The last 3000 years in the Ría de Vigo (NW Iberian Margin): climatic and hydrographic signals
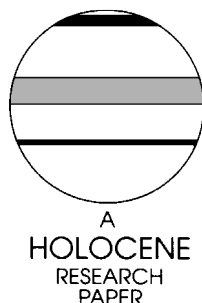
Paula Diz,[1]* Guillermo Francés,[1] Carles Pelejero,[2]** Joan O. Grimalt[2] and Federico Vilas[1]

(*[1]Department of Xeociencias Mariñas e Ordenación do Territorio, Facultad de Ciencias, University of Vigo, 36200 Vigo, Spain; [2]Department of Environmental Chemistry (ICER-CSIC), Jordi Girona, 18, 08034 Barcelona, Catalonia, Spain)*

Abstract: The hydrographic evolution of the Ría de Vigo (NW Spain) during the last 3000 years has been reconstructed using benthic foraminiferal assemblages, stable oxygen isotopes, molecular biomarkers and sea-surface temperatures (SST) reconstructed from the U_{37}^{K} index. Benthic oxygen isotopes and SST records provide evidence of episodic salinity contrasts between surface and bottom waters. The comparison of SSTs with other climate records for the Northern Hemisphere has allowed the inference of oceanographic and climatic signals, which describe the changes in hydrographic conditions of the ría. In general, two different periods can be recognized. From 975 cal. BC to cal. AD 1000, the organic carbon is mainly of continental origin, benthic foraminiferal assemblages are typical of environments that are poorly oxygenated, rich in organic matter and dominated by eurihaline taxa. Percentages of planktonic foraminifera are low and SSTs are warmer than today. These data suggest a restricted environment where the exchange with open ocean waters was diminished. At cal. AD 1000, an important hydrographic change in the ría circulation involved an intensification of coastal upwelling processes as reflected in colder SSTs and increases in the contribution of marine organic carbon and planktonic and opportunistic benthic foraminifera. In these conditions, the sediments of the ría recorded not only local factors but also several well-known Northern Hemisphere climate signals.

Key words: Benthic foraminifera; ría, palaeoclimatology, sea-surface temperature, C_{37} alkenones, *n*-hexacosan-1-ol, molecular biomarkers, oxygen isotopes, late Holocene, Spain.

Introduction

Recent studies suggest that the Holocene had a more dynamic climate than previously thought, exhibiting significant variability over millennial timescales (Bond *et al.,* 1997; 1999; Bianchi and McCave, 1999). In particular, several climate oscillations have characterized the last 3000 years. Important climate changes related to solar forcing have been identified around the Subboreal-Subatlantic transition (van Geel *et al.*, 1996; 2000). Recent attention has been focused on the two youngest intervals of contrasting climate during the last millennium, i.e., the 'Mediaeval Warm Period' (MWP) and the 'Little Ice Age' (LIA). Evidence for these warm and cold climate stages comes from historical data (Lamb, 1995), marine records (Keigwin, 1996; Bianchi and McCave,

1999; Bond *et al.*, 1999), ice cores (Meese *et al.*, 1994; O'Brien *et al.*, 1995; Dahl-Jensen *et al.*, 1998; Kreutz *et al.*, 1997) and alpine glaciers (Grove, 1988). These climate oscillations seem to be related to variations in solar output in the last millennium (Stuiver *et al.*, 1997), but solar forcing itself can not explain the whole Holocene climate record. Other mechanisms must be invoked; oceanic/atmospheric forcing certainly seems to play an important role (Broecker *et al.*, 1999; Bond *et al.*, 1999; Keigwin and Boyle, 2000).

Records of Holocene climate fluctuations from shallow marine environments are very scarce. However, the high sedimentation rates that characterize shallow marine areas allow the attainment of very detailed reconstructions in terms of temporal resolution. Thus, such environments allow the study, over short time periods, of the timing and geographic extent of both the local and the global climate forcing mechanisms.

The present work is devoted to the reconstruction of the hydrographic changes in an incised valley, the Ría de Vigo (NW Spain), by means of the study of a 380 cm long sediment core which

spans the last 3000 years. The high sedimentation rates have allowed several aspects of the palaeoenvironmental evolution of the Ría de Vigo to be established accurately. Benthic foraminifera assemblages, stable oxygen isotopes, molecular biomarkers and sea-surface temperatures reconstructed from the $U^{K'}_{37}$ index have been used with this aim. The whole data set has been compared to several relevant climate reconstructions for the Northern Atlantic region in order to determine how the global variations are recorded on the Ría de Vigo. Overall, it appears that, depending on the regional circulation pattern, the signal of local processes can mask those from global climate or vice versa.

Environmental setting

The Galician Rías Baixas are a set of four incised valleys located in the northwest of the Iberian Peninsula, the Ría de Vigo being the southernmost one. It consists of an elongated funnel-shaped embayment of 33 km long and 10 km wide at its mouth, which is partially closed by a group of islands. The most important bathymetric feature is the central channel with a maximum depth of 48 m. Shallower areas are located towards the margins and the inner part (Figure 1). The mean circulation of the Ría de Vigo is driven by tides, freshwater discharge and winds (Prego and Fraga, 1992). The most significant freshwater input comes from several relatively small rivers that flow into San Simón Bay, which behaves as an estuary. The rest of the ría is under strong oceanic influence and exhibits a residual circulation in two layers, a sur-

face current running towards the ría mouth and a bottom current running in the opposite direction (Fraga and Margalef, 1979). These two water bodies give rise to a stratified system that is normally maintained throughout the whole year. Winds play an important role in the circulation causing upwelling and down-welling cycles with a strong seasonal pattern. During winter, under the influence of strong southerly winds, downwelling takes place and surface water accumulates at the coast, obstructing the outflow of freshwater. Low water renewal and nutrient impoverishment are characteristic of these conditions. During summer, northerly winds, blowing on the Galician coasts from April to September, force cooler and nutrient-rich Eastern North Atlantic Water (ENAW, Ríos *et al.*, 1992) into the Rías Baixas, increasing the marine productivity. The marine productivity of the Ría de Vigo is therefore lower in winter than in summer (Prego, 1993). The mean annual value is very close to the typical values encountered in continental-shelf areas (Romankevich, 1984). However, during upwelling events it can reach values similar to those measured on the NW African upwelling systems (Huntsman and Barber, 1977).

