Continental Shelf Research 30 (2010) 1250–1266

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): Depositional history and late Holocene climatic and environmental signals

Philippe Sorrel [a,*], Bernadette Tessier [a], François Demory [b], Agnès Baltzer [a], Firas Bouaouina [a], Jean-Noël Proust [c], David Menier [d], Camille Traini [d]

[a] Morphodynamique Continentale et Côtière, Université de Caen, UMR CNRS 6143, 2-4 rue des Tilleuls, 14000 Caen, France
[b] CEREGE, UMR 6635, Europole de l'Arbois, 13090 Aix-en-Provence, France
[c] Géosciences Rennes, Université de Rennes 1, UMR CNRS 6118, Campus de Beaulieu, 35042 Rennes Cedex, France
[d] EA 2219 Géoarchitecture & UMR 6118 Géosciences, Université Européenne de Bretagne, rue Yves Mainguy, 56017 Vannes, France

ARTICLE INFO

Article history:
Received 16 September 2009
Received in revised form
26 February 2010
Accepted 7 April 2010
Available online 20 April 2010

Keywords:
Sedimentary infilling
Holocene transgression
Climatic change
North Atlantic Oscillation
Medieval Warm Period
Human activity

ABSTRACT

The late Holocene is of particular interest to our understanding of the evolution of coastal sedimentary systems because this period encompasses warmer and cooler periods, and rising sea level in northern Europe. Based on an approach combining AMS ^{14}C, sedimentological and rock magnetic analyses on sediment cores complemented with seismic data collected in the macrotidal Bay of Vilaine (south Brittany), we document the depositional history of the inner bay coeval to the mid- to late-Holocene transgression in south Brittany. Correlation between sedimentary archives revealed the main sedimentary infilling phases during the last 6000 years. Four units (U1–U4) are recognized in the coastal sediment wedge of the system, corresponding to the stepwise marine invasion of the bay. We show that (1) marine inundation, due to the steep morphology of the bedrock, is diachronous between distal and proximal records. A time lag of $\sim$1000 years is inferred over a distance of less than 5 km; (2) in the outer areas, the sedimentation has been condensed since 3000 years; (3) proximal estuarine archives offer the best record of sedimentary processes covering the last 2000 years, including the Medieval Warm Period (MWP).

Correlations in proximal records in the Bay of Vilaine assess the connection between coastal sedimentary dynamics, climatic conditions and anthropogenic activities during the MWP. We match the preservation of clay deposits to increased river-borne suspended matter transported to the estuary probably as a result of accelerated land-use development (higher soil erosion) in the catchment area between ca. 880 and 1050 AD. Because the preservation of estuarine sedimentary successions is favoured when coastal wave sediment reworking is minimal, it is proposed that the prevailing climatic regime in south Brittany during the MWP likely resembled to that of the preferred negative phase of the North Atlantic Oscillation (NAO). Our data are fairly consistent with other late Holocene records from northern Europe including the Atlantic seaboard. However, they outline the difficulty in interpreting climatic and anthropogenic signatures in coastal sedimentary records where high-resolution chronologies required to unravel their respective influences are still missing.

1. Introduction

Recent climatic outlook has produced a growing interest on the response of coastal sedimentary systems to rising sea levels during the 21st century (IPCC, 2007). It is widely recognized that late Quaternary sea level changes, and especially since the Last Glacial Maximum (Lambeck, 1997), had a primary impact on the physiography of Holocene and present-day coastal environments in the French Atlantic and English Channel systems. During the past 20 years, Late Quaternary infill of incised valleys and estuaries had concentrated research efforts, with the main aim being the ability to produce sedimentary infill models for transgressive sediment sinks with high reservoir potential (e.g., Allen and Posamentier, 1993, 1994; Dalrymple et al., 1994; Zaitlin et al., 1994). On the Atlantic coastline, the combination of sedimentological and seismic studies provided a detailed understanding of the infill of incised valleys during the Holocene transgression (Chaumillon and Weber, 2006a,

* Corresponding author at: Present address: UMR CNRS 5125 PEPS, Université Claude Bernard–Lyon 1, 27-43 Bld du 11 novembre, 69622 Villeurbanne Cedex, France. Tel.: +33 472 445 869; fax: +33 472 431 688.
E-mail addresses: philippe.sorrel@univ-lyon1.fr (P. Sorrel), bernadette.tessier@unicaen.fr (B. Tessier), demory@cerege.fr (F. Demory), agnes.baltzer@unicaen.fr (A. Baltzer), jean-noel.proust@univ-rennes1.fr (J.-N. Proust), david.menier@univ-ubs.fr (D. Menier), camille.traini@univ-ubs.fr (C. Traini).

0278-4343/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2010.04.004

b; Féniès and Lericolais, 2005; Lericolais et al., 2001; Menier, 2004; Menier et al., 2006, 2010; Proust et al., 2001; Tessier et al., 2010; Weber et al., 2004). In south Brittany, the mapping and the morphology of incised valleys has recently been revealed by high- to very high-resolution seismic data, with emphasis on the timing of the stepwise marine invasion between the Bay of Quiberon and the Bay of Vilaine (Menier et al., 2006; 2010). These authors pinpointed the relevance of the bedrock morphology of this highly irregular rocky coast, including the role of topographic sills, on the shape of incised valleys and the different patterns of sedimentary infill towards the coast (Menier et al., 2010). If the diachroneity of the transgression offshore and landwards of a major topographic sill is demonstrated, information dealing with the timing of the marine invasion in most proximal areas of the Bay of Vilaine is still missing.

One main concern of this study encompasses the opportunity to explore the impact of climatic changes on the pattern of sedimentary infill of the Bay of Vilaine during the late Holocene. There is indeed growing evidence that periods of coastal barrier destabilization (Billeaud et al., 2009) and increased estuarine hydrodynamics (Sorrel et al., 2009) are proxy records of the impact of storms in coastal settings, linked to Holocene periodic climatic deteriorations (Bond et al., 1997; 2001; Mayewski et al., 2004). A thorough understanding of the patterns of past storminess is of particular importance in the context of modern anthropogenically driven climatic change (Carnell et al., 1996), because the models predict higher sea levels and a higher storm frequency by the end of the current century (Keim et al., 2004; Lozano et al., 2004). Therefore a proxy-based record of storminess and climatic-induced hydrological changes in Holocene coastal archives would provide both a basis for the evaluation of the impact of past climatic variability on sedimentary dynamics and key data for future predictions of coastal evolution. However, relationships between climate variability at multi-centennial timescales and coastal sedimentary processes on the French Atlantic coast have received insufficient consideration to date. Another challenge on coastal climatic records is to track the influence of the North Atlantic Oscillation (NAO), the major modes of interdecadal and longer-term climate variability in the Northern Hemisphere (Hurrell, 1995; Hurrell and van Loon, 1997; Hurrell et al., 2003; Rodwell et al., 1999; Rogers, 1984; Thompson et al., 2003; Wanner et al., 2001, 2008) on the sedimentary infilling of estuaries and/or embayment systems. Hence due to the proximity of south Brittany to climatic zones dominated by the NAO+ mode in northern France (Hurrell and Deser, 2009), the Bay of Vilaine in south Brittany has a strategic climatologic position to evaluate the fingerprint of past NAO variability on climatic change as preserved in sedimentary successions.

Here we present a comprehensive study dealing with the depositional history of the macrotidal inner Bay of Vilaine, where most of the coastal sediment wedge is related to the mid- to late-Holocene marine flooding of the incised valley. This study focuses on the final stage of infilling, and tackles the impact of past climatic changes on sediment deposition and preservation. Based on an approach combining sedimentological and rock magnetic data, conducted on sediment cores, complemented with very high-resolution (VHR) seismic data, our objectives are three-fold: (i) to establish the timing of the different infilling stages and to evaluate the diachroneity of the marine inundation within the inner bay between external and proximal sedimentary records, (ii) to identify relationships between fluvial and marine dynamics and their influence on coastal sedimentary processes during the infill, (iii) to document connections with other regional records from the French Atlantic and neighbouring coasts during the late Holocene.

2. Environmental setting

2.1. Physiography and geology

The Bay of Vilaine is located in the northern part of the Atlantic coast of France, southeast of the Armorican Massif [47°20′–47°35′N; 2°50′–2°30′W] on the Armorican passive continental margin (Fig. 1). It stretches out on a surface that dips gently to the southwest (1:1000 average gradient; Dubrulle et al., 2007). This study focuses on the "internal domains" (Vanney, 1977) or "*précontinent breton*" (Pinot, 1974) situated between the coastline and the −50 m isobath. These internal zones, varying in width from 5 to 14 km, can be distinguished in two parts (Fig. 1): (i) an inshore part, with water depths shallower than 25 m, mostly consisting in bays (Quiberon and Vilaine) and (ii) an offshore part, featured by peninsulas (Quiberon), islands (Houat, Hoëdic, etc.) and shoals (plateaus of Artimon, le Four, la Recherche, etc.) trending N120, parallel to a major regional fault, the South Armorican Shear Zone.

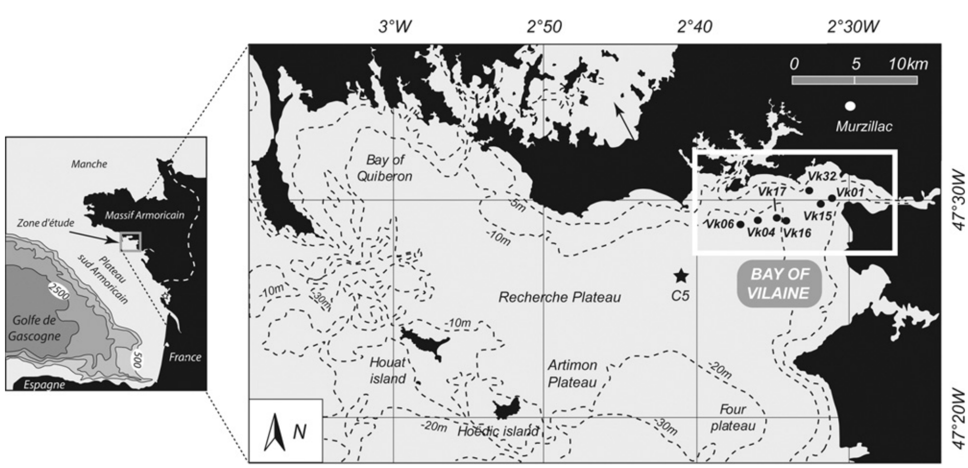

Fig. 1. Geographical location of the study area in south Brittany, and close-up on the bay of Quiberon, the La Recherche Plateau and the Bay of Vilaine (white rectangle). General map (left): the white star corresponds to the position of vibrocores collected in the Ré-Oléron Island area, as discussed in Section 6.2. Core positions are indicated with black circles. Core numbers correspond to the labelling as detailed in the text. Isobaths are given in meters lowest low tide level (LLTL); at le Havre, 0 m a.m.s.l. (above mean sea level) ∼ −4.4 m LLTL (negative and positive values refer to below and above LLTL, respectively). Note that the black star C5 refers to the BRGM drillhole retrieved form the La Recherche Plateau (Bouysse et al., 1974).

The physiography of the Bay of Vilaine stems from the geological inheritage of the region, being limited by two major structural discontinuities linked to the late Hercynian evolution of this area: the south Armorican Shear Zone in the north and the south Armorican fault zone in the south (Pinot, 1974; Vanney, 1977). The bay is characterized by a Cenozoic sedimentary cover, which overlies basal igneous and metamorphic rocks emplaced during the Hercynian orogeny. Cenozoic formations consist in faulted, tilted and slightly folded calcareous rocks of Bartonian and Ypresian ages (Andreieff et al., 1968; Guillocheau et al., 2003). A discordance marks the transition with upper Plio-Quaternary deposits made up of terrigenous sediments (Barbaroux et al., 1971; Bouysse et al., 1974; Horn et al., 1966; Menier, 2004; Menier et al., 2006; Proust et al., 2001). The Bay of Vilaine originates from the flooding of the last glacial incised valley during the Holocene transgression, such as other modern coastal systems (Dalrymple et al., 1992, 1994; Perillo, 1995; Zaitlin et al., 1994). This study focuses on the upper part of the Holocene infilling sequence.

2.2. Climatic and hydrodynamic setting

The climatic regime in south Brittany is marked by temperate and oceanic conditions (mean annual precipitation range: 800–1000 mm) with mostly cool and rainy winters resulting from the influence of the NAO (Fig. 2).

The hydrodynamics within the Bay of Vilaine are governed mainly by waves, tides and river inputs (Pingree and Le Cann, 1989). Over the southern Brittany shelf, the general currents show a marked seasonal character largely due to the dynamics of the dominant winds. They are oriented towards the northwest in winter and towards the southeast in summer. The strongest swells are associated with westerly storms, favouring the resuspension and the transport of fine sediments towards the Vilaine estuary. The wave regime in the Bay of Vilaine is characteristic of sheltered coastlines. The mean significant wave height lies between 1 and 2 m for a mean period of 2–5 s (Tessier, 2006). Regional winds, which generate wave agitation, blow dominantly from the west and northwest directions.

The tide is semi-diurnal with a mean spring tidal range of 4.5 m. Associated tidal currents are weak (maximum: 0.25–0.4 m/s during spring tides) and strongly giratory on the continental shelf (S.H.O.M., 1993). However, they become much stronger in the vicinity of the coasts and especially in the passages between the Quiberon peninsula and the neighbouring islands (Houat and Hoëdic), and are amplified in shallower water depths (Pinot, 1974; Vanney, 1977). In the Vilaine estuary, currents attain 1.5 m/s during spring tides, both during floods and ebbs (S.H.O.M., 1997).

Sedimentation in the Bay of Vilaine is predominantly sandy pelitic and muddy (Vanney, 1977). Most of siliciclastics originate from the reworking on the shelf of the last glacial sandy deposits, and from the erosion of the modern sandy coastal environments to the north through the action currents generated by longshore drift. The main source of fine material in the bay is the Vilaine River (catchment area: 11,400 km^2) with sediment fluxes estimated at 0.1.10^6 tonnes/year (suspended discharge) (Jouanneau et al., 1999). The fine-sediment fluxes from the remaining small rivers of south Brittany are poorly known but fluxes can be estimated to be very low. However, the contribution of marine-borne deposits and sediment inputs from the Loire River is not negligible, as reported from geochemical analyses on clayey and non-clayey system tracts (Barbaroux and Gallene, 1973; Bouysse and Vanney, 1966; Gouleau, 1975; Lafond, 1961).

