Marine Geology 337 (2013) 140–155

Contents lists available at SciVerse ScienceDirect

Marine Geology

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

Transgressive systems tract of a ria-type estuary: The Late Holocene Vilaine River drowned valley (France)

C. Traini [a,*], D. Menier [a,b], J.-N. Proust [c], P. Sorrel [d]

[a] Geoarchitecture EA2219, Géosciences Marine & Géomorphologie Littorale, Université de Bretagne Sud, rue Yves Mainguy, 56017 Vannes cedex, France
[b] Universiti Teknologi PETRONAS Tronoh, Perak, Malaysia
[c] UMR CNRS 6118 Géosciences, Université Européenne de Bretagne, Campus de Beaulieu, 35000 Rennes, France
[d] UMR CNRS 5276 LGL-TPE (Laboratoire de Géologie de Lyon: Terre, Planètes, Environnements), Université Claude Bernard–Lyon 1/ENS Lyon, 27-43 bd du 11 Novembre, 69622 Villeurbanne cedex, France

ARTICLE INFO

Article history:
Received 24 April 2012
Received in revised form 18 February 2013
Accepted 19 February 2013
Available online 4 March 2013

Communicated by J.T. Wells

Keywords:
Holocene
sea-level
sedimentary facies
estuary
chirp
Atlantic coast

ABSTRACT

The understanding of control parameters of estuarine-infilling at different scales in time and space is important for near-future projections and better management of these areas facing sea-level change. During the last 20 years, the stratigraphy of late Quaternary estuaries has been extensively investigated leading to the development of depositional models which describe the sedimentary facies distribution according to changes in sea level, tidal range and wave activity but few of them describe in detail the influence of the estuarine geomorphology. On the Atlantic coast, recent studies provide a detailed understanding of the sedimentary infill succession of incised valleys during the late Holocene transgression with recent emphasis on the macrotidal bay of the Vilaine River in South Brittany. The latter has shown the importance of the inherited morphology in controlling the preservation of the sedimentary deposits. However, until now, there has been little information available on the geometry of the underlying bedrock of the estuary and its immediate approaches including the Holocene history of the most proximal part of the Vilaine River estuary. The recent acquisition of very-high resolution seismic reflection (Chirp) and sediment core data in the Vilaine Estuary provides the opportunity to address several of these issues leading to the identification of the controlling factors that played a role in the sedimentary filling of the estuary.

The estuary of the Vilaine River is one of the most sheltered estuaries of the Atlantic coast and thus shows an excellent record of the successive transgressive phases since the last glacial period. The valley of this ria-type estuary is incised in the Hercynian magmatic and metamorphic rocks of the Armorican Massif along the striking branches of the South Armorican Shear Zone and filled with well-stratified sediments.

The study of the morphology of the substratum in the estuary reveals narrow paleovalleys (1 km wide) with a maximum depth of 20 m. The shapes and dimensions of these paleovalleys are comparable with those observed upstream in the present-day Vilaine River valley. Facies analysis of seismic and sedimentary data, complemented by 21 AMS radiocarbon age dating, enables the reconstruction of the infilling of the estuarine valley. The valley is filled by Pleistocene to early Holocene alluvial, coarse-grained, pebbly sands overlain by mid- to late Holocene marine sands, silts and muds. From 10,000 to 5000 cal. BP, the marine transgression shows a rapid initial phase of transgression followed by a progressive slowing down which can be recognised over more than 90 km in an upstream direction. The rapid transgression developed homogeneously over the entire length of the estuary with a widespread expression of tidal currents (tide-dominated estuary). The slow phase of the transgression gives rise to a differentiated expression of the hydrodynamic factors according to the geomorphological setting. The sedimentary deposits of the innermost and narrow part of the estuary reflect a strong control of tidal and river currents when the influence of tidal currents increases at the expense of fluvial control in a downstream direction. The sedimentary filling of the outer reaches of estuary shows a strong influence of tidal currents modulated by changes in sea level where, from 5700 to 3000 cal. BP, the progressive decrease in accommodation space promotes the expression of wave action (wave-dominated estuary). Finally, from 5000 years BP to present day, the stabilisation of sea level gives birth to scour and lag sedimentary morphologies (scour and lag estuary). The sedimentary record appears thus strongly marked by the Holocene transgression and the geomorphological setting where hydrodynamic

* Corresponding author at: Institut für Geowissenschaften, Exzellenzcluster "Ozean der Zukunft" JRG Meeresspiegelanstieg und Küstenerosion, Christian Albrechts Universität zu Kiel, Otto-Hahn-Platz 1, 24118 Kiel, Germany. Tel.: +49 431 880 5046.
E-mail addresses: ct@gpi.uni-kiel.de (C. Traini), David.Menier@univ-ubs.fr (D. Menier), jean-noel.proust@univ-rennes1.fr (J.-N. Proust), philippe.sorrel@univ-lyon1.fr (P. Sorrel).

http://dx.doi.org/10.1016/j.margeo.2013.02.005

parameters superimposed on the geomorphological and eustatic contexts expressed in different ways in time and space govern the evolution of the estuarine system.

1. Introduction

Sea-level changes strongly controlled the evolution of coastal environments in northwestern Europe during the late Quaternary. The rapid sea-level rise of the beginning of the Holocene resulted in the flooding of the downstream portion of incised valleys, and the slowing down of the transgression around 7500 years BP led to the building of estuary systems (Nichols and Biggs, 1985).

During the last 20 years, the stratigraphy of late Quaternary coastal sedimentary systems has been extensively investigated (Swift et al., 1991; Allen and Posamentier, 1993, 1994; Dalrymple et al., 1994; Thomas and Anderson, 1994; Zaitlin, 1994). Models were developed according to the shape of the valley, the tidal range and the wave activity (Boyd et al., 2006). Such models show how these three parameters are decisive in controlling sedimentary facies distribution within three system tracts, which are related to the sea-level evolution.

On the Atlantic coast, recent studies provide a detailed understanding of the sedimentary infill succession of incised valleys during the late Holocene transgression (Lericolais et al., 2001; Proust et al., 2001; Menier, 2004; Weber, 2004; Fénies and Lericolais, 2005; Chaumillon and Weber, 2006; Chaumillon et al., 2006; Menier et al., 2006; Chaumillon et al., 2008; Thinon et al., 2008; Menier et al., 2010; Proust et al., 2010), with recent emphasis on the macrotidal bay of the Vilaine River in South Brittany (Proust et al., 2001; Menier, 2004; Menier et al., 2006, 2010; Sorrel et al., 2010). This Vilaine River estuary occupies a very particular position facing a 200 km wide, passive margin continental shelf (Fig. 1A) affected by a meso- to macro-tidal range. The Vilaine River estuary is the most sheltered estuary of the French Atlantic coast. It is located at the back of the Vilaine Bay bounded by the Quiberon peninsula, the islands of Houat and Hoëdic and the Croisic peninsula (Fig. 1B). This sheltered position preserved a unique and complete sedimentary record of the last marine transgression.

However, while the Holocene sedimentary infill of the Vilaine Bay and the estuary is relatively well documented (Sorrel et al., 2010) we still lack information about the depositional history in the most proximal estuarine part of the system. In particular, the relationships between sedimentary successions preserved in the bay, in the innermost part of the estuary and in the fluvial domain are still poorly understood. This is however of crucial interest for a detailed understanding of the development of the marine flooding of an incised valley within a meso-macrotidal system, in time and space.

The aim of this study is to describe the infilling of Vilaine River estuary and to position the depositional model with respect to other estuarine systems (e.g., the Gironde estuary, the Charente River, the Loire River) (Allen and Posamentier, 1993; Weber et al., 2004; Chaumillon et al., 2010; Proust et al., 2010); rias from Spain (Méndez and Vilas, 2005; Vis et al., 2008) with similar dimensions, structural and geological settings but subjected to stronger wave activity and facing a narrower continental shelf; and English Channel estuaries such as the bays of Mont Saint Michel and the Seine estuary, which are both located behind a bay system comparable to the Vilaine River estuary but which are subject to a stronger tidal range (Tessier et al., 2012).

With the acquisition of new very-high resolution (VHR) seismic data (Chirp) and boreholes in the estuary, it is possible to determine the bedrock morphology of the Vilaine River valley, as well as its geometry and sedimentary architecture. A total of 21 AMS age dating results obtained on sediment samples allow us to evaluate the rate of transgression across the estuary. Analyses of sedimentary facies reveal the variable sedimentary expressions of the hydrodynamic parameters as a function of the transgression rate and the geomorphological context.

2. Regional setting

Located in the northwestern part of France (Fig. 1A), the Vilaine River is the largest river of Brittany. The river is 227 km long and its catchment drains one third of the area of Brittany (10,530 km^2) (Carthage database, http://sandre.eaufrance.fr/). The bedrock of the Vilaine Bay consists of Hercynian magmatic and metamorphic rocks, Bartonian limestones and Tertiary alterites (Proust et al., 2001). The two N110-striking branches of the South Armorican Shear Zone (SASZ, trending N110°–N130°) delimit geological and structural heterogeneities in the bedrock (Central-Armorican, Ligerian, and South-Armorican domains) (Jegouzo and Rosello, 1988; Truffert et al., 2001). A third tectonic discontinuity (the Quessoy-Nort-sur-Erdre fault), which strikes N140, is still active and has led to the uplift of the western part of the catchment by 30 m since the beginning of the Pleistocene. Thus, the present drainage network, which began to develop 0.7 to 0.5 My ago (Cromerian) (Bonnet, 1998; Bonnet et al., 2000), is seen to cut across many geological and structural heterogeneities.

During the 1960s and 1970s, pioneering work was undertaken to map the currently submerged incised valleys in the Vilaine Bay (Bouysse et al., 1966; Horn et al., 1966; Boillot et al., 1971; Delanoë et al., 1972). More recently, high-resolution (HR) and very-high resolution (VHR) seismic data have been collected (Bingolaine survey) (Menier et al., 2002), with the aim at documenting the morphology and the stratigraphy of the incised valleys in south Brittany (Proust et al., 2001; Menier, 2004; Menier et al., 2006, 2010; Sorrel et al., 2010; Menier et al., 2011).

Taken together, these data show that the valleys are parallel or perpendicular to the coast, thus reflecting both Cadomian and Hercynian fault trends and lithological contrasts. The valleys are 200 to 4000 m wide and display a range of cross-sectional shapes (see Menier, 2004; Menier et al., 2006).

The valley morphology has been recognised as determining the expression of the sedimentary fill of the Vilaine Bay (Menier, 2004; Menier et al., 2006). According to Proust et al. (2001), the infill of incised valleys on the south Brittany shelf is mostly composed of two main units: (i) braided channel deposits laid down during the Saalian lowstand (Menier et al., 2006), and (ii) estuarine and meandering channel deposits grading towards offshore clays containing storm layers. In the central part of the Vilaine Bay, the basal part of the clay deposits has been dated at 8110 ± 200 years BP (Bouysse et al., 1974) (Core C5, see map Fig. 7 for location).

