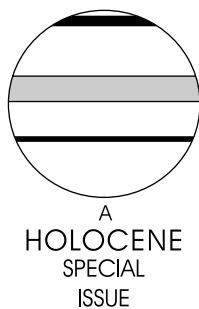


# Climate change and coastal hydrographic response along the Atlantic Iberian margin (Tagus Prodelta and Muros Ría) during the last two millennia

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**Abstract:** The Tagus Prodelta (W Portugal) and the Muros Ría (NW Spain) are areas of high deposition rates registering high-resolution palaeoclimatic records for western Iberia. We compare the climatic conditions of the two areas over the last two millennia based on proxies of temperature (sea surface temperatures and oxygen isotopes), continental input (grain size, iron and magnetic susceptibility) and productivity (inorganic and organic carbon, carbon isotopes, benthic foraminifera and diatoms). Biogeochemical changes in the Tagus Prodelta reflect widely recognized North Atlantic climatic periods encompassing the Roman Period (AD 0–350), the Dark Ages (AD 400–700), the ‘Mediaeval Warm Period’ (MWP; AD 800–1200) and the ‘Little Ice Age’ (LIA; AD 1300–1750). The atmospheric North Atlantic Oscillation (NAO) drives the Tagus Prodelta multidecadal, long-term variability in precipitation-river input during cold periods (negative NAO) and marine upwelling during warmer periods (positive NAO), a scheme that is reversed in the Galician region. The Muros Ría shows only local hydrodynamics until AD 1150, including a ‘suboxic’ event in the inner Ría around AD 500–700. Since AD 1150 Atlantic warm upwelled waters have ventilated the outer Ría but only reach the inner Ría at AD 1750. The twentieth-century records are also interpreted as a reflex of the inverse NAO mode in both areas, resulting in amplification of the LIA biogeochemical water conditions. Centennial-scale solar activity appears to be another important forcing mechanism (or the only one, if solar activity drives the NAO and ‘Bond-cycles’) behind changes in the hydrography of the Tagus Prodelta, and primary production, bottom ventilation and organic carbon degradation in the Muros Ría.

**Key words:** Iberia, Tagus River, Muros Ría, NAO, ‘Mediaeval Warm Period’, ‘Little Ice Age’, hydrographic change, climatic change, HOLSMEER project.

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## Introduction

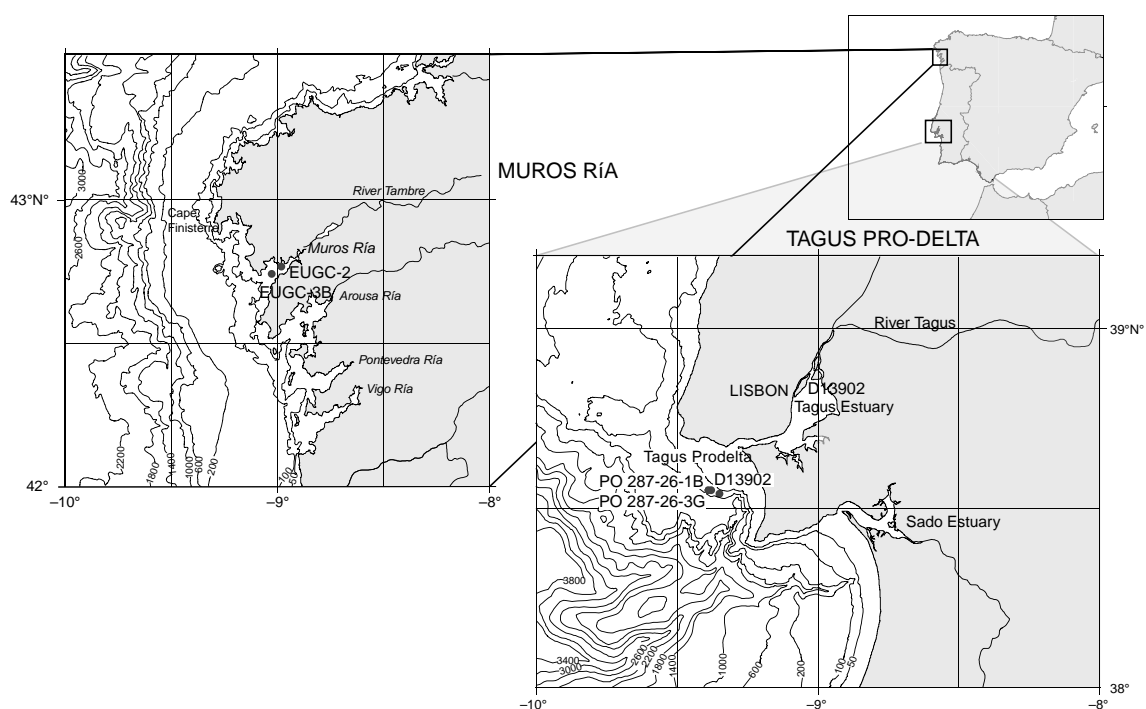
The Tagus Prodelta and the Muros Ría are representative areas of shallow marine-continental processes in which hydrography is profoundly affected by climatic changes. Only the analysis of high sedimentation rate sequences can provide insights into decadal and (multi-)decadal climate variability characterized by the North Atlantic Oscillation (NAO) or solar activity; we do not yet know how widely these affect the Earth's biogeochemical cycles. Furthermore, regional-scale histories of different proxy variables are needed to expand our knowledge on climate variability beyond the instrumental record (Jones *et al.*, 2001). Only in this way can we estimate the natural and human contribution to climate variability and provide more accurate predictions for the future.

Today, the western Iberian climate is mainly determined by the atmospheric NAO, the eastern North Atlantic surface circulation, particularly the Portuguese–Canary boundary current, and the intermediate Eastern North Atlantic Central Water (ENACW). The Portuguese–Canary boundary brings cool water from the northernmost latitudes along the Iberian margin. The ENACW, which Fiúza (1983) defined with two origins, subtropical (st) and subpolar (sp), converge at Cape Finisterre. Upwelling of ENACWst (salty and warm) or ENACWsp (fresh and cold) into the Muros Ría depends on favourable northerly winds from late spring to early autumn and the interannual hydrographic position of the front between these two watermasses (Álvarez-Salgado *et al.*, 1993; Varela *et al.*, 2005). In the south, ENACWst upwells along the Tagus Prodelta. The NAO determines the direction and speed of the westerlies and precipitation over Europe and the Atlantic. The NAO Index measures the difference in atmospheric pressure at sea level between the Icelandic and Lisbon poles, mainly in winter (Hurrell, 1995). Close to the Lisbon pole, significant climate anomalies are evidenced by NAO impact on the precipitation anomaly fields (mm/month) determined for a 40 yr time series from southern to northern Iberia (Trigo *et al.*, 2002a,b).

The Tagus Prodelta is an organic-rich, fine-sediment prism located off the Tagus River on the Portuguese continental shelf (Monteiro and Moita, 1971; Cabeçadas and Brogueira, 1997) (Figure 1). The Tagus mouth is preceded by a 340 km<sup>2</sup> (at high tide) tidal lagoon estuary-type (Vale and Sundby, 1987). The output of freshwater to the estuary is 80–720 m<sup>3</sup>/s, occasionally reaching 2200 m<sup>3</sup>/s (Loureiro, 1979). The suspended sediment load entering the estuary is  $4 \times 10^5$  t (c. Vale, unpublished data, 1987), as estimated from catastrophic floods such as that of 1979, amounting to a volume of sediment sufficient to deposit a 7-mm thick sheet over its entire surface (Vale and Sundby, 1987). Estuary sediments are mud and sand facies responding to changes in current and river flow regimes. The stronger river flood events are registered in the shelf sediments, alternating with productive episodes resulting from coastal upwelling enhancement (Abrantes *et al.*, 2005a).

The Muros Ría (97 km<sup>2</sup>) is a drowned river system deeply incised into the coastline that traps fluvial material rather than discharging it onto the Spanish continental shelf (Oliveira *et al.*, 2002). The most significant freshwater input comes from the River Tambre (54 m<sup>3</sup>/s mean discharge), which mostly influences the estuarine characteristics of the inner Ría. The outer Ría is under strong oceanic control, exhibiting a residual circulation in two layers (Fraga and Margalef, 1979; Prego, 1990). Muros is the only Galician Ría without a group of islands at its mouth, which favours oceanic intrusion.