According to these hydrodynamic and sedimentary parameters, the inner Bay of Vilaine is a macrotidal sheltered coastal environment with moderate mixed energy controlled by wave and tides and with low marine and fluvial inputs.

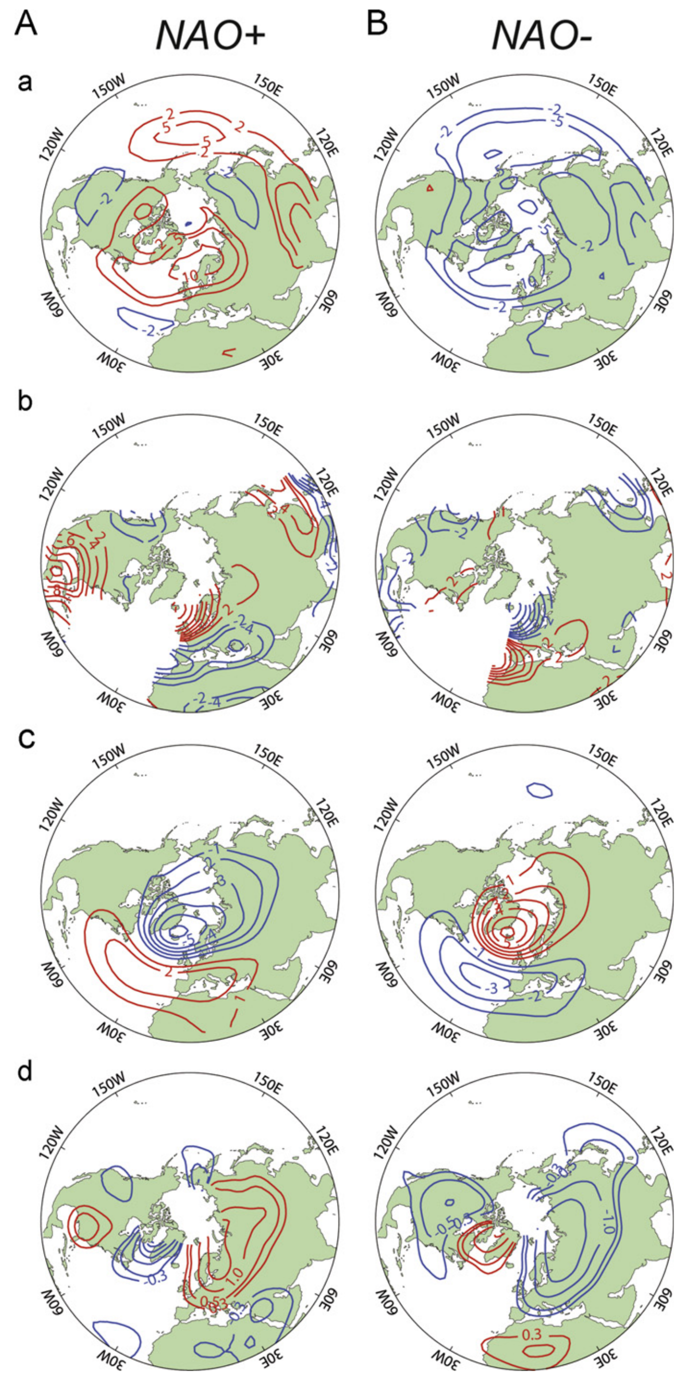

Fig. 2. Northern Hemisphere pattern of winter climate variability associated to the North Atlantic Oscillation. A: Average anomalous conditions during high NAO winters (NAO+); B: Average anomalous conditions during low NAO winters (NAO−). a: Storm activity anomalies (%); b: Precipitation anomalies (mm/month); c: Sea-level pressure anomalies (mb); d: Temperature anomalies (degrees C). Data are from http://www.cru.uea.ac.uk/cru/info/nao/.

3. Material and methods

3.1. Seismic data

Two seismic campaigns were conducted in the study area within the frame of the Cotarmor research program (Proust, 1999) and the University of southern Brittany research projects (2000, 2007, 2008). One high-resolution seismic survey was carried out on board the R/V "Côtes de la Manche" (CNRS/INSU) using a sparker-SIG1580 source (600–1000 Hz frequency band, 650 J);

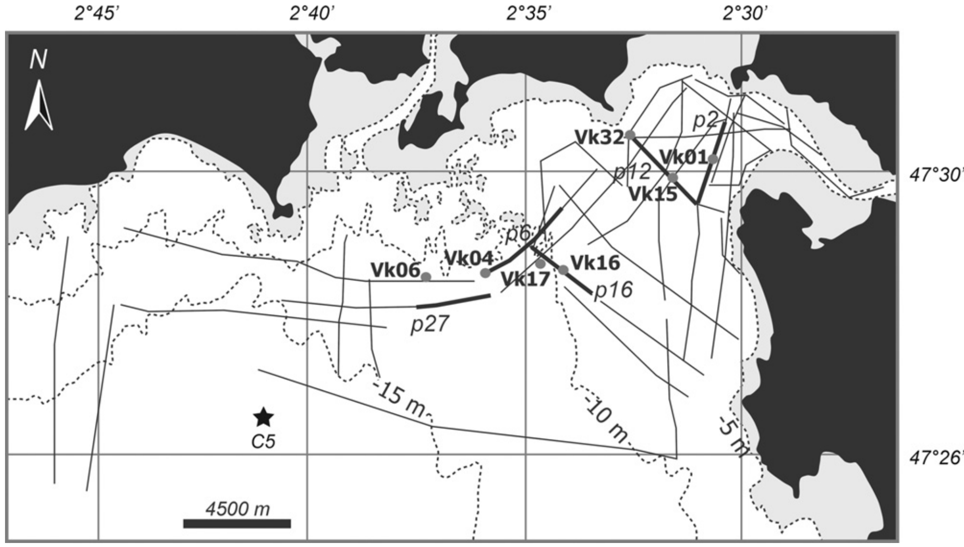

Fig. 3. Position of the VHR seismic profiles (boomer Seistec) shot in the inner Bay of Vilaine (Bingolaine survey, R/V Sepiola). Thick lines indicate the profiles shown in Figs. 4 (p6 and p16), 5 (p27) and 6 (p2 and p12). All the cores described in the paper are displayed on the profiles.

Table 1
Radiocarbon dates for the Bay of Vilaine cores. AMS ^{14}C ages were measured at Poznań Radiocarbon Laboratory (Poland). Poz-23588 (Vk15) was corrected to calibrated (cal.) ages using the mixed Marine Northern Hemisphere curve (Mixed Marine NoHem) (program CALIB Rev. 5.0.1.), because this sample contains dead carbon from both continental and marine sources. For all other radiocarbon data, we used the Marine calibration curve (Marine04) because dead carbon was most probably of predominant marine origin during 6000–3000 BP. Calibrated ages indicate values with 2 standard deviations (95% of confidence). We recalibrated the AMS ^{14}C date performed on the BRGM drillhole C5 (8110 ± 200 ^{14}C years BP) by using the Marine04 curve. TOC: total organic carbon. MI: missing information.

Lab. no.	Core depth (cm)	Altitude LLTL (m)	AMS ^{14}C ages (radiocarbon years BP)	Reservoir age (R)	ΔR	Calibrated age (2σ) (cal. years BP)	Dated material
Vk06 (Poz-23589)	97–100	−8.5	3985 ± 35	264	44	3487–3811	TOC
Vk06 (Poz-23591)	246–249	−9.9	4890 ± 35	264	44	4694–5016	TOC
Vk06 (Poz-23592)	375–378	−11.3	5560 ± 40	264	44	5556–5839	TOC
Vk15 (Poz-23588)	165–168	−3.7	1340 ± 30	264	44	829–865 (0.05%); 882–1049 (0.95%)	TOC
Vk16 (Poz-23649)	100–103,5	−1.5	3690 ± 30	264	44	3161–3431	TOC
Vk16 (Poz-23691)	174–177	−2.2	3970 ± 35	264	44	3470–3797	TOC
Vk16 (Poz-23693)	294–297	−3.4	4760 ± 40	264	44	4519–4824	TOC
C5 (Bouysse et al., 1974)	1030	MI	8110 ± 200	264	44	7901–8854	Molluscs

one VHR seismic survey (Bingolaine survey) was performed on board the R/V "Sepiola" (Bailleron marine station, University of Rennes 1) using a boomer-IKB Seistec source (1–10 Hz frequency band, 200 J). The sparker data were used to establish the general frame of the post-glacial infilling of the Bay of Vilaine (Proust et al., 2001). For the present study, which focuses on the internal domain of the bay, i.e., the outer Vilaine estuary, only the boomer data were used (Fig. 3). Both their vertical resolution (<50 cm) and their quality in shallow water settings (Simpkin and Davis, 1993) are suitable for fulfilling the objectives of this study. Data visualization and recording in real time were carried out with the ELICS DELPH software, which also allowed acquisition with simultaneous positioning guaranteed by a digital GPS. Seismic data were processed (gain, high and low band pass filtering) using the Seismic Unix software. For interpretation of the data, a P-wave velocity of 1600 m/s was used for the time-to-depth conversion in unconsolidated sediments (Maroni, 1997).

3.2. *Core location and sediments*

In the frame of the Cotarmor research program, 12 sediment vibrocores (10 cm diameter, 2–4.5 m in length; Table 1) were collected in the outer estuary and the Bay of Vilaine during the Carosub mission (Ifremer/Génavir R/V Thalia) in 2004. The cores were taken from water depths ranging from 0 to 10 m below lowest low tide level (LLTL) (Fig. 3; Table 1). Core locations were determined using the data of the boomer seismic survey. Lithological description and photographs were made directly after core opening on split core half surfaces (Bouaouina, 2006). Sediment quality is generally good though sediment disturbances sometimes occur in the topmost part of cores due to coring artefacts. Bioturbation is not extensively developed down-core and, therefore, does not affect the preservation of primary sedimentary structures and beddings. For the purpose of this study, seven cores have been investigated within the study area 47°28′–47°31′N; 2°30′–2°40′W (Fig. 1): cores Vk01, Vk04, Vk06, Vk15, Vk16, Vk17 and Vk32.

3.3. *AMS ^{14}C dating*

AMS radiocarbon dating was carried out on 4 cores (Vk06, 15, 16, 17) using bulk organic carbon (Table 1) since bioclastic material was absent within the intervals considered for dating. For each sample, AMS ^{14}C dating was made using a minimum amount of 1.0 mg of pure carbon. Measurements were conducted at the Poznań Radiocarbon Laboratory (Poland). Absolute dating

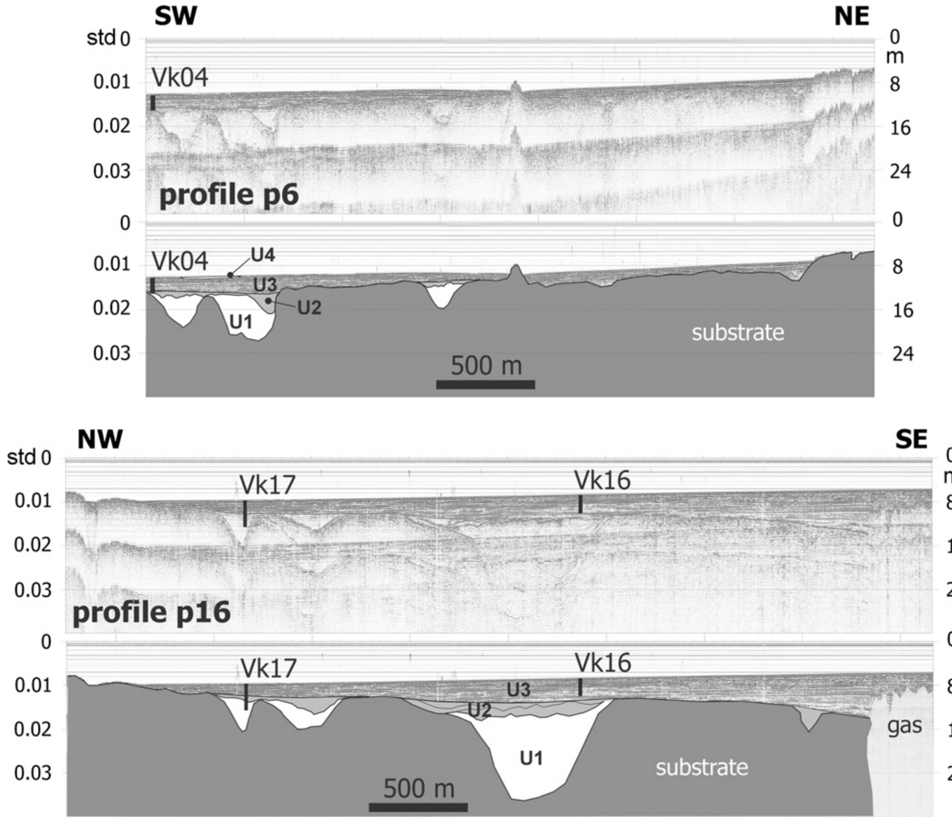

Fig. 4. VHR (Boomer Seitec) seismic profiles p6 and 16 and their interpretation in terms of seismic units.

