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# Buried sandbodies within present-day estuaries (Atlantic coast of France) revealed by very high resolution seismic surveys

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**Abstract**

Studies of sandbanks within estuaries and macrotidal bays are critical for management of those coastal environments where human activity concentrates. They are also excellent analogues of reservoirs. New very high resolution (VHR) seismic profilers are now available for studying, at the outcrop resolution scale, sandbodies in very shallow water. We present here a VHR seismic study, constrained by vibrocores, repetitive bathymetric surveys and radiocarbon dating, which provide evidence of buried sandbodies in mixed tide and wave influenced estuaries of the French Atlantic coast. The three selected buried sandbodies are chosen because they are located at various water depths and have different internal architecture and outer shape. They include (1) a very shallow water (around −2 m under low tide) elongated nearshore sandbody, emplaced during the last centuries; (2) a −6 to −7 m deep, elongated nearshore sandbody dated to 2965±30 BP and (3) sandwaves lying around −17 m of water depth over the top of a large rounded shape sandbody dated to 5260±30 BP. Deepest (−6 and −17 m) sandbodies are interpreted as remnants of lower sea levels and thus transgressive sandbodies. All those sandbodies are buried under estuarine mud, which have been mainly emplaced during the last millenium. Such major sedimentary transition from basal sand to upper mud is assumed to record a major environmental change in relation to both natural infilling of estuaries, climate change and increasing human activities. Anthropogenic perturbations are however believed to be the most important factor. They have mainly consisted of land reclamation and are responsible for (1) rapid infilling of tidal bays, (2) tidal prism and tidal current energy decreases and (3) deposition of muddy sediments upon sandbodies.


*Keywords:* sandbodies; mud drape; estuaries; very high resolution seismic surveys

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## 1. Introduction

One key point when studying sedimentary dynamics along the coast line or in estuaries is to decipher sandbodies that are in equilibrium with present-day hydrodynamics from those which are inherited from older environmental conditions, particularly lower sea levels. Present-day estuaries are natural sediment sinks where sandbanks are widespread (Kraft et al., 1974; Ludwick, 1974; Weil et al., 1974; Ludwick, 1975; Wright et al., 1975; Harris, 1988; Liu et al., 1989; Harris et al., 1992; Gomez and Perillo, 1992; Dalrymple and Rhodes, 1995). They have been drowned and progressively filled by sediments during the last sea level rise and subsequent highstand (Dalrymple et al., 1992; Allen and Posamentier, 1993; Ashley and Sheridan, 1994; Zaitlin et al., 1994). They provide an opportunity to study the preservation of sandbanks which are analogues of reservoirs (Tillman, 1999). Studying such features in present-day estuaries has several advantages, including: (1) good knowledge of present-day hydrodynamic processes and recent environment changes, including, sea level variations, climate changes and shoreline evolution; (2) relatively thin sedimentary units, accurately imaged thanks to very high resolution (VHR) seismic profilers. The innovation point in such studies is that new VHR seismic profilers allow scientists to obtain continuous geophysical records of surficial sedimentary units, in very shallow water. This is the case of the IKB-Seistec boomer, with a vertical resolution of 0.25 m, that we used for the present work (Simpkin and Davis, 1993). Such resolution allows direct correlation with cores or outcrops and characterisation of sedimentary units emplaced at millennia to centuries time scales. With this aim in view, we have conducted VHR seismic surveys in estuaries of the French Atlantic coast where high resolution bathymetric data, available since the beginning of the 19th century, provide evidence for sediment gain and loss during the last two centuries (Chaumillon et al., 2002; Chaumillon et al., 2003).

The aim of this study is to improve our understanding of the sedimentary record of sea level rise, climate changes and anthropogenic perturbations, using VHR seismic profiling along with radiocarbon dated sediment cored.

## 2. General setting

### 2.1. Geology and physiography

The studied area is located on the western Atlantic coast of France, belonging to the passive continental margin of the Bay of Biscay (Fig. 1). The morphology of the coastline is characterised by two embayments (Pertuis Breton northward and Pertuis d'Antioche southward, Fig. 1), approximately 10 km wide and 40 km long. The bathymetry of these embayments is characterised by water depth of $-40$ m in the Pertuis d'Antioche and $-58$ m in the Pertuis Breton (Fig. 1). These deeps are isolated from the shelf by crescent-like shoals, culminating at about $-20$ m (Fig. 1). Previous seismic studies (Chaumillon et al., 2000; Weber et al., 2003) have shown that those embayments belong to incised valley segments and can be classified as estuaries, according the definition of Dalrymple et al. (1992).

### 2.2. Hydrodynamic setting

Due to small size of rivers and drainage basin areas (10 000 km$^2$ for the largest Charente, drainage basin), these estuaries are characterised by small fluvial input (100 m$^3$ s$^{-1}$ annual averaged value for the Charente river, largest river of the area, Tesson, 1973). The tidal regime of the study area is semi-diurnal and the tidal range varies from less than 2 m during neap tides to more than 6 m during spring tides. Tidal currents are weak on the continental shelf (S.H.O.M., 1993), but they can locally reach up to 2 m s$^{-1}$ enhanced by the funnel shape of the coastline (Tesson, 1973). Large swells, predominantly coming from West and Northwest directions (more than 56%) can propagate inside the embayments due to the wide (about 10 km) and deep (about 20 m) estuary mouths (L.H.F., 1994). The yearly average significant wave height is about 1.5 m, whereas wave height during storm events can exceed 6 m (Barthe and Castaing, 1989). This wave climate induces a southward net littoral drift along the wave-dominated coasts. Taking into account these hydrodynamic parameters we consider these estuaries as mixed, wave-and-tide, influenced estuaries.

