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Late Holocene history of the rainfall in the NW Iberian peninsula—Evidence from a marine record

P. Bernárdez [a,b,*], R. González-Álvarez [a], G. Francés [a], R. Prego [b], M.A. Bárcena [c], O.E. Romero [d,e]

[a] *Departamento de Geociencias Marinas y Ordenación del Territorio, Facultad de Ciencias del Mar, Campus Lagoas-Marcosende s/n. Universidad de Vigo, 36310, Vigo, Spain*
[b] *Departamento de Oceanografía, Grupo de Biogeoquímica Marina, Instituto de Investigaciones Marinas (CSIC).C/Eduardo Cabello 6, 36208 Vigo, Spain*
[c] *Departamento de Geología, Facultad de Ciencias, Universidad de Salamanca, 37008, Salamanca, Spain*
[d] *Department of Geosciences, University of Bremen, P.O. Box 330440, 28334 Bremen, Germany*
[e] *Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Facultad de Ciencias, Campus Fuentenueva, 18002 Granada, Spain*

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Abstract

This study reconstructs climatic variability over the last 4700 yr in the NW Iberian Peninsula on the basis of lithological, sedimentological, biogeochemical, micropaleontological (diatoms and biosiliceous compounds) and AMS ^{14}C analyses conducted in a gravity core retrieved from the Galician continental shelf. The core was recovered at the *Galicia Mud Patch*, a muddy sedimentary body highly influenced by the terrestrial supply of the Miño and Douro rivers, and thus controlled by the rainfall variations over the catchment area. River plume transports the lithogenic and continental-derived compounds to the shelf area allowing us to recognize several periods of terrestrial/marine influence. These periods are well correlated with the lithological units identified. Coarser sediments, high values of Ca/Al, low values of Fe, Al and lithogenic Si (LSi) are representative of the marine-influenced periods. These stages are related to dry conditions and winds coming from the NE under a NAO positive-like phase.

Terrestrial-influenced stages are characterized by muddy sediments, with high content of Fe, Al and LSi, freshwater and benthic diatoms, continental-derived organisms (crysophycean cysts and phytoliths) and high amount of land-derived organic matter as reported by the C/N ratios. The influence of NAO positive- and NAO negative-like periods and solar activity are the two mechanisms quoted to explain the climatic variability during the last 4700 years.

Proxies for the lithogenic input and terrigenous content (non-organic material) show an increase at around 2000–1800 cal. yr BP, linked to the warmer conditions and high precipitation patterns during the Roman Warm Period, and soil erosion due to forest degradation and other anthropic activities. A strong river flow event is recorded in shelf sediments during 800–500 cal. yr BP. A pervasive NAO negative-like period, and the high irradiance registered during the Grand Solar Maximum (GSM) controlled the precipitation and induced a high run-off and riverine influx during this event.

Keywords: Paleoclimatology; Late Holocene; North Atlantic Oscillation; River-input; Rainfall; Diatom assemblages; NW Iberian Peninsula

* Corresponding author. Departamento de Oceanografía, Grupo de Biogeoquímica Marina, Instituto de Investigaciones Marinas (CSIC). C/ Eduardo Cabello 6, 36208 Vigo, Spain. Tel.: +34 986 231930; fax: +34 986292762.
E-mail address: pbernard@iim.csic.es (P. Bernárdez).

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1. Introduction

The view of stability of the present Holocene epoch has been questioned (Meese et al., 1994; O'Brien et al., 1995; Bond et al., 1997; Bianchi and McCave, 1999; deMenocal et al., 2000; Mayewski et al., 2004). The stable and warm climate has undergone a series of climate fluctuations and reorganizations, but their worldwide distribution on a global scale in different environmental archives and chronology is still being discussed (Bradley and Jones, 1993; Hughes and Diaz, 1994; Stuiver et al., 1995; Keigwin, 1996; Broecker, 2001). In addition, the forcing mechanisms of the Holocene changes are still a matter of debate (van Geel et al., 1999; Crowley 2000; Jones and Mann, 2004).

The NW Iberian Peninsula off the Galician coast is a high sensitive area where climate is susceptible to change due to variations of the polar front and the Canarian–Iberian upwelling system. Moreover, this area has also a great potential for determining the hydrographic interaction between riverine and ocean waters because of the proximity of the Miño and Douro river mouths (Fig. 1).

Despite increased and well-deserved attention toward climatic and oceanographic variability during the Holocene (e.g. Bond et al., 1997; deMenocal et al., 2000), there are few high-resolution records over this time span for the NW Iberian Peninsula. Recent studies in the Holocene period in this region have identified several major climatic changes (Martínez-Cortizas et al., 1999; Diz et al., 2002; Desprat et al., 2003; Abrantes et al., 2005; Álvarez et al., 2005; González-Álvarez et al., 2005b; Martins et al., 2005; Bartels-Jónsdóttir et al., 2006; Martins et al., 2006a, b; Lebreiro et al., 2006).

Climatic fluctuations have long been noted as being cyclical in nature responding to several processes. Causes of these variations and abrupt and slight transitions at different time intervals have been hypothesized, including solar activity, astronomical forcing, CO_2, global thermohaline circulation and oceanography, or oscillations in the atmospheric pressure system, such as the North Atlantic Oscillation index (NAO).

Despite these climatic factors affecting the sedimentary record, anthropogenic influence can also be documented as having strong influence. Human impacts in the last 3000 years registered in a wide variety of temporal archives in the nearby area have been identified by several authors, such as mining activities (Kylander et al., 2005), and changes in vegetation and in land use (Desprat et al., 2003; Martínez-Cortizas et al., 2005). The study of a marine sediment core as an environmental archive has allowed us to reconstruct the climatic history of the last 4700 years on a regional and a global scale, and discriminate the possible human impacts on the record.

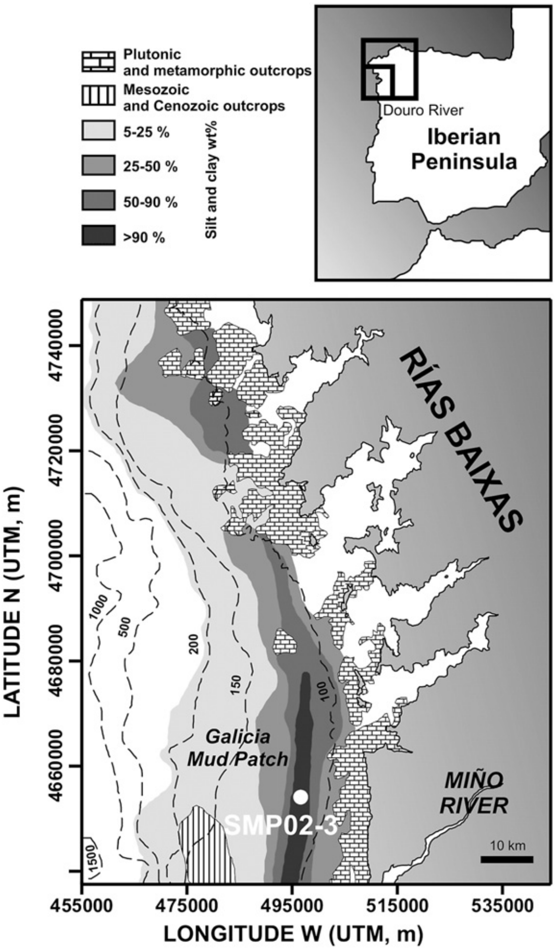

Fig. 1. Localization of the study area on the northwestern Iberian margin. Simplified map showing the present surface sediments distribution of the Galician continental shelf (modified from Dias et al., 2002a) and the location of the core SMP02-3.

We focused on the Late Holocene climate changes and involved processes affecting the NW Iberian margin region. This paper reports the study of a sedimentary record retrieved from the Galician continental shelf. Many paleoenvironmental proxies in the core have been examined, including lithological information, X-ray radiography, sedimentary structures, sediment composition, metals content and diatom flora and biosiliceous compounds. This multivariable approach is needed in order to get a more comprehensive view of the physical and biogeochemical processes involved. In the present manuscript, the main objective is to outline the environmental evolution of climate and anthropogenic influence in the NW Iberian Peninsula extending back 4700 cal. yr BP. This study is specifically targeted to use the terrestrial-derived fractions as a potential index of climatic, hydrologic and past fluvial input conditions over the NW Iberian Peninsula. We focus on the description of alternating wetter/drier periods and marine/terrestrial influence. This paper also explores the forcing factors of climate in the NW Iberian area and how these climatic signals are recorded in the sediments. In addition, we address the influence of local human activities on land and its record in the continental shelf sediments.