The surface distribution of sediments is controlled by the water dynamics described above. A detailed description can be found in Vilas *et al.* (1995). Around the central axis, in the deepest areas, surface sediments mainly consist of organic-rich mud (4–6% of organic matter). Near the margins and contouring the mud, the sea bed is often sandy (2–4% of organic matter). Gravel, which is mainly bioclastic, is restricted to the northern edge, close to the coastline (Figure 1).

Samples and methods

The present study is based on material from core Vir-18 (42°14.07N, 8°47.37W; 45 m of water depth and 380 cm of length) recovered from the muddy central axis in 1990 (Figure 1). The core was split and x-rayed. After splitting, it was visually described and sampled. Subsamples 2 cm thick were taken at every 10 cm interval. These were used for analysis of molecular biomarkers, oxygen isotopes and benthic foraminifera. The core was also sampled in order to determine sedimentological features, including grain-size analysis and organic carbon content.

The particle-size distribution of the sediments was measured using a combination of dry-sieving for grain sizes larger than 63 μm and x-ray nephelometry for particles smaller than 63 μm (Micromeritics, Sedigraph 5100). Clay is the most frequent grain size along the core (55% of medium value). The average silt content is 43%, displaying a gradual decrease of about 5% from the base to the top. The percentages of coarser fractions, sand and gravel, are lower than 17% and consist of bioclastic fragments of bivalves and gastropods. Higher contributions of sand and gravel are found at the bottom of the core (380–376 cm) and within the 338–277 cm interval (Figure 2B). The colour of the sediment is mainly dark olive-grey, but it is noteworthy that a change to lighter colours occurs between 347 and 338 cm. Bioturbation is the only sedimentary structure observed and is recorded in the core by intervals, no more than 1 cm thick, of lighter colour (Figure 2A). The Sawerlandt method modified by Guitián and Carballas (1976) was used for organic carbon measurements. The data are given as weight per cent of organic carbon relative to the dry sediment.

The samples used for microfossil analyses were dried (<50°C), weighed, soaked in distilled water, washed through 125, 63 and 37 μm sieves, dried and weighed again. A microsplitter was used to obtain a representative split of 300 benthic foraminifera from the >125 μm fraction, although in some levels the whole sample had to be used owing to the scarcity of individuals. Higher concentrations of benthic foraminifera are recorded at intervals of
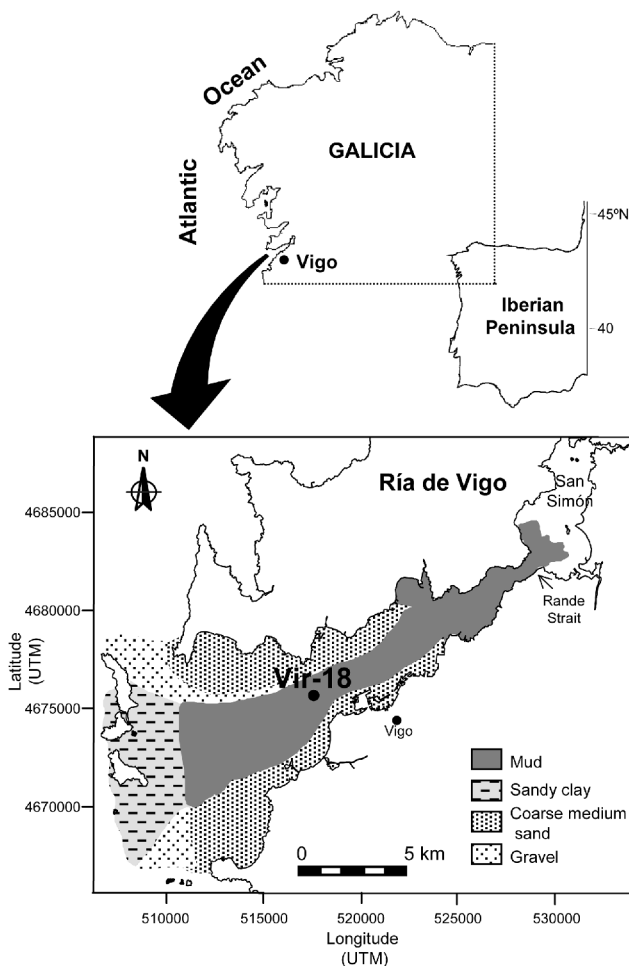

Figure 1 Situation of the Ría de Vigo. Simplified distribution map of the present surface sediments (modified from Vilas *et al.*, 1995) and location of core Vir-18.
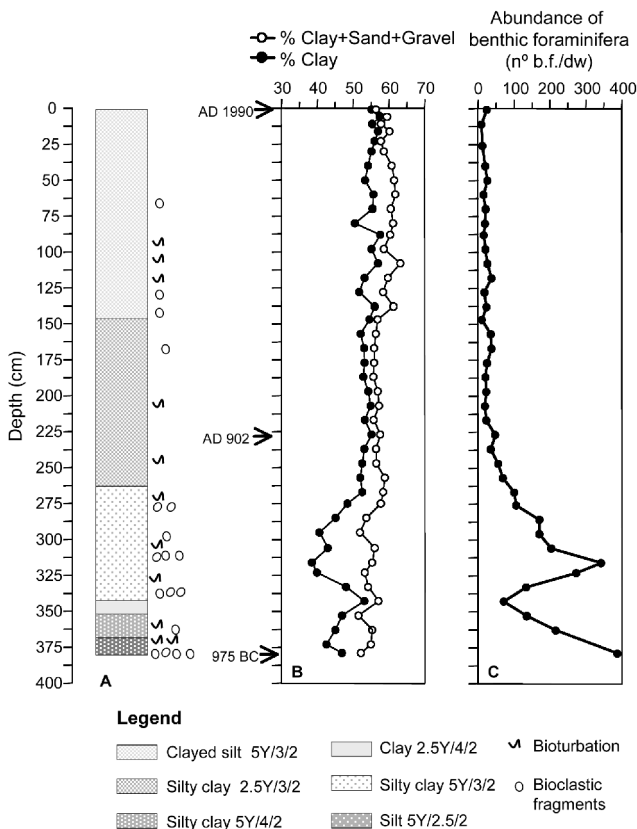
Figure 2 Sedimentological features of core Vir-18. (A) Lithological description of the main sedimentological features; the sediment colour given in the legend refers to the Mussel Soil Color Chart. (B) Percentage of clay and clay + sand + gravel. (C) Concentration of benthic foraminifera expressed as number of foraminifera in the >125 μ m fraction per gram of bulk dry weight sediment. Arrows indicate the position of radiocarbon dated samples, and numbers the middle point of calibrated dates. For details about radiocarbon dates, see Table 1.

higher contribution of sand and gravel (Figure 2C). For each split the percentage of planktic foraminifera has been calculated.

