

## A multiproxy approach of the Holocene evolution of shelf–slope circulation on the NW Iberian Continental Shelf

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Received 22 February 2006; received in revised form 15 November 2006; accepted 17 November 2006

### Abstract

Textural, mineralogical, geochemical and microfaunal data (benthic foraminifera) were studied along the OMEX core KSGX 40 recovered in the Galicia Mud Deposit, of the NW Iberian outer continental shelf, off the Ría de Vigo (North of Spain). This core included the records of the last ca. 4.8 ka cal BP and consists, from the base to the top, of a sedimentary sequence exhibiting gradual upward decrease in grain size. Sediments of this core are mainly siliciclastic, largely composed of quartz, K-feldspars, plagioclases, and phyllosilicates (mica/illite, kaolinite and chlorite) showing a great continental influence in this zone. Two periods of deposition of finer sediments are registered between ~2.2–1.2 ka cal BP and ~0.5–0 ka cal BP.

Since the last ~2.2 ka BP, but mainly during both muddy intervals, the Galicia Mud Deposit was nourished with a lower and finer supply of detrital minerals compensated by higher amounts of organic matter, as it is suggested by a Benthic Foraminifera High Productivity (BFHP) proxy. Processes involved in organic matter degradation by aerobic organisms led to depressed levels of oxygen in the sediments, as shown by a Benthic Foraminiferal Oxygen Index (BFOI). Peaks of redox-sensitive elements, like Mn, Fe, Cu, Ni, Cr, Co, Zn, Ni and Pb as well as the presence of diagenetic minerals, such as pyrite, suggest the development of anoxic conditions beneath the sedimentary surface and early diagenetic changes due to high organic matter flux, in both muddy intervals.

Two different hydrodynamic regimes were inferred through the analysis of the different proxies (textural, mineralogical, geochemical and benthic foraminifera): (1) A strong hydrodynamic regime between ~4.8 and 2.2 ka cal BP characterized by the prevalence of winter storms, which gave rise to a deep mixed layer on the shelf. (2) Weak hydrodynamic regime between ~2.2–1.2 ka cal BP and ~0.5–0 ka cal BP with a high predominance of upwelling and an increase in oceanic stratification.

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**Keywords:** Late Holocene; shelf–slope circulation; NW Iberia; sedimentology; benthic foraminifera

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## 1. Introduction

### 1.1. Morphologic features of the NW Iberian Margin

The NW Iberian Continental Shelf (see Fig. 1) is rather narrow (30 km) off the Rías but slightly broader (50 km) elsewhere, with a shelf break around 160 and 180 m water depth (Dias et al., 2002a). The northwestern Portuguese coastal zone (between latitudes 41°05'N

and 41°52'N) is drained by five major rivers: the Minho, Lima, Cávado, Ave and Douro. The basins of the Minho and Douro rivers are the larger ones and their discharges and sediment loads the greater (e.g. Dias et al., 2002a,b). The Galicia coastal zone is characterized by the existence of four Rías: Vigo, Pontevedra, Arosa, and Muros (the Rías Baixas), reaching in general 40–50 m of water depth. They have a WSW–ENE development and mouths wider than 10 km.

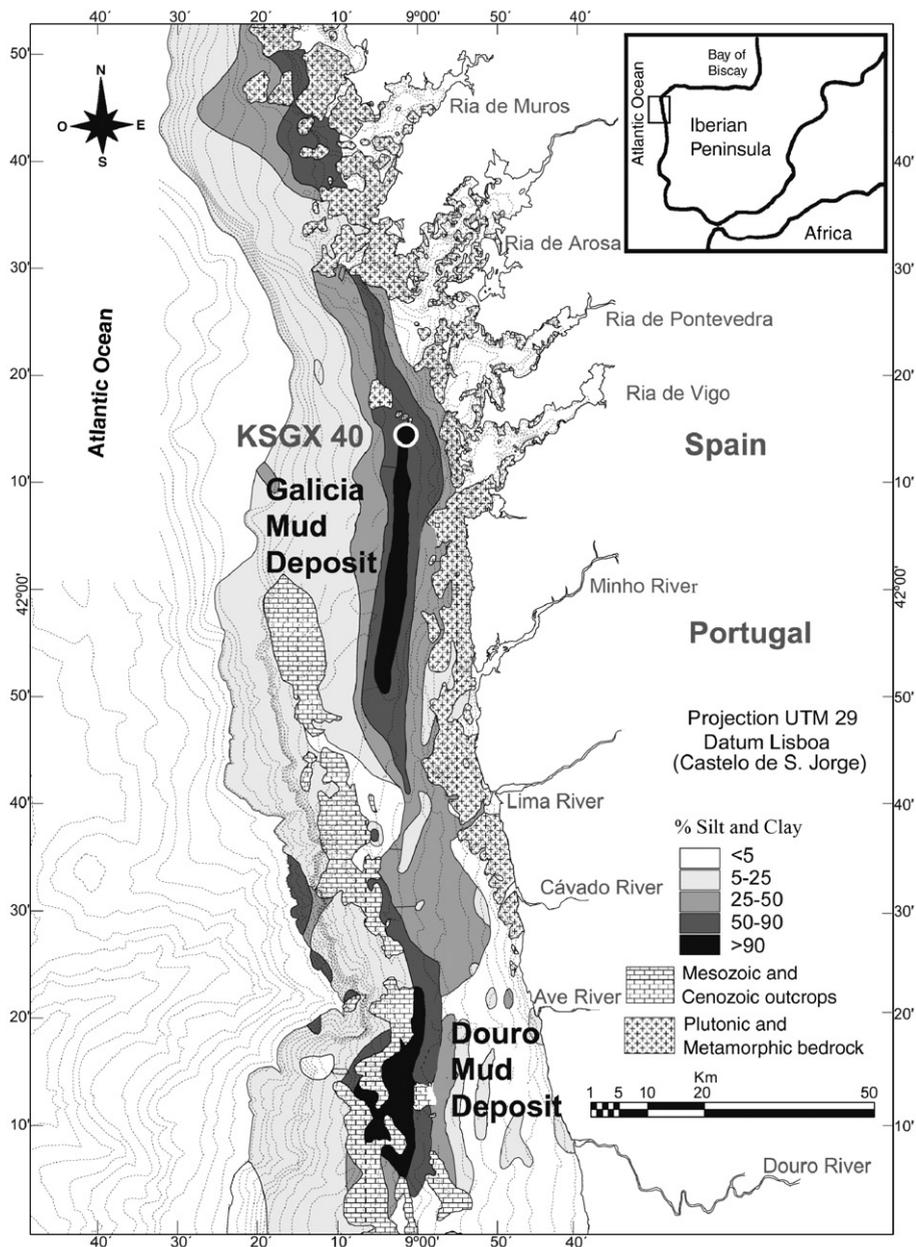


Fig. 1. The core KSGX 40 position in the Galicia Mud Deposit (adapted from Dias et al., 2002b).

These Rías are structurally controlled by Tertiary river valleys, bounded by steep hills and mountains (Salgado, 1993). The NW Iberian continental margin is characterized by a combined mesotidal and a high energy regime where hydrodynamic forces can transport and rework sediments to depths as great as 100 m (Dias et al., 2002a).

Sandy deposits cover broad areas of the NW Iberian Continental Shelf, probably due to sediments remobilisation by the highly energetic hydrodynamic conditions (Dias and Nittrouer, 1984). Two major deposits of fine-grained sediments occur along the NW Iberian shelf (Fig. 1) related to the Douro and Minho rivers (e.g. Araújo et al., 2002). They are elongated features covering the mid shelf area below the 60 m isobath. These muddy deposits are recent sedimentary bodies. Morphological barriers acting as sediments traps and favourable hydrographic conditions allowed the accumulation of fine sediments in these zones (e.g. Dias et al., 2002a,b; Jouanneau et al., 2002).

The Galicia Mud Deposit forms a narrow belt over the Galician shelf, orientated north/south, 50 km long and 2–3 km wide, extending northward off the Minho River estuary, at a water depth of 110–120 m (Dias et al., 2002a).

### 1.2. Shelf–slope circulation patterns driven by atmospheric forcing

The strength and position of the atmospheric pressure cells that govern the North Atlantic climatology, the Azores High and the Greenland/Iceland low, force the development of along-shore winds in the Western Iberian Margin, with seasonal variability. These atmospheric regimes determine two main coastal circulation patterns, upwelling and downwelling, along the Western Iberian Margin. The upwelling season occurs from March–April to September–October, when the weakening of the Greenland/Iceland Low and the strengthening of Azores High displaces northward, promoting northerly winds. During the peak summer months, the upwelling winds are strengthened by the development of a thermal low over central Iberia.