3. Material and methods

3.1. Chirp seismic reflection data

To characterise the bedrock morphology and the sediment fill architecture of the Vilaine River estuary (Figs. 3 and 4), a seismic reflection survey (Proust2008-Vilaine) was undertaken onboard the RV Haliotis using a Chirp at a speed of approximately 5 knots. The Chirp was mounted on the hull of the Research Vessel, which runs with a draught of 0.8 m. The Chirp was operated with a 1.7–5.5 kHz pulse bandwidth, enabling a vertical resolution of up to 20 cm. The shot frequency was set at two pulses per second with impulsions of 50 ms at 190 dB. We acquired 165 km of high-resolution seismic profiles, logged digitally in “segy” format using the software SUBOP (IFREMER). The seismic profiles have been reprocessed using the freeware “Kogeo 2.7”. Seismic wave propagation in sediment was based on a sound velocity of 1500 m s^{-1} to convert travel time to depth. We interpreted the seismic

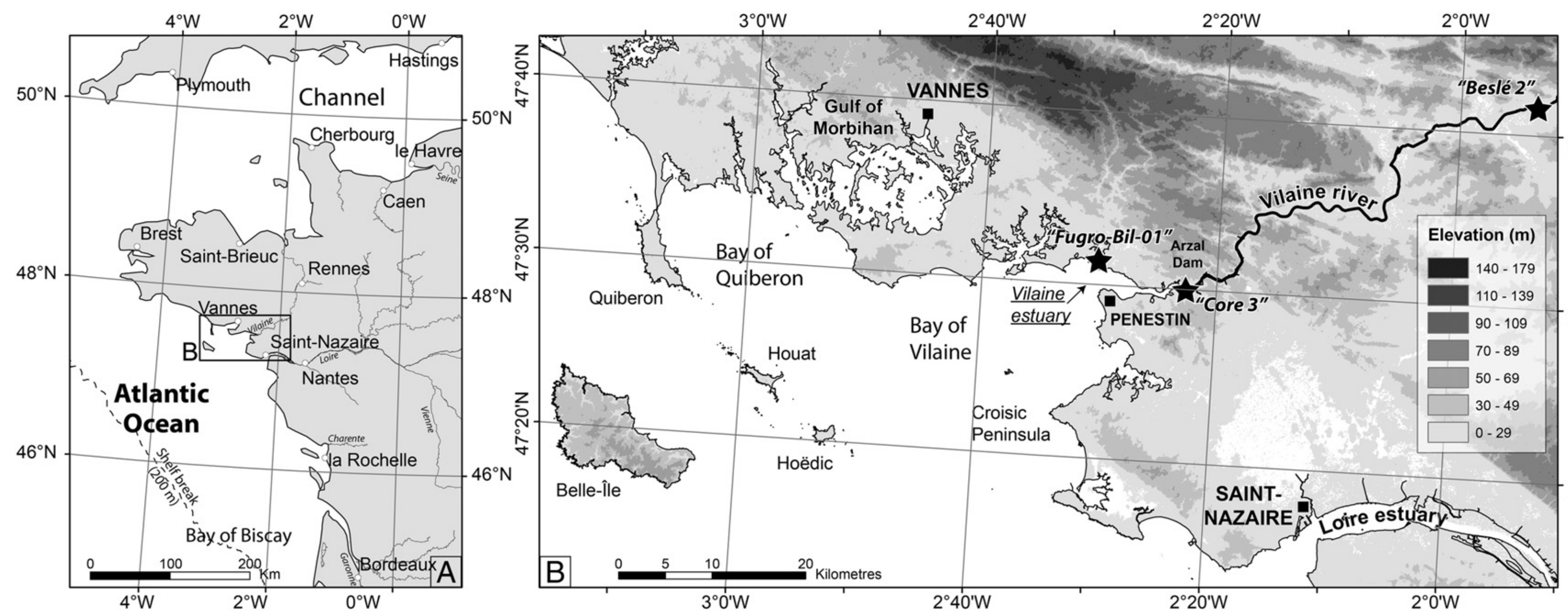

Fig. 1. Location map of the Vilaine Estuary. Stars indicate the position of cores Fugro-Bil-01, Core 3 and Beslé 2.

data according to the principles of Mitchum and Vail (Mitchum et al., 1977; Vail et al., 1977) (Fig. 5).

3.2. Sediment core data

Two onshore sampling campaigns have been carried out by manual and mechanical coring to investigate the nature and the geometry of the deposits (Cr-Bil-01/02, Cr-Pen-02, Cr-Gre-01(1st campaign) and Fugro-Bil-01 (2nd campaign); Fig. 2). This new set of data is complemented by a number of core samples and cross-sections that have already been described and published elsewhere (Vanney, 1965; Bouysse et al., 1974; Morzadec-Kerfourn, 1974; Audren et al., 1975; Penven et al., 2008). The Infoterre database (BRGM) is also available as a source to find descriptions of technical drillings (Table 1). These new data allow correlations with our seismic records acquired offshore, and provide material for ^{14}C dating. Core samples collected during the first campaign have been retrieved using a Russian Peat Corer and are representative of the whole estuary (Fig. 2). Manually extracted cores have been described and photographed (Table 2). These core samples have not been preserved. The core obtained from the second campaign was described and photographed, and then stored in cold room at the University of South Brittany (Table 2).

3.3. AMS dating

The analysis of 21 AMS radiocarbon dating was performed on sediments using either $CaCO_3$ from marine shells (*Cerastoderma edule* and *Scrobicularia plana*) collected in life-up position, or bulk organic carbon when bioclastic material was absent (Table 3). Measurements have been performed at the Erlangen Radiocarbon Laboratory (Germany) and at the Beta Analytic laboratory in Miami (USA). Absolute dates have been calibrated using the programme Calib Rev 6.0.1. We used the terrestrial radiocarbon calibration curve "IntCal09" for plant material and organic sediment, and the marine radiocarbon calibration curve "Marine09" for marine shell samples (Reimer et al., 2009). These calibrations yield ages with 1 and 2 standard deviations (1 sigma, 68.3% confidence level; 2 sigma, 95.4% confidence level). We assumed a marine reservoir correction of 264 ± 44 years (Marine reservoir correction database: http://intcal.qub.ac.uk/marine/). For each datation, a value of δ^{13}C was obtained and used as proxy to indicate the origin of the organic matter (Polach, 1976; Stuiver and Polach, 1977; Wilson et al., 2005).

3.4. Analysis of scopix images

The entire core Fugro-Bil-01 was imaged using the Scopix Scanner (Migeon et al., 1999; Lofi and Weber, 2001). To optimise the image quality, the sediment thickness was equalized by transferring half-core sedimentary sections into a rectangular steel plate gutter. Images are displayed in grey scale depending on the density of the sediment. Dark grey area represents denser, usually coarser grained sediment, whereas light grey horizons represent lighter and finer grained sediment.

4. Results

4.1. Facies analysis

By combining new chirp data ("Proust2008-Vilaine") with cross-cutting previous boomer data obtained during the "Bingolaine" seismic cruise in 2000 (Menier et al., 2002), we refine the morphology of the estuary valley floor (Fig. 3) and its sediment fill (Fig. 4).

4.1.1. Bedrock morphology

The digital terrain model (DTM) of the Vilaine River valley floor covers 20 km in East–west direction and 7 km from North to South (Fig. 3). The main palaeovalley is 1000 to 2000 m wide cutting down up to 35 m below present day sea level and opening out to the West. Three secondary valleys are identified: two in the Northern and one in southeastern sector of the DTM. The Southern limit of the DTM does not reach the Northern limit of the Artimon valley (Menier et al., 2006). The structure of the valley in the innermost zones of the estuary is masked by acoustic blanking due to the degradation of organic matter in the sediment, which affect the acoustic signal (García-Gil et al., 2002; Baltzer et al., 2005; Bertin and Chaumillon, 2005; Roussel et al., 2009).

4.1.2. Seismic facies descriptions

The analysis of the chirp seismic reflection data in the sediment infilling of the valley shows five main different seismic facies (Figs. 4C and 5.)

The acoustic signal in Fs0 is characterised by chaotic reflectors with very weak continuity, high amplitude and medium frequency (Facies Fs0). The strong reflection at its upper boundary corresponds to the acoustic basement of the paleovalley mapped in the DTM. This seismic facies is overlaid by chaotic to prograding reflectors of medium continuity, with medium to high amplitude and medium frequency (Facies Fs1). Transparent reflectors of poor continuity, with low amplitude and frequency make up the Facies Fs2. Facies Fs3 has an erosive contact with Facies Fs2 displaying two subfacies. The first subfacies (Fs3a) shows aggrading and parallel reflectors, with medium to poor continuity, low amplitude and low frequency. The second subfacies (Fs3b) shows a configuration of parallel to sigmoidal aggrading reflectors. The continuity of these reflectors is good and their amplitude and frequency is medium to high. Fs3 is covered by aggrading parallel reflectors of medium continuity, amplitude and frequency (Facies Fs4a) directly followed by parallel to sigmoidal aggrading reflectors of medium continuity and frequency and high amplitude (Fs4b). We have split here the Facies Fs4 into two differentiated subfacies, though it has previously been documented as a single seismic facies (Menier et al., 2010). The last seismic ensemble shows parallel to sigmoidal aggrading reflectors of poor continuity, with low amplitude and frequency (Facies Fs5).

4.1.3. Sedimentary facies descriptions

Seven sedimentary facies (Fa–Fg) (Figs. 2 and 4A) are recognised in this study. The cores have been collected by using a mechanical driller and a Russian corer along the estuary shoreline.

The coarser facies is composed of rounded quartzite gravels with shell debris (Facies Fa). It is formed of structureless and unsorted deposits laid down generally with a sharp erosive contact at the top of silty-clay or sandy clay material. No bioturbation structures (burrows) have been observed. This facies is present in cores Fugro-Bil-01, Cr-Bil-01/02 and Cr-Pen-02. Repetitive fining-upward units of 3 to 5 cm thick (grading from medium shelly sands to organic clays) are found in core Fugro-Bil-01 (Facies Fb), exclusively, with no erosive surfaces between the different units. Sea grasses or organic-rich material occur at the top of each unit. Homogenous mud intercalated between fine to medium laminated micaceous sand layers characterises the Facies Fc. This facies is usually found above Facies Fe. Laminations are millimetric (Cr-Bil-01/02) to centimetric (Fugro-Bil-01) in scale (in Fc). The Facies Fd occurs only in core Fugro-Bil-01. It consists of silty clays indicative of low- to medium-energy conditions. X-ray imaging reveals the presence of crossed laminations in a 90-cm-thick interval. Another facies is composed of both structureless sands and silty clays with sandy laminae enriched in muscovite (Facies Fe). It contains a mix of well-preserved and broken shells. The two last sedimentary facies (Ff and Fg) are concomitant (except for core *Cr-Gre-01*). The first consists of silty clays with occasional sandy laminae enriched in muscovite (Facies Ff). No bioturbation is observed except in core Fugro-Bil-01 where burrows have been identified. Few shell debris are present in Facies Ff. This facies is immediately followed up by oxidized clays containing organic debris (roots and rhizome structures),

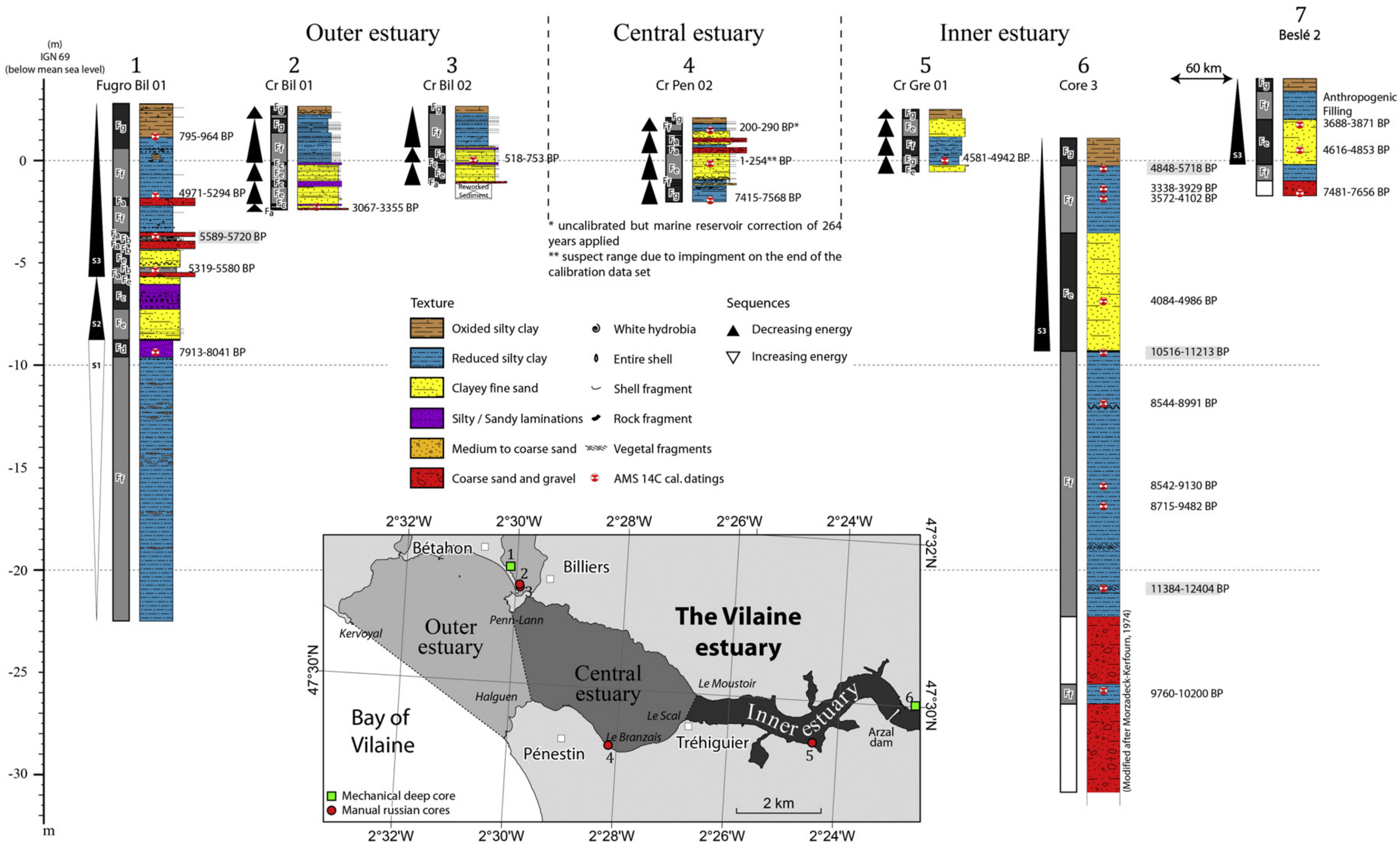

Fig. 2. Core location map displaying the main morphological parts of the Vilaine Estuary. Lithological description of the sedimentary cores. The description of each core indicates the variations in energy, the sedimentary facies and the texture of sediments, and AMS ^{14}C datings. AMS ^{14}C datings are summarised in Table 3. Note location of core "Beslé2" is 60 km to the east of the inset figure.