The $\delta^{18}O$ record is based on about 70 handpicked specimens per sample of *Cibicides* spp. although most of them were *C. ungerianus* (d'Orbigny). These analyses were carried out at the P203/97 Laboratory of the University of Salamanca. They have a precision of $\pm 0.069‰$. Results are expressed in the δ notation referred to the PDB standard.

C_{37-38} alkenones and the long chain alcohol, *n*-hexacosan-1-ol, were analysed following the method of Villanueva *et al.* (1997b). The concentration of each compound is expressed both as μ g/g of dry weight sediment and normalized to total organic carbon (μ g/gC), for comparison purposes.

SST was reconstructed from the unsaturation index $U_{37}^{K'}$ (Prahl *et al.*, 1988) using the global core-top calibration equation of Müller *et al.* (1998; $U_{37}^{K'} = 0.033$ SST + 0.044). The $U_{37}^{K'}$-SST value obtained in this way for our top core sample (14.1°C) matches precisely the instrumentally measured values in the area (14°C at 15 m water depth under moderate upwelling conditions; Alvarez *et al.*, 1999). This value is similar to the six years average of bottom-water temperatures (40 m) measured in a fixed station situated very close to the core sampling site during the occurrence of phytoplankton blooms (13.2°C; Nogueira *et al.*, 1997). Unfortunately, most of the studies to date on primary production in the Ría de Vigo have been focused on diatom, dinoflagellates and ciliates (e.g., Margalef *et al.*, 1955; Durán *et al.*, 1956) and, to the best of our knowledge, there are no reports available on the seasonal dynamics of Haptophyceae algae for this area. In the

absence of these data, and after the close matching of our uppermost $U_{37}^{K'}$-SST values to the modern temperatures during the upwelling season, we suggest as a first approximation that coccolithophorid species probably proliferate, following closely the reported periods of maximum productivity of the studied phytoplanktonic species (April to September, as mentioned above). This situation is also the most likely in view of the scheme proposed by Margalef (1978; see also Young, 1994) which included *Emiliania huxleyi* (Lohmann) (one of the main C_{37-38} alkenone producers; see Interpretation and discussion below) as a characteristic species of mid-succession eutrophic conditions.

The chronology of our core is based on two AMS radiocarbon measurements on bivalve shells (*Venus* sp.) found in living position, one at the 226–228 cm interval and the other at the core bottom, 380 cm, where bioclastic fragments are present. These analyses were carried out in the 757–138 Paleobotany and Paleolimnology Laboratory of the University of Utrecht. Radiocarbon data were converted into calibrated ages using the radiocarbon calibration program Calib 4.3 (Stuiver and Reimer, 2000, based on Stuiver and Reimer, 1993). Owing to the short water residence time of the ría, which depends upon upwelling conditions (Prego and Fraga, 1992) no local reservoir effect was considered (Table 1; Figure 2).

Results

Organic carbon and molecular biomarkers
Organic carbon content of the sediments defines three well-differentiated intervals (Figure 3A). From the bottom core to 353 cm (650 cal. BC), significant abrupt variations up to 2% are observed, which could be related to bioturbation. From this first interval and between 347 cm and 338 cm (560–420 cal. BC) the lowest organic carbon content values (1.7%) are encountered, coinciding with the lighter colours described (Figures 2 and 3A). At 330 cm (about 400 cal. BC) a pronounced increase in organic carbon content is observed, reaching mean values of about 4.5% which are maintained till cal. AD 1290. In the uppermost differentiated interval, from 140 cm (cal. AD 1330) to the top, the values drop back and are around 1% lower (Figure 3A).

Variations in selected molecular biomarker abundances through a sedimentary record have often been used to assess the relative importance of the different organic matter contributions over time (Prahl *et al.*, 1988; Villanueva *et al.*, 1997a). *n*-Hexacosan-1-ol can be considered of terrigenous origin, being derived from terrestrial higher plants (Eglinton and Hamilton, 1967), and long-chain unsaturated alkenones are biosynthesized by some Haptophyceae algae: among them, the cocolithophorid *E. huxleyi* is the most ubiquitous (Volkman *et al.*, 1980; Marlowe *et al.*, 1984). In this respect, recent coccolithophore counting performed for the same core has revealed significant and stable percentages of *E. huxleyi*

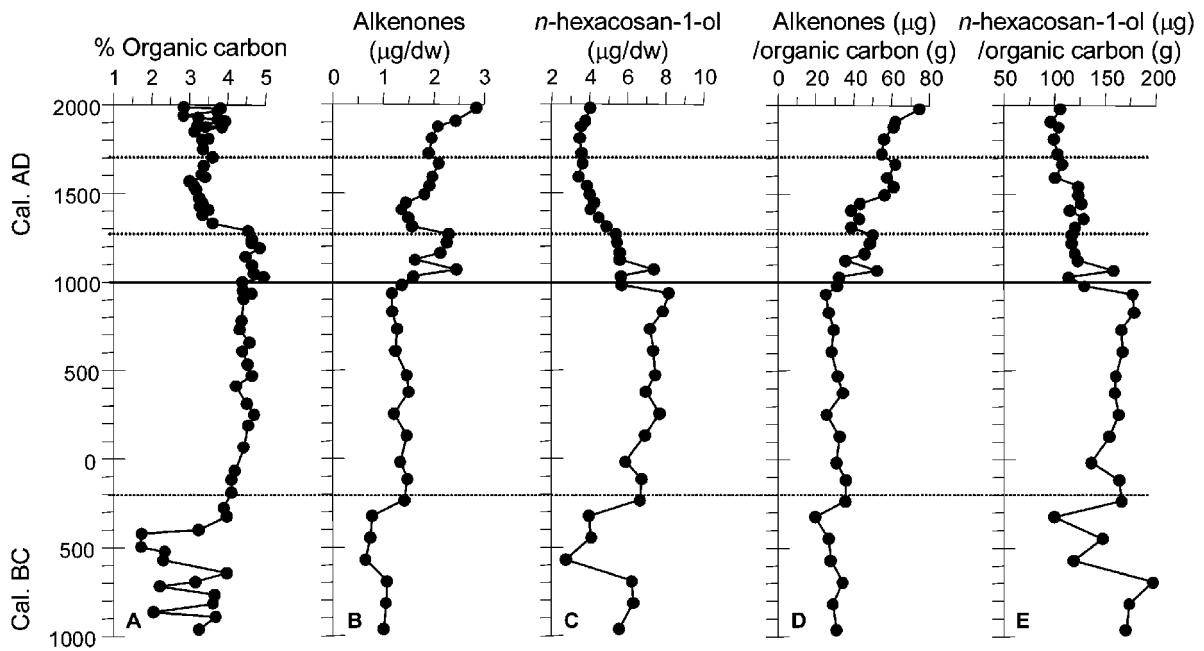| Lab. number	Sample number	Radiocarbon date BP	Calibrated date	Calibrated age BP
UtC-5956	Vir-18, 226–228 cm	1502 ± 27	AD 881 (902) 946	1069 (1048) 1004
UtC-5957	Vir-18, 380 cm	3151 ± 32	1010 (976) 9235 BC	2959 (2925) 2872