Considerable inter-annual variability is observed at the time of the onset and cessation of the upwelling favourable season. However, the most important source of variability is caused by the short-term fluctuations of the wind regime that can generate upwelling and downwelling events in either season.

During the winter season, the dominant wind direction changes to southerlies, and poleward flow becomes a conspicuous feature at all levels between the

surface and the Mediterranean Water, along the Iberian shelf edge and slope. The surface poleward flow carries relatively warm and salty water. The generation of this poleward flow has been attributed to the interaction between the meridional oceanic density gradient and the continental slope and shelf (Peliz et al., 2003), as well as the reversal of the wind regime, which has a southerly component during this time of the year. Strong events of upwelling during the winter season have been documented (Vitorino et al., 2002; Oliveira et al., 2004), and may have consequences on bottom stratification, and reversals of circulation patterns as discussed later.

On the other hand lenses of low salinity water, with their source in river runoff, can result in buoyant plumes that develop into inshore currents, predominantly in the poleward direction. This feature has been named the Western Iberian Buoyant Plume (WIBP) (Peliz et al., 2002).

### 1.3. The aims of this work

The main goal of this work is to analyse a core of sediments on the Galicia outer shelf, based on sedimentological, geochemical, mineralogical and microfaunal (benthic foraminifera) methods in order to:

- (i) Reconstruct and discuss the hydrodynamic regimes and the main characteristics of oceanic shelf circulation processes of the North Western Iberian Margin in the last ca. 4.8 ka cal BP.
- (ii) To identify the time variation of low and high productivity regimes in that region.
- (iii) To identify the periods of higher/lower carbon export to the sediments influencing shelf sedimentary processes.

## 2. Materials and methods

The OMEX (Ocean Margin Exchange Project) core KSGX 40 (164 cm long) was collected during the oceanographic cruise NO CÔTES DE LA MANCHE – Mission GAMINEX (8/ 07/1998–19/07/1998), in the Galicia Mud Deposit, off the Ría of Vigo, at latitude 42°14'98"N, longitude 09°01'01"W and sea depth of 115 m (Fig. 1). This muddy deposit is located on the NW Iberian outer continental shelf (North of Spain). Samples were taken at each centimetre or at 1-cm intervals.

Three radiocarbon dates of mixed foraminifera tests (10 mg to 20 mg) were determined from the sedimentary size fraction > 125 µm of the selected layers (39–40 cm, 69–70 cm and 134–135 cm) and were carried out by

Table 1  
Diagnostic peaks and weighting factors

	Peak (Å)	The area was divided by:
Minerals of fine fraction		
Quartz	3.34	2
Phyllosilicates (global clay minerals composition)	4.45	0.1
K-feldspars	3.21	1
Plagioclases	3.18	1
Calcite	3.03	1
Anatase	3.52	1
Anhydrite	3.49	1.5
Dolomite	2.88	1
Hematite	2.68	1.3
Pyrite	2.71	1
Siderite	2.79	1
Clay minerals		
Illite	10, in natural specimen	0.5
Kaolinite	7, in natural specimen	1 (depleted of the previously calculated chlorite area)
Chlorite	7 and 14 (after heating at 500 °C)	1.25 (7 Å)
Smectite	17, in glycolated specimen	4

AMS method in “Beta Analytic Inc.”, Miami, FL, USA. The CALIB 4.3 program of [Stuiver et al. \(1998\)](#) was used to update radiocarbon dates to calendar years BP. In the model age of this core, we used  $2\sigma$  calibration intervals with a standard marine reservoir correction of approximately 400 yrs estimated for the Iberian Margin ([Soares, 1989](#)).

A laser microgranulometer (Mastersizer S instrument, Malvern Instruments) was used for determining the particle sizes (in the range between 0.05 and 878  $\mu\text{m}$ ) of the sediments in each sample.

Mineralogical studies were carried out on the <63  $\mu\text{m}$  (silt) fraction and <2  $\mu\text{m}$  (clay) fraction of

the sediments through X-ray diffraction (XRD). The mineral composition was determined both on unoriented powder mounts for silt fraction analyses and on oriented aggregates for the clay fraction ones. The clay fractions were separated by sedimentation according to Stokes law, using 1% sodium hexametaphosphate solution to avoid flocculation. For the preparation of preferentially oriented clay mounts, the suspension was placed on a thin glass plate and air-dried. XRD measurements were performed using Philips PW1130/90 and X’Pert PW3040/60 equipment using Cu K $\alpha$  radiation. Scans were run between 2° and 60° 2 $\theta$  (unoriented powder mounts) or between 2° and 20° 2 $\theta$  (oriented clay mounts) in the air-dry state after a previous glycerol saturation and heat treatment (300 and 500 °C).

Qualitative and semiquantitative mineralogical analyses followed the criteria recommended by [Schultz \(1964\)](#), [Thorez \(1976\)](#) and [Mellinger \(1979\)](#). For the semiquantification of the identified principal minerals, peak areas of the specific reflections were calculated and weighted by empirically estimated factors (Table 1), according to [Galhano et al. \(1999\)](#) and [Oliveira et al. \(2002\)](#). In order to perform a joint analysis of both fractions, the amount of phyllosilicates (global clay minerals) computed for the silt fractions was redistributed between the three main clay minerals (illite, kaolinite and chlorite) according to their relative proportions in the clay fractions.

Two mineralogical indexes ([Vidinha et al., 1998](#); [Fradique et al., 2006](#)) were computed in fraction <63  $\mu\text{m}$ : Detrital Minerals (quartz+feldspars+phyllosilicates), Fine Detrital Minerals/Coarse Detrital Minerals, i.e. phyllosilicates/(quartz+K-feldspars+plagioclases), demonstrating the relative importance of the terrigenous supply and hydrodynamic sorting intensity, respectively.

Concentrations of the chemical elements Al, Co, Cr, Cu, Fe, Mn, Ni and Pb were determined in the fine fraction (<63  $\mu\text{m}$ ) of sediment samples collected along the core KSGX 40. These concentrations represent the

Table 2  
Results of radiocarbon dating determined in the Laboratory “Beta Analytic Inc.”, Miami, FL, USA

Samples (cm)	Measured radiocarbon age	Conventional radiocarbon age	Radiocarbon age ( $2\sigma$ calibration)	Beta analytic no.	Average sediment accumulation rate (cm/kyr)
39–40	1110 $\pm$ 40 BP	1500 $\pm$ 40 BP	Cal AD 800–1000 Cal BP 1140–950	154.383	27
69–70	2270 $\pm$ 40 BP	2680 $\pm$ 40 BP	Cal BC 510–350 Cal BP 2460–2300	154.384	25
134–135	3820 $\pm$ 40 BP	4250 $\pm$ 40 BP	Cal BC 2490–2290 Cal BP 4440–4240	154.385	41

The estimate of the average sediment accumulation rate is based on conventional radiocarbon age.

amount of metals dissolved after the application of the three-acid dissolution method. Therefore, 1 g of each sample was dissolved according to the three-acid moisture ( $\text{HCl}_{\text{conc}} + \text{HNO}_{3\text{conc}} + \text{HF}_{\text{conc}}$ ) in a Teflon beaker (Lecomte and Sondag, 1980). The mixture was gently heated in a hot plate until completely dry. The residue was redissolved with 10 ml 4 M  $\text{HNO}_3$  solution and filtered (Whatman 45). Finally, the solution was diluted to 25 ml with de-ionized water. These solutions were analysed for Al, Co, Cr, Cu, Fe, Mg, Mn, Ni and Pb, by Atomic Absorption Spectrophotometry (GBC 906 Spectrophotometer). For quality assurance of the result, method blanks were used by analysing three replicate blanks and results were above detection limit for all parameters. In order to control the analytical process, precision of the analytical results was obtained by calculating variation between duplicate analyses. Ten percent of samples were digested and analysed in duplicate and relative standard deviation (RSD) was calculated (values ranged from 2% to 8%: 2% for Cu and Mn; 3% for Ni; 4% for Fe, Cr and Al; 6% for Mg and Pb; 8% for Co). Two reference materials were used: BCR 141R, calcareous loam soil and BCR 142R, light sandy soil. Reference materials were subject to three-

acid ( $\text{HCl}_{\text{conc}} + \text{HNO}_{3\text{conc}} + \text{HF}_{\text{conc}}$ ) digestion, following the same procedure of samples. Recoveries values range from 88% to 104% in the BCR141R sample and from 81% to 107% in the BCR142R sample.