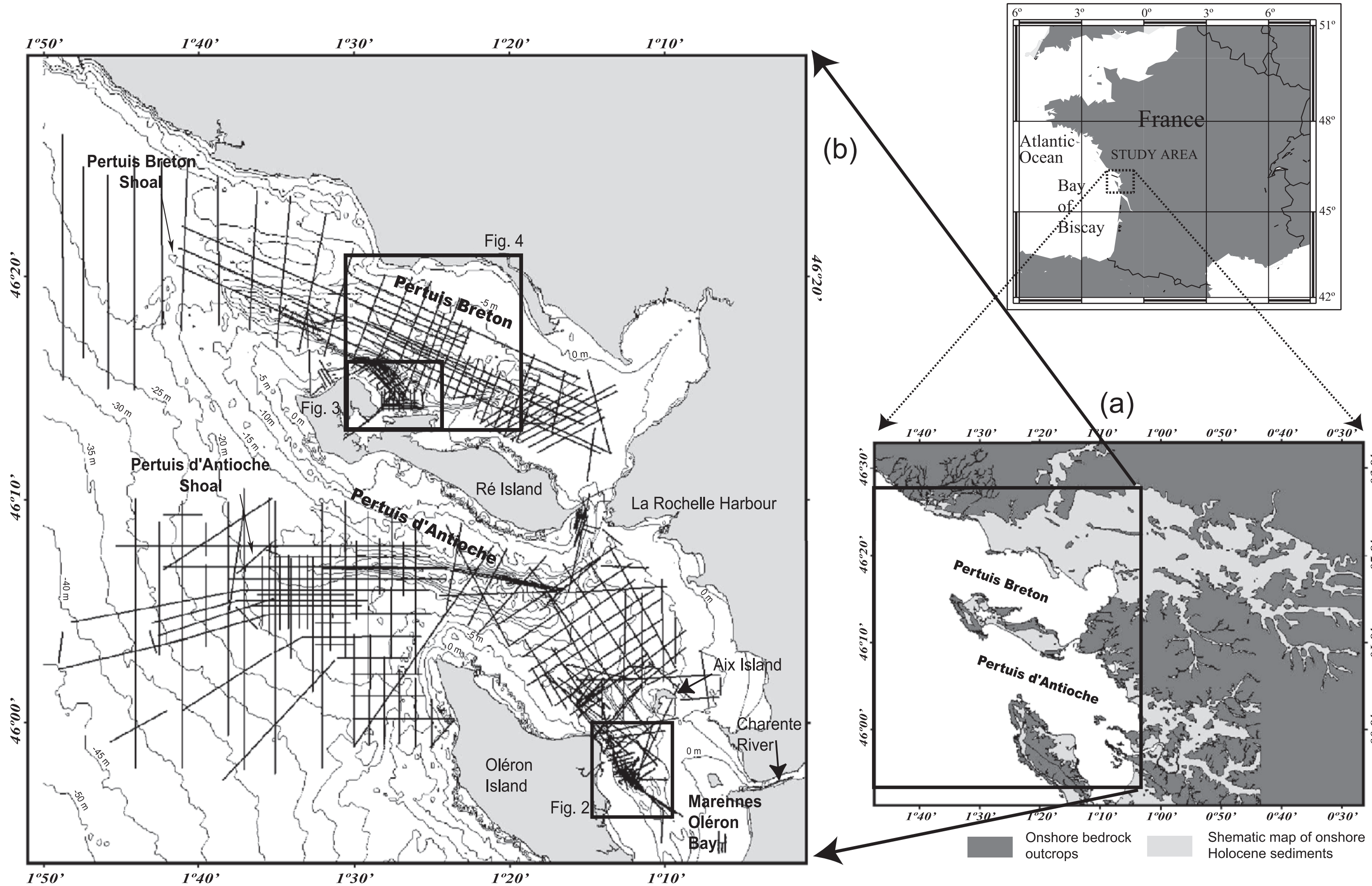



Fig. 1. (a) Study area map showing onshore Holocene sediments and bedrock outcrops. The boundary between Holocene sediments and bedrock approximatively corresponds to the maximum of transgression that occurred around 2000 BP. (b) Simplified bathymetric map (contour interval is 5 m, reference level of sounding reduction is the marine chart-sounding datum at La Rochelle Harbour, that is −3.504 m with reference to Institut Géographique National 1969, SHOM, 2003) showing position plan of VHR seismic profiles used in this study. Areas where sandbodies buried under estuarine muds occur are indicated: Rade des Trousses (Fig. 2), Banc du Bûcheron (Fig. 4), buried sandwaves (Fig. 6).

### 2.3. Holocene to present-day sedimentation

Sedimentation rates have been locally calculated, in the Marennes-Oléron bay, southward of the Pertuis d'Antioche (Fig. 1), using $^{210}$Pb measurements (Gouleau et al., 2000). Values range from 0.97 cm year$^{-1}$ on the lower part of the mudflat, to 0.26 cm year$^{-1}$ on the upper part of the mudflat. Timing of estuary infill is known onshore, close to the present-day Charente river mouth (Fig. 1), where the base of the infill lies at about −30 m below present-day sea level (Carbonnel et al., 1998). Mixed sand and mud facies, located at −20 m deep, are radiocarbon dated at 7400±170 BP (Carbonnel et al., 1998). They constitute transgressive facies, deposited at the end of the Holocene sea level rise. Estuary fill onlaps directly mesozoic strata. Offshore, the study of the stacking pattern of seismic units shows typical incised valley fills (Weber et al., 2003) as well as present-day active sand banks (Chaumillon et al., 2002). In both cases, all seismic units recognized over the Mesozoic substrate are interpreted as Holocene to present-day deposits since the previous Quaternary sedimentary cover has been removed or reworked during the last Glacial Maximum (Chaumillon et al., 2000, Weber et al., 2003).

### 2.4. Buried sandbodies location and setting

The present study focuses on sandbodies capped by a mud-dominated sheet drape. Three examples are presented, each illustrating sandbody preservation at various water depths (Figs. 1, 2, 3 and 4). From shallowest to deepest water, we will describe: (1) the "Rade des Trousses" buried sandbody (RTBSB), located within the upper nearshore, its upper surface lying at −1 to −3 m (Fig. 2a); (2) the "Bûcheron" buried sandbody (BBSB), located at the seaward foot of a present-day sand spit, with an upper surface at− 6 to −7 m of water depth (Fig. 3); (3) buried sandwaves (BSW) located around −17 m water depth, in the middle part of the northern estuary (Pertuis Breton, Fig. 4).

### 2.5. The "Rade des Trousses" buried sandbody (RTBSB)

The RTBSB is located in the northwestern part of Marennes-Oléron bay, the first oyster farming area in Europe (Fig. 1), which is occupied by intertidal zones (Fig. 1; Bassoulet et al., 2000). The western part of the embayment is dominated by mixed mud and sand while the eastern part is characterised mainly by cohesive sediments (Chaumillon et al., 2003). Strong tidal currents (>1 m s$^{-1}$) are recorded within tidal channels (Tesson, 1973). The other main hydrodynamic forcing corresponds to windwaves and ocean swells attenuated by the Longe de Boyard sand bank (Fig. 2a, Chaumillon et al., 2002). The RTBSB is located along the western wall of a tidal channel (the so-called "Passage de l'Ouest") close to a modern prograding coast (Fig. 2a and b).

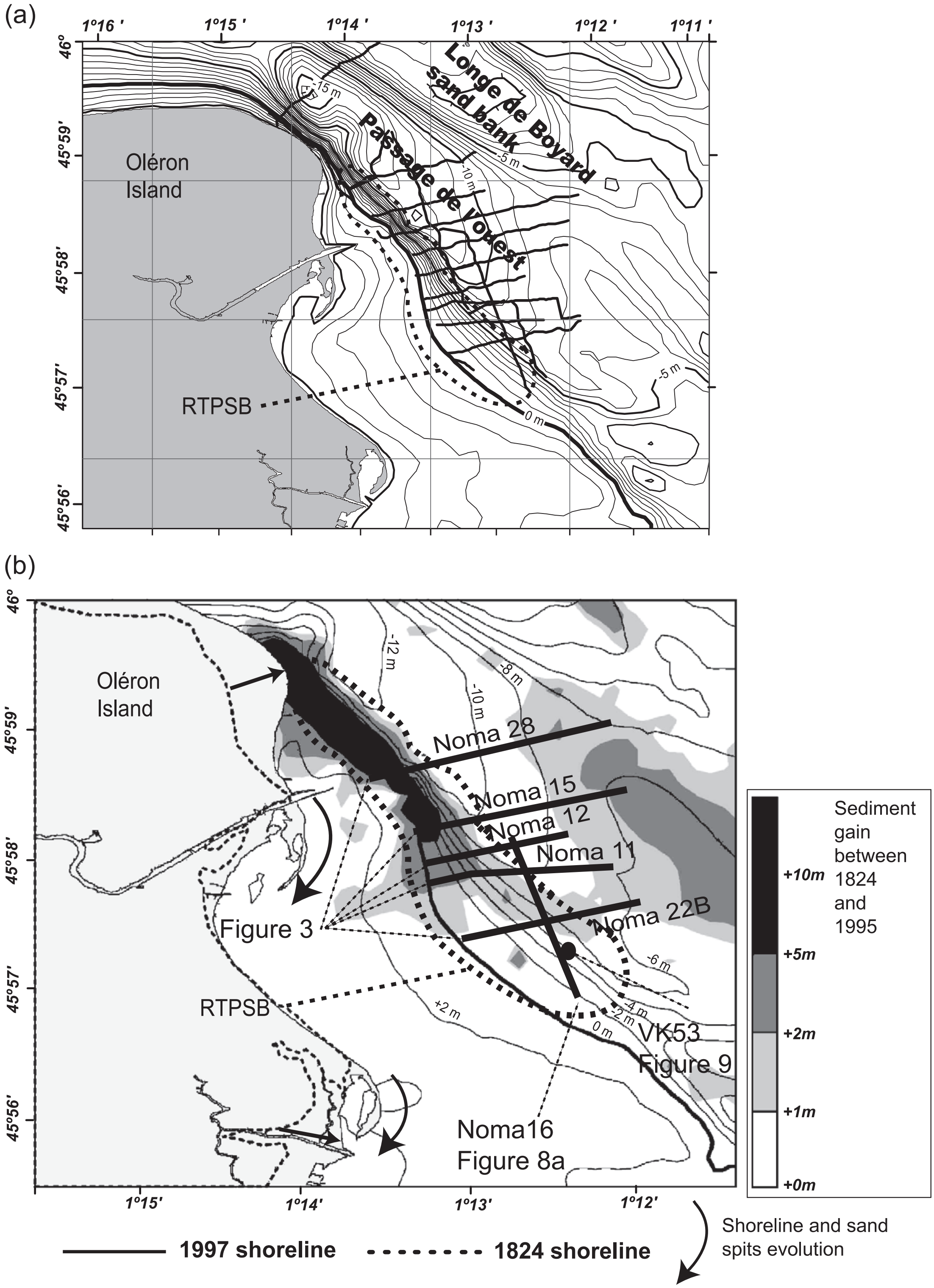
### 2.6. The "Banc du Bûcheron" buried sandbody (BBSB)