2. Regional setting

This study has been carried out in the Galician continental shelf, NW Iberian Peninsula. This coast is characterized by the presence of the Rías Baixas, small coastal embayments drowned by the sea during the last transgression (Rey, 1993). In this area, the shelf is relatively narrow. The slope change is located at a distance of 15–30 km from the shoreline (Fig. 1). Surface sediments have been described as fine silty-clays, building up the *Galicia Mud Patch*, a sedimentary body situated in the middle shelf. In deeper and coast areas sandy sediments cover the seabed. The *Galicia Mud Patch* is an elongated North–South-orientated deposit, that yields and age of 2650±280 years BP at about 80 cm depth in the Portuguese part (Drago, 1995), extending off the Miño River. The origin of the *Galicia Mud Patch* is related to the abundant supply of sediment, especially during episodic flood events, shelf morphology and hydrographic conditions that favour the accumulation of muddy sediments (Dias et al., 2002b; Jouanneau et al., 2002; Vitorino et al., 2002a,b) (Fig. 1). The main sediment source of clayey–silty sediments deposited at the Galician shelf, as shown by their geochemical properties, come from the Douro River (Araújo et al., 2002; Oliveira et al., 2002a,b), although the contribution of the Miño River is not negligible. These fine sediments were remobilized and transported from the adjacent Portuguese shelf towards the *Galicia Mud Patch* by several oceanographical mechanisms (Vitorino et al., 2002a,b). River influx at the heads of the Rías is very low and export of sediment from Rías to the shelf is small (Rey, 1993).

Sediment spreading off-shelf is low, since sediment transport when river floods, storms and riverine supplies are high, is northwards (Jouanneau et al., 2002). Sedimentation rates in the Portuguese–Galician shelf range overall from 0.05 to 0.40 cm yr^{-1} (Jouanneau et al., 2002). In nearby cores sedimentation rates vary between 0.009 and 0.19 cm yr^{-1} (Jouanneau et al., 2002; González-Álvarez et al., 2005b; Martins et al., 2006a,b).

Galician shelf area is located in the northern boundary of the Canarian–Iberian upwelling system, where the along-shoreline winds interact with the topography to generate upwelling–downwelling dynamics with a marked seasonal cycle (Wooster et al., 1976; McClain et al., 1986). The position of the Azores anticyclone and the Iceland Low determines the passage of fronts in this area, leading to two characteristic situations. During winter, the Azores anticyclone is located in the northwest African coast and a low-pressure center over Iceland. This situation induces prevailing southwesterly winds blowing over the shelf and resulting in a reversal of the typical circulation and the development of a downwelling regime (Vitorino et al., 2002a,b). On the contrary, in spring and summer the Azores anticyclone moves to the North inducing high pressures with N-NNE winds, and generating frequent upwelling events off the coast and the intrusion of the *Eastern North Atlantic Central Water* mass (ENACW) (Fraga, 1981; Prego and Bao, 1997).

Other typical oceanographic features in winter are the *Western Iberian Buoyant Plume* (WIBP) and the *Iberian Poleward Current* (IPC) flowing northwards along the Galician–Portuguese shelf border (Haynes and Barton, 1990; Frouin et al., 1990; Peliz et al., 2003; Varela et al., 2005). The WIBP is a low-salinity surface water mass driven by the winter-intensified run-off of the rivers flowing on the NW Iberian Peninsula (Peliz et al., 2002). The discharge regime of Miño and Douro rivers is influenced by Atlantic fronts which cross the Iberian Peninsula mostly during winter. Under favourable winds and high riverine discharge, the river plume spreads northwards of the river mouth, towards the Rías Baixas (Álvarez et al., 2006). During typical non-upwelling winter conditions, the plume is confined to the inner shelf (Peliz et al., 2002). Nutrient fluxes and input of detrital and terrestrial particles to the shelf from river flood events are high during this situation. The stratification conditions at the surface layer, induced by the presence of the WIBP, and the high nutrient levels can be suitable conditions for phytoplankton growth.

The atmospheric sea level pressure difference between the Azores High and the Iceland Low, defined as NAO index, also controls the regional patterns of precipitation and aridity (Björck et al., 2006). Over the Iberian Peninsula, atmospheric storminess and increased precipitation coincide with NAO negative periods (Hurrell, 1995), whereas lower humidity on the continent and therefore, a dry period, is linked to NAO positive phases. This parameter varies on decadal timescales, but it shows extending phases of both positive and negative periods. In this way, this parameter should be a useful mechanism for explaining climatic conditions and extreme flood events related with increased rainfall.

3. Sampling and analyses

3.1. Location of the core and sampling

The material used in this study was obtained from the gravity core SMP02-3 (42°02.207′N, 9°02.363′W, 260 cm long, 121 m below sea level), collected in 2002 at the *Galicia Mud Patch* (Fig. 1). The core was sealed just after collection and kept in storage refrigerated at 4 °C until analyses were performed in the laboratory. The core was routinely sectioned longitudinally in two halves, visually described and photographed. After splitting, 1-cm thick and 30-cm long slices were removed from one half of the core to perform radiographical analyses using Cabinet X-ray System (Faxitron Series, Hewlett-Packard). The working-halves of the gravity core were sampled into 1-cm thick horizons. Each slice was then divided into subsamples for different studies within the project: metals and biogenic components analyses, grain-size determinations, microsiliceous fossils and siliceous compounds counts. Content of Fe, Al and Si, Total carbon (TC), Total nitrogen (TN), $CaCO_3$ and opal determinations were conducted every 6 cm.

3.2. Procedures and analytical strategies

3.2.1. AMS dating

Age control was established using six ^{14}C AMS (accelerator mass spectrometry) dates on planktonic foraminifera determined on ~10 mg of carbonate at the Geochron Laboratories (Massachusetts, USA) and at the AMS facility of the Aarhus University (Denmark) (Table 1).

All ^{14}C dates were corrected for ^{13}C and for the marine reservoir age ($\delta R = 376 \pm 46$, +400 years; $\Delta R = 0$) and then converted into calendar years (cal. yr BP) using the CALIB 5.0.1 software (modified version 2002; Stuiver and Reimer 1993; Hughen et al., 2004). In upwelling-influenced areas, such as off Galicia, reservoir ages may be higher than the global reservoir correction value. However, as pointed out by Abrantes et al. (2005), the local reservoir-effect correction is negligible and was not applied. A calibrated age range within two sigma confidence limits was obtained, being ages mentioned in this manuscript expressed in calibrated years before 1950 (cal. yr BP).

3.2.2. Grain size, organic carbon, calcium carbonate, nitrogen, opal and terrigenous content determinations

Grain-size analyses were performed every 6 cm. Sample treatment consisted of organic matter removal with hydrogen peroxide (H_2O_2) and dispersion with sodium hexametaphosphate. The coarse fraction (>63 µm) was separated from the fine fraction by wet-sieving. Grain-size distribution of the coarse fraction was determined by wet-sieving, with sieve columns ranging from 8 mm to 63 µm, spaced at 1 phi. Fine fraction (<63 µm) distribution was determined by an X-ray nephelometry technique using a Micromeritics, Sedigraph 5100.

