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Inter-Connection between the Atlantic Ocean and a Coastal System, the Ria de Vigo (NW Spain), during the Late Holocene

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ABSTRACT

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The main aim of this work is to identify changing and characterise the hydrographical regime in the outer sector of the Ria de Vigo during the late Holocene. Sediment samples were collected every centimetre along the core KSGX 24 and used for textural, mineralogical and microfaunal studies (benthic foraminifera). The age model was based on four AMS radiocarbon dating. This sedimentary sequence recording the last ~3 ka cal BP has a mean grain size varying between 13-26 µm. Fine fractions represent 76-92 % of the bulk sediment. Detrital minerals are the main constituents of the sediments (55-85 %). A total of 202 benthic foraminiferal taxa were identified. A significant amount of tests belongs to exotic species. Two finer sections were identified between 175-75 cm and 35-0 cm. These sections are characterised by the slight increase of detrital minerals and by the decline of carbonated minerals. In the first section the percentage of benthic foraminifera tests supplied from deeper waters and the percentage of the species related with high flux of organic matter, increased. These results suggest the occurrence of a higher oceanic influence in the Ria de Vigo, between ~2.2-1.2 ka cal BP, probably induced by stronger up-welling events followed by periods of relaxation which were followed by weaker events of down-welling. During the later period between ~0.5-0 ka cal BP it is possible that stronger up-welling events may have occurred, followed by stronger down-welling events which have probably enhanced the vertical water mixing and caused lower retention of sediments inside the outer sector of the Ria.

ADDITIONAL INDEX WORDS: *hydrographical regime*; *up-welling*; *down-welling; climate oscillations*

INTRODUCTION

Several well know climatic oscillations have characterised the last 3000 years. The most important has been identified at the Subboreal/Subatlantic transition, at about 2950-2450 cal. BP. In Scandinavia, for instance, the Subboreal/Subatlantic shift in climate, is recorded by a warm period with high sea level (ca. 2700-2600 C14 years BP) followed by a short period of intense draught (2600-2500 C14-years BP) and then a general cooling with increased precipitation, beginning around 2500 C14-years BP (Mörner, 2003). The Little Ice Age (LIA), between 1375-1820 AD, was another recent climate oscillation characterised by atmospheric temperatures lowering (Moore *et al*., 2004). The LIA was preceded by the Medieval Warm Period (MWP), 900–1250 AD (Lamb, 1995), another climatic fluctuation well identified in the last millennium.

However, the knowledge about the influence of these climatic oscillations in the Iberian coastal systems is still poor. Records from such areas provide relevant information, allowing the understanding of an inter-connection between the ocean and the continent, during the Holocene.

The present study is based on the gravity core KSGX 24 (236 cm) recovered from the outer sector of the Ria de Vigo (Spain). This Ria is the southernmost of the Galician Rias Baixas, with a NNE-SSW orientation and a water depth reaching a maximum of 48 m in the central channel. It is a mesotidal system with tidal ranging between 2-4 m. The main continental freshwater inputs to this Ria is localised in its inner (75% of the total discharge) and southern zones (Nombela *et al*., 1995). The rest of the ria is under strong oceanic influence. Hydrography is controlled mainly by the winds influence over the continental shelf (Souto *et al*., 2003) causing up-welling and down-welling cycles with a strong seasonal pattern (Álvarez-Salgado *et al*. 2000). The main aim of this work is to study the influence of climatic oscillations over the NW Iberian Margin in the inter-connection between the ocean and a coastal system, the Ria de Vigo, during the late Holocene.

METHODS

The gravity core KSGX 24 was collected in the Ria de Vigo (Spain), at 42°12.48'N, 8°51.90'W and water depth 39 m (Fig. 1), during the GAMINEX cruise of the OMEX Project (Ocean Margin Exchange) which took place in July, 1998. Samples, 1cm thick, were submitted to grain size, mineralogical and microfaunal (benthic foraminifera) analyses. A MALVERN 3600E micro-granulometric diffractometer was used in grain size analysis. The mineralogical composition of the sediments was evaluated in its fine fraction (<63 µm) and was realised using X-ray diffraction techniques. Sand fraction (>63 µm) of each sample was used to identify and characterise the benthic foraminifera assemblages.