The BBSB is located seaward of the "Banc du Bûcheron", an intertidal sandbody, emplaced at the mouth of a coastal marsh (Figs. 1 and 3). It is a sand spit, attached to the land at one end (westward) and terminating in open water at the other (eastward). At low tide, it is about 2400 m in length, 400 m in width and 4 m high. Strong tidal currents have been recorded (2 to 2.5 m s$^{-1}$) and are ebb dominated (Schillinger, 2000). Hydrodynamic parameters also include attenuated ocean swells and wind waves.

### 2.7. The buried sandwaves (BSW)

Buried sandwaves are located in the central part of the Pertuis Breton (Figs. 1 and 4). Sandwaves refer to the terminology of Boythroyd and Hubbard (1975), Dalrymple et al. (1978), Stride (1982) and Amos and King (1984) and is equivalent to subaqueous dunes

Fig. 2. (a) Bathymetric map (1995 data, contour interval is 1 m, reference level of sounding reduction is the marine chart-sounding datum at La Rochelle Harbour, that is −3.504 m with reference to Institut Géographique National 1969, SHOM, 2003) and seismic tracks in the Rade des Trousses area, dotted line approximately indicate the Rade des Trousses buried sand body (RTBSB) location. (b) Simplified bathymetric map (1995 data), shoreline and bathymetric changes in the Rade des Trouses area between 1824 and 1995. Position plan of VHR seismic profiles (bold lines) and vibrocore (VK53) used to characterize the RTBSB are indicated.


(a)
1°16 '
1°15 '
1°14 '
1°13 '
1°12 '
1°11 '
46°
45°59'
45°58'
45°57'
45°56'
Longe de Boyard
sand bank
Passage de l'ouest
Oléron
Island
-15 m
-10 m
-5 m
0 m
RTPSB
(b)
46°
45°59'
45°58'
45°57'
45°56'
1°15'
1°14'
1°13'
1°12'
Oléron
Island
-12 m
-10 m
-8 m
-6 m
-4 m
-2 m
0 m
+2 m
Noma 28
Noma 15
Noma 12
Noma 11
Noma 22B
Figure 3
RTPSB
VK53
Figure 9
Noma16
Figure 8a
Sediment
gain
between
1824
and
1995
+10m
+5m
+2m
+1m
+0m
1997 shoreline
1824 shoreline
Shoreline and sand
spits evolution

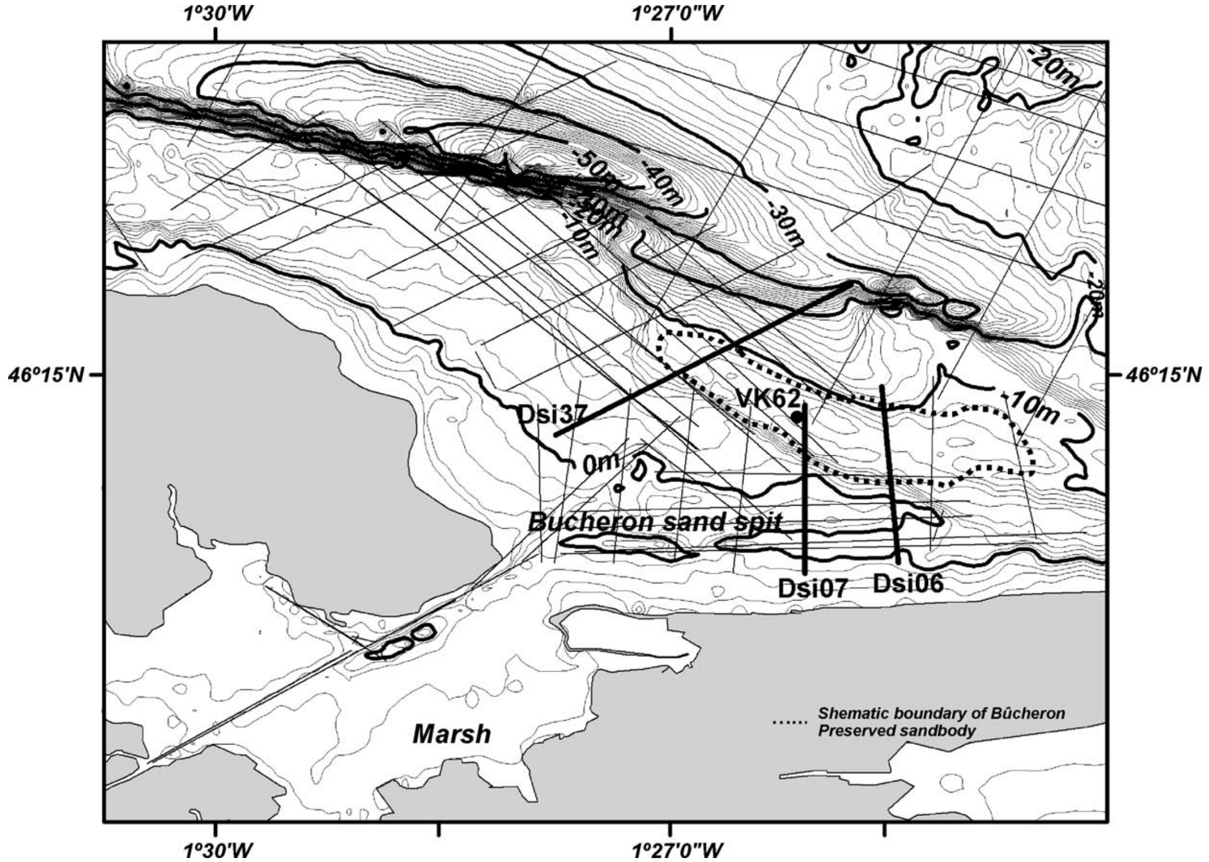



Fig. 3. Bathymetric map (contour interval is 1 m, reference level of sounding reduction is the marine chart-sounding datum at La Rochelle Harbour, that is −3.504 m with reference to Institut Géographique National 1969, SHOM, 2003) and seismic tracks in the Bûcheron sand spit area. The thick dotted line approximately indicates the Bûcheron Preseved sandbody (BBSB) location. The present-day boundary of the Bûcheron intertidal sand spit approximately corresponds to 0 m contour line in bold. VHR seismic profiles (Dsi06, 07 and 37 in bold) and vibrocore (VK62) used to characterize BBSB are indicated.

