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The Holocene transgression as recorded by incised-valley infilling in a rocky coast context with low sediment supply (southern Brittany, western France)

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Key-words. – Incised valley, Rocky coast, Holocene infill, Low sediment supply, Geomorphology, VHR seismic, Vibrocoring, Southern Brittany

Abstract. – A combination of morphobathymetric studies, very high-resolution seismics, core sampling and radiocarbon age data is used to investigate the latest stage of the sedimentary infilling of incised valleys in southern Brittany, related to the Holocene transgression. Owing to the bedrock morphology of this highly irregular rocky coast, two main types of valleys are defined by topographic rocky highs parallel to the coastline: 1) wide and rather shallow incised valleys offshore from a topographic sill, 2) narrow and relatively deep valleys between the sill and the coast (ria-type valley). The sedimentary infilling in both types of valleys becomes highly differentiated as the transgression advances onto the coastal area. In the wide valley seaward of the topographic sill, the infilling consists mainly of offshore heterolithic facies while, in the ria-type valley, most of the infill is composed of brackish mudflat deposits and estuarine tidal muddy sands. As the transgression proceeds, the rocky highs are flooded and the whole area is finally covered by the offshore facies. Radiocarbon dating indicates that: 1) the marine ravinement surface is highly diachronous (a few thousand years cross-shore); 2) the top of the offshore facies, coarser and very shelly, represents an episode of condensed sedimentation from about 3000 to 4000 years ago, amalgamating the maximum flooding surface (MFS) and the highstand systems tract (HST). However, we observe a muddy drape, strongly bioturbated in places, in the most proximal areas, overlying the offshore facies. It is thought to represent the modern and most recent stage of sedimentary infilling. This mud cover is made of fine-grained sediments of fluvial and biological origin, and is interpreted as a prograding HST. It reflects an increased influx, partly due to human activities. Finally, the main features of incised valley sedimentary infilling in a rocky coast context with low sediment supply can be characterized by (i) the very strong control of bedrock morphology, (ii) the diachronous character of the transgression, (iii) the late position of the MFS, and (iv), the highly reduced volume of the HST.

Transgression holocène enregistrée dans le remplissage des vallées incisées sur une côte rocheuse en contexte de faible apport sédimentaire (Bretagne Sud, Ouest de la France)

Mots-clés. – Vallée incisée, Côte rocheuse, Remplissage holocène, Flux sédimentaire faible, Géomorphologie, Sismique THR, Vibrocarottage, Bretagne Sud

Résumé. – Des données morphobathymétriques, de sismique très haute-résolution, de carottages et des datations ^{14}C ont été utilisées afin d'étudier au cours de la transgression holocène la dernière étape du remplissage sédimentaire en mer des vallées incisées du sud de la Bretagne. Dans un contexte où la côte rocheuse est rugueuse et la morphologie du substratum très irrégulière, deux principales vallées ont été identifiées : 1) une vallée large et assez peu incisée au sud d'un seuil topographique orienté parallèlement au littoral, 2) et une vallée relativement profonde entre ce seuil et la côte (vallée de type ria). Au cours de la transgression, le remplissage sédimentaire diffère fortement dans les deux types de vallées. Dans la vallée large, le remplissage se compose principalement de faciès sédimentaire hétérolithique d'offshore, tandis que dans la vallée de type ria, le remplissage est composé de vasières de fond de baie et de dépôts sablo-argileux mis en place dans un contexte dominé par la marée. La transgression se poursuit, les seuils rocheux sont alors inondés et l'ensemble de la région est enfin couverte par le faciès d'offshore. La datation par radiocarbone indique que : 1) la surface de ravinement marin est fortement diachrone (quelques milliers d'années); 2) le sommet des faciès d'offshore, grossier et très coquillier, représente un épisode sédimentaire condensé d'environ 3 000 à 4 000 ans, où sont amalgamés la surface d'inondation maximale (MFS) et le cortège de haut niveau marin (HST).

Un drapage argileux d'extension non continue, fortement bioturbé et compact représente l'unité sédimentaire la plus récente de ce remplissage. Cette couverture argileuse correspond à des sédiments fins d'origine mixte, fluviale et biologique, interprétée comme des dépôts progradants. Elle reflète une augmentation du flux, en partie dus aux activités humaines. Enfin, les principales caractéristiques du remplissage sédimentaire des vallées incisées dans un contexte de

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côte rocheuse où le flux sédimentaire est faible, peut être caractérisée par (i) la très forte maîtrise de la morphologie rocheuse, (ii) le caractère diachrone de la transgression, (iii) la position tardive de la MFS, et (iv) la forte diminution du volume du HST.

INTRODUCTION

Quaternary variations of sea level strongly influenced the evolution and the distribution of ancient and present-day coastal systems in the world. On several occasions, marine transgressions advanced along valleys incised during the previous sea-level falls. Over the last 20 years, the stratigraphy and infilling of incised valleys worldwide has also given rise to many studies [Allen and Posamentier, 1993 and 1994; Dalrymple *et al.*, 1994; Thomas and Anderson, 1994; Zaitlin *et al.*, 1994]. On the Atlantic seaboard, more recent studies have allowed us to specify a model for the filling of the "fossil" valleys leading out onto the continental shelf [Proust *et al.*, 2001; Lericolais *et al.*, 2001; Fénies and Lericolais, 2005; Weber, 2004; Weber *et al.*, 2004; Menier, 2004; Menier *et al.*, 2006; Chaumillon *et al.*, 2008b; Chaumillon and Weber, 2006; Thinon *et al.*, 2008]. More recently (1998 to 2007), new high-resolution and very high-resolution (HR and VHR) seismic data were gathered to get better constraints on the mapping and the morphology of the incised valleys, as well as the stratigraphy of their sedimentary fillings [Proust *et al.*, 2001; Menier, 2004; Menier *et al.*, 2006]. The valleys are oriented parallel or at right angles to the south Brittany coast, and range in width from 200 to 4000 m [Menier, 2004]. They display several morphologies in cross-section, including V-shaped valleys with rounded bottoms, flat-bottoms and steep sided valleys, as well as valleys with stepped terraces. The reconstruction of the longitudinal profiles also reveals major discontinuities characterized by the presence of topographic highs. Most of them can be associated either with the reactivation of the major Cadomian and Hercynian fractures in the area, or with lithological contrasts, or even a combination of both factors [Menier, 2004; Menier *et al.*, 2006].

According to Proust *et al.* [2001] the infilling of incised valleys in southern Brittany is generally composed of two sedimentary sequences. The basal sequence appears to correspond to braided-river sediments deposited during Saalian and/or Elsterian sea-level lowstands, or even older [Menier *et al.*, 2006]. This basal sequence is capped by a second depositional sequence related to meandering and estuarine fluvial environments, of unknown age, evolving later into open marine facies (offshore). The base of the marine facies has been dated to 8627 +/– 243 cal yr B.P. from an offshore drillhole in the Bay of Vilaine described by Bouysse *et al.* [1974] (fig. 2). Therefore, it seems that incised valleys of southern Brittany are characterized by a compound infilling whose preservation is interpreted as resulting from recent tectonic reactivation of the South Armorican block [Proust *et al.*, 2001].

Here we present a detailed description of the upper sequence, which is also the best developed, and where most of the deposits are coeval to the last postglacial marine flooding of the incised valleys. This work focuses on the final stage of infilling. It is based on an approach combining seismic and morphobathymetric surveys between the Bay of Vilaine and the Bay of Quiberon. In particular, this study evidences the drastic influence of the basement morphology on the successive infilling stages and associated stratigraphy, as well as on the differentiation and the evolution of shallow marine environments in South Brittany, characterized by a rocky coast context with low sediment supply.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The Bay of Quiberon and the Bay of Vilaine are located in the southeast of the Armorican Massif on the northern part of the Armorican oceanic margin (between Long. 3^o15 – 2^o30 W and Lat. 47^o45 – 47^o15 N), extending from the ria of Etel in the west to the Pointe de Croisic in the east (fig. 1). This physiographical unit corresponds to the "internal domains" or "*précontinent breton*" defined by Pinot [1974], while the two other units defined by Vanney [1977] are termed "central domains" and "external domains" on the scale of the South Armorican plateau. The internal domains are located between the coast and the -50 m isobath, with a width varying from 5 to 14 km. They comprise two parts (fig. 1):

– an inshore part, with water depths shallower than 25 m, made up of bays (Quiberon and Vilaine);

– an offshore part, with 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, or more rarely N030-060. These features are separated from each other by fossil valleys (passage of La Teignouse), that are incompletely filled [Ferronière, 1922; Guilcher, 1948; Pinot, 1974; Vanney, 1977].