Off Iberia, primary production patterns are mainly conditioned by (1) summer persistent upwelling of cool and nutrient-rich ENACW from 100–300 m depth; (2) water column stratification; (3) nutrient availability; and (4) the composition and distribution of phytoplankton (Fraga, 1981; Estrada, 1984; Varela *et al.*, 1987; Abrantes, 1988; Ríos *et al.*, 1992; Abrantes and Moita, 1999). During upwelling conditions (summer), water column chlorophyll *a* concentrations increase to 6 mg/m<sup>3</sup> in the Tagus (Moita, 2001) and >7 mg/m<sup>3</sup> in Muros (Nogueira *et al.*, 1997). Diatoms are the main contributors at both sites, while coccolithophorids dominate the phytoplankton during non-upwelling, non-productive conditions (winter) (Bode *et al.*, 1994; Abrantes and Moita, 1999). On the Tagus shelf, solar irradiation and river discharge



**Figure 1** Geographic location of targeted areas in the Iberian Margin. Position of cores studied in the Tagus Prodelta and Muros Ría

results in maximum water stratification in summer, redistributing nutrients in the water column (Moita, 2001). In the two-layer stratified estuary of Muros, with a surface freshwater outflow and a bottom oceanic inflow circulation, the export of nutrients and phytoplankton to the ocean reinforce the upwelling effect (Estrada, 1984). Furthermore, remineralization of organic matter enriches the subsurface water inflow which brings nutrients back into the Ría (Estrada, 1984). The range of primary production rates off Lisbon ( $0.6\text{--}1.6\text{ g C/m}^2$  per day; Antoine and Morel, 1996; Behrenfeld *et al.*, 2001) and NW Spain ( $0.7\text{--}3.7\text{ g C/m}^2$  per day; Nunes *et al.*, 1984; Prego, 1993) are similar to those recorded in the Benguela ( $0.5\text{ g C/m}^2$  per day; Brown and Field, 1986; Brown *et al.*, 1991) and Peru upwelling regions ( $1.9\text{ g C/m}^2$  per day; Barber and Smith, 1981) or the California coastal upwelling system ( $0.5\text{--}2.6\text{ g C/m}^2$  per day; Pilskaln *et al.*, 1996). Thus, in the Galician rías, productivity is primarily influenced by shelf winds as well as coastal and estuarine processes (Varela *et al.*, 2001; Varela *et al.*, 2005). On the Tagus Prodelta, primary productivity can be triggered either by an intensification of coastal upwelling along the Atlantic Iberian margin (Abrantes, 1988; Abrantes and Moita, 1999) or increased input of nutrients by the river into the area.

This paper presents high-resolution palaeodata, including O and C stable isotopes, benthic foraminifera, diatoms, grain size and land-derived major chemical elements, from two Iberian sedimentary systems: the Tagus Prodelta (Portugal) and the Muros Ría (NW Spain). Our objective is to analyse the regional response to 'high-frequency' climate forcing mechanisms, such as the NAO and solar activity.

## Material and methods

### Core description

From the Tagus Prodelta, a spliced sediment sequence composed of box core PO287-26-1B, gravity core PO287-26-3G and giant piston core D13902, collected during the

Portuguese PALEO1 campaign onboard the R/V *Poseidon*, in 2002, and the British *Discovery* 249 cruise, in 2000, were used for this study. From the Muros Ría, two gravity cores EUGC-2 (inner Ría) and EUGC-3B (outer Ría), were collected during the B/O *Mytilus* cruise, in 2001. The records of both areas cover the last 2000 years (Table 1, Figure 1).

Although the recovered length of core D13902 is 600 cm, the sediment above 189 cm was disturbed, as demonstrated by  $^{14}\text{C}$  datings (Abrantes *et al.*, 2005a; see samples AAR-7823, OS-37286, AAR-7824, table 4 in Bartels-Jónsdóttir *et al.*, 2006), and discarded, and 0 cm assigned to depth 189 cm. In this study only the interval between 189 and 400 cm, which covers the last 2000 years, is considered. From core PO287-26-3G, located about 2 km from D13902 (Figure 1), only the section 0–150 cm was considered, in an effort to partially substitute the 350-yr hiatus in core D13902 arising from the AD 1755 Lisbon earthquake and tsunami (Abrantes *et al.*, 2005a). Core EUGC-2 contains modern sediments at its top, but in core EUGC-3B the top has been dated to AD 1470. The upper part of the sequence was lost during recovery.

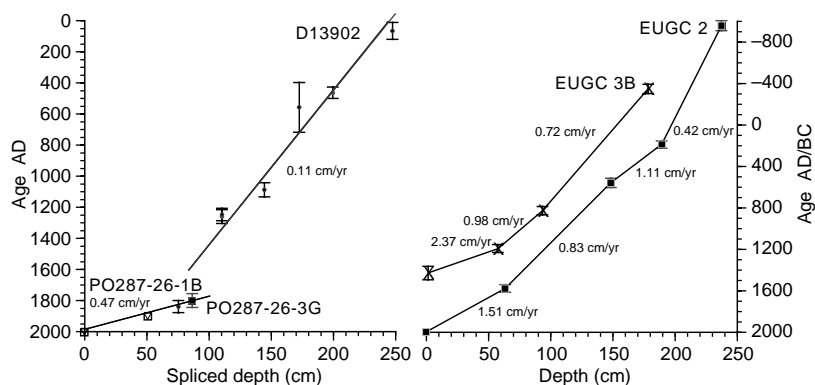
### Chronology

For the Tagus Prodelta, accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dating of either molluscs or planktonic foraminifera was performed on 18 samples from the three cores.  $^{14}\text{C}$  ages were 400 year reservoir-age corrected after a test on three regional live-collected pre-bomb mollusc shells (Abrantes *et al.*, 2005a) and calibrated using CALIB 4.4 (Stuiver *et al.*, 1998a) (Table 2).  $^{210}\text{Pb}$  analyses were performed on 18 samples (16 in PO287-26-1B and 2 in D13902). For the Tagus Prodelta spliced sequence we follow the age model proposed in Abrantes *et al.* (2005a). In this sequence a 1-cm sampling interval gives a mean time resolution of 1.5 years between AD 2001 and 1759 and 8.4 years between AD 1600 and 0 (Figure 2). For the Muros Ría cores, a total of eight samples were dated by AMS  $^{14}\text{C}$  (four for each core) on benthic foraminifera and entire articulated bivalve shells (Table 2). Sedimentation rates have been calculated by interpolation between dated points (Figure 2).

**Table 1** Location, water depth and core length for the five cores in the Tagus Prodelta and Muros Ría

Core number	Core type	Water depth (m)	Core length <sup>a</sup> (m)	Latitude (N)	Longitude (W)
PO287-26-1B	box	96	0.51	38°33.49'	9°21.84'
PO287-26-3G	gravity	96	3.05 (1.50)	38°33.49'	9°21.84'
D13902	piston	90	6.00 (2.10)	38°33.24'	9°20.13'
EUGC-2	gravity	33.3	3.50 (2.00)	42°45.5'	8°59.9'
EUGC-3B	gravity	37.9	4.10 (1.60)	42°45.1'	9°00.2'

<sup>a</sup>Numbers in parentheses indicate metres of core corresponding to the last 2000 years.