More than 300 benthic foraminifera were counted and identified using a binocular, in each sample. For the foraminifera determination, the taxonomy of LOEBLICH and TAPPAN (1988) was followed. In order to be dated by 14C (using AMS), 10 mg to 20 mg of mixed foraminifera shells were separated from the sediment grain size fraction >125 µm, corresponding to the sedimentary layers 33-34 cm, 71-72 cm, 143-144 cm, 193-194 cm.

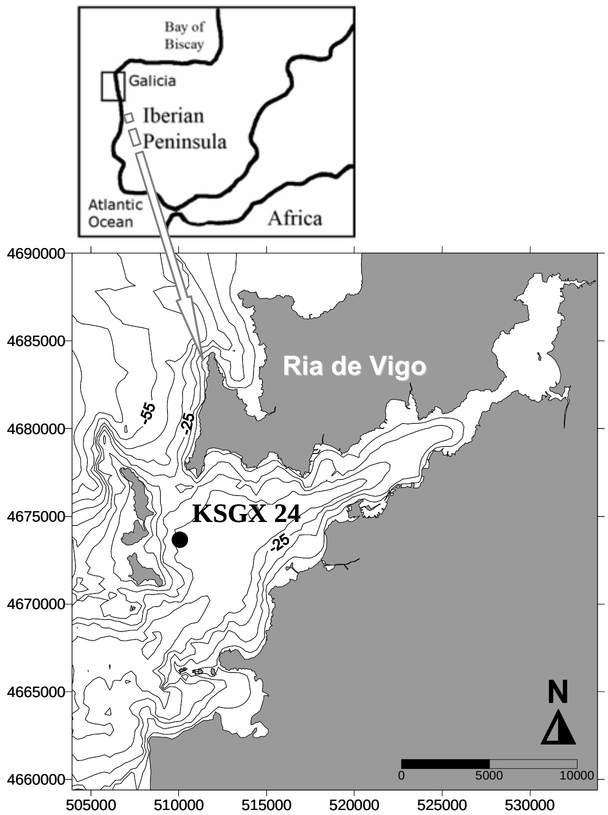

Figure 1. Location of core KSGX 24 in the Ria de Vigo

RESULTS

The chronology of this core is supported by four AMS radiocarbon dates (Table 1). The age depth of the core KSGX 24 was based on linear interpolation, between 2 sigma calibrated (STUIVER *et al*., 1998) radiocarbon dates, corrected for a marine reservoir effect of about 400 years (SOARES, 1989).

This core is predominantly composed by muddy sediments. It has a mean grain size ranging between 13-26 µm. The percentage of fine fractions (<63 µm) varies between 93-76 % (average 84 %) and is higher in the sections 175-75 cm and 40-0 cm (Fig. 2). The percentage of "fine silt and clay fractions" (<15 µm) and "medium silt" (15-30 µm), increases in these sections. The percentage of sand-sized material varies between 9-24%.

The mineralogical composition shows that the sediments are largely siliciclastic. The main constituents are quartz (17-42 %), phyllosilicates (11-48 %), calcite (1-22 %) and feldspars (2-15 %). Traces of several other minerals, such as opal (0-10 %), anatase (0.3-9 %, in general), pyrite (0.3-6 %), siderite (0-3 %, in general), dolomite (0-5 %) and anhydrite (0-3 %), were also found. The percentage of detrital minerals (quartz + phylosilicates+ feldspars) increases slightly in the sections where the sediments became finer (shadow sections of the Figs. 2, 3). The percentage of carbonated minerals (calcite + dolomite +siderite) shows a tendency to have lower values, in these sections.

Table 1: Results of radiocarbon dating determined in the Laboratory "Beta Analytic Inc.", Miami, Florida, USA. The estimated average sediment accumulation rate (ASAR) is based on conventional radiocarbon age.

