of ^{210}Pb to sedimentation studies, In:
662 Ivanovich, M., Harmon, R.S. (Eds.), *Uranium Series Disequilibrium*. Oxford
663 University Press, Oxford, pp. 731–778.
- 664 Araújo, E.L.S., 2005. Geoturismo: Conceptualização, Implementação e Exemplo de
665 Aplicação ao Vale do Rio Douro no Sector Porto-Pinhão. Unpublished MSc thesis,
666 Universidade do Minho, Braga, 213 pp.
- 667 Araújo, M.F., Valério, P., Jouanneau, J-M., 1998. Heavy metal assessment in
668 sediments of the Ave river basin (Portugal) by EDXRF. *X-Ray Spectrometry* 27, 305-
669 312.

- 670 Araújo, M.F., Conceição, A., Barbosa, T., Lopes, M.T., Humanes, H., 2003. Elemental
671 Composition of marine sponges from the Berlengas natural park, western
672 Portuguese coast. *X-Ray Spectrometry* 32, 428-433.
- 673 Alves, A., 1996. Causas e Processos da Dinâmica Sedimentar na Evolução Actual do
674 Litoral do Alto Minho. Unpublished PhD thesis, Universidade do Minho, Braga,
675 Portugal. 442 pp.
- 676 Behre, K.-E., 2007 (January). A new Holocene sea-level curve for the southern North
677 Sea. *Boreas* 36, 82–102.
- 678 Benito, G., 2006. Paleofloods and historical flood records along the middle Tagus river
679 catchment: climatic and flood hazard implications, *Tagus Floods Abstracts*, p. 35.
- 680 Benito, G., Machado, M.J., Pérez-González, A., 1996. Climate change and flood
681 sensitivity in Spain. In: Branson, J., Brown, A.G., Gregory, K.J. (Eds.), *Global*
682 *Continental Changes: The Context of Palaeohydrology*. Geological Society Special
683 Publication 115, 95–98.
- 684 Benito, G., Thorndycraft V.R., Rico, M., Sánchez-Moya, Y., Sopeña, A., 2008.
685 Palaeoflood and floodplain records from Spain: Evidence for long-term climate
686 variability and environmental changes. *Geomorphology* 101, 68–77.
- 687 Benito G., Rico, M., Sánchez-Moya, Y., Sopeña, A., Thorndycraft, V.R., Barriendos, M.,
688 2010. The impact of late Holocene climatic variability and land use change on the
689 flood hydrology of the Guadalentín River, southeast Spain. *Global and Planetary*
690 *Change* 70, 53–63.

691 Bernárdez, P., González-Álvarez, R., Francés, G., Prego, R., Bárcena, M.A., Romero,
692 O.E., 2008a. Late Holocene history of the rainfall in the NW Iberian peninsula -
693 Evidence from a marine record. *Journal of Marine Systems* 72, 366–382.

694 Bernárdez, P., González-Álvarez, R., Francés, G., Prego, R., Bárcena, M.A., Romero,
695 O.E., 2008b. Palaeoproductivity changes and upwelling variability in the Galicia
696 Mud Patch during the last 5000 years: geochemical and microfloral evidence. *The*
697 *Holocene* 18, 1207–1218.

698 Bettencourt, A., Ramos, L., Gomes, V., Dias, J.M.A., Ferreira, G., Silva, M., Costa, L.,
699 2003. *Estuários Portugueses*. Ed. INAG – Ministério das Cidades, Ordenamento
700 do Território e Ambiente. Lisboa. 311 pp.

701 Bradley, R.S., Jones, P.D., 1993. ‘Little Ice Age’ summer temperature variations: their
702 nature and relevance to recent global warming trends. *The Holocene* 3, 367-376.

703 Brázdil, R., Pfister, C., Wanner, H., von Storch, H., Luterbacher, J., 2005. Historical
704 climatology in Europe – the state of the art. *Climatic Change* 70, 363.

705 Brown, J., Colling, A., Park, D., Philips, J., Rothery, D., Wright, J., 1991. *Waves, tides*
706 *and shallow-water processes*. The Open University. 187 pp.

707 Burdloff, D., Araújo, M.F., Jouanneau, J.-M., Mendes, I., Monge Soares, A.M., Dias,
708 J.M.A., 2008. Sources of organic carbon in the Portuguese continental shelf
709 sediments during the Holocene period. *Applied Geochemistry* 23, 2857-2870.

710 Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North
711 Atlantic Oscillation on sand invasion and coastal dune accretion in western
712 Portugal. *The Holocene* 16, 341-355.

- 713 Clemmensen, L.B., Murray, A., Heinemeier, J., de Jong, R., 2009. The evolution of
714 Holocene coastal dune fields, Jutland, Denmark: a record of climate change over
715 the past 5000 years. *Geomorphology* 105, 303–313.
- 716 Cook, E. R., Seager, R., Heim Jr. R. R., Vose, R. S., Herweijer, C., Woodhouse, C.,
717 2010. Megadroughts in North America: Placing IPCC projections of hydroclimatic
718 change in a long-term palaeoclimate context. *Journal Quaternary Science*. 25, 48–
719 61.
- 720 Costas, S., Jerez, S., Trigo, R.M., Goble, R., Rebêlo, L., 2012. Sand invasion along the
721 Portuguese coast forced by westerly shifts during cold climate events. *Quaternary*
722 *Science Reviews* 42, 15–28.
- 723 DeCastro, M., Lorenzo, M., Taboada, J.J., Sarmiento, M., Alvarez, I., Gómez-Giesteira,
724 M., 2006. Influence of teleconnection patterns of precipitation variability and on
725 river flow regimes in the Miño River basin (NW Iberian Peninsula). *Climate*
726 *Research* 32, 63-73.
- 727 De la Rosa, J.M., Araújo, M.F., González-Pérez, J.A., González-Vila, F.J., Soares,
728 A.M., Martins, J.M., Leorri, E., Corbett, R., Fatela, F., 2012. Organic matter
729 sources for tidal marsh sediment over the past two millennia in the Minho River
730 estuary (NW Iberian Peninsula). *Organic Geochemistry* 53, 16–24.
- 731 Dellwig, O, Hinrichs, J., Hild, A., Brumsack H.-J., 2000. Changing sedimentation in tidal
732 flat sediments of the southern North Sea from the Holocene to the present: a
733 geochemical approach. *Journal of Sea Research* 44, 195-208.

- 734 Debenay, J.-P., Guiral, D., Parra, M., 2002. Ecological factors acting on microfauna in
735 mangrove swamps. The case of foraminiferal assemblages in French Guiana.
736 Estuarine, Coastal and Shelf Science 55, 509–533.
- 737 Delgado, A., 2011. Caracterização hidrodinâmica e sedimentar do estuário do rio
738 Minho. Unpublished MSc thesis, Universidade do Porto, Portugal. 197 pp.
- 739 Desprat, S., Goñi, M.F.S., Loutre, M.-F., 2003. Revealing climatic variability of the last
740 three millennia in northwestern Iberia using pollen influx data. Earth and Planetary
741 Science Letters 213, 63–78.
- 742 Devy-Vareta, N., 1986. Para uma geografia histórica da floresta portuguesa. do declínio
743 das matas medievais à política florestal do renascimento (séc. xv e xvi). Revista
744 da Faculdade de Letras - Geografia. I Série, Vol. I, 5-37, Porto.
- 745 Domingos, S.I.S. (2006). Análise do índice de seca Standardized Precipitation Index
746 (SPI) em Portugal Continental e sua comparação com o Palmer Drought Severity
747 Index (PDSI). Unpublished Msc thesis, Universidade de Lisboa, Portugal, 53 pp.
- 748 Domínguez-Castro, F., Santisteban, J.I., Barriendos, M., Mediavilla, R., 2008.
749 Reconstruction of drought episodes for central Spain from rogation ceremonies
750 recorded at Toledo Cathedral from 1506 to 1900: A methodological approach,
751 Global Planetary Change 63, 230–242.
- 752 Do Ó, A., Roxo, M. J., 2008. Drought events in Southern Portugal from the 12th to the
753 19th centuries: integrated research from descriptive sources. Natural Hazards 47,
754 55–63.
- 755 Drago, T., Freitas, M.C., Rocha, F., Cachão, M., Moreno, J., Naughton, F., Fradique, C.,