Table 1
Table summarising previous studies carried out in the Vilaine River incised valley.

Name	Longitude	Latitude	Depth	Elevation (IGN 69)	Bedrock elevation (IGN 69)	Authors/sources
Cores						
04194X0004/S4-1	1°53.49 W	47°41.68 N	11.5 m	4 m	<−2.25 m (not reached)	http://infoterre.brgm.fr[a]
Beslé 2	1°51.20 W	47°42.43 N	5.70 m	4 m	<−1.70 m (not reached)	(Penven et al., 2008)
Massérac 2	1°55.36 W	47°41.05 N	6.25 m	4 m	<−2.25 m (not reached)	(Penven et al., 2008)
Core 18	2°05.38 W	47°37.72 N	20.00 m	5.6 m	≤−12.40 m	(Morzadec-Kerfourn, 1974)
Core 36	2°05.77 W	47°35.88 N	24.00 m	5.6 m	≤−15.40 m	(Morzadec-Kerfourn, 1974)
Core 3	2°22.20 W	47°30.18 N	32.00 m	1.10 m	<−30.00 m (not reached)	(Morzadec-Kerfourn, 1974)
04195X0003/S1	2°05.77 W	47°35.85 N	27.00 m	3.5 m	≤−18.90 m	http://infoterre.brgm.fr[a]
VA 70 n°5 (C5)	2°40.00 W	47°26.30 N	13.50 m	−16.4 m	<−29.90 m (not reached)	(Bouysse et al., 1974)
Cross-sections						
04187X0040/SA3	2°16.71 W	47°34.59 N			≤−27.13 m	http://infoterre.brgm.fr[a]
04187X0002/SA	2°18.52 W	47°31.15 N			≤−30.33 m	http://infoterre.brgm.fr[a]
P1, P2 & P3	2°23.24 W	47°30.01 N			≤−40.00 m	(Audren et al., 1975)
S1–S8	2°26.30 W	47°29.88 N			<−35.00 m (not reached)	DDE[b]

[a] Hyperlink containing the exact address of the exploited document.
[b] DDE = Direction Départementale de l'Equipement.

reflecting a low to very low energy environment (Facies Fg). This facies occurs in the topmost part of all the cores. Shell fragments are rare, but they can occur as pure beds of (i) bleached *Hydrobia sp.* shells or (ii) unidentified shell debris.

4.2. Sedimentary facies successions

This section describes the facies successions in cores *Fugro-Bil-01*, *Cr-Bil-01*, *Cr-Bil-02*, *Cr-PEN-02*, *Cr-Gre-01* collected in this study and also in cores collected earlier: *core 3* (Morzadec-Kerfourn, 1974) and *Beslé 2* (Penven et al., 2008). See Fig. 2 for a summary of core descriptions and Table 3 for the corresponding set of calibrated ages.

The *Fugro-Bil-01* core (Fig. 2) is 25.25 m long and exhibits three sequences of variations in energy levels within the sedimentary successions (S1, S2 and S3), which are related to different hydrodynamic regimes. Sequence S1 begins with an accumulation of more than 12 m of reduced silty clays, including some slightly more oxidized bioturbated layers (Facies Ff). This facies grades up into 90 cm of clayey silts (Facies Fd) dated to about 8000 cal. BP (Table 3).

Sequence S2 is separated from S1 by an erosional surface. At its base, the sequence contains a facies made up of muddy sands including unsorted bioclastic debris (Facies Fe). This facies is overlain by laminated sands and muds, which are occasionally rich in shell debris (Facies Fc). Based on the ^{14}C dating, this interval was dated to 7900–5300 cal. BP.

Sequence 3 overlies sequence 2 with an erosional surface. The basal deposits of the sequence are coarse-grained, consisting of coarse shell debris in a clayey sand matrix (Facies Fa). The upper part of S3, which lies above the uppermost coarse deposits, is made up of bioturbated muds (Facies Ff). This facies evolves into muddy sediments rich in root remains with intercalated layers of fine shell debris (Facies Fg).

Table 2
Identification and coordinates of the cores used for this study. See Fig. 2 for location.

Name	Longitude	Latitude	Length	Elevation (IGN 69)
CR-Gre-01	2°24.61′ W	47°29.50′ N	3.10 m	2.50 m
CR-Pen-01	2°28.20′ W	47°29.40′ N	3.20 m	2.40 m
CR-Pen-02	2°28.20′ W	47°29.40′ N	4.10 m	2.10 m
CR-Bil-01	2°30.30′ W	47°31.25′ N	5.04 m	2.65 m
CR-Bil-02	2°30.00′ W	47°31.20′ N	4.51 m	2.65 m
Fugro-Bil-01	2°30.22′ W	47°31.41′ N	25.50 m	2.80 m

The cores *Cr-Bil01* and *Cr-Bil-02* have been collected behind the most distal part of the sandy spit of Bétahon, near the tidal creek of Billiers (Fig. 2). These cores consist of several layers related to different energy conditions. The base of the two cores is made of coarse sediment with shell debris (Facies Fa). Above it, sediments are made of two Fe and Fc facies successions. The base of the first succession, close to the coarser facies (Fa), is dated to ca. 3250 cal. BP, and the base of the second to ca. 600 cal. BP. These deposits are overlain by finer deposits (Facies Ff and Fg).

Core *Cr-PEN-02* was collected close to Pénestin (Fig. 2). It is 4.10 m long and it contains four energy-related sequences. The base of the first sequence is made of bioturbated fine sediments (Facies Fg) dating back to 7500 cal. BP, which evolve to shelly remains upwards (Facies Fe). The overlying sequence consists of coarse deposits (Facies Fa). The fourth and uppermost sequence displays Facies Ff and Fg.

Core *Cr-Gre-01* is localised in the narrow upstream part of the Vilaine River estuary (Fig. 2). It records four energy-related sequences making up a thickness of 3.10 m. Facies Fe, Ff and Fg are also present. The Facies Fg located at 2.55 m is dated to ca. 4800 cal. BP.

Ten datings have been obtained in *core 3* (Morzadec-Kerfourn, 1974), showing ages ranging between 10,200 and 3500 years BP. All samples contain the marine species of Foraminifera *Jadamina macrescence*. *Core 3* sediment shows a coarse basal unit (8.5 m) overlain by 13 m of fine sediments (ca. 9500 and 8500 years BP). The altered peaty horizon identified at 19 and 22 m core depth is probably indicative of sediment reworking from the riverbank by currents. The argillaceous interval is truncated by an erosional surface overlain by 5.5 m of fine sands (Facies Fe) (AMS ^{14}C dating provides an age of around 11,000 years BP), which are weathered at its base. The fine sand is dated to ca. 4000–5000 years BP. The channel fill sequence is completed by clays (Facies Ff and Fg; 4100–3300 cal. BP).

Beslé 2 core (Penven et al., 2008) (Table 1) is the most upstream borehole. It is located in the flood plain 20 m away from the modern river bank. It is 5.70 m-thick. The "Beslé 2" core shows a succession of facies comparable to that found in core 3 i.e. Facies Ff, Fe, Ff and Fg. These facies lay down sediment consisting of pebbles and sands. The diameter of the pebbles rarely exceeds 5 cm in size. The succession begins with fine sediments (muddy to sandy loams), which we have identified as corresponding to Facies Ff. These deposits are overlain by a 2.20 m-thick succession consisting of silty to sandy loams that we assumed as corresponding to Facies Fe. Organic matter is present. AMS ^{14}C dating have been performed on a wood fragments, and indicate ages of ca. 4775 and 3750 years BP. On top of it appears a 1.34 m-thick layer, which has been recognised to be of anthropogenic origin (Penven et al., 2008). The core is topped by a 0.66 m-thick

Table 3
Summary of ^{14}C AMS dating available for this study. Note that the dates highlighted in grey are assumed to be reworked.

UniCode	Labcode	Material	Date BP	BP error	δ^{13}C	Depth (m)	Calibrated date: 2 Sigma 95.4%	Calibration curve
CR-BIL-01-0500	Erl-11404	Organic sediment	3009	48	−23.4	5	[cal BP 3067: cal BP 3355] 1.	IntCal09
CR-BIL-02-0266	Erl-11445	Shell (*Scrobicularia plana*)	1335	54	−5.9	2.66	[cal BP 518: cal BP 753] 1.	Marine09
CR-PEN-02-0068	Erl-11443	Shell (*Scrobicularia plana*)	559	51	−6.2	0.68	has an invalid age using its selected calibration curve (Valid radiocarbon ages are [448: ?0.46805])	Marine09
CR-PEN-02-0230	Erl-11444	Shell (*Cerastoderma edule*)	762	52	−4.2	2.3	[cal BP 1: cal BP 254] 1.[a]	Marine09
CR-PEN-02-0410	Erl-11405	Organic sediment	6551	52	−24.7	4.1	[cal BP 7415: cal BP 7568] 0.946155	IntCal09
CR-GRE-01-0255	Erl-12130	Shell (*Cerastoderma edule*)	4836	45	−5.6	2.55	[cal BP 4581: cal BP 4942] 1.	Marine09
MORZ-ARZ-**03**-0150	Erl-12804	Organic sediment	4633	185	−27	1.5	[cal BP 4848: cal BP 5718] 1.	IntCal09
MORZ-ARZ-**03**-0250	Erl-12805	Organic sediment	3360	131	−24.9	2.5	[cal BP 3338: cal BP 3929] 0.993215	IntCal09
MORZ-ARZ-**03**-0300	Erl-12806	Organic sediment	3553	108	−24.9	3	[cal BP 3572: cal BP 4102] 0.978674	IntCal09
MORZ-ARZ-**03**-0800	Erl-12807	Organic sediment	4075	171	−25.6	8	[cal BP 4084: cal BP 4986] 0.988064	IntCal09
MORZ-ARZ-**03**-1050	Erl-12808	Organic sediment	9549	135	−25.8	10.5	[cal BP 10516: cal BP 11213] 1.	IntCal09
MORZ-ARZ-**03**-1300	Erl-12675	Organic sediment	7883	78	−25.6	13	[cal BP 8544: cal BP 8991] 1.	IntCal09
MORZ-ARZ-**03**-1700	Erl-12809	Organic sediment	7972	111	−25.5	17	[cal BP 8542: cal BP 9130] 1.	IntCal09
MORZ-ARZ-**03**-1800	Erl-12810	Organic sediment	8186	148	−25.5	18	[cal BP 8715: cal BP 9482] 0.993063	IntCal09
MORZ-ARZ-**03**-2200	Erl-12811	Organic sediment	10207	133	−26.2	22	[cal BP 11384: cal BP 12404] 0.989338	IntCal09
MORZ-ARZ-**03**-2700	Erl-12674	Organic sediment	8895	67	−25.6	27	[cal BP 9760: cal BP 10200] 0.99178	IntCal09
Fugro-Bil-01-0162	Beta-278086	Plant material	990	40	−20.3	1.62	[cal BP 795: cal BP 964] 1	IntCal09
Fugro-Bil-01-0453	Beta-278087	Organic sediment	4470	40	−23.6	4.53	[cal BP 4971: cal BP 5294] 1	IntCal09
Fugro-Bil-01-0652	Beta-278088	Plant material	4910	40	−23	6.52	[cal BP 5589: cal BP 5720] 1	IntCal09
Fugro-Bil-01-0815	Beta-278089	Plant material	4700	40	−16.8	8.15	[cal BP 5319: cal BP 5425] 0.55151	IntCal09
Fugro-Bil-01-1216	Beta-278090	Organic sediment	7140	50	−24.6	12.16	[cal BP 7913: cal BP 8041] 0.849615	IntCal09

[a] Suspect range due to impingement on the end of the calibration data set.
Characters in bold refer to the name of the core used in the text.

organic-rich soil made of brown sediments, which are mainly composed of clayey silts; we have associated it to the Facies Fg.

5. Discussion

5.1. Facies and sequences interpretation

5.1.1. Acoustic facies/units interpretation

Chirp facies correlate with the six units (U0–U5) defined by Menier et al. (2010) based on Boomer data, and interpreted in terms of depositional environments (Fig. 5).