Figure 3 Percentage of organic carbon (A). Concentrations of molecular biomarkers in $\mu g/g$ of dry weight sediment; alkenones (B) and *n*-hexacosan-1-ol (C). Normalization of alkenones (D) and *n*-hexacosan-1-ol (E) to organic carbon ($\mu g/gC$). Solid line indicates the most important change on benthic foraminifera assemblages; dashed lines separate the five main assemblages of benthic foraminifera (see text and Figure 4).

for the whole period, which points towards a dominant role of this species in the long chain alkenones input in the studied setting (Alvarez *et al.*, 2000).

The abundances of these marine and terrigenous markers are remarkably high, between 0.5–3 $\mu g/g$ and 2–8 $\mu g/g$ for C_{37} alkenones and *n*-hexacosan-1-ol, respectively (Figure 3, B and C). Their concentration profiles display significantly different patterns. Throughout most of the record, the concentration of *n*-hexacosan-1-ol follows a similar trend to that for organic carbon contents, which qualitatively suggests a dominance of terrigenous organic matter to the sediments (Figure 3, A and C). This is particularly so for the period between 975 cal. BC (core bottom) and around cal. AD 930 (221 cm depth) and suggests a dominance of higher plant inputs to the sedimentary environment during that time. From 221 cm to 125 cm depth (cal. AD 1400), *n*-hexacosan-1-ol decreases from about 8 $\mu g/g$ to 4 $\mu g/g$ and then, between 125 cm to the core top, the values range between 3 and 4 $\mu g/g$. Conversely, during this period, alkenones reach high concentrations of about 2 $\mu g/g$ during a clear maximum centred at cal. AD 1000–1250 (200–150 cm), and then further increase towards the top of the core (2.8 $\mu g/g$; Figure 3C). This suggests an enhanced contribution of marine organic carbon to the sediments during the last 1000 years in the ría, an interpretation equally inferred by means of normalization of biomarkers to total organic carbon (Figure 3, D and E).

Benthic foraminifera assemblages

Benthic foraminiferal assemblages are dominated by calcareous forms. *Bulimina* spp. and *Nonion boueanum* (d'Orbigny) are the most common taxa throughout the core. *Bulimina* spp. includes mainly *Bulimina gibba* Fornasini and *Bulimina elongata* (d'Orbigny), although *Bulimina aculeata* d'Orbigny and *B. marginata* d'Orbigny are also present. From the base to the top of the core, five main assemblages have been identified (Figure 4). From 975 to 200 cal. BC the assemblage includes *N. boueanum*, *Bulimina* spp. and *Ammonia beccarii* (Linné). The latter shows a pronounced decreasing trend from 40% to 20% along this interval (Figure 4E). The second assemblage is found between 200 cal. BC and cal. AD 1000 and it is characterized by *Bulimina* spp.,

N. boueanum, *Cibicides ungerianus* (d'Orbigny) and *A. beccarii* (Figure 4, B, D and E).

The most significant change in the benthic foraminifera assemblage takes place at cal. AD 1000, when *A. beccarii* is progressively replaced by *Eggerelloides scabrus* (Williamson) (Figure 4, E and F). This shift also coincides with a significant increase in the percentage of planktonic foraminifera (Figure 4A). During the last 1000 years, three assemblages can be recognized. The first one (cal. AD 1000–1250) is dominated by *Bulimina* spp., *N. boueanum*, *C. ungerianus* and the agglutinated foraminifera *Discammina compressa* (Göes) and *E. scabrus*. The next assemblage (cal. AD 1250–1700) is dominated by epifaunal taxa like *C. ungerianus* and *D. compressa*. This period is also characterized by minor contributions of *Bulimina* spp. and *N. boueanum* as well as an oscillating percentage of *E. scabrus*. Finally, the youngest assemblage includes *E. scabrus, N. boueanum* and *Bulimina* spp. In particular, *E. scabrus* becomes progressively more abundant, reaching 49% at the core top (Figure 4F).

Sea-surface temperatures and the benthic oxygen-isotope signal

$U_{37}^{K'}$-SST values range from 13.3 to 16.4°C (Figure 5A). A long warm period with temperatures usually higher than 15.5°C appears between 975 cal. BC and cal. AD 1000. At about cal. AD 1000, SSTs begin to decrease until around cal. AD 1450–1500, when the lowest values of 13.3–13.5°C are recorded. From this minimum to present, there is a slight increase in $U_{37}^{K'}$-SST, albeit with a relative minimum (13.9°C) centred at cal. AD 1700. The stable oxygen-isotope signal shows maximum values at about 60 cal. BC and cal. AD 420 and the lowest value at cal. AD 1360. These differences with respect to SST could be due to the effect of parameters other than temperature (e.g., salinity) on the isotopic composition and/or the $U_{37}^{K'}$ ratio itself (see further discussion below).