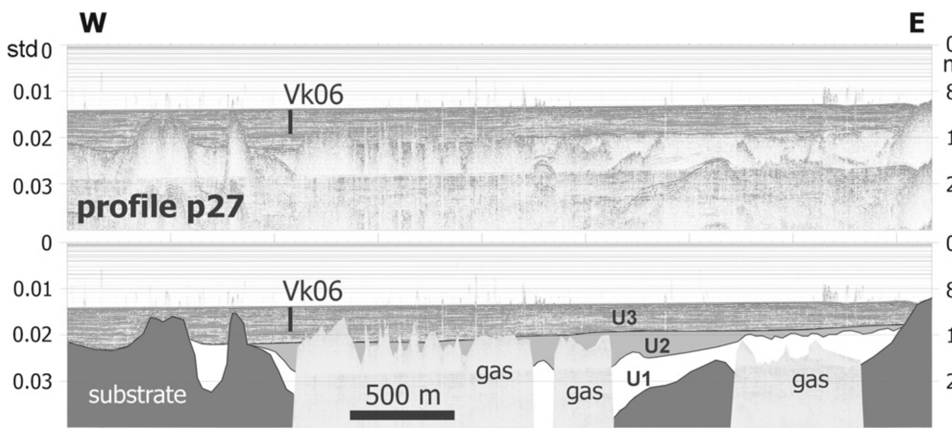

Fig. 5. VHR (Boomer Seistec) seismic profile p27 and its interpretation in terms to seismic units. The core Vk06 is located about 1 km north to this profile (cf. Fig. 3). Its position has been projected on p27 (see text for explanation).

was corrected for the mean ^{14}C age difference between the atmosphere and oceanic surface waters by applying a reservoir correction (R) of 264 years with an applied regional deviation (ΔR) of 44 years in the Bay of Arcachon (Stuiver et al., 2005). Absolute dating was then calibrated using (i) the Marine04 curve for sediments (or samples) whose deposition is coeval to the marine transgression during ca. 6000–3000 year BP, and (ii) the mixed Marine Northern Hemisphere curve for samples belonging to the time interval 0–2000 year BP (increasing influence of river-borne carbon sources due to the slowing down of the transgression and the seaward progradation of the sediment wedge). The calibration was performed using the program CALIB 5.01 (Stuiver and Braziunas, 1993). Calibrated ages indicated values with 2 standard deviations (2σ; 95% of confidence).

3.4. Rock magnetic analyses

Rock magnetic analyses were conducted at the CEREGE institute (Aix en Provence, France). Core Vk15 was continuously subsampled using 8 cm^3 plastic boxes pushed into the split surface at quasi-regular intervals (2.2 cm). Rock magnetic measurements were carried out to characterize the magnetic assemblage in sediments, which is typically composed of particles originating from erosion in the catchment area, in-situ dissolution and authigenesis of magnetic particles (Berner, 1980; Demory et al., 2005; Ellwood et al., 2000; Snowball, 1993; Williamson et al., 1998). Low field magnetic susceptibility (κ_{LF}) was measured using a AGICO MFK1 Kappabridge. κ_{LF} is a measure of the ease with which sediments are magnetized when subjected to a low

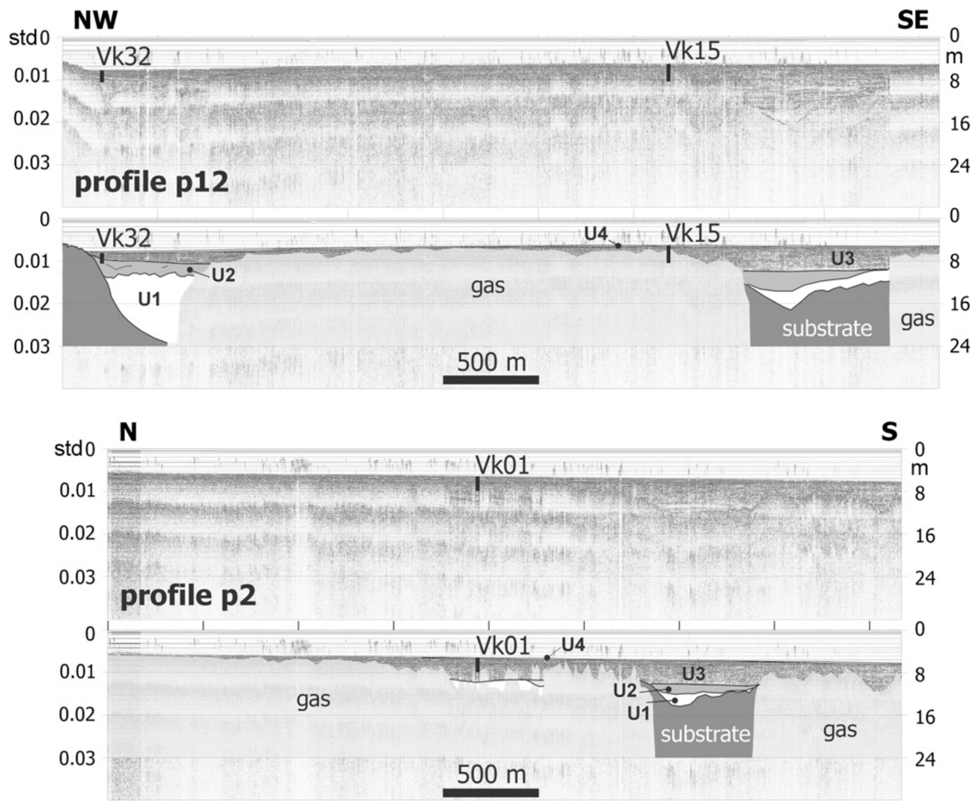

Fig. 6. VHR (Boomer Seitec) seismic profiles p12 and 2 and their interpretation in terms of seismic units.

magnetic field. κ_{LF} is mostly dominated by ferromagnetic *s.l.* material (i.e. magnetite) but can also be influenced, especially when values are low, by paramagnetic (i.e. clays) and diamagnetic material (i.e. carbonates).

All following remanent magnetizations were measured with a fully automated 2G Enterprises DC-SQUID cryogenic magnetometer 2G 760R. Anhysteretic Remanent Magnetization (ARM) was produced along the *z*-axis of the samples with 100 μT steady field and 100 mT alternating field amplitude. ARM was measured and subjected to stepwise alternative field (AF) demagnetization (up to 65 mT). ARM quantifies the concentration in low-coercivity ferromagnetic minerals (i.e. magnetite).

The saturated isothermal remanent magnetization (SIRM) was acquired at 3 T using a pulse magnetizer. ARM/SIRM was used as a magnetizer grain size indicator since ARM affects preferably finer grains. ARM/SIRM decreases with the coarsening of the magnetic carriers (Maher, 1988). Once the SIRM is obtained, all the samples were magnetized in a field of 0.3 T in the opposite direction. The ratio of high (hematite, goethite) to low-coercive ((titano-) magnetite) mineral concentration is expressed as (Frederichs et al., 1999)

$$S_{ratio} = \frac{1}{2}\left(1 - \frac{IRM_{-0.3T}}{IRM_{3T}}\right) \tag{1}$$

S-ratio close to 1 indicates the predominance of low-coercivity particles whereas a decrease of the *S*-ratio documents an increasing proportion of high-coercivity minerals. Here we use the *S*-ratio parameter to examine intervals possibly affected by selective reductive dissolution of magnetite (Demory et al., 2005). In addition the high isothermal remanent magnetization (HIRM) (2), which estimates absolute concentrations in high-coercivity minerals in sediments (Maher and Dennis, 2001), was also calculated.

$$HIRM = \frac{1}{2}(SIRM - IRM_{0,3T}) \tag{2}$$

HIRM is less affected by redox conditions (hematite being more stable under oxidizing conditions than magnetite—e.g. Dillon and Bleil, 2006; Emiroglu et al., 2004; Garming et al., 2005; Yamazaki et al., 2003) and confirms that the hard magnetic mineral content is the best tracer of detrital input (Demory et al., 2005; Frederichs et al., 1999; Peck et al., 1994). Hence the HIRM was used as a proxy for changes in terrestrial inputs from the Vilaine River.

4. Stratigraphic pattern

4.1. Seismic data (Figs. 3–6)

Previous seismic data are available in the study area, and most of them are based on high-resolution sparker profiles (Proust et al., 2001; Menier et al., 2006; 2010). These data were used to reconstruct the geometry of the Holocene sediment wedge preserved into the incised valley network of the Bay of Vilaine. For the purpose of the present study, which focuses on the most internal domain of the bay, the use of VHR boomer profiles was explored to provide complementary data for core interpretation and correlation. Five seismic profiles have been selected, extending from the most internal to the most external part of the study area, and which cover the core locations (Figs. 3–6). The quality of the seismic data is generally good though in some places, acoustic turbidity due to the presence of biogenic gas into the sediment hides seismic information (Figs. 5 and 6), especially above the deepest part of the incised valley where the sedimentary infill is the thickest. This is a usual feature in estuarine settings (e.g. Garcia-Gil et al., 2002; Bertin and Chaumillon, 2005; Baltzer et al., 2005). Elsewhere, the quality of the seismic data is good, especially along the edges of the incised valley. They have allowed the distinction of different seismic facies and boundary surfaces, and of four seismic units (named U1–U4) in the sedimentary infill above the rocky substratum (named U0).

- The rocky substrate unit, U0, is characterized by a transparent facies due to the non-penetration of the acoustic signal into the Palaeozoic metamorphic rocks that constitute most of the basement of the study area. The highly irregular top of U0 corresponds to the surface of the main valley network incision;
- Unit U1: it rests on U0 and represents the main part of the valley infilling. It is an aggradational unit. Because of the presence of gas and multiple reflections, the most basal part of U1 is very poorly imaged on the seismic profiles from the inner Bay of Vilaine. The acoustic facies of U1 is mostly characterized by low amplitude planar reflectors of high-to-moderate continuity. They usually onlap the valley walls, but may locally drape them;
- Unit U2: It overlies U1 with a channelizing erosive basal surface. It represents the uppermost part of the valley infill above U1. Internal reflectors are of high-to-moderate amplitude and moderate-to-low continuity. They are either oblique parallel or divergent, locally planar, with dowlap, onlap or conformable termination. The upper surface of U2 is a flat erosive surface;
- Unit U3: It is the most widespread unit of the study area. It rests on U2, U1 or U0, extending over the valleys and interfluves. It rests on the flat basal surface eroding the underlying units. U3 is an aggradational unit with planar internal reflectors of high amplitude, high continuity and high frequency. The top of U3 corresponds, in most places, to the seafloor although it locally matches with the base of U4;
- Unit U4: This final unit is only present as a very thin (<0.25 m) drape present at the seafloor, usually found in the most internal areas. It is distinguished due to a thick white reflector, the frequency and continuity of which is much lower than that of U3 (e.g. Figs. 4 and 6).

These four units have already been described in the previous studies related to the general sedimentary infill pattern of the Bay of Vilaine area (Menier et al., 2010; Proust et al., 2001). This succession is interpreted as resulting from the Holocene transgression over the incised valley network. By using high-resolution seismic data, Proust et al. (2001) recognized a first unit at the base of the infill, which they interpreted as the remnant of Pleistocene fluvial terraces. This most basal unit is not imaged here. In addition, an uppermost very thin unit (U4) is recognized in this study. This uppermost draping unit is more developed in inner areas located to the North of the La Recherche Plateau (Menier et al., 2010), and is described as a transparent to chaotic unit attaining 1 m in thickness.

The seismic data presented herein provide, for the first time, crucial information on the sedimentary infilling of the inner Bay of Vilaine. Seismic data are calibrated by radiocarbon-dated cores, and sedimentary facies were carefully examined to establish correlation between cores.

4.2. Sedimentary facies

Lithological description combined with smear slides observations revealed that sediment cores from the Bay of Vilaine comprise material of variable origin and size. The sediments consist mostly of silty-clays and sands (fine- to coarse sands and pebbles) either as homogeneous layers with shell fragments in various contents, or as heterolithic tidal facies made of alternations between sandy and silty-clay beds. Massive clayey to silty-clay intervals are also preserved in a few cores (Vk01, 15). Bioturbation (bivalve burrows) occurs locally but is not extensively developed. Seven sedimentary facies have been identified within the cores based on the lithology, the sedimentary structures, the grain size and bioturbation (Fig. 7). Facies description relies on classic models (Reineck and Singh, 1980). The different facies have been interpreted in terms of shallow coastal depositional environments.

- Facies A (F_A): Coarse gravels and pebbles of metamorphic origin (mostly quartzites), structureless facies with a sharp basal erosive surface. Some shell debris may occur, but very rarely. This heterolitic facies is interpreted as a tidal channel floor deposit;
- Facies B (F_B): Medium to coarse sands, rich in shell debris (ranging in size from 0.1 to 1.0 cm), a structureless facies with a sharp basal erosive surface. Some intervals consist only of shell fragments stacked together without any primary organization, suggesting that these deposits probably accumulated very rapidly. Few entire bivalve valves have been preserved, and complete *Turritella comunis* shells are common. No bioturbation is observed. F_B reflects high-energy depositional processes typical of storm deposits at subtidal depths;
- Facies C (F_C): Fine to medium well-sorted sands including locally preserved mud drapes. Shell debris is frequent and bivalve burrows are common. F_C reflects relatively high-to-moderate energy deposits and is interpreted as a subtidal flat and/or tidal channel deposit;
- Facies D (F_D): Silty-clays to silts and very fine sands with wavy- and planar bedding. The sediments most frequently consist of alternations of centimetres to millimetre-scale laminae or bundles of laminae without any obvious vertical rhythmic pattern in the variability of lamina thickness. Organic matter sometimes occurs both as a dispersed phase within the matrix and as forming individual horizons (1–3 mm thick). Shell debris is usually found in the sandy layers. Bioturbation is frequent as burrows. F_D is interpreted as a heterolithic intertidal deposit based on the occurrence of typical tidal bedding;
- Facies E (F_E): Massive, homogeneous grey to greenish silty-clays, rich in organic matter, which occurs both as a dispersed phase within the matrix and as well defined and laterally continuous laminations (1–2 mm thick). There are no shell debris but a few metamorphic pebbles are present occasionally. Bioturbation is very common. This facies is characterized by very low contents in $CaCO_3$ (0.2–3%) and the presence of pyrite framboids (Bouaouina, 2006). F_E is interpreted as a brackish ria-type or inner intertidal mudflat deposit;
- Facies F (F_F): Brownish clays to silty-clays with a flat basal surface, and overlain by coarse erosive sands. No shell debris was found. Bioturbation is rare. F_F is interpreted as an estuarine flood-deposit linked to the expulsion of the clay plug from the Vilaine River;
- Facies G (F_G): Brown water-rich homogenous muds, locally colonized by the crustaceans *Haploops* sp. Only rare shell debris are present. These upper, topmost, deposits occur throughout the inner Bay of Vilaine although they are usually thicker in most internal areas. This unit corresponds to sub-recent to recent depositional conditions, and documents the modern increase of river-borne fine sediments entering the