From a geological point of view, the bays of Vilaine and Quiberon are limited by two major structural discontinuities related to the late Hercynian history of this area: in the north, the South Armorican shear zone and, in the south, the South Armorican fault zone [Pinot, 1974; Vanney, 1977; Thinon *et al.*, 2008]. The two bays are characterized by a Cenozoic sedimentary cover, a few tens of metres thick, which overlies a basement made up of igneous and metamorphic rocks (granitoids, gneisses and mica schists) emplaced during the Hercynian orogeny. The Cenozoic cover is made up of faulted, tilted and slightly folded calcareous rocks, attributed to the Bartonian and Ypresian [Andreieff *et al.*, 1968; Guillocheau *et al.*, 2003]. They are overlain with an angular discordance by poorly sorted terrigenous sediments of Plio-Quaternary age [Horn *et al.*, 1966; Barbaroux *et al.*, 1971; Bouysse *et al.*, 1974; Proust *et al.*, 2001; Menier, 2004; Menier *et al.*, 2006]. The upper part of this sequence, Holocene in age, is presented in this article. The base can be sub-outcropping, sometimes weathered [Bouysse *et al.*, 1966; Bouysse and Vanney, 1966], and is locally overlain by Eocene and more recent sediments (plateaus of Artimon and Le Four).

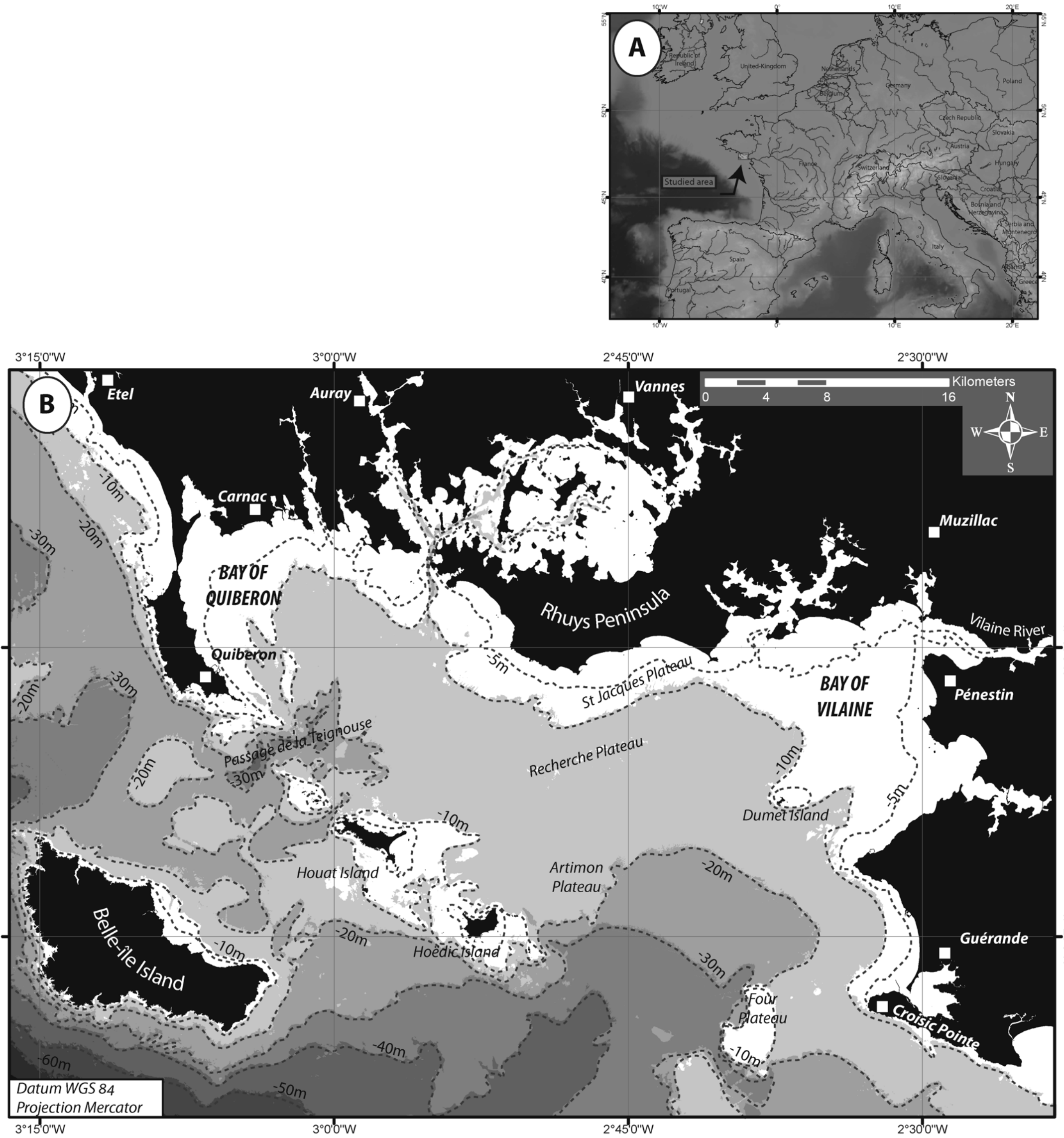

FIG. 1. – A) General location. B) Bathymetric map of the Bay of Quiberon - Bay of Vilaine coastal area.
FIG. 1. – A) *Localisation générale.* B) *Carte bathymétrique de la baie de Quiberon et de la Vilaine.*

Present-day hydrodynamics and sedimentology

The hydrodynamic conditions of the studied area are characterized by their close dependence on the geomorphological context.

The strongest swells are in general associated with westerly gales. To the south of Belle-Ile, wave have heights ranging from 4 to 6 m (Hs), a mean period of 6 to 8 s, and mainly come from the W-NW [Tessier, 2006]. In the Bay of Quiberon and Bay of Vilaine, swell dynamics shows a strong variability of periods and heights compared to farther offshore. The mean significant wave height lies between 1 and 2 m for a mean period of 2 to 5 s [Tessier, 2006].

The tide is semi-diurnal with an average range of 4-5 m. The tidal currents are moderate, with a maximum of about 0.25 to 0.4 m/s during mean spring tides, and are strongly eddying. Closer to the coasts, the current becomes much stronger in the passageways between the Quiberon peninsula and the neighbouring islands (Belle-Ile, Houat and Hoëdic). Hence, during mean spring tides at the passage of La Teignouse, the surface current reaches a velocity of 0.9 m/s at flood and 1 m/s at ebb [S.H.O.M, 1990]. At the entrance of the Gulf of Morbihan, the current reaches 2.2 m/s during ebb and 1.8 m/s during flood. In the Vilaine estuary, currents reach 1.5 m/s during spring tides, both at flood and at ebb [S.H.O.M, 1997].

Sedimentation in the Bay of Quiberon and Bay of Vilaine is primarily sandy pelitic. Grain-size and chemical analyses of the deposits reveal two sectors within the Bay of Quiberon [Vanney, 1977]. One sector is located west of the longitude of Houat, where the muddy sediment supply is associated with abundant quantities of shelly sands. The seafloor is shaped by sediment waves a few tens of centimetres high, with a wavelength superior to 1000 m. Sand-dominated raised areas border channels that are richer in muds. The seafloor becomes more regular towards the east, forming the muddy floor of Houat. Grab sampling in this sector recovered a fine loamy blue mud, with rare sands except in the immediate vicinity of the belt of strong currents. The type of morphology and coating of the Houat muddy floor resembles that of the Bay of Vilaine situated farther north, since this latter is mainly occupied by muds around the rocky limestones of the Artimon and Four plateaus [Vanney, 1977].