For foraminiferal studies the samples were carefully washed through a set of sieves of 63  $\mu\text{m}$  and 1000  $\mu\text{m}$ , dried in an oven at 40 °C and weighed. For the study of benthic foraminifera, assemblages more than 300 individuals, relatively well preserved, were identified and quantified in the dried residue (63–1000  $\mu\text{m}$ ) of each sample using a light microscope. Foraminifera abundance (number per gram) was determined by counting tests from a known weighted sediment split. Benthic foraminifera diversity was evaluated using the Shannon–Wiener index:  $H = -\sum p_i \ln p_i$ , where  $p_i$  is the proportion of each species (Shannon and Weaver, 1999). The species equitability, or the uniformity of abundance in an assemblage of species, was used to identify changes in the structure of benthic foraminifera assemblages:  $E = H / \ln S$ . Equitability is greatest when species are equally abundant.

The data sets obtained were studied by a combination of univariate (such as mean moving average values and the mean of the values and trend lines with  $R^2 \geq 0.50$  or

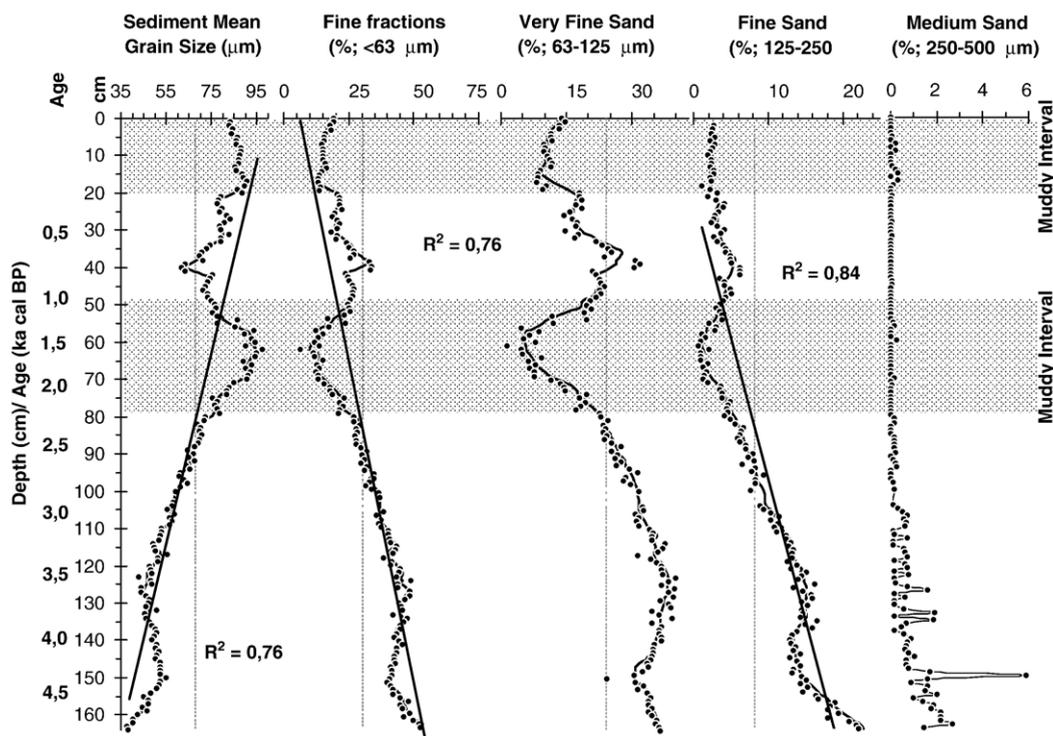


Fig. 2. The core KSGX 40 is a fining upward sequence with two muddy sections (80–50 and 20–0 cm) signed in this figure. Smoothed lines (solid black curves) between data (marks), the mean of the values (grey hatched line) and some trend lines (solid inclined black line) are also represented.

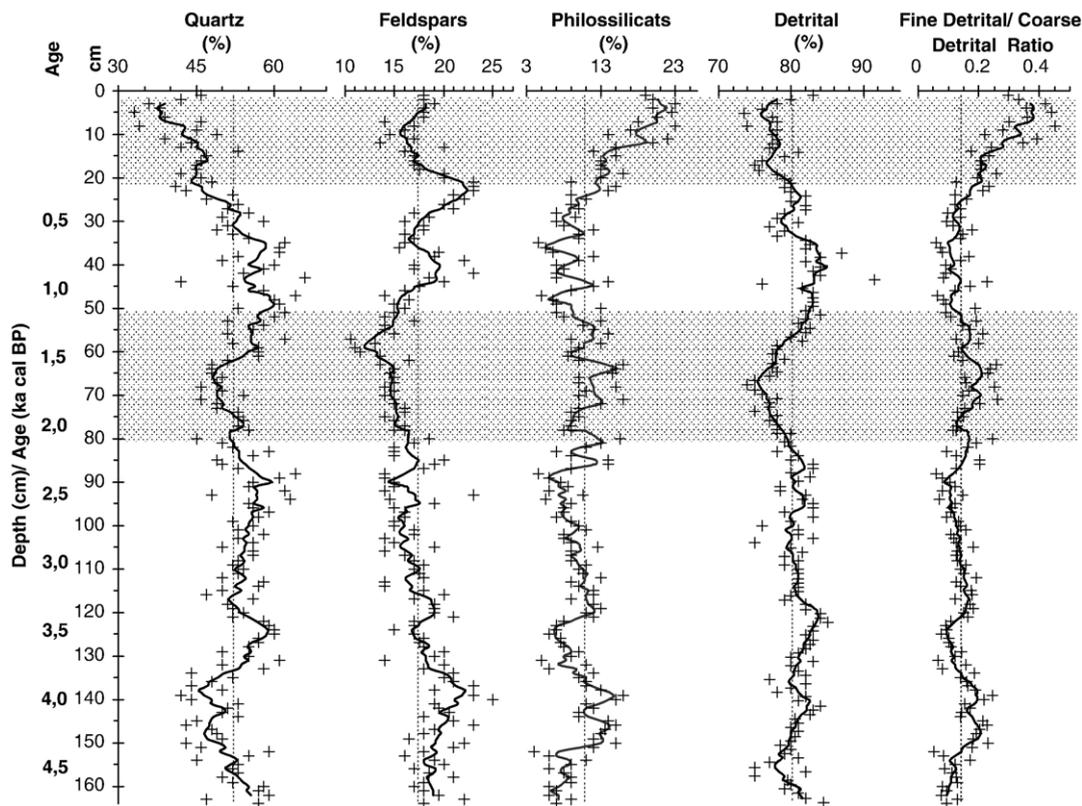


Fig. 3. Sediments of the both muddy sections (80–50 and 20–0 cm) are composed of lower values of quartz, feldspars and higher values of phyllosilicates (mica/illite, kaolinite, and chlorite). Detrital minerals decreased in both muddy sections while the fine detrital minerals increased. Smoothed lines (solid black curves) between data (marks), the mean of the values (grey hatched line) and some trend lines (solid inclined black line) are also represented.