Beta n.º	Sample (cm)	Conventional Radiocarbon Age (BP)	2 Sigma Calibration (Cal BP)	ASAR cm/kyrs
209729	33-34	1520±40	1160-970	22
164243	71-72	1970±40	1610-1420	84
164244	143-144	2440±40	2160-1980	153
164245	193-194	2850±40	2720-2470	122

Most of the benthic foraminifera tests found along the core KSGX 24 belong to typical oceanic species (DIZ *et al*., 2006, 2004; LEVY *et al*., 1995). They may live at the nearby continental shelf. Species such as, *Amphicoryna scalaris, Bolivina difformis, Bolivina seminuda, Bolivina skagerrakensis, Bolivina striatula, Brizalina spathulata*, *Brizalina subaenariensis*, *Bulimina aculeata, Bulimina exilis*, *Buliminella tenuata, Cassidulina minuta*, *Epistominella vitrea*, *Fursenkoina loeblichi, Globocassidulina subglobosa, Gyroidina umbonata, Hyalinea balthica, Melonis barleeanum, Nonionella bradii, Nonionella turgida*, *Trifarina angulosa, Uvigerina peregrina* and *Valvulineria bradyana* are generally sparse in the inner shelf environments but they increase their relative abundance in the middle and/or outer shelf (e.g. LEVY *et al*., 1995, MENDES *et al*, 2004). They could have been transported from the shelf deeper environments. The depth-plot of the total percentage of this group (Fig. 3) gives us an idea of the varying degree of marine influence along the core.

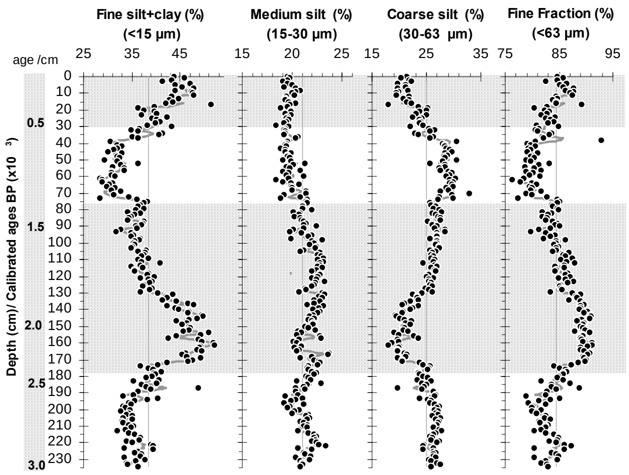

Figure 2. Logs showing fine fractions data of the core KSGX 24. Smoothed lines (solid grey curves) between data (marks), the average values (grey hatched line) are also represented.

According to ÁLVAREZ-IGLESIAS *et al*. (2006) this coastal system can receive *C*org by (1) terrestrial organic matter inputs from the rivers, (2) the richness of marine flora in the area (seagrasses: *Zostera marina* and *Zostera noltii*; macroalgae: *Ulva* and *Enteromorpha*), (3) the biological production for marine cultures and from open sea inputs (mainly algal blooms), and (4) the contribution from urban sewage discharges. Although, terrestrial organic matter includes, in general, a higher proportion of biologically resistant organic compounds, which are less susceptible to biological degradation and to be used by benthic foraminifera. According to DIZ *et al*. (2004), the abundance of bolivinids, buliminids and the species belonging to the genera *Fursenkoina*, *Nonionella* and *Stainforthia* are related with finer sediments and high sedimentary content in organic matter, in the Ria de Vigo. Organic matter with high quality is the main source of food to this group. The total percentage of the refereed taxa (Fig. 3) was used as a benthic foraminifera high productivity proxy (BFHP) to identify changing in the *C*org supplied to the bottom. The higher values of the BFHP proxy may suggest higher productivity in the Ria de Vigo but mainly in the nearby oceanic waters.

