Upwelling dominated oceanographic periods in the Ria de Vigo during the late Holocene

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ABSTRACT


Different oceanographic regimes were identified at millennial scale in the last 3 ka cal BP in a sedimentary sequence from the outer sector of Ria de Vigo (NW Spain) based on a multi-proxy approach (textural, mineralogical, geochemical and benthic foraminifera data). The prevalence of stronger wave climate linked with a developed downwelling regime and a more efficient erosion phase, allowed the deposition of coarser sediments, enriched in geogenic (Si/Al and Zr/Al) and biogenic chemical elements (Ca/Al and Sr/Al), coarse detrital minerals (quartz and feldspars) and carbonates during the periods ≈2.9-2.3 ka cal BP and ≈1.5-0.6 ka cal BP. However the prevalence of soother wave climate regime, linked with reinforced upwelling events, could have occurred between ≈2.5–1.5 ka cal BP and ≈0.5–0 ka cal BP, giving origin to a finer sedimentation enriched in organic matter and phyllosilicates. In these muddy events the consumption of oxygen during aerobic organic matter degradation caused suboxic/anoxic conditions in the sediments, which induced higher early diagenetic changes with pyrite formation in anoxic environments. When the sediments became again oxic/suboxic precipitation of redox, sensitive elements such as Fe and Ni could have arisen.

ADDITIONAL INDEX WORDS: Late Holocene, climatic conditions, NW Iberian Margin, sedimentary dynamic, paleoproductivity, diagenesis

INTRODUCTION

Ria de Vigo is the southernmost Ria Baixa from Galicia, NW Spain. This large temperate coastal embayment, with a NNE-SSW orientation, is separated from the Atlantic by two large islands (Isles Cies) located at its mouth. The Isles Cies leave two relatively narrow corridors at the north and south entrances, which allow its intercommunication with the ocean.

The ria behaves as a partially mixed estuary (García-Gil et al., 1995) with a two-layered positive residual circulation pattern, which allow its intercommunication with the ocean.

The main aim of this work is to identify the influence of different oceanographic regimes caused by late Holocene climate changes over millennial timescales, in the outer sector of Ria de Vigo.

METHODS

Sediments along the OMEX (Ocean Margin Exchange Project) core KSGX 24 (236 cm long), collected in the Ria de Vigo, near the Isles Cies (42°12'48 N, 8°51'90 W, 39 m depth; Fig. 1) were submitted to grain size, geochemical, mineralogical and microfaunal (benthic foraminifera) studies. The core was sampled at every centimetre. Grain size and mineralogical data were obtained from each cm of the core.

A laser microgranulometer (Mastersizer S instrument, Malvern Instruments) was used for determining the particle
sizes (in the range between 0.05 to 878 μm) of the sediments in each sample.

Mineralogical studies were carried out on the <63μm (silt) fraction of the sediments through X-ray diffraction (XRD) according to the procedure described in Martins et al. (2007).

Geochemical results were determined by Atomic Absorption Spectrophotometry, based on dissolved sediments with three-acid decomposition, HCl(aq)+HNO₃(aq)+HF(aq) and provided the concentrations of several elements e.g. Al, Ca, Cr, Fe, Ni, Si, Sr and Zr, in 45 selected samples.

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

Benthic foraminifera assemblages were determined in the sediment fraction >63 μm, considering the proportion of each species, considering at least 300 specimens, in 118 samples. Benthic Foraminifera High Productivity index (BFHP) was used in this core to identify periods of high supply of C₄₃ to the sea floor. This microfaunal proxy includes the total percentage of species related to high and sustainable flux of metabolizable organic matter and was determined following the procedure of Martins et al. (2006, 2007).

Four radiocarbon ages of mixed foraminifera tests (10 mg to 20 mg) were determined from the sedimentary size fraction >125 μm of selected layers (33-34 cm, 71-72 cm, 143-144 cm and 193-194 cm) and were carried out by AMS method in “Beta Analytic Inc.”, Miami, Florida, USA.

RESULTS

Radiocarbon results of selected layers provided the following 2 sigma calibrated (cal) ages before present (BP): Cal BP 970 to 1160, for 33-34 cm; Cal BP 1610 to 1420, for 71-72 cm; Cal BP 2160 to 1980, for 143-144 cm; Cal BP 2720 to 2470, for 193-194 cm. The age model was based on these intercalated ages. According to Soares and Dias (2007) the ΔR results from the western and northwestern Galician coasts (Rias Baixas and Rias Altas regions, respectively) for the period 2500 to ~900 BP point to a reduced offset between atmospheric and surface water δ¹³C content.