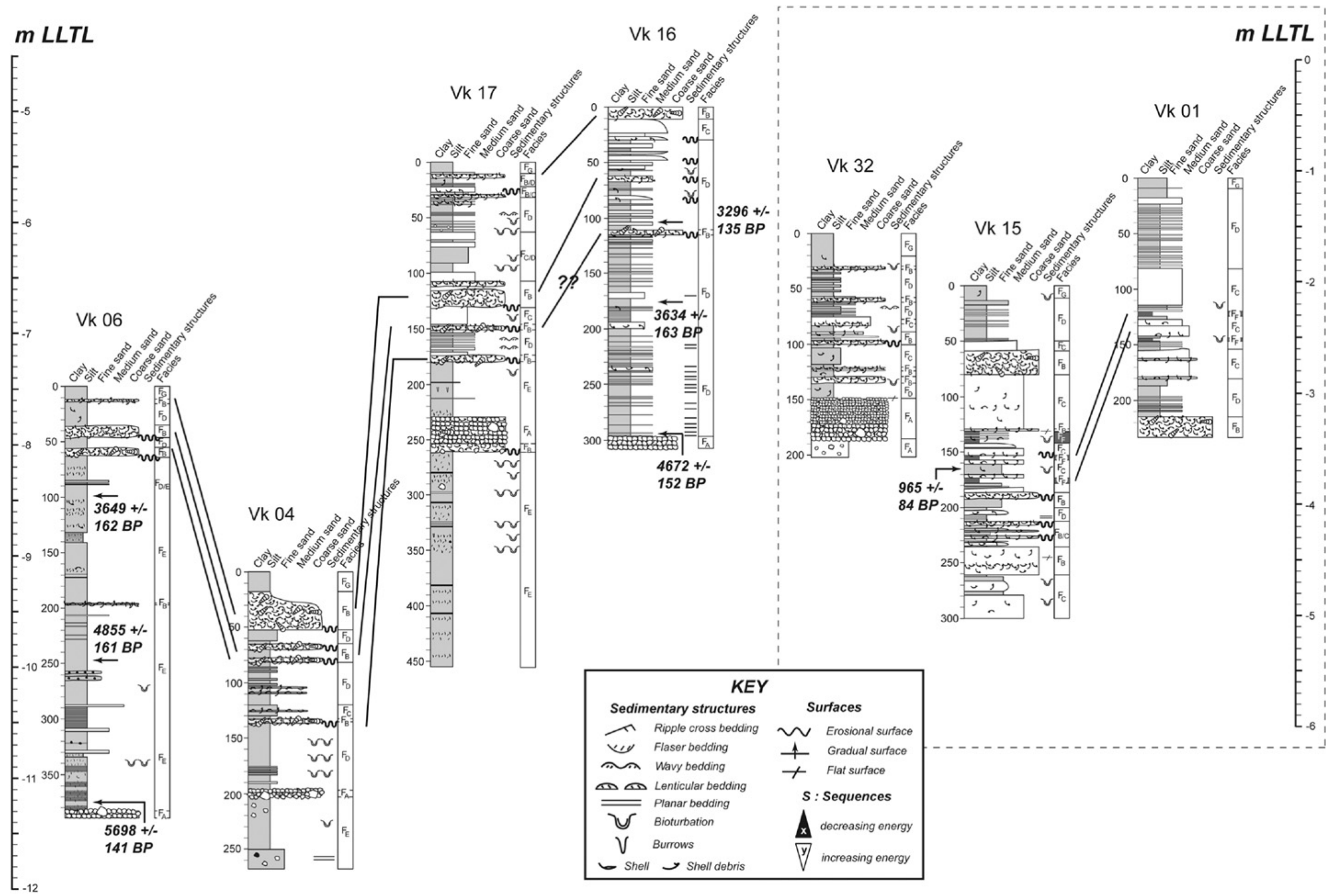

Fig. 7. Sedimentological description and sequence stratigraphy of seven cores from the Bay of Vilaine. Variations in sedimentary facies (F_A, F_B, F_C, F_D, F_E, F_G) are reported on the right side of the cores. All ages are calibrated AMS ^{14}C dates (cal. BP; see Table 1). Black full lines document the correlation of high-energy deposits (storm deposits) between outer cores Vk06, Vk04, Vk17 and Vk16 in the bay. The en-dashed rectangle shows proximal cores Vk32, Vk15, Vk01 collected in the inner part of the bay. LLTL: lowest low tide level.

bay, mostly linked to the intensification of anthropogenic activities (Menier et al., 2010).

4.3. Facies succession and core correlation

In order to document the sedimentary evolution of the inner Bay of Vilaine, seven cores were selected: cores Vk06, Vk04, Vk17, Vk16, Vk32, Vk15 and Vk01. The latter is the most internal while Vk15 serves as a pilot core to establish correlation with more external records (Fig. 1). Cores were collected 1–3 km off from the northern margin of the bay, in water depths ranging from -1.07 m (core Vk01) to -9.14 m below lowest low tide level (LLTL) (core Vk04) (Fig. 7). Available AMS ^{14}C dating provide us with a time window covering the last 6000 years, i.e. the mid- to late-Holocene period. Core to core correlation relies on the match between sedimentary trends inferred from facies successions and seismic data. The data provided by the drilllhole C5 collected from the southeast of the La Recherche Plateau in the outer Bay of Vilaine (Bouysse et al., 1974, in Proust et al., 2001) were used as additional information to give a comprehensive understanding of the timing (including possible time lags) of the depositional history of the system.

Cores Vk06, 04, 17 and Vk16 are the most external archives in the study area. Cores Vk16 and Vk17 were collected on the seismic profile p16 (Fig. 3). Vk16 penetrates the seismic unit U3 mainly, whereas Vk17 penetrates the units U3, U2 and reaches the top of U1 (Figs. 4 and 8). Vk04 was taken on profile p06 and, as Vk17, penetrates the units U3, U2 and reaches the top of U1 (Figs. 4 and 8). Core Vk06 is located on the seismic profile p07 (not shown). Unfortunately the numerical file of this profile was damaged and the analogic profile (paper) is unusable. Hence core Vk06 was projected onto the nearest profile (p27; Fig. 5). Vk06 is mainly confined to the seismic unit U3.

Cores Vk04 and Vk17 provide the most complete succession of the sedimentary infill. However, no AMS ^{14}C dating is available for these cores. The lowermost unit U1 is composed of homogenous clays enriched in organic matter (facies F_E) and represents a sheltered depositional environment with intermittent marine influence (ria-type estuary). Although no data are available for the ria muds in U1, we can assume that the aggradation of the mudflats are coeval to the beginning of the Holocene (Menier et al., 2010). The boundary between the aggradational unit U1 and unit U2 is a sharp erosional surface overlain by a layer of shell debris passing abruptly into a very coarse gravel/pebble succession with shell fragments (F_A). The very poorly sorting of the sediments of this succession and the channel-like geometry of the basal boundary suggest that these deposits are characteristic of tidal channel bottom and intertidal flat deposits linked to the installation of estuarine tidal channels. The erosive base thus corresponds to a tidal-ravinement surface (TRS). Above U2, the unit U3 in cores Vk04 and Vk17 consists of mud-dominated sediments (F_D) intercalated with sandy shell layers (F_B, F_C), which reflect episodes of higher energy in the bay (i.e. storm events). The

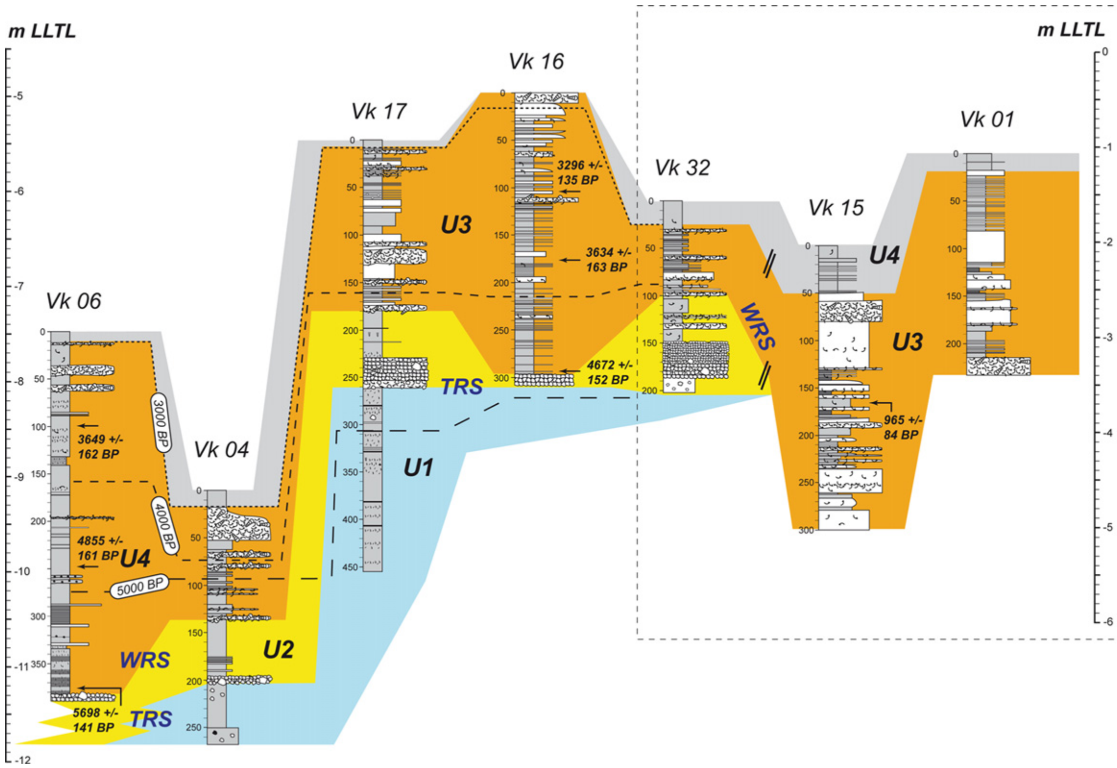

Fig. 8. Correlation of seismic units U1–U4 on a distal–proximal transect in the Bay of Vilaine, with emphasis on the timing of deposition of the successive units. Note the time lag for the TRS and the WRS between core Vk06 and Vk16 (see text for detail). All ages are calibrated AMS ^{14}C ages (cal. BP; see Table 1). The en-dashed rectangle shows proximal cores Vk32, Vk15 and Vk01 collected in the inner part of the bay. LLTL: lowest low tide level.

boundary between U2 and U3 is a flat surface marking a conspicuous change in sedimentary conditions from an inshore intertidal environment to more open marine conditions associated with the deposition of offshore muds. The basal surface of U3 is, therefore, regarded as a wave ravinement surface (WRS) coeval to the onset of full-marine conditions in the inner Bay of Vilaine. The topmost 10–20 cm in both cores mark the transition to the uppermost seismic unit U4 although the latter is hardly recognizable on the seismic profiles p06 and p16 (Fig. 4). These upper deposits are composed of a brown water-rich homogenous mud (F_G) contrasting with the underlying silty-clays (F_D). Grab samples demonstrate that this superficial unit is locally, but densely, colonized by the crustacean *Haploops* sp. (Menier et al., 2010).

Cores Vk06 (the most external core) and Vk16 provide a very detailed record of unit U3 (Figs. 7 and 8). Several AMS ^{14}C dating were conducted in this unit (both within and at the base of the unit; Fig. 7, Table 1). It allows the dating of the deposits that seal the WRS to 5556–5839 cal. BP in Vk06 and 4519–4824 cal. BP in Vk16. In both cores, the sedimentary facies constituting U3 are indicative of overall low-to-moderate energy conditions as inferred from the dominance of silty-clays (F_C, F_D), interrupted by layers of coarse shelly or sandy deposits (F_B) interpreted as storm deposits. A similar facies succession is recorded in the distal drillhole C5 (Bouysse et al., 1974, in Proust et al., 2001) with the dominance of low energy deposits which overlie a coarse gravely interval and a marine ravinement surface (WRS) dated in this outer part of the Bay of Vilaine to 8110 ± 200 ^{14}C year BP (8378 ± 476 cal. BP). The upper part of U3 in cores Vk06 and Vk16 records a coarsening-upward succession, where the frequency of sandy and shelly layers is significantly higher (F_D to F_C/F_B). In Vk16, this increase in storm event frequency is further accompanied by a thickening of the coarse-grained deposits. AMS ^{14}C dating indicates a time lag of about 1000 years with respect to the beginning of the deposition of U3 in cores Vk06 (ca. 5700 cal. BP) and Vk16 (4700 cal. BP). This delay in the establishment of full-marine conditions in the bay is related to the slow progression of the late Holocene transgression over the highly irregular regional bedrock locally characterized by steep slopes and numerous topographic sills (Menier et al., 2006, 2010).

Core Vk32, which was collected close to the coast, is one of the most proximal record in the Vilaine estuarine mouth. Vk32 is located on the profile p12 (Fig. 3) and penetrates the seismic units U4 and U3, reaching the top of U2 (Figs. 6 and 8). Although it probably did not reach U1 (cf. Fig. 6), Vk32 displays a succession equivalent to that preserved in external cores Vk04 and 17. Vk32 provides therefore, for the internal domain, a good analogue of the sedimentary evolution recorded in the main bay. Due to the very proximal location of Vk32 close to the shore and the high altitude of the bedrock in that area, U3 appears much more condensed in Vk32 compared to that in cores Vk04 and Vk17.