- 756 Araújo, F., Silveira, T., Oliveira, A., Cascalho, J., Fatela, F., 2006.
 757 Paleoenvironmental evolution of estuarine systems during the last 14 000 years -
 758 the case of Douro estuary (NW Portugal). *Journal of Coastal Research*, SI 39,
 759 186-192.
- 760 Duhau, S., 2006. Solar activity, Earth's rotation rate and climate variations in the secular
 761 and semi-secular time scales. *Physics and Chemistry of the Earth* 31, 99–108.
- 762 Fatela, F., Taborda, R., 2002. Confidence limits of species proportions in microfossil
 763 assemblages. *Marine Micropaleontology* 45, 169–174.
- 764 Fatela, F., Moreno, J., Antunes, C., 2007. Salinity influence on foraminiferal tidal marsh
 765 assemblages of NW Portugal: an anthropogenic constraint? *Thalassas, An*
 766 *International Journal of Marine Sciences* 23, 51–63.
- 767 Fatela, F., Moreno, J., Moreno, F., Araújo, M. F., Valente, T., Antunes, C., Taborda, R.,
 768 Andrade, C., Drago, T., 2009. Environmental constraints of foraminiferal
 769 assemblages distribution across a brackish tidal marsh (Caminha, NW Portugal).
 770 *Marine Micropaleontology* 70, 70–88.
- 771 Fatela, F., Moreno, J., Leorri, E., Corbett, R., 2013. High marsh foraminiferal
 772 assemblages response to intra-decadal and multi-decadal precipitation variability,
 773 between 1934 and 2010 (Minho, NW Portugal). *Journal of Sea Research*,
 774 <http://dx.doi.org/10.1016/j.seares.2013.07.021>.
- 775 Font Tullot I., 1988. *Historia del clima de España*. Spanish Meteorological Institute
 776 (INM), Madrid. 297 pp.

- 777 Gehrels, W.R., 1994. Determining relative sea level change from salt marsh
778 foraminifera and plant zones on the coast of Maine, USA. *Journal of Coastal*
779 *Research* 10, 990–1009.
- 780 Gehrels, W.R., Newman, S.W.G., 2004. Salt-marsh foraminifera in Ho Bugt, western
781 Denmark, and their use as sea-level indicators. *Danish Journal of Geography* 104,
782 49–58.
- 783 Gil-Garcia, M.J., Ruiz Zapata, M.B., Mediavilla, R., Santisteban, J.I., Dominguez-Castro,
784 F., Dabrio, C.J., 2008. Registro de los cambios humanos y naturales en el
785 humedal de las Tablas de Daimiel (Ciudad Real, España). *Geo-Temas* 10, 1471–
786 1474.
- 787 Gómez-Gesteira, M., Gimeno, L., de Castro, M., Lorenzo, M.N., 2011. The state of
788 climate in NW Iberia. *Climate Research* 48, 109–144.
- 789 González-Álvarez, R., 2013. Cambios climáticos de pequeña magnitud durante el
790 Holoceno: sus efectos en la paleoceanografía de la plataforma continental
791 gallega. Unpublished PhD thesis, Universidade de Vigo, España, 306 pp.
- 792 Graham, N., Ammann, C. M., Fleitmann, Cobb, K. M., Luterbacher, J., 2011. Support for
793 global climate reorganization during the “medieval climate anomaly.” *Climate*
794 *Dynamic*. 37, 1217–1245, doi:10.1007/s00382-010-0914-z.
- 795 Granja, H.M., 1990. Representar a geodinâmica da zona costeira: o passado e o
796 presente; que futuro? Unpublished PhD Thesis, Universidade do Minho, Braga,
797 Portugal. 347 pp.
- 798 Granja, H.M., Carvalho, G.S., 1992. Dunes and Holocene deposits of the coastal zone
799 of Portugal, north Mondego Cape. In: Carter, R.W.G., Curtis, T.G.F., Sheehy-

- 800 Skeffington, M.J. (Eds.), Coastal Dunes: geomorphology, ecology and
801 management for conservation. Proceedings of the Third European Dune
802 Congress, Galway, Ireland, pp. 43–50.
- 803 Granja, H.M., 1999. Evidence for Late Pleistocene and Holocene sea-level, neo-
804 tectonic and climatic control in the coastal zone of northwest Portugal. *Geologie en*
805 *Mijnbouw* 77, 233–245.
- 806 Granja, H.M., 2007. Multidisciplinary Analysis of Historical Sources - The
807 Geomorphological Approach. *European Seaport Systems in the early modern age.*
808 *A comparative approach. International Workshop Proceedings. Porto, IHM-UP,*
809 *70–78.*
- 810 Haigh, J.D., 2007. The sun and the earth's climate. *Living Review Solar Physics* 4, 1-64.
811 URL (accessed 03.12.13): <http://www.livingreviews.org/lrsp-2007-2>.
- 812 Haslett, J., Parnell, A., 2008. A simple monotone process with application to
813 radiocarbon-dated depth chronologies. *Applied Statistics*, 57, 399-418.
- 814 Hayward, B.W., Grenfell, H.R., Reid, C., M., Hayward, K.A., 1999. Recent New Zealand
815 shallow-water benthic foraminifera: taxonomy, ecologic distribution, biogeography,
816 and use in paleoenvironmental assessment. *Institute of Geological & Nuclear*
817 *Sciences, monograph 21. Lower Hutt, New Zealand. 264 pp.*
- 818 Head, K., 1980. *Manual of soil laboratory testing*. Volume 1: Soil classification and
819 compaction tests. Pentech Press, London. 339 pp.
- 820 Hippensteel, S.P., Martin, R.E., Harris, M-S., 2005. Records of prehistoric hurricanes on
821 the South Carolina coast based on micropaleontological and sedimentological

822 evidence, with comparison to other Atlantic Coast records: Discussion. Geological
823 Society of America Bulletin 117, 250-253.

824 Horton, B.P., 1999. The distribution of contemporary intertidal foraminifera at Cowpen
825 Marsh, Tees Estuary, UK: implications for studies of Holocene sea-level changes.
826 Palaeogeography, Palaeoclimatology, Palaeoecology 149, 127–149.

827 Horton, B.P., Edwards, R.J., 2005. The application of local and regional transfer
828 functions to the reconstruction of Holocene sea levels, north Norfolk, England. The
829 Holocene 15, 216–228.

830 Horton, B.P., Murray, J. W., 2006. Patterns in cumulative increase in live and dead
831 species from foraminiferal time series of Cowpen Marsh, Tees Estuary, UK:
832 Implications for sea-level studies. Marine Micropaleontology 58, 287-315.

833 Horton, B.P., Culver, S. J., 2008. Modern Intertidal Foraminifera of the Outer Banks,
834 North Carolina, U.S.A. and their Applicability for Sea-Level Studies. Journal of
835 Coastal Research 24, 1110-1125.

836 Jager, C., Duhau, S., 2009. Episodes of relative global warming. Journal of Atmospheric
837 and Solar-Terrestrial Physics 71, 194–198.

838 Jager, C., Nieuwenhuijzen, H., 2013. Terrestrial ground temperature variations in
839 relation to solar magnetic variability, including the present Schwabe cycle. Natural
840 Science 5, 1112-1120.

841 Keigwin, L.D., Pickart, R.S., 1999. Slope water current over the Laurentian Fan on
842 interannual to millennial time scales. Science 286, 520–23.