**Figure 2** Age models and sedimentation rates for the Tagus Prodelta (left: triangles, PO287-26-1B; squares, PO287-26-3G; circles, D13902) and Muros Ría (right) cores

**Table 2** Results of  $^{14}\text{C}$  AMS datings of the Tagus Prodeltá box-core PO287-26B, gravity-core PO287-26G and piston-core D13902 (levels in italic correspond to ages not considered for the age model) (above); and Muros Ría cores EUGC-3B and EUGC-2 (below)

Core/(depth) (cm)	Laboratory code	Spliced depth (cm)	Species	$^{14}\text{C}$ age BP	Reservoir corr. $^{14}\text{C}$ yr age	Calendar years BP	SD ( $\pm 1$ s)	Age AD	$\delta^{13}\text{C}$	Sed rate (cm/yr)
PO287-26B (32–33)	AAR-8368.2-K <sup>a</sup>	51	mollusk shell	440	40	51	25	1899	– 1.09	0.45
D13902 (27–28)	OS-37286 <sup>b</sup>	75.4	mollusk shell	492	92	111	39	1839	0	0.11
<i>D13902 (31–32)</i>	<i>AAR-8338<sup>a</sup></i>	<i>79.4</i>	<i>mollusk shell</i>	<i>2150</i>	<i>1700</i>	<i>1700</i>	<i>80</i>	–	<i>0</i>	
<i>D13902 (37–38)</i>	<i>AAR-7826<sup>a</sup></i>	<i>85.4</i>	<i>mollusk shell</i>	<i>8955</i>	<i>8555</i>	<i>8555</i>	<i>70</i>	–	<i>+0.01</i>	
<i>D13902 (46–47)</i>	<i>AAR-8301<sup>a</sup></i>	<i>94.4</i>	<i>mollusk shell</i>	<i>7075</i>	<i>6675</i>	<i>6675</i>	<i>50</i>	–	<i>+0.79</i>	
D13902 (62–63)	AAR-7207 <sup>a</sup>	110.4	mollusk shell	1160	760	691	45	1259	+1.44	0.11
D13902 (62–63)	AAR-7208 <sup>a</sup>	110.4	<i>turritella</i>	1185	785	704	40	1246	+2.15	0.12
D13902 (96–97)	AAR-7209 <sup>a</sup>	144.4	mollusk shell	1370	970	863	45	1087	+2.19	0.13
D13902 (124–125)	OS-37307 <sup>b</sup>	172.4	foraminifera <sup>c</sup>	1880	1480	1394	160	556	0	0.14
D13902 (151–152)	AAR-7828 <sup>a</sup>	199.4	mollusk shell	2007	1607	1487	37	463	+2.68	0.15
D13902 (199–200)	AAR-7826 <sup>a</sup>	247.4	mollusk shell	2340	1940	1885	55	65	+0.71	0.16
PO287-26-3G (86–87)	OS-42381 <sup>b</sup>		mollusk shell	545	145	147	45	1801	+0.86	0.17
EUGC-3B (1–2)	AAR-8453 <sup>a</sup>		<i>Nonion commune</i>	920	520	522	65	1429	– 2.53	
EUGC-3B (57–58)	AAR-7966 <sup>a</sup>		<i>Venus nux</i>	1229	829	799	39	1193	– 1.97	2.37
EUGC-3B (93–94)	AAR-7502 <sup>a</sup>		<i>Myrtea spinifera</i>	1575	1183	1172	40	826	– 0.84	0.98
EUGC-3B (178–179)	AAR-7967 <sup>a</sup>		<i>Myrtea spinifera</i>	2623	2223	2347	45	– 349	– 0.14	0.72
EUGC-2 (63–65)	AAR-7969 <sup>a</sup>		<i>Lucinoma borealis</i>	730	330	370	37	1581	+1.00	1.51
EUGC-2 (148–149)	AAR-8508 <sup>a</sup>		<i>Nonion commune</i>	1855	1455	1390	45	561	– 5.33	0.83
EUGC-2 (189–190)	AAR-8662 <sup>a</sup>		<i>Nonion commune</i>	2170	1770	1761	35	190	– 4.08	1.11
EUGC-2 (237–238)	AAR-7970 <sup>a</sup>		<i>Myrtea spinifera</i>	3136	2736	2904	47	– 955	+0.31	0.42

<sup>a</sup>AMS  $^{14}\text{C}$  Laboratory of the University of Aarhus (Denmark).<sup>b</sup>National Ocean Sciences AMS Facility of the Woods Hole Oceanographic Institution (USA).<sup>c</sup>*Globigerina bulloides*, *Globigerinoides ruber* white and *Globigerinella calida*.

### Non-destructive physical properties

Low-field magnetic susceptibility of core D13902 was carried out in U-channels at a 4 cm interval resolution at the LSCE/CNRS, Gif-sur-Yvette, France; for the other four cores, magnetic susceptibility was measured using a Multi Sensor Core Logger system at 1 cm interval at the University of Bremen, Germany (ARI-Paleostudies Program). Fe, Ti, K, Ca, Sr abundance in counts per second was measured by means of non-destructive scanning X-ray fluorescence (Jansen *et al.*, 1998) at 1 cm resolution for four cores, and 2 cm interval for core D13902, at the University of Bremen, Germany (ARI-Paleostudies Program). Only Fe is shown here.

### Textural data

Grain size was determined for the size fraction less than 2 mm using a Coulter LS230 laser particle analyser. Sample treatment consisted of organic matter removal with hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) and dispersion with sodium hexametaphosphate (0.033M). Prior to analysis, samples were homogenized and stirred. Resolution is 1 cm for the three Tagus Prodelta cores and 2 cm for Muros core EUGC-3B.

### CaCO<sub>3</sub> and C<sub>org</sub>

From an initial volume of 2 mg of dried, ground and homogenized sample, calcium carbonate was calculated by the difference between total carbon and organic carbon (C<sub>org</sub>) measurements using a CHNS-932 Leco element analyser. The C<sub>org</sub> is combusted at 400°C. Data are presented in weight percentage. The relative precision of two repeated measurements of both samples and standards was 0.03wt%. Sample resolution is 1 cm for cores PO287-26-1B and D13902, 5 cm for core PO287-26-3G and 2 cm for core EUGC-3.

### Foraminifera

Samples for foraminiferal counts were wet-sieved at 63 µm and dry-sieved at 125 and 2000 µm. Benthic foraminifera were analysed in the >125 µm fraction. Resulting from the observation that biogenic carbon from high C<sub>org</sub> sediments suffers dissolution when the samples are stored in a sodium hexametaphosphate 0.033M solution (unpublished INETI-DGM data, 2006), samples were washed only with distilled water. Total benthic foraminiferal assemblages were identified counting at least 300 individuals. Agglutinated foraminifera are excluded in the calculations for the Tagus Prodelta because of their poor preservation potential (Bartels-Jónsdóttir *et al.*, 2006), but considered an important part of the assemblage in Muros because no significant taphonomic loss was observed. Sample resolution in the Tagus Prodelta is 1 cm in PO287-26-1B, 2–5 cm in PO287-26-3G and approximately 3–4 cm in D13902; in Muros, sample resolution is 2 cm for both EUGC-2 and EUGC-3B.

### Oxygen and carbon isotopes

Oxygen and carbon stable isotopes were analysed using a Finnigan MAT 251 mass spectrometer at the Department of Geosciences of the University of Bremen (Germany). All samples were measured relative to the VPDB standard with reproducibility of 0.07‰ for δ<sup>18</sup>O and 0.06‰ for δ<sup>13</sup>C. Measurements were performed on the benthic species *Uvigerina* sp. 221 and planktic *G. bulloides* and *G. inflata* (PO287-26-1B, PO287-26-3G and D13902) at every centimetre, and on *Nonion commune* (EUGC-2 and EUGC-3B) at 2 cm interval resolution. On average, six specimens from the ≥250 µm fraction were used for the Tagus Prodelta and about 20 specimens from the ≥125 µm fraction for the Muros Ría.

### Diatoms

For diatom slide preparation, a fixed amount of 1–2 g of fresh sediment from each sample was cleaned following Abrantes *et al.* (2005b) and placed to dry on plates (Battarbee, 1973). To calculate diatom fluxes (number of valves per square centimetre per year), diatom frustules were counted following the counting protocol of Schrader and Gersonde (1978) and Abrantes (1988). Cores PO287-26-1B and EUGC-3B were sampled at 1 cm resolution, PO287-26-3G at 5 cm and D13902 unevenly between 5 and 12 cm.