(Ashley, 1990; Berné et al., 1989). The first evidence of buried sandwaves, within the Pertuis Breton, was one seismic profile published by Berné (2000). Tidal currents in the central part of the Pertuis Breton are flood dominated with maximum values of 0.75 m $s^{-1}$ during flood and 0.55 m $s^{-1}$ during ebb (S.H.O.M., 1993). Ocean swells are attenuated in this central part of the Pertuis Breton (L.H.F., 1994).

## 3. Methods

Our study is mainly based on very high resolution (VHR) seismic data analysis, using two different seismic packages: (1) A mini sparker source (50 J, band pass frequency: 200–1200 Hz), associated with a traditional single-channel streamer, used on seismic cruises, MOBIDYC1, 2000 and MOBIDYC2, 2001; and (2) a boomer source (1–10 kHz) associated with a line-in-cone receiver, the IKB-Seistec boomer (Simpkin and Davis, 1993), used for shallow water seismic profiling (cruises NOMADES, 2000 and DSIRé, 2001), and previously used for investigating very shallow shoreface architecture (Tessier et al., 2000). In the present case, boomer profiles are exclusively used for shallower targets, i.e. the Rade des Trousses (Fig. 5) and the Bûcheron Sandbodies (Fig. 6) while the buried sandwave field was examined using sparker profile data (Fig. 7). Accurate positioning of each profile was provided by

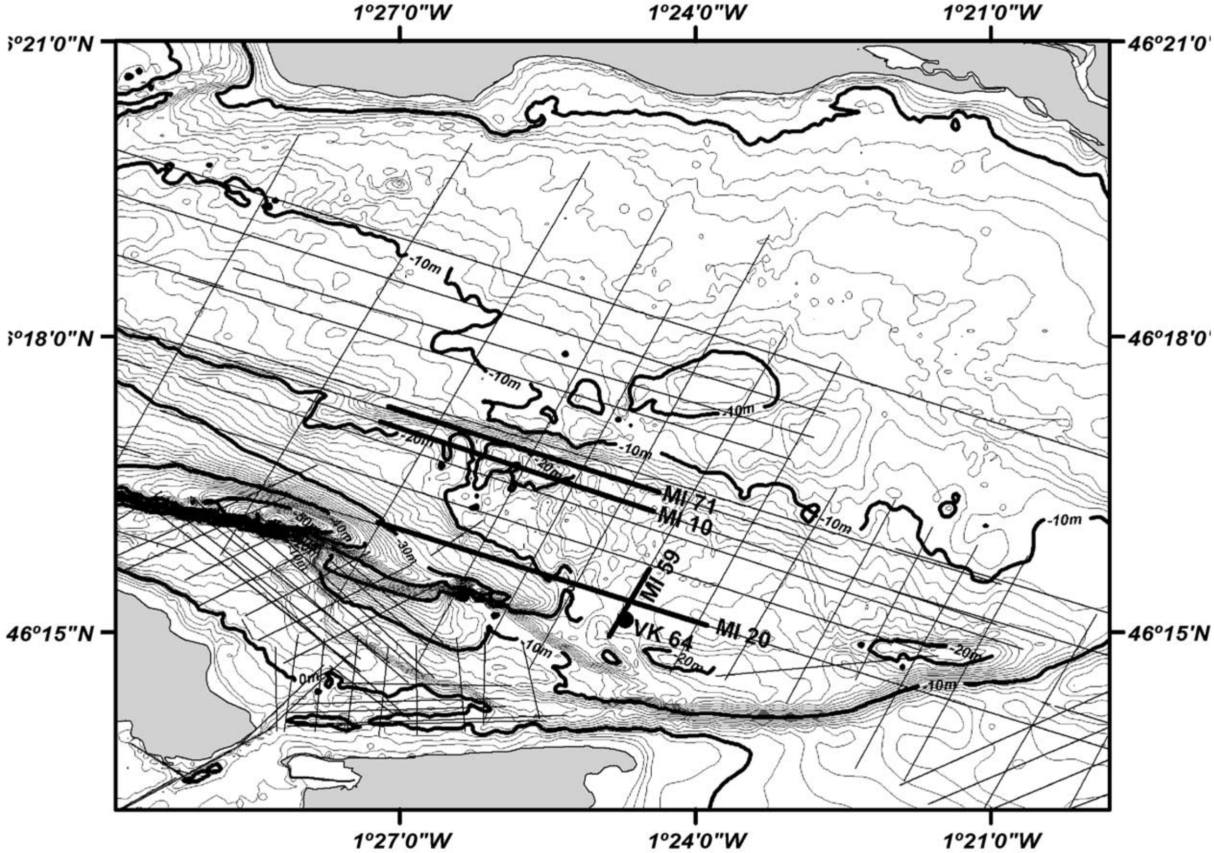



Fig. 4. Bathymetric map (contour interval is 1 m, reference level of sounding reduction is the marine chart-sounding datum at La Rochelle Harbour, that is −3.504 m with reference to Institut Géographique National 1969, SHOM, 2003) and seismic tracks in the central part of the Pertuis Breton. Bathymetric curve −6 m corresponds to seaward boundary of a terrace-like feature on both sides the Pertuis Breton. VHR seismic profiles (Mi10, 20 and 71 in bold) and vibrocore (VK64) used to characterize the buried sandwaves (BSW) are indicated.

using a differential GPS navigational system. Seismic data were digitised in real time using a Delph seismic V.2.01 system. Processing of seismic data includes: (1) Frequency band pass filtering, (2) amplitude correction by applying an automatic gain correction, (3) swell filtering, (4) stacking of adjacent traces (facultative). For P wave travel time to depth conversion, we used 1500 m $s^{-1}$ for the water and 1600 m $s^{-1}$ for unconsolidated sediment (Maroni, 1997). Seismic data interpretation was done following the general concepts of seismic stratigraphy (Payton, 1977).

Seismic data interpretations are constrained by two complementary data sets: (1) vibracore sampling (Coring cruise MOBIDYC3, 2002) and (2) repetitive bathymetric surveys recorded since the beginning of the 19th century (French Hydrographic Office, SHOM and Direction Départementale de l'Equipement de Charente-Maritime, DDE17).

Vibrocores were collected within the buried sandbodies (Figs. 2, 3, 4 and 8) in order to correlate sedimentary facies, based mainly on granulometric analysis, with acoustic units.

Radiocarbon dating (ages radiocarbon) was established using AMS analysis on intact shells (Beta Analytic and Poznan Radiocarbon Laboratory).

Bathymetric analysis is based on two surveys obtained in 1824 and 1995, in the Rade des Trousses area (Figs. 1 and 2). Data of 1824 were collected using lead line, positioned using horizontal sextant (SHOM) and were digitised from the original collector tracing map. The 1995 measurements were acquired digitally by DDE17. In order to compare these data files, we reduced positions to the same datum (WGS 84) and converted soundings to the same reference level (the reference level of sounding reduction is the marine chart-sounding datum at La Rochelle Harbour, that is −3.504 m with reference to Institut Géographique National 1969 or reference level of Nivellement Général de la France: 0 NGF, SHOM, 2003). From these data, digital elevation models (DEM) were established, accordingly to the mean initial data sampling. Taking into account corrections and uncertainties, the relative error does not exceed: (1) ±10 m in position and ±0,5 m in depth, for 1824 data; (2) ±1 m in position and ±0.1 m in depth, for 1995 data. This reliability of measurements has been checked by the enrochment stability between each surveys (Bertin et al., 2004). Then bathymetric changes between 1824 and 1995 were calculated using Surfer software (Fig. 2b).