In this sense, and prior to further interpretation of $U_{37}^{K'}$ data in terms of SST, examination of possible biases of this index due to salinity variations in this coastal environment has been performed. It is important to evaluate this since, recently, several studies have noted a significant anomalous pattern of this unsaturated index for
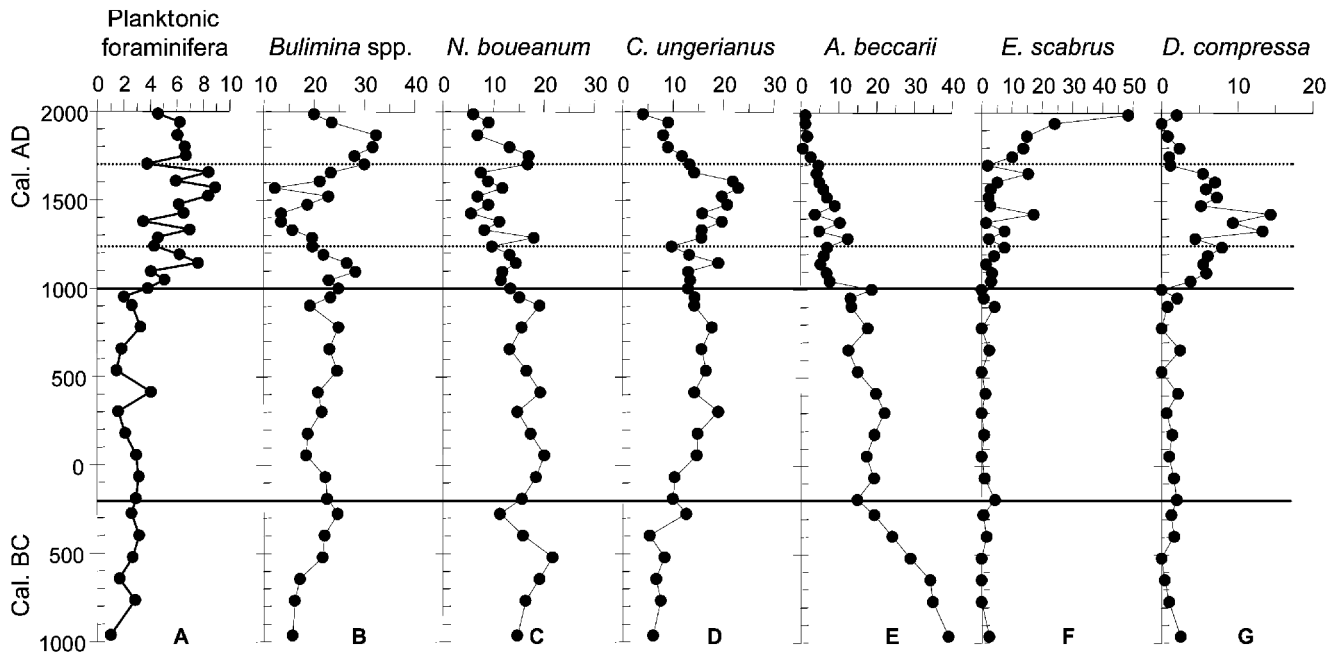
Figure 4 Constituents of the foraminiferal assemblages in core Vir-18: (A) percentage of planktonic foraminifera and (B–G) percentage of the most significant species of benthic foraminifera. Solid line indicates the most important change on benthic foraminifera assemblages; dashed lines separate the five main assemblages of benthic foraminifera (see text).
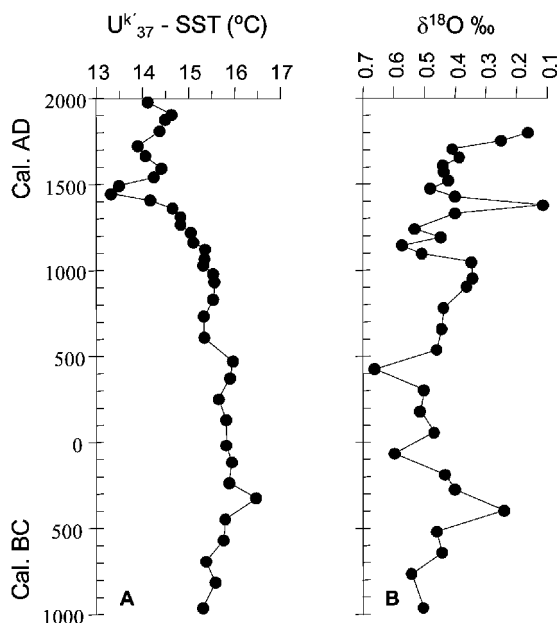

Figure 5 Sea-surface temperature (SST) curve reconstructed from (A) the $U_{37}^{K'}$ index and (B) downcore variation of the oxygen-isotope signal from benthic foraminifera (*Cibicides* spp.).

low-salinity areas. For example, in deep-sea sediments from the Baltic Sea, Schulz *et al.* (2000) have reported a poor correspondence of this index to temperatures for most of the fresher-water areas. A similar anomalous alkenone mixture was encountered in sediments from a Norwegian fjord during the times when it was characterized by a lacustrine environment (Ficken and Farrimond, 1995). Interestingly, these studies highlighted significantly higher concentrations of the C_{37} tetra-unsaturated compound as well as an absence of C_{38} methyl alkenones for these sediments corresponding to low-salinity environments which were indicative of alkenones deriving from other algae. Moreover, a broad core-top sediment survey from the North Atlantic and the Nordic Seas evidenced that, for sediments with percentages of the tetra-

unsaturated C_{37} alkenone higher than 5%, $U_{37}^{K'}$ was not a reliable palaeothermometer (Rosell-Melé, 1998).

Concerning the Ría de Vigo samples, important amounts of C_{38} methyl alkenones have been detected throughout the whole record and, for most of the samples, the tetra-unsaturated C_{37} compound was absent, being found only in small amounts during the coldest sections, according to the $U_{37}^{K'}$ record. In particular, only one sample displayed values close to 5% of the tetra-unsaturated C_{37} alkenone, which corresponds to the 114 cm depth section (about cal. AD 1450–1500 and the coldest period). Thus, in spite of the peculiar coastal characteristics of our studied area, the sedimentary composition of alkenones there encountered does not display any significant difference from most of the typical marine samples shown to provide reliable $U_{37}^{K'}$-SST measurements. Moreover, the ratio of C_{37} to C_{38} alkenones throughout the core ranges from 1 to 1.3, which falls within the typical interval for sediments from marine environments with a dominant input of alkenones from *E. huxleyi*.