For the geochemical analyses, sediment samples were kept in storage in plastic bags at 4 °C until analyses were performed in the laboratory. Samples were also analyzed every 6 cm, dried and ground to powder before processing. Total carbon (TC) and total nitrogen (TN) were measured with a LECO CN-2000 elemental analyzer at the Research Support Service (CACTI) of the University of Vigo. TC was measured by high-temperature combustion and detection of the gaseous by-products. Inorganic carbon (TIC) was measured with a LECO CC-100 analyzer attached to the CN-2000. The gases produced with the CC-100 are analyzed by the CN-2000, and then, the percentage of TIC in the sample from the CO_2 released is calculated. Organic carbon (TOC) was

Table 1
Radiocarbon dates and calibrated ages from core SMP02-3

Lab. number	Spliced depth (cm)	Sample type	^{14}C AMS raw age (yr BP)	$\delta^{13}C$ (‰)	Calibrated age 2σ (yr BP)	Calendar age (AD/BC)
GX-30664-AMS	5–6	Mixed planktonic foraminifera	580±30	−1.7	126 (207) 288	1662 (1743) 1824 AD
GX-32033-AMS	91–22	Mixed planktonic foraminifera	1310±40	−1.1	748 (841.5) 935	1015 (1108.5) 1202 AD
AAR-9450	149–150	Mixed planktonic foraminifera	1714±41	−0.74	1174 (1259.5) 1345	605 (690.5) 776 AD
GX-32034-AMS	194–195	Mixed planktonic foraminifera	2840±50	−0.4	2427 (2577) 2727	778 (627) 478 BC
AAR-9451	203–204	Mixed planktonic foraminifera	3458±50	−0.61	3207 (3330) 3453	1504 (1380) 1258 BC
GX-30665-AMS	254–255	*N. pachyderma* (right-coiling)	4460±40	−0.3	4517 (4652) 4787	2838 (2702) 2568 BC

Samples were pretreated and measured at the radiocarbon laboratories of Geochron Laboratories, USA and AMS ^{14}C Dating Centre of the Aarhus University, Denmark. The age estimations were derived from the intercepts of the radiocarbon age plus and minus two times the total standard deviation of the age (2σ) with the linear interpolation of the marine calibration data set (Marine 04, Hughen et al., 2004). Conversions of radiocarbon ages to calibrated ages are worked out by using the CALIB 5.0.1 program after Stuiver and Reimer (1993, modified 2002). No local reservoir effect has been applied.

then determined as the difference between TC and TIC. Calcium carbonate ($CaCO_3$) content was calculated by multiplying the TIC using the molecular mass ratio 8.33, assuming that all the inorganic carbon is in the form of calcium carbonate. In order to investigate if the organic carbon is of marine or terrestrial-derived origin, the TOC/TN ratio (hereafter C/N ratio) was calculated as the percentage weight of organic carbon versus the percentage weight of nitrogen.

The amount of biogenic silica contained in the bulk sediment was determined by direct dissolution using a wet alkaline leaching procedure devised by Mortlock and Froelich (1989). Dissolved silicate extracted during leaching was measured by means of the molybdate blue spectrophotometry according to Hansen and Grashoff (1983) using a continuous flow analyser AutoAnalyser Technicon II. The analytical deviation of the method was determined analysing two or more replicates of each sample, striving for a deviation below ±0.2% (Bernárdez et al., 2005).

Percentage of terrigenous content of the core sediment was calculated as the residual after subtracting the measured contributions of the main biogenic components (i.e. TN, opal, TOC and $CaCO_3$).

3.2.3. Metal analyses

Previously to metal determinations, around 40–50 mg of dry bulk sediment were microwave-digested in 6 ml HNO_3 (65%) and 2 ml HF (48%) in Teflon® bombs using a Milestone MLS 1200 Mega microwave oven following the EPA 3052 guideline (EPA, 1996) for siliceous-type matrices. Handling and analysis of samples were carried out in a clean laboratory. Plastic labware employed for sampling, storage and sample treatment was previously acid-washed (HNO_3 10%) for at least 48 h and rinsed throughout with Milli-Q water (Millipore). Fe, Al and Si, were determined using flame atomic absorption spectrometry (FAAS) technique with a Varian 220FS apparatus. The accuracy of the analytical procedure was checked using certified reference materials (CRMs), PACS-2 from the National Research Council of Canada. The results obtained (Table 2), agree well with the certified values and the relative standard deviations (RSDs) were typically lower than 10%, excepting Si (14.2%).

Table 2
Results of the analysis of the PACS-2 (NRCC, Canada) certified reference sediment

	Al (mg g^{-1})	Fe (mg g^{-1})	Si (mg g^{-1})
Measured value	67.6±3.9 n=3	41.6±2.0 n=3	279.7±39.7 n=4
Certified value	66.1±5.3	40.9±0.6	~276 [a]

[a] Information value only.

The Si percentage due to lithogenic compounds, or lithogenic Si content (LSi), was calculated by subtracting the total Si measured by FAAS and the biogenic Si contribution (BSi) derived from the biogenic opal, determined by applying the molar weight of amorphous opal (SiO_2) and Si.

The Ca/Al ratio was obtained after the Ca content determined using the Ca and $CaCO_3$ weight molar ratio and assuming that all the inorganic carbon is in this chemical form, versus the total Al content.

3.2.4. Preparation sample cleaning and mounting of slides for siliceous compounds counting

Preparation of the samples was done following the method proposed by Abrantes (1988). A fixed amount of dry sediment (2 g) was placed in 600 ml beakers and treated with hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2 110 vols.) for carbonate and organic matter destruction. First, the reaction took place over a hot plate at room temperature until the reaction stopped. Distilled water was added and left to settle for about 8 h and then, the excess liquid was removed by means of a vacuum pump. Clay fraction was removed by adding pyrophosphate sodium and distilled water to the beakers, leaving for 8 h and removing the excess of liquid with the vacuum pump. This process was repeated until no clays remained in the suspension. For each sample, total volume and suspension volume used to mount the slides were known. For slide preparation, suspension was strewn evenly onto cleaned 18 × 18 mm cover slips placed in a circular Petri dish (Battarbee, 1973) after stirring the solution for homogenization. After the trays had been dried, slides were removed and assembled with a toluene-based synthetic resin mounting medium (Permount™, Fisher Scientific).

3.2.5. Diatom and biosiliceous compounds quantification

Qualitative and quantitative analyses were performed with a LEICA DMLB and a Zeiss light microscope with phase contrast illumination, using a ×100/1.00 planapochromatic oil-immersion objective. Several transverses across the cover slips were examined depending on the diatom abundance (1/3 to 1/16). For each sample, 300–500 diatom valves were identified, and raw counts were converted into relative abundances. Schrader and Gersonde (1978) counting protocol was followed for diatom counts and total number estimates. Number of the biosiliceous compounds of the sediment, such as diatom fragments, silicoflagellates, sponge spicules, phytoliths, crysophycean cysts and radiolaria per gram of sediment was also assessed, as well as palynomorphs abundance.

Grass phytoliths were identified on the basis of the classification of Twiss et al. (1969) and Madella et al. (2005).

Diatom genera identification was based on the work by Round et al. (1990) and, whenever possible, each individual was identified to the species level following author's description and specific bibliography (Hustedt, 1930; Hustedt, 1959; Hartley, 1996; Hasle and Syvertsen, 1996; Witkowski et al., 2000, and other taxonomic sources). The diatom taxa were also grouped by their ecological significance.

Diatoms are relatively abundant in the sediment along the Galician–Portuguese margin (Bao et al., 1997; Abrantes and Moita, 1999) reflecting water column productivity conditions induced by upwelling. They can be used as a powerful paleoclimate indicators in the sedimentary record. Freshwater and the benthic assemblages are the ecological groups used in this work, since they are indicators of material transported from the coastal zone to the shelf area. Benthic group includes forms living attached to a substratum or associated with sediments. Since benthic diatoms are limited to the euphotic zone, high percentages of this group at the core site indicate offshore transport. The contribution of freshwater and benthic diatoms is especially significant, since the presence of these species in the marine domain may help to track intensity of river flow or direction of currents that divert the river plume. In this case we use the reworked origin of both assemblages as a proxy of riverine input.