Acoustic signal of Facies Fs0 displaying chaotic reflectors (and which intensity decreases with depth) is interpreted as corresponding to the Hercynian basement and represents the acoustic unit U0. The Ypresian formations described by Proust et al. (2001) at the top of the Hercynian magmatic and metamorphic rocks in the Bay of Vilaine are not recognised here. This first acoustic facies is covered by Facies Fs1 (sandy material) interpreted as braided fluvial sandy channel deposits (Proust et al., 2001); it corresponds to unit U1 in this study. The Facies Fs2 is interpreted as muddy sediments representing an agradational mud flat in a ria-type context; it corresponds to unit U2. The Facies Fs3a displays fine material interpreted as a tidal flat and Facies Fs3b, which is a coarser facies, is interpreted as representing abandoned tidal channels. The Facies Fs4 is subdivided into two sub-facies (Fs4a and Fs4b). Facies Fs4a corresponding to fine sediments is interpreted as offshore marine deposits. The Facies Fs4b (which is more layered) is interpreted as representing offshore muds with abundant storm beds. The Facies Fs5 described in another study (Souron, 2009) is characteristic of homogenous muds, locally bioturbated by the crustacean *Haploops sp*.

5.1.2. Sedimentary facies/sequences interpretation

Fugro-Bil-01 is the longest (25.25 m) and the only core where it has been possible to identify three sedimentary sequences (S1, S2 and S3) related to different hydrodynamic regimes (Fig. 2).

The first sequence (Sequence S1) displays a trend of increasing energy. It is made up of two sedimentary facies (Ff and Fd). The Facies Ff represents an open marine low-energy environment, which is interpreted as a half-closed bay protected from the action of waves. It is also characterised by a continental influence (plant fragments). Facies Ff is topped by Facies Fd interpreted as lower shoreface deposits (Reineck and Singh, 1980; Sedgwick and Davis, 2003) in an area subjected to wave action. Facies Fd is indicative of a slight increase in depositional energy. The latter facies is dated to approximately 8000 cal. BP (Table 3). Facies Ff located at the base of cores "Core 3" and "Beslé 2" matches in time with the sequence S1 of Fugro-Bil-01. The time interval of the low-energy part of the sequence S1 might correspond to the rapid transgression widely recognised along the French Atlantic coast, which continued up to 7500 cal. BP (Ters, 1986).

The second sequence (Sequence S2) shows a decrease in energy levels. This sequence begins abruptly with Facies Fe (muddy sands including unsorted shell debris). It reflects a medium-energy environment, and is interpreted as subtidal to tidal channel lag deposits

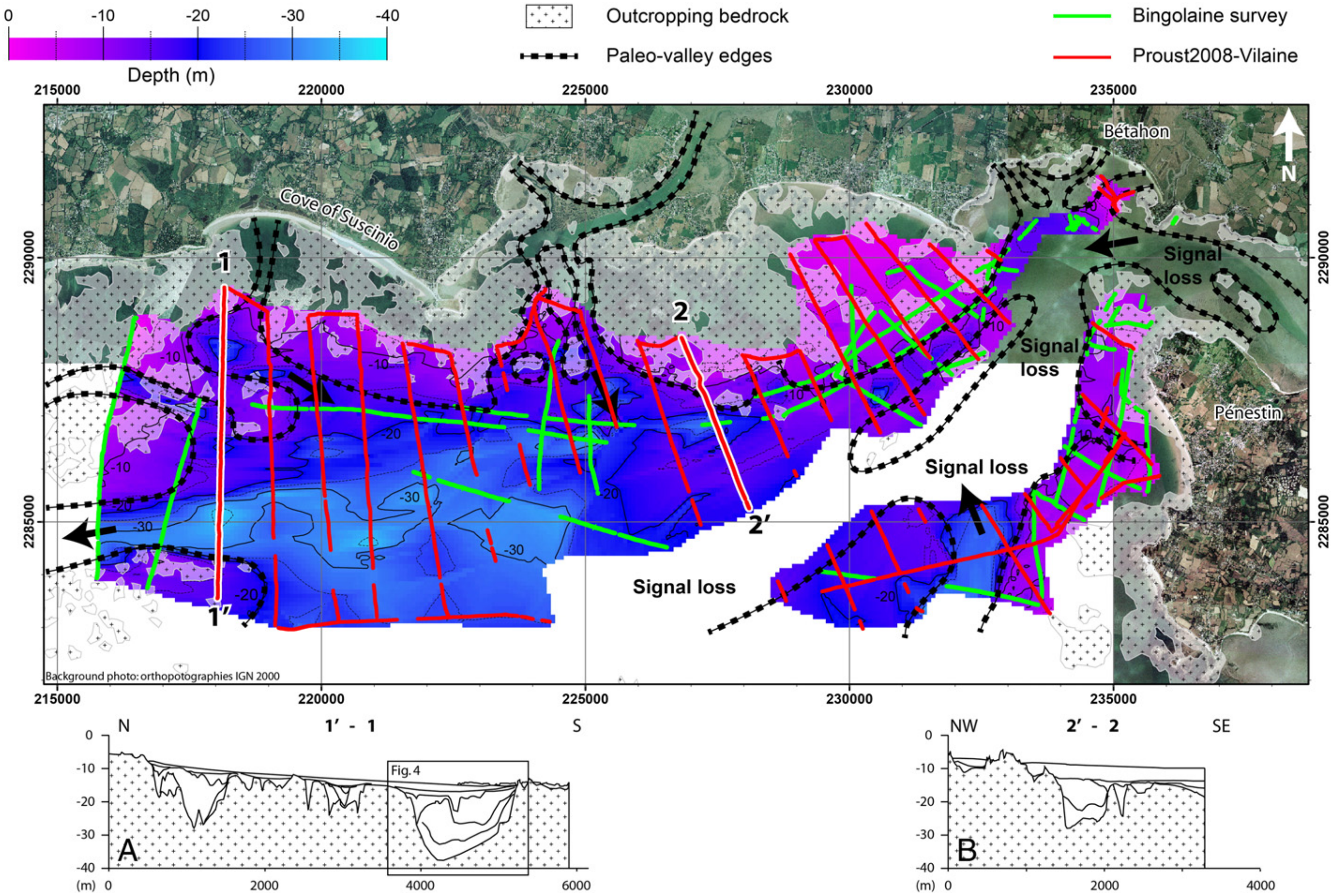

Fig. 3. Incised valley morphology of the paleoVilaine. Thin green and red lines indicate the position of the dataset array used to build the digital terrain model (Bingolaine and Haliotis surveys). Dashed bold black lines indicate the paleovalley boundaries. Black thick arrows indicate the flow direction. A and B represent interpreted Chirp profiles selected to illustrate cross-sections of the paleovalley (highlighted in figure). Background photography of this figure: BD ORTHO® Orthophotographie IGN 2000.

(Clifton, 1983). It is followed by Facies Fc, which is regarded as a tidal channel or "mixflat" [mixed tidal flat] deposits. Mixed mud and sands reflect equal periods of suspension and bed load deposition. Because there is no clear vertical rhythmic variation in lamina thickness, we refrain from interpreting Facies Fc as tidal rhythmites. Nevertheless, this facies might ultimately reflect incomplete neap-spring cycles (Reading, 1996). This facies succession represents a tidal channel fill during the deceleration of the sea-level rise recorded regionally at 7500 years BP (Ters, 1986) (Fig. 9) and is thus consistent with the establishment of an estuarine system at the river mouth.

The last sedimentary sequence (Sequence S3) begins with very coarse sediment (Facies Fa) assimilated to storm deposits. In the specific case of Fugro-Bil-01, this facies is immediately followed by Facies Fb interpreted as repetitive washover deposits of medium energy developed in ponded water bodies or intertidal zones during spring tide surges (Sedgwick and Davis, 2003) (Fig. 2). Facies Fa appears as an isolated sedimentary body in Fugro-Bil-01, and probably corresponds to storm deposits. The sequence S3 ends with the fining-up succession of Facies Fe, Ff and Fg. Facies Fg is interpreted as saltmarsh deposits (Clifton, 1983). Note that in core Fugro-Bil-01 two salt marsh bluff breccias have been recognised at 2.50 m (Fig. 2). They indicate a mudflat environment and the presence of tidal channels (Clifton, 1983). Thus, the sequence S3 shows the formation of a salt-marsh environment during the last 5000 to 6000 years BP; it is thus indicative of a stabilisation of the sea-level.

The sequence S3 constitutes most of the other cores (Cr-Bil-01 and 02; Cr-Pen-02; Cr-Gre-01; Core 3 and Beslé 2). It displays a succession of sub-sequences in cores located the most seaward (Cr-Bil-01 and 02; Cr-Pen-02); and a regular and unique sequence for cores located the most landward (Core 3 and Beslé 2).

Cores "Cr-Bil-01" and "Cr-Bil-02" begin with storm deposits (Facies Fa) and continue with tidal channel patterns (Facies Fc and Fe). Facies Fc and Fe are probably related to the dynamics of the Billiers tidal creek which can migrate under the influence of tidal currents behind the sandy barrier beach. They evolve with finer deposits corresponding to intertidal mudflat and end into areas of salt marsh as currently observed today. Similar observations can be made for the core Cr-Pen-02 (Fig. 2). The first sequence of Core Cr-PEN-02 is interpreted as characteristic of a salt marsh sedimentary succession (topped by tidal channel lag deposits). The overlying facies (Facies Fa) is interpreted as resulting from storm washovers, which remobilised sedimentary bodies such as cheniers or sand spits on the salt marsh through intense episodic wave action (Fig. 6). The topmost Facies Ff and Fg reflects an intertidal mudflat environment evolving into a salt marsh. Core Cr-PEN-02 represents an environment strongly controlled by the action of tidal currents, but sporadically influenced by strong storm waves (Fa). Cores Cr-Bil-01 Cr-Bil-02 and Cr-Pen-02 express a "cut and fill process" linked to active tidal channels.

The fine sand of "core 3", located at the base of sequence S3, dated at between 4000 and 5000 years BP probably corresponds to the base of the tidal channel of the Vilaine River since the phase of stabilisation of sea-level recorded regionally at 7500 years BP (Ters, 1986). The channel fill is completed by mud-flat (slikke) clays (Facies Ff), which evolves into a vegetated salt marsh (Facies Fg). Core "Beslé 2" (Penven et al., 2008) (Table 1) is the most upstream borehole showing evidence for marine influence. It displays a unique succession of Facies Fe, Ff and

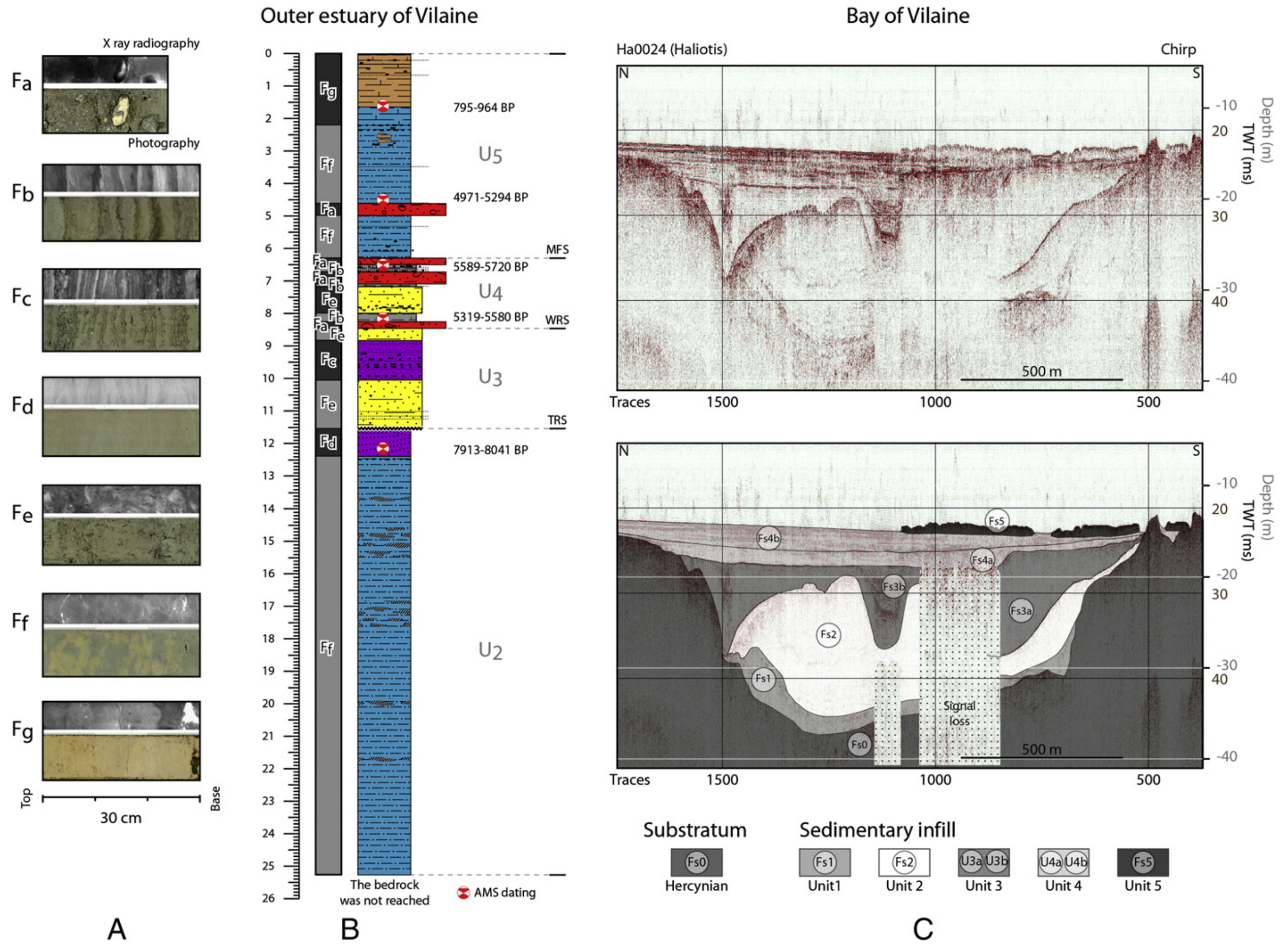

Fig. 4. Detailed illustration of the sedimentary facies based on X-ray photography and coloured photography (A), schematically represented by the stratigraphic log of the core Fugro-Bil-01 (B) and correlation with the geophysical interpretations (C) See Fig. 3 for line location. See Fig. 5 for illustration and description of the different acoustic units and facies.