With concern to the most internal records, the cores Vk15 (located on the seismic profile p12) and Vk01 (located on the seismic profile p02) provide a detailed record of the sedimentary evolution in the main axis of the incision, close to the mouth of the Vilaine River (Fig. 6). Both cores contain well-preserved sedimentary successions mostly pertaining to unit U3 and U4 (Figs. 6 and 8). In contrast to distal records, U3 sediments in Vk15 and Vk01 mostly consist of facies indicating higher energy conditions, i.e., with higher contents of sandy intervals (F_B–F_C). These coarser-grained facies reflect the more proximal location of the cores to the influence of terrestrial input. From the base to the top of U3, the sedimentary successions in Vk15 and Vk01 nevertheless document a fining-upward evolution (Figs. 7 and 8) that terminates with the deposition of clay to silty-clay intervals. This evolution, indicative of decreasing energy, is interpreted as resulting from the progressive infill of the Vilaine estuary. At both sites, the U3 succession contains two to three 4–

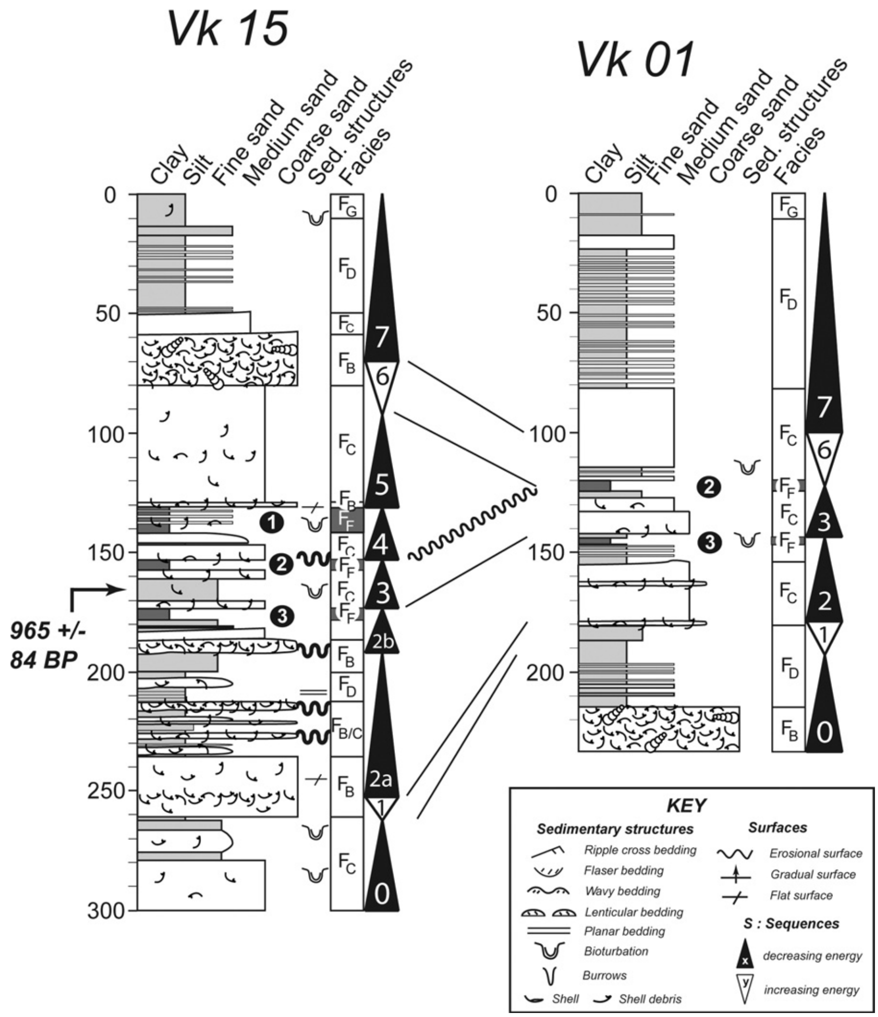

Fig. 9. Close-up on the correlation between sedimentary successions from cores Vk15 and Vk01 in the inner part of the Bay of Vilaine (see Fig. 1). The correlation is primarily based upon the match between clay deposits (named $F_{F\ 1}$, $F_{F\ 2}$, $F_{F\ 3}$). Note that the sequences 4 and 5 are not preserved in core Vk01. Based on one AMS ^{14}C age (given as cal. BP) performed on core Vk15, these clay intervals are assigned to the Medieval Warm Period (see text for detail).

10 cm thick clay intervals ($F_{F\ 1\text{–}3}$) preserved between medium- and coarse-grained sand beds (F_B and F_C) (Fig. 9). In detail, the mud intervals have a flat basal surface and consist in rather homogeneous deposits often deprived of a primary structural organization. At the top, the boundary between the deposition of clays (F_F) and the overlying coarse sandy facies (F_C) is a sharp erosive surface corresponding to the return of stronger hydrodynamic conditions (Fig. 9). However, the occurrence of thin upgrading laminations at this boundary may account for a transitional return of sand deposition. Therefore, based on sedimentological criteria, there is strong evidence for the preservation of well-correlated events between cores Vk15 and Vk01 (Fig. 9), which are interpreted as estuarine flood deposits linked to the expulsion of the clay plug of the Vilaine River. Similar processes and deposits were described in the Seine estuary (Garnaud et al., 2002; Lesourd, 2000; Sorrel et al., 2009). One radiocarbon date from Vk15 indicates an age of 965 ± 84 cal. BP, i.e. 882–1049 AD, and thus corresponds to the Medieval Warm Period (MWP) in the middle part of U3 (Table 1). Hence it suggests that, in contrast to more distal records where the upper successions extend back to ca. 3000 cal. BP, sediments from cores Vk15 and Vk01 probably preserve the last 1500–2000 years only, i.e. the very latest component of the Holocene transgression.

5. Rock magnetic parameters

Down-core variations of rock magnetic parameters within core Vk15 are shown in Fig. 10. HIRM was calculated to determine the abundance of high-coercivity minerals (e.g., hematite). The stratigraphic variations of HIRM (0–140 mA m^{-1}) almost mirror that of κ_{LF} ($100\text{–}500\times10^{-6}$ SI) although less high frequency variability is found in HIRM. In general, variations in κ_{LF} and HIRM reflect lithological changes, especially in the intervals consisting of a well-defined alternation of clayey and sandy deposits (130–170 cm). Higher κ_{LF} ($350\text{–}500\times10^{-6}$ SI) and HIRM (80–140 mA m^{-1}) most commonly coincide with finer deposits (clays to silty-clays; F_D–F_F), whilst lower κ_{LF} ($100\text{–}300\times10^{-6}$ SI) and HIRM (0–80 mA m^{-1}) correspond to coarser facies (sands to sandy silts; F_B–F_C). It is worth mentioning that the highest HIRM values (120–140 mA m^{-1}) are found in the two upper clay intervals $F_{F\ 1\text{–}2}$ in U3 (see Fig. 9), indicating a trend of elevated detrital inputs (180–130 cm; $F_{F\ 1\text{–}3}$) during Medieval times. In addition, HIRM marks a background pattern of persistent increasing absolute concentration in hematite from the base to the top of core Vk15. Higher S-ratios generally indicate higher relative abundance of (low-coercivity) ferromagnetic minerals (magnetite), whereas changes to lower S-ratios reflect the contribution of (higher coercivity) anti-ferromagnetic minerals.

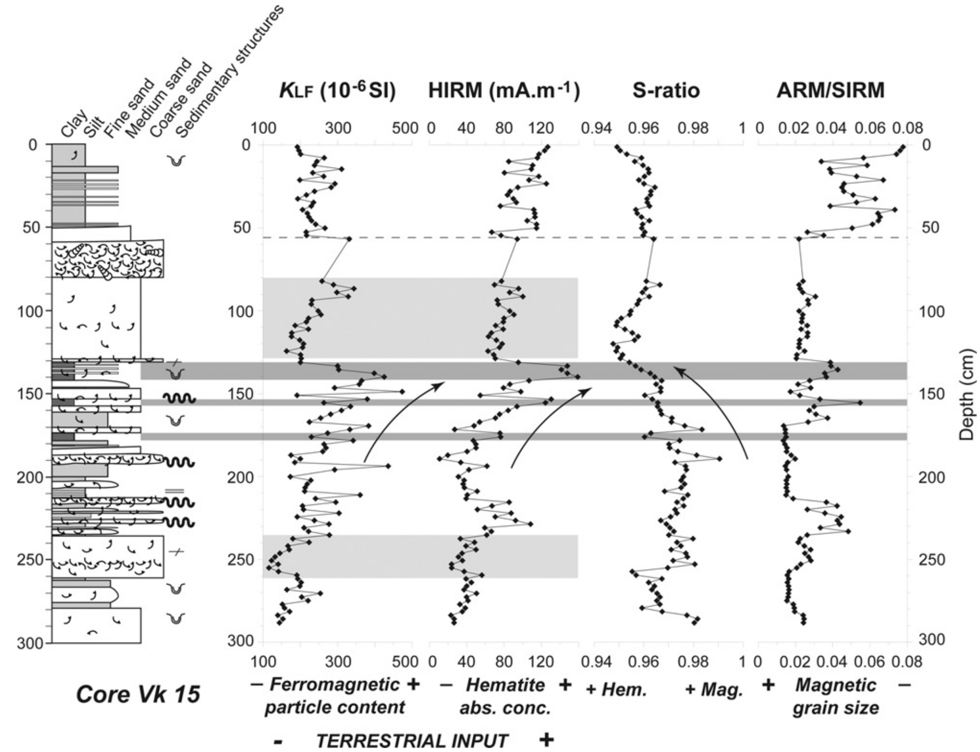

Fig. 10. Down-core variations of rock magnetic parameters and lithological description of core Vk15. κ_{LF}: low field magnetic susceptibility; HIRM: high isothermal remanent magnetization; ARM: anhysteretic remanent magnetization; SIRM: saturated isothermal remanent magnetization. Dark grey shadings show increases in the contribution of fine continental inputs to the estuary during the MWP, as characterized by high magnetic susceptibility (κ_{LF}), high HIRMs, low *S*-ratios (increase in hematite contents) and high ARM/SIRMs. Note that such episodes match with occurrences of clay deposits in core Vk15. In contrast, light grey shadings refer to coarser sandy intervals with low terrestrial inputs (low HIRM/κ_{LF}). Note also the upward pattern of persistent increasing HIRMs (see text for detail). Hematite abs. conc=hematite absolute concentration.

S-ratios are rather stable throughout the core (0.95–0.99), indicating the strong predominance of fine magnetite grains in the sediments. The well-defined decreases in *S*-ratio generally coincide with HIRM increases, thereby ruling out the possibility that lower *S*-ratios may be associated with early diagenesis in the sediments.

ARM/SIRM is commonly used as a proxy for magnetic grain size of ferrimagnetic particles (i.e. magnetite), with higher (lower) values corresponding to finer (coarser) grain sizes. Significant enhancements of ARM/SIRM are recognized in the sedimentary intervals 258–210, 170–140 and 55–0 cm. Mean ARM/SIRM values in the topmost interval range at higher levels (0.03–0.08) than in the lower stages 258–210 and 170–140 cm (0.02–0.06). It is notable that this fluctuation pattern is not clearly expressed in the lithology. Therefore, changes in the magnetic grain size in core Vk15 are presumably independent of facies types, but may instead reveal an increasing contribution of a source of fine (river-borne) magnetic material or fluctuate with the distance from the supplying source(s). Moreover, variations in the magnetic carrier grain size also coincide with fluctuations in *S*-ratios and HIRMs, towards a fining-up of magnetic particles (higher ARM/SIRM). We propose, therefore, that low *S*-ratios, high HIRMs and high ARM/SIRM within Medieval clay intervals $F_{F\ 1}$–$F_{F\ 3}$ (ca. 880–1050 AD; Table 1), but also in the interval 258–210 cm, indicate a strong enhancement of fine detrital inputs in the bay most likely linked with increased discharges of fine sediments from the Vilaine River.

The topmost pattern (55–0 cm) in core Vk15 is unique. All rock magnetic parameters depict a prominent change in the magnetic assemblage towards an increase of fine magnetite grains judging from a significant strengthening of the ratio ARM/SIRM (0.03–0.08) and steadily high *S*-ratios (0.95–0.96). Additionally, higher HIRMs (80–125 mA m^{-1}) suggest an enhanced contribution of high-coercivity minerals in the topmost sediments. Hence rock magnetic parameters offer detailed sedimentological features of unit U4, and document a pronounced shift in environmental conditions within the system during the most recent period by, for instance, a perturbation of hydro- and sedimentary dynamics both in the bay and in the catchment area. The deposition of U4 is probably linked to an increase in river-borne fine sediments on a regional scale, and is partly of anthropogenic origin. It should be regarded as a prograding highstand system tract (Menier et al., 2010).

The occurrence of biomagnetite in sediments is very likely, especially in the lower part of core Vk15 where *S*-ratios most commonly exceed 0.97 (190–255 cm). The precipitation of biogenic magnetite in bottom sediments (detected as *S*-ratio approaches 1) has been documented in various environmental settings, such as in lakes (Demory et al., 2005; Peck and King, 1996), hemipelagic sediments (Stolz et al., 1986) and in coastal sediments (Faivre and Schüler, 2008). Its predominance at depth in the magnetic carrier is strongly suggested within some intervals (170; 187–190; 238; 253; 285–288 cm), where *S*-ratios attain 0.98 or even 0.99 (190 cm) and HIRMs are generally low. It should be stressed, however, that only the highest *S*-ratios reflect the precipitation of biomagnetite in sediments.