Species and genera included in the freshwater group are *Aulacoseria* spp. Thwaites 1848, *Ctenophora pulchella* (Ralfs ex Kützing) Williams et Round 1986, *Cyclotella* spp. (Kützing) de Brébisson 1838, *Cymbella* spp. Agardh 1830, *Diatoma* spp. Bory 1824, *Epithemia* spp. Kützing 1844, *Eunotia* spp. Ehrenberg 1837, *Fragilaria* complex, *Gomphocymbella* spp. Muller 1905, *Gomphonema* spp. Ehrenberg 1832, *Hannaea arcus* (Ehrenberg) Patrick 1966, *Luticola* spp. (Kützing) Mann 1990, *Meridion circulare* (Greville) Agardh 1831, *Pinnularia* spp. Ehrenberg 1843, *Sellaphora* spp. Mereschkowsky 1902, *Stauroneis* spp. Ehrenberg 1843, *Stephanodiscus* spp. Ehrenberg 1845, *Synedra* spp. Ehrenberg 1830 and *Tabellaria* spp. Ehrenberg 1840. The benthic assemblage is composed by *Achnanthes* spp. Bory 1822, *Amphora* spp. (Ehrenberg) Kützing 1844, *Campyloneis grevillei* (Smith) Grunow 1867, *Cerautulus turgidus* Ehrenberg 1843, *Cocconeis* spp. Ehrenberg 1837, *Diploneis* spp. (Ehrenberg) Cleve 1894, *Grammatophora* spp. Ehrenberg 1840, *Hantzschia* spp. Grunow 1877, *Mastogloia* spp. (Thwaites) Smith 1856, *Navicula distans* (Smith) Ralfs in Pritchard, 1861, *N. digitoradiata* (Gregory) Ralfs in Pritchard 1861, *N palpebralis* (de Brébisson) Smith 1853, *Nitzschia compressa* (Bailey) Boyer 1916, *Opephora* spp. Petit 1888, *Pleurosigma* spp. Smith 1852, *Podosira stelligera* (Bailey) Mann 1907, *Psammodiscus nitidus* (Gregory) Round and Mann 1980, *Surirella fastuosa* (Ehrenberg) Kützing, 1844, *Toxarium* spp. Bailey 1854, *Trachyneis aspera* (Ehrenberg) Cleve 1894 and *Tryblionella* spp. Smith (1853).

4. Results

4.1. Sediment lithostratigraphy, chronology and age-depth model

Core sediment at SMP02-3 mainly consists of terrigenous and detrital material, quartz and glauconite grains, with a lesser biogenic fraction, containing low abundance of calcareous and siliceous microfossils. Four sedimentary units or intervals were recognized as obtained by visual observations, X-ray radiographs and grain-size distribution (Fig. 2): (i) Unit 1 from 260 to 204 cm (5Y 2.5/2 Munsell Soil Colour Chart®, 4700–3300 cal. yr BP) is composed by glauconitic sands, bioclastic remains and quartz. It is characterized by high carbonate content and low values of opal and organic carbon. This sedimentary unit is a fining upwards sequence and it is slightly bioturbated at the top. (ii) Unit 2, from 204 to 163 cm (3300–1700 cal. yr BP) is composed by homogeneous clayish sediments (Colour 2.5Y 4/3, Munsell Soil Colour Chart®) with very low values of the biogenic compounds. (iii) Unit 3, from 163 to 130 cm (1700–1200 cal. yr BP) is characterized by coarser sediments than the previous one. This unit is slightly laminated. (iv) The upper greenish muddy interval, Unit 4 (1200–0 cal. yr BP), has the same characteristics as the present seabed in the core of the *Galicia Mud Patch*. This unit registers highly organic silt and clay with sparse gastropods and bivalve broken shells. In a general view, textural and lithological patterns indicate a progressive decrease in energy from the bottom to the top of the core.

The age-depth model is based on six calibrated AMS ^{14}C dates (Fig. 3) of the tests of mixed planktonic foraminifera (Table 1). These ages provide an excellent chronology of this sedimentary record. Ages between dated levels were obtained by linear interpolation between the nearest AMS-dated points. The top of the core (0–1 cm) is assumed to correspond to 0 cal. yr BP. Sedimentation rate ranges between 0.12 and 1.39 mm yr^{-1}. A sharp increase in sedimentation rate is identified at 150 cm, implying a major change in sedimentation conditions at this level (Fig. 3).

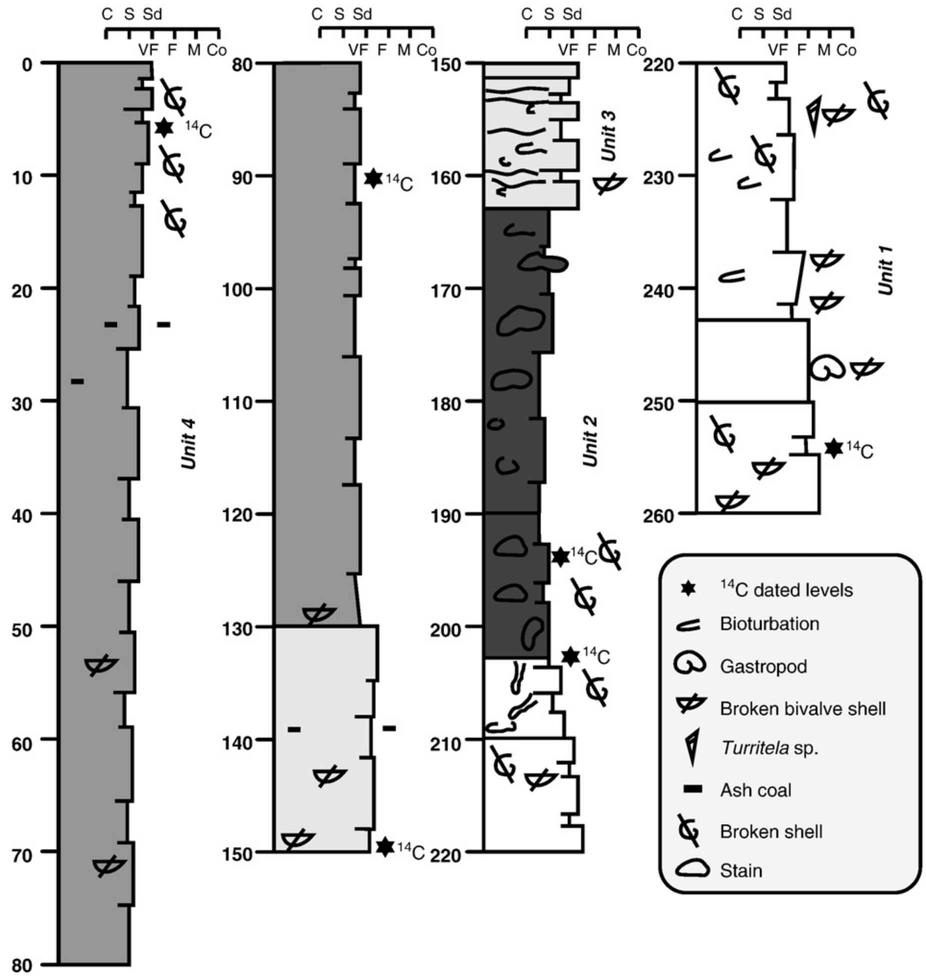

Fig. 2. Sedimentological features and lithological description of the core. C: Clay. S: Silt. Sd: Sand. VF: Very fine sand. F: Fine sand. M: Medium sand. Co: Coarse sand.

4.2. C/N ratio and terrigenous content

C/N ratio and TOC show the same downcore profile, due to the stability of the values of TN content. C/N ratio registers low values at the bottom of the core (~7.6), increasing progressively to values around 13 at 3300 cal. yr BP. Afterwards, the profile becomes stable, with values around 10, but at 1200 cal. yr BP a sharp rise is identified. To the top of the core, C/N values range between 13 and 19 (Fig. 4). Shelf sediments receive autochthonous particulate matter, mainly plankton due to the important biological activity in its waters, and allochthonous particulate matter derived from river run-off. Assuming that elevated C/N ratios (>20) are of terrestrial origin (continental vegetation) and marine phytoplankton displays C/N ratios between 5 and 10, the sharp shift at 1200 cal. yr BP would be related to a change in the intensity of terrestrial input into the Galician shelf.

Terrigenous fraction clearly dominates the composition of the sediment, accounting for 78.2 to 95.6% of the bulk sediment. The amount of detritics follows an opposite trend to the calcium carbonate distribution, and shows a good linear correlation ($r^2=0.64$) with the sum of Fe, Al and LSi content ($p<0.01$). Lower percentages are recorded at the bottom of the core increasing progressively up to reach the maximum value (95.6%) around 2000 cal. yr BP. A small decrease was recorded later, but between 870 cal. yr BP to the present, a sharp increase in the percentage occurs, even reaching values of 94% (Fig. 4).