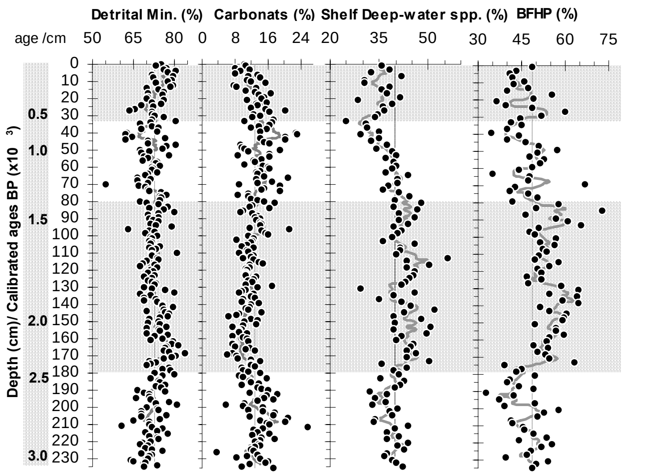

Figure 3. Logs showing some mineralogical and microfaunal data. In these logs is represented the percentage of the detrital and carbonated minerals. The total percentage of benthic foraminifera specimens transported from the shelf deep-waters, as well as the benthic foraminifera high productivity proxy (BFHP), are also plotted. Smoothed lines (solid grey curves) between data (marks), the average values (grey hatched line) are also represented.

DATA ANALYSIS

The studied core was collected in a muddy zone of the central part of the outer sector of the Ria de Vigo, protected by the Cyes islands. At present, this sector is under strong oceanic influence and receives a negligible input of freshwater (NOGUEIRA *et al*., 1997). The benthic foraminifera assemblage also agrees with a weak freshwater influence in this zone.

The R-mode Cluster analysis used to recognise similarities within the data set studied in this work, established two groups. Whereas the carbonated minerals are more correlated with the coarser sediment fractions; the detrital minerals, as well as the shelf deeper-water benthic foraminifera and the BFHP proxy are more correlated with the finer sedimentary fractions. The benthic foraminifera results, trace the entrance of oceanic materials in the Ria de Vigo,

The decrease of the sediments grain size between 175-75 cm and 35-0 cm was coincident with the slight enrichment in detrital minerals and with the slight impoverishment in carbonate minerals. The presence of a significant number of exotic specimens along the core, reveals that in the last 3 ka cal BP years, the Ria de Vigo received a significant amount of sediments (mostly fine sediments) transported from the ocean. However, this amount should be higher during the period corresponding to the first section (175-75 cm), characterised by a higher accumulation rate and by a clear increase of benthic foraminifera specimens imported from shelf deep-waters to the Ria de Vigo.

The carbonates content decrease, whereas the detrital particles increase in both finer sections (175-75 cm; 35-0 cm). The carbonate content varies with the grain size distribution in the Ria de Vigo. The grain size distribution in the entrance channels, north and south of the Cyes Islands, is in general characterised by a high sand proportion, especially in the northern mouth, whereas along the central and inner parts of the ria, it is dominated by clay and silt fractions with high organic matter content (4-6% of organic matter; VILAS *et al*., 1995). The maximum percentage of carbonates are recorded in the south entrance channel, whereas the minimum carbonate content is recorded in the central axis of the ria where the sediments are finer (GARCÍA *et al*., 2005). The muddy sediments of the Galician Rias do not contain a high proportion of biogenic calcium carbonates (e.g. RUBIO *et al*., 2000). The remineralisation of organic matter generates the consume of oxygen and can produce low oxic conditions in the sediments. In the studied core this situation can be inferred by the presence of diagenetic minerals, such as pyrite and siderite. These low oxic conditions prevent the development of the benthic fauna (such as molluscs and foraminifera) that requires oxygenated environments to reproduce, to have a high reproduction rate and/or to live. Several authors have attributed the low values of carbonates in the Ria muddy sediments to lower pH generated in microenvironments, due to the organic matter diagenesis, which results in the dissolution of the carbonates (GARCÍA *et al*., 2005). Other authors also attribute the low values in carbonates to the dilution caused by the fluvial inputs, which are in general poor in carbonates (ÁLVAREZ-IGLESIAS *et al*., 2006). In this core the lowering of carbonates in both finer sections may have been caused by dilution by terrigenous materials (increase of detrital minerals, see Fig. 3), mostly in the first section (175-75 cm), with a higher accumulation rate or loss by erosion of slight carbonated particles, such as tests of foraminifera (in the section 35-0 cm).