This core, that records the last ~3 ka, is a muddy sedimentary sequence with mean grain size varying between 13-26 μm. Fine fraction represents 76-92 % of the bulk sediment. Sediments are mainly composed of quartz (42-17%), phyllosilicates (49-11%), anatase (<31%), feldspars (27-10%), calcite (22-1%), dolomite (<5%), siderite (<8%) and opal C/T (<11%). Minimum, maximum and median values of Al, Ca, Fe, Ni, Si, Sr and Zr are represented in table 1. Aluminium concentrations are positive and significantly correlated with fine fraction and phyllosilicates proportion. Elemental content have been normalized using Al as the reference element.

A total of 202 benthic foraminiferal taxa were identified. The most abundant species are *Nonion fahum* (<38%), *Cibicides ungerianus* (>35%), *Bolivina pseudoplicata* (>26%), *Brizalina spatulata* (<22%), *Bolivina lowmani densipunctata* (<22%), *Balaminia elongata* (<14%), *Ammonia tepida* (<13%), *Bolivina variabilis* (<12%), *Bolivina compacta* (<9%), *Elphidium gerthi* (<8%), *Asterigerinata mammila* (<8%), *Gavelinopsis praegeri* (<8%) and *Lobatula lobatula* (<5%). BFHP, including mostly bolivinids and buliminids, varies between (25-57%).

Aiming at identifying similar patterns of distribution of BFHP, Al concentrations and element-Al ratios, and some selected granulometric, chemical and mineralogical data were submitted to cluster analyses using Pearson correlation and the Ward’s distance method. Two main clusters were established (Fig. 2). *Cluster 1* which includes variables with positive and significant correlations with fine fraction (finer sediments): pyrite, phyllosilicates, BFHP, Al concentrations and Fe/Al and Ni/Al values. BFHP, fine fraction percentage, Al concentration and Fe/Al values represent this cluster in Fig. 3. *Cluster 2* joins variables which increase in coarser sediments (sand fraction), such as carbonates, Ca/Al, Sr/Al, Zr/Al and Si/Al. Variables of cluster 1 reach in general higher values, for instance between ~175-80 cm and in the upper ~30 cm. Variables of cluster 2 have an opposite pattern, their values co-vary with sand fraction content and increase in the sections ~220-190 cm and ~80-30 cm.

<table>
<thead>
<tr>
<th>Element</th>
<th>Max</th>
<th>Min</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si (%)</td>
<td>28.2</td>
<td>24.3</td>
<td>26.7</td>
</tr>
<tr>
<td>Al (%)</td>
<td>8.2</td>
<td>5.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Ca (%)</td>
<td>5.3</td>
<td>2.8</td>
<td>4.7</td>
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<tr>
<td>Fe (%)</td>
<td>3.5</td>
<td>2.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Ni (mg/kg)</td>
<td>38</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td>Sr (mg/kg)</td>
<td>388</td>
<td>256</td>
<td>335</td>
</tr>
<tr>
<td>Zr (mg/kg)</td>
<td>396</td>
<td>231</td>
<td>301</td>
</tr>
</tbody>
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Table 1: Range of concentrations for the chemical elements analysed in sediment fine fraction (<63 μm) of core KSGX 24.

ANALYSIS

Sedimentation rate was higher along the section ~194-72 cm, i.e. between ~2.5–1.5 ka cal BP. During this period finer sediments, enriched in Al and phyllosilicates, were deposited (Fig. 2, 3). This muddy period is also characterized by the increase in BFHP values and pyrite percentage (3-6 %). This suggests an increased supply of organic matter to the bottom of the outer sector of Ria de Vigo and the establishment of sub-oxic/anoxic environments/microenvironments in the sediments. Processes involved in organic matter degradation by aerobic organisms caused diagenetic changes and pyrite formation. In the first part of this period, lower values of Si/Al, Zr/Al (Fig. 3), feldspars and quartz are recorded, which agree with an impoverished supply of coarse detrital contribution. As soon as grain size became progressively coarser, between ~1.9-1.5 ka cal BP, sediment pore-waters became more oxic, giving place to the precipitation of redox-sensitive metals such as Fe and Ni as...
reveal the increase of Fe/Al and Ni/Al (see Fe/Al evolution pattern in Figure 3; Ni/Al has a similar evolution according to the cluster 1 of figure 2). Another section enriched in muddy sediments with similar characteristics is identified in the upper part of the core (≈30-0 cm), i.e. since ≈0.6 ka cal BP.

In the intercalated sections (≈220-190 cm, ≈80-30 cm), i.e. during the period between ≈2.2-2.5 ka cal BP and ≈1.5-0.6 ka cal BP, sediments with higher content in sand fraction were deposited. In these phases, BFHP, pyrite and phyllosilicates content was reduced. The ratios values of Fe/Al and Ni/Al also decreased; however Si/Al, Zr/Al, Ca/Al, Sr/Al and carbonates content had an opposite trend. These results suggest that the supply of organic matter to the bottom was reduced and the sediments oxygenation was improved, thus allowing a better preservation of biogenic carbonates (represented by Ca/Al and Sr/Al). Reproduction rate of species with carbonated tests and shells (such as foraminifera and molluscs), more exigent in terms of oxic conditions, was also probably higher.