4.3. Metals content in bulk sediments: Fe, Al, LSi and Ca/Al

The vertical distribution of several metals in the bulk sediment is shown in Fig. 4. Fe content along the core is in the range of 17.8–48.49 mg g^{-1}. Maximum values of

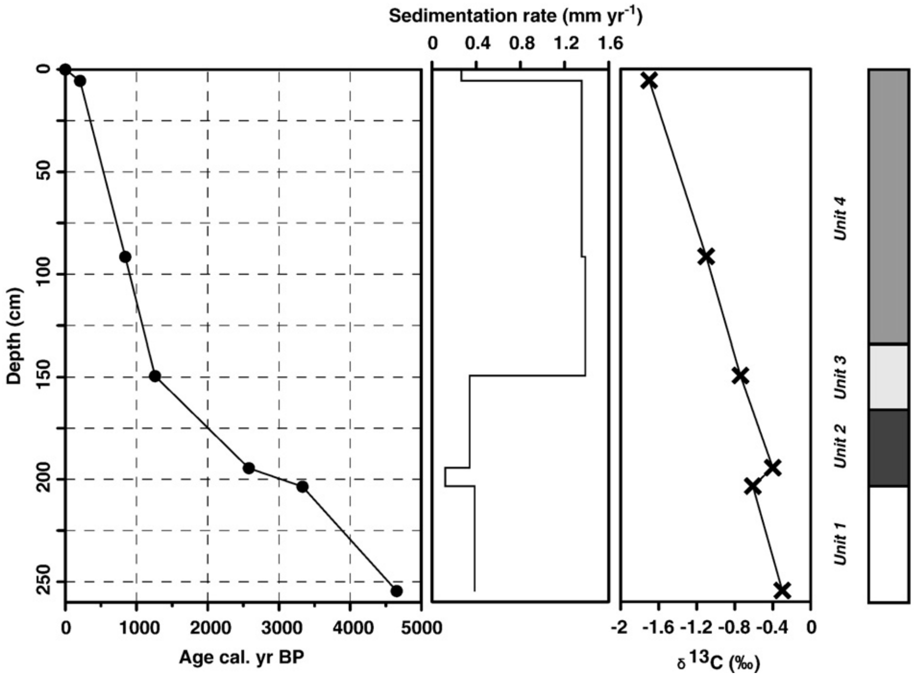

Fig. 3. Age versus depth model for core SMP02-3 based on calibrated ages listed in Table 1. Solid line represents the theoretical age model assuming linear sedimentation rates between ^{14}C dated levels (black circles). Downcore variations of the δ^{13}C (‰) in foraminiferal tests, sedimentation rate (mm yr^{-1}).

the metals considered for this study are generally registered in the muddy upper sequences, especially in the Unit 4. Concentrations are low at the bottom of the core (17.8 mg g^{-1}, Unit 1), progressively increasing up to 45.3 mg g^{-1} at 2500 cal. yr BP and ~45 mg g^{-1} between 1990 and 1816 cal. yr BP. A second peak in the Fe content is recorded between 790 and 540 cal. yr BP. Al content varies from 33.22 mg g^{-1} to 118.76 mg g^{-1}, showing a prominent peak between 790 and 540 cal. yr BP, as observed for Fe. High Al content is also detected around 2000 cal. yr BP.

LSi profile ranges between 77.01 and 358.26 mg g^{-1}. Values steadily increase from the bottom of the core towards the top, peaking at 870–520 cal. yr BP. Its distribution displays a similar pattern to those found for Fe and Al, however around 2000 cal. yr BP the LSi concentration diminishes (Fig. 4).

Ca/Al downcore variations mirror the distribution of the terrigenous material (Fig. 4, note the inversed scale). Ca/Al ratio is used as a tracer of fluctuations of the terrigenous input into the continental shelf. Lower ratios indicate stronger discharge of terrigenous material and the subsequent dilution of marine biogenic carbonate fraction. This marker also shows distinct changes at 3300 cal. yr BP and at 1200 cal. yr BP. Lowest values are found between 2500 and 1640 cal. yr BP (Fig. 4).

4.4. *Occurrence of diatoms in marine sediments: Freshwater and benthic assemblages*

Diatom abundance varies depending on diatom productivity, preservation and/or dissolution of the diatom valves, and dilution with terrigenous and/or organic supplies. The number of diatom valves per gram of sediment (not shown) has an irregular distribution throughout the core. Large fluctuations varying from 7.5×10^4–1.6×10^5 valves g^{-1} to values up to 2.5×10^6 at 790–613 cal. yr BP occur. Two levels barren of diatoms (4700–3300 and 2100–1100 cal. yr BP) point out to changes in the silica preservation conditions or low primary production rates. The freshwater and benthic diatom groups plotted against time are shown in Fig. 4. The diatom assemblage of the freshwater flora is not especially abundant throughout the core, ranging from 1.1 to 4.8%, averaging 2.8%. Higher abundances occurs between 870 and 610 cal. yr BP. Although wind could also bring freshwater diatoms to the marine area, we infer that this aeolian transport is negligible in comparison with the run-off transport. The relative high abundance of this group likely reflects the influence of the discharge of the rivers to the continental shelf and a subsequent northward transport.

Relative abundance of the benthic assemblage falls in a similar range that of freshwater (2.4–5.7%), accounting

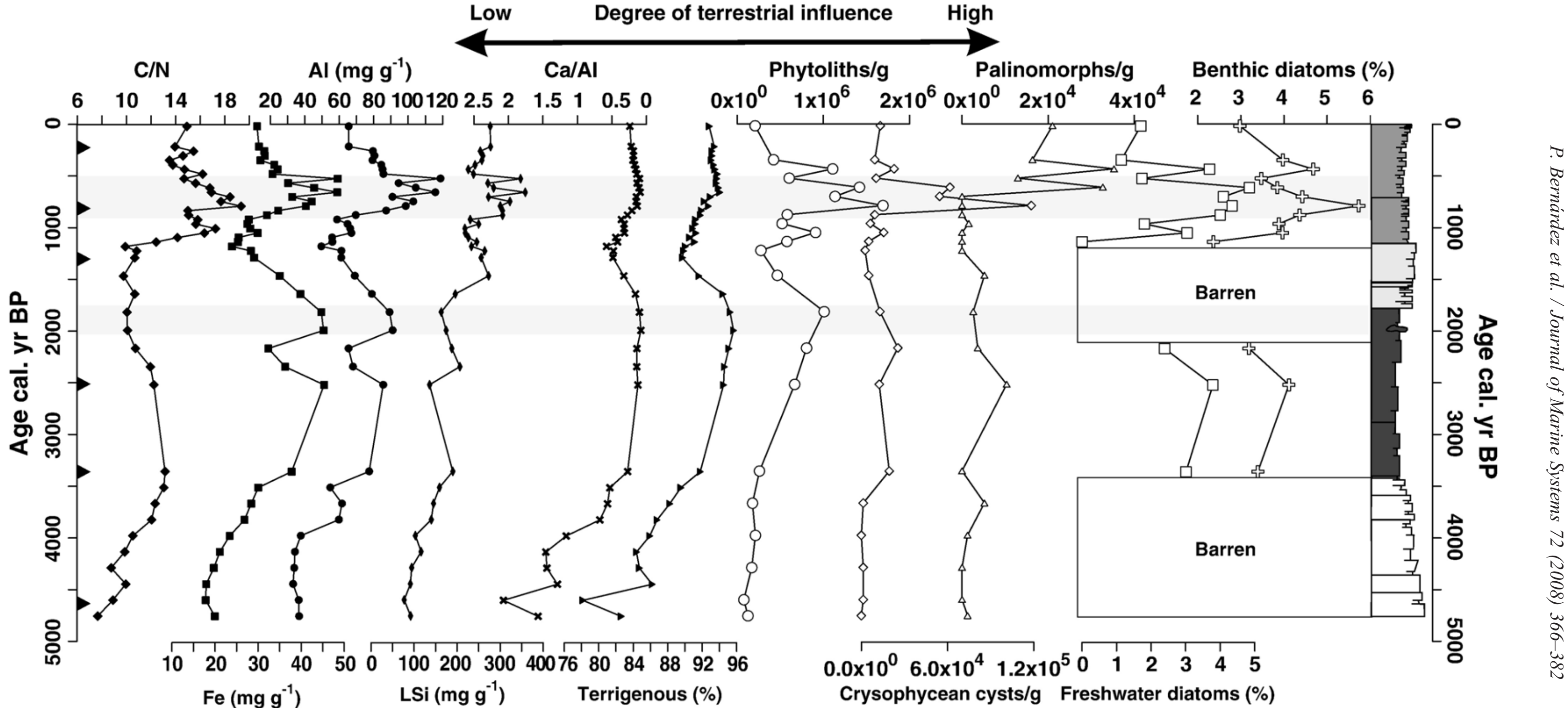

Fig. 4. Plot showing the downcore profiles of paleo-indicators of terrestrial input used. Note the inversed scale for Ca/Al ratio. Solid triangles indicate positions where dating samples were collected. Shaded areas indicate rainy climatic events discussed in the text.

averagely for 3.9%. Downcore profile also shows a small peak around 800–520 cal. yr BP (Fig. 4).