Fg deposited since about 5000 BP. Cores "Core 3" and "Beslé 2" are displaying the progressive filling of a river channel.

Core "Cr-Gre-01" is located 3 km downstream from the "core 3" in the narrow and meandering estuarine part. The facies succession is indicative of a channelising environment (Fe) similar to that currently observed at the core location. Lateral facies variability is characteristic of mud flat (Ff) and salt marsh (Fg) environments.

5.1.3. Correlations between acoustic signal and the sedimentary core successions

The *Fugro-Bil-01* core penetrates most of the acoustic units identified in the bay, apart from the basal fluvial unit U1. This core is thus used as a reference core to associate sedimentary units, seismic facies and sedimentary facies (Table 4).

The acoustic Facies Fs1 may correspond to the coarse facies at the base of cores "Core 3" and "Beslé 2". Facies with pebbles of "Beslé 2" core was interpreted as an alluvial plain, which is believed to have operated until about 7600 BP (Penven et al., 2008). These results are derived from a pollen analysis of the "Beslé 2" core, which is corroborated by the presence of dinoflagellate cysts in the "Massérac 2" core located nearby (Penven et al., 2008). It also matches with the acoustic unit U1 and the base of core 3 from Morzadec-Kerfourn (1974) (Fig 2).

The sequence S1 (Facies Ff and Fd) matches in time with the acoustic Facies Fs2, which indicates thick accumulation of fine sediments (aggradational mud flat). Sequence S1 further corresponds to the seismic unit U2, which has also been recognised in the Bay of Vilaine by Menier et al. (2010) and Sorrel et al. (2010) (Ha0024 profile, Figs. 4C and 5) and dated to ca. 7000 cal. BP. The boundary between U1 and U2 is interpreted as a flooding surface (FS).

The two seismic sub-facies (Facies Fs3a and Fs3b) belonging to Facies Fs3 are associated to the sedimentary successions Fe and Fc (sequence S2), and match to the acoustic unit U3 (dated to 7000 to 5000 BP by Menier et al., 2010). They are interpreted as corresponding to a tidal environment. The erosional surface on which the sequence S2 lies is thus interpreted as a tidal ravinement surface (TRS).

The Facies Fs4 corresponds for the coastal area to the sedimentary Facies Fa, Fb and Fe. Facies Fa (base of sequence S3) reflects high-energy depositional processes, and is interpreted as resulting from the deposition of distal storm-washover fans (Sedgwick and Davis, 2003). These storm deposits are older than ca. 5450 years BP, which seems to correspond to the earliest storm event recorded in the Vilaine Bay (Menier et al., 2010). The boundary between the acoustic unit U3 and the base of unit U4 is thus interpreted as a wave ravinement surface (WRS).

The Facies Fs5 matches Ff and Fg (top of sequence S3). Facies Fg deposits correspond in age to the acoustic units U4b and U5 (5500 years

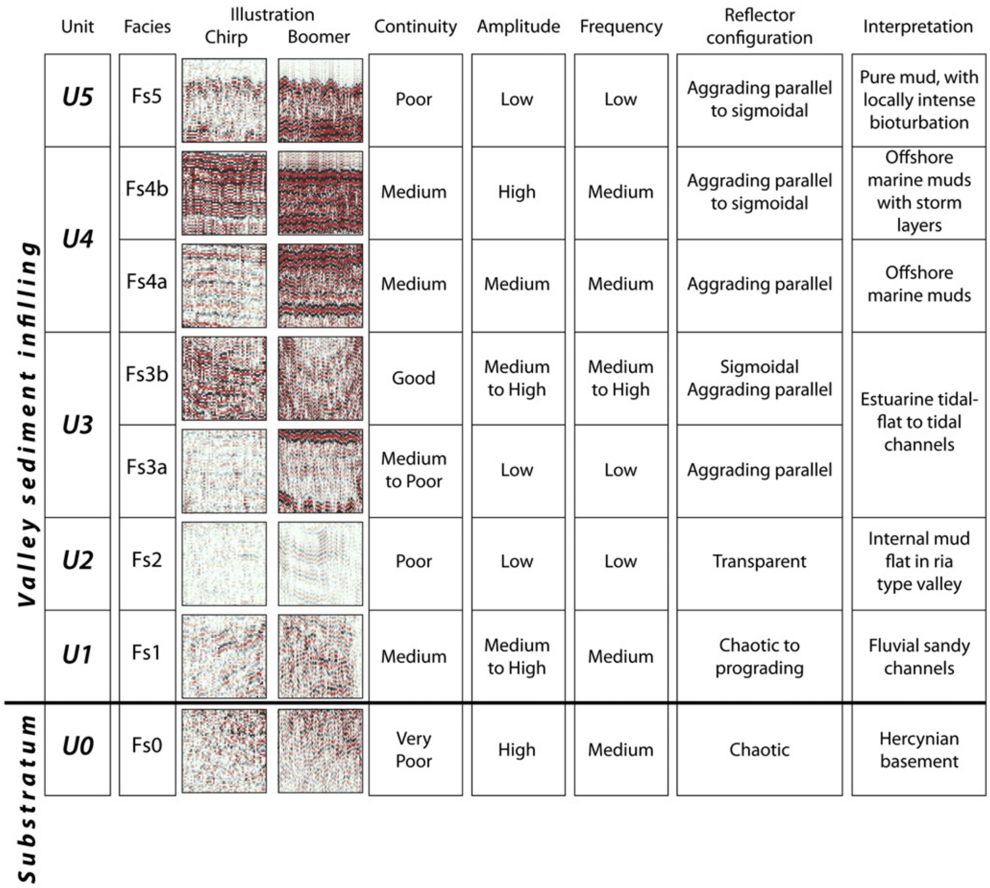

Fig. 5. Description of the different acoustic units and facies encountered both on chirp (this study) and boomer profiles (modified after Menier et al., 2010).

BP–present time). The boundary between Units U4 and U5 is thus interpreted as a maximum flooding surface (MFS).

5.2. Reconstruction of the Vilaine River infill

The Vilaine River estuary, established within the Hercynian bedrock, corresponds to a ria-type environment. The age of the fluvial erosion is controversial and might be as old as Miocene in age (Lericolais et al., 2001; Thomas, 2005). The earliest sediment fills are reported with some uncertainty from the Pliocene (Brault et al., 2004) but good age controls as available only from the late Mid-Pleistocene (Bonnet, 1998; Dabrio et al., 2000; Posamentier, 2001; Proust et al., 2001; Menier et al., 2006). At present, the Vilaine Estuary forms a long and narrow valley cutting across the geological structures or following the regional strike. The valley sides are generally abrupt with cliffs subjected to wave action at the outlet. The incision is less than 40 m deep in the valley axis, but disappears 50 km away on the continental shelf as well as for the Loire, Odet and Blavet Rivers (Proust et al., 2001, 2010; Paquet et al., 2010). Other incised valleys of the French Atlantic coast located on narrower parts of the continental shelf such as the Charente and Lay-Sèvre Rivers (Weber et al., 2004; Chaumillon et al., 2008, 2010), or the Spanish and Portuguese rias (Méndez and Vilas, 2005; Vis et al., 2008) are deeper (60 m) and goes to the shelf edge (Posamentier and Allen, 1999; Törnqvist et al., 2006). The shallow depth of incision of the Vilaine River thus seems related to the large width of the continental shelf (ca. 200 km).

5.2.1. The initial alluvial river from the Pleistocene to 10,000 cal. BP (U1)

The basal incision is covered by weathered coarse deposits of Pleistocene age (U1) (Fig. 8). This basal unit was identified in the bay (Proust et al., 2001) in the narrow and meandering estuarine part (*core 3*, Morzadec-Kerfourn, 1974) and as far upstream as Beslé (*Beslé 2* core), 70 km inland and in the Loire River paleovalleys (Proust et al., 2010). This unit is preserved by patches only in the Charente Valley, in front of the Ré and Oléron Islands (Weber et al., 2004) probably because the area is largely exposed to the swell of the Atlantic coast (waves coming from N to W are driven through the Antioche deep). Such deposits do not occur in the Mont-Saint-Michel Bay, since the transgressive prism lies directly on weathered bedrock (Billeaud et al., 2007; Tessier et al., 2012), in a zone with an important tidal current amplification. The relatively more sheltered conditions of the Vilaine Bay might have favoured the preservation of Pleistocene alluvial deposits.

5.2.2. A tide-dominated estuary from 10,000 to 5000 cal. BP (U2 and U3)

The good radiocarbon age control together with results from facies and depositional environments analysis and from the nature of the foraminiferal content in the succession above this basal unit (U1), indicate that the sedimentary filling of the Vilaine River estuary continued for approximately 10,000 years under the marine influence. Therefore, the valley infill is posterior to that occurring in the Spanish rias, which comprise Rissian and Würmian deposits in their deep valleys (García-García et al., 2005). The very gentle slope of the Vilaine River (Fig. 7) led to a rapid flooding of the valley during the early Holocene transgression. The sediment record consists of more than 12 m of silty clays (U2, Fig. 8), rich in organic matter, accumulated in a sheltered environment (*Fugro-Bil-01*, 8000 cal. BP), with a marked fluvial influence in the narrow and meandering part of the estuary. Farther upstream, traces of the marine influence are detected around 7600 cal. BP at 70 km inland (Beslé).

A similar thick silty-clay unit has been recognised on the Atlantic coast (e.g. Weber et al., 2004; García-García et al., 2005) and in the

Fig. 6. View of the salt marsh of Pénestin. The photograph shows a washover fan spilling into a tidal creek of the salt marsh.

English Channel (Billeaud et al., 2007; Sorrel et al., 2010; Tessier et al., 2012), coevally with the rapid transgression observed along the French Atlantic coast (Morzadec-Kerfourn, 1974; Lambeck, 1997). The initial phase of estuary infill thus takes place under strong eustatic control.

In the outermost part of the estuary, the core *Fugro-Bil-01* shows an increase in swell and tidal energy (Facies Fd) underscored by a tidal ravinement surface once the sea-level rise decelerates at ca. 7500 years BP (Fig. 9). This might be indicative of a decrease in accommodation space. The sea-level rise deceleration is most probably 500 to 1000 years earlier than that was recorded in the Mont-Saint-Michel Bay and the Seine estuary (6500 years BP, Tessier et al., 2012). This time offset could be due to the more proximal location of the Vilaine Estuary with respect to the "transgressive wave" than the Bay du Mont St Michel, which is encased into a deep re-entrant of the coastline. Alternatively, the sheltered conditions of the Vilaine Estuary might have enhanced a rapid infilling of the accommodation space due to the low energy conditions. The phase of deceleration marked by a decrease in water depth and increase in tidal and wave energy is observed in U3 (Fig. 8) on the entire length of the studied stretch (90 km), up to ca. 5700 BP in the Vilaine Bay (Sorrel et al., 2010), 5600 BP in the approaching estuary and probably before 5000 years BP at Beslé (Fig. 8).

5.2.3. A wave dominated estuary from 5700 to 3000 cal. BP (U4)

Tidal processes end up with the development of a wave ravinement surface identified in the bay and the outermost part of estuary overlain by coarse deposits (Fa). These coarse deposits mark the initial stages of the establishment of the Bétahon sand spit, which cuts off the Bétahon/Billiers marshes and leads to the development of sheltered ponded water bodies or tidal flats at its back (Facies Fb). The wave activity increases in two phases.