Rivers entering the Gulf of Morbihan and the Bay of Vilaine represent the principal source of terrigenous supply in the Bay of Quiberon and in the Bay of Vilaine. The only precise data available referring to sediment fluxes from the Vilaine river, provide estimation of 0.1 x 10^6 tonnes per year (suspended discharge) [Jouanneau *et al.*, 1999]. Moreover, geochemical analyses of the clayey and non-clayey assemblages of the superficial deposits [Lafond, 1961; Bouysse *et al.*, 1966; Gouleau, 1975] allow proposing a marine origin supplemented by sediment inputs of the Loire river [Barbaroux and Gallene, 1973]. However, the amount of sediment supplied in suspension from the Loire river to the bay of Vilaine remains unknown.

Methods

The present study is based on a combined approach involving morphobathymetric and seismic data supplemented locally by vibrocores (fig. 2).

The morpho-bathymetric data used here are derived from the multibeam data available from the Hydrographic and Oceanographic Service of the French Navy (S.H.O.M). After tide correction, the whole data set is used to elaborate a regular grid by geostatistical interpolation, leading to a digital elevation model (DEM) implemented with the ArcGis software.

The seismic data result from campaigns carried out within the framework of the Cotarmor research project [Proust, 1999] as well as a scientific program headed between 2000 and 2008 by the University of Southern Brittany (D. Menier). The seismic surveys were carried out on board the R/V "Côtes de la Manche" (CNRS/INSU) and the R/V "Sepiola" (Bailleron marine station, University of Rennes 1). The seismic profiles cover a zone extending from the present-day mouth of the Vilaine and heading southwest towards Belle-Ile and south of Hoëdic, up to water depths of about 40 m. These data were gathered with a sparker and a SIG monotrace streamer (HR data), as well as an IKB-Seistec Boomer [VHR data: Menier *et al.*, 2001] characterized by a line-in-cone receiver [Simpkin and Davis, 1993]. During the survey, seismic data acquisition was carried out with the DELPH ELICS software. Positioning, ensured by a DGPS, was recorded also with Delph Elics simultaneously with the seismic data. Seismic data were processed using the seismic Unix software. Swell filtrering was made following a method developed at the La Rochelle University and briefly described in Chaumillon *et al.* [2008a]. The results obtained from the interpretation of the profiles were then exploited by means of the Seisvision software. For time-to-depth conversion, a seismic wave velocity of 1800 m/s was assumed in the sediment from the infilling.

In addition to the morphobathymetric and seismic data, sedimentary cores were collected by vibrocoring during the Carosub survey (Ifremer/Génavir R/V "Thalia"). Although

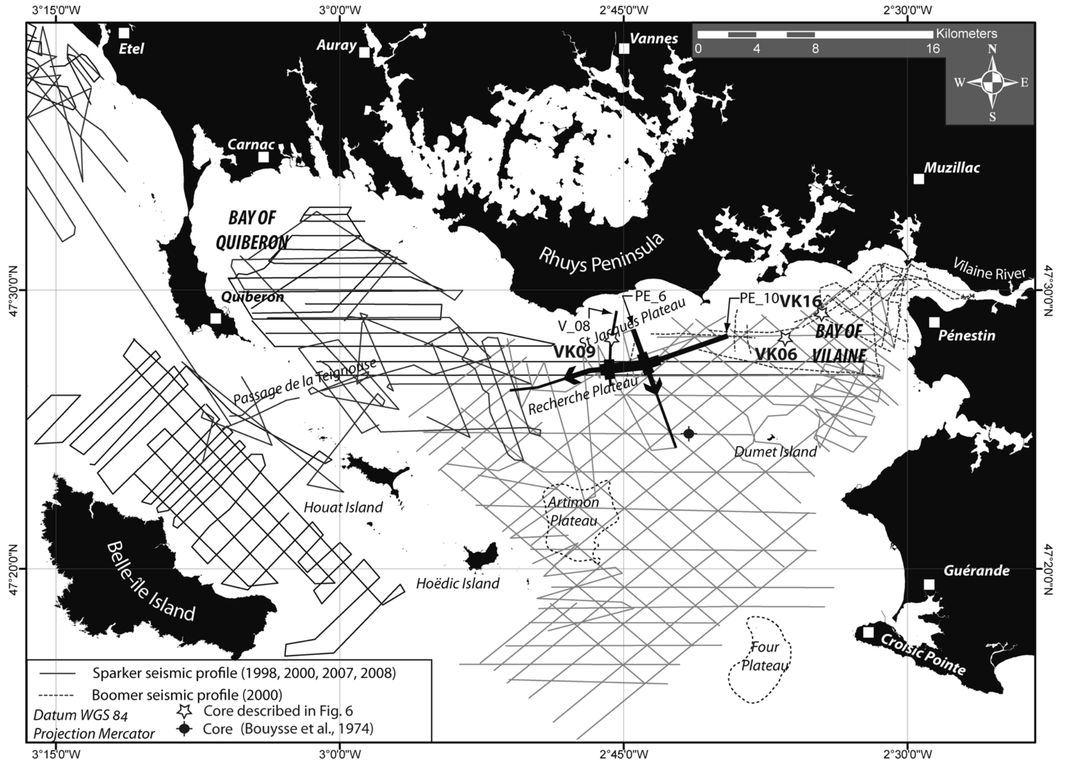

FIG. 2. – Map showing the position of HR (full lines) and VHR (dotted lines) seismic profiles available in the study area. The three profiles shown on figures 3, 4 and 5 are indicated as bold lines.

FIG. 2. – *Carte montrant la position des profiles sismiques* HR *(traits pleins) et* THR *(pointillés) disponibles dans la zone d'étude. Les trois profils des figures 3, 4 et 5 sont indiqués en gras.*

rather short (maximum: 4 m), the cores allowed us to calibrate the sedimentological nature of most infilling units [Bouaouina, 2006]. Some key marker beds were dated in these cores. AMS radiocarbon dating was carried out on intact shells and bulk sediment. Measurements were performed at the Poznan Radiocarbon Laboratory (Poland).

RESULTS

Seismic data

The analysis of seismic profiles consists in defining the characteristics (continuity, amplitude and frequency), configuration and termination of the reflectors according to the classic rules of seismic stratigraphy as defined by Mitchum *et al.* [1977]. Analyses and description of acoustic facies and seismic units have already been detailed in previous studies [Proust *et al.*, 2001; Menier, 2004; Menier *et al.*, 2006]; therefore we only provide hereafter a brief overview of the results. The seismic units are described along with their boundaries, while the characteristics of the acoustic facies are summarized in table I.

To illustrate the Holocene infilling of the incised valleys in the sector located between the Bay of Vilaine and the Bay of Quiberon, we selected three seismic profiles (two sparker lines and a boomer line). These profiles are located in the central part of the study zone, between the two bays, in the area of La Recherche plateau to the south of the Rhuys peninsula.

On the three profiles (sparker profiles: PE10 and PE6; boomer profile V08), located at water depths ranging from 5 to 15 m, we identified seven main seismic units, two of them belonging to the basement. The Quiberon, Vilaine and Artimon valleys cut down into Hercynian and Ypresian formations, which correspond to the seismic units U01 and U02, respectively (fig. 3, 4 and 5; table I). U01 is characterized by discontinuous reflectors with a chaotic configuration. It represents the acoustic basement made up of faulted magmatic and/or crystalline metamorphic rocks. The U02 unit, visible to the south of the Recherche plateau (figs. 3, 4 and 5; table I) overlies the U01 unit through an irregular surface. U02 shows a set of continuous reflectors of strong amplitude, gently sloping and locally deformed. Based on a drill hole in the Bay of Vilaine [Bouysse *et al.*, 1974] and on land exposures in the Tertiary basins of the Vendée [Borne, 1986; Thomas, 1999], these deposits correspond to the Ypresian formations interpreted as shallow marine detrital facies [Borne, 1986; Thomas, 1999].

Five seismic units, named U1, U2, U3, U4 and U5 from the base towards the top, were identified in the sedimentary infilling of the incised valleys, overlying the units of the substratum U01 and U02 (figs. 3, 4 and 5; table I). These units are illustrated on the selected profiles, except for U5, which is only visible on the boomer profile V08 (fig. 5).