## 4. Results

The results concerning the three selected buried sandbodies are now presented in order from the shallowest to the deepest: (1) RTBSB, (2) BBSB, (3) BSW. For each example, seismic data are described first, followed by complementary data, including vibrocore analysis, radiocarbon dating and bathymetric results. Differences between bathymetric maps from 1824 and 1995, in the Rade des Trousses area, are measured to infer net changes in seabed morphology. Indeed in the Rade des Trousses area mean bathymetric sampling is similar for both 1824 and 1995.

In all the studied areas, seismic profiles show the same basal acoustic unit (U0), with an erosional upper boundary (EU0), which is a strong amplitude and low frequency reflector. Internal configuration is parallel with tilted or folded reflectors. Reflectors of U0 crop out close to the shore and consist of folded and faulted Mesozoic strata (Chaumillon et al., 2000, 2002; Weber et al., 2003). EU0 is a regional erosion surface that forms the base of different channels incised into Mesozoic bedrock (Chaumillon et al., 2000, 2002; Weber et al., 2003). It is interpreted as a typical SB2 sequence boundary (Posamentier et al., 1988; Posamentier and Vail, 1988) formed progressively during previous Quaternary lowstands (Chaumillon et al., 2000, 2002; Weber et al., 2003) and reactivated during the last sea-level drop and subsequent lowstand.

### 4.1. *The "Rade des Trousses" buried sandbody (RTBSB)*

#### *4.1.1. Seismic results*

Seismic profiles indicate four major seismic units overlying the Mesozoic bedrock upper boundary (EU0, Figs. 5 and 8). From base to top, they are $U_T1$, $U_T2$, $U_T3$ and $U_T4$.

(1) Unit $U_T1$ consists of small lenses, filling the bottom of incisions cutting across Mesozoic rocks. Seismic facies is chaotic or transparent;
(2) Unit $U_T2$ consists of a sheet drape, lying upon both the incised Mesozoic bedrock and $U_T1$. Its thickness varies from about 2 to more than 13 m. Seismic facies are characterized by small to middle amplitude reflectors. Internal geometry consists of subhorizontal to gently ondulating reflectors. Its upper boundary is a flat erosional unconformity (EU1);
(3) Unit $U_T3$ consists of a progradational seismic package. It is an elongated unit of at least 5 km length and 2 km width. Its thickness ranges from 4 to 10 m. Seismic facies are characterized by high frequency, middle amplitude reflectors. Internal geometry is mainly oblique parallel with northeastward dipping reflectors. Its upper boundary is a toplap surface, locally erosional and lying at −1 to −3 m below lowest sea level.
(4) Unit $U_T4$ consists of a sheet drape, bounded downward by EU1 ($U_T2$ upper unconformity), and upward by the present-day seafloor. $U_T4$ maximum thickness reaches 4 to 5 m in the southern part of the studied area. $U_T4$ thins progressively towards north and west and disappears in the deepest part of the Passage de l'Ouest, northward. Seismic facies are characterized by high frequency, middle amplitude reflectors. Internal geometry consists of subparallel reflections onlapping and draping $U_T2$ and $U_T3$ units.

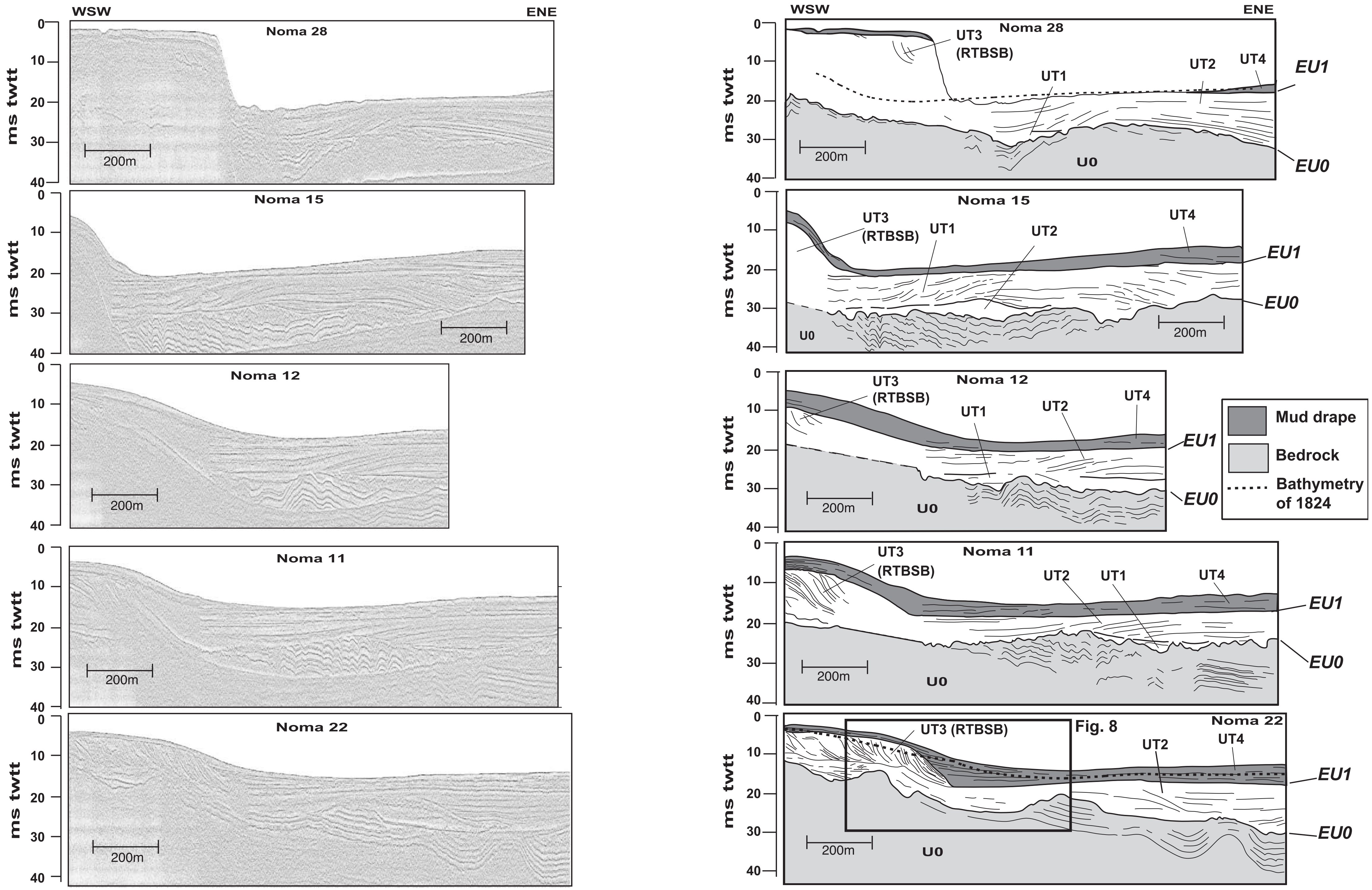



Fig. 5. Selected VHR seismic profile (Boomer IKB Seistec) and their interpretations showing the internal architecture of acoustic units and their lateral evolution in the Rade des Trousses area. The Rade des Trousses buried sandbody (RTBSB) corresponds to Unit $U_T3$ and is buried by the sheet drape that corresponds to Unit $U_T4$. Seabottom of 1824 is indicated thank to a dotted bold line on profiles Noma 22 and 28.