6. Discussion

6.1. The late Holocene sedimentary infilling: depositional history

The results show that stratigraphic patterns, revealed by sedimentological and seismic data together with AMS ^{14}C ages,

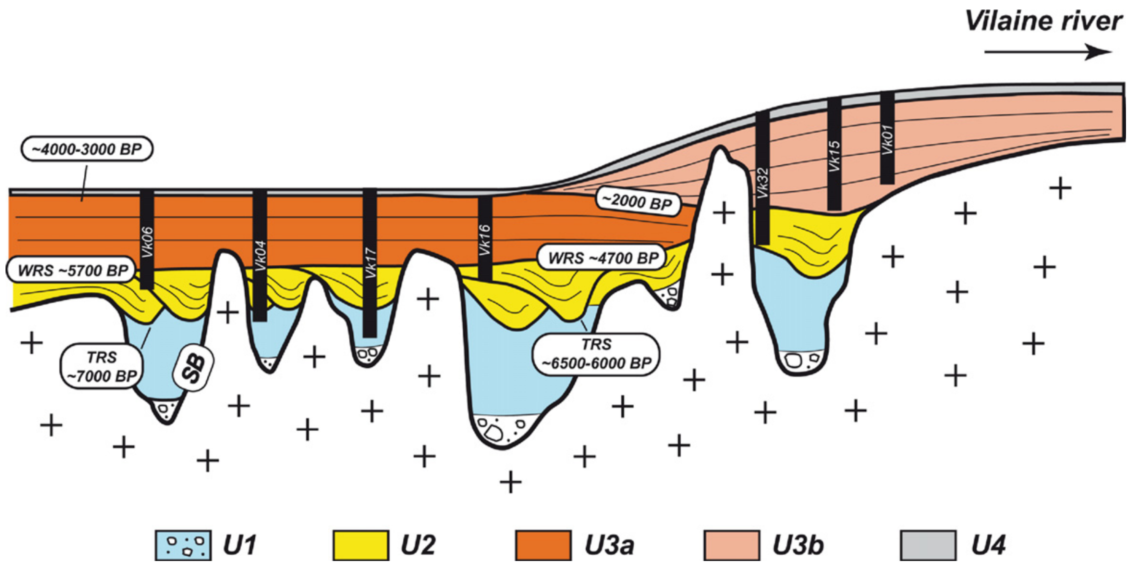

Fig. 11. 2-D reconstruction of the sedimentary infill of the Bay of Vilaine coastal wedge during the last 6000 years (late Holocene), as based on sedimentological, AMS ^{14}C dating and seismic data. This schematic reconstruction depicts the main depositional units and key stratigraphical surfaces (TRS, WRS), including the timing of the marine invasion in the different parts of the system (see text for detail). Note that the vertical scale is exaggerated compared to the horizontal axis. SB: surface boundary; TRS: tidal-ravinement surface: WRS: wave-ravinement surface. U3a corresponds to the mid- to late-Holocene period (6000–3000 BP) and is recorded solely in the external part of the Bay of Vilaine while U3b refers to the late-Holocene component (i.e. the last 2000 years) that is best recorded in most internal sedimentary archives.

correlate well throughout the inner Bay of Vilaine during the last six millennia both in (i) internal records (Vk01, Vk15, Vk32), (ii) external records (Vk06, Vk04, Vk17, Vk16) and (iii) between them. The scheme proposed in Fig. 11 summarizes the sedimentary infill of the estuary during the mid- to late-part of the Holocene transgression, with emphasis on the time lag of the marine flooding between the proximal and the more distal settings. Moreover, the drillhole C5 retrieved in the outermost Bay of Vilaine (Fig. 1) indicates that the marine ravinement and flooding of the outer entrances of the Bay of Vilaine occurred at 8378 $\pm$ 476 cal. BP (Bouysse et al., 1974 in Proust et al., 2001) and is thus coeval with the beginning of the Holocene.

Prior to the marine transgression of the inner Bay of Vilaine, the sedimentary infill in the incised valley network consisted of the deposition of an aggradational rich-organic facies which had accumulated on a sheltered mudflat with persistent continental influences (U1). The top of these deposits is preserved at the base of the outer estuarine cores (Vk04, Vk17). The installation of an estuarine channel belt (unit U2) above a tidal-ravinement surface which eroded U1 indicates an increase of tidal energy in the bay as the sea level rose. Based on the available dating, U2 is older than ca. 5700 cal. BP in core Vk06 (Figs. 8 and 11). Clearly, the aggradation of this estuarine channel belt is coeval with the slowing down of the transgression at about 7000–6500 BP.

U2 is truncated by a wave ravinement surface (WRS) overlain by offshore clays containing storm deposits (U3). This succession documents the definitive drowning of the inner Bay of Vilaine, the opening of the system to the ocean and a much higher influence of offshore swells on sediment deposition and preservation in the estuary. Hence, the top of this unit corresponds to the maximum flooding surface. Dating of the WRS, and therefore of the final marine flooding in innermost areas, varies within the bay depending on their proximity to the shore. We show that a time lag of about 1000 years was involved at the beginning of the deposition of U3 between cores Vk06 (ca. 5700 cal. BP) and Vk16 (ca. 4700 cal. BP) (Fig. 8). This delay in the marine invasion is consistent with the difference in altitude between the coring sites Vk06 and Vk16 (about 3 m) when a 3 mm/year rise at the beginning of the late Holocene is considered (Lambeck, 1997). Hence, it emphasizes the role of the bedrock morphology on the timing of the marine inundation and sediment infilling, as previously demonstrated in Menier et al. (2006, 2010).

Dating at cores Vk06 and Vk16 has shown that U3 offshore clays were deposited during a trend of high but decelerating sea-level between 6000 and 3000 cal. BP, within a context of an increasing frequency of storm deposits towards 3000 cal. BP, i.e. the late Holocene period. The impact of increased storminess on north Atlantic coastal systems has been widely recognized around 3000 years BP. This interval encompasses the recurrent erosion and dismantling of coastal dune and barrier systems as revealed by sedimentary successions which document the drowning of back-barrier lagoons by marine invasions (Baeteman et al., 2002; Billeaud et al., 2009; Clavé, 2001; Long et al., 1996; Meurisse et al., 2005; Régnauld et al., 1996; Spencer et al., 1998). In the Seine estuary, increased storminess is evidenced by the preservation of high-energy events (coarse shelly intervals), which disrupt the sedimentary successions in several occasions (Sorrel et al., 2009).

The final infilling stage within the Bay of Vilaine is preserved as the unit U4. It consists of a very muddy interval which has been intensively colonized by the crustacean *Haploops* sp. U4 strongly contrasts with the underlying offshore clays. No dates are available for this uppermost unit, but we assume that it documents the modern increase of fine sediments entering the bay, linked to the intensification of anthropogenic activities (shellfish farms, dredging, land reclamation) (Menier et al., 2010).

Dating of the upper sediments (U3) from cores Vk16 and Vk06 infer that sedimentation diminished considerably after 3000 BP. The correlation with the other external cores Vk04 and Vk17 further strengthens this trend. These upper coarse and shelly successions most probably correspond to a period of condensed sedimentation. In contrast, the U3 successions from proximal cores (Vk01, Vk15) provide a detailed record of depositional conditions spanning the late Holocene (including the Medieval Warm Period), but do not yield any evidence of sediment preservation older than 2000 BP. We therefore assume that time discrepancies in the preservation of late Holocene sediments between internal and external areas stem from the difference in core top altitudes between proximal (e.g. Vk01, Vk15) and more distal cores (Vk16, Vk17, Vk04, Vk06) (Fig. 8). As regards to this pattern, the mid- to late-Holocene period (6000–3000 BP) is recorded solely in the external part of the inner Bay of Vilaine, whilst the late Holocene component (i.e. the last 2000 years) is best recorded in most internal sedimentary archives. It is also noteworthy that the late Holocene depositional history is not preserved in the external part of the system.

Judging from most proximal cores Vk01 and Vk15, an increase in the contribution of riverine inputs occurred during the MWP (Figs. 7, 9, 10). Hence it raises the question as to how, and to what extent, climate variability and/or human activities influenced sediment deposition and preservation in the Bay of Vilaine during the past millennium.

6.2. A widespread environnemental change during medieval times: climatic change or anthropogenic influence?

The most relevant evidence of a prominent environmental change during the last 1000 years comes from the preservation of well-correlated events in sedimentary successions from the inner part of the Bay of Vilaine, close to the present-day river mouth. Judging from sedimentological and rock magnetic parameters (κ_{LF}, HIRM, ARM/SIRM), the proximal records Vk15 and Vk01 contain two- to three-clay intervals ($F_{F\ 1-2/3}$; Fig. 9), most probably dating back to the Medieval Warm Period, which are interpreted as estuarine flood deposits linked to increases discharges of fine terrestrial inputs transported by the Vilaine river to the estuary. Yet, the source of the fine muddy sediments deposited during these intervals has not been assessed. However, both the evidence for increased detrital inputs of anti-ferromagnetic minerals (hematite as inferred from high HIRMs; see Fig. 10) and the unique and restricted occurrence of facies F_F in cores located near to the river mouth supports the hypothesis of a primary continental origin for these medieval clay deposits. This is also concomitant with higher ARM/SIRMs, which infer a sharp decrease in the magnetic grain size. The influence of marine-borne fine sediments should, nevertheless, not be dismissed but the brownish colour of F_F muds indicates rather a continental than a marine origin. In general, Holocene marine clays encountered in the cores (F_D in U3; F_E in U2 for instance; see Fig. 7) are grey to green-greyish, and most usually contain silts and shell fragments, which are totally absent in clays $F_{F\ 1-2/3}$. Hence the hematite-rich fine terrigenous material of facies F_F most likely originate from the catchment area of the Vilaine River, which delivered increased terrestrial inputs at times of strong fluvial influences in the estuary during ca. 880–1050 AD. Coevally, the preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal. This is in accordance with the results of Meeker and Mayewski (2002) based on the GISP2 core Na series from Greenland, who reported that the MWP was marked by the predominance of the low (negative) phase of the NAO on multidecadal timescales. Proctor et al. (2000) also reported a drastic decline of the NAO during the 11th century ca. (1030–1080 AD). Hence, at times of estuarine flood deposition, climatic conditions were probably maximal in south Brittany, with decreased winter storminess and reduced coastal hydrodynamics. It is noteworthy that the inner part of the Bay of Vilaine is naturally protected from the action of south-westerly swells by the shallow bottom and the topographic sill extending from the Houat-Hoëdic Islands to the Quiberon Peninsula (Fig. 1). Lower wave dynamics in the Bay of Vilaine thus involves a waning of sediment reworking at subtidal depths and, as a consequence, the preservation of sedimentary successions was maximal in the estuary during ca. 880–1050 AD. This interpretation is consistent with previous studies where medieval clay deposits in the Seine estuary were assumed to reflect milder MWP climatic conditions (Sorrel et al., 2009) during a period of reduced sediment remobilization in the estuary.

Such pronounced changes in environmental conditions could not have been confined to northwestern France and, therefore, similar patterns should be found elsewhere along the Atlantic coast. The preservation of fine-grained sediments during the Middle Ages has indeed been reported in other coastal settings. A drastic decrease in hydrodynamics together with an enhanced supply of fine-grained material marked by the occurrence of a widespread mud-drape has been identified in the area of the Pertuis Breton and the macrotidal bay of Marennes-Oléron (Ré-Oléron Island area, see Fig. 1) (Billeaud et al., 2005; Chaumillon et al., 2004). The base of these mud deposits is dated to the beginning (1230 ± 30 cal. BP) and the end of the MWP (850 ± 40 cal. BP). Because an abrupt change in sea-level cannot account solely for this environmental change (Lambeck, 1997), these authors assumed that MWP climatic variations combined with human interferences are likely responsible for the rapid infill and the deposition of muddier sediments in the Marennes-Oléron Bay over the last 1000 years. In this study, the impact of anthropogenic activities on the development of this mud-drape on a regional scale is also considered with serious caution. The MWP indeed corresponds to a period of accelerated land use development – agriculture, deforestation – in western Europe (Barbier et al., 2002; Freitas et al., 2002; Chaumillon et al., 2004; Lesueur et al., 1996, 2002). Dearing et al. (2001) also evidenced that soil erosion induced by human land-use in the catchment area of the lake d'Annecy is well reflected in magnetic mineral data covering the last 1000 years. The evidence for the preservation of a predominant fine-grained sedimentation between south Brittany and the Ré-Oléron Island area also show similarities with sedimentary successions from the Gironde mud fields on the Aquitaine continental shelf, where an important increase in suspended matter originating from the Gironde estuary was recorded after 1100 years BP (Lesueur and Tastet, 1994; Lesueur et al., 1996). Further south, on the Iberian coast, a greater influence of fluvial influence was reported at ca. 1000 ^{14}C years BP (Goy et al., 1996), whereas an increased marine influence and accelerated coastal progradation occurred during the Little Ice Age (LIA). Therefore, all sedimentary records from the French and Spanish Atlantic coasts agree on the preservation of an intensified fluvial contribution in estuarine sedimentary systems during the past 1000 years. More particularly, the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development. Thus, in the Bay of Vilaine, the two–three layers found in medieval sedimentary successions (Figs. 9 and 10) are assumed to reflect a time of increased sediment delivery, partly due to human activities, rather than single river flood events of unequivocally climatic origin. Nevertheless, milder climatic conditions during ca. 880–1050 AD may have favoured the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and thus reduced coastal hydrodynamics at subtidal depths.

Judging from the sedimentary patterns in cores Vk15 and Vk01, the upper successions in U3 mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals (Vk15; Figs. 7 and 9). This shift most probably documents the transition from the MWP to the Little Ice Age (LIA) and the prevalence of marine hydrodynamics on fluvial influences. In Northern Europe, the LIA is associated with changes in the general circulation pattern, with an intensification of atmospheric contrasts causing increased storminess both in the marine and continental ecosystems (Lamb 1979; Clarke and Rendell, 2009). This increase in storminess has indeed been associated to the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard et al., 2007; Clemmensen et al., 2007, 2009; Matthews and Briffa, 2005), France (Meurisse et al., 2005), Netherlands (Jelgersma et al., 1995) and Scotland (Dawson et al., 2004). The impact of intensified LIA storm activity on coastal sedimentary patterns has also been reported elsewhere, notably along the coasts of the English Channel. In the Seine estuary, the continuity of the sedimentary record was significantly affected during the LIA, suggesting a stronger impact of marine hydrodynamics on sediment preservation (Sorrel et al., 2009). In the present study, however, the lack of chronological data in topmost sediments inhibits further comparison with other LIA coastal records.