Unit U1

This unit lies above unit U01 (figs. 3, 4 and 5), showing a thickness varying between 5 ms and 8 ms TWTT (i.e. 4.5 to 7 m). It is recognized mainly in the area north of the

TABLE I. – Characteristics of acoustic facies and seismic units, and their interpretation in terms of depositional environment.
TABL. I. – *Caractéristiques des faciès acoustiques et des unités sismiques, et leurs interprétations en terme d'environnements de dépôts.*

	Unit	Facies	Illustration		Continuity	Amplitude	Frequency	Reflectors configuration	Interpretation
			Boomer	Sparker					
Valley sediment infilling	U5	Fs 6b			Low	Low	Low	Aggradant parallel to sigmoid	Pure mud, with locally intense bioturbation
	U4	Fs 6a			Medium	High	Medium	Aggradant parallel	Offshore marine muds with storm layers
	U3	Fs 5b			High	Medium to High	Medium to High	Sigmoid aggradante parallel	Estuarine tidalflat to tidal channels
		Fs 5a			Medium to Low	Low	Low	Aggradant parallel	
	U2	Fs 4			Low	Low	Low	Chaotic to agradant	Internal mudflat in ria type valley
	U1	Fs 3			Medium	Medium to High	Medium	Chaotic to progradant	Fluvial sandy channels
Substratum	$U0_2$	Fs 2			Low	High	Medium	Chaotic	Ypresian
	$U0_1$	Fs 1			Very low			Chaotic	Hercynian basement

Recherche plateau. The base of U1 corresponds to an onlap, downlap or a concordant surface, while its top is marked by a high amplitude reflector corresponding to a rather irregular surface. The basal surface locally exhibits the morphology of a flat to rounded-bottom valley, the sides of which are locally very steep. The reflectors of U1 show a medium continuity and frequency with medium to high amplitude. Their configuration is oblique sigmoidal to oblique parallel. These acoustic characteristics led Proust *et al.* [2001] to interpret U1 as fluvial channels. This unit has never been reached by coring.

Unit U2

U2 overlies units U01 and U1 (figs. 3, 4 and 5), and shows an acoustic thickness varying from 5 to 20 ms TWTT (i.e. 4.5 to 18 m). Its base is delimited by a surface of onlap, downlap or concordance, while the top is a surface of irregular truncation. It is composed of facies Fs4 (table I), which is characterized by poorly continuous reflectors of low amplitude and frequency, evolving laterally to a better continuity and higher amplitude. The configuration is parallel to sub-parallel (aggrading geometry). These acoustic characteristics are interpreted as corresponding to fine-grained deposits characteristic of a low-energy environment such as mudflats in an embayment or inner estuary.

Unit U3

This unit occurs above units U01 and U2 (figs. 3, 4 and 5), showing an acoustic thickness that can reach 15 ms TWTT (approximately 13.5 m). Its base is delimited by a surface of onlap or concordance. This surface is characterized by channelised structures with rounded bottom and smoothed sides. The top of U3 corresponds to a planar erosional surface. The channels can pass laterally into more planar geometries. Unit U3 is made up of two seismic facies (Fs5a and Fs5b; table I), interpreted as tidal flat deposits and coarser deposits within tidal channels.

Unit U4

This unit overlies units U01, U02 and U3 (figs. 3, 4 and 5). It extends over the entire study area except for the shoals of la Recherche, St Jacques and Ile Dumet (fig. 3) and reaches a thickness of 20 ms TWTT (about 18 m). Its top corresponds to the present-day seafloor or to the base of unit U5. U4 is made up of an acoustic facies characterized by parallel planar reflectors of medium to high continuity and frequency, and strong amplitude. U4 is interpreted as the offshore muds already defined by Proust *et al.* [2001] and identified as the main sedimentary unit in the BRGM drillhole C5 [Bouysse *et al.*, 1974].

Unit U5

U5 rests on top of unit U4, and even, very locally, directly on U01 (fig. 5). Its thickness does not exceed 1-2 ms TWTT (approximately 0.9-1.8 m). It is present exclusively to the north of La Recherche Plateau, but can only be confidently identified on VHR Boomer profiles. Its acoustic facies is characterized by chaotic low amplitude reflectors. The basal surface of U5 is concordant while its top surface corresponds to the seafloor, which appears highly irregular. Grab samples show that this unit corresponds to a black mud, locally intensely colonized by crustacean amphipod tubes of the genus *Haploops tubicola*.

It should be noted that acoustically turbid zones related to the presence of gas are locally associated with units U2 or U3, in areas where they are well developed at the bottom of encased paleovalleys to the north of plateau of La Recherche. Alternatively, gas masks can be associated with unit U4 in sectors where it reaches a great thickness, i.e. to the south of La Recherche plateau (fig. 4). Methane genesis

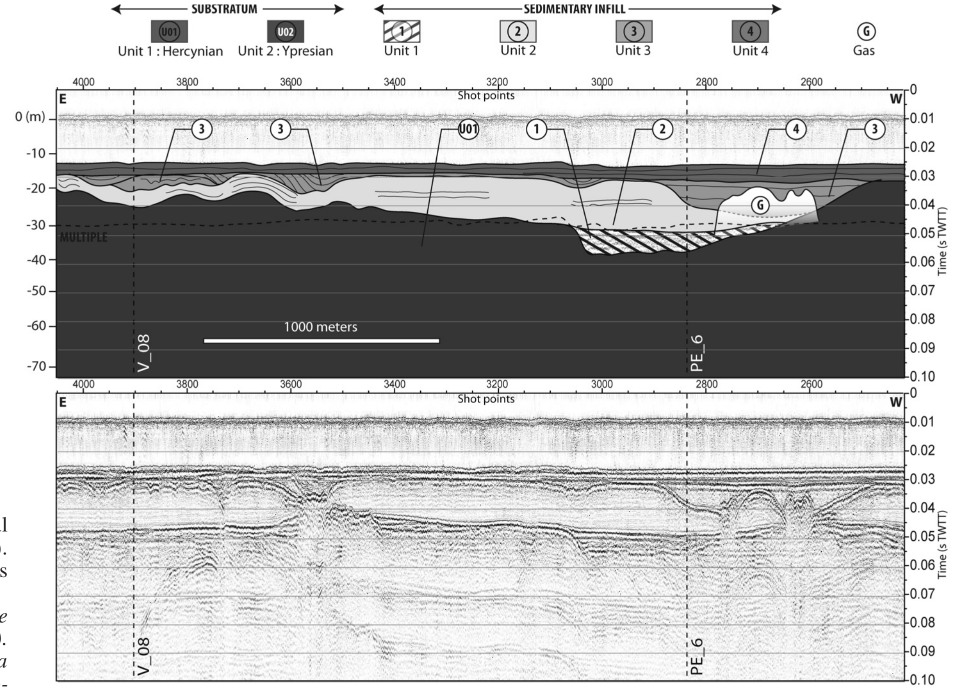

FIG. 3. – Sparker seismic profile PE10. Vertical scale in two-way travel time in seconds (s TWTT). The scale in meters is established for sediments with a P-wave velocity of 1800 m/s.

FIG. 3. – *Profil sismique sparker PE10. Echelle verticale en seconde temps double (s STD). L'échelle en mètres de l'épaisseur des sédiments a été obtenue en tenant compte d'une vitesse de propagation des ondes P de 1 800 m/s.*

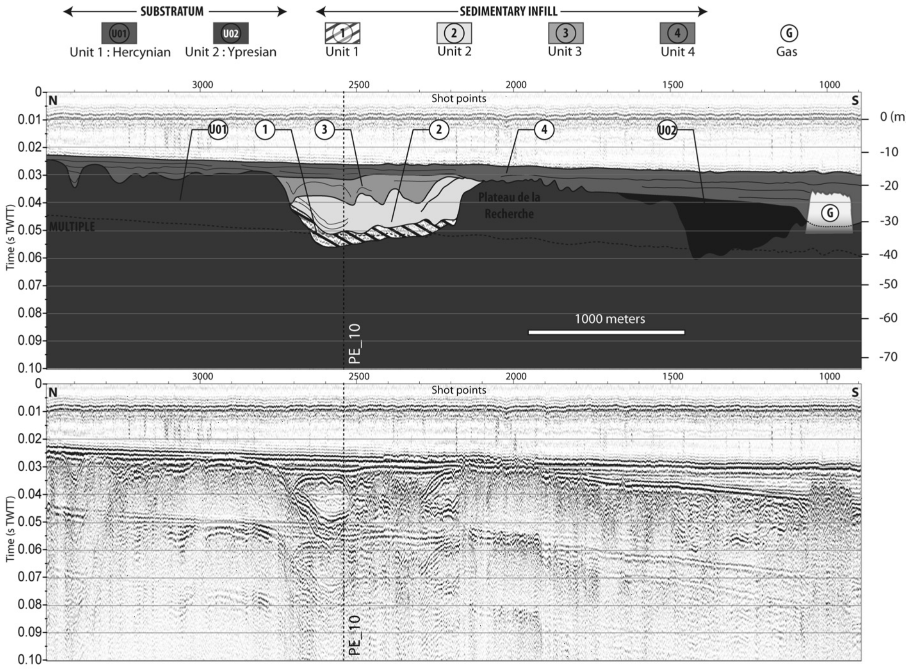

FIG. 4. – Sparker seismic profile PE06. Vertical scale in two-way travel time in seconds (s TWTT). The scale in meters has been established for P-wave velocity in sediment of 1800 m/s.