4.5. Phytoliths, crysophycean cysts and palinomorphs: biosiliceous land-input indicators

Phytoliths abundance displays a relatively stable profile along the core, but it gradually increases from 3300 cal. yr BP to *ca*. 2000 cal. yr BP, showing a small peak at 1800 cal. yr BP. High phytoliths content is recorded at 790–440 cal. yr BP reaching the maximum value at 790 cal. yr BP (Fig. 4).

Crysophycean cysts per gram of sediment have very low and constant values throughout the core. However, larger fluctuations in abundance occur in the upper part of the core, corresponding to 790–610 cal. yr BP, reaching values between 1.18×10^5 and 5.45×10^4 phytoliths g^{-1} (Fig. 4).

The amount of palinomorphs displays a constant profile, with very low values from the bottom of the core up to 960 cal. yr BP. A sharp increase in the abundance is detected at 613–347 cal. yr BP. Pollen influx is high in the recent period (Fig. 4).

5. Discussion

Core SMP02-3 provides an excellent record of the climatic changes occurred during the past 4700 yr in the Galician shelf. Lithostratigraphic information provided the first approach to the sedimentary conditions in the marine environment. Paleoenvironmental interpretation was carried out taking into account the environmental-derived signals described for each parameter, together with sedimentological, geochemical and micropaleontological. Four sedimentary units are defined on the basis of lithological characteristics revealing changing sedimentological conditions and different oceanographic situations. Thus, the paleoenvironmental analysis of Galician continental shelf record is explained below for each of the four defined time periods. Moreover, several periods with a distinct degree of marine/terrestrial influence were recognized in the core as shown by the terrestrial and lithogenic input tracers. The mechanisms put forward to explain these sedimentological and geochemical shifts have involved several processes and driving climate forcings as discussed below. Finally, our observations were compared with other paleoenvironmental data in the same area.

5.1. Period 1: 4700–3300 cal. yr BP

This interval is characterized by a fining upwards sequence from the bottom of the core up to the 204 cm depth. Relatively high sand content and high abundance of bioclast remains (Fig. 2) indicate energetic hydrodynamic conditions. High abundances of calcium carbonate remains, related to the marine production, were recorded at the core bottom. Ca/Al ratio is also in the highest values at this period.

C/N values ranging between 6.7 and 12, indicate that there is a high contribution of marine-derived organic material. Terrigenous material, as well as low contents of Fe, Al and LSi also show a persistent marine control. Phytoliths and crysophycean cysts present very low abundances in this phase. The progressive increasing in the C/N values, as well as a higher amount of terrestrial influx proxies and biosiliceous continental compounds point to a increasing riverine input towards the end of this period (3300 cal. yr BP).

Low values of organic carbon (not shown) as well as the high energetic conditions registered during the deposition of this sandy sequence imply oxic sediment conditions. As a result, diatom frustules are not preserved during this interval due to the low preservation efficiency of this biosiliceous material in sandy sediments (Ragueneau et al., 2000). Moreover, the top of this sequence is highly bioturbated, this being indicative of dissolution of the diatoms remains (Hay et al., 2003). The benthic foraminifera assemblage studied on a nearby core is composed by species related to full oxygenation conditions and relatively high velocity flows (Martins et al., 2006a). The prevalence of a winter regime, rains and downwelling conditions under SW winds at this period favoured the deposition of coarser sediments (Martins et al., 2006a). Our data, however, do not support their interpretation. In fact, the sediments recovered at this period, mainly very fine sand, indicate marine influence (high abundance of foraminiferal tests, high Ca/Al ratios) and low supply of fine-material derived from the riverine plume when precipitation is high (Abrantes et al., 2005) (Fig. 5).

Between 4700 and 3300 cal. yr. B.P., a warm and dry period characterized by low nutrient levels and productivity at the inner Galician shelf occurred, as also revealed by planktonic foraminifera (González-Álvarez and Frances, 2005; González-Álvarez et al., 2005a). Around 3900–3600 cal. yr BP, aeolian sediments in the Cíes beach barrier-lagoon and at a the Traba coastal wetland were deposited, induced by arid climatic conditions and N-NE winds (Bao et al., 2007; Costas, 2006). Furthermore, analyses of different paleoenvironmental records (e.g. peat bogs) in NW Iberian Peninsula suggest that a series of abrupt climatic changes occurred during this period, involving alternate episodes of cooling, drought and increased rainfall and wind intensification. Important

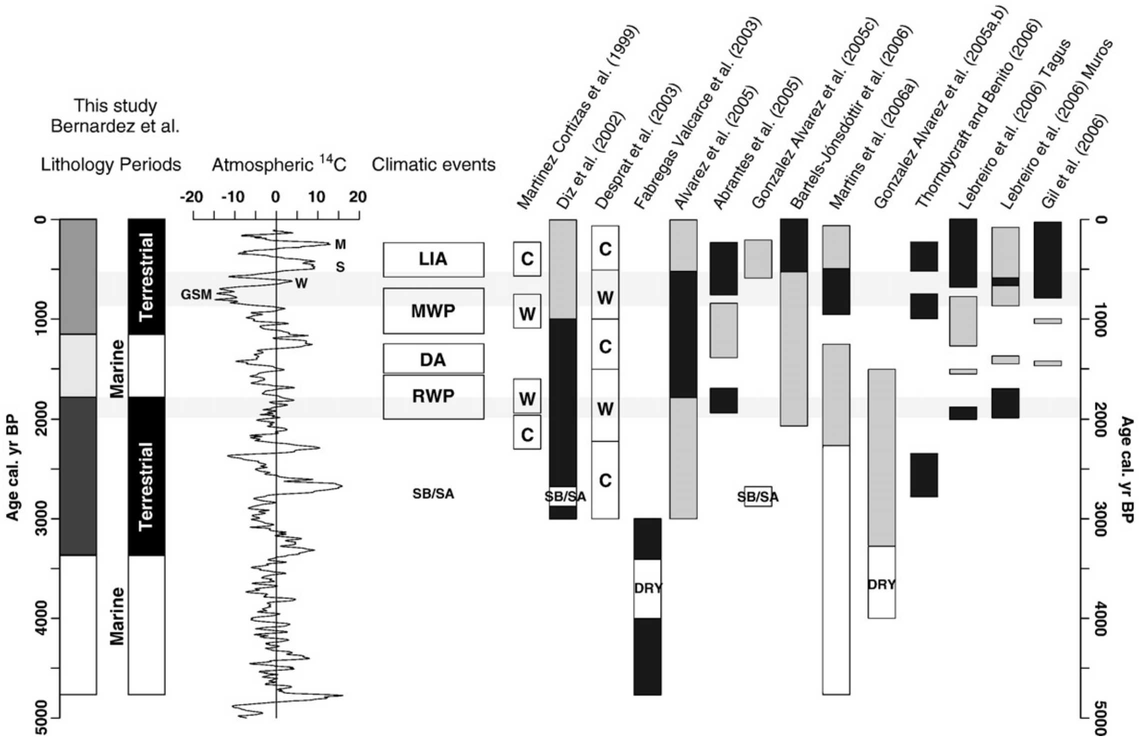

Fig. 5. Summary scheme of the periods described, their relationship with the main global climatic events, the correlation with intervals/episodes defined by other proxies and other authors in the nearby area, and climate forcing mechanisms. Dark grey squares represent periods of high rainfall whereas Light grey squares are indicative of high productivity and upwelling influence. C: Cold. W: Warm. SB/SA: Subboreal/Subatlantic Transition. RWP: Roman Warm Period. DA: Dark Ages. MWP: Medieval Warm Period. LIA: Little Ice Age. GSM: Grand Solar Maximum. W: Wolf. S: Spörer. M: Maunder.

variations in humidity were found by Fábregas-Valcarce et al. (2003) at 4700–4000 cal. yr BP and 3400–3000 cal. yr BP in different environmental archives. However, these rainy episodes were not detected in our marine core. Only a slight increase of the terrestrial-derived particles at 3300 cal. yr BP in our record might be indicative of the last humid phase described by these authors. Cold temperatures, low rainfall and elevated wind strength at 4000–3400 cal. yr BP are consistent with the paleoenvironmental conditions recorded at our record (Fig. 5).