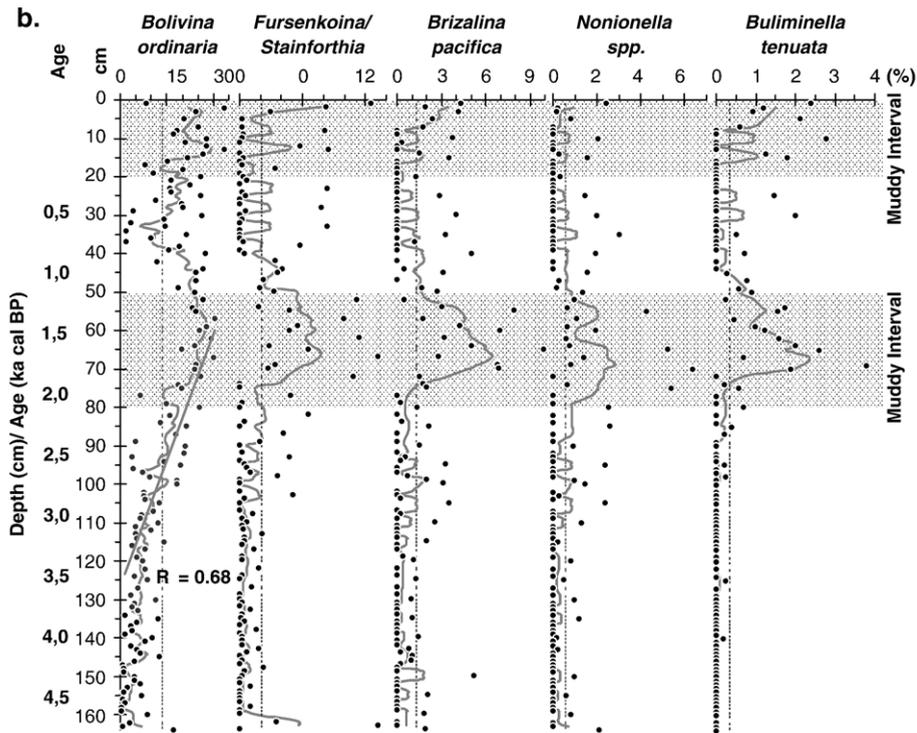
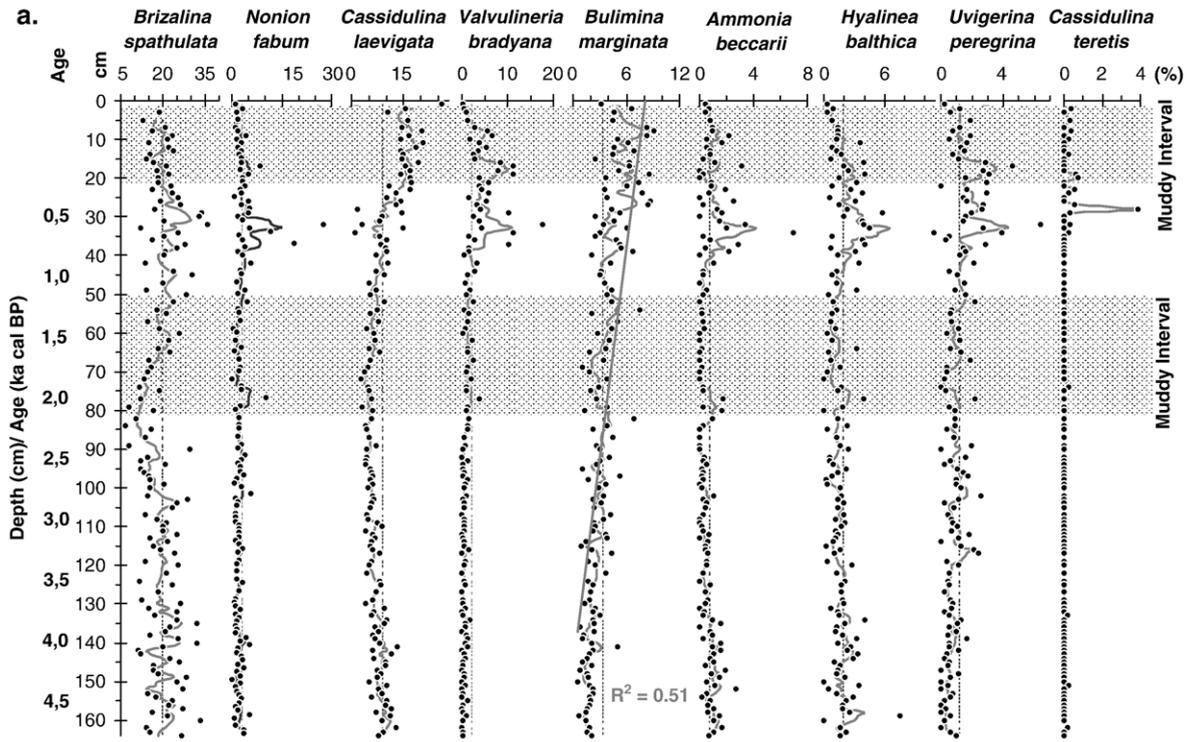
close to 50%) and multivariate statistical methods. Three-point moving average values and trend lines, computed in Excel, were used to identify general tendencies in the data evolution. Multivariate analysis was carried out by using the STATISTICA (v.5.1) software package.

### 2.1. Benthic foraminifera proxies

To better understand some of the changes in the sediment composition, and considering that benthic foraminifera respond sensitively to changes in organic

carbon flux, oxygenation and near-bottom current velocity were used two benthic foraminifera proxies. The total percentage of species related to a high and sustainable flux of metabolizable organic matter (see Appendix) was used in this core as a Benthic Foraminifera High Productivity index (BFHP) to identify periods of high supply of  $C_{org}$  to the sea floor. By the application of a Benthic Foraminiferal Oxygen Index (BFOI), based on Kaiho (1994), alterations in oxygen content of sediment pore-waters were evaluated. According to this author, the BFOI can be calculated following the definition of benthic foraminifera indicators

Fig. 4. The depth plot of the most abundant species of benthic foraminifera taxa (%). Smoothed lines (solid black curves) between data (marks), the mean of the values (grey hatched line) and some trend lines (solid inclined black line) are also represented. Species included in group B are in general more abundant in finer sediments (upper section of the core). While group C is more represented in sand richer sediments (lower section of the core). The evolution of the percentage of the most abundant species along this core shows significant changes. Species/taxa such as *Bolivina ordinaria*, *Brizalina pacifica*, *Fursenkoina/Stainforthia* and *Nonionella* spp. and *Buliminella tenuata* increase their percentage in the muddy intervals. Whereas *Brizalina spathulata*, *Bolivina pseudoplicata* and *Bulimina elongata/gibba*, for instance, decrease their relative abundance in these intervals. Other species such as *Cibicides ungerianus*, *Cassidulina minuta*, *Gavelinopsis praegeri*, *Globocassidulina subglobosa*, *Bolivina difformis*, and *Cassidulina crassa* are more represented in coarser sediments decreasing their percentage up-core (in finer sediments). See discussion in the text.



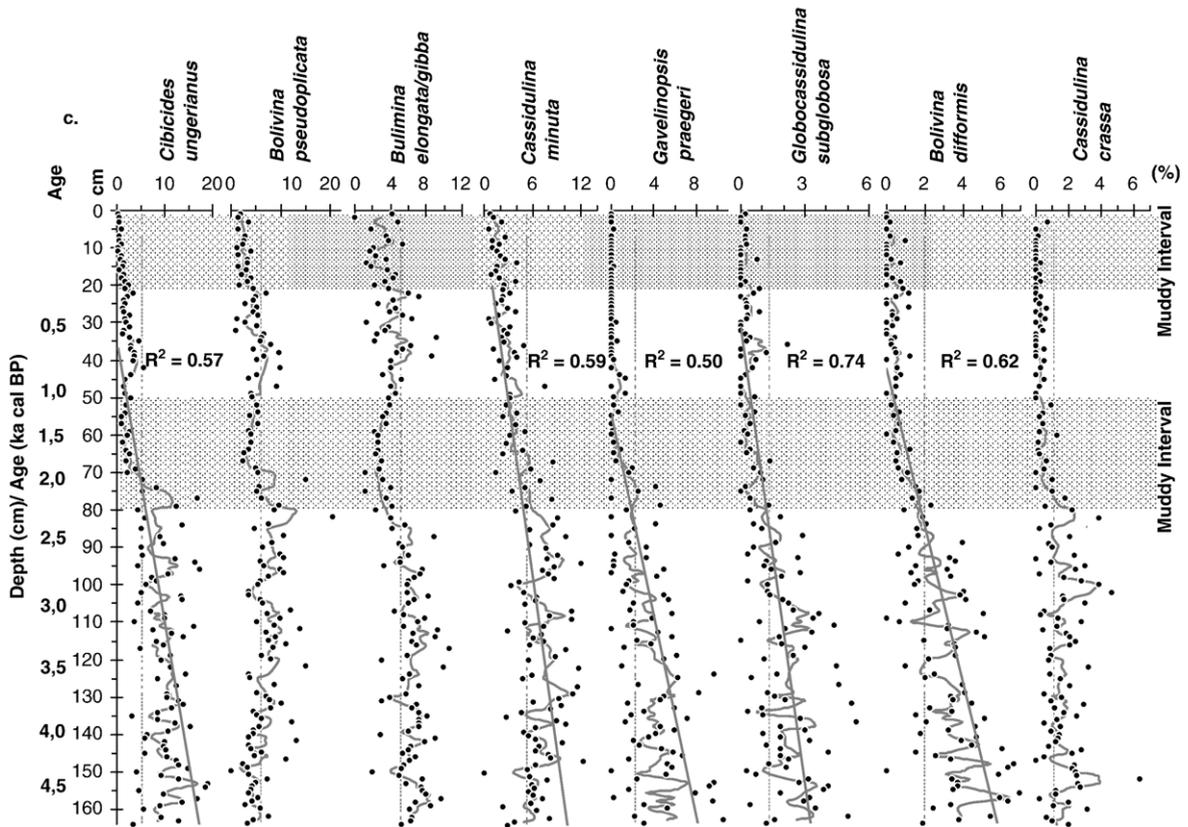


Fig. 4 (continued).