## Results and discussion

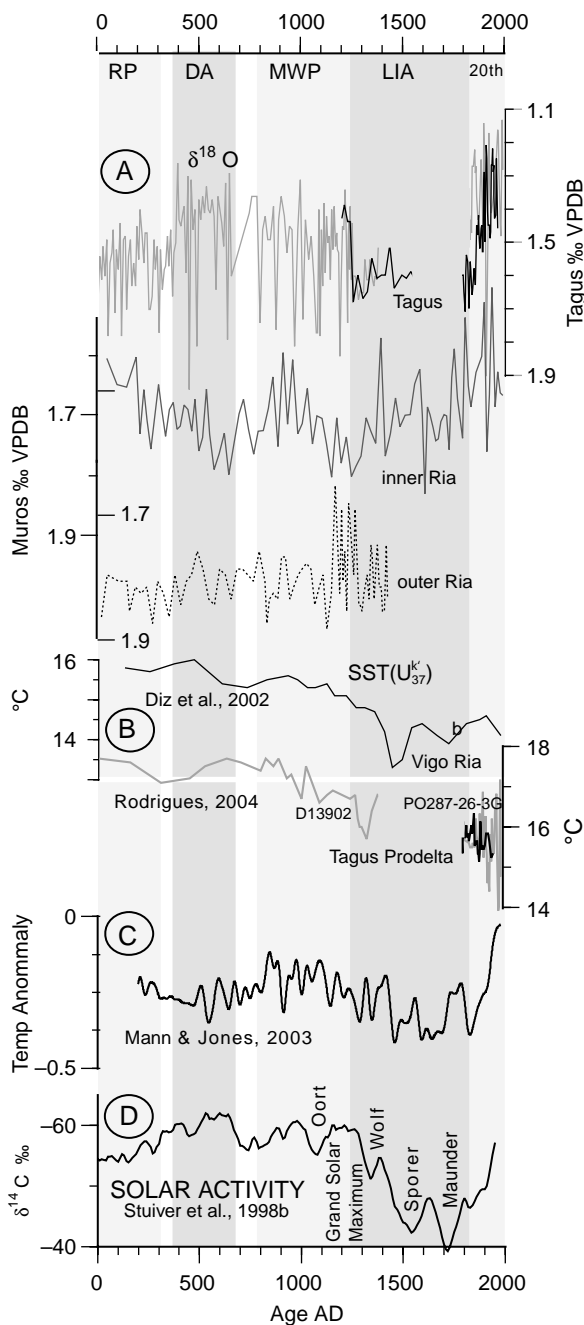
### Major North Atlantic climatic periods

The last two millennia circumscribe five relatively well time-constrained climatic periods, Roman Period (RP; ~AD 0–400; eg, Lamb, 1985), Dark Ages (DA; ~AD 400–700; eg, Keigwin and Pickart, 1999; Mikkelsen and Kuijpers, 2001), 'Mediaeval Warm Period' (MWP; AD 800–1300; eg, Hughes and Diaz, 1994; Hass, 1996), 'Little Ice Age' (LIA; AD 1350–1900; eg, Bradley and Jones, 1993) and a warming twentieth century, indicated by instrumental temperature measurements of the last two centuries, extended using proxy records back in time.

Oxygen isotopes have been widely used to infer water temperatures (eg, Shackleton, 1974; Keigwin, 1996) in marine records. As no significant ice volume changes have occurred during the last 2000 years, δ<sup>18</sup>O should reflect bottom water temperature at our sites, and deviations from other independently derived temperatures indicate salinity effects.

In the Tagus Prodelta, δ<sup>18</sup>O oscillates between 1.9 and 1.15‰, clearly defining four distinct intervals. Two periods with 1.55‰ average values, AD 0–350 (encompassing the Roman Period) and 1.6‰ AD 1250–1850 (the so-called 'Little Ice Age'); the latter is punctuated by a relatively lighter event centred at AD 1400. Lighter δ<sup>18</sup>O values are found between AD 400 and 650 (corresponding to the Dark Ages) and AD 800–1250 ('Mediaeval Warm Period'), reaching mean values around 1.4–1.5‰, and during the twentieth century, with the highest oxygen isotope values (1.3‰) (Figure 3A). At this location, major fluctuation in the δ<sup>18</sup>O is probably related to strong temperature changes at interannual time scale rather than to salinity changes. In the Muros Ría, although the data have a smaller amplitude (1.9–1.6‰), values remain around 1.7–1.8‰ until AD 1750, with the exception of the interval AD 1200–1300 in the outer Ría, becoming gradually lighter towards the present in the inner Ría (Figure 3A). In general, the lighter oxygen isotopes at the Tagus Prodelta point to water temperatures reflecting warmer/less saline waters than the Muros Ría (Figure 3A, Figure 4).

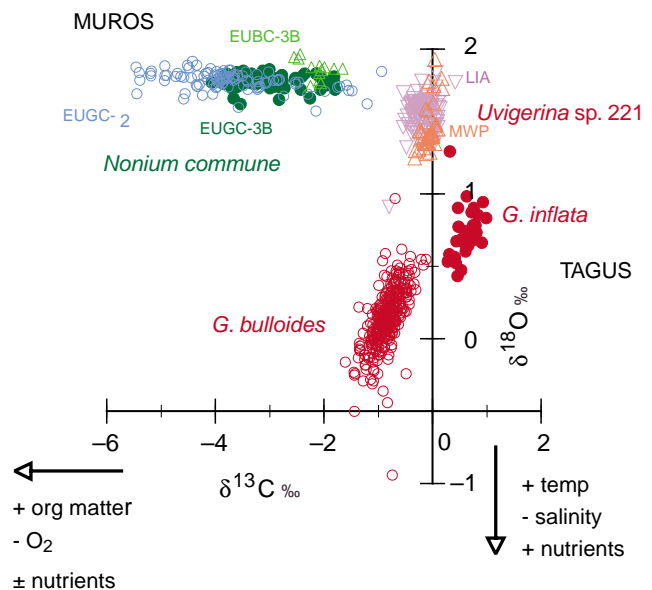
To support the hypothesis that lighter δ<sup>18</sup>O reflects higher water temperature, we compared the δ<sup>18</sup>O results from the Tagus Prodelta with SST based on the alkenone U<sub>37</sub><sup>k</sup> index. High values (17.5°C) are observed during AD 0–900, with a gradual decrease of 2°C up to AD 1400. Low temperatures (15°C) remain until AD 1900, when SST starts to oscillate with high amplitude between 14 and 17°C (Rodrigues, 2004; Abrantes *et al.*, 2005a) (Figure 3B). Clearly, temperature explains the difference in δ<sup>18</sup>O in the intervals AD 400–1250 (DA–MWP) and AD 1250–1850 (LIA). The warmings in the RP and the last century, however, are not fully supported by our data. In the Vigo Ría, south of Muros, a similar SST record exists (Diz *et al.*, 2002); this is probably representative for all the Galician region (Figure 3B). Here, since AD 1150, relatively warmer/less saline waters came into the Ría (outer



**Figure 3** Comparison of temperature indicators between the Tagus Prodelta and the Muros Ría. A, stable oxygen isotopes; B,  $U_{37}^k$  sea surface temperatures for the Tagus and the Vigo Ría; C, temperature anomaly; D,  $^{14}C$  solar activity. Note different scales in  $\delta^{18}O$ . RP, Roman Period; DA, Dark Ages; MWP, 'Mediaeval Warm Period'; LIA, 'Little Ice Age', 20<sup>th</sup>, twentieth century. See text for details

site EUGC3B), only to reach and affect the inner Ría much later, around AD 1700.

Additionally, our  $\delta^{18}O$  records can be compared with the North Atlantic temperature variability registered by instrumental data, showing that the two major established global temperature climatic periods MWP and LIA (see discussion in Jones and Mann, 2004) are well marked in the Iberian margin (Figure 3C). Moreover, the DA is demarcated from the MWP in our records. The Tagus SST do not mirror the rapidly warming twentieth-century curve of Mann and Jones (2003), hence the very light oxygen isotopes values must indicate lower salinity rather than higher temperature.