In summary, this period was characterized by the reduced flux of land-derived organic matter to the bottom. The degree of the continental influence increases progressively to the top of this sequence. A wind pattern with prevailing NE component is invoked to be the forcing mechanism that explains this environmental setting under a cold and arid situation.

5.2. Period 2: 3300–1700 cal. yr BP

This period spans from 3300 to 1700 cal. yr BP, although as shown in Fig. 4 our record lacks of data of geochemical and microsiliceous proxies in the lower part. However, we have extended it from 2500 back to 3300 cal. yr BP based on the lithology of the core, which is characterized by an abrupt drop in the organic material content and elevated concentrations of fine sediments, mainly clays. The high amount of fine-material suggests an increase in the terrigenous sediment influx to the shallow Galician shelf. Variation in the fine-material content at our core site could be an indicator of the terrigenous supply due to rainfall events leading to floods at the shelf area with a high fine suspended sediment load material.

Increasing values of Fe, Al, LSi and detrital material suggest that riverine influence is higher in this period than in the previous one. Al follows the Fe profile quite closely (correlation coefficient $R^2 = 0.87$), indicating that Fe is also a well-accepted marker of terrestrial input. Al is interpreted as a proxy of aluminosilicates content in the sediment and it is introduced into the marine system mainly by river run-off. LSi is considered a good proxy of the lithogenic silicate compounds of the sediment, mainly by quartz particles. Si enrichment of sediments over the inner shelf may result from a preferential settling of the coarser quartz particles (Araújo et al., 2002). In addition, the Miño river sediments have a relatively high Si content, being predominantly coarse quartz particles (Araújo et al., 2002). The high content of ash coals are also indicative of the high contribution of the organic matter from the continental domain, explained by general deforestation and occurrence of fires after 4000 cal. yr BP (Santos et al., 2000). The occurrence of freshwater diatom flora and benthic species in this period also suggests an increased release of freshwater to the Galician shelf. Frequent salinity changes, as well as the establishment of a restricted environment, was identified in the Ría de Vigo from 3000 to around 1800 cal. yr BP (Diz et al., 2002). High alkenone-derived SST (Diz et al., 2002) and a warm cocolith assemblage (Álvarez et al., 2005) in the Ría de Vigo also support the interpretation of a warm and humid environment during this period in the Galician area (Fig. 5).

The most remarkable event during this period occurs *ca*. 2000–1700 cal. yr BP. This event is characterized by an increase in Fe, Al, phytoliths abundance and terrigenous percentage. The C/N ratio, however, falls in the range of marine organic matter which could indicate a reduced supply of organic matter of continental provenance. NE winds from land could have transported the ferroalumino-particles and phytoliths to the marine domain, but this climatic scenario would point to relatively dry and arid conditions, an explanation that the paleoenvironmental markers do not support. In fact, Desprat et al. (2003) identified a warm period and the development of temperate vegetation during the Roman colonization in Galicia (RWP, peaking at 1800 cal. yr BP), suggesting relatively humid conditions (Fig. 5).

In the Tagus depocentre deposit an excess precipitation period was also recorded around 2000 cal. yr BP (0–550 AD) (Abrantes et al., 2005) related with more frequent NAO negative-like periods. Moreover, in the Ría de Muros, the northernmost of the Rías Baixas, an event recording high values of Fe and Ti was also identified at *ca*. 2000 cal. yr BP (Lebreiro et al., 2006). These authors pointed to a climatic-triggered mechanism to explain their record. However, this increase in the terrigenous markers can also be explained by anthropic-derived activities on land. In this way, the raise in the lithogenic indicators could be explained by the gold mining by Romans in the Miño River catchment area (Pérez García et al., 2000). One of the most important tributaries of the Miño River, the Sil River, underwent an intensive mining activity around 2000 years ago, through elaborate hydraulic mining methods using water supplied by hundreds of kilometres of canals that traversed the mountains leading to lode deposits (Spiering et al., 2000). Martínez-Cortizas et al. (2005) identified during Roman times a period of forest clearance. Therefore, anthropic activities on land together with a NAO negative phase could induce an increase in soil erosion and the subsequent record in the shelf sediments.

5.3. Period 3: 1700–1200 cal. yr BP

During this period low values of the C/N ratio are recorded, and Fe, Al and detritic compounds show an important decreasing trend. On the other hand, higher values of the Ca/Al ratio as well as a slightly rise in sand content is observed. Low diatom abundances, as consequence of strong dissolution and/or low production, result in the impossibility of define the diatom assemblage. Paleoproxies point to a return to marine influence during this short period, that can be considered an analog to the first described period 1 (4700–3300 cal. yr BP).

Driving climate mechanisms point to a recover in the relatively dry conditions in the continent. This dry and cold climatic situation is triggered by N and NE winds prevailing on land, occurring for example when NAO index is positive. Gil et al. (2006) reconstruction of the position of the Icelandic low and Azores high during Dark Ages (DA) indicates that Azores high was located over the Iberian Peninsula, on a typical position under NAO positive-like phase. A cold period at the DA probably related with this atmospheric situation was also identified using the pollen influx in the Ría de Vigo sediments (Desprat et al., 2003) (Fig. 5).

5.4. Period 4: 1200–0 cal. yr BP

Last period is characterized by the high content of mud with the same lithological features as those found in the present seabed at the core site. The C/N ratio with values between 12 and 18 indicates that the organic matter is mostly of continental origin. The presence of benthic diatoms at significant percentages in a core that is located well deeper than the euphotic zone likely indicates transport from inner areas. Moreover, freshwater species are also well represented in this interval. The non-organic material content remains high and constant during this period revealing high influx of land-derived particles. All these data point to enhanced flow of the Miño and Douro rivers and, therefore, an increase in the precipitation over the NW Iberian Peninsula since 1200 cal. yr BP.

These terrestrial input proxies show good general agreement with changing precipitation patterns (wet/dry) over this time interval with other archives in the same climatic area. The high number of paleoflood records after 1300 cal. yr BP (Thorndycraft and Benito,

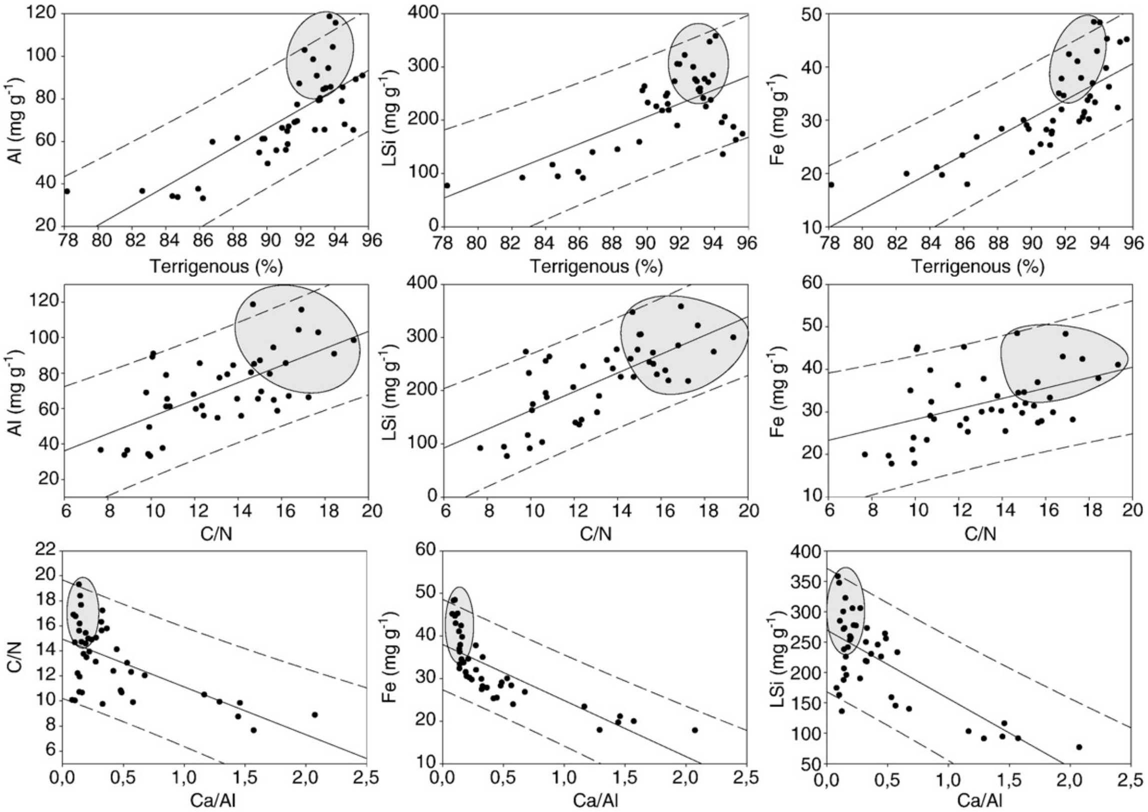

Fig. 6. Scatter diagrams of Al, Fe, LSi, Ca/Al, C/N ratio and terrigenous content. Linear regression is shown (solid line). Dashed lines represent the prediction intervals at the 95% confidence interval. Pearson's correlation coefficients are shown in the Table 3 ($p<0.01$). Grey areas indicate the strong rainy period described in the text.