Interpretation and discussion

The general feature of the benthic foraminifera assemblages is the prevalence of taxa related to organic matter-rich and poorly oxygenated environments, such as *Bulimina* spp. and *N. boueanum*. *Bulimina* spp. is found in the living assemblages at the muddy external areas of the Ría de Vigo, preferring an infaunal microhabitat. According to several studies (Sen Gupta and Machain-Castillo, 1993; Bernhard, 1996; Bernhard and Sen Gupta, 1999), the presence of this group is related to high organic supply and low oxygenation levels into the sediment. *N. boueanum* is the most common taxon of central and external muddy bottoms in Galician rías (Colom, 1952; van Voorthuysen, 1973). In the Ría de Vigo, *N. boueanum* shows a shallow infaunal behaviour and, from its seasonal distribution, it can be inferred that it is a species not adapted to very poor oxygenated environments (Diz *et al.*, 2000). In addition to the above-mentioned taxa, the two older assemblages present a significant contribution of *A. beccarii* (Figure 3E). This species is typical of shallow marine

environments, estuaries and lagoons (Fatela and Silva, 1990; Murray, 1991; Albani *et al.*, 1998; Sen Gupta, 1999) and thus tolerates a broad range of salinity and temperature. In this sense, and with regard to the Ría de Vigo, *A. beccarii* can be found alive either at the most external part of San Simón Bay or around Rande Strait (see Figure 1 for locations), an area with important salinity oscillations depending on the season, ranging from 31 to 35‰ (Prego *et al.*, 1986).

The important presence of *A. beccarii* from 975 cal. BC to cal. AD 1000 (Figure 4E) can be taken as evidence that the marine environment was unstable during this period, mainly due to frequent salinity changes, and that the sediments received an important supply of organic carbon mainly of terrestrial provenance. The latter is supported by the relatively higher contribution of *n*-hexacosan-1-ol than alkenones during this period and by the resemblance between the terrestrial proxy and the organic carbon curve (Figure 3). Moreover, normalization of *n*-hexacosan-1-ol concentrations to total organic carbon provides essentially the same information on greater terrigenous influence during this period (Figure 3).

From 570 to 420 cal. BC, the significant decreases in both organic carbon content and the concentrations of molecular biomarkers, together with pale sediment colours, suggest an important change in the water dynamics of the Ría de Vigo (Figures 2 and 3). Hence, the environmental conditions apparently led to a decrease in the organic carbon supply arriving on the sea floor, owing to decreased inputs from shallow areas or water-column productivity. The timing of this event corresponds approximately to the Subboreal-Subatlantic transition (Mangerud *et al.*, 1974), a period for which there is evidence for significant climate change in other shallow areas (van Geel *et al.*, 1996) and also in the Ría de Vigo (Margalef, 1956).

The most conspicuous microfaunal change is recorded at cal. AD 1000. At this time, a noticeable increase of planktic foraminifera percentage occurred, *A. beccarii* declined to very low abundances and agglutinated foraminifera increased progressively towards the core top. Moreover, the percentage of epifaunal species also increased, being the dominant taxa between cal. AD 1250 and 1700. All these changes in species abundance represent a transition from an eutrophic and changing system to one more similar to the present environment. In particular, during a first stage (cal. AD 1000–1700), the increase of epifaunal species together with the lowest percentages of *Bulimina* spp. and *N. boueanum* suggest a mesotrophic environment where the organic matter flux to the sea bed, which was mainly from marine provenance, was reduced. During the youngest stage, the environment again became eutrophic. The assemblage is dominated by *E. scabrus*, *Bulimina* spp. and *N. boueanum*. *E. scabrus* begins to be recorded at cal. AD 1000, showing an increasing trend until the present, when it reaches the 49% of the total foraminifera. This pattern is not continuous, but exhibits sharp fluctuations that are not attributable to taphonomic processes. First, *E. scabrus* is an important component of the living assemblage along the central axis of the Ría de Vigo. During winter it prefers a deep infaunal microhabitat, but in summer, when the productivity increases, it migrates to the surface. From the actual distribution and microhabitat preference of *E. scabrus*, it can be inferred that this species is adapted to high organic-matter concentrations and low oxygenation values in the sediment (Diz *et al.*, 2000). Moreover, high percentages of *E. scabrus* at the core top are in agreement with the increase of agglutinated foraminifera during the last decades (Alve and Murray, 1995; Alve, 1996). Recent increases of *E. scabrus* can be justified by the increase of organic inputs (Alve, 1995), caused by the intensification of aquaculture and subsequent organic enrichment (in fact, mussel farming has become a widespread activity during the last 30 years in the Ría de Vigo). Finally, a noticeable inverse relationship between lower percentages of *E.*

scabrus and cooler SSTs is apparent (Figure 6A). The same result is also found in a more seaward core (Vir-37), 2 km away from Vir-18 (Figure 6B). Accordingly, the high percentage of *E. scabrus* in the fossil record implies greater influence of oceanic water and enhanced water-column productivity. This interpretation is supported by the increasing trend of the C_{37} alkenones concentration during this period (Figure 3B). In this sense, the abrupt alkenone increase between cal. AD 1000 and 1250 coincides with the beginning of the higher percentages of epifaunal taxa, and from cal. AD 1700 to the present the significant increasing trend in this biomarker is closely followed by *E. scabrus* (Figure 4F). Moreover, the highest percentage of the most significant epifaunal taxa, *C. ungerianus* and *D. compressa* (cal. AD 1250–1700), coincides with a cooling in SST. This could indicate also a better oxygenation of the bottom waters during this period.

Accordingly, both benthic foraminiferal assemblages and molecular biomarkers reflect an important change on the environment of the Ría de Vigo around cal. AD 1000. It involved a transition from a restricted environment that supported frequent salinity changes and received mainly terrestrial organic carbon to one with more influence of oceanic waters.

Further insight into the origin of the change of these palaeoenvironmental conditions can be obtained by comparison of SST to other relevant climate records such as the relative ^{14}C atmospheric production for the last 3000 years (Stuiver *et al.*, 1998; Figure 7C), the borehole temperature reconstruction from the Greenland Ice Sheet (Dahl-Jensen *et al.*, 1998; Figure 7D), the Northern Hemisphere temperature reconstruction for the last 1000 years (Mann *et al.*, 1999a; Figure 7E) and the temperature index for Galician areas (Martinez-Cortizas *et al.*, 1999a; Figure 7B).