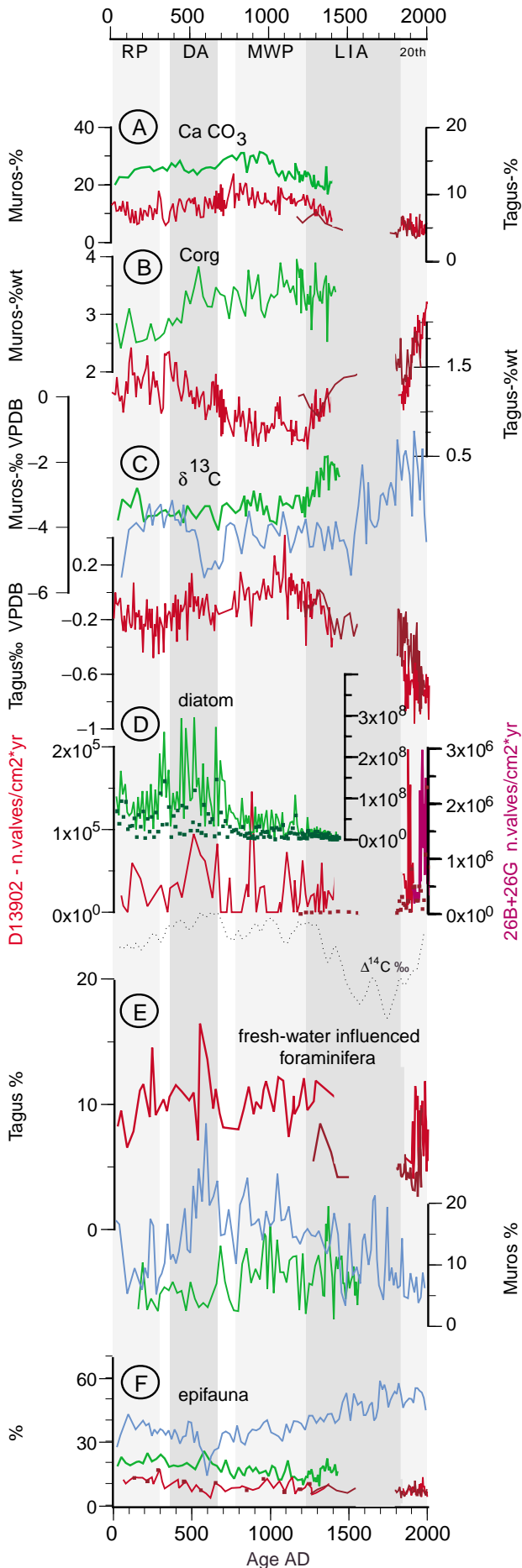
**Figure 4** Water masses characterization on the basis of oxygen and carbon stable isotopes for the Tagus Prodelta (*G. bulloides*, *G. inflata* and *Uvigerina* sp. 221) and Muros Ría (*Nonium commune*). EUGC-3B is a box-core from the Muros Ría at the same position as gravity core EUGC-3B.  $0.24\text{‰}$  in  $\delta^{18}O \equiv \Delta 1^\circ C$  (Shackleton, 1974)

#### Climatic conditions and the productivity record

$C_{org}$ ,  $CaCO_3$ ,  $\delta^{13}C$  and micro-organisms provide good indications of past changes in productivity (eg, Broecker and Peng, 1982; Zahn *et al.*, 1987; Fisher and Wefer, 1999) (Figure 5).

Organic carbon in the Tagus core shows very low values (0.5–1.5 wt%) for the period AD 500–1250, and relatively higher values between AD 0–400 and AD 1250–1850 (1–1.7 wt%). For the last century values increase to near 2.3 wt%, exceeding all previous maxima levels (Figure 5B). An inverse correlation exists between organic and inorganic carbon (Figure 5A,B). The Muros Ría contains higher than average organic carbon, although within a similar range of variation (2.5–3.5 wt%). Nevertheless, organic and inorganic carbon curves follow each other quite closely. The higher content of organic carbon in the Muros Ría relative to the Tagus Prodelta highlights different environments and either stronger productivity or better *in situ* organic carbon preservation in the Ría (Figure 5B). Comparing both areas, organic carbon in the outer site of the Muros Ría diverges from the Tagus Prodelta between AD 400 and 1300 (DA and MWP), suggesting different water conditions in the two areas. However, the Tagus and Muros inorganic carbon mimic each other (data available only for outer site and AD 0–1400).

$\delta^{13}C$  of benthic foraminifera in the Tagus Prodelta fluctuates between 0.4 and  $-0.9\text{‰}$ . It shows relatively low values between AD 100 and 500, increases until around AD 1300 with a minimum centred at AD 650 (Figure 5C). The lowest values are documented during the last century (Suess effect). The Muros Ría presents a higher range variation in  $\delta^{13}C$  ( $-1$  to  $-5.4\text{‰}$ ), with the largest fluctuations for the inner Ría, more negative values between AD 100 and 1500, and rapid increase for the last 500 years. Lighter values ( $-5\text{‰}$ ) are evident for the interval AD 550–700, indicating stagnant water conditions.  $\delta^{13}C$  is less negative and more constant for the outer Ría, until around AD 1200 when a sharp increase occurs. More positive  $\delta^{13}C$  are indicative of more ventilated, mixed waters, influenced by marine upwelling. In the Tagus Prodelta,  $\delta^{13}C$  data validate our previous interpretation of light  $\delta^{18}O$ ,



reflecting temperature and not salinity during the DA, MWP, and hence suggests intense upwelling during these times. In contrast, river runoff is dominant during the RP, the LIA and the twentieth century. However, in the Muros Ría and in light of the carbon isotope results, the same water mass influenced the Ría until AD 1150, although slightly better ventilation and/or less organic matter accumulation characterized the outer Ría (Figure 5C). Since AD 1150 the inflow of warmer, oceanic waters caused more intense bottom ventilation in the outer Ría, very likely due to reinforced upwelling. The enhancement of bottom ventilation is delayed in the inner Ría by 400 years. A similar pattern is found in the neighbouring Vigo Ría (Diz *et al.*, 2002). Therefore, as opposed to the Tagus Prodelta area, in the Muros Ría the LIA is marked by marine influence. The fact that the Muros Ría records much higher values and variability in the  $\delta^{13}\text{C}$  data than in the Tagus Prodelta reflects the importance of organic matter preservation-related processes in the more protected environment of the Ría (Figure 4).

Diatom accumulation rate in the Tagus Prodelta indicates periods of productivity with pulses centred at AD 550, AD 900 and weakly at AD 100 and AD 1100. These four pulses of diatoms, composed by the mixing and upwelling-related species (mainly *Paralia sulcata* (Ehrenberg) Cleve and *Chaetoceros* spp.), are tied with the RP, the DA and the MWP. The four pulses also coincide with heavier  $\delta^{13}\text{C}$  manifesting ventilation and turbulence. With the onset of the LIA, since AD 1300, diatom concentrations seem to diminish, coeval with a steady decrease in  $\delta^{13}\text{C}$ . This weakening of upwelling conditions is coherent with an increase in phytoliths (Gil *et al.*, 2006), ie, a shift to continental river inputs. Much higher fluxes ( $\times 10$ ) characterize the last 100 years (Figure 5D), partially owing to better preservation. It is known that in general, one order of magnitude in the abundance of diatoms is lost by dissolution in the surface sediments, as well as diversity in the fossil assemblage (Bao *et al.*, 1997; Abrantes and Moita, 1999). During the last century, and in particular around AD 1900, brackish diatoms are more frequent, together with less negative  $\delta^{13}\text{C}$ , reaching the lightest values at present. This reinforces the climatic tendency to more continental influence since the onset of the LIA (Figure 5C). Spread of brackish diatoms and phytoliths for the last 150 years further confirm the very light  $\delta^{18}\text{O}$  signal for this period, not only because of lower SST (Figure 3A) but also less saline waters.