of oxic ( $O$ ) and dysoxic ( $D$ ) conditions, and by the application of the following equation when  $O$  is greater than 0 (the situation of this core):  $[O/(O+D)] \times 100$  (where  $O$  and  $D$  are numbers of specimens of oxic and dysoxic indicators, respectively). Species used as oxic ( $O$ ) and dysoxic ( $D$ ) are included in the Appendix.

### 3. Results

#### 3.1. Age model: textural and mineralogical composition of sediments

This core age model, based on the interpolation of three  $^{14}\text{C}$  measurements (Table 2), was established by Martins et al. (2006a). This core, which records the last ca. 4.8 ka cal BP, is a fining upward sequence with a sedimentary mean grain size varying between 6.5 and 56.0  $\mu\text{m}$ . Sand fractions ( $>63 \mu\text{m}$ ) are more abundant between 164 and 80 cm and they gradually reduce in the upward direction (Fig. 2). Medium sand fraction (250–500  $\mu\text{m}$ ) was only recorded in the lower part of the core. It is vestigial in the upper core 110 cm. Two finer sections can be observed between 80–50 cm and 20–0 cm.

According to the X-ray diffractometric results (analysed in the fine fraction) the mineralogical composition along this core is mainly siliciclastic (Fig. 3). Quartz is the main constituent (32.8–66%), which prevails over the feldspars (10.5–25.0%), i.e. plagioclase (7.0–14.0%) and K-feldspar (3.0–14.0%), and over the phyllosilicates (4–23%), i.e. mica/illite (2.5–15.0%), kaolinite (1–6.5%) and chlorite (0.0–2.0%). Calcite represents 6–12% of the mineralogical composition of the sediments. Accessory minerals are also represented by traces of several other minerals such as anatase (1–5%), anhydrite (1–4%), dolomite (0.5–5%), hematite (0–2%), opal (0.5–3%), pyrite (0.5–4%), siderite (0–2%) and zeolites (0–1%). Pyrite is underestimated in this analysis since the XRD approach could give a minimum estimate of the occurrence of a mineral, reflecting only the crystallized fraction.

Pearson's correlations between minerals reveal negative and significant correlations between quartz and phyllosilicates and feldspars. Sediments of both muddy sections (80–50 and 20–0 cm) are composed of lower values of quartz, feldspars and higher values of phyllosilicates (mica/illite, kaolinite, and chlorite). In

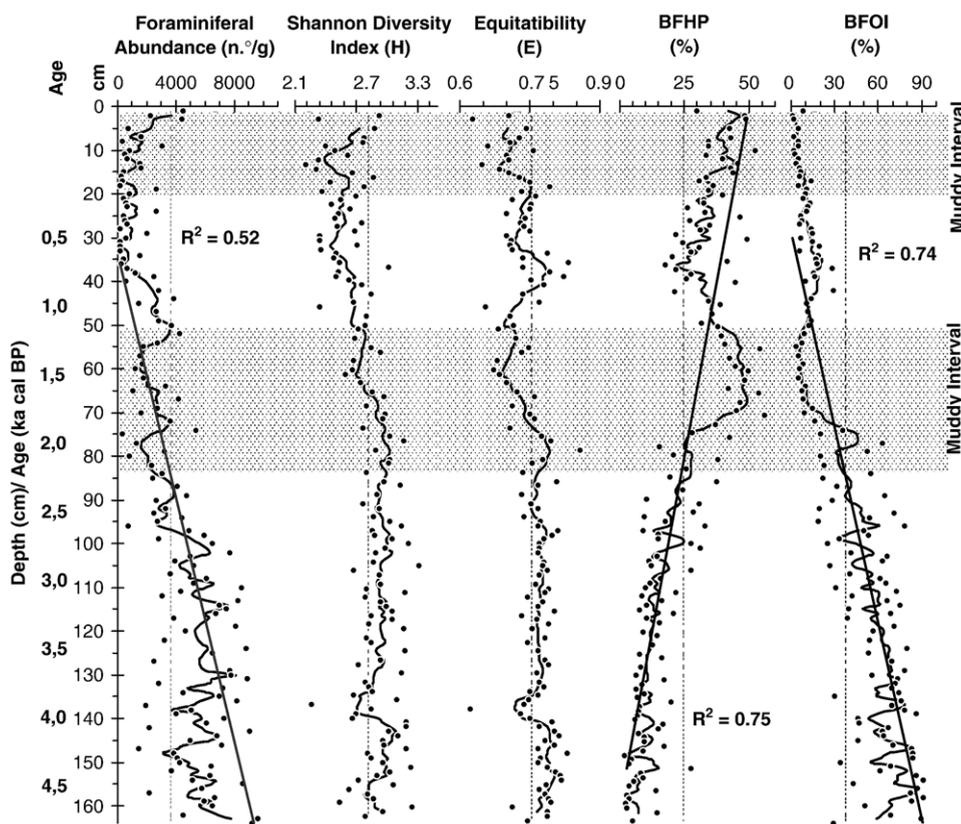


Fig. 5. The benthic foraminifera abundance (no./g) diversity, evaluated by the Shannon index, and equitability. Values of BFHP (Benthic Foraminifera High Productivity Proxy) and BFOI (Benthic Foraminiferal Oxygen Index) are also plotted. Smoothed lines (solid black curves) between data (marks), the mean of the values (grey hatched line) and some trend lines (solid inclined black line) are also represented.

one or both of these sections, there are slight increases in anatase, dolomite, anhydrite, siderite and hematite.

### 3.2. Benthic foraminifera abundance, structure and proxies

Results of benthic foraminifera assemblages were previously studied by Martins et al. (2006a). *Bolivina/Brizalina* spp. (23–67%), *Cassidulina/Globocassidulina* spp. (3–30%), *Bulimina* spp. (3–16%), *Cibicides* spp. (0.3–19%), *Fursenkoina/Stainforthia* spp. (0–13%), and *Nonionella* spp. (0–6%) are the most abundant taxa. The depth plots of the most frequent species found along this core are included in Fig. 4. The percentage of species such as *Brizalina spathulata*, *Bolivina ordinaria*, *Brizalina pacifica*, *Stainforthia fusiformis*, *Nonionella stella* and *Buliminella tenuata* increase in finer sediments. These species are related with a high and sustainable flux of organic matter and a low velocity of bottom currents and were included in the computation of the BFHP (see Appendix). The

BFHP depth profile (Fig. 5) shows an upward increase, being incremented mainly in the upper 80 cm, i.e. in the last 2.2 ka cal BP, but mainly between 80–50 cm (~2.2–1.2 ka cal BP) and 20–0 cm (0.5–0 ka cal BP). Otherwise the BFOI values have a generic opposite trend because several species, such as *Cibicides ungerianus*, *Cassidulina minuta*, *Gavelinopsis praegeri* and *Globocassidulina subglobosa*, known to be oxic indicators (see references in Appendix), reach higher percentages in sand rich facies, at the lower section of the core (Fig. 4c). These species are also good indicators of low flux of  $C_{org}$  and high velocity of bottom currents.