A first phase of moderate wave activity occurred at 5700 cal. BP (U4a) in the bay and the outer estuary, while a second and intensified phase (U4b) is recorded thereafter. The latter continues up to present times in the outer parts of the bay, but ends up much sooner (at ca. 5000 cal. BP) at the estuarine entrance where it is supplanted by tidal action (Fig. 4C).

The rapid emplacement of the Bétahon spit at ca. 5400 years BP protected the outer estuary from the swell influence but fostered accommodation space creation by tidal current downcutting.

The first intense period of wave activity occurred at 5700–5400 BP, while another is recorded later, at ca. 3250 cal. BP (base of core Cr-Bil-01, Fig. 2). These events may be coeval to two of four Bond cold events recognised in other coastal settings (Billeaud et al., 2009; Sorrel et al., 2009). The two events observed here instead of

Table 4
Table of correspondence between seismic and sedimentary facies with their environmental interpretations.

Unit	Seismic facies	Lithology	Sedimentary sequences	Sedimentary facies	Environments
U5	Fs5	Fine sediment structureless	S3	Fa–Ff–Fg	Homogenous muds, locally bioturbated by the crustacean Haploops sp. or storm layer
U4	Fs4b	Sandy to muddy laminated sediment		Fa–Fb–Fe	Offshore marine-mud with abundant storm layers
	Fs4a	Muddy to sandy laminated sediment			Offshore marine-mud
U3	Fs3b	Fine to coarse laminated sediment	S2	Fc–Fe	Abandoned tidal channels
	Fs3a	Fine sediment with slight parallel lamination			Tidal flat
U2	Fs2	Fine sediment structureless	S1	Fd–Ff	Aggradational mud-flat
U1	Fs1	Coarse to very coarse sediment few to not laminated			Braided fluvial sandy channel
U0	Fs0	Rocky material			Hercynian basement

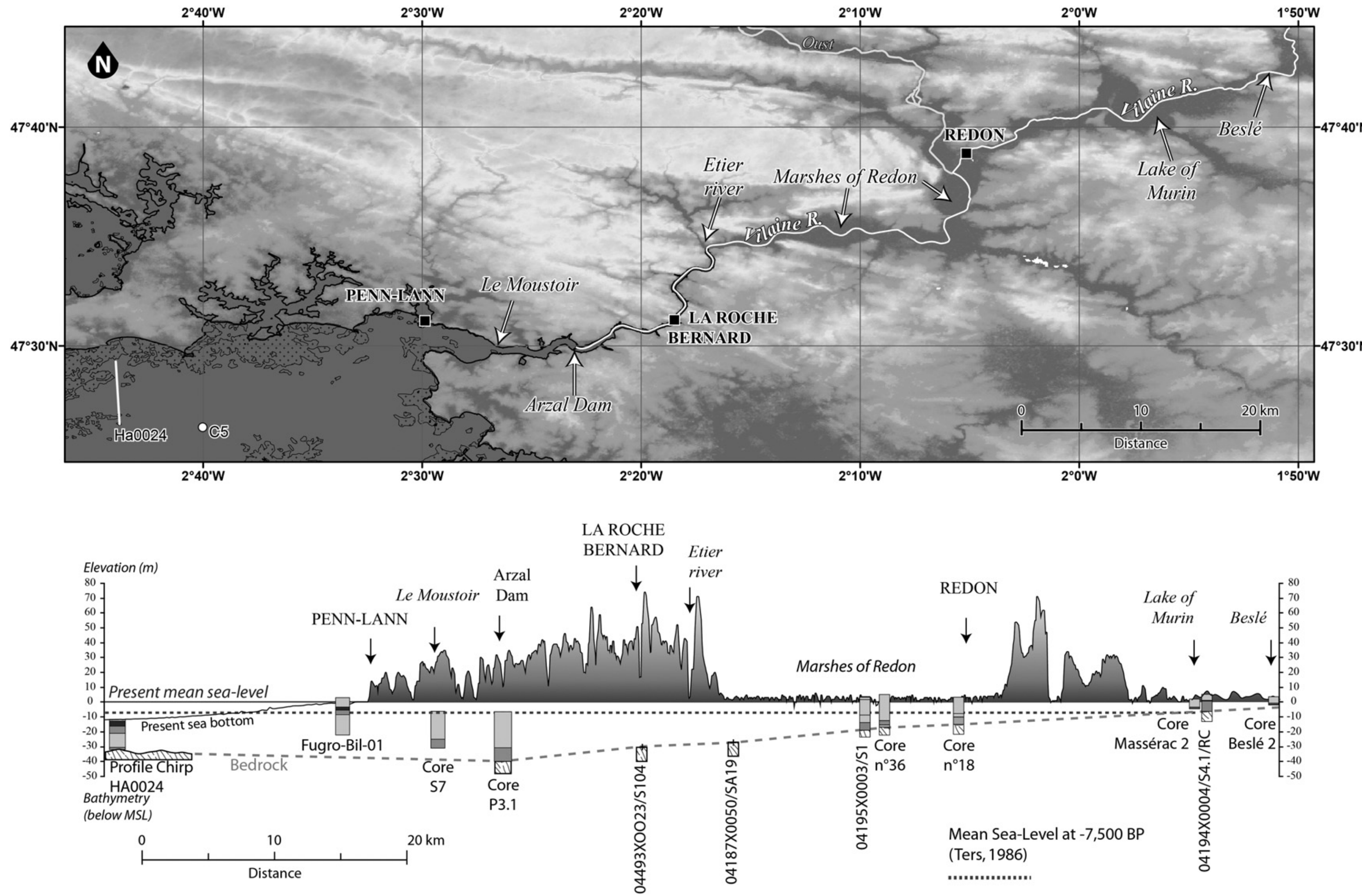

Fig. 7. Longitudinal cross-section of the Vilaine incised valley. The section extends downstream to the marine domain of the Bay of Vilaine and upstream to the landward limit of tidal action before the construction of the Arzal Dam. The depth of the bedrock is based on the DTM (Proust2008-Vilaine), as well as cores and cross-sections where the basement is reached (Table 1). The description of sedimentary log matches with the sedimentary units displayed in Figs. 4 and 8.

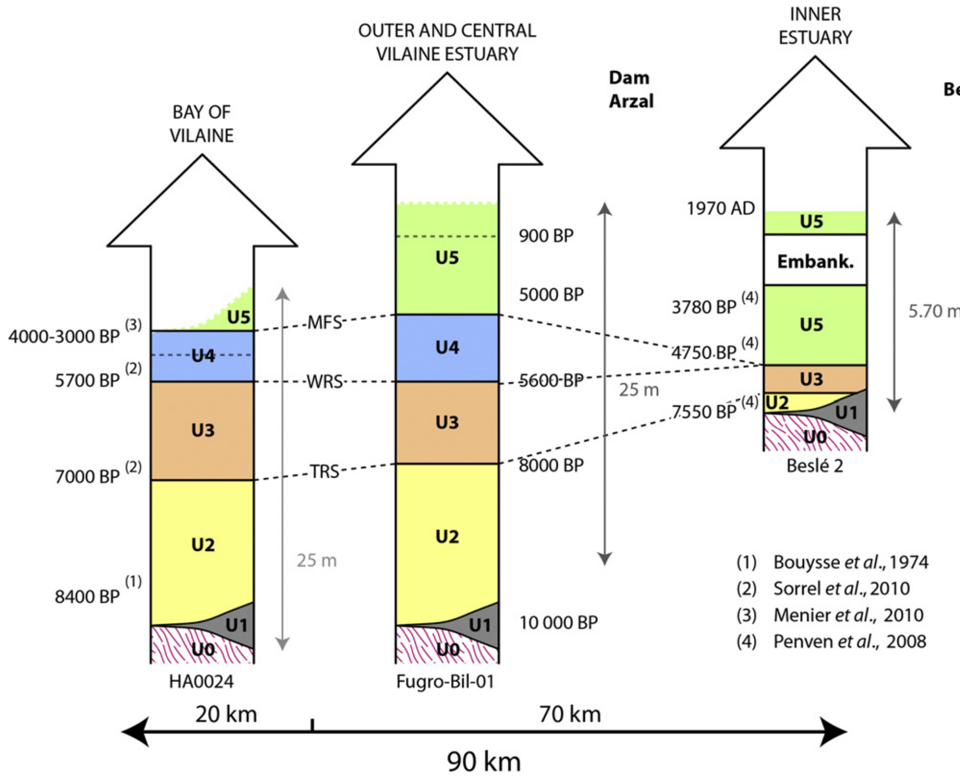

Fig. 8. Summary of acoustic, sedimentary units and boundaries revealed by the Bay of Vilaine dataset and of age estimate of each boundary. Vertical thick arrows show sediment accretion through time in the Bay of Vilaine, in the present-day estuary (delimited today by the Arzal Dam) and at the upstream limit of the estuary before the dam construction (Beslé). See core location if Fig. 2.

the four in the Mont-Saint-Michel Bay (Billeaud et al., 2009) is attributed to the more sheltered setting of the Vilaine Bay due to the presence of the sand spit, the reduction of the accommodation space, and the orientation of the Vilaine Estuary.

Extracts of plant remains from sample Fugro-Bil-01-0815 collected from the back-barrier zone at a core depth of 8.15 m yield a $\delta^{13}C$ value of −16.8‰. This value suggests organic material derived from fresh-water plants or marine algae (Polach, 1976; Stuiver and Polach, 1977; Wilson et al., 2005; Lamb et al., 2006), which supports the hypothesis of a confined marine environment. The sand spit appears to have remained relatively stable for the last 5000 years BP, since no disturbance can be inferred apart from that recorded at ca. 5000 cal. BP. This stability indicates that the conditions have not changed since the earlier phases of dune establishment. Therefore, despite the relatively sheltered position of the bay, the sediment transport, depending on weather and tidal influences, is very active.

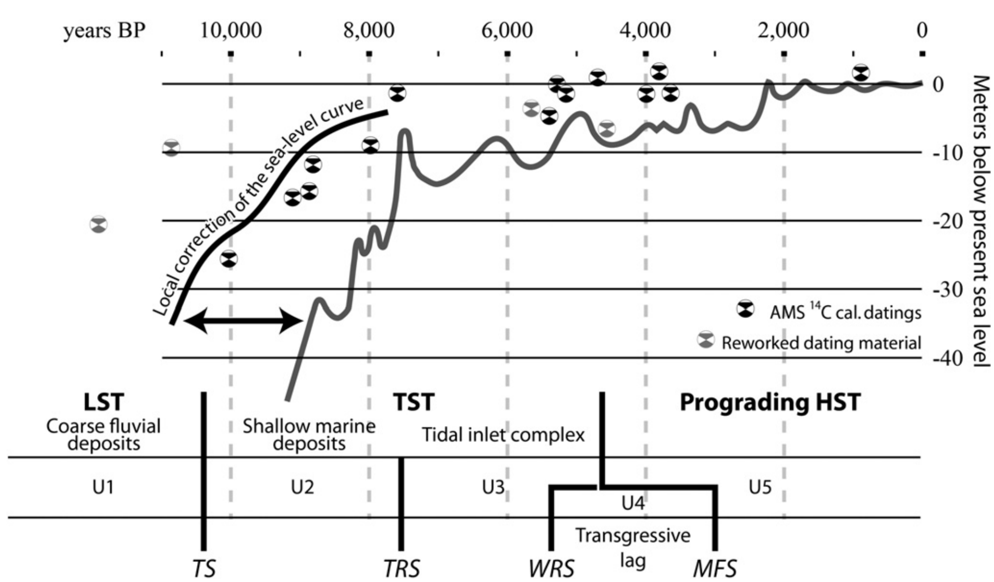

Fig. 9. Sea-level curve evolution and infilling model of the Vilaine Estuary. Original sea level curve is modified after Ters (1986). Correction of the sea-level curve is based on the AMS ^{14}C dating obtained in this study. AMS: Accelerator Mass Spectrometer; LST: Lowstand System Track; TST: Transgressive System Track; HST: Highstand System Track; TS: Transgressive Surface; TRS: Tidal Ravinement Surface; WRS: Wave Ravinement Surface; MFS: Maximum Flooding Surface.

5.2.4. A scour and lag estuary from 5000 years BP to present day (U5)

Unit 4 is absent in the innermost parts of the estuary. Unit 4 is set under the influence of storm waves that cannot reach the most sheltered parts of the inner estuary. However, tidal currents and riverine discharges control the deposition of Unit 5 whose intensity increases from the outer reaches to the confined parts of the estuary.