- 843 Keller, C., 2004. 1000 Years of climate change. *Advances in Space Research* 34, 315–
844 322.
- 845 Kolditz, K., Dellwig, O., Barkowski, J., Bahlo, R., Leipe, T., Freund H., Rgen Brumsack,
846 H.-J., 2012. Geochemistry of Holocene salt marsh and tidal flat sediments on a
847 barrier island in the southern North Sea (Langeoog, North-west Germany).
848 *Sedimentology* 59, 337–355.
- 849 Lamb, H.H., 1985. *Climate history and the future*. Princeton University Press, 835 pp.
- 850 Llasat, M.-C., Barriendos M., Barrera, A., Rigo T., 2005. Floods in Catalonia (NE Spain)
851 since the 14th century. Climatological and meteorological aspects from historical
852 documentary sources and old instrumental records. *Journal of Hydrology* 313, 32–
853 47.
- 854 Lebreiro, S.M., Frances, G., Abrantes, F., Diz, P., Bartels-Jónsdóttir, H.B., Stroynowski,
855 Z.N., Gil, I.M., Pena, L.D., Rodrigues, T., Jones, P.D., Nombela, M.A., Alejo, I.,
856 Briffa, K.R., Harris, I., Grimalt, J.O., 2006. Climate change and coastal
857 hydrographic response along the Atlantic Iberian margin (Tagus Prodelta and
858 Muros Ría) during the last two millennia. *The Holocene* 16, 1003–1015.
- 859 Leorri, E., Horton, B.P., Cearreta, A., 2008. Development of a foraminifera-based transfer
860 function in the Basque marshes. *Marine Geology* 251, 60-74.
- 861 Leorri, E., Cearreta, A., 2009a. Quantitative assessment of the salinity gradient within the
862 estuarine systems in the southern Bay of Biscay using benthic foraminifera.
863 *Continental Shelf Research* 29, 1226-1239.

- 864 Leorri, E., Cearreta, A., 2009b. Recent sea-level changes in the southern Bay of Biscay:
865 transfer function reconstructions from salt-marshes compared with instrumental data.
866 *Scientia Marina* 73, 287-296.
- 867 Leorri, E., Gehrels, W.R., Horton, B.P., Fatela, F., Cearreta, A., 2010a. Distribution of
868 foraminifera in salt marshes along the Atlantic coast of SW Europe: Tools to
869 reconstruct past sea-level variations. *Quaternary International* 221, 104–115.
- 870 Leorri, E., Cearreta, A., Corbett, R., Blake, W., Fatela, F., Gehrels, R., Irabien, M.J.,
871 2010b. Identification of suitable areas for high-resolution sea-level studies in SW
872 Europe using commonly applied ^{210}Pb models. *Geogaceta* 48, 35–38.
- 873 Leorri, E., Fatela, F., Cearreta, A., Moreno, J., Antunes, C., Drago, T., 2011. Assessing the
874 performance of a foraminifera-based transfer function to estimate sea-level changes
875 in northern Portugal. *Quaternary Research* 75, 278–287.
- 876 Leorri, E., Drago, T., Fatela, F., Bradley, S., Moreno J., Cearreta, A., 2013. Late Glacial
877 and Holocene coastal evolution in the Minho estuary (N. Portugal): implications for
878 understanding sea-level changes in Atlantic Iberia. *The Holocene* 23, 352-362.
- 879 Leri, A.C., Myneni, S.C.B., 2012. Natural organobromine in terrestrial ecosystems.
880 *Geochimica et Cosmochimica Acta* 77, 1-10.
- 881 Leri, A.C., Hakala, A., Marcus, M.A., Lanzirotti, A., Reddy, C.M., Myneni, S.C.D., 2010.
882 Natural organobromine in marine sediments: New evidence of biogeochemical Br
883 cycling. *Global Biogeochemical Cycles* 24, GB4017: 1-15.
- 884 Loeblich, A.R. Jr., Tappan, H., 1988. *Foraminiferal Genera and their Classification* Van
885 Nostrand Reinhold Company, v. 1, 970 p., v. 2, 847 pl.

- 886 Luque, J.A., Juliá, R., 2002. Lake sediment response to land-use and climate change
887 during the last 1000 years in the oligotrophic Lake Sanabria (northwest of Iberian
888 Peninsula). *Sedimentary Geology* 148, 343–355.
- 889 Luterbacher, J., Rickli, R., Xoplaki, E., Tinguely, C., Beck, C., Pfister, C., Wanner, H.,
890 2001. The Late Maunder Minimum (1675–1715) – A Key period for studying
891 decadal scale climatic change in Europe. *Climatic Change* 49, 441–462.
- 892 Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D.,
893 Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins
894 of the little ice age and medieval climate anomaly. *Science* 326, 1256–1260.
- 895 Marques, J., 2001. Estados do Tempo e Outros Fenómenos na Região de Braga, no
896 Século XVIII", In: *Bracara Augusta*. Vol. L, n. 2 104-105 (117–118).
- 897 Marquina, J.R., 1949. Crecidas Extraordinarias del Rio Duero. *Revista de Obras*
898 Públicas. Tomo I, n. 3, 202–213.
- 899 Martín-Chivelet, J., Muñoz-García, M.B., Edwards, R.L., Turrero, M.J., Ortega, A.I.,
900 2011. Land surface temperature changes in Northern Iberia since 4000 yr BP,
901 based on $\delta^{13}\text{C}$ of speleothems. *Global and Planetary Change* 77, 1–12.
- 902 Martínez Cortizas, A., Pontevedra-Pombal, X., Garcia-Rodeja, E., Novoa-Muñoz, J.C.,
903 Shotyk, W., 1999. Mercury in a Spanish peat bog: Archive of climate change and
904 atmospheric metal deposition. *Science* 284, 939–942.
- 905 Martín-Puertas, C., Valero-Garcés, B.L., Mata, M.P., Gonzalez-Samperiz, P., Bao, R.,
906 Moreno, A., Stefanova, V., 2008. Arid and humid phases in Southern Spain during
907 the last 4000 years: the Zonar Lake record, Cordoba. *The Holocene* 18, 1–15.

- 908 Martín-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C.,
909 Aldahan, A., Possnert, G., van Geel, B., 2012. Regional atmospheric circulation
910 shifts induced by a grand solar minimum. *Nature Geoscience* 5, 397–401.
- 911 McKee, T. B., Doesken, N. J., Kleist, J., 1993. The relationship of drought frequency and
912 duration to time scales, in: 8th Conference on Applied Climatology, American
913 Meteorological Society, Boston, 179–184.
- 914 Mohamed, K.J., Rey, D., Rubio, B., Vilas, F., Frederichs, T., 2010. Interplay between
915 detrital and diagenetic processes since the last glacial maximum on the northwest
916 Iberian continental shelf. *Quaternary Research* 73, 507–520.
- 917 Moreira, E. E., Mexia, J. T., Pereira, L. S., 2012. Are drought occurrence and severity
918 aggravating? A study on SPI drought class transitions using log-linear models and
919 ANOVA-like inference. *Hydrological Earth System Sciences* 16, 3011–3028.
- 920 Moreno, F., Araújo, M.F., Moreno, J., Fatela, F., Drago, T., 2005a. Caracterização
921 geoquímica de sedimentos superficiais do estuário do rio Minho e do sapal de
922 Caminha (NW de Portugal) – estimativa do potencial de stress biológico. XIV
923 Semana de Geoquímica & VIII Congreso de Geoquímica dos Países de Língua
924 Portuguesa. Universidade de Aveiro, Portugal, pp. 675–678.
- 925 Moreno, F., Moreno, J., Fatela, F., Valente, T., Guise, L., Araújo, M.F., Drago, T.,
926 2005b. Geoquímica de sedimentos em ambientes típicos de sapal – o exemplo do
927 sapal de Caminha (NW de Portugal). XIV Semana de Geoquímica & VIII
928 Congreso de Geoquímica dos Países de Língua Portuguesa. Univ. Aveiro,
929 Portugal, pp. 661–664.