In the Muros Ría, a single diatom record exists (EUGC-3B), but diatoms show higher abundances in the Muros Ría (two orders of magnitude) than in the Tagus Prodelta, with accumulation rate peaks over  $1.5 \times 10^8$  valves/cm<sup>2</sup> per yr. This core, in the outer Ría, reveals a stronger diatom concentration between AD 270 and 670, marking three peak episodes, and a much weaker pulse around AD 50. There is some overlap with the earlier Tagus pulses (Figure 5D), encompassing the RP and partially the DA. Contrary to the

**Figure 5** Comparison of productivity indicators between the Tagus Prodelta (red, darker red for PO287-26-3G) and the Muros outer (green) and inner (blue) Ría. A, Calcium carbonate; B, organic carbon; C, carbon stable isotopes; D, diatom accumulation rates (*Chaetoceros* in bold squares); E, benthic foraminifera species influenced by freshwater; and F, benthic foraminifera epifauna. We considered 'freshwater influence' the species driving in estuarine and shelf environments influenced by freshwater flux from rivers producing brackish water conditions. See text for details. Note change of scales between Tagus and Muros in  $\text{C}_{\text{org}}$ ,  $\text{CaCO}_3$ ,  $\delta^{13}\text{C}$  and diatom AR. Also in the Tagus Prodelta records, change of scale in diatom AR for box PO287-26-1B and gravity core PO287-26-3G. The curve of  $^{14}\text{C}$  solar activity from Figure 3D is given for reference. RP, Roman Period; DA, Dark Ages; MWP, 'Mediaeval Warm Period'; LIA, 'Little Ice Age'; 20<sup>th</sup>, twentieth century

Tagus Prodelta, light and quite constant  $\delta^{18}\text{O}$  until AD 1100, poor water ventilation and an increment in 1 wt% of organic carbon (Figure 5B) point to diatom productivity as a result of nutrient input by the Tambre River, in a system that remained isolated from Atlantic influence. Varela *et al.* (2001) stated that although the Tambre fluvial output into the Ría is low, it can still be a significant source of nutrients for phytoplankton blooms. From AD 670 to 1470 (mid-MWP), diatom concentrations decay in the Muros. The assemblage itself changes too, from local benthic species, to open-ocean centrals (*Thalassiosira* spp., *Rhizosolenia* spp., Z.N. Stroynowski, personal communication, 2005) and, most notably, the assemblage shows an increase in *Chaetoceros* spp. Lower species diversity and the change in the species assemblage suggests an increase in frequency of upwelling events but the drop in productivity is interpreted as a decrease in preservation (Stroynowski, personal communication, 2006). This poor preservation could be due to a decrease in bottom waters or surface sediment porewater silica saturation (Bernárdez *et al.*, 2006). Unfortunately, we do not have the upper record of EUGC-3B and cannot verify the evolution of diatom concentrations in the Ría after AD 1470.

Benthic foraminifera are grouped, in the two areas, by (1) specific assemblages according to the different environments; (2) species tolerant to salinity changes that are good markers of periods of river discharge (referred to as a 'brackish' assemblage in the Tagus and an 'inner assemblage' in Muros, and integrated as 'fresh-water influence' in Figure 5E) or coastal upwelling (shelf assemblage for the Tagus and outer assemblage for Muros); and (3) indicators of labile (epifauna) or refractory organic matter availability at the bottom and, therefore, degree of ventilation of the water masses.

In the Tagus Prodelta, benthic foraminifera assemblages are dominated by typical continental shelf *Cassidulina laevigata*, *Hyalinea balthica*, *Bolivina* spp. and opportunistic species (Bartels-Jónsdóttir *et al.*, 2006). *C. laevigata* and *H. balthica*, show an inverse abundance until AD 900 and convergence since then (Bartels-Jónsdóttir *et al.*, 2006). Together they denote persistent upwelling for the period AD 400–1300. *H. balthica* and *Nonion commune* (*N. arerizans* according to Bartels-Jónsdóttir *et al.*, 2006) have also been related to upwelling by Levy *et al.* (1993) and Diz *et al.* (2002, 2006). Both are abundant for AD 0–400, and reflect high flux of fresh labile organic matter related to upwelling and primary productivity (Bartels-Jónsdóttir *et al.*, 2006). Around AD 1800 *H. balthica* becomes very rare, being almost absent in the last 100 years. At AD 1330, the onset of the LIA is marked by a significant faunal change to low foraminiferal fluxes and diversity because of reduced quality and quantity of food. *Bolivina* spp., together with *Stainforthia fusiformis*, show rather low values from AD 0 to 1300, after which they increase to the highest values during the last century (Bartels-Jónsdóttir *et al.*, 2006). These species show high correlation with the increasing organic carbon content, which is, at this location, mainly of terrigenous origin. Species tolerant to salinity changes or brackish environments, such as *Ammonia beccarii*, *Haynesina* spp. and *Elphidium* spp., compose an important group of the total assemblage (Bartels-Jónsdóttir *et al.*, 2006) (Figure 5E), showing two times higher average values from AD 0 to 1300 (includes the RP, DA and MWP) than during AD 1300–1850 (LIA). During the last century average abundance increases to similar values as in the MWP (10%). In the Tagus Prodelta, epibenthic foraminifera (species such as *Valvulineria bradyana*, *Cibicides* spp., *Cancriis auriculus* and *Planorbulina mediterraniensis* that live at the surface of the sediment) decrease from 13% during AD 0–500, to 10% until AD 1300 and 8% to AD 1800 (Figure 5F). In soft

sediments the epibenthic species also live in the top centimetre of the sediment (shallow infaunal) and are known to respond to good quality food levels at the sediment–water interface (Diz *et al.*, 2004). On the basis of benthic foraminiferal assemblages changes, Bartels-Jónsdóttir *et al.* (2006) distinguished four well-defined consecutive phases in the Tagus Prodelta waters for the last 2000 years, which fit the four climatic periods. In the RP (AD 0–400) upwelling conditions bring nutrients from deep waters, leading to flux of fresh labile organic matter; in the DA and MWP (AD 400–1400) even more persistent upwelling occurs; at AD 1300–1400 a significant climatic change happens with a decrease in the quality of food available in bottom waters presumably caused by river runoff that remains over the LIA (AD 1400–1800); and the last two centuries that are warm and reveal the effect of anthropogenic activities.

In the Muros Ría, the external site (EUGC-3B) is dominated by *Bulimina gibbalelongata*, *Nonion commune*, *Rectuvigerina phlegeri* and *Uvigerina* sp. (referred to as the outer Ría assemblage), while in the inner site (EUGC-2) *Eggerelloides scaber* and *Elphidium gerthi* (inner Ría assemblage), as well as epifaunal taxa (*C. refulgens*, *P. mediterraneensis*, *Rosalina* spp., *G. praegeri*, *L. lobatula* and *E. pulchella*) are the most abundant. Similar assemblages are found in the neighbouring Vigo Ría (Diz *et al.*, 2004, 2006). In the Galician rías, *A. beccarii* is considered as a separated marker because its presence could indicate transport processes from shallower areas. EUGC-3B is dominated by high values (40–50%) of the outer Ría assemblage from AD 0 to 600 and between AD 1000 and 1200, low values occur between AD 850 and 1000, and there is a sharp decrease around AD 1200 (Figure 5E). The inner Ría assemblage in core EUGC-3B shows low-amplitude variability around 5% from AD 0 to 500, and higher amplitude centred at 8% between 500 and 1250 AD, followed by a gradual decrease. *A. beccarii* follows a similar pattern, with very low values after the abrupt change at AD 1250. In core EUGC-2, the inner assemblage exhibits increasing values (up to 30%) from AD 0 to 600 (Figure 5E), and then a progressive decrease is recorded to present times, on which important fluctuations are superimposed. *A. beccarii* oscillates around 5% up to AD 1250, when its percentage abundance declines as at the outer site. In the outer Muros Ría, the epifaunal species are rather stable until around AD 1100 when they increase and the  $\delta^{13}\text{C}$  becomes heavier (Figure 5B). In the inner Ría, the epifauna falls slightly during the first 1000 years of the record collapsing at AD 500–700. This minimum coincides with a well-marked event of lighter carbon isotopes assumed to represent stagnant water. These species increase again during the last millennium reflecting steadily enhanced marine upwelling conditions (Figure 5F). The evolution of the assemblages during the last 2000 years emphasizes the different conditions between the outer and the inner sites, with core EUGC-3B and EUGC-2 dominated by the inner assemblage and the epifauna until AD 1100. Thus a widespread inner Ría benthic assemblage, associated with light and quite constant  $\delta^{13}\text{C}$ , and high organic carbon of terrestrial provenance, reveals local conditions until AD 1100 (Figure 5E). Progressively, after AD 1250 the outer assemblage becomes more abundant, indicating improved water ventilation, also supported by heavier  $\delta^{13}\text{C}$  isotopes, suggesting a more active circulation caused by intrusion of upwelling waters that reach the inner part with a delay of 300 years. The Muros Ría behaviour resembles that of the Vigo Ría to the south (Diz *et al.*, 2002).