In a wider perspective it is of interest to denote that the deposition of the estuarine flood deposits in the innermost Bay of Vilaine occurred during a period of widespread human activities and prominent climatic change, the Medieval Warm Period (800–1100 AD), which is recognized as the warmest period of the last two millennia (Mayewski et al., 2004; Moberg et al., 2005). Hence, within a context of global warming and sea-level rise, this could indicate a link between the NAO atmospheric forcing on marine hydrodynamics, human adaptations to changing climate conditions, and the pattern of sedimentary successions preserved in coastal depositional systems.

7. Summary and conclusions

Our multi-pronged approach conducted on sediment cores from the macrotidal Bay of Vilaine (NW France) demonstrates that the sedimentary infill of an incised (ria-type) valley have embedded within it the records of human land-use activities and climatic changes which coincided with the Medieval Warm Period (MWP). The combination of sedimentological, rock magnetism, AMS ^{14}C and high-resolution seismic data were used to document the infilling history of the inner bay and its temporal relationships with the Holocene transgression in south Brittany. The late Holocene depositional history, as reconstructed from the correlation of seven cores collected along a proximal—distal transect within the inner bay (Fig. 11), allow the evaluation and the correlation of coastal sedimentary dynamics related to sea-level change, past regional storminess and anthropogenic activities in the catchment area.

The following conclusions can be stated:

(1) The Holocene sediment wedge of the inner Bay of Vilaine contains four main infilling units: U1 consisting in aggrading ria-type sediments which accumulated within a sheltered mudflat; U2 composed of channel bottom and tidal-like sediments indicative of the development of an estuarine channel belt overlying a tidal-ravinement surface (TRS) dated to about 7000–6500 BP; U3 consisting in offshore clays with intercalated storm deposits, resting on a flat wave ravinement surface (WRS); U4 composed of organic-rich muds intensively colonized by the crustaceans *Haploops* sp. It is assumed that this uppermost unit, developed only in most proximal settings, covers the last decades and documents the recent increased amount of fine sediments introduced into the bay with to the intensification of anthropogenic activities;

(2) Due to (i) the slowing-down of the sea-level rise during the late Holocene and (ii) the highly irregular bedrock morphology with steep slopes and several topographic highs, the Holocene marine invasion of the inner Bay of Vilaine was stepwise. Our AMS ^{14}C data demonstrate that a time lag of about 1000 years is inferred from the sedimentary record of the WRS between the external core Vk06 (ca. 5700 cal. BP) and the more proximal core Vk16 (ca. 4700 cal. BP) (Fig. 8);

(3) Core to core correlation between external records (Vk06, Vk04, Vk17, Vk16) outlines a higher frequency of storm deposits during 3000–4000 BP, shortly before sedimentation rates drastically decline (after 3000 cal. BP). Hence uppermost deposits correspond to a condensed sedimentation in the external part of the inner Bay of Vilaine. In contrast, more proximal archives (Vk15, Vk01) offer a detailed and extended record of the estuarine sedimentary infill during the last 2000 years, including the MWP and the LIA.

In addition, the sedimentological and rock magnetic data link the preservation of the medieval clay intervals in most proximal sedimentary successions with prominent increases in continental inputs between 880 and 1050 AD. Hence we contend that the clay intervals date back to the MWP, and correspond to estuarine flood deposits linked with a significant increase in sediment delivery from the Vilaine River. The deposition of the clay intervals are likely related to an accelerated land-use development and reclamation in the catchment area, which caused increased soil erosion and enhanced suspended matter transport to the shelf. This scenario for the Middle ages may thus sheds light on the genuine impact of anthropogenic activities during a period of widely recognized climate warming. Just to pinpoint one event: large forest cleanings were initiated by the Cistercians between the 10th and the 12th centuries. This should have resulted in the remobilization of considerable amounts of terrestrial material in the hinterland. Further studies should tackle the detection of anthropogenic activities in sedimentary archives during historical times and, according to the results presented here, rock magnetic data are likely to be most promising.

Besides, the preservation of medieval estuarine flood deposits implies that sediment reworking by marine dynamics was considerably reduced between 880 and 1050 AD. Hence climatic conditions were probably mild enough to prevent coastal erosion in northwestern France, i.e. a climate regime resembling that of the (low) negative phase of the NAO on multidecadal timescales. Concurrently, the increased influence of marine hydrodynamics after the medieval period compares well with other records reporting enhanced storminess in northern Europe during the LIA. An increased frequency of storm layers was also recorded towards 3000 BP in the Bay of Vilaine, which is fairly consistent with other records of pronounced higher cyclonic activity in north Atlantic costal systems at that time. Therefore, the results provide evidence that, at least during the past millennium, the NAO likely exerted an influence on the preservation of sedimentary successions deposited in the coastal wedge of the Bay of Vilaine. This is of strong relevance, because changes resulting from variations in the atmospheric circulation have substantial implications on coastal morphology, and to date climatic models seem still unable to forecast at a regional scale (Pirazzoli, 2000; Pirazzoli et al., 2004; Régnauld et al., 2004). Hence it challenges our urgent need to predict the variability of the NAO at the sub-decadal scale, and its impact on the evolution of open coasts subjected to flooding by surges. On-going research on past coastal sedimentary archives should therefore proceed in developing high-resolution chronologies and key climatic proxies in sediments, which should help to explore the decadal to sub-decadal fingerprint of NAO variability on the short-term evolution of past coastal environments. In this regard, the climatic optimum of the Middle Ages, which is the most recent Holocene equivalent of a phase of climatic warming in northern Europe accompanied by prominent societal reorganizations, offers the most rewarding interval to study.

Acknowledgments

We thank two anonymous reviewers for their constructive comments. This study was funded in the framework of the Institut d'Aménagement de la Vilaine and the University of south Brittany (coordinator D. Menier) research projects. P. Sorrel benefited a CNRS post-doctoral grant. We acknowledge Tomas Goslar (Poznán Radiocarbon Laboratory, Poland) for high-quality AMS ^{14}C data. We greatly thank Lionel Allano, the captain of the R/V Sepiola (University of Rennes 1, France), as well as the crew of the R/V Thalia (Ifremer/Genavir).

References

Aagaard, T., Orford, J., Murray, A.S., 2007. Environmental controls on coastal dune formation; Skallingen Spit, Denmark. Geomorphology 83, 29–47.
Allen, G.P., Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill : the Gironde estuary, France. Journal of Sedimentary Petrology 63 (3), 378–391.
Allen, G.P., Posamentier, H.W., 1994. Transgressive facies and sequence architecture in mixed tide and wave-dominated incised valleys: example from the Gironde estuary, France. In: Dalrymple, R., Zaitlin, B., Boyd, R. (Eds.), Incised Valley Systems: Origin and Sedimentary Sequences. SEPM Special Publication 51, pp. 225–240.
Andreieff, P., Bouysse, P., Horn, R., L'Homer, A., 1968. Données récentes sur l'Eocène au large de la Bretagne méridionale. Comptes rendus sommaires des séances de la Société Géologique de France 5, 151–162.
Baeteman, C., Scott, D.B., van Strydonck, M., 2002. Changes in coastal zone processes at a high sea-level stand: a late Holocene example from Belgium. Journal of Quaternary Science 17, 547–559.
Baltzer, A., Tessier, B., Nouzé, H., Bates, R., Moore, C., Menier, D., 2005. Seistec seismic profiles: a tool to differentiate gas signatures. Marine Geophysical Researches 26, 235–245.
Barbaroux, L., Blondeau, A., Margerel, J.P., 1971. Présence d'Yprésien fossilifère sur le plateau continental à l'ouest du plateau du four. Comptes Rendus de l'Académie des Sciences de Paris 273D, 12–15.
Barbaroux, L., Gallene, B., 1973. Répartition des minéraux argileux dans les sédiments récents de la Loire et du plateau continental. Comptes Rendus de l'Académie des Sciences de Paris 277D, 1609–1612.
Barbier, B., Visset, L., Burnouf, J., 2002. Une source pollinique et son exploitation. A propos de la tourbière de Glatinié (Mayenne). Histoires et Sociétés Rurales 18, 137–158.
Berner, R.A., 1980. Early Diagenesis—A Theoretical Approach. Princeton University Press, Oxford, United Kingdom.
Bertin, X., Chaumillon, E., 2005. New insights in shallow gas generation from very high resolution seismic and bathymetric surveys in the Marennes-Oleron Bay, France. Marine Geophysical Researches 26, 225–233.
Billeaud, I., Chaumillon, E., Weber, N., 2005. Evidence of a major environmental change recorded in a macrotidal bay (Marennes-Oléron Bay, France) by correlation between VHR seismic profiles and cores. Geo-marine Letters 25, 1–10.
Billeaud, I., Tessier, B., Lesueur, P., 2009. Impact of late Holocene rapid climate changes as recorded in a macrotidal coastal sediment wedge (Mont-Saint-Michel Bay, France). Geology 37 (11), 1031–1034.
Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Science 278, 1257–1266.
Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2136.
Bouaouina, F., 2006. Dynamique récente de remplissage de la Baie de Vilaine: corrélation sismique très haute résolution et carottes. Mémoires de Master 2 Recherche, Université de Caen, France, 36 pp.
Bouysse, P., Vanney, J.R., 1966. La baie de la Vilaine: Étude sédimentologique et morphologique. Cahiers Océanographiques 18 (4), 319–341.
Bouysse, P., Chateauneuf, J.J., Ters, M., 1974. Présence d'Yprésien, niveau transgressif et taux de sédimentation flandriens en baie de la Vilaine. Comptes Rendus de l'Académie des Sciences 279D, 1421–1424.
Carnell, R.E., Senior, C.A., Mitchell, J.F.B., 1996. An assessment of measures of storminess: simulated changes in the northern hemisphere winter due to increasing CO_2. Climate Dynamics 12, 467–476.
Chaumillon, E., Tessier, B., Weber, N., Tesson, M., Bertin, X., 2004. Buried sandbodies within present-day estuaries (Atlantic coast of France) revealed by very high-resolution seismic surveys. Marine Geology 211, 189–214.
Chaumillon, E., Weber, N., 2006a. Spatial variability of modern incised valleys on the French Atlantic coast: comparison between the Charenet and the Lay-Sèvre incised valleys, Incised Valleys in Time and Space. SEPM Special Publication 85, pp. 57–85.
Chaumillon, E., Weber, N., 2006b. Incised valley morphologies and sedimentary infill within the northern Bay of Biscay inner shelf. In: Proceeding of the 10th International Symposium on Oceanography of the Bay of Biscay, Vigo, Galicia Spain, pp. 127–130.
Clarke, M.L., Rendell, H.M., 2009. The impact of North Atlantic storminess on western European coasts: a review. Quaternary International 195, 31–41.
Clavé, B., 2001. Évolution des paléoenvironnements côtiers à l'Holocène: exemple de l'Aquitaine Septentrionale. Ph.D. Thesis, University of Bordeaux, France.
Clemmensen, L.B., Bjørnsen, M., Murray, A., Pedersen, K., 2007. Formation of aeolian dunes on Anholt, Denmark since AD 1560: a record of deforestation and increased storminess. Sedimentary Geology 199, 171–187.
Clemmensen, L.B., Murray, A., Heinemeier, J., de Jong, R., 2009. The evolution of Holocene coastal dune fields, Jutland, Denmark: a record of climate change over the past 5000 years. Geomorphology 105, 303–313.
Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Geology 62, 1130–1146.
Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1994. Incised-valley Systems: Origin and Sedimentary Sequences Society of Economic Paleontologists and Mineralogists. Special Publication 51 391 p.
Dawson, S., Smith, D.E., Jordan, J., Dawson, A.G., 2004. Late Holocene coastal sand movements in the Outer Hebrides, NW Scotland. Marine Geology 210, 281–306.
Dearing, J., Hu, Y.D., Pippa, J., Peter, A., Brauer, A., 2001. Preliminary reconstruction of sediment-source linkages for the past 6000 yr at the Petit Lac d'Annecy, France, based on mineral magnetic data. Journal of Palaeolimnology 25 (2), 245–258.
Demory, F., Oberhänsli, H., Nowaczyk, N., Gottschalk, M., Wirth, R., Naumann, R., 2005. Detrital input and early diagenesis in sediments from Lake Baikal revealed from rock magnetism. Global and Planetary Change 46, 145–166.
Dillon, M., Bleil, U., 2006. Rock magnetic signatures in diagenetically altered sediments from the Niger deep-sea fan. Journal of Geophysical Research, 111, doi:10.1029/2004JB003540.
Dubrulle, C., Jouanneau, J.M., Lesueur, P., Bourillet, J.F., Weber, O., 2007. Nature and rates of fine sedimentation on a mid-shelf: "La Grande Vasière" (Bay of Biscay, France). Continental Shelf Research 27, 2099–2115.
Ellwood, B.B., Crick, R.E., El Hassani, A., Benoist, S.L., Young, R.H., 2000. The magneto-susceptibility event and cyclostratigraphy (MSEC) method applied to marine rocks: Detrital input versus carbonate productivity. Geology 28 (12), 1135–1138.
Emiroglu, S., Rey, D., Petersen, N., 2004. Magnetic properties of sediment in the Ria de Arousa (Spain): dissolution of iron oxides and formation of iron sulphides. Physics and Chemistry of the Earth 29, 947–959.
Faivre, D., Schüler, D., 2008. Magnetotactic bacteria and magnetosomes. ASAP Chemical Review, 10.1021/cr078258w.
Féniès, H., Lericolais, G., 2005. Architecture interne d'une vallée incise sur une côte à forte énergie de houle et de marée (vallée de la Leyre, Côte d'Aquitaine, France). Comptes Rendus Géosciences 337, 1257–1266.
Frederichs, T., Bleil, U., Däumler, K., von Dobeneck, T., Schmidt, A.M., 1999. The magnetic view on the marine paleoenvironment: parameters, techniques and potentials of rock magnetic studies as a key to paleoclimatic and paleoceanograhic changes. In: Fischer, G., Wefer, G. (Eds.), Use of Proxies in Paleoceanography: Examples from the South Atlantic. Springer Verlag, Berlin, pp. 575–579.
Freitas, M.C., Andrade, C., Cruces, A., 2002. The geological record of environmental changes in southwestern Portuguese coastal lagoons since the Lateglacial. Quaternary International 93–94, 161–170.
Garcia-Gil, S., Vilas, F., Garcia-Garcia, A., 2002. Shallow gas features in incised-valley fills (Riá de Vigo, NW Spain): a case study. Continental Shelf Research 22, 2303–2315.
Garming, J.F.L., Bleil, U., Riedinger, N., 2005. Alteration of magnetic mineralogy at the sulfate–methane transition: analysis of sediments from the Argentine continental slope. Physics of the Earth Planetary Interiors 151, 290–308.
Garnaud, S., Lesueur, P., Lesourd, S., Poupinet, N., Brun-Cottan, J.-C., 2002. Caractérisation des variations lithologiques saisonnières des sédiments de la baie de Seine orientales: impact des crues de la Seine (France). Comptes Rendus Géosciences 334, 220–323.
Goy, J.L., Zazo, C., Dabrio, C.J., Lario, J., Borja, F., Sierro, F.J., Flores, J.A., 1996. Global and regional factors controlling changes of coastlines in southern Iberia (Spain) during the Holocene. Quaternary Science Reviews 15, 773–780.
Gouleau, D., 1975. Les premiers stades de la sédimentation sur les vasières littorales atlantiques: rôle de l'immersion. Thèse de l'Université de Nantes, tome I, 241 pp., tome II, 123 pp.
Guillocheau, F., Brault, N., Thomas, E., Barbarand, J., Bonnet, S., Bourquin, S., Estéoule-Choux, J., Guennoc, P., Menier, D., Néraudeau, D., Proust, J.-N., Wyns, R., 2003. Histoire géologique du Massif Armoricain depuis 140 Ma (Crétacé-Actuel). Association des géologues du Bassin de Paris 40 (1), 13–28.
Horn, R., Vanney, J.R., Boillot, G., Bouysse, P., Leclaire, L., 1966. Résultats géologiques d'une prospection sismique par la méthode «boomer » au large