- 930 Moreno, J., Fatela, F., Andrade, C., Cascalho, J., Moreno, F., Drago, T., 2005c. Living
931 Foraminiferal assemblages from Minho/Coura estuary (Northern Portugal): a
932 stressfull environment. *Thalassas* 21, 17–28.
- 933 Moreno, J., Fatela, F., Andrade, C., Drago, T., 2006. Distribution of “living”
934 *Pseudothurammina limnetis* (Scott and Mediolli): an occurrence on the brackish
935 tidal marsh of Minho/Coura estuary – Northern Portugal. *Révue de*
936 *Micropaléontologie* 49, 45–53.
- 937 Moreno, J., Valente, T., Moreno, F., Fatela, F., Guise, L., Patinha, C., 2007. Calcareous
938 Foraminifera occurrence and calcite-carbonate equilibrium conditions — a case
939 study in Minho/Coura estuary (N Portugal). *Hydrobiologia* 597, 177–184.
- 940 Mörner, N-X., 2010. Solar Minima, Earth's rotation and Little Ice Ages in the past and in
941 the future. The North Atlantic–European case. *Global and Planetary Change* 72,
942 282–293.
- 943 Murray, J.W., 1971. *An Atlas of British Recent Foraminiferids*. Heinemann Educational
944 Books, 244 pp.
- 945 Murray, J.W., 2006. *Ecology and Applications of Benthic Foraminifera*. Cambridge
946 University Press, Cambridge, 438 pp.
- 947 Nittrouer, C.A., Sternberg, R.W., Carpenter, R., Bennett, J.T., 1979. The use of ^{210}Pb
948 geochronology as a sedimentological tool: application to the Washington
949 Continental Shelf. *Marine Geology* 31, 297–316.
- 950 Parnell, A., Haslett, J., Allen, J., Buck, C., Huntley, B., 2008. A flexible approach to
951 assessing synchronicity of past events using Bayesian reconstructions of
952 sedimentation history. *Quaternary Science Reviews*, 27, 1872–1885.

- 953 Pfister, C., Garnier, E., Alcoforado, M.-J., Wheeler D., Luterbacher, J., Nunes, M.F.,
954 Taborda, J.P., 2010. The meteorological framework and the cultural memory of
955 three severe winter-storms in early eighteenth-century Europe. *Climatic Change*
956 101, 281–310.
- 957 Phleger, F.B., 1965. Patterns of marsh foraminifera, Galveston Bay, Texas. *Limnology*
958 and *Oceanography* 10, 169–180.
- 959 Pires, V.C., Álvaro, S., Mendes, L., 2010. Riscos de secas em Portugal continental.
960 *Territorium* 17, 27-34.
- 961 Pla, S., Catalan, J., 2005. Chrysophyte cysts from lake sediments reveal the
962 submillennial winter/spring climate variability in the northwestern Mediterranean
963 region throughout the Holocene. *Climate Dynamics* 24, 263–278.
- 964 Poirier, C., Chaumillon, E., Arnaud, F., 2011. Siltation of river-influenced coastal
965 environments: Respective impact of late Holocene land use and high-frequency
966 climate changes. *Marine Geology* 290, 51–62.
- 967 Price, N.B., Calvert S.E., Jones, P.G.W., 1970. Distribution of iodine and bromine in
968 sediments of the south western Barents Sea. *Journal of Marine Research* 28, 22-
969 34.
- 970 Rhew, R.C., Miller, B.R., Bill, M., Goldstein A.H., Weiss R.F., 2002. Environmental and
971 biological controls on methyl halide emissions from southern California coastal salt
972 marshes. *Biogeochemistry* 60, 141-161.
- 973 Riera, S., Wansard, G., Juliá, R., 2004. 2000-year environmental history of a karstic
974 lake in the Mediterranean Pre-Pyrenees: the Estanya lakes (Spain). *Catena* 55,
975 293–324.

- 976 Rodrigues, R., Brandão C., Costa, J., 2003. As cheias no Douro, ontem, hoje e
977 amanhã. Ed. Ministério das Cidades, Ordenamento do território e Ambiente,
978 Instituto da Água, Lisboa, 29 pp.
- 979 Rodrigues, T., Grimalt, J.O., Abrantes, F.G., Flores, J.A., Lebreiro, S.M., 2009.
980 Holocene interdependences of changes in sea surface temperature, productivity,
981 and fluvial inputs in the Iberian continental shelf (Tagus mud patch), *Geochemistry*
982 *Geophysics Geosystems* 10, 1-17.
- 983 Scaffeta, N., 2012. Multi-scale harmonic model for solar and climate cyclical variation
984 throughout the Holocene based on Jupiter–Saturn tidal frequencies plus the 11-
985 year solar dynamo cycle. *Journal of Atmospheric and Solar - Terrestrial Physics*
986 80, 296–311.
- 987 Schellekens, J., Buurman, P., Fraga, I., Martínez-Cortizas, A., 2011. Holocene
988 vegetation and hydrologic changes inferred from molecular vegetation markers in
989 peat, Penido Vello (Galicia, Spain). *Palaeogeography, Palaeoclimatology,*
990 *Palaeoecology* 299, 56–69.
- 991 Scott, D.B., Medioli, F.S., 1978. Vertical zonations of marsh foraminifera as accurate
992 indicators of former sea-levels. *Nature* 272, 528–531.
- 993 Scott, D.B., Medioli, F.S., 1980. Quantitative studies of marsh foraminiferal distributions
994 in Nova Scotia: implications for sea level studies. *Special Publication - Cushman*
995 *Foundation for Foraminiferal Research* 17, 58 pp.
- 996 Scott, D.B., Medioli, F.S., Schafer, C.T., 2001. *Monitoring in Coastal Environments*
997 *Using Foraminifera and Thecamoebian Indicators.* Cambridge University Press,
998 USA. 177 pp.

999 Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., Waple, A., 2001. Solar forcing of
1000 regional climate change during the Maunder Minimum. *Science* 294, 2149–2152.

1001 Smith, J.N., 2001. Why should we believe ^{210}Pb sediment geochronologies? *Journal of*
1002 *Environmental Radioactivity* 55, 121–123.

1003 Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U.,
1004 Kubik, P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H.,
1005 Wilhelms, F., 2012. 9,400 years of cosmic radiation and solar activity from ice
1006 cores and tree rings. *PNAS* 109, 5967–5971.

1007 Stine, S., 1994. Extreme and persistent drought in California and Patagonia during
1008 Medieval Time. *Nature* 369, 546–549.

1009 Taborda, R., Dias, J.M.A., 1991. Análise da sobre-elevação do nível do mar de origem
1010 meteorológica durante os temporais de 1978 e 1981. *Geonovas*, SI 1, 89–97.

1011 Trigo R.M., Pozo-Vázquez D., Osborn T.J., Castro-Díez Y., Gámis-Fortis S., Esteban-
1012 Parra M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow
1013 and water resources in the Iberian Peninsula. *Int. J. Climatol.* 24, 925–944.

1014 Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., Frank, D. C., 2009.
1015 Persistent positive North Atlantic Oscillation mode dominated the medieval climate
1016 anomaly. *Science*, 324, 78–80.

1017 Usoskin, I.G., Solanki, S.K., Kovaltsov, G.A., 2007. Grand minima and maxima of solar
1018 activity: new observational constraints. *Astronomy & Astrophysics* 471, 301–309.

1019 Usoskin, I., 2013. A History of Solar Activity over Millennia. Living Rev. Solar Phys. 10,
 1020 1-94. URL (accessed 25th November, 2013): [http://www.livingreviews.org/lrsp-](http://www.livingreviews.org/lrsp-2013-1)
 1021 [2013-1](http://www.livingreviews.org/lrsp-2013-1).