In summary, benthic foraminiferal assemblages are mainly controlled by water mass properties (temperature/salinity), and primary productivity and oxygen concentration in the bottom

(Figure 4). Even in shallow water environments it is difficult to discriminate the effect of these factors in benthic foraminiferal assemblages (van der Zwaan *et al.*, 1999). In the Tagus Prodelta, the assemblages show prevailing upwelling conditions until around AD 1300, when they are overtaken by river-induced productivity. Even in the Muros Ría assemblage, which shows only strictly local dynamics until AD 1150, the later period is influenced by the open marine regional Atlantic signal with invasion of upwelled waters. The strong 'suboxic' event detected between AD 550 and 700 in the inner Ría, is barely recognized either in the outer Ría or the Tagus Prodelta.

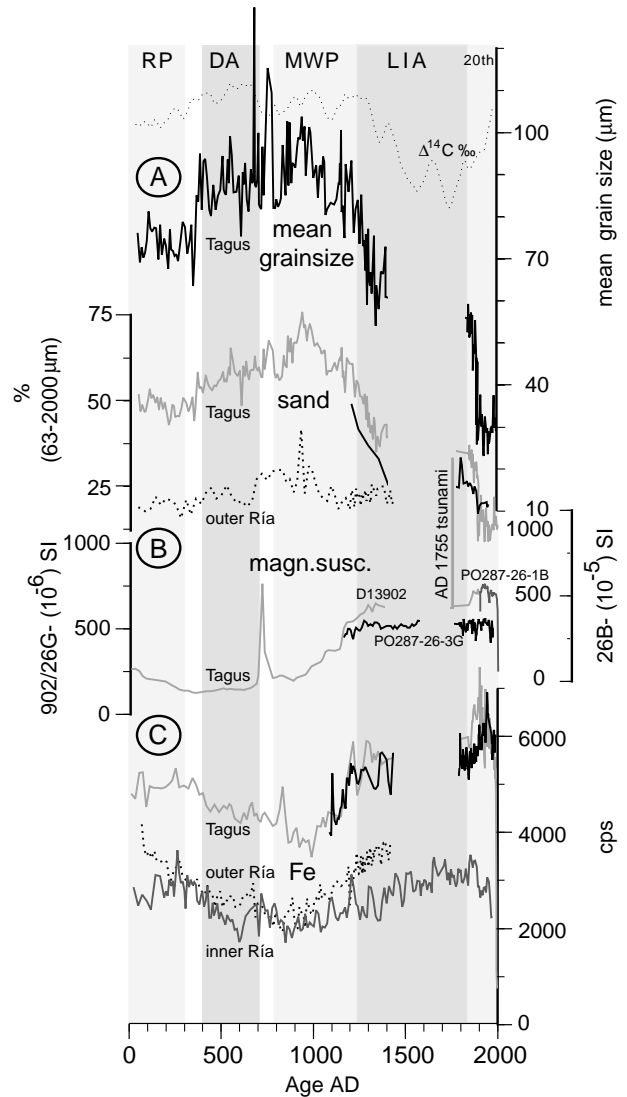
### Evolution of Tagus Prodelta and Muros Ría sedimentary regimes during major climatic changes

The two sedimentary systems compared in this study are affected by different dominant marine and continental processes at different times. The Tagus Prodelta is situated in a marine domain affected by river discharge (from the Tagus River). The Muros Ría is a semi-enclosed environment dominated by continental input (Tambre River) and processes involving organic matter production and preservation, and is only temporarily influenced by more open coastal processes.

The Tagus Prodelta, between AD 400 and 1300, shows percentages of sand above 45%, corresponding with mean grain size greater than 70  $\mu\text{m}$ . This sand fraction contains mainly biogenic particles such as marine foraminifera (Figures 6A, 4E). Before AD 400 sand values do not exceed 45% and from AD 1100 to present values decrease dramatically to about 10% around AD 1900, pointing to abrupt changes in the regime from dominant marine to fluvial inputs at  $\sim$ AD 1300. Magnetic susceptibility variations represent magnetic minerals concentrated in the fine fraction ( $<$  63  $\mu\text{m}$ ) (Figure 6B). Major elements, such as Fe, Ti, and K, widely considered as continental-derived markers (eg, Adegbe *et al.*, 2003) (Figure 6C) mimic magnetic susceptibility and finer grain-size fractions, supporting evidence for fine continental sediment input from river discharge. Instead,  $\text{CaCO}_3$  content reflects abundant marine foraminiferal sands (Figure 5A). In general terms, low organic carbon coincides with low values of terrigenous markers (Fe, Ti, K) and greater grain size.

We have mean grain size data only for the outer Muros Ría core (EUGC-3B). Between AD 400 and 1100, sand rises to 27%, with a relative minimum around AD 600 (Figure 6A), consisting of biogenic grains, mainly fragmented mollusc shells and agglutinated foraminifera. In this interval Fe concentration is low (Figure 6C). A slow increase in the mud content occurs from AD 1100 to 1470 (top sequence is missing) in core EUGC-3B, suggesting the contribution of very fine biogenic components, probably calcareous nannoplankton (Figure 5A). Fe and Ti concentrations from AD 0 to 400 and AD 1100 to 1900 in cores EUGC-3B (outer Ría) and EUGC-2 (inner Ría) are high, corresponding to fine grain sizes. Over the last century, land markers (Fe, Ti, K) mimic the Tagus Prodelta record. Low TOC correlates with high terrigenous markers in the outer Ría, the inverse of the Tagus.

Comparing the two areas, there is double the amount of sand in the Tagus record than in the Muros Ría. At first glance, based on grain size and major land markers, the two sedimentary environments appear apparently similar: finer sediments and high Fe-Ti during the coldest periods and coarse biogenic sands and low Fe-Ti during warm periods. However, assumed correlation between Ca-Sr, and Fe-Ti, with provenance of marine and terrigenous components, respectively (eg, Arz *et al.*, 1999) is correct in the Tagus, but shows an inverse trend in Muros.



**Figure 6** Comparison of land input indicators between the Tagus Prodelta and the Muros Ría. A, mean grain size and % sand; B, magnetic susceptibility; C, Fe in counts per second, similar to Ti and K. Note change of scale in magnetic susceptibility for the Tagus core PO287-26-1B. The curve of  $^{14}\text{C}$  solar activity from Figure 3D is given for reference. RP, Roman Period; DA, Dark Ages; MWP, 'Mediaeval Warm Period'; LIA, 'Little Ice Age'; and 20<sup>th</sup>, twentieth century. See text for details

Regarding the faunal species as independent indicators, the two sedimentation regimes diverge in their character. During the DA and MWP (AD 400 to 1300) in the Tagus Prodelta, coarse biogenic sand is of marine origin, concurrent with shelf foraminiferal species such as *C. laevigata* and upwelling-related diatom species, while in the Muros, coarse biogenic sand coincides with brackish foraminifera, the dominant inner assemblage, and more benthic diatoms, likely indicating freshwater discharge of the Tambre River. During the colder LIA (AD 1300–1850), high mud accumulation and Fe-land markers, but absence of diatoms in both areas, point to stratified waters. Although productivity is related to increased river-runoff in the Tagus Prodelta (Abrantes *et al.*, 2005a) intensification of upwelling conditions with better water ventilation occurs in Muros. In the neighbouring Vigo Ría, upwelling-related nannoplankton species dominate during the LIA (Álvarez *et al.*, 2005). Since AD 1900, the Tagus Prodelta has been under the influence of a strong continental regime, as proved by a 90% mud grain size and higher terrestrial Fe content, as well as high abundance of species dependent on refractory organic

matter (*Bulimina marginata*), presence of phytoliths, and lighter C and O isotope values. In Muros, a reinforcement of the upwelling conditions are indicated by heavier C isotopes and a higher proportion of marine foraminiferal species. Although we do not have a SST for the Muros Ría, Diz *et al.* (2002) show both  $\delta^{18}\text{O}$  and SST curves for the Vigo Ría and, taking into account the close similarity between the Tagus and Muros isotope curves, we can assume a comparable SST (western Galicia). The twentieth-century SST show, for both south and north Iberia, temperatures similar to those characterizing the LIA.