The absolute abundance of benthic foraminifera (number of specimens per gram of bulk dry sediment) decreases clearly and progressively upward as sediment mean grain size decreases (Fig. 5). Not only the abundance but also the diversity of benthic foraminifera, evaluated by the Shannon–Wiener diversity index, decreased in the upper section of the core reflecting changing in the assemblage's structure (Fig. 5). In both

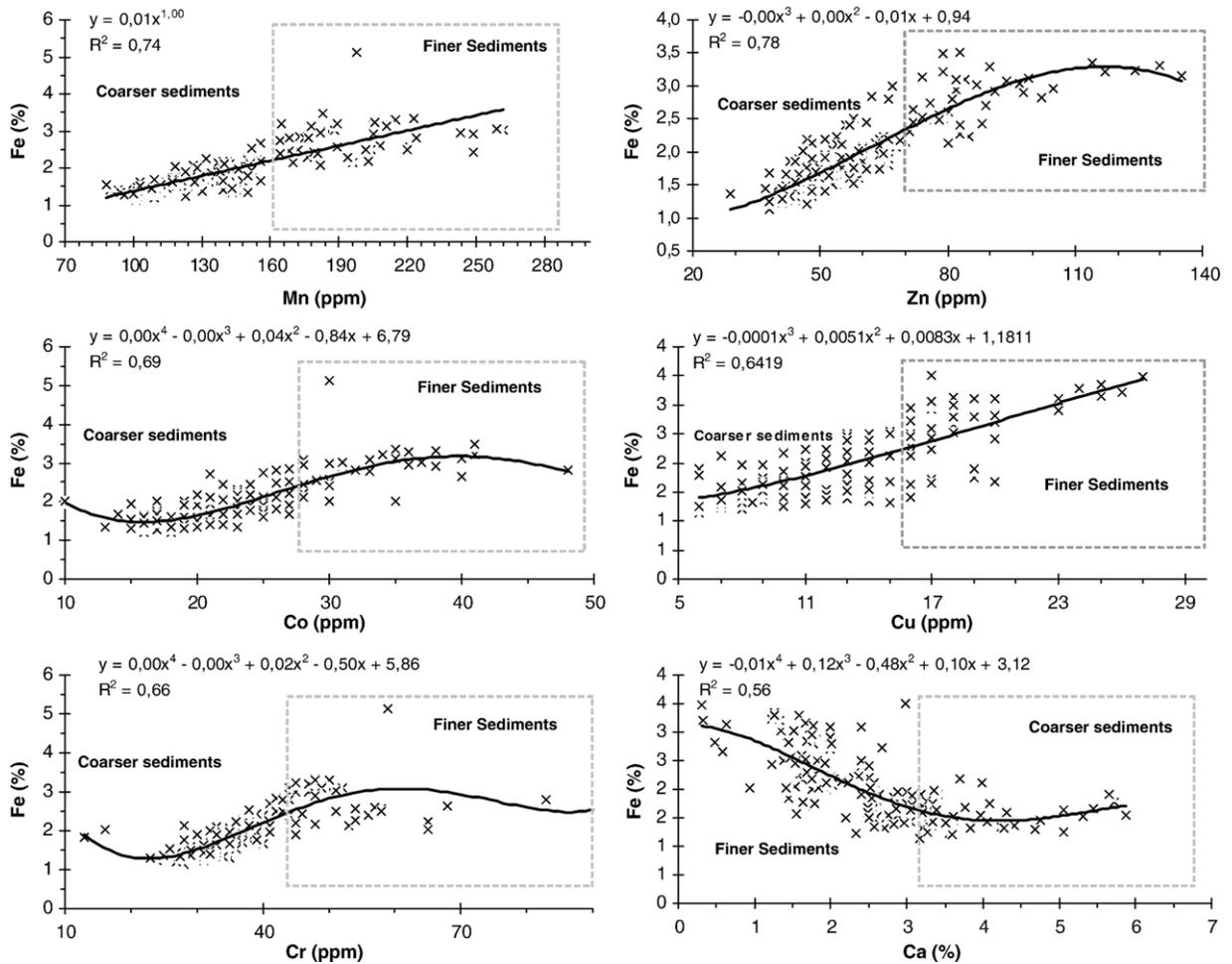


Fig. 6. The binary graphics between chemical elements with higher values of  $R^2$ . The higher concentrations of Fe, Mn, Zn, Co, Cu and Cr are found in finer sediments. A negative correlation there is between Fe and Ca.

muddy sections there is a decrease in the equitability values (Fig. 5).

### 3.3. Changes in the sediments geochemical composition

Sediment fine fractions have positive and significant Pearson's correlations with Fe, Mn, Al, Zn, Cr, Ni, Co, Pb, and Cu (0.53–0.86,  $P < 0.050$ ). Magnesium has weak correlations with the other elements while Fe has the higher correlations. Iron has positive correlations with Mn, Al, Zn, Cr, Ni, Co, Pb and Cu but a negative one with Ca. This means that these elements have similar depth profile trends with higher concentrations in both muddy sections (80–50 cm, 20–0 cm; see Martins et al., 2006b). Some binary graphics between Fe and other elements are represented in Fig. 6, showing that higher concentrations of these elements were found in finer sediments, except for Ca. Thus, Ca concentra-

tions have positive and significant correlation with sediment mean grain size (see value of  $R^2$  in Fig. 7). This means that this element, in general, increases as the

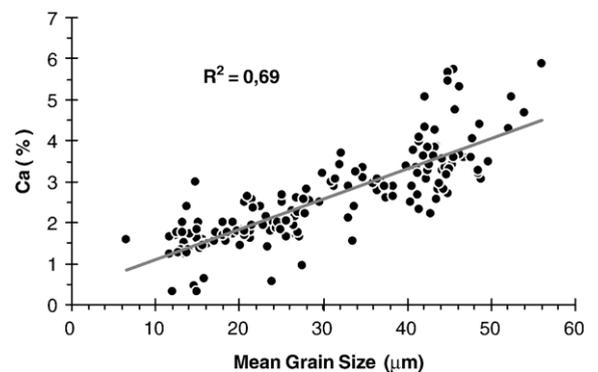


Fig. 7. Sediments calcium content have high  $R^2$  values with the sediments mean grain size.



#### 4.2. Hydrodynamic regimes and its influence on the carbon export

The lower section, between 164 and 80 cm (~4.8–2.2 ka cal BP), is characterized by coarser sediments (richer in detrital minerals and carbonate particles) and higher percentages of benthic foraminifera, which are related to high intensities of bottom currents. This seems to be related with the prevalence of high near-bottom current velocities.

Textural and mineralogical results (low values in coarse detrital minerals such as quartz and feldspars) agree with the occurrence of finer sedimentation between ~2.2–1.2 ka cal BP and ~0.5–0 ka cal BP (80–50 cm and 20–0 cm), i.e., during the two muddy intervals. These intervals suggest the occurrence of weak hydrodynamic conditions on the Galicia outer shelf.

The higher values of BFHP (earlier than ~2.2 ka cal BP) also agree with a strong hydrodynamic regime that arrested the settling of organic matter to the sea floor. Based on the higher values of benthic foraminifera abundance (numbers/g) and diversity (see Fig. 5), we can presume that during this period the decay of organic matter (food) to the bottom was enough to sustain the development of a rich and diverse benthic fauna in well-oxygenated surface sedimentary pore-waters. Under stronger bottom current regimes, benthic foraminifera suspension feeders (such as *C. ungerianus*, *G. praegeri*, *G. subglobosa*, see Fig. 4c) and other larger epibenthos also benefited from the re-suspended food supply.

The BFHP values also suggest a steady increase in the organic carbon flux and nutrient load since 2.2 ka cal BP (Fig. 5). The weak hydrodynamic conditions enabled the deposition of finer sedimentation enriched in organic matter mainly between ~2.2–1.2 ka cal BP and ~0.5–0 ka cal BP (80–50 cm and 20–0 cm). In these periods, when the flux of settling organic matter exceeded the flux of oxygen into these fine sediments, the exhaustive aerobic decay caused dysoxia (lower values of BFOI, see Fig. 5) in the sediment pore-waters in spite of the oxygenated overlying water. The redoxcline (defined here as the depth of zero oxygen content in pore-water) should have been established at a shallow depth in the sediments in both muddy intervals. The oxygen became a limiting factor for several species of benthic foraminifera. An oxygen deficit and/or a low near-bottom flow suppressed benthic foraminifera suspension feeders, as well as larger endobenthos (such as molluscs with carbonated shell) leading to the minor percentages of calcium sedimentary content and foraminifera abundance during these periods. In such adverse conditions only the low oxix-tolerant species survived.