 1022 Valente, T., Fatela F., Moreno, J., Moreno, F., Guise; L., Patinha, C., 2009. A
 1023 comparative study of the influence of geochemical parameters on the distribution
 1024 of foraminiferal assemblages in two distinctive tidal marshes. Journal of Coastal
 1025 Research, SI 56, 1439-1443.

 1026 Versteegh, G.J.M., 2005. Solar forcing of climate. 2: evidence from the past. Space
 1027 Science Reviews 120, 243–286.

 1028 Vicente-Serrano, S.M., Cuadrat, J.M., 2007. North Atlantic oscillation control of droughts
 1029 in north-east Spain: evaluation since 1600 A.D. Climatic Change 85, 357–379.

 1030 Vis, G.-J., Bohncke, S.J.P., Schneider, H., Kasse, C., Coenraads-Nederveen, S.,
 1031 Zuurbier, K., Rozema, J., 2010. Holocene flooding history of the lower Tagus
 1032 valley (Portugal). Journal of Quaternary Science 25, 1222 e1238.

 1033 Wanner, H., Beer, J., Bütikofer, J., Crowley, T., Cubasch, U., Flückiger, J., Goosse, H.,
 1034 Grosjean, M., Joos, F., Kaplan, J., Küttel, M., Müller, S., Prentice, I., Solomina, O.,
 1035 Stocker, T., Tarasov, P., Wagner, M., Widmann, M., 2008. Mid- to Late Holocene
 1036 climate change: an overview. Quaternary Science Reviews 27, 1791-1828.

 1037 Yamada, Y., 1968. Occurrence of bromine in plants and soil. Talanta 15, 1135-1141.
 1038 <http://snirh.pt> (18th June 2012)
 1039 <http://drought.unl.edu> (22th May 2013)

1040 <http://www.ipma.pt/pt/oclima/observatorio.secas/spi/apresentacao/evolu.historica/> (5th
1041 June 2013)

1042 [ftp://ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/steinhilber2012.t](ftp://ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/steinhilber2012.txt)
1043 [xt](#) (25th November 2013)

1044 [Appendix A]

1045 [Appendix B]

1046 [Appendix C]

1047 [Appendix D]

1048 [Appendix E]

1049 [Appendix F]

1050

1051

1052

1053

1054

LIST OF FIGURES

1055 Fig. 1. Location of core FCPw1 in the Caminha tidal marsh (Minho estuary, NW
1056 Portugal.

1057 Fig. 2. Age model for the core FCPw1 and estimated 2σ errors, based on six AMS- ^{14}C
1058 dates, performed on total organic sediment, and ^{210}Pb chronology. The data
1059 interpolation was obtained with Bchron 3.2 software. The lowermost 10 cm have been
1060 extrapolated from the Bchron calculation between 81 and 91 cm depth by linear
1061 regression.

1062 Fig. 3. Percentage distribution of benthic foraminifera in core FCPw1. **Age (yr AD)** –
1063 age in calendar years AD; **Salt marsh spp.** - Distributions of the group of brackish salt
1064 marsh benthic species; **Low Sal. spp.** - Distributions of the group of low salinity benthic
1065 species; **NF** - Number of foraminifera per cm^3 ; **FAZ** - Foraminiferal assemblages zones;
1066 **Litos in** - Periods of continental lithogenic inputs to the shelf (see references in the text
1067 and appendix E); **Clime Pe.** - Climate periods in the last 2 millennia (see references in
1068 the text); **Solar Irr. Anomaly** – Solar irradiance anomaly using a 22 years running
1069 average reconstruction (after Steinhilber et al., 2012); **Solar Ev.** - Solar events (see
1070 references in the text); **T anomal.** - Temperature anomaly using a 10 years running
1071 average reconstruction (after Martín-Chivelet et al., 2011).

1072 Fig. 4. Sedimentological, geochemical and summary of benthic foraminifera data in core
1073 FCPw 1. **Age (yr AD)** - age in calendar years AD; **Salt marsh spp.** – Percentage
1074 distributions of the group of brackish salt marsh benthic species; **Low Sal. spp.** –
1075 Percentage distributions of the group of low salinity benthic species; **NF** - Number of

foraminifera per cm³; **FAZ** - Foraminiferal assemblages zones; **Litos in** - Periods of continental litogenic inputs to the shelf (see references in the text and appendix E); **Clime Pe.** - Climate periods in the last 2 milenia (see references in the text); **Solar Irr. Anomaly** – Solar irradiance anomaly using a 22 years running average reconstruction (after Steinhilber et al., 2012); **Solar Ev.** - Solar events (see references in the text); **T anomal.** - Temperature anomaly using a 10 years running average reconstruction (after Martín-Chivelet et al., 2011).

Fig. 5. Relationship between foraminiferal data and Standardized Precipitation Index (12 months: SPI_12), after Moreira et al., (2012), from Porto (Serra do Pilar: 41° 08' 19.20" N – 08° 36' 09.68" W). A - number of foraminifera per cm³ and dating bar error of sediment samples; B - percentage of "normal" (stars) and "low" salinity (open squares) species; C – number of severe and extreme droughts (gray bars) calculated with the SPI_12, grouped in intervals of ca. 30 years, from 1864 to 1894, 1895 to 1922, 1923 to 1953 and 1982 to 2010; D – SPI_12 time series, from hydrological year 1863/64 to 2007/08), gray column represent the field of severe and extreme droughts (SPI ≤ -1.5).

LIST OF TABLES

Table 1. Radiocarbon ages data determined in the Laboratory "Beta Analytic Inc.". (AMS - Standard delivery).

Table 2. Summary of micropaleontological and sedimentological data. The values represents the average (bold) and the range; Low Sal. spp % - low

1098 salinity species group; Salt marsh spp % - "normal" salinity species group; NF -
1099 number of foraminifera; S - number of species.

1100

1101

1102

1103 LIST OF APPENDICES

1104 Appendix A. ^{210}Pb Excess and ^{137}Cs content (Bq kg^{-1}) in the FCPw 1 core -
1105 Caminha tidal marsh.

1106 Appendix B. Foraminiferal data (%) from core FCPw1 - Caminha tidal marsh.

1107 Appendix C. Sedimentological and geochemical data from core FCPw1 -
1108 Caminha tidal marsh.

1109 Appendix D. Data from organic geochemistry proxy core FCPw1 (After De la
1110 Rosa et al., 2012) - Caminha tidal marsh.

1111 Appendix E. Chronology of main floods and palaeofloods from the Iberian
1112 Atlantic and NW Portuguese regions.

1113 Appendix F. Foraminifera faunal list from core FCPw1 - Caminha tidal marsh.

Table I

Sample	Depth (cm)	$\delta^{13}\text{C} \text{ ‰}$	Conventional radiocarbon age	$\Delta^{14}\text{C} \text{ ‰}$	Calibrated years AD (2 Sigma range)
CM 41	40-41	-26.7	380 $\pm$ 30 BP	-46.20 $\pm$ 3.6	1490 to 1666
CM 45	44-45	-26.8	650 $\pm$ 35 BP	-84.57 $\pm$ 3.9	1330 to 1453
CM 64	63-64	-25.9	1010 $\pm$ 50 BP	-122.49 $\pm$ 1.9	1032 to 1197
CM 67	66-67	-25.9	1030 $\pm$ 34 BP	-124.97 $\pm$ 1.9	934 to 1082
CM 82	81-82	-25.8	1570 $\pm$ 40 BP	-181.66 $\pm$ 1.9	463 to 650
CM 91	90-91	-27.2	1760 $\pm$ 30 BP	-196.80 $\pm$ 3.0	215 to 429

^{210}Pb CRS chronology supported by ^{137}Cs and total Pb concentrations of Caminha high marsh sediment core (FCPw 1) are available in Appendix A.