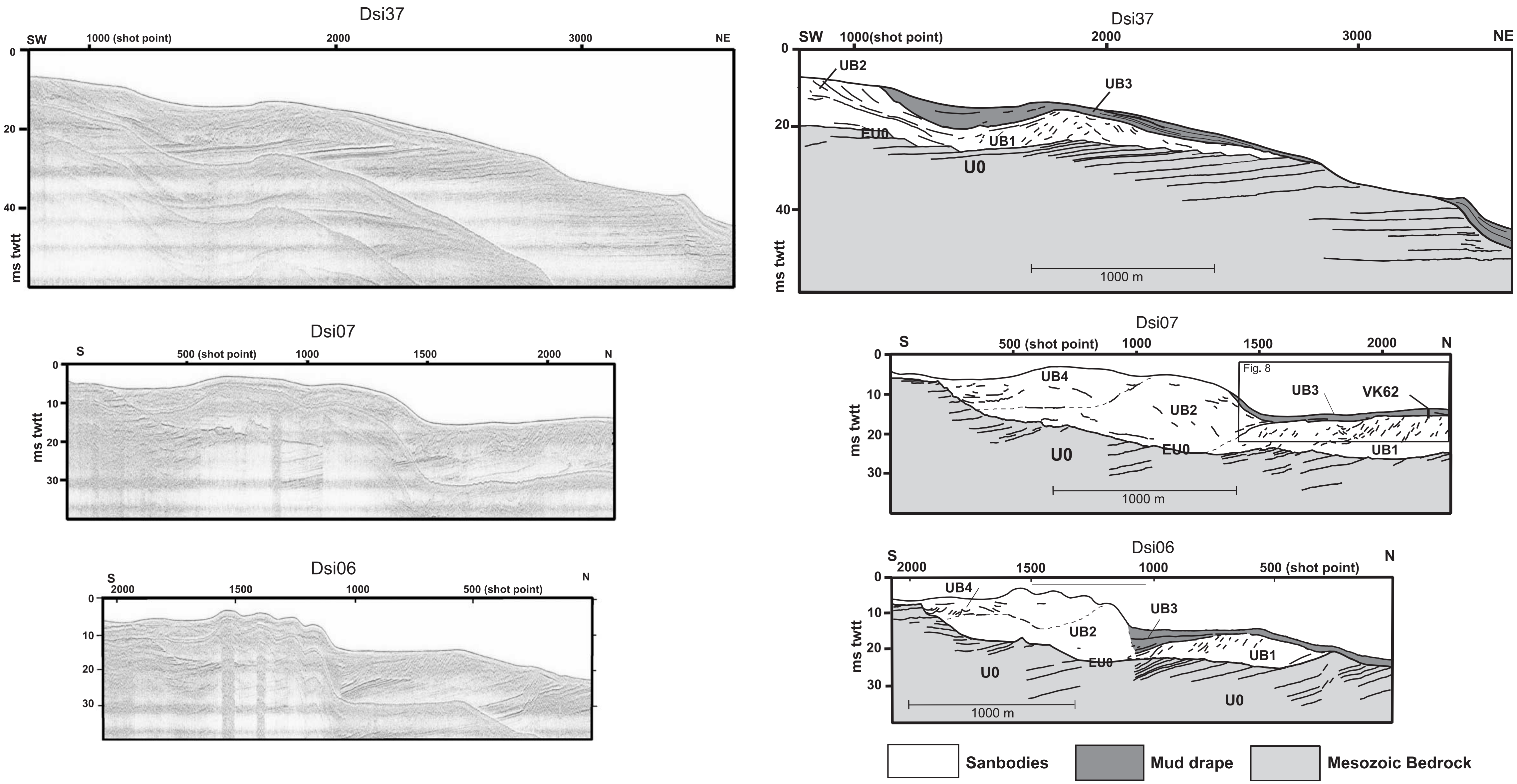



Fig. 6. Selected VHR seismic profiles (Boomer IKB Seistec) and their interpretations showing the internal architecture of acoustic units in the Banc du Bûcheron area. The Bûcheron buried sandbody (BBSB) corresponds to Unit $U_B1$ and is buried by the sheet drape that corresponds to Unit $U_B3$.

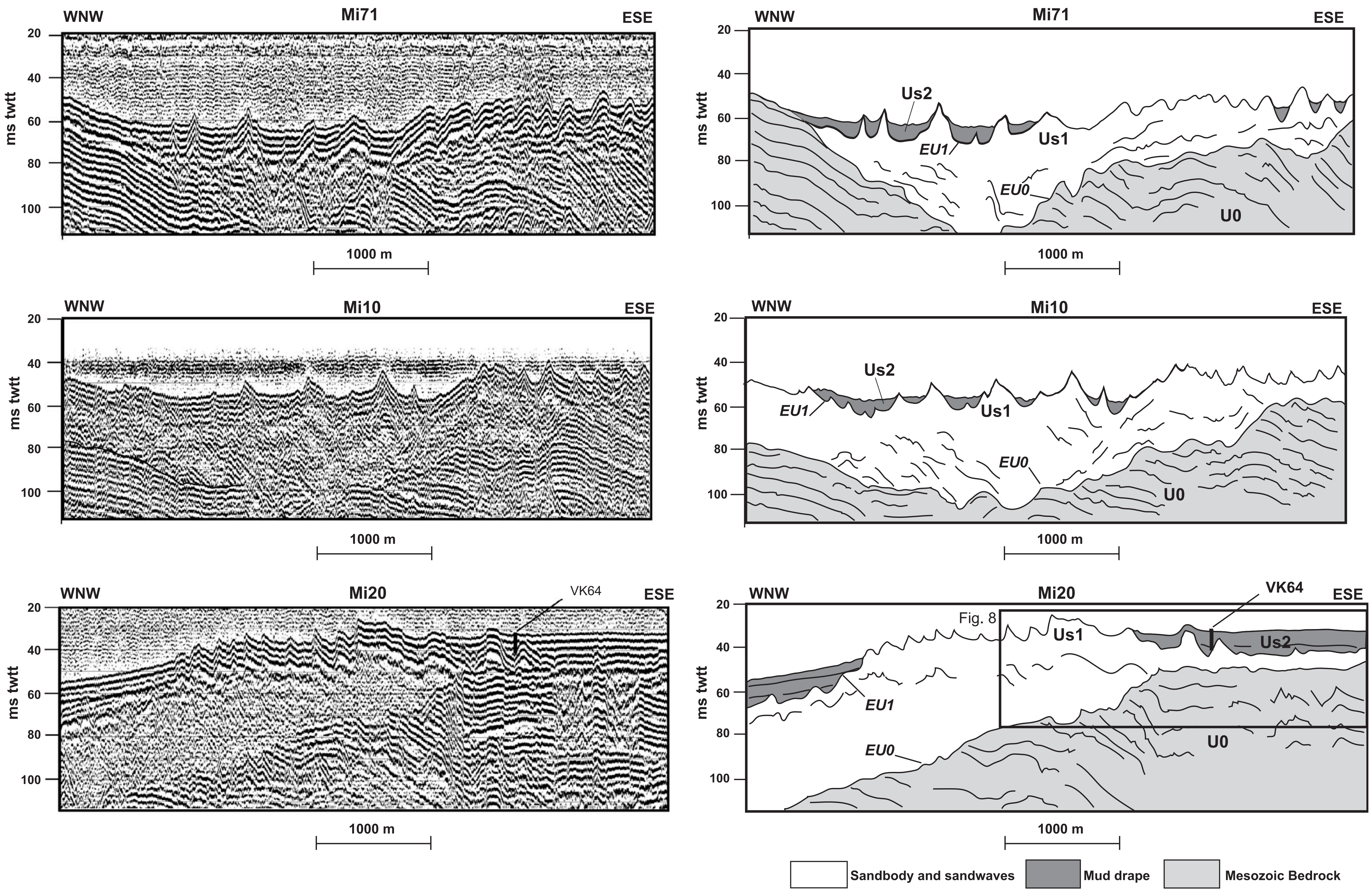



Fig. 7. Selected VHR seismic profiles (Mini Sparker) and their interpretations showing the internal architecture of acoustic units in the central part of the Pertuis Breton. The buried sandwaves (BSW) correspond to the top of Unit $U_S1$ and are buried by the sheet drape that corresponds to Unit $U_S2$.