### Climate forcing mechanisms

The Holocene spectrum of the carbon isotope benthic foraminifera of core EUGC-3B was analysed by Pena *et al.* (L.D. Pena, G. Francés, P. Diz, M.A. Nombela and I. Alejo, unpublished data, 2006) who found a mean periodicity of  $1500 \pm 500$  years (the so-called 'Bond events'). The DA and LIA would be the two most recent 'cold' isotopic events (Bond *et al.*, 2001). At the millennial-scale, Pena and co-authors attributed changes in hydrographic conditions to the N–S migration of the ENACWsp/ ENACWst front, and linked the cold episodes (warmer, eg, MWP) with enhancement of ENACWsp (ENACWst) upwelling, and hence heavier  $\delta^{13}\text{C}$  (lighter), indicating ventilation at the sea floor, and retention of the organic matter produced in the Ría. Bond *et al.* (2001) demonstrated statistically significant coherence among records in millennial (hematite stained grains) and centennial ( $^{14}\text{C}$ ,  $^{10}\text{Be}$ ) bands. It seems then that a solar forcing mechanism underlies the North Atlantic millennial-scale surface hydrographic changes (Stuiver *et al.*, 1997; Chapman and Shackleton, 2000; Bond *et al.*, 2001; Mayewski *et al.*, 2004). In fact, solar activity, reflected in atmospheric  $\Delta^{14}\text{C}$  concentrations, forces changes in the oceanic circulation with centennial-scale (the 80 yr Gleissberg cycle) cyclicity (Keller, 2004). Several other authors have specifically coupled the MWP/LIA to changes in solar activity (Crowley, 2000; Bard *et al.*, 2000; Keller, 2004), including workers focussing on Iberia (Diz *et al.*, 2002; Desprat *et al.*, 2003). Higher production rates of cosmogenic nuclides are related to reduced solar irradiance (Masarik and Beer, 1999).

If one looks into the higher frequency of curves from our Tagus and Muros sites, both millennial (DA, MWP, LIA) and centennial-scale variability is observed. Our proxies for temperature, salinity, primary productivity and water ventilation (oxygen and carbon isotopes, organic carbon, foraminifera and diatom records) match strikingly the atmospheric  $\Delta^{14}\text{C}$  swings. This cannot be a coincidence. In the DA and MWP period, the Tagus foraminiferal oxygen isotopes follow closely each maximum/minimum of the solar activity curve (Figure 3A,D). In addition, the main concentration of diatoms match the three solar maxima (Figure 5D). High  $C_{\text{org}}$  (Figure 5B) and lower mean grain size values (Figure 6A) are, however, tied to reduced solar output. Therefore, indicators of oceanic circulation and dominant upwelling during the DA and MWP seem to have a more direct relationship with maximum solar centennial-scale irradiance. Conversely, indicators of terrestrial inputs coincide with minimum solar activity during the LIA. This is in agreement with our previous hypothesis of an oceanic (terrestrial) influenced MWP (LIA). According to Keller (2004) the magnitude of solar forcing does not necessarily respond to the amount of solar activity, as indirect solar forcings, like biogeochemical intermediate processes, could account significantly for climate variability. In fact, if we analyse the Muros Ría, for the same DA and MWP period, the primary productivity-related proxies are the ones connected

with solar maxima. For example, what we called the 'suboxic' light  $\delta^{13}\text{C}$  DA-event, localized in the inner Ría, is contemporaneous with diatom blooms, high  $C_{\text{org}}$ , reduced epifauna and flux of freshwater (Figure 5B–F) and links with the DA highest solar irradiance over the last 2000 years. Thus, in the Ría, solar forcing at a millennial scale seems to influence hydrographic changes, while primary production and organic carbon degradation processes appear to reflect the centennial scale of solar activity.

Most of our records reveal an enhancement of biogeochemical processes during the twentieth century not seen during the previous 1900 years. This might be due to less oxidation of sediment given the shorter passage of time since deposition. On the other hand, Mayewski *et al.* (2004) might be correct in stating that indirect natural feedbacks amplify the weak forcing related to fluctuations in solar output. Furthermore, Lean and Rind (2001) and Keller (2004) conclude that less than half of the twentieth-century warming was caused by an increase in solar irradiance.

However, hydrography is not only affected by millennial and/or solar activity. At a multidecadal scale, the atmospheric NAO system with persistent positive (stronger pressure differences) and negative (weaker North–South gradient) modes during the MWP and LIA, respectively, seem to cause biogeochemical changes in the subtropical eastern North Atlantic (Abrantes *et al.*, 2005a), and also in the western North Atlantic (Sargasso Sea; Keigwin, 1996). In the Tagus Prodelta, long-term negative NAO characterizes the LIA, with storminess, excess precipitation and river discharge, while the MWP presents more frequent extreme positive NAO, producing enhanced upwelling (Abrantes *et al.*, 2005a). Álvarez *et al.* (2005) present the opposite scenario for DA–MWP and LIA at the Vigo Ría, in agreement with the climatic changes we propose here for the Muros Ría. After reconstructing precipitations for the last five centuries, Pauling *et al.* (2006) assert that winter precipitation over southern Iberia is mainly maintained by the negative NAO mode, whereas European winter precipitation is rather insensitive to NAO. The northwest of Iberia, Galician Rías Baixas, is positioned between the two NAO poles, explaining the contrary sedimentary conditions when compared with the Tagus during the MWP/LIA. The results of Pauling *et al.* (2006) also suggest that the connection of precipitation to large-scale atmospheric circulation over decadal timescales is not stable on its own, requiring complementary patterns, other than the NAO, to explain precipitation variability. Kirov and Georgieva (2002) go further, suggesting the influence of long-term solar activity on the NAO, forcing the position and strength of its poles. With respect to the DA, the Tagus light oxygen isotopes, SST and solar irradiance correlate with the North Atlantic low temperatures of Mann and Jones (2003), supposedly regulated by the atmospheric NAO (Figure 3A,C,D). In detail, however, there are significant discrepancies, and biological feedbacks cannot be ignored.

Overall, in the Iberian peninsula, high-resolution sedimentary sequences reveal solar irradiance plus the NAO (or maybe the latter is also forced by solar irradiance), as the two (or one) main climatic driving mechanism(s) inducing changes in atmospheric and water circulation, and climate as a whole.

## Conclusions

Solar activity and the NAO are the two forcing mechanisms behind the changes of temperature/salinity and primary production in the water and the sediment regimes in the Tagus

Prodelta and Muros Ría. Our biogeochemical proxies respond to climatic variability at millennial and centennial to the (multi-)decadal scales.

The most distinct change occurs at the transition between the MWP and the LIA in both areas, although with opposing hydrographic signals. In the Tagus, ocean circulation (productivity and coastal upwelling) dominates the MWP whereas precipitation (river flux and continental inputs into the shelf) takes over during the LIA. In the Muros, at AD 1200 a fluvial regime switches to an open marine regime. Before AD 1200, local processes related to productivity and organic carbon preservation characterize the Ría. We attribute these climatic changes to long NAO trends, either dominant river runoff mode (NAO<sup>-</sup>) or dominant upwelling mode (NAO<sup>+</sup>) in the northern and southern sites. The reversal in both areas depends on the latitudinal migration of the persistent position of the Azores/Lisbon and Iceland pressure poles. In the Tagus area it is also possible to distinguish the RP and DA on the basis of hydrographic changes. The DA could have been as warm as the MWP. In the inner Muros Ría, a 'suboxic' event is detected in the DA (AD 500–700). Solar irradiance maxima and minima are closely connected to biogeochemical changes in both areas over the last 2000 years.

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