![Tree Diagram for 13 Variables Ward’s method 1-Pearson r](image)

Figure 2. Cluster analysis using Pearson correlations and Ward method for variables agglomeration based on: pyrite (Pyr), phyllosilicates (Phyl), BFHP, fine fraction (mud), carbonates (Carb) and sand fraction (Sand) percentage. Aluminium concentrations and element/Al ratios were also considered in the analysis.

DISCUSSION

According to Vilas et al. (2005) the sediments grain size distribution in Ria de Vigo is related to a marked energy-depositional condition. Wave climate strongly drives the sediment distribution and their early diagenetic path (Rey et al., 2002). Thus the coarser sediments of core KSGX 24, enriched in geogenic and biogenic chemical elements (Si/Al, Zr/Al, Ca/Al and Sr/Al – Cluster 2), deposited in the periods ≈2.9-2.5 ka cal BP and ≈1.5-0.6 ka cal BP may be related to higher hydrodynamic conditions and to a phase of more efficient erosion granitoid rocks (hard rocks). Stronger wave climate is typical in the area, essentially due to winter oceanographic regime (PO-WAVES Group, 1994), when southerly and westerly winds are predominant and downwelling is established (Figueiras et al., 2002). Under these conditions surface coastal water enters into the Ria and develops a downwelling front located at the meeting point of the inner waters with higher continental influence linked with rivers runoff, which is augmented by higher precipitation during winter. The Ria circulation is characterized by the outflow towards the ocean at the bottom layer, in an outer circulation cell, while the inner cell maintains a positive circulation forced by rivers runoff (Crespo et al., 2006). This circulation pattern can favour the escape of fine grained sediments from the outer sector of Ria de Vigo to the shelf.

However the summer wave regime is characterised by low energy wave conditions, with significant wave heights typically of about 2 m (PO-WAVES Group, 1994). Wind-driven upwelling of nutrient-rich Eastern North Atlantic Central Water (e.g. Rosón et al., 1997) occurs typically from April to September which increases primary production (Fraga, 1981). The upwelled nutrients are efficiently trapped in this system (Álvarez-Salgado et al., 1999). The upwelling regime forces a two layer density-induced positive circulation in the Ria de Vigo, characterised by the outflow of surface water compensated by the inflow of upwelled water at the bottom (Crespo et al., 2006). Under these conditions sedimentation rate can be increased in the outer sector of Ria de Vigo, mainly under wet climatic conditions, prevailing a fine grained deposition of sediments (Cluster 1).

The analysed results of core KSGX 24 suggest that the prevalence of an upwelling regime due to northerly winds reinforcement could have occurred between ≈2.3–1.5 ka cal BP and ≈0.5–0 ka cal BP. Under the action of slower bottom currents the area was nourished with finer sediments enriched in organic matter, partly also provided from continental sources, as find González-Álvarez et al. (2005) which gave place to higher diagenetic changes (pyrite formation – Cluster 1). Reducing of Si and Zr in the first part of this period (≈2.3–1.9 ka cal BP) may be related to a less efficient phase of erosion of granitoid rocks (hard rocks). The higher sedimentation rate in the first period (≈2.3–1.5 ka cal BP) may indicate wetter climatic conditions than in the last one (≈0.5–0 ka cal). Similar changing was also recorded in the Galicia Muddy Deposit by Martins et al. (2007).

CONCLUSION

Geochemical, mineralogical and microfaunal results of this core indicate the occurrence of changing in the amount and composition of sediments supplied to the outer sector of Ria de Vigo during the last 3 ka cal BP.

The prevalence of weaker hydrodynamic regime, between ≈2.3–1.5 ka cal BP and ≈0.5–0 ka cal BP, could have been related to a predominance of the upwelling. Erosion could be more efficient and the hydrodynamic conditions stronger in the periods ≈2.9-2.5 ka cal BP and ≈1.5-0.6 ka cal BP due to stronger wave climate and the reinforcement of the downwelling regime.

These results indicate that during the late Holocene the tendency events of reinforced upwelling or downwellin may have occurred at millenial scale as also observed by Álvarez et al. (2005) and Diz et al. (2002).

REFERENCES


Figure 3. The vertical evolution of some variables selected to represent each cluster/sub-cluster defined by the dendrogram included in figure 2. The mean value is represented in each plot. The mean moving averages of each variable are represented, as well as radiocarbon dating and a chronologic scale. The muddy sections are shadowed.