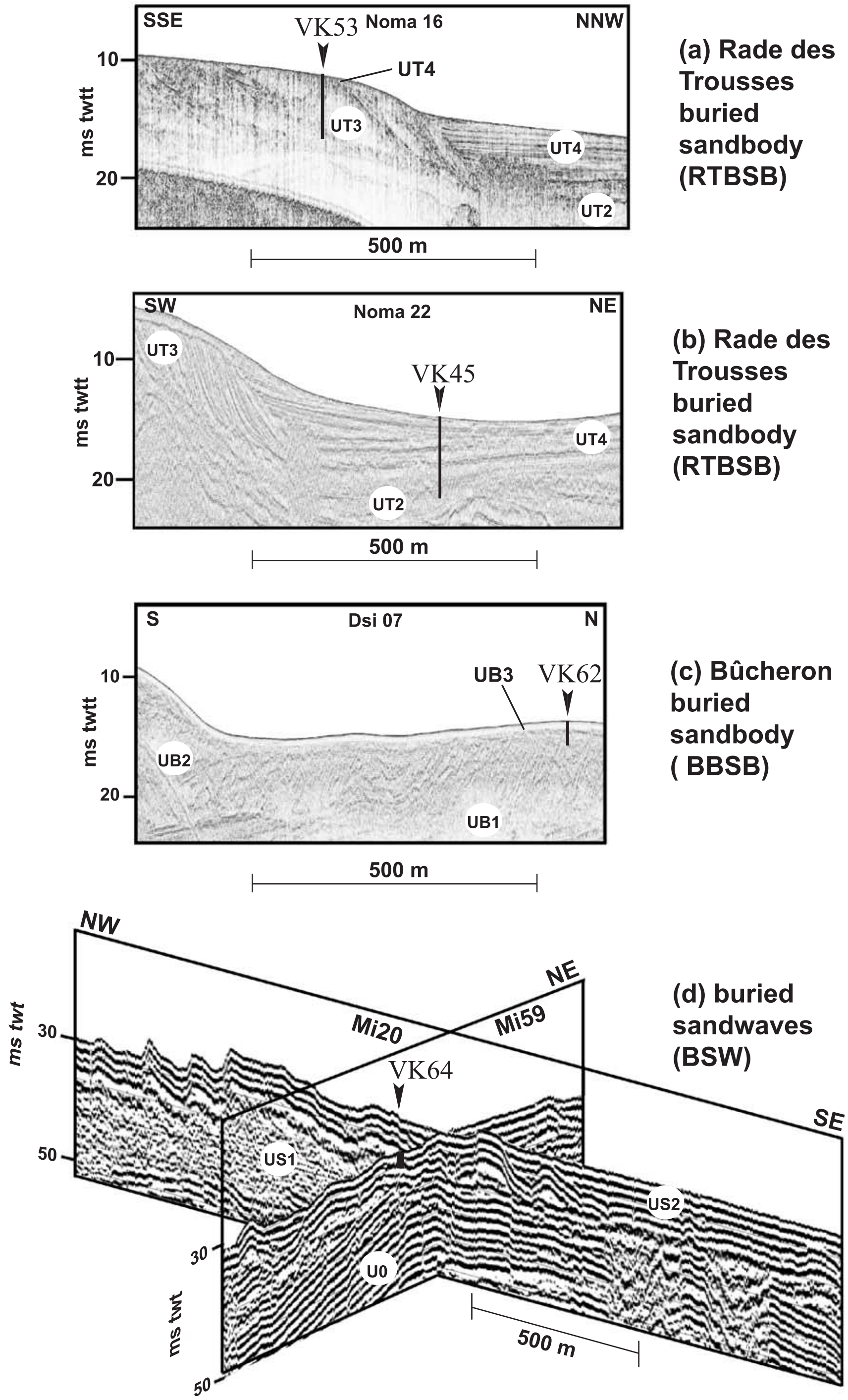



Fig. 8. Selected parts of VHR seismic profiles showing the internal architecture of the three kind of buried sandbodies and location locations of vibrocores on seismic profiles. (a and b) Rade des Trousses Buried Sandbody (RTBSB), Boomer IKB Seistec profile; (c) Bûcheron Buried Sandbody (BBSB), Boomer IKB Seistec profile; (d) buried sandwaves (BSW), Mini Sparker profile.

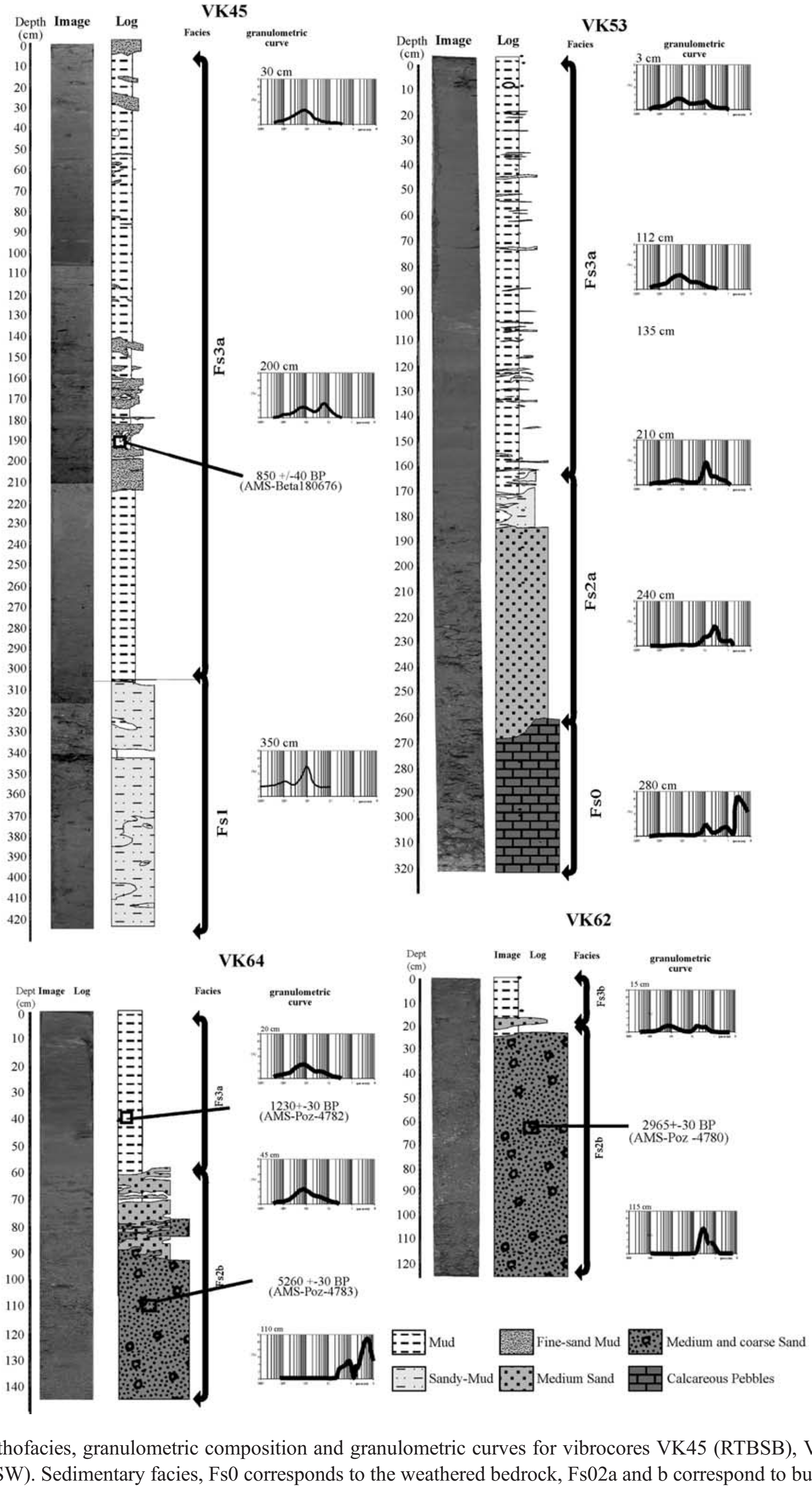



Fig. 9. Photographs, lithofacies, granulometric composition and granulometric curves for vibrocores VK45 (RTBSB), VK53 (RTBSB), VK62 (BBSB) and VK64 (BSW). Sedimentary facies, Fs0 corresponds to the weathered bedrock, Fs02a and b correspond to buried sandbodies, Fs03a and b corresponds to the mud drape.