FIG. 4. – *Profil sismique sparker PE06. Echelle verticale en seconde temps double (s STD). L'échelle en mètres de l'épaisseur des sédiments a été obtenue en tenant compte d'une vitesse de propagation des ondes P de 1 800 m/s.*

from organic-rich sediments is a common process in coastal environments, since rapid burial allows the decomposition of organic matter [Garcia-Gil *et al.*, 2002; Bertin and Chaumillon, 2005; Baltzer *et al.*, 2005; Roussel *et al.*, 2009].

Sedimentary successions and ages

In order to illustrate the lithology of each seismic unit and determine the timing of sediment deposition, we selected three cores: VK09, VK06 and VK 16 (fig. 6). We also use additional data obtained from the drillhole C5 [Bouysse *et al.*, 1974] collected on the southeast of La Recherche plateau (fig. 2).

Core VK09 (fig. 6), pointed on the boomer profile V08 (fig. 5), allows us to document the almost complete sedimentary infilling succession, from unit U2 to unit U5. On the other hand, no date was obtained on this core. The base of VK09 consists of a pure compact brown decarbonated mud, which corresponds to the unit U2. The depositional environment is interpreted as being very sheltered (ria-type estuary, inner mudflat). Unit U2 is capped by an erosional surface overlain by a grey muddy sand succession containing very abundant shell debris, often fetid with locally gravel beds. These very poorly sorted sediments are interpreted as tidal deposits preserved in a low- to high-energy environment (tidal flats and tidal channels). This succession corresponds to the seismic unit U3. The erosive base has a channel-like geometry (cf. V08 profile), and is interpreted as a tidal ravinement surface. The topmost part of the core (1 m) consists of marine muddy sands with crude bedding in the lower part (U4), while the pure brown mud at the top (U5) corresponds to the fluid mud containing *Haploops tubicola* sampled with the grab.

Cores VK06 and VK16, which were sampled to the east of La Recherche plateau, in the mouth of the Bay of Vilaine, enable us mainly to illustrate unit U4 that is difficult to characterize in the preceding core VK09. These cores also provide dates at the base of U4 as well as inside. In both cores, unit U4 corresponds to marine silty mudstones reflecting overall low energy conditions, with intercalations of coarse shelly or sandy beds interpreted as storm deposits. Similar facies types are described in the drillhole C5 [Bouysse *et al.*, 1974]. Moreover both cores VK06 and VK16, together with the C5 drillhole, exhibit a very coarse layer with gravels corresponding to the base of unit U4, interpreted as a marine ravinement surface. In their upper part, VK06 and VK16 show a coarsening-upward trend, with the presence of many shelly beds. Several radiocarbon ages were obtained on each core (fig. 6). In VK06 and VK16, the base of U4 is dated at approximately 6000 and 5000 cal yr B.P., respectively. The base of U4 in drillhole C5 [Bouysse *et al.*, 1974] yields an age of 8627 +/– 243 ^{14}C cal yr B.P. The other dates obtained on VK06 and VK16 show that the major part of the succession was deposited before 3000-4000 cal. yr B.P.

Morphology of the incised valleys

A number of authors have illustrated that the valley-fill architecture is strongly dependent on the morphology of the bedrock [e.g. Heap and Nichol, 1997; Lobo *et al.*, 2003; Menier *et al.*, 2006; Chaumillon *et al.*, 2008b; Burningham, 2008]. In the Bay of Quiberon and the Bay of Vilaine, the morphobathymetric analysis coupled with the seismic data allows distinguishing two hydrographic networks, with very distinct morphologies (fig. 8). These networks correspond

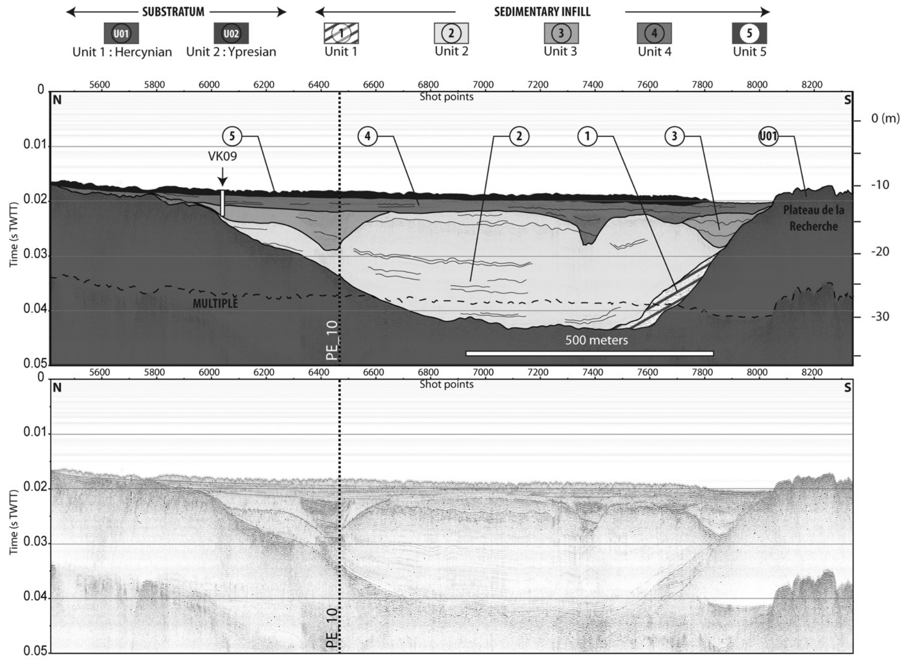

FIG. 5. – Boomer seismic profile V08. Vertical scale in two-way travel time in seconds (s TWTT). The scale in meters is established for sediments with a P-wave velocity of 1800 m/s.

FIG. 5. – *Profil sismique Boomer V08. Echelle verticale en seconde temps double (s STD). L'échelle en mètres de l'épaisseur des sédiments a été obtenue en tenant compte d'une vitesse de propagation des ondes P de 1 800 m/s.*

to the Vilaine paleovalley, on one hand, and to the Artimon paleovalley on the other hand.

The Vilaine paleovalley is oriented parallel to the coast from the present-day mouth of the Vilaine to the west of the plateau of La Recherche, and then bends slightly towards the south (fig. 7). Three distinct sectors can be recognized, corresponding to the eastern, middle and western parts of the study area.

In the eastern sector, we distinguish three valleys. The first runs up from the south and is located between the basin of Asserac and the plateau of Dumet island; the second corresponds to a paleovalley facing the beach of La Mine d'Or (Pénestin), interpreted as the paleovalley of the Loire and Vilaine [Brault *et al.*, 2001; Guillocheau *et al.*, 2003]; the third lies opposite the current outlet of the Vilaine. In this eastern sector, the cross-sections of the valleys range in width between 250 and 750 m. The average depths of incision are about 15-20 m. Three morphological terraces have been defined in this sector [Menier, 2004; Menier *et al.*, 2006].

In the middle sector, the paleovalley follows a rectilinear trend. It is constrained in the north and south by two shoals, the St Jacques and La Recherche plateaus, respectively. Many small valleys converge towards this main axis, in particular the Pénerf paleovalley. In this middle sector, the main valley has an average width of 1200 m. At least three morphological terraces are recognized.

In the western sector, the main paleovalley converges towards the passage of La Teignouse, along with other paleovalleys coming from the North (Gulf of Morbihan: rivers of Crac'h, St Philibert and Auray) as well as older fossil valleys (Sarzeau) joining from the northeast. Their widths range between 800 and 1000 m for an average depth of incision of approximately 20 m. Exceptionally, depths of incision ranging between 30 and 40 m are noted at the exit of the mouth of the Gulf of Morbihan.