#### 4.3. Early diagenetic changes

Changes in the redox conditions during both muddy events could also lead to early stages of diagenesis. Fe, Zn, Cr, Ni, Co, Pb and Cu have positive and significant correlations with Mn and Fe. This is a clear evidence of metal redistributions associated with Fe and Mn recycling. The accessory group of minerals (such as anatase, dolomite, siderite, pyrite and hematite) may be also related with intense chemical alteration or early stages of diagenesis in marine, continental or transitional environments in that time.

Manganese reacts to the reducing conditions developed in sediments by  $C_{org}$  remineralization (Calvert and Pedersen, 1993). Under strong reducing conditions, during the periods of higher supply of organic matter associated with a finer sedimentation, Mn oxyhydroxides act as electron acceptors and  $Mn^{4+}$  is reduced to soluble  $Mn^{2+}$ . This  $Mn^{2+}$  stays diffused in solution under anoxic/suboxic conditions. But soluble  $Mn^{2+}$  is oxidized to less soluble  $Mn^{4+}$ , when it escapes to the surface-oxygenated sediments, to form diagenetic oxyhydroxides.

The same holds true for the system  $Fe^{2+}/Fe^{3+}$ , with the difference that the reduced species remain in solution only at much lower levels of dissolved oxygen in pore-waters (Froelich et al., 1979). Fe is released from reducible minerals such as oxides/oxyhydroxides and silicates within the sedimentary layers in which sulphate reduction occurs (Canfield, 1989) and gives rise to ferrous iron. This subsequently reacts with dissolved  $H_2S$  to produce amorphous FeS and/or crystallized FeS, such as mackinawite and greigite, which are considered precursors of the pyrite generation (e.g. Schoonen and Barnes, 1991). The presence of pyrite in the sediments signs anoxic conditions (e.g. Burke and Kemp, 2002). Under favourable conditions pyrite can co-precipitate with other trace elements (e.g. Morse and Luther, 1999).

No high amounts of pyrite have been found using the X-ray diffraction technique in the sedimentary fine fraction. However, using a binocular microscope to analyse the composition of the sand fraction, a high number of sedimentary particles of framboidal pyrite, occurring as solitary spherules or irregular masses and pyritized tests of benthic foraminifera along the studied core, can be observed. As X-ray diffraction only identifies crystallized structures, we can deduce that not all the pyrite is well crystallized and its abundance is higher in this core than was detected by this technique.

Siderite ( $FeCO_3$ ) is another mineral present in this core that increases in both muddy events. It is also a

diagenetic mineral produced also in organic-rich environments. Its production requires the absence of sulphur and so it is generally associated with freshwater and deltaic (non-marine) sediments while pyrite is more common in marine sediments (Berner, 1971). The formation and preservation of stable siderite requires an anoxic sedimentary environment. In the presence of O<sub>2</sub>, pyrite and siderite are oxidized to goethite or hematite.

The tendency of higher values of pyrite and siderite in finer sediments of the studied core suggest: (i) a high flux of organic matter and the establishment of anoxic conditions in the sediments; (ii) that most of the pyrite and siderite after their formation remained in the anoxic environment and were therefore preserved.

#### 4.4. What kind of phenomena induced changes in oceanic hydrodynamics on the outer shelf?

##### 4.4.1. Late Holocene sea level change

Two main sea level changes, since the Holocene maximum transgression around 7000 yrs BP took place: a slight drop between 6900 and 2700 yrs BP, followed by a slight rise between 2400 yrs BP and the present (Zazo et al., 1996). Leorri and Cearreta (2004) also observed, through the study of stratigraphic sequences and foraminiferal interpretation, in the Bilbao estuary (northern Spain), that the sea level reached approximately its present position around 3 ka cal BP. There are several records agreeing with the occurrence of late Holocene small sea level oscillations in the Iberian Peninsula (e.g. Fidalgo and Romani, 1993; Cearreta and Murray, 1996). However these small oscillations had not enough (vertical) amplitude to directly influence the benthic hydrodynamic regime of the Galicia outer shelf. Thus, other oceanographic phenomena related to climate conditions should be the key to interpret the records of sediments analysed in this work.

##### 4.4.2. Shelf–slope circulation regime during the period of strong hydrodynamism

According to Dias et al. (2002a,b), the main mechanism supplying sediments to the NW Iberian shelf at present time, are floods of the northern Portuguese river basins. Nowadays the amounts of sand reaching the deeper areas of the NW Iberian Continental Shelf are small due to the presence of dams in the main rivers. However during the winter season higher amount of sediments are introduced in the ocean due to the river floods. In this season, southwesterly storms (from October to April approximately) result in considerable reworking and redistribution of previously

deposited sediments on the shelf. These storms coinciding with a downwelling regime and the development of the poleward flow, result in the hydrodynamical transfer of resuspended material northwards (Jouanneau et al., 2002) and offshore through the bottom boundary layer. Under these conditions coarser sediments are also transported and redistributed and can eventually be deposited on the Douro and Galicia Mud Deposits after a series of resuspension events (Dias et al., 2002a).

We interpret the coarse sediments of this core as the result of extreme winters, during the period ~4.8–2.2 ka cal BP, associated with: (i) large river runoff, with large load of sediments, (ii) resuspension of sediments associated to SW storms and large waves, and (iii) downwelling favourable conditions promoting northward and offshore transport through the bottom boundary layer.

These conditions also had influence in benthic foraminifer assemblages, allowing the development of a rich fauna, characterized by higher amount of suspension feeders (such as *C. ungerianus*, *G. praegeri*, *G. subglobosa*, see Fig. 4c) related to the strengthening of bottom velocities and bottom stresses.

On the other hand, benthic foraminifera key indicators of oceanic stratified conditions, such as *Bolivina/Brizalina*, *Bulimina marginata* and *Nonionella* spp., according to Scott et al. (2003), Scourse et al. (2002) and Evans et al. (2002), are scarce in the lower section. The small amount of these species can be a consequence of the presence of deep mixed layers (deeper than the shelf-break depth, say 400 m or more) which are supposed to be common during the winter season in this particular regime of strong hydrodynamics. The higher values of calcium (due to the higher amount of foraminifera and molluscs bioclasts) also support the idea that an export of materials from the shallow sea and the adjacent continental areas also happened during this period.

##### 4.4.3. Shelf–slope circulation during the period of weak hydrodynamics: evidence of upwelling intensification

After 2.2 ka cal BP, finer and organic-rich sediments were deposited under weak hydrodynamic bottom currents on the outer shelf. This agrees with the observations of Jouanneau et al. (2002): finer terrigenous materials and higher amount of C<sub>org</sub> are presently deposited under weak hydrodynamic activity in calm areas of the NW Iberian shelf. However a question arises: can the weak hydrodynamic activity be enough to explain the high deposition of organic matter in the upper section of the core?

The C<sub>org</sub> flux to the studied area can be provided not only by local marine productivity but also by lateral

transport. However, for ecological function, the importance of the deposited  $C_{\text{org}}$  depends on the lability of the transported materials and the trophic status of the region that receives these materials (Álvarez-Salgado et al., 2001). Labile (nutrient-rich) organic matter constitutes an important source of food for the benthic foraminifera assemblages (Loubere and Fariduddin, 1999). This group responds mostly to the flux of labile organic matter. The influx of biologically labile material not only increases benthic foraminiferal standing stocks but also enhances bacterial activity. Foraminifera could either feed directly on bacterial stocks, or bacteria could degrade organic compounds that are not suitable for consumption by benthic foraminifera in their original form (Jörisen et al., 1998). Refractory organic debris is not used as a food source for foraminifera since the bacterial breakdown of refractory organic matter into labile organic matter is a slow process (Fenchel and Finlay, 1995).

So we interpret the increase of  $C_{\text{org}}$  flux on the sea floor, measured by BFHP, as being a consequence of the input of labile organic matter resulting from the improvement of oceanic productivity. The oceanic primary productivity can be enhanced, in the studied area, by the introduction of nutrients during recurrent upwelling episodes (Tenore et al., 1995), of cold and nutrient-rich Eastern North Atlantic Central Water (Blanton et al., 1987). The interaction between the upwelling events and the flooded tectonic valleys in the west coast of Galicia (Rías Baixas) also allows the existence of highly productive systems (Hanson et al., 1986), which in turn supports an elevated extraction of edible mussels. The outwelling water from the Rías Baixas to the shelf areas also contributes to the increase of biological production on the adjacent shelf during the upwelling season (Álvarez-Salgado et al., 1997).