2006) also supports this hypothesis of increased land-material input to the Galician shelf. In the Ría de Vigo, a period of frequent salinity changes and high run-off has been identified during the Medieval Warm Period (MWP) until the onset of the Little Ice Age (LIA) (Álvarez et al., 2005) (Fig. 5).

A relevant event is recognized around 800–500 cal. yr BP. Phytoliths, crysophycean cysts and palinomorphs abundances are also considered as terrestrial input markers due to their continental origin. They are transported to the ocean by river run-off and/or wind (Romero et al., 1999). High river run-off and thus, an increase in the rainfall, or transport by N-NE winds from the continent could explain the presence of these tracers at the core site. However, due to the proximity of the Atlantic river mouths, we infer that riverine run-off is the main driving process acting, and the abundance of these markers are employed as freshwater discharge indicators. These land-input indicators show an abrupt increase at this interval. The rise of these proxies is coupled with the

Table 3
Pearson correlation matrix of the main riverine input proxies used in this work

	Ca/Al	Terrigenous	Si_{lit}	C/N	Al	Fe
Ca/Al		−0.966 **	−0.734 **	−0.617 **	−0.800 **	−0.769 **
Terrigenous	−0.966 **		0.650 **	0.505 **	0.775 **	0.786 **
Si_{lit}	−0.734 **	0.650 **		0.710 **	0.731 **	0.563 **
C/N	−0.617 **	0.505 **	0.710 **		0.646 **	0.444 **
Al	−0.800 **	0.775 **	0.731 **	0.646 **		0.928 **
Fe	−0.769 **	0.786 **	0.563 **	0.444 **	0.928 **	

Good correlations have been found between parameters, showing their potential use for terrestrial input markers.
** $p<0.01$.

highest content of Fe, Al and LSi, suggesting increased continental-derived contribution, which is in good agreement with the freshening of the surface waters indicated by the appearance of freshwater diatoms. Scatter plots showing the linear correlations between the geochemical tracers (Al, Fe and LSi), as well as the C/N, Ca/Al ratio and terrigenous content of the sediment are shown in Fig. 6. Good correlation, as shown by the Pearson's correlation coefficients ($p<0.01$; Table 3), point out the usefulness of all these proxies for the interpretation of the degree of oceanic and terrestrial influence. Fe, Al, and LSi profiles, combined with the C/N and Ca/Al ratio, suggest reduced riverine input and regionally dry conditions when these markers are in low values, and high terrigenous input to the shelf area when they are high. Thus, this strong terrestrial input stage and consequently, wet period, is identifiable in the scatter plots showing the linear correlations between the most important terrestrial input indicators (Fig. 6).

In the Iberian Peninsula, paleoflood records indicate at least two phases of increased frequency of large magnitude floods, and therefore, increased precipitation related to climatic variability during the last *ca.* 1200 years, namely 975–790 cal. yr BP and 520–265 cal. yr BP appearing to coincide with the MWP and the LIA (Thorndycraft and Benito, 2006). Martins et al. (2006a) found an interval of increased river discharge, coinciding with the rainy event recorded in our core, linked to the appearance of brackish-water benthic foraminifera. A strong humid period was also identified by several authors at the Tagus mouth matching that found in our record (Abrantes et al., 2005; Bartels-Jónsdóttir et al., 2006; Lebreiro et al., 2006; Gil et al., 2006) (Fig. 5).

The identification of this wet period during a cold stage, such as the LIA, indicates a precipitation-influenced forcing mechanism. Increased flood magnitude and/or frequency in the Miño and Douro rivers discharge is strongly related to increased winter precipitation in the NW Iberian Peninsula. High rainfall is related to a low-pressure cell located in Iceland, advecting cold fronts into the NW Iberian Peninsula with predominantly SW-NE directions. A blocked situation of this low-pressure cell would give to persistent precipitation and increased fluvial discharge at the river mouths. This seasonal pattern, if maintained, could be related to a persistent NAO negative-like phase over the Iberian Peninsula (Hurrell et al., 2003).

Periods of solar maxima are believed to be related to low values in the North Atlantic Oscillation (NAO) index, which are associated with high winter precipitation and river flow in the Atlantic basins of the Iberian Peninsula. Cross-correlation of the curves of our indicators with that of atmospheric $\Delta^{14}C$ (Stuiver et al., 1998), reflecting solar activity, is significant. The good parallelism between our record and the solar activity, especially during the Grand Solar Maximum (GSM), reflects the influence of the global climate shifts on the climate variability in this area. Therefore, this wet interval can be explained by several forcing climate mechanisms: increased precipitation and run-off to the shelf related to a NAO negative-like stage, and for the recent rainy period (800–500 cal. yr BP), the high irradiance and warmer conditions due to the GSM could also be involved.

6. Summary and conclusions

Our reconstruction of paleoclimate and paleoenvironment provides evidence for a variable Late Holocene period in the NW Iberian Peninsula. The study of a marine sediment core allows us to identify changes in the riverine input, marine influence and human impact in the Galician continental shelf sedimentary record for the past 4700 cal. yr BP. On the basis of the aforementioned discussions several conclusions are drawn:

Lithostratigraphic and geochemical data allow identifying alternative periods of terrestrial influence (Period 2: 3300–1700 cal. yr BP and Period 4: 1200–0 cal. yr BP) and marine influence (Period 1: 4700–3300 cal. yr and Period 3: 1700–1200 cal. yr BP) in the shelf zone. The marine-influenced periods are characterized by coarser sediments, low values of Fe, Al, LSi, C/N, biosiliceous land indicators, high Ca/Al ratios and the lack of diatom frustules due to the low preservation efficiency. Conversely, the terrestrial-influenced periods are represented by muddy sequences that register high values of the lithogenic indicators (Fe, Al) and C/N ratios, and high abundances of benthic and freshwater diatoms.

Several climatic forcing mechanisms can be invoked to explain these changes in the high/low marine/terrestrial influence. During periods 1 and 3, prevailing dry conditions over the NW Iberian Peninsula were triggered by winds blowing from the N-NE.

Continental-influenced periods are linked to NAO negative-like periods. In this scenario, increased rainfall in the catchment areas of Miño and Douro rivers leads to higher run-off to the shelf. Major peaks of terrestrial and lithogenic input proxies are interpreted as the record of flood-like events and increased rainfall in the area.

An important riverine input peak around 2000–1800 cal. yr BP has been detected at the top of the terrestrial-influenced period 2, being related to the warmer conditions during the RWP. Past changes mediated by anthropic activities (forest degradation, soil erosion on land or gold mining activities in the catchment area) in NW Iberian Margin are identified in the sedimentary record.

The strongest terrestrial signal has been identified between 800 and 500 cal. yr BP. This humid period is linked to the establishment of rainy conditions in the catchment areas of Miño and Douro rivers. The warm conditions at the Grand Solar Maximum could also be one of the forcing factors of climate suggesting that our sedimentary record reflects global climatic signals, as well as regional factors.

The chronology of main events in our record responds to changes in intensity and wind direction triggered by the position of the high/low-pressure systems. Therefore, the NAO drives the rainfall patterns and river discharges to the Galician continental shelf. Within the uncertainties of the age model, these events and their paleoclimatic implications match relatively well with those described by several authors in the study area, as well as with global climatic events.

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