The relative ^{14}C atmospheric production curve, which relates inversely to solar insolation, shows two prominent maxima at 750 and 300 cal. BC (Figure 7C). The borehole temperature reconstruction also shows an increasing trend that culminates around AD 1000, coinciding with the MWP (Figure 7D). The shape of these curves is roughly coincident with the SST record of the Ría de
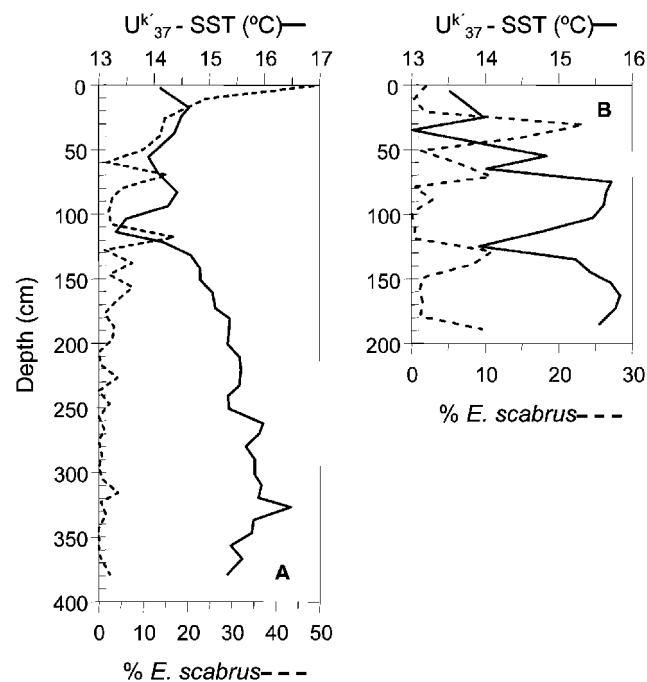

Figure 6 Relationship between SSTs reconstruction (solid line) and *E. scabrus* (dashed line) in (A) the studied core and (B) a more seaward core Vir-37, situated 2 km away from Vir-18. The inverse relation between both parameters is more significant in the external core.
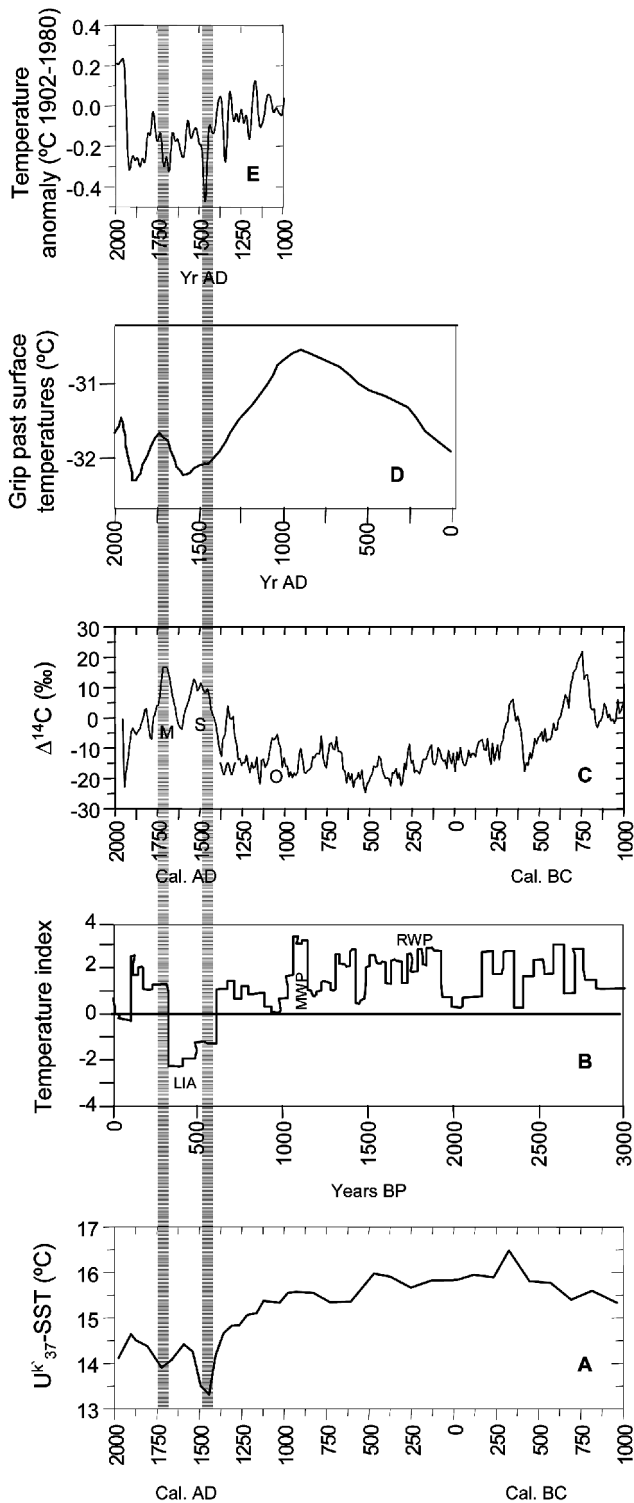
Vigo (Figure 7A). Furthermore, the Galician palaeoclimate curve also resembles our SST reconstruction, although it includes several fluctuations from temperatures very close to the present ones to warm periods like the Roman Warm Period (RWP) and the MWP (Figure 7B).

However, the high isotopic benthic $\delta^{18}O$ values at 60 cal. BC and cal. AD 420 do not coincide with low SST. This difference could be explained by strong salinity contrasts between surface and bottom waters: warmer and less saline surface waters could have enhanced water-column stratification accompanying events of a higher influence in runoff (Figure 5). In fact, these two phases of suggested enhanced water stratification are coincident in time with the RWP (2000–1500 yr. BP, 0–500 AD), which have been described as a rainy period for the northwest of Spain (Martinez-Cortizas *et al.*, 1999b). Alternatively, differences between oxygen isotopes and $U_{37}^{K'}$-SSTs could also be ascribed to deviations in the pattern of the alkenone mixture during periods of diminished upwelling and thus more important runoff, which seem to have prevailed from 975 cal. BC to cal. AD 1000. However, as indicated above, no significant amounts of tetra-unsaturated C_{37} alkenones were found during this period, which can be taken as evidence that expected decreases in salinity for the surface waters did not affect our $U_{37}^{K'}$-SST estimations. Moreover, and as already mentioned, studies on coccoliths from the same samples do not evidence significant changes in alkenone-producer species during the whole record (Alvarez *et al.*, 2000). Thus, it is very likely that salinity variations in the portion of the Ría de Vigo here studied did not experience divergences out of the 31.5–36.5‰ range, an interval for which no salinity effects to the $U_{37}^{K'}$ index were encountered (Sonzogni *et al.*, 1997).