The Artimon paleovalley exhibits a SW-NE trend. It is a dendritic-type network corresponding to a catchment area disconnected from the present-day drainage network. Moreover, it is separated from the network of the Vilaine paleovalley by a watershed extending between the island of Houat and the plateau of Dumet island through the plateau of La Recherche. It is characterized by three main branches (fig. 7).

A northern branch is situated between the plateau of La Recherche and the plateau of Dumet island. In this area, the valley reaches 4000 m in width. The depth of incision is rather shallow and rarely exceeds a few metres.

A second branch starts southwest of plateau of La Recherche and runs towards the southeast with a narrowing in the passageway that separates Hoëdic island from the Artimon plateau. The width of the valleys varies between 600 and 400 m. The depths of incision can reach 10 to 15 m, even increasing to about 30 m to the east of Hoëdic.

A third branch arises to the north and south of plateau of Four. The valleys here have widths of about 400 to 750 m, with an incision depth of 20 to 25 m.

The second and third branches are oriented parallel to the alignment formed by Quiberon and the islands of Houat and Hoëdic, which is controlled by the inherited geomorphological features of this sector. Indeed, the rivers follow the main N120-trending fractures (faults). The orientation of the paleovalley network is constrained by the presence of shoals, which are themselves delimited by tectonic discontinuities of the basement [Menier, 2004; Menier *et al.*, 2006]. The three branches then converge towards the southwest to form a single thalweg joining the valleys of the paleo-Loire.

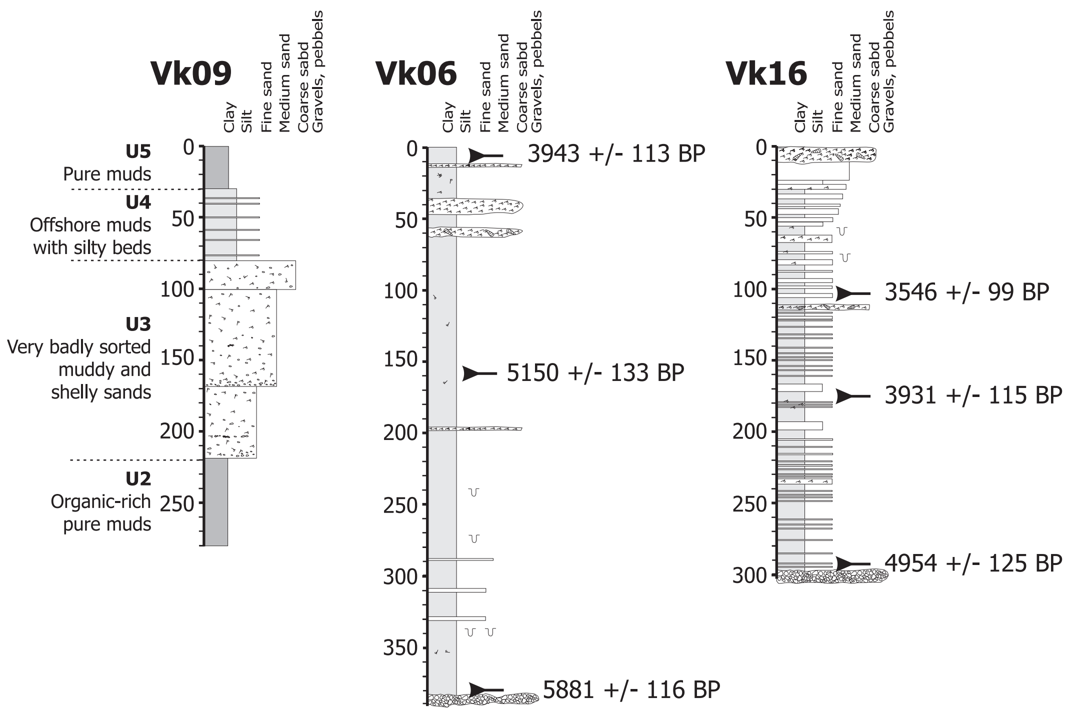

FIG. 6. – Lithological description of selected cores collected in the Vilaine estuary (Vk09, Vk06, Vk16) (cf. fig. 2 for location). Vk09 has been selected because it allows illustrating almost all Holocene seismic units (from U2 to U5) that compose the Vilaine incised valley infilling. Vk06 and Vk16 have only crossed the seismic unit U4 (offshore muds) and reached its bottom (the wave ravinement surface). AMS ^{14}C ages calibrated and shown in years B.P.
FIG. 6. – *Description lithogique des sondages sélectionnés et collectés dans l'estuaire de la Vilaine (*Vk09, Vk06, VK16*) (cf fig. 2 for location).* Vk09 *a été sélectionnée parce qu'elle illustre la presque totalité des unités sismiques (depuis* U2 *à* U5*) qui compose le remplissage sédimentaire de la vallée incisée de la Vilaine.* Vk06 *et* VK16 *traversent seulement l'unité sismique* U4 *(argiles d'offshore) et atteint vers le sommet la surface de ravinement par la houle. Les âges AMS ^{14}C sont calibrés et exprimés en années B.P.*

To summarize, the Vilaine paleovalley is a rectilinear elongate valley following a general N030 trend from the present-day mouth to the passage of La Teignouse. A maximum depth of incision of about 40 m is reached near the present-day mouth and also near the passage of La Teignouse. The width very rarely exceeds 1000 m. The Artimon paleovalley, by contrast, does not show any preferred orientation, except for a N120-trending segment to the north of Houat and Hoëdic. It forms a very wide valley, particularly in the north where the width can exceed 4000 m and the incision is less deep than in the Vilaine valley. Only the segments to the north of Hoëdic and the plateau of Le Four are narrower and deeper, the incision reaching a depth of 30 m to the east of Hoëdic.

Hence, the morphology of the roof of the substratum differs between the Vilaine paleovalley in the north, which forms a "trough" incised homogeneously over almost the entire area, and the Artimon paleovalley farther offshore to the south (fig. 8).

DISCUSSION

Morphological inheritance, sea-level rise and environmental conditions of deposition

The reconstruction of the main stages of the last sea-level rise in the Bay of Quiberon and the Bay of Vilaine allows us to document the paleogeographic evolution of the coastal landscapes. This schematic reconstruction was based on flooding the morphology of the top of the bedrock. Due to the presence of a topographic rocky high extending from Houat to Pointe de Croisic, passing via the plateau of La Recherche, the ocean only communicated partially with these two bays, before invading them completely through the passage of La Teignouse and another passage located south of Hoëdic (fig. 8). Thus, the conditions of deposition differed greatly between the Artimon and Vilaine paleovalleys, located offshore and landward of the topographic sill, respectively. Consequently, the fossil valley of the Vilaine was filled for the most part under calm conditions of deposition, protected from the action of southwesterly swells by this structural sill. At the same time, the sea invaded the Artimon paleovalley, which was less incised and more exposed to the higher energy conditions of the open marine environment.

The Holocene sedimentary infilling: bedrock control, stratigraphy, hydrodynamic forcing and anthropogenic factors

As transgression started in the lowest parts of the valleys, during the rapid rise of sea level at the beginning of the Holocene, the basal sediments were deposited on remnants of river terraces built up during the preceding low sea-level stand(s) (U1). In the lower valley of the Vilaine, these basal deposits correspond to embayment or estuarine facies belonging to an aggrading unit (U2) formed by inner mudflat facies. At the same time, the sea had already invaded the lower valley of Artimon, covering by coarse transgressive sands (at the base of U4 in C5 drillhole) the metamorphic bedrock or the lowstand fluvial deposits (U1) where these were preserved.