DISCUSSION

The two finer sections of this core are in accordance with the occurrence of two periods of lower hydrodynamism in the outer sector of the Ria de Vigo, the first one between ~2.2-1.2 ka cal BP and the second since ~0.5 ka cal BP. Both periods may have occurred during the prevalence of more stratified conditions, similar to nowadays' which are normally maintained throughout the whole year (DIZ *et al*., 2002). MARTINS *et al*. (2006 a, b) also identified equivalent periods of lower hydrodynamism in the nearby outer continental shelf. During the same periods, SCOTT *et al*. (2003), SCOURSE *et al*. (2002) and EVANS *et al*. (2002) also observed similar results of seasonal stratification in the central to northern North Sea region, resulting in large areas of stratified water: in the Celtic Sea (the first two) and in the North Sea (the last), northeast England (NW European Continental Shelf).

A- The lower hydrodynamic period between ~2.2-1.2 ka cal BP

During the first period of finer deposition of sediments (2.2-1.2 ka cal BP) the increasing values of the benthic foraminifera high productivity proxy (see Fig. 3) suggests that the *Corg* flux to the bottom was higher. BARTELS-JÓNSDÓTTIR *et al*. (2006) associated this phase of high productivity to the intensification of the up-welling events at the W Iberian Margin. At that time more frequent and more intense events of up-welling should have taken place on the NW Iberian Margin. The presence of diagenetic minerals in the sediments composition of the studied core, such as pyrite and siderite, which are only formed or preserved under anoxic conditions, testify the occurrence of low oxygen levels in pore-waters below the sediment-water interface. The high organic matter content, characteristic of fine sediments of the Ria de Vigo (about 5%; e.g. NOMBELA *et al*., 1995; VILAS *et al*., 1995) and its sequential remineralisation, as well as the weak reoxidation of pore–waters, may have led to disoxic or anoxic conditions.

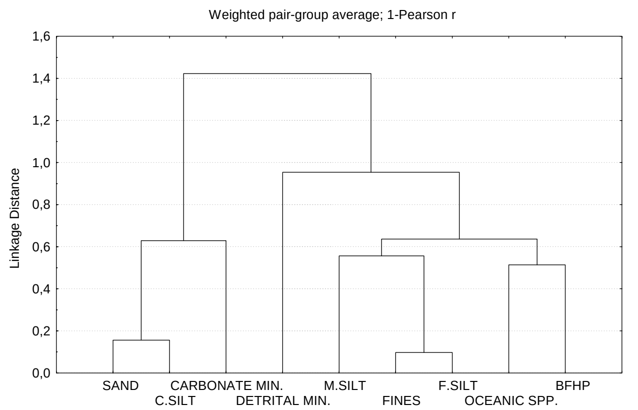

Figure 4. Dendrogram resulting from a cluster analysis based on textural, mineralogical and microfaunal data, using the Pearson correlation and for agglomeration the "weighted pair-group average".