The sedimentary sequence in Unit 5 changes laterally in a downstream direction. In the innermost part of the estuary, it is comprised of a single fluvio-marine sequence (topmost 10.5 m of the sediment column in core 3 i.e. Facies Fe, Ff and Fg) which lies directly on unit U3 (ca. 8750 years BP) (Fig. 8) through a maximum flooding surface. In the outer estuary, between the headlands of Penn-Lann and Halguen and the narrow of Tréhiguier, tidal and storm washover facies alternate (Facies Ff and Fa in core Cr-PEN-02). These deposits, which are less than 300 years old, lie down on much older deposits (7500 cal. BP). They represent storm washover migrating on back barrier marshes (Fig. 6). In the bay, fluvio-marine deposits are observed in the immediate vicinity of the estuary of the Vilaine River. The morphology and the structure of the valley inherited from the Hercynian bedrock control the lateral distribution of sediment. In the narrow parts of the estuary, the narrowness of the valley prevents the lateral migration of tidal channels. Tidal currents and river flow maintain the cross-sectional profile through the well known estuarine "scour and lag" phenomena (Straaten and Kuenen, 1958; Postma, 1967) for c. 5,000 years.

In the large parts of the estuary, salt marsh occasionally encroached on the channel zone between ca. 4600 and 4500 cal. BP (see core Cr-Gre-01). A temporary reduction of the river flow or an increase in the input of marine sediments resuspended by more frequent storms (contemporary with the U4 unit) favour the lateral progression of salt marshes. In the central part of the estuary the accommodation space enables the development of tidal flats. Waves refract on it and generate sand-shelly wash-over fans on the uppermost part of the tidal flat. The sedimentary succession thus suggests a sheltered environment similar to back-barrier marshes. The superposition of these recent deposits (no more than 300 years old) on much older deposits (7500 cal. BP) is interpreted as resulting from a "cut and fill" phenomenon (Billeaud et al., 2007), which is explained by the migration of the tidal channels across the salt marsh zone in the context of a "back-barrier" formed under climatic influence and during a stabilisation of sea levels (Fig. 6). This latter unit corresponds to the highstand system tract related to the stabilisation of the sea level. However, it should be noted that this fluvio-marine unit probably contains a very low proportion of sediments of fluvial origin. Indeed, the Vilaine River catchment area is of moderate size and low elevation, which is not likely to favour a strong sedimentary input. Moreover, since the 1970s, the construction of the Arzal Dam 8 km from the mouth has potentially blocked 99% of the river sediment load (Brandt, 2000). But, no material is accumulating behind this structure. So, the sediment accumulation downstream of the dam would thus be made up mainly of sediments of marine origin. Thus, unit 5 recognised in the external part of the estuary would be linked to the saturation of the accommodation space due to the narrowness of the valley and the presence of the dam.

This evolution is contrary to the model of Zaitlin (1994) (sedimentary material of fluvial origin). The valley was already filled before the construction of the dam, and sediments mainly of marine origin are deposited under the action of fluvio-tidal dynamics at the mouth of the estuary i.e. outside the present-day incised valley. In such a case, in the framework of the definition of Hart (1995), we would be dealing with a "delta front estuary" formed by fluvio-tidal dynamics, but whose sedimentary source is mainly of marine origin.

5.2.5. Infilling model of the Vilaine's ria-type Estuary

The infilling sequence of the Vilaine Estuary (Fig. 9) is composed of five units (U1–U5). Unit 1 is comprised of lowstand deposits, whereas Units 2, 3 and 4 correspond to transgressive successions. The uppermost unit (Unit 5) characterises highstand conditions. The lowstand unit (U1) drapes the lower part of the incised valley where it is sheltered from the direct oceanic wave activity. The transgressive units 2 and 3 extend largely, capped by a tidal inlet complex, up to 60 km upstream due to the gentle slope of the valley floor. However, the narrowness of the valley limits the presence of the transgressive lag of Unit 4 to the bay area. Consequently, the highstand system track (U5) starts early, lying directly, through an erosion surface, on Unit 3 in the confined part of the estuary (ca. 4500 cal. BP), and through a conformable surface on Unit 4 in the external part of the estuary (c.3000 cal. BP onwards).

The age/depth model applied for core Fugro-Bil-01, indicates a sea-level rise starting about 2000 years earlier than described by Ters (1986) (Fig. 9) providing an average sedimentation rate of 1.4 mm/year from 8000 years BP up to the present. This rate matches with the deceleration of the marine transgression, which took place at 1 to 2 mm/year (Lambeck, 1997).

The sedimentary infill is strongly controlled by the geomorphological inheritage of the Vilaine Estuary. The gentle slope of the valley allowed the tidal estuarine transgressive system track to spread far into the ria when the narrowness of the ria limited the extension of the transgressive lag (U4) to the outer parts of the estuary. Today, the narrowness of the ria offers a limited accommodation space as the highstand system track had already filled the valley.

The estuarine part of rias in Spain or Portugal is shorter probably because the thalweg of the rivers are steeper due to their proximity to the continental shelf. But Iberian rias are sometimes wider and directly exposed to the oceanic wave activity (e.g. Ría of Vigo (García-García et al., 2005) limiting the deposition of the highstand system tract sediments and keeping more present day accommodation space.

The Vilaine River ria-type estuary shares a number of similarities with the stratigraphic model of the Gironde Estuary (Allen and Posamentier, 1993; Lericolais et al., 2001). The transgressive lag placed between the WRS and the MFS is particularly well developed in the case of the Vilaine Estuary despite its context of a sheltered bay. In the Gironde Estuary, the highstand systems tract is limited to the inner estuary, whereas in the case of the Vilaine, it also spreads out to the outer reaches of the estuary. The non-sheltered conditions of the Gironde River mouth could explain in part this difference. But the Vilaine River has been dammed since 1970, and all suspended sediments originating from the bay are confined to a reduced estuarine area.

6. Conclusion

The narrow and elongated morphology of the Vilaine River estuary, in addition to its particularly sheltered position for an estuary located on the Atlantic seaboard, has led to the accumulation of a sedimentary record reflecting the regional Holocene history. Indeed, on the contrary to the valleys of south-west England or to the south of Spain (Dabrio et al., 2000), which have recorded several phases of incision and sedimentation corresponding to the various Pleistocene sea-level changes, the sediments preserved in the Vilaine River valleys record only the last phase of the marine transgression. The new data from seismic reflection surveys, coring and dating, combined with previous studies, enable us to establish the nature and chronology of the sedimentary infilling, which is composed of five main sedimentary units. The sedimentary infill is dominated by marine facies probably because of the moderate size of the catchment area, which generates low fluvial sedimentary loads. These hydrological conditions would not have changed significantly during the period of infilling, which had taken place by the Mid Pleistocene (Bonnet, 1998; Bonnet et al., 2000; Gibbard and Lewin, 2009).

The morphological characteristics of the bay and of the estuary, together with the eustatic conditions, play a determining role in controlling the facies distribution related to the action of swells and tides during the infill. The onset of the transgression is very rapid and immediately creates conditions favourable for the deposition of fine particles, helped by the presence of rocky shoals which shelter the bay from the action of swell. The accommodation space is gradually filled until the appearance of conditions allowing the expression of tidal currents. The setting of the bay and its funnel shape amplify the tidal currents, leading to the generation of powerful currents and a tidal ravinement surface (TRS) observable on a regional scale. The effect of the tide is thus felt over a distance of 90 km (20 km in the bay + 70 km upstream in the valley of the Vilaine River). It is only from around 5000 years BP that the action of swell extends over the whole of the bay and in the outermost parts of the estuary of the Vilaine River forming a wave ravinement surface (WRS) of regional extent because of the reduction in the water depth. This phenomenon is reflected by the accumulation of storm deposits in the bay from 3000 years BP and by the formation of a sand spit enclosing the Bétahon/Billiers marshes. At the same time, no action of swell is recorded in the innermost part of the estuary, beyond the Tréhiguier narrowing, where fluvio-tidal conditions are maintained up until the complete infilling of the valley.

Finally, no human impact is observed in the sedimentary record except over the last 40 years following the construction of the Arzal Dam 8 km from the mouth, which deprives the downstream reach from sedimentary supply. However, downstream to the dam, silting up continues to be active in the narrow and meandering part of the estuary. The marine origin of the sediments thus remains to be established; they could be derived from the bay itself, due to reworking during storms. Some studies also suggest the influence of the turbid plume coming from the Loire estuary, which can penetrate into the Vilaine Bay under certain conditions of wind and currents. If this hypothesis is validated, the estuary of the Vilaine River would thus represent an additional and particularly well-sheltered area of storage for suspended particles discharged by the Loire River.

Acknowledgement

This work has been funded by the Conseil Géneral of Morbihan and the Région Bretagne. The authors would like to thank the captain and the crew (Arnaud Gillier and Renaud Cagna) of the "RV Haliotis" for the chirp data acquisition of this study. We would like to thank Philippe Martinez, Isabelle Billy and Joël Saint Paul (University of Bordeaux 1, France) for SCOPIX analyses. We also acknowledge the BRGM for kindly providing on-line descriptions of technical drillings, the Sandre for providing informations on hydrographic characteristics of the Vilaine River's catchment, and the Chrono Centre of the Queens University, Belfast, for providing marine reservoir correction.

References

Allen, G.P., Posamentier, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde Estuary, France. Journal of Sedimentary Research 63, 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.W., Boyd, R.J., Zaitlin, B.A. (Eds.), Incised-valley Systems: Origin and Sedimentary Sequences. SEPM, Tulsa, pp. 225–240.

Audren, C., Jegouzo, P., Barbaroux, L., Bouysse, P., 1975. Note explicative de la feuille La Roche-Bernard à 1/50000, Carte géologique de la France à 1/50000. BRGM, Orléan.

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.

Bertin, X., Chaumillon, E., 2005. New insights in shallow gas generation from very high resolution seismic and bathymetric surveys in the Marennes-Oléron Bay, France. Marine Geophysical Researches 26, 225–233.

Billeaud, I., Tessier, B., Lesueur, P., Caline, B., 2007. Preservation potential of highstand coastal sedimentary bodies in a macrotidal basin: example from the Bay of Mont-Saint-Michel, NW France. Sedimentary Geology 202, 754–775.

Billeaud, I., Tessier, B., Lesueur, P., 2009. Impacts of late Holocene rapid climate changes as recorded in a macrotidal coastal setting (Mont-Saint-Michel Bay, France). Geology 37, 1031–1034.

Boillot, G., Bouysse, P., Lamboy, M., 1971. Morphology, sediment and Quaternary history of the continental shelf between the Strait of Dover and Cape Finisterre. In: Delany, F.M. (Ed.), The Geology of the East Atlantic Continental Margin, ICSU/SCOR Working Party 31. Institute of Geological Science Report, Cambridge, pp. 75–90.

Bonnet, S., 1998. Tectonique et dynamique du relief: Le socle Armoricain au Pléistocène, Sciences & Sciences de l'Ingénieur. Université de Rennes 1, Rennes 352.

Bonnet, S., Guillocheau, F., Brun, J.-P., Driessche, J.V.D., 2000. Large-scale relief development related to Quaternary tectonic uplift of a Proterozoic–Paleozoic basement: the Armorican Massif, NW France. Journal of Geophysical Research 105, 19,273–219,228.

Bouysse, P., Goni, J., Parent, C., Calvez, Y.L., 1966. Recherches sur le plateau continental (Baie de Vilaine). Mémoires du B.R.G.M. 5, 2–77.

Bouysse, P., Chateauneuf, J.-J., Ters, M., 1974. Présence d'Yprésien, niveau transgressif et taux de sédimentation flandriens en baie de Vilaine (Bretagne Méridionale). Comptes Rendus de l'Académie des Sciences Série D 279, 1421–1424.

Boyd, R., Dalrymple, R.W., Zaitlin, B.A., 2006. Estuarine and incised-valley facies models. In: Posamentier, H.W., Walker, R.G. (Eds.), Facies Models Revisited. Soc. Econ. Paleont. Mineral, Tulsa, pp. 171–235.

Brandt, S.A., 2000. Classification of geomorphological effects downstream of dams. Catena 40, 375–401.

Brault, N., Bourquin, S., Guillocheau, F., Dabard, M.P., Bonnet, S., Courville, P., Estéoule-Choux, J., Stepanoff, F., 2004. Mio-Pliocene to Pleistocene paleotopographic evolution of Brittany (France) from a sequence stratigraphic analysis: relative influence of tectonics and climate. Sedimentary Geology 163, 175–210.

Chaumillon, E., Weber, N., 2006. Spatial variability of modern incised valleys on the French Atlantic coast: comparison between the Charenet and the Lay-Sevre incised valleys. Society of Economic Paleontologists and Mineralogists 85, 57–85.

Chaumillon, E., Proust, J.-N., Menier, D., Weber, N., 2006. Incised Valley morphologies and sedimentary fills within the northern of the bay of Biscay inner shelf. X International Symposium on Oceanography of the Bay of Biscay, Vigo, Galicia, pp. 127–130.