Table II

FAZ	Depth cm	Age CalAD	Benthic Foraminifera %	Low Sal. spp. %	Salt marsh spp. %	NF/cm3	S	pH	OM %	mud %
I	0 - 4	2010 1985	H. manilaensis (49; 40-56); Haplophragmoides spp. (23; 2-65), M. fusca (12; 2-20) and T. salsa/irregularis (9; 7-11), Cribrostomoides spp. (5; 2-10), T. inflata (7; 2-13); H. wilberti , P. limnetis , T. comprimata , J. macrescens and P. guaratibaensis ≤5	84 77-88	12 8-21	253 22-498	9 7-11	5.1 4.6-5.4	53 46-65	63 50-69
II	4 - 10	1985 1900	H. manilaensis , (35; 16-63), T. salsa/irregularis (11; 4-15), M. fusca (6; 5-6), associated with T. inflata (12; 3-41), J. macrescens (11; 3-14), T. comprimata (4; 1-8) H. wilberti (8; 4-13); P. guaratibaensis , S. lobata and P. limnetis ≤5	58 36-78	37 14-59	168 68-252	9 7-10	5.4 5.1-5.7	38 36-40	74 51-88
III	10 - 20	1900 1780	H. manilaensis (32; 21-51), T. salsa/irregularis (19; 10-32), M. fusca (4; 1-8), Haplopragmoides spp. (46); J. macrescens (17; 12-23), T. inflata (12; 3-22), T. comprimata (7; 3-13); Cribrostomoides spp., H. wilberti , P. guaratibaensis , P. ipohalina and P. limnetis ≤5	57 44-78	35 10-47	79 17-205	8 6-9	5.7 5.7-5.8	33 22-40	79 66-88
IV	20 - 29	1780 1690	T. salsa/irregularis (59; 16-74), H. manilaensis , (26; 6-63), M. fusca (5; 1-16); Cribrostomoides spp., H. wilberti , P. limnetis and T. comprimata , J. macrescens , T. inflata , P. guaratibaensis , P. ipohalina ≤5	91 84-95	4 1.3-11	244 161-345	6 4-9	5.8 5.7-5.9	30 25-38	86 81-90
V	29 - 46	1690 1380	T. salsa/irregularis (77; 74-92), M. fusca (7; 1-16), Haplopragmoides spp. (4; 0.7-12), Cribrostomoides spp. (4; 0.8-9), T. comprimata (4; 0.7-6); H. manilaensis , P. limnetis , P. guaratibaensis , S. lobata , J. macrescens , T. inflata , P. ipohalina ≤5	88 82-95	4 1.4-9	260 63-609	5 4-8	6.1 5.8-6.6	19 12-24	91 80-95
VI	46-100	1380 140	T. salsa/irregularis (59; 21-80), Cribrostomoides spp. (14; 2-42), Haplopragmoides spp. (10; 4-26), J. macrescens (3; 1-7); M. fusca , T. inflata , P. ipohalina ≤5	76 59-88	3 0.8-8	3 0.1-13	3 2-5	4.8 3.8-6.7	8 6-13	97 93-100

Figure 1

[Click here to download high resolution image](#)

Figure 2

[Click here to download Figure: Fig2_Rev2_MorenoEtAl_QR2014.pdf](#)

Figure 3
[Click here to download Figure_Fig3_Rev2_MorenoEtAl_QR2014.pdf](#)

Figure 4
Click here to download Figure: Fig4_Rev2_MorenoEtAl_QR2014.pdf

Figure 5
[Click here to download Figure: Fig5_Rev2_MorenoEtAl_QR2014.pdf](#)

$^{210}\text{Pb}_{\text{Excess}}$ and ^{137}Cs content (Bq kg ⁻¹)				
Depth (cm)	$^{210}\text{Pb}_{\text{Excess}}$	error	^{137}Cs	error
0.5	328.8	38.3		
1.5	250.7	29.7		
2.5	166.1	20.9		
3.5	121.1	16.4	16.7	1.7
4.5	113.6	15.6	17.7	1.7
5.5	108.9	15.3	20.0	1.7
6.5	88.2	13.0	28.5	1.7
7.5	125.9	16.8	40.5	1.3
8.5	66.8	10.9	74.3	2.7
9.5	30.5	7.4	45.7	1.7
10.5	12.5	5.6		
11.5	5.0	4.9		
12.5	2.4	4.6		
13.5	2.1	4.6		

Appendix B

Depth (cm)	<i>Cribo. spp.</i>	<i>Hapl. spp.</i>	<i>H. man</i>	<i>T. salsa/irreg.</i>	<i>M. fusca</i>	<i>J. macrescens</i>	<i>T. inflata</i>	<i>P. linnetis</i>	<i>H. wilberti</i>	<i>T. comprimata</i>	<i>S. lobata</i>	<i>P. guaratibaensis</i>	<i>P. ipohalina</i>	Low Salinity spp.	Salt marsh spp.	NForam/cm3	AD Age
0-1		17.0	40.4	7.1	12.8		12.8	3.5	4.3					77.3	20.6	498.0	2010
1-2	2.0	6.6	55.6	11.3	12.6		7.3			2.0				88.1	9.3	98.8	2002
2-3	4.3	2.2	50.7	10.1	19.6	0.7	2.2	2.2			0.7	2.2		87.0	8.0	22.1	1995
3-4	9.7	64.9		8.2	2.2		4.5	1.5						85.1	9.0	391.4	1988
4-5	0.9		63.2	12.0	1.7		5.1	0.9		5.1		2.6		77.8	13.7	251.7	1983
5-6																	1976
6-7	4.6		59.2	3.8	4.6	3.1	3.1	0.8	13.1	3.8		1.5		72.3	25.4	178.3	1967
7-8			33.8	13.8	6.2	13.8	13.8	0.8	5.4	2.3	3.8	1.5		53.8	41.5	181.7	1960
8-9	2.2		15.9	12.3	5.8	9.4	40.6		4.3	0.7	1.4	2.2		36.2	58.7	159.1	1934
9-10			29.8	14.9	6.1	14.0	26.3	0.9		3.5				50.9	44.7	67.8	1910
10-11			35.0	10.0	5.0	12.5	22.5			8.3				50.0	43.3	44.1	1885
11-12	0.8		34.1	15.5	3.1	12.4	14.0	0.8		4.7	3.9			53.5	35.7	75.8	1876
12-13		46.3		9.8	0.8	13.0	17.1			7.3	0.8			56.9	38.2	66.3	1861
13-14			28.0	25.4	1.7	17.8	14.4			7.6				55.1	39.8	16.7	1852
14-15			39.3	16.4	1.6	13.9	13.1			2.5	0.8	3.3		57.4	33.6	100.1	1838
15-16	2.5		23.8	12.3	5.7	23.0	16.4			4.1	0.8			44.3	46.7	84.8	1829
16-17			21.2	31.7	7.7	23.1	11.5	1.9			1.9		2.5	60.6	38.5	34.0	1819
17-18	2.5		27.5	25.8		20.0	5.0	0.8	0.8	6.7				55.8	33.3	105.9	1805
18-19	0.8		33.1	24.1	2.3	15.8	3.8		0.8	12.8				60.2	33.8	205.3	1796
19-20	1.6		51.2	20.8	4.0		3.2			7.2				77.6	10.4	58.5	1783
20-21	2.4		63.4	16.3	1.6	2.4	1.6	1.6	4.1	0.8				83.7	10.6	127.4	1774
21-22			43.5	48.9	0.8		0.8			0.8				93.1	1.5	209.2	1761
22-23			36.2	53.7	3.4							1.3		93.3	1.3	160.6	1751
23-24	1.6		17.2	74.2	1.6									94.5		344.7	1738
24-25			22.9	64.9	2.3		0.8					0.8	0.8	90.1	2.3	308.4	1729
25-26			15.2	73.6	5.6							1.6	0.8	94.4	2.4	257.2	1720
26-27			16.9	64.1	3.5					4.9			0.7	84.5	5.6	282.6	1707
27-28	3.8		11.5	69.2	6.9					3.1			0.8	91.5	3.8	307.4	1698
28-29	0.8		6.3	66.4	15.6							3.1		89.1	5.5	196.0	1685
29-30	0.8			74.6	16.2					4.6				91.5	4.6	303.9	1677
30-31																	1663
31-32	2.1	11.9		67.8	10.5					4.2		0.7	1.4	92.3	6.3	372.3	1654
32-33																	1640
33-34		3.9		81.3	6.3					5.5				91.4	5.5	221.3	1631
34-35																	1617
35-36			5.1	66.9	11.8	0.7				5.9			2.2	83.8	8.8	189.9	1607
36-37																	1592
37-38	2.7	4.1		75.3	0.7					0.7			0.7	82.9	1.4	169.6	1582
38-39																	1565
39-40	8.1		2.4	74.2		0.8							1.6	84.7	2.4	149.8	1552
40-41																	1533
41-42	8.8	0.7		79.4	1.5		0.7	0.7			0.7		2.9	90.4	5.1	609.1	1495
42-43																	1472
43-44		1.5		80.2		0.8							2.3	81.7	3.1		1438
44-45																	1412
45-46	2.8			91.7	0.9								1.9	95.4	1.9	63.1	1378
46-47																	1360
47-48																1.7	1339
48-49																	1328
49-50																1.0	1312
50-51																	1301
51-52																	1290
52-53																1.3	1272
53-54																	1261
54-55																	1244
55-56		3.5	1.7	80.0		0.9	0.9							85.2	1.8	4.4	1233
56-57																	1216
57-58																	1205
58-59		9.8		78.6		1.8								88.4	1.8	3.9	1189
59-60																	1178
60-61																	1159
61-62																9.0	1143
62-63																	1122
63-64																	1084
64-65	41.6			32.7		6.9							1.0	74.3	7.9	12.5	1069
65-66																	1050
66-67																	1031
67-68	13.1	26.2		21.3	1.6	1.6								62.3	1.6	6.3	979
68-69																	950
69-70																	914
70-71		8.3		71.9									2.1	80.2		1.6	890
71-72																	853
72-73																	828
73-74																0.9	803
74-75																	766
75-76																	742
76-77	1.6	4.9		72.4			0.8							78.9	0.8	1.9	706
77-78																	682
78-79																	646
79-80	1.7	10.3		61.2										73.2		1.6	622
80-81																	598
81-82																	550
82-83	25.8	9.0		41.6	1.1								1.1	77.5	1.1	6.4	522
83-84																	494
84-85																	477
85-86	2.1	7.0		72.7										81.8		1.5	451
86-87																	434
87-88																	409
88-89		10.5		66.7									1.0	77.2		0.9	393
89-90																	367
90-91																	343
91-92																0.2	321
92-93																	299
93-94																	277
94-95				59.0	1.0									59.0		0.1	254
95-96																	232
96-97																	210
97-98																0.6	187
98-99																	165
99-100																0.2	143