It is our belief that the increase of BFHP values since 2.2 ka cal BP, but especially between ~2.2–1.2 ka cal and 0.5–0 ka cal BP, are a consequence of the increase of upwelling events. The first period was also identified by Bartels-Jónsdóttir et al. (2006) as a phase of high productivity due to the intensification of the upwelling events. These authors studied a high-resolution sedimentary sequence recovered in the Tagus prodelta on the western Iberian Margin, Portugal. Diz et al. (2002) in the Ría de Vigo and Soares and Dias (2006) in the NW Galician Margin also identified an intensification of coastal upwelling processes coinciding with the second period.

As discussed above, the presence and or the increase of benthic foraminifera considered key indicators of stratified conditions on the continental shelf, in the upper section of this core, suggest an increase in the

frequency of stratification near the bottom on the outer shelf during both muddy intervals.

We propose that there are two mechanisms that can help explain the presence of stratification associated to the weak hydrodynamic regime:

- (1) During winter, roughly from October to April, the predominance of southerly winds and the mechanism described in the Introduction favours the development of poleward current on the slope and the shelf area. However, this characteristic pattern of winter circulation can be disrupted by upwelling events driven by persistent and strong northerly winds (Vitorino et al., 2002).

During this season, cooling of the surface, generates a mixer layer (with typical thickness ~200 m) covering the whole shelf (Oliveira et al., 2004). The mixed layer is separated from the central waters below, by a characteristic winter pycnocline, which is depressed at the slope (associated with poleward flow).

When strong northerly winds are present in winter, the pycnocline, which is usually located at the shelf-break (~200 m), rises to the middle shelf, generating significant bottom stratification (Vitorino et al., 2002, Fig. 8). During these events, a marked stratification close to the bottom between the shelf-break and the middle shelf can be generated. The benthic foraminifera, which are key indicators of bottom stratified conditions, should be related with this phenomenon.

- (2) During spring–summer time, the presence of northerly winds induces the upwelling and rise of the pycnocline, bringing stratified waters to the middle shelf (Peliz et al., 2002).

Both mechanisms associated with upwelling and favourable winds may explain the presence of these benthic foraminifera which have been observed to increase during this weak hydrodynamic regime.

## 5. Conclusions

This work is based on the study of sediments collected in a core of the Galicia Mud Deposit (outer continental shelf). Two different hydrodynamic regimes of the shelf circulation were found: a strong hydrodynamic regime between ~4.8 and 2.2 ka cal BP and a weak hydrodynamic regime between ~2.2 and 0 ka cal BP. The strong hydrodynamic regime should be related with the prevalence of winter storms, with the development of poleward flow and downwelling. This interpretation is based on

the presence of coarser sediments, and on the higher abundance of benthic foraminifera species related with high bottom velocities and well-oxygenated waters. Associated with the weak hydrodynamic regime, we also hypothesize the prevalence of upwelling regime induced by the prevalence of northerly winds regime. Benthic foraminifera key indicators of stratified conditions indicated periods of increased bottom stratification associated to the prevalence of upwelling events during this weak hydrodynamic regime. The increase of benthic foraminifera species in this regime is related to both the sustainable flux of metabolizable organic matter and to the high productivity related to the upwelling regime. Depressed levels of oxygen in the sediments, giving place to anoxia and to higher chemical precipitation due to early diagenetic changes (revealed by the geochemical and mineralogical results), also indicate a high decay of organic matter during this regime.

## Acknowledgements

We would like to thank the editor Dr. David J.W. Piper, and the reviewers Professor David B. Scott of Dalhousie University, Halifax, Canada, and Professor Nathalie Fagel, of URAP, Université Libre de Liège, for providing constructive and very important suggestions for the discussion of the data analysed in the manuscript. We would like to thank also Dr. David J.W. Piper by his kindness correcting the English of this work. The authors also wish to express their thanks to all the people involved in the Mission GAMINEX (8/07/1998–19/07/1998) of the oceanographic cruise NO CÔTES DE LA MANCHE which collected the OMEX (Ocean Margin Exchange Project) core KSGX 40.

## Appendix A

### A.1. Species used in the computation of the Benthic Foraminifera High Productivity (BFHP)

Bolivinids, such as *Bolivina ordinaria*, *Brizalina pacifica* (e.g. Sen Gupta and Machain-Castillo, 1993; Bernhard and Sen Gupta, 1999), Buliminids, such as *Bulimina marginata/aculeata* (e.g. Mackensen et al., 1990), *Buliminella tenuata* (e.g. Douglas and Heitman, 1979; Silva et al., 1996), *Nonionella* spp., such as *Nonionella iridea* (Gooday and Hughes, 2002), *Nonionella stella* (Silva et al., 1996), *Nonionella turgida* (Duijnsteet et al., 2004), *Fursenkoina/Stainforthia* spp. (e.g. Alve, 1994), *Uvigerina peregrina* (e.g. de Rijk et al., 1999; Altenbach et al., 2003) and *Valvulineria bradyana* (e.g. Van der Zwaan and Jörisen, 1991).

### A.2. Species used in the computation of the Benthic Foraminiferal Oxygen Index (BFOI)

#### A.2.1. Well oxygenated bottom waters/low concentrations of organic carbon indicators

*Cibicides ungerianus* (Barmawidjaja et al., 1995; Altenbach et al., 2003), *Cibicides gerthi* (Barmawidjaja et al., 1995; Altenbach et al., 2003), *Discorbis* spp. (Geraga et al., 2000), *Elphidium* spp. (such as *Elphidium macellum aculeatum*, *Elphidium crispum*, *Elphidium fichtellianum*, in this work *Elphidium jenseni*; e.g. Geraga et al., 2000), *Gavelinopsis praegeri* (Barmawidjaja et al., 1995; Schönfeld, 1997; Altenbach et al., 2003), *Globocassidulina subglobosa* (Altenbach, 1992; Linke and Lutze, 1993), *Hanzawaia nitidula* (as *Hanzawaia concentrica*; Barmawidjaja et al., 1995; Schönfeld, 1997; Altenbach et al., 2003), *Hyalinea balthica* (Geraga et al., 2000), *Lepidodeuterammia ochracea* (as *Deuterammia ochracea*; Schönfeld, 2002a,b), *Lobatula lobatula* (Banner et al., 1994; Schönfeld 2002a,b), *Paumotua terebra* (as *Eponides* sp.; De Stigter et al., 1998), *Planorbulina mediterraneanensis* (Coppa and Di Tuoro, 1995), *Quinqueloculina* spp. (Kaiho, 1994; Geraga et al., 2000), *Spiroplectinella sagittula* (Schönfeld, 2002a,b), *Trifarina angulosa* (e.g. Mackensen et al., 1990, 1995; Schönfeld, 2002b), *Textularia* spp. (Schönfeld, 1997; Geraga et al., 2000; Altenbach et al., 2003), and *Trochammina* spp. (Schönfeld, 2002a,b).

Note: some species included in this sub-group were separated based on morphological criteria (e.g. Corliss and Chen, 1988; Murray, 1991); because planoconvex taxa are considered to be epifaunal, whereas biconvex or more elongate taxa are considered as shallow infaunal. So in well-oxygenated bottom waters were also include other planoconvex species like: *Asterigerinata* spp., *Eoeponidella pulchella*, *Lamarckina haliotidea*, *Neonorbina parkerae*, *Patellina corrugata*, *Remaneica helgolandica*, *Rosalina* sp.

#### A.2.2. Dysoxic indicators

*Bolivina ordinaria* (Hermelin and Shimmield, 1990; Aharon et al., 2001), *Brizalina pacifica* (Douglas and Heitman, 1979), *Bulimina aculeata* (Mackensen et al., 2000), *Bulimina marginata* (e.g. Rohling et al., 1993; Alve and Bernhard, 1995), *Buliminella tenuata* (e.g. Bernhard and Sen Gupta, 1999), *Chilostomella* spp. (e.g. Bernhard and Sen Gupta, 1999; de Rijk et al., 1999), *Globobulimina* spp. (e.g. Sen Gupta and Machain-Castillo, 1993; Kaiho, 1994; de Rijk et al., 1999), *Nonionella stella* (e.g. Bernhard and Sen Gupta, 1999; Van der Zwaan et al., 1999) *Stainforthia fusiformis* (e.g. Alve and

Murray, 1997; Bernhard and Sen Gupta, 1999; Van der Zwaan et al., 1999).

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