de massif Armoricain méridional. Comptes Rendus de l'Académie des Sciences de Paris 263, 1560–1563.
Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperature and precipitation. Science 269, 676–679.
Hurrell, J.W., van Loon, H., 1997. Decadal variations in climate associated with the North Atlantic Oscillation. Climate Change 36, 301–326.
Hurrell, J.W., Kushnir, Y., Visbeck, M., Ottersen, G., 2003. An overview of the North Atlantic Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M. (Eds.), The North Atlantic Oscillation, Climatic Significance and Environmental Impact, vol. 134. AGU Geophysical Monograph, pp. 1–35.
Hurrell, J.W., Deser, C., 2009. North Atlantic climate variability: the role of the North Atlantic Oscillation. Journal of Marine Systems, 10.1016/j.jmarsys.2008.11.026.
IPCC, 2007. Climate Change 2007: Mitigation. In: Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L. (Eds.), Contribution of Working Group III to the Fourth Assessment Report of the intergovernmental Panel on Climate Change. Cambridge University Press, New York, 851 pp.
Jelgersma, S., Stive, M.J.F., van der Walk, L., 1995. Holocene storm surge signatures in the coastal dunes of the western Netherlands. Marine Geology 125, 95–110.
Jouanneau, J.M., Weber, O., Cremer, M., Castaing, P., 1999. Fine-grained sediment budget on the continental margin of the Bay of Biscay. Deep-sea Research II 46, 2205–2220.
Keim, B.D., Muller, R.A., Stone, G.W., 2004. Spatial and temporal variability of coastal storms in the North Atlantic Basin. Marine Geology 210, 7–15.
Lafond, L.R., 1961. Etude minéralogique des argiles actuelles du basson de la Vilaine. Comptes Rendus de l'Académie des Sciences de Paris 252, 3614–3616.
Lamb, H.H., 1979. Climatic variations and changes in the wind and ocean circulation. Quaternary Research 11, 1–20.
Lambeck, K., 1997. Sea-level change along the French Atlantic and Channel coasts since the time of the Last Glacial Maximum. Palaeogeography, Palaeoclimatology, Palaeoecology 129, 1–22.
Lericolais, G., Berné, S., Féniès, H., 2001. Seaward pinching out and internal stratigraphy of the Gironde incised valley on the shelf (Bay of Biscay). Marine Geology 175, 183–197.
Lesourd, S., 2000. Processus d'envasement d'un estuaire macrotidal: zoom temporel du siècle à l'heure; application à l'estuaire de la Seine. Ph.D. Thesis, University of Caen-Basse-Normandie, France, 280 pp.
Lesueur, P., Tastet, J.P., 1994. Facies, internal structures and sequences of modern-derived muds on the Aquitaine inner shelf, France. Marine Geology 120, 267–290.
Lesueur, P., Tastet, J.P., Marambat, L., 1996. Shelf mud fields formation within historical times: examples from offshore the Gironde estuary, France. Continental Shelf Research 16, 1849–1870.
Lesueur, P., Tastet, J.P., Weber, O., 2002. Origin and morphosedimentary evolution of fine-grained modern continental shelf deposits: the Gironde mud fields (Bay of Biscay, France). Sedimentology 49 (1), 1299–1320.
Long, A.J., Plater, A.J., Waller, M.P., Innes, J.B., 1996. Holocene coastal sedimentation in the Eastern English Channel: new data from the Romney Marsh region, United Kingdom. Marine Geology 136, 97–120.
Lozano, I., Devoy, R.J.N., May, W., Andersen, U., 2004. Storminess and vulnerability along the Atlantic coastlines of Europe: analysis of storm records and of a greenhouse gases induced climate scenario. Marine Geology 210, 205–225.
Maher, B.A., 1988. Magnetic properties of some synthetic sub-micron magnetites. Geophysical Journal 94, 83–96.
Maher, B.A., Dennis, P.F., 2001. Evidence against dust-mediated control of glacial–interglacial changes in atmospheric CO_2. Nature 411, 176–180.
Maroni, C.S., 1997. Détermination automatique de la stratigraphie des fonds marins à l'aide d'un sondeur de sédiments. Unpublished Thesis, UBO University, 262 pp.
Matthews, J.A., Briffa, K.R., 2005. The 'Little Ice Age': re-evaluation of an evolving concept. Geografiska Annaler 87A, 17–36.
Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quaternary Research 62, 243–255.
Meeker, L.D., Mayewski, P.A., 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. The Holocene 12 (3), 257–266.
Menier, D., 2004. Morphologie et remplissage des vallées fossiles sud-armoricaines: apport de la stratigraphie sismique. Doctorat de l'Université de Bretagne Sud, Mémoires Géosciences Rennes 110, 202 pp.
Menier, D., Reynaud, J.Y., Proust, J.N., Guillocheau, F., Guennoc, P., Tessier, B., Bonnet, S., Goubert, E., 2006. Inherited fault control on the drainage pattern and infilling sequences of late glacial incised valleys, SE coast of Brittany, France, Incised Valleys in Time and Space. SEPM Special Publication no. 85, pp. 37–55.
Menier, D., Tessier, B., Proust, J.N., Baltzer, A., Sorrel, P., Traini, C., 2010. The Holocene transgression as recorded by incised-valley infilling in a rocky coast context with low sediment supply (southern Brittany, western France). Bulletin de la Société Géologique de France 181 (2), 115–128.
Meurisse, M., van Vliet-Lanoë, B., Talon, B., Recourt, P., 2005. Complexes dunaires et tourbeux holocènes du littoral du Nord de la France. Comptes Rendus Géosciences 337, 675–684.
Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlén, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433, 613–617.
Peck, J.A., King, J.W., Colman, S.M., Kravchinsky, V.A., 1994. A rock-magnetic record from Lake Baikal, Siberia: evidence for Late Quaternary climate change. Earth and Planetary Science Letters 122, 221–238.
Peck, J.A., King, J.W., 1996. Magnetofossils in the sediments of lake Baikal, Siberia. Earth and Planetary Science Letters 140 (1–4), 159–172.
Perillo, G.M.E., 1995. Geomorphology and sedimentology of estuaries, Developments in Sedimentology 53. Elsevier, Amsterdam.
Pingree, R.D., Le Cann, B., 1989. Celtic and Armorican slope and shelf residual currents. Progress in Oceanography 23, 303–338.
Pinot, J.P., 1974. Le précontinent breton entre Penmarc'h, Belle-Ile et l'escarpement continental. Étude géomorphologique. Ph.D. Thesis, University of Brest, 256 pp.
Pirazzoli, P.A., 2000. Surges, atmospheric pressure and wind change and flood probability on the Atlantic coast of France. Oceanologica Acta 23, 643–661.
Pirazzoli, P.A., Régnauld, H., Lemasson, L., 2004. Changes in storminess and surges in western France during the last century. Marine Geology 210, 307–323.
Proctor, C.J., Baker, A., Barnes, W.L., Gilmour, M.A., 2000. A thousand year speleothem record of North Atlantic climate from Scotland. Climate Dynamics 16, 815–820.
Proust, J.N., 1999. Le domaine côtier péri-armoricain : état ancien, état actuel et prévisions d'évolution pour le 21ème siècle. Projet PRIR COTARMOR, région Bretagne.
Proust, J.N., Menier, D., Guillocheau, F., Guennoc, P., Bonnet, S., Le Corre, C., Rouby, D., 2001. Les vallées fossiles de la Vilaine : nature et évolution du prisme sédimentaire côtier du Pléistocène armoricain. Bulletin de la Société Géologique de France 6, 737–749.
Régnauld, H., Jennings, S., Delaney, C., Lemasson, L., 1996. Holocene sea-level variations and geomorphological response: an example from northern Brittany (France). Quaternary Science Reviews 15, 781–787.
Régnauld, H., Pirrazoli, P.A., Morvan, G., Ruz, M., 2004. Impact of storms and evolution of the coastline in western France. Marine Geology 210, 325–337.
Reineck, H.E., Singh, I.B., 1980. Depositional sedimentary environments. Springer Verlag, New York.
Rodwell, M.J., Powell, D.P., Folland, C.K., 1999. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature 398, 320–323.
Rogers, J.C., 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. Monthly Weather Review 112, 1999–2015.
Service Hydrographique et Océanographique de la Marine (S.H.O.M.), 1993. Courants de marée de la côte ouest de France. Imprimerie de l'EPSHOM, Brest, 42 pp.
Service Hydrographique et Océanographique de la Marine (S.H.O.M.), 1997. Instructions nautiques pour la plaisance, France, Bretagne Sud de la Pointe de Penmarc'h à la Vilaine.
Simpkin, P.G., Davis, L., 1993. For seismic profiling in very shallow water, a novel receiver? Sea Technology 34 21–28.
Snowball, I.F., 1993. Geochemical control of magnetite dissolution in subarctic lake sediments and the implications for environmental magnetism. Journal of Quaternary Science 8 (4), 339–346.
Sorrel, P., Tessier, B., Demory, F., Delsinne, N., Mouazé, D., 2009. Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France). Quaternary Science Reviews 28, 499–516.
Spencer, C.D., Plater, A.J., Long, A.J., 1998. Rapid coastal change during the mid- to late Holocene: the record of barrier estuary sedimentation in the Romney March region, southeast England. The Holocene 8, 143–163.
Stolz, J.F., Chang, S.-B.R., Kirschvink, J.L., 1986. Magnetotactic bacteria and single domain magnetite in hemipelagic sediments. Nature 321, 849–851.
Stuiver, M., Braziunas, T.F., 1993. Sun, ocean, climate and atmospheric $^{14}CO_2$: an evaluation of causal and spectral relationships. The Holocene 3, 289–305.
Stuiver, M., Reimer, P.J., Reimer, R.W., 2005. CALIB 5.0.1. http://calib.org.
Tessier, B., Delsinne, N., Sorrel, P., 2010. Holocene infilling of a tide-dominated estuarine mouth. The example of the macrotidal Seine estuary (NW France). Bulletin de la Société Géologique de France 181 (2), 87–98.
Tessier, C., 2006. Caractérisation et dynamique des turbidités en zone côtière: l'exemple de la région marine Bretagne sud, 428 pp.
Thompson, D.W.J., Lee, S., Baldwin, M.P., 2003. Atmospheric processes governing the Northern Hemisphere Annular Mode/North Atlantic Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M. (Eds.), The North Atlantic Oscillation: Climate Significance and Environmental Impact. Geophysical Monograph Series 134, Washington, DC, pp. 81–112.
Vanney, J.R., 1977. Géomorphologie de la marge continentale sud-armoricaine. S.E.D.E.S. éd., Paris, 473 pp.
Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B., Xoplaki, E., 2001. North Atlantic Oscillation—concept and studies. Survey in Geophysics 22, 321–381.
Wanner, H., Beer, J., Bütikofer, J.B., Crowley, T.J., Cubasch, U., Flückiger, J., Goose, H., Grosjean, M., Joos, F., Kaplan, J.O., Küttel, M., Müller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., Widmann, M., 2008. Mid- to Late Holocene climate change: an overview. Quaternary Science Reviews 27, 1791–1828.

Weber, N., Chaumillon, E., Tesson, M., Garlan, T., 2004. Architecture and morphology of the outer segment of a mixed tide and wave-dominated-incised valley, revealed by HR seismic reflection profiling: the paleo-Charente River France. Marine Geology 207, 17–38.

Williamson, D., Jelinowska, A., Kissel, C., Tucholka, P., Gibert, E., Gasse, F., Massault, M., Taieb, M., Van Campo, E., Wieckowski, K., 1998. Mineral-magnetic properties of erosion/oxidation cycles in tropical maar-lake sediments (Lake Tritrivakely, Madagascar): paleoenvironmental implications. Earth and Planetary Science Letters 155 (3–4), 205–219.

Yamazaki, T., Abdeldayem, A.L., Ikehara, K., 2003. Rock-magnetic changes with reduction diagenesis in Japan Sea sediments and preservation of geomagnetic secular variation in inclination during the last 30,000 years. Earth Planets and Space 55, 327–340.

Zaitlin, B.A., Dalrymple, R.W., Boyd, R., 1994. The stratigraphic organization of incised valley systems associated with relative sea-level change. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), Incised-valley Systems: Origin and Sedimentary Sequences. Society of Economic Paleontologists and Mineralogists. Special Publication 51, pp. 45–60.