Depth (cm)	OM %	pH	H ₂ O%	S (wt%)	Cl (wt%)	Ca (wt%)	Br (mg/kg)	Sr (mg/kg)	Zr (mg/kg)	Mud %	Silt/ Clay	AD Age
0-1	51.4	4.61	75.6	0.46	0.68	0.33	779	123	99	67.1		2010
1-2	64.5	4.99	75.3	0.56	0.52	0.38	1100	138	119	67.1	4.59	2002
2-3	52.1	5.39	74.8	0.60	0.65	0.35	1100	129	119	50.2	8.51	1995
3-4	45.3	5.41	73.5	0.58	0.46	0.36	1100	126	123	69.1	4.74	1988
4-5	39.9	5.27	73.2	0.56	0.63	0.37	1100	123	122	51.0	6.49	1983
5-6	37.7	5.11	53.9	0.45	0.54	0.36	900	113	111	84.6	5.31	1976
6-7	39.7	5.24	68.9							87.9	4.42	1967
7-8	37.3	5.50	69.8	0.41	0.49	0.28	948	113	114	66.5	6.14	1960
8-9	37.6	5.66	67.7	0.39	0.34	0.26	831	113	145	84.0	5.01	1934
9-10	35.7	5.69	67.9	0.40	0.46	0.25	817	117	153	67.6	4.60	1910
10-11	35.7	5.83	62.8	0.34	0.24	0.2	690	138	173	75.1	3.56	1885
11-12	32.1	5.70	61.1	0.30	0.31	0.18	540	118	157	80.6	4.25	1876
12-13	32.3	5.67	62.4	0.31	0.23	0.19	566	120	160	77.9	4.39	1861
13-14	35.6	5.69	64.8	0.35	0.39	0.2	611	116	152	65.5	4.71	1852
14-15	35.3	5.70	65.5	0.34	0.28	0.2	603	121	157	81.4	4.13	1838
15-16	39.8	5.65	63.0	0.31	0.28	0.2	624	120	151	83.6	4.38	1829
16-17	31.6	5.67	61.0	0.30	0.38	0.18	585	116	143	70.0	4.14	1819
17-18	38.4	5.69	60.8	0.28	0.26	0.19	615	131	161	88.2	5.39	1805
18-19	22.6	5.72	61.1	0.29	0.27	0.19	586	121	157	83.3	3.72	1796
19-20	22.4	5.66	63.4	0.30	0.33	0.19	633	120	160	86.0	4.35	1773
20-21	26.9	5.80	65.7	0.34	0.52	0.19	805	113	137	86.6		1774
21-22	37.5	5.82	61.5	0.29	0.31	0.2	693	115	170	86.5	4.29	1761
22-23	28.4	5.73	62.4	0.33	0.32	0.2	758	118	142	80.9	4.02	1751
23-24	25.4	5.88	62.2	0.33	0.50	0.2	836	113	144	84.9	3.90	1738
24-25	28.7	5.81	61.7	0.30	0.36	0.2	818	111	143	88.9	4.12	1729
25-26	31.9	5.87	65.9	0.35	0.47	0.21	1100	113	145	86.3	4.29	1720
26-27	30.8	5.84	66.4	0.36	0.47	0.21	1300	118	138	88.0	3.78	1707
27-28	31.8	5.85	64.2	0.37	0.45	0.22	1100	120	151	91.3	4.28	1698
28-29	25.2	5.87	62.2	0.33	0.65	0.21	931	119	152	83.7	4.46	1685
29-30	24.2	5.85	60.3	0.31	0.43	0.21	806	122	154	86.4	4.63	1677
30-31	21.6	5.77	60.4							91.7	4.13	1663
31-32	21.3	5.79	60.1	0.28	0.45	0.21	712	122	157	91.9	4.38	1654
32-33	21.9	5.84	59.1							91.9	3.73	1640
33-34	21.9	5.89	60.3							90.3	3.96	1631
34-35	22.2	5.88	59.4							79.5	3	

Depth cm	Age Cal/AD	C _{org} /N	$\delta^{13}\text{C}$ ‰	n-Alkanes				n-Alkan-2-ones	
				CPI ALKa (o/e)	TAR ALK b	ACL ALK d	C ₃₁ /C ₂₇	CPI KET g (o/e)	C ₂₅ /C ₂₇
0-2	2010-2002	16.5	-26.6	3.0	7.5	27.4	3.6	3.4	0.5
4-6	1983-1977	12.1	-25.0						
10-12	1885-1876	18.0	-26.6	3.0	11.7	28.3	5.0	2.9	0.5
14-16	1838-1829	17.0	-26.1						
20-22	1774-1761	17.4	-26.9	3.1	13.5	28.6	4.8	3.3	0.4
24-26	1729-1720	16.5	-27.4						
30-32	1663-1654	16.2	-27.2	3.5	15.1	28.7	6.7	3.5	0.3
34-36	1617-1607	18.9	-27.4						
40-42	1533-1495	17.5	-27.4	1.8	8.0	28.0	3.4	2.7	0.4
44-46	1412-1378	17.9	-27.1						
50-52	1301-1290	18.5	-27.1	2.0	3.8	26.9	3.3	3.2	0.3
54-56	1244-1233	19.0	-26.5						
60-62	1159-1143	19.9	-26.6	2.4	14.2	28.2	3.0	4.0	0.4
64-66	1069-1050	16.9	-26.3						
70-72	890-853	16.4	-26.8	2.7	13.8	27.3	3.9	4.4	0.4
74-76	766-742	17.9	-26.1						
80-82	598-550	17.0	-26.8	2.2	7.9	27.2	2.9	4.4	0.4
84-86	477-451	18.5	-26.9						
90-92	343-321	13.4	-26.7	2.9	9.9	27.3	3.9	4.0	0.5
94-96	254-232	15.0	-25.5						
98-100	165-143	13.8	-26.4	2.9	8.0	27.1	3.6	4.1	0.4