Nowadays under the influence of northerly shelf winds, the positive residual circulation is reinforced in the Ria de Vigo: the inflow is done through the bottom layer and the outflow, through surface layer (ÁLVAREZ-IGLESIAS *et al*., 2006). Under extreme cases of up-welling the Ria de Vigo sediments act as a nutrient trap as well as a deposit of high fluxes of organic carbon (ÁLVAREZ-SALGADO *et al*., 2001). On the other hand, when southerly winds blow, down-welling conditions occur, causing a strong reversal in the estuarine circulation, with the up-welled water being rapidly evacuated through the bottom of the Ria (ÁLVAREZ-IGLESIAS *et al*., 2006). This reverse circulation enhances the sediments mobilization, introducing high fluxes of sediments in the water-column (DIZ *et al*., 2006) and perhaps in the shelf. So, the inflow through the bottom layer of shelf waters during reinforced up-welling events could be propitious to the transportation of sediments supplied from the shelf, into the Ria. The increase of benthic foraminifera specimens, supplied from the shelf deeper environments, suggests the occurrence of a period of higher oceanic influence in the outer sector of the Ria de Vigo during this period. The average sediment accumulation rate was the highest of this core, agreeing with the hypothesis of the occurrence of strengthened up-welling events (inducing high productivity and making the inflow of sediments into the ria, easy), followed by periods of relaxation and by weaker events of down-welling: i) during the up-welling events strengthened inflow through the bottom layer transporting oceanic particles and increasing the bioproductivity in the shelf and in the ria waters; ii) during relaxation events higher deposition of sediments (detrital and *C*org provided by continental and oceanic sources) and enhanced pelagic and benthic remineralisation processes; iii) during weakened down-welling events feeble mixing water and out-flows and low sediments remobilisation (less loss of sediments).

B - The lower hydrodynamic period between ~0.5-0 ka cal BP

DIZ *et al*. (2002) concluded that the marine organic contribution to the TOC content in sediments of the Ria de Vigo increased in the last millennium. The tendency to augment the percentage of the shelf deep-water species, in the firsts 30 cm of this core, signs the occurrence of a new phase of increased oceanic influence in the Ria, in accordance with the observations of ÁLVAREZ *et al*. (2005) based on the quantitative distribution of coccolithophores and molecular biomarkers. However the values of the BFHP proxy don't confirm the occurrence of a high flux of organic matter to the bottom of the Ria de Vigo outer sector, during this period. ÁLVAREZ-IGLESIAS *et al*. (2006) also found decreased values of *C*org toward the present period in TOC profiles of sediments of the ria. They supposed that these values could be explained by several factors: (1) a decrease in riverine organic carbon input, (2) a change in the kind of input (marine vs continental) and/or (3) an increase in the sedimentation rate (e.g. dilution). The last hypothesis is not confirmed by our data, because the average sediment accumulation rate was the lowest of the core.

So, the evolution pattern of our data allows us to suppose that the circulation pattern, during this period, must have been somewhat different compared with the later one (also dominated by up-welling events). During the last 0.5 cal BP years strengthened up-welling events should be followed by stronger down-welling events which should have enhanced the vertical water mixing and improved the connection between the Ria and the shelf, with a consequent lower retention of sediments (namely organic matter).

C – Periods of strong water-column stratification ruled by climate oscillations

In the NW Iberian Margin the up-welling intensity is related to the strengthening of northerly winds (PITCHER *et al.*, 1998), which have a good correlation with colder periods in the Nordic Seas (BOND *et al.*, 1992). In fact, the two main intervals (~2.2-1.2 ka cal BP and ~0.5-0.1 ka cal B P) of strong water-column stratification occurred during two colder late Holocene oscillations: the first after the Subboreal/Subatlantic transition; the second during the Little Ice Age.

CONCLUSION

Nowadays, the seasonality is an evident feature of the environmental conditions in the Ria de Vigo, with down-welling dominating in the winter and up-welling being more important in the summer, in spite of short-term variability (CRESPO *et al*., 2006). The climatic variability, during the last 3 ka cal BP, may have caused significant changing in the up-welling/down-welling regime off the Iberian Peninsula, causing significant changing in the coastal systems, such as the Ria de Vigo. The sedimentary record of the core KSGX 24 suggests the occurrence, for instance, of more important events of upwelling followed by weaker down-welling events, between ~2.2-1.2 ka cal BP, and important events of upwelling followed by stronger down-welling events, between 0.5-0 ka cal BP, in the NE Atlantic Ocean. These conditions caused a higher infilling of fine sediments in the outer sector of the Ria de Vigo, in the first period, and a lower deposition and retention of fine sediments during the second period. Both these periods coincided with cold climate phases: the first after the Subboreal/Subatlantic transition and the second coinciding with the Little Ice Age.

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