At the beginning of the second period (defined from cal. AD 1000 to the present) the climate proxies display the warm signal coincident with the MWP (Figure 7, B and D), but the SST record for the Ría de Vigo initiates a cooling that culminates at cal. AD 1440–1490. From that minimum to present, a slight increasing temperature trend is recorded, but a relative minimum is also observed at cal. AD 1720 (Figures 5A and 7A). These two cooler temperatures are coeval with the Spörer minimum (AD 1415–1535) and Maunder minimum (AD 1645–1715) respectively, the two youngest phases of solar radiation (Figure 7C) characterizing the LIA in our record. These two negative temperature anomalies are also shown in the curve of Mann *et al.* (1999b; Figure 7E) where the lowest temperature occurs at about AD 1400. A cooling trend similar to our SST curve is followed by the reconstruction of Dahl-Jensen *et al.* (1998), although their minimum temperatures are displayed later, at around AD 1550 (Figure 7D). The Galician palaeoclimate curve only shows a single minimum for the LIA. It lasts more than 100 years and could be embracing the two cold phases recorded by the other climate proxies. Minor offsets of the Galician curve in relation to the rest of the records are expected since this record is plotted on radiocarbon ages (Martinez-Cortizas *et al.*, 1999a).

The absence of a clear common trend between SST and the other climate records from 975 cal. BC to cal. AD 1000 suggests that local oceanographic conditions could have driven the palaeoenvironment during this period. These conditions should be such as to justify high percentages of *A. beccarii*, low percentages of planktic foraminifera, organic carbon from higher plants, episodic water-column stratification and warmer surface temperatures. Based on present oceanographic models for the Ría de Vigo, the circulation should have been driven mainly by southerly winds. Nowadays, such a wind pattern provokes downwelling that piles up oceanic waters at the ría mouth. This obstructs the normal outflow of fresh water and stops the positive residual circulation into two layers. Lower renewal of waters favours the summer heating of surface waters, the impoverishment in nutrients and an accumulation of waters from runoff (Prego and Fraga, 1992).

Figure 7 Comparisons between sea-surface temperature record for the Ría de Vigo (curve A) and four published climate proxies. (B) The temperature index for the last 3000 years for Galicia (modified from Martinez-Cortizas *et al.*, 1999a; this curve is exceptionally plotted in radiocarbon ages). Reprinted with permission from Martinez-Cortizas, A., Pontevedra-Pombal, X., García-Rodeja, E., Novoa-Muñoz, J.C. and Shotyk, W.; Mercury in a Spanish Peat Bog: Archive of climate change and atmospheric metal deposition; *Science* 284, 939–942. Copyright 1999 American Association for the Advancement of Science. (C) The global decadal record of $^{14}CO_2$ atmospheric production for the last 3000 cal. BP as a proxy of solar radiation (data from the INTCAL 98 curve; Stuiver *et al.*, 1998). Letters indicate the Maunder (M), Spörer (S), and Wolf (W) $\Delta^{14}C$ maxima for the last millennium. (D) The borehole temperature reconstruction from the Greenland Ice Sheet for the last 2000 years (from Dahl-Jensen *et al.*, 1998). (E) The temperature reconstruction for the last millennium by Mann *et al.* (1999a; data from Mann *et al.* 1999b, smoothed with a FFT filter of 25 points).

Thus, it seems likely that the atmospheric and oceanographic conditions during this first stage (from 975 cal. BC to cal. AD 1000) led to a partial isolation of the ría from the open ocean. Under this situation, the climatic signal preserved in the ría sediments would probably reflect better local rather than global conditions.

A reorganization of the regional climate system is likely to have taken place at cal. AD 1000, when the SST began to cool; meanwhile other climate proxies display the warmth of the MWP. This results from a balance between the emerging cool waters from the upwelling and the warming of surface waters from solar radiation. When the upwelling was strong enough, waters coming into the ría were colder, even with higher atmospheric temperatures, but when the climate was cold surface waters attained lowest temperature values as a consequence of the combined effect of relatively low atmospheric temperatures and the influence of colder Atlantic waters. The strongest coupling with the climate signals is observed during the LIA, which is recorded in our SST record by the lower temperatures around cal. AD 1450 and 1720. Important changes in the atmospheric circulation in the North Atlantic region have been suggested to have occurred during the LIA. Keigwin (1996) attributed changes in SST, salinity and nutrients to stronger westerlies and southwestward shifts in storm tracks. Kreutz *et al.* (1997) have recorded an enhanced zonal and meridional circulation in the polar region that influenced mid- to low-latitude circulation. Black *et al.* (1999) also suggested a change of the Northern Hemisphere climate variability about 700 years ago. The data presented here suggest that the most important atmospheric circulation change took place around cal. AD 1000, some years before the beginning of the LIA. This is in agreement with Soares (1993), who proposed that between 1100 and 1300 yr BP a shift in climatological parameters caused intensification of the coastal upwelling in the Portuguese Atlantic coast. These reported changes are also reflected in our studied core, not only by the decreasing SSTs but also by the conspicuous change in benthic foraminifera assemblages and the increased contribution of organic carbon from marine origin to the sediments. All these data suggest an increased water exchange between the ría and the open ocean from cal. AD 1000 to the present. During this period, the main process controlling the hydrographic conditions was the upwelling of Central North Atlantic waters driven by northerly winds. It was under these circumstances, when the Ría de Vigo behaved as an open environment tightly connected to the open ocean, that the sediments deposited in the ría were able to record the global climate imprint.

Conclusions

Benthic foraminifera assemblages, stable oxygen isotopes, molecular biomarkers and sea-surface temperatures derived from the $U_{37}^{k'}$ index have allowed us to establish the hydrographic conditions during the last 3000 years for the Ría de Vigo (NW Spain). Two different periods have been distinguished. From 975 cal. BC to cal. AD 1000, benthic foraminiferal assemblages and molecular biomarkers reflect a restricted environment characterized by frequent salinity changes and high organic carbon inputs of terrestrial provenance. Prevailing southerly winds piling up waters at the ría mouth were probably the cause of the relative isolation of the ría. The lack of a common pattern between SST and other relevant climate records reinforces the interpretation of a palaeoenvironment controlled by local conditions at that time.

At cal. AD 1000 a reorganization of the eastern boundary climate system is likely to have taken place, heralding the establishment of hydrographic conditions very close to the present ones. The pronounced increase in the percentage of planktic foramini-

fera, the change in benthic foraminiferal assemblages to those dominated by several opportunistic species and the increase in the supply of organic matter of marine provenance suggest an environment with close connection to the open ocean. That situation was caused by a change to prevailing northerly winds that triggered upwelling. Decreased SSTs reflect the combined effect of emerging cold waters from the upwelling, probably accompanied by colder atmospheric temperatures. Under these conditions, global climate signals such as the cooling of the LIA were recorded.

Acknowledgements

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