NW Portuguese River floods	Iberian Atlantic River floods
2002-03 (a)	1989 (h)
1989, 1987 (a)	1981 (h)
1962, 1959 (a)	1980 - 1960 (g)(i); 1978, 1979 (h)
1909-10 (a)	1950 - 1930 (g)(i); 1947, 1941, 1940 (h)
1888, 1877, 1865, 1860 (b)	1912 (h); 1900 (i)
1859, 1855, 1853, 1850, 1843 (b)	1895, 1876, 1855, 1823 (h); 1870 (i)
1825, 1823 (b)	1810 (g)(i); 1808 (h)
1788, 1779, 1727, 1739 (b)	1780 (g)(i); 1760, 1730 (i)
1582 (c)	1640 (i); 1610 (g)(i)
1575 (c); 1573 (d)	1597 (d); 1590 (g)(i); 1573 (d)
1526 (b); 1529 (d)	1540 (i)
1453 (e); 1450 (to 1150) lithos shelf (f)	1290 (g)
1402 (e)	1258 (j)
1207 (g)	1211 (j); 1210 (i); 1200 (j)
1181, 1178, 1168 (g)	1181, 1878, 1868 (j)
1150 (to 1450) lithos shelf (f)	1160 - 1150 (g)(i)
1094 - 1088 (e)	1113 (j)
AD 250 - BC 50 lithos shelf (f)	

(a) Araújo, 2005; (b) Rodrigues et al., 2003; (c) Granja, 2007; (d) Marques, 2001; (e) Abrantes et al., 2011; (f) Bernárdez et al., 2008a; (g) Benito et al., 2008; (h) Loureiro, J., M., 2009. Rio Tejo As Grandes Cheias 1800 – 2007, ARH Tejo, 79p.; (i) Benito, 2006
(j) De Villalta, F. & Benito G., 2001. Historical Flood Data Analysis Using a GIS: The Paleotagus Database. In: T. Glade et al. (eds.), The use of Historical Data in Natural Hazard Assessments, 101-112. Kluwer Academic Publishers. Netherlands.

Species	Citation
<i>Cribrostomoides</i> sp.	
<i>Haplophragmoides manilaensis</i> Andersen, 1953	<i>Haplophragmoides manilaensis</i> Andersen, 1953: p. 22, pl. 4, fig. 7, 8. Remarks: interspecific variability in this species includes forms with lobate periphery, depressed straight sutures and forms with almost smooth periphery and slightly depressed, curved sutures. Multiple apertures with supplementary areal pore(s) can also be present especially in lobate forms.
<i>Haplophragmoides</i> sp.	
<i>Haplophragmoides wilberti</i> Andersen, 1953	<i>Haplophragmoides wilberti</i> Andersen, 1953: p. 21, pl. 2, figs. 5,6, pl. 3, figs. 9-16.
<i>Jadammina macrescens</i> (Brady, 1870)	<i>Trochammina inflata</i> (Montagu) var. <i>macrescens</i> Brady, 1870: p. 290, pl. 11, figs. 5a-c. <i>Jadammina polystoma</i> Bartenstein and Brand, 1938: p. 381, text-figs. 1-3. <i>Trochammina macrescens</i> Brady; Phleger and Walton, 1950: p. 281, pl. 2, figs. 6,7. <i>Jadammina macrescens</i> (Brady); Murray, 1971: p. 41, pl. 13, figs. 1-5.
<i>Lepidodeuterammina ochracea</i> (Williamson, 1858)	<i>Rotalia ochracea</i> Williamson, 1858: p. 55, pl. 4, fig. 112, pl. 5, fig. 113. <i>Trochammina ochracea</i> (Williamson 1858); Murray, p. 37, pl. 11, fig. 1-5. <i>Lepidodeuterammina ochracea</i> (Williamson 1858); Loeblich & Tappan, p. 127, pl. 135, fig. 10-14.
<i>Miliammina fusca</i> (Brady, 1870)	<i>Quinqueloculina fusca</i> Brady, 1870: p. 286, pl. 11, fig. 2a-c. <i>Miliammina fusca</i> (Brady); Horton and Edwards, 2006: p. 68, pl. 1, figs. 5a, b.
<i>Paratrochammina guaratibaensis</i> Brönnimann, 1986	<i>Paratrochammina guaratibaensis</i> Brönnimann, 1986; Debenay et al., 2002: p. 531, pl. 2, figs. 11-14.

Polysaccammina ipohalina
Scott, 1976

Polysaccammina ipohalina Scott, 1976: p. 318, pl. 2, fig.1-4, text-figs. 4a-c; Zaninetti et al., 1977: p. 176, pl.1, fig.7; Scott and Mediolli, 1980, p. 43, pl. 2, fig. 8-9.

Psammosphaera sp.

Pseudothurammina limnetis
(Scott and Mediolli, 1980)

Thurammina ? limnetis, Scott and Mediolli, 1980: p. 43, pl. 1, figs. 1-3.
Pseudothurammina limnetis, (Scott and Mediolli); De Rijk, 1995: p. 28, pl. 1, figs. 15, 16.

Saccammina sp.

Siphotrochammina lobata
Saunders, 1957

Siphotrochammina lobata Saunders, 1957: p. 9-10, pl. 3, fig. 1-2; Brönnimann et al., 1992, p. 31, pl. 4, fig. 1-2; De Rijk, 1995, p. 33, pl. 3, figs. 9, 11-13.

Tiphotrocha comprimata
(Cushman and Bronniman, 1948)

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, 1808)

Nautilus inflatus Montagu, 1808: p. 81, pl. 18, fig. 3.
Trochammina inflata (Montagu); Horton and Edwards, 2006: p. 69, pl. 2, figs. 8a-d.

Trochamminita salsa
(Cushman and Brönnimann, 1948)

Labrospira salsa Cushman and Brönnimann 1948 b, p.16, p l.3 , fig. 5,6. *Alveophragmium salsum* (Cushman and Brönnimann). Todd and Brönnimann 1957, p. 23, pl. 2, fig. 3.
Trochamminita salsa (Cushman and Brönnimann). Saunders 1957, p. 6, pl. 1, fig. 3-8.
Trochamminita irregularis Cushman and Brönnimann 1948b, p. 17, pl. 4, fig. 1-3. - Saunders, 1957, p. 4, pl. 2, fig. 3- 8. - Todd and Brönnimann 57,p. 30, pl. 4, fig. 19-22.- Topping 1973, p. 21, pl. 3, fig. 4-7.

Remarks: *T. salsa* and *T. irregularis* are considered as synonymous in several works (e.g., Hayward et al. 1994; Guilbault et al., 1995); in this work they are identified separately but considered as one single group for interpretation. *Trochamminita salsa* is

abundant in the low salinity environment at the head of estuaries and in the mouth of small streams; mostly occurs at or above mean high waters, under plentiful freshwater seepage or groundwater and stream discharge, but also lives subtidally (e.g., Hayward et al. 1994, 1999). This species was not present in Caminha coarse sandy subtidal and tidal flat surface sediment.