Chaumillon, E., Proust, J.-N., Menier, D., Weber, N., 2008. Incised-valley morphologies and sedimentary-fills within the inner shelf of the Bay of Biscay (France): a synthesis. Journal of Marine Systems 72, 383–396.

Chaumillon, E., Tessier, B., Reynaud, J.Y., 2010. Stratigraphic records and variability of incised valleys and estuaries along French coasts. Bulletin De La Societe Geologique de France 181, 75–85.

Clifton, H.E., 1983. Discrimination between subtidal and intertidal facies in Pleistocene deposits, Willapa Bay, Washington. Journal of Sedimentary Petrology 53, 353–359.

Dabrio, C.J., Zazo, C., Goy, J.L., Sierro, F.J., Borja, F., Lario, J., González, J.A., Flores, J.A., 2000. Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cadiz, Southern Spain). Marine Geology 162, 381–404.

Dalrymple, R., Boyd, R., Zaitlin, B.A., 1994. Incised valley system: origin and sedimentary sequences. Society of Economic Paleontologists and Mineralogists 51, 45–60.

Delanoë, Y., Dieucho, A., Pinot, J.-P., 1972. La zone périlittorale entre les Îles de Génan et Île de Houat. Etude géomorphologique et géologique. Bulletin de la Société Géologique de France XIV, 249–260.

Fénies, 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 de Géosciences 1257–1266.

García-García, A., García-Gil, S., Vilas, F., 2005. Quaternary evolution of the Ría de Vigo, Spain. Marine Geology 220, 153–179.

García-Gil, S., Vilas, F., García-García, A., 2002. Shallow gas features in incised-valley fills (Ría de Vigo, NW Spain): a case study. Continental Shelf Research 22, 2303–2315.

Gibbard, P.L., Lewin, J., 2009. River incision and terrace formation in the Late Cenozoic of Europe. Tectonophysics 474, 41–55.

Hart, B.S., 1995. Delta front estuaries. In: Perillo, G.M.E. (Ed.), Developments in Sedimentology. Elsevier, pp. 207–226.

Horn, R., Vanney, J.R., Boillot, G., Bouysse, P., Leclaire, L., 1966. Résultats géologiques d'une prospection sismique par la méthode "Boomer" au large du massif Armoricain méridional. Comptes Rendus de l'Académie des Sciences 263, 1560–1563.

Jegouzo, P., Rosello, E.A., 1988. La Branche Nord du Cisaillement Sud-Armoricain (France): un essai d'évaluation du déplacement par l'analyse des mylonites. Comptes Rendus de l'Académie des Sciences 307, 1825–1831 (Paris).

Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. Earth-Science Reviews 75, 29–57.

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., Fénies, H., 2001. Seaward pinching out and internal stratigraphy of the Gironde incised valley on the shelf (Bay of Biscay). Marine Geology 183–197.

Lofi, J., Weber, O., 2001. SCOPIX — digital processing of X-ray images for the enhancement of sedimentary structures in undisturbed core slabs. Geo-Marine Letters 20, 182–186.

Méndez, G., Vilas, F., 2005. Geological antecedents of the Rias Baixas (Galicia, northwest Iberian Peninsula). Journal of Marine Systems 54, 195–207.

Menier, D., 2004. Morphologie et remplissage des vallées fossiles sud-armoricaines: apport de la stratigraphie sismique, Sciences & Sciences de l'Ingénieur. Université de Bretagne Sud, Rennes, p. 211.

Menier, D., Goubert, E., Le Corre, C., Proust, J.-N., Bonnet, S., Tessier, B., Baltzer, A., 2002. Rapport Mission Bingolaine. Université de Bretagne Sud, Vannes, p. 46.

Menier, D., Reynaud, J.-Y., Proust, J.-N., Guillocheau, F., Guennoc, P., Bonnet, S., Tessier, B., Goubert, E., 2006. Basement control on shaping and infilling of valleys incised at the southern coast of Brittany, France. In: Dalrymple, R.W., Leckie, D.A., Tillman, R.W. (Eds.), Incised Valleys in Time and Space. SEPM (Society for Sedimentary Geology), p. 343 (Clothbound).

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, 115–128.
Menier, D., Tessier, B., Dubois, A., Goubert, E., Sedrati, M., 2011. Geomorphological and hydrodynamic forcing of sedimentary bedforms — example of Gulf of Morbihan (South Brittany, Bay of Biscay). Journal of Coastal Research 1530–1534.
Migeon, S., Weber, O., Faugeres, J.C., Saint-Paul, J., 1999. SCOPIX: a new X-ray imaging system for core analysis. Geo-Marine Letters 18, 251–255.
Mitchum, R.M., Vail, P.R., Sangree, J.B., 1977. Seismic stratigraphy and global changes of sea level, part 6: stratigraphic interpretation on seismic reflection patterns in depositional sequences. In: Payton, C.E. (Ed.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration, vol. 26. American Association of Petroleum Geologists, Tulsa, pp. 117–133.
Morzadec-Kerfourn, M.-T., 1974. Variations de la ligne de rivage armoricaine au quaternaire. Université de Rennes 1, Rennes, p. 208.
Nichols, M.M., Biggs, R.B., 1985. 2 estuaries, In: Davis, R.A. (Ed.), Coastal Sedimentary Environments, 2 ed. Springer, p. 716.
Paquet, F., Menier, D., Estournès, G., Bourillet, J.-F., Leroy, P., Guillocheau, F., 2010. Buried fluvial incisions as a record of Middle–Late Miocene eustasy fall on the Armorican Shelf (Bay of Biscay, France). Marine Geology 268, 137–151.
Penven, M.J., Dupont, N., Marguerie, D., 2008. Mosaïque spatiale des fonds alluviaux et fonctionnement hydrogéomorphologique du lit majeur lors des inondations. Rapport scientifique final du programme inondations dans le bassin de la Vilaine: paramètres hydrogéomorphologiques et flux terrigènes, pp. 91–177.
Polach, H.A., 1976. Radiocarbon dating as a research tool in archaeology-hopes and limitations. In: Barnard, N. (Ed.), Symposium on Scientific Methods of Research in the Study of Ancient Chinese Bronzes and South East Asian Metal and Other Archaeological Artifacts. Dept Far Eastern History, Australian Natl Univ.
Posamentier, H.W., 2001. Lowstand alluvial bypass systems: incised vs. unincised. AAPG Bulletin 85, 1771–1793.
Posamentier, H.W., Allen, G.P., 1999. Siliciclastic sequence stratigraphy: concepts and applications. Society of Economic Petrologists and Paleontologists, Tulsa.
Postma, H., 1967. Sediment Transport and Sedimentation in the Estuarine Environment. In: Lauf, G.H. (Ed.), Estuaries. American Association for the Advancement of Science, Washington, pp. 158–179.
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.
Proust, J.-N., Renault, M., Guennoc, P., Thinon, I., 2010. Sedimentary architecture of the Loire River drowned valleys of the French Atlantic shelf. Bulletin Société Géologique de France 181, 129–150.
Reading, H.G., 1996. Sedimentary Environments: Processes, Facies and Stratigraphy, Third edition. Blackwell Science, Oxford, p. 557.
Reimer, P., Baillie, M., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Ramsey, C.B., Buck, C., Burr, G., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., McCormac, F., Manning, S., Reimer, R., Richards, D., Southon, J., Talamo, S., Turney, C., Plicht, J.v.d., Weyhenmeyer, C., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.
Reineck, H.-E., Singh, I.B., 1980. Depositional Sedimentary Environments with Reference to Terrigenous Clastics. Srpinger verlag, Berlin. Heidelberg. New York.
Roussel, E.G., Sauvadet, A.-L., Allard, J., Chaduteau, C., Richard, P., Bonavita, M.-A.C., Chaumillon, E., 2009. Archaeal methane cycling communities associated with gassy subsurface sediments of Marennes-Oléron Bay (France). Geomicrobiology Journal 26, 31–43.
Sedgwick, P.E., Davis, R.A., 2003. Stratigraphy of washover deposits in Florida: implications for recognition in the stratigraphic record. Marine Geology 200, 31–48.
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.
Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J.-N., Menier, D., Traini, C., 2010. Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): depositional history and late Holocene climatic and environmental signals. Continental Shelf Research 30, 1250–1266.
Souron, A., 2009. Sédimentologie des vasières subtidales à Haploops sp. sur les fonds à pockmarks de Bretagne Sud, Science de la Mer et du Littoral. Université de Bretagne Occidentale, Brest, p. 53.
Straaten, L.M.J.U.v., Kuenen, P.H., 1958. Tidal action as a cause of clay accumulation. Journal of Sedimentary Research 28, 406–413.
Stuiver, M., Polach, H.A., 1977. Discussion: reporting of ^{14}C data. Radiocarbon 19, 355–363.
Swift, D.J.P., Oertel, G.F., Tillman, R.W., Thorne, J.A., 1991. Shelf Sand and Sandstone Bodies, Facies and Sequence Stratigraphy. International Association Of Sedimentologists, Wiley, p. 328.
Ters, M., 1986. Variations in Holocene sea level on the French Atlantic Coast and their climatic significance. Climate: History, Periodicity and Predictability. Von Nostrand Reinhold, New York, pp. 204–237.
Tessier, B., Billeaud, I., Sorrel, P., Delsinne, N., Lesueur, P., 2012. Infilling stratigraphy of macrotidal tide-dominated estuaries. Controlling mechanisms: sea-level fluctuations, bedrock morphology, sediment supply and climate changes (The examples of the Seine estuary and the Mont-Saint-Michel Bay, English Channel, NW France). Sedimentary Geology 279, 62–73.
Thinon, I., Menier, D., Guennoc, P., Proust, J.-N., 2008. Carte au 1/250000 de la marge Sud-Armoricaine, in: Minières, B.d.R.G.e. (Ed.).
Thomas, E., 2005. Géologie succincte du massif armoricain (Bretagne), La géologie en Bretagne. Bureau de recherches géologiques et minières, Bretagne, p. 6.
Thomas, M.A., Anderson, J.B., 1994. Sea-level controls on the facies architecture of the Trinity/Sabine incised valley system, Texas, in: Miner., S.e.P. (Ed.), Incised Valley Systems: Origin and Sedimentary Sequences, pp. 63–82.
Törnqvist, T.E., Wortman, S.R., Mateo, Z.R.P., Milne, G.A., Swenson, J.B., 2006. Did the last sea level lowstand always lead to cross-shelf valley formation and source-to-sink sediment flux? Journal of Geophysical Research 111, F04002.
Truffert, C., Gumiaux, C., Chantraine, J., Perrin, J., Galdeano, A., Gapais, D., Ballèvre, M., Asfirane, F., Guennoc, P., Brun, J.-P., 2001. Levé géophysique aéroporté dans le Sud-Est du Massif armoricain (programme GéoFrance3D Armor2). Magnétisme et radiométrie spectrale detailed airborne geophysical survey in southeast Armorican massif (GéoFrance3D programme). Magnetism and spectral radiometry. Comptes Rendus de l'Académie des Sciences Series IIA: Earth and Planetary Science 333, 263–270.
Vail, P.R., Mitchum, R.M.J., Todd, R.G., Widmier, J.M., Thompson, S.I., Sangree, J.B., Bubb, J.N., Hatlelid, W.G., 1977. Seismic stratigraphy and global changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy — Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoirs, pp. 49–212.
Vanney, J.-R., 1965. Étude sédimentologique du Mor Bras, Bretagne. Marine Geology 3, 195–222.
Vis, G.-J., Kasse, C., Vandenberghe, J., 2008. Late Pleistocene and Holocene palaeogeography of the Lower Tagus Valley (Portugal): effects of relative sea level, valley morphology and sediment supply. Quaternary Science Reviews 27, 1682–1709.
Weber, N., 2004. Morphologie, Architecture des dépôts, Evolution Séculaire et millénaire du littoral Charentais: Apports de la sismique réflexion combinée à des suivis bathymétriques et validée par des vibrocarottages. Université de La Rochelle, La Rochelle, p. 372.
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.
Wilson, G.P., Lamb, A.L., Leng, M.J., Gonzalez, S., Huddart, D., 2005. Variability of organic [delta]^{13}C and C/N in the Mersey Estuary, U.K. and its implications for sea-level reconstruction studies. Estuarine, Coastal and Shelf Science 64, 685–698.
Zaitlin, B.A., 1994. Incised-valley systems: origin and sedimentary sequences. Society of Economic Paleontologists and Mineralogists 51, 45–60.

Web references of databases available online (Last time acceded: Nov 2011)

BRGM database: http://infoterre.brgm.fr/.
Carthage database: http://sandre.eaufrance.fr/.
Marine reservoir correction database: http://intcal.qub.ac.uk/marine/.