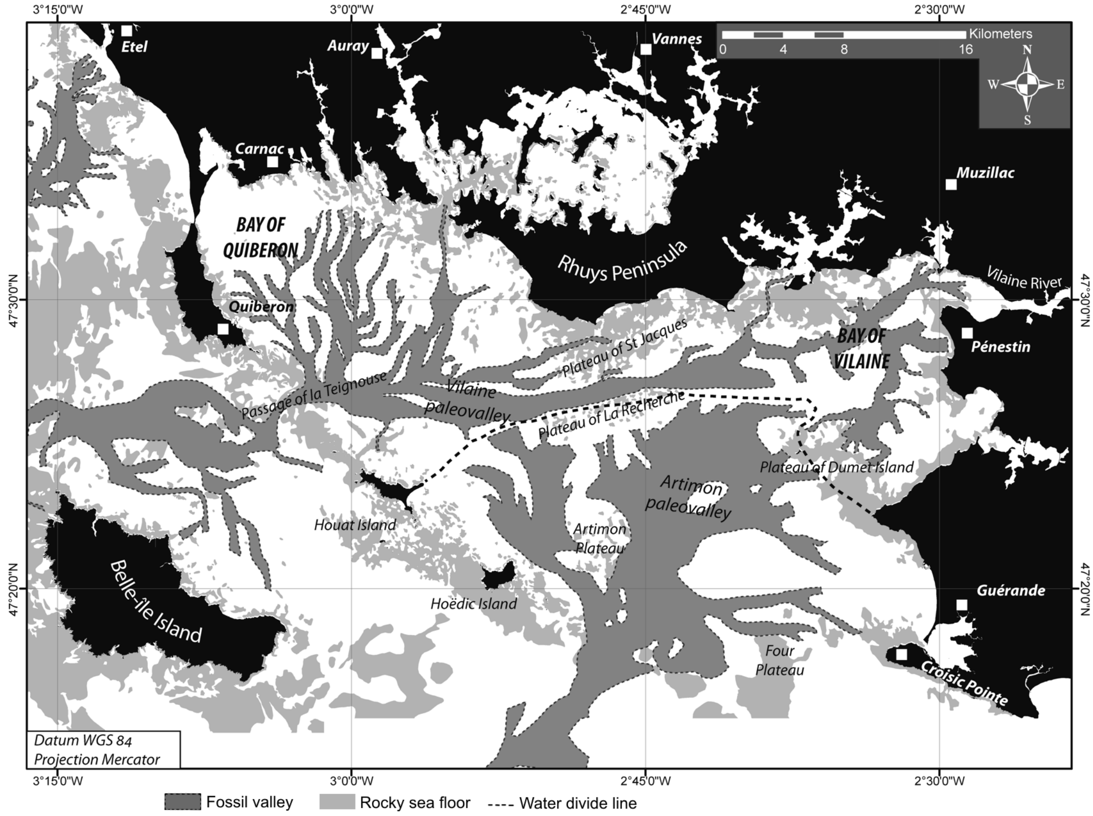

FIG. 7. – Reconstruction of the paleovalley network in the Bay of Quiberon - Bay of Vilaine study area [after Menier, 2004 and Menier *et al.*, 2006].
FIG. 7. – *Reconstitution du réseau de paléovallées en baie de Quiberon et en baie de Vilaine [d'après Menier, 2004 et Menier* et al., *2006].*

While the marine incursion proceeded over the Artimon Valley, which was filled by muds intercalated with storm deposits (U4), the advance was probably not so rapid in the valley of the Vilaine located behind the bedrock high represented by the axis "Houat – Hoëdic – La Recherche plateau". The aggradation of the ria mudflats in the Vilaine was followed by the formation of a channelled belt that reflects the transgressive trend towards an active estuary mouth environment (U3). The accumulation of this meandering channel-unit indicates a slowing down in the rate of sea-level rise, even though the transgression continued. The sea eventually submerged the topographic high and definitively flooded the valley of the Vilaine. The latter then became subject to the action of offshore swell, which led to a partial erosion of the estuary mouth and finally to its cover of muds interbedded with storm deposits (U4). At the same time, the accumulation of these offshore muds continued in the Artimon valley.

The final stage of filling is expressed by the muddy unit U5, which is located in the proximal sectors north of La Recherche plateau. The accumulation of these lower energy muddy sediments, locally colonized by *Haploops tubicola* (Crustaceans, amphipods), reflects depositional conditions that contrast very strongly with the underlying muds.

Regarding the chronology of the infilling, AMS ^{14}C analyses allow to date the successive stages of sedimentation.

Seaward of the topographic high, the Artimon Valley was flooded at the beginning of the Holocene, as indicated by the 8627 +/– 243 cal. yr B.P. age obtained at the base of U4 in the BRGM drillhole C5.

Landward (to the north) of the topographic high, the marine incursion is dated to 5000-6000 cal. yr B.P., as indicated by radiocarbon ages of the marine ravinement surface, matching the base of U4 in this sector. The marine flooding is, therefore, delayed by at least 2000 years landward of the topographic high. The formation of the tidal channel belt pre-dates this marine incursion. The slowing down of sea-level rise recorded by the tidal channel belt infers the presence of the rocky sill acting as a barrier, but it is also likely related to the slower rate of Holocene sea-level rise at 7000-6500 cal. yr B.P. No data are available concerning the age of sedimentation of the lowermost unit (inner mudflat deposits of U2). However, we might assume that aggradation of the mudflats started at the beginning of the Holocene.

The ages obtained at the top of Unit U4 in cores VK06, and VK16 show that sedimentation was extremely reduced over the last 3000-4000 years. Thus, the coarse upper part of these cores corresponds to a condensed interval, rich in shelly beds, which amalgamates the maximum flooding surface (MFS) and the highstand systems tract (HST) (fig. 9).

In the most proximal zones, seismic data show that U4 is covered by a mud drape (U5) intensely colonized locally by the amphipods (*Haploops tubicola)*. Recent results in this area [Traini *et al.*, 2008] show that these muds are extending both laterally and vertically. The main factors responsible for this mud expansion trend appear to be of both natural and anthropic origin. From a geomophological point of view, the Bay of Vilaine is sheltered from strong swells.

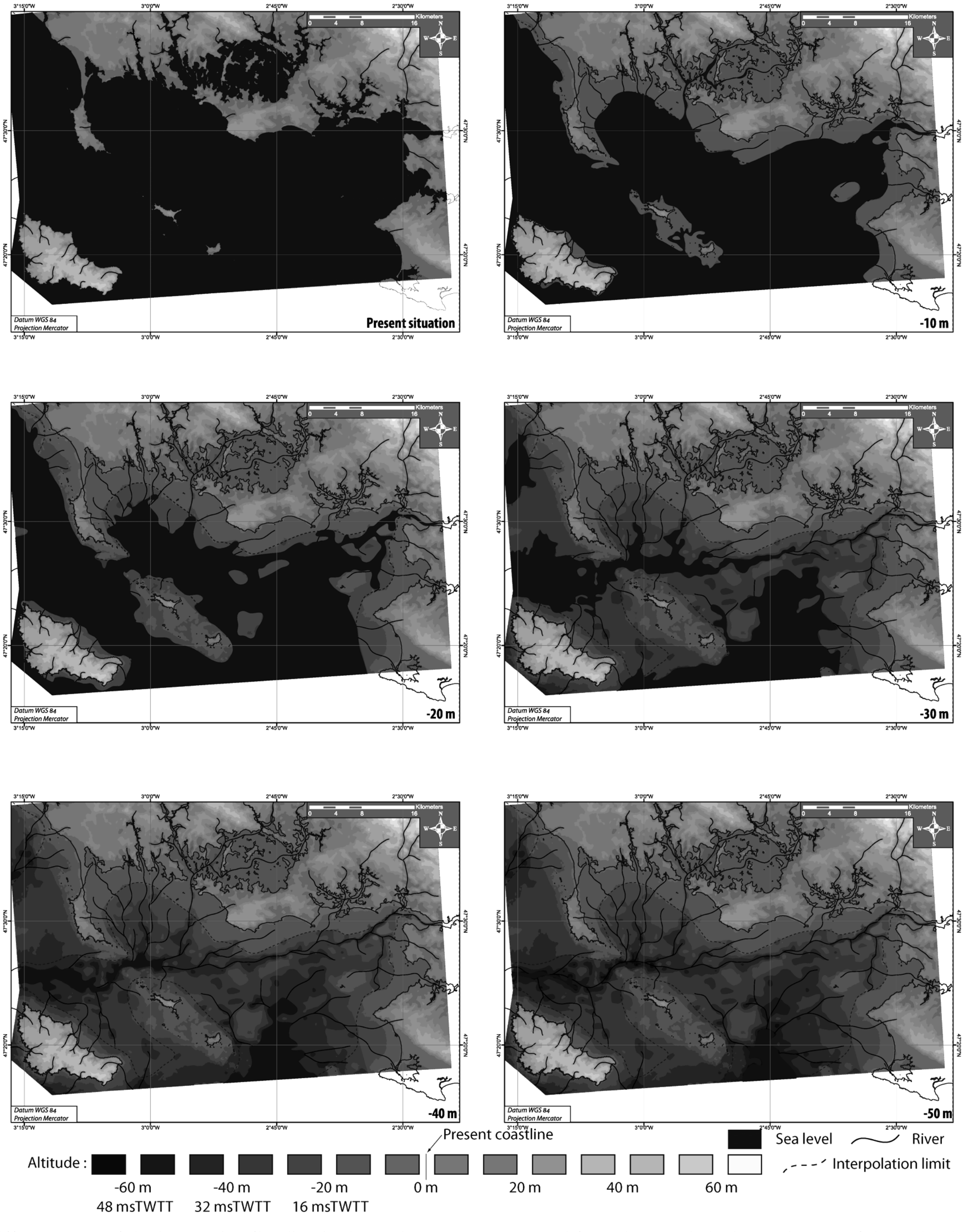

FIG. 8. – The different steps of the last marine flooding in the study area, reconstructed from the morphobathymetric map of the bedrock [after Menier *et al.*, 2009].

FIG. 8. – *Différents stades de la dernière inondation marine dans la zone d'étude, reconstitués à partir de la carte des isohypses du substratum [d'après Menier* et al.*, 2009].*

Also, tidal currents remain fairly moderate, which favours the settling of fine particles. This fine sediment can have several origins. It may be partly supplied from turbid plumes of the Loire river and from floods of the Vilaine River. Considerable loads of suspended particulate matter (SPM) usually occur during fluvial flood events [Goubert, 1997]. In addition, the production of organic particles is favoured by the presence of numerous shellfish farms, both in the Bay of Vilaine and the Bay of Quiberon. Finally, since several years, the techniques of dredging during fishing provoke heavy seafloor reworking and fine-grained sediment resuspension. This human activity induced the deposition on the seafloor of a fine particle layer, 20 to 40 cm thick. We thus believe that the influence of anthropogenic resuspension is significant on the redistribution of sedimentary particles and on the increasing amount of fine sediments into the bay. As mentioned previously, unit U5 is locally intensively colonized by the amphipods (*Haploops*

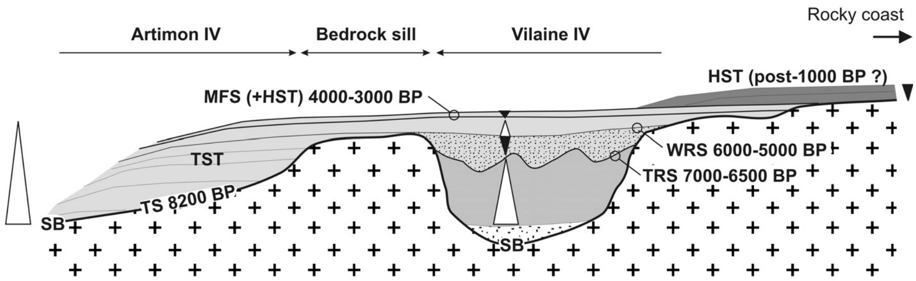

FIG. 9. – Schematic reconstruction of the sedimentary infilling into the Artimon and Vilaine incised valleys (Artimon IV and Vilaine IV) showing the main depositional units and the stratigraphical key surfaces with their ages (the age of 8200 B.P. is after Bouysse *et al.* [1974] and dates the base of the offshore muds overlying LST fluvial deposits). The later have not been shown herein). The general infill is mainly composed of the TST, the HST being very reduced and recent. In the Vilaine IV, two parasequences are defined due to the bedrock sill (see text for explanation). White triangle: transgressive trend, black triangle: regressive trend. SB: surface boundary, TS: transgressive surface (marine ravinement); TRS: tidal ravinement surface; WRS: wave ravinement surface; MFS: maximum flooding surface; TST: transgressive systems tract; HST: highstand systems tract.

FIG. 9. – *Modèle schématique du remplissage des vallées incisées de l'Artimon et de la Vilaine montrant les principales unités de remplissage, les surfaces stratigraphiques remarquables et les âges associés (La datation 8 627 +/- 243 yr cal B.P. [Bouysse* et al.*, 1974] date la base des argiles d'offshore situées au dessus des dépôts fluviatiles). Ces dépôts plus anciens ne sont pas datés. Au sein de la vallée incisée de la Vilaine, deux paraséquences sont définies due à la présence de hauts fonds au toit du substratum (voir explications dans le texte). Le remplissage est principalement composé d'un* TST, *le* HST *étant très réduit et récent. Triangle blanc : corps transgressif, triangle noir : corps régressif.* SB*: limite de séquence,* TS*: surface transgressive (ravinement marin) ;* TRS *: surface de ravinement tidale ;* WRS *: surface de ravinement par la houle ;* MFS *: surface d'inondation maximale ;* TST *: cortège transgressif ;* HST *: cortège de haut niveau.*

tubicola). This gregarious tubicolous species highly impacts on its environment [Ehrhold *et al.*, 2005]. Reported as early as in the 1970s in the Bay of Vilaine [Le Bris, 1988; Le Bris and Glémarec, 1995], *Haploops* now develops over areas of several tens of km^2. Le Bris and Glémarec [1995, 1996] suggest that the recent development of *Haploops* in the Bay of Vilaine could account for the increasing eutrophication of the site related to the increase in inorganic nutrient inputs.

Although no age is available for U5 yet, we assume that this unit is mostly recent, perhaps deposited during the last few decades or centuries coevally to the beginning of anthropogenic activities, which have modified the dynamics of the river catchments and the sea bed. It is noteworthy that a muddy drape unit is also described farther south in the Bay of Marennes-Oléron sector. Here, its occurrence has been partly attributed to anthropic causes and dated to 1000 yr B.P. [Billeaud *et al.*, 2005; Allard *et al.*, 2010]. In any case, U5 marks an important change in the sedimentary dynamics of the Bay of Vilaine and the Bay of Quiberon infillings, contrasting sharply with the underlying unit U4. The deposition of U5 is probably linked to an increase in riverborne fine sediment supply on a regional scale, partly of anthropic origin, and should be thus regarded as a prograding HST (fig. 9).

CONCLUSION

Based on geophysical data coupled with core sampling, morphobathymetric studies and ^{14}C dating, we provide a paleogeographical and paleogeomorphological reconstruction of the sedimentary infilling of the Vilaine and Artimon incised valleys during the Holocene transgression. The "fossil" valley of the Vilaine shows a rather homogeneous incision and is flanked by shoals, contrary to the Artimon valley that appears broad and moderately incised. Several conclusions can be highlighted.

Due to the presence of a topographic rocky sill between the Vilaine and Artimon valleys, the filling is differentiated. In the Vilaine valley, the sedimentary infilling comprises a transgressive systems tract (TST) dominated by sediments deposited under low energy conditions (ria mudflats and estuarine channels), since this inner sector of the bay is sheltered from the action of southwesterly swells by a structural, submerged sill located in the outer inner-shelf. In the Artimon valley, the transgression takes place in a context of more open marine conditions, with a stronger influence of offshore hydrodynamics. The TST consists in offshore sandy to silty muds.

Once the transgression overflowed the topographic high, the whole area was covered by this mud facies. The coarse and shelly topmost part of the transgressive sequence corresponds to an episode of condensed sedimentation from about 3000-4000 cal. yr B.P., which amalgamates the MFS and HST. In the studied area, the MFS is recorded at around 3000-4000 cal. yr B.P., which is later than in most incised valleys from the Channel-Atlantic coastal systems where the MFS is recorded during the Holocene climatic optimum at ca. 6500 B.P. [Tessier *et al.*, 2010a, b]. Along with the extremely reduced volume of the HST, the late development of the MFS can be regarded as a characteristic of the sedimentary infilling of incised valleys located in a context of rocky coasts with low sedimentary supply.

The uppermost depositional unit observed so far in this area is restricted to the proximal coastal zone (U5). This unit belongs to the HST. In contrast with unit U4, it reflects an opposite trend of sedimentation marked by the progradation of fine riverborne sediments onto the offshore marine facies of U4. The deposition of this unit is recent, probably related to the increased human activities that have modified the dynamics of the catchments and the seabed over the last centuries.

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