*4.1.2. Coring results, radiocarbon dating and correlation with seismic profile*

The results obtained from two vibrocores: VK53 collected 16 m from NOMA16 seismic profile (Figs. 2, 8 and 9) and VK45 collected 16 m from NOMA22 seismic profile (Figs. 2 and 9), indicate three lithofacies, distinguished on the basis of granulometric parameters (Table 1). From base to top, they are:

(1) Facies Fs0 consists of calcareous pebbles and gravel. It is observed in the lowest part of the core VK53 (315–270 cm), and is correlated with the top of U0 (Mesozoic bedrock).
(2) Facies Fs1 consists of mud (31%), fine sand (53%) and medium sand (16%). It extends from −420 to −290 cm in VK45, and is correlated with $U_T2$.
(3) Facies Fs2a consists of gravel (11%), medium sand (29%), fine sand (32%) and mud (27%). It extends from −270 to −170 cm in VK53, and is correlated with $U_T3$.
(4) Facies Fs3a consists of black and grey mud (86%), fine sand (12%) and medium sand (3%). It extends from −170 to 0 cm in VK53 and from −290 to 0 cm in VK45 and is correlated with $U_T4$.

An intact mollusc shell (Dentalium), collected at 1.9 m sediment depth in core VK 45, within facies Fs3a, gave an age of 850±40 years BP (Beta-180676).

*4.1.3. Bathymetric results and correlation with seismic and coring data*

The bathymetric substraction map between 1824 and 1995 (Fig. 2b) shows that sediment gain occurred within two main areas: (1) the southeastern part of the Passage de l'Ouest; (2) the western wall of Passage de l'Ouest (Fig. 2b). Maximum sediment deposition occurred along the channel wall and led to local sediment thickening of up to 10 m throughout the last 171 years (about 6 cm year$^{-1}$). It is contemporaneous with adjacent shoreline progradation (Fig. 2b).

We have superimposed bathymetric cross sections, based on the 1824 DEM, on seismic profiles (Fig. 5), in order to identify seismic units younger than the beginning of the 19th century. Taking into

Table 1
Granulometric composition and radiocarbon dates of the main sedimentary units corresponding to the buried sandbodies and their overlying mud drape

| Buried Sandbodies | Facies number | Core No. depth (cm) | Sedimentary Facies description | Correlations with seismic unit | Radiocarbon date (yr BP) Core No. depth (cm) |
|---|---|---|---|---|---|
| RTBSB | Fs3a | VK53_170-0 VK45_290-0 | Black and grey mud (86%), fine sand (12%) and medium sand (3%) | $U_T4$ | 850±40 (Beta-180676) VK45-190 |
| | Fs2a | VK53_270-170 | Fine sand (32%), medium sand (29%), mud (27%) and gravel (11%) | $U_T3$ | / |
| | Fs1 | VK45_420-290 | Fine sands (53%), mud (31%), and medium sands (16%) alternations | $U_T2$ | / |
| | Fs0 | VK53_315-270 | Calcareous pebbles and gravel | U0 | / |
| BBSB | Fs3b | VK26_20-0 | Black and grey mud (56%) fine sand (20%) and medium sand (18%) | $U_B3$ | / |
| | Fs2b | VK62_125-20 | Coarse orange sand and gravel (94%) with fine sand (2%) and mud (4%) | $U_B1$ | 2965±30 (Poz-4780) VK62-65 |
| BSW | Fs3a | VK64_75-0 | Black and grey mud (86%) fine sand (12%) and medium sand (3%) | $U_S2$ | 1230±30 (Poz-4782) VK64-40 |
| | Fs2b | VK64_145-75 | Coarse orange sand and gravel (94%) with mud (4%) and fine sand (2%) | $U_S1$ | 5260±30 (Poz-4783) VK64-110 |

RTBSB: Rade des Trousses buried sandbody, BBSB: Bûcheron buried sandbody, BSW: buried sandwaves.

account uncertainties of bathymetric data, this correlation provides an estimate of the time scale for seismic unit deposition. In 1824, the seafloor was slightly above EU1, indicating that the upper part of seismic unit, $U_T4$, corresponds with sediments deposited since the beginning of the 19th century. This is in good agreement with radiocarbon dating of the lower part of UT4 (850±40 BP). This correlation also indicated that $U_T3$ was emplaced before (southern part of UT3, NOMA22, Fig. 5) and after (northern part of UT3, NOMA28, Fig. 5) the last two centuries.

### 4.2. The "*Banc du Bûcheron*" buried sandbody (BBSB)

#### 4.2.1. Seismic results

Seismic profiles, shot across the Bûcheron sand spit area (Fig. 3), reveal four major seismic units overlying the bedrock upper boundary (EU0). Seaward of the present-day sand spit, represented by $U_B4$ (Fig. 6), we distinguish three units from bottom to top (Figs. 6 and 8):

(1) Unit $U_B1$ consists of an elongate (at least 3000 m long, 700 m wide, 6–7 m thick at the maximum) seismic unit, displaying southward dipping reflectors, emplaced seaward of the present-day intertidal sand spit (−6 to −7 m of water depth), upon the mesozoic bedrock acoustic basement. $U_B1$ upper boundary is a sharp and flat unconformity, locally convex upward (Figs. 6 and 8).

(2) Below the present-day sand spit, represented by $U_B4$ (Fig. 6), the internal architecture is difficult to observe because of the seabed multiple. Middle amplitude reflectors, displaying both sub-horizontal and northward dipping clinoforms, can be locally described ($U_B2$).

(3) Unit $U_B3$ consists of a sheet drape (1,5 m thick in average) emplaced upon both $U_B1$ and $U_B2$; it consists of sub-horizontal and sub-parallel reflectors.

#### 4.2.2. Coring results, radiocarbon dating and correlation with seismic profile

One vibrocore collected −64 m from Dsi07 seismic profile is presented (VK62, Figs. 3, 6, 8 and 9). Two lithofacies are distinguished based on granulometric parameters (Table 1). From base to top, they are:

(1) Facies Fs2b consists of coarse orange sand and gravel (94%) with fine sand (2%) and mud (4%). It extends from −125 to −20 cm and correlates with $U_B1$. An intact mollusc shell (Dentalium), collected at 0.65 m sediment depth in core VK 62, gave an age of 2965±30 years BP (Poz-4780).

(2) Facies Fs3b consists of black and grey mud (56%) fine sand (20%) and medium sand (18%). It extends from −20 to 0 cm and correlates with $U_B3$.

### 4.3. Buried sandwaves (BSW)

#### 4.3.1. Seismic results

Sparker profiling reveals two major seismic units ($U_S1$ and $U_S2$, Fig. 7) overlying the Mesozoic bedrock upper boundary (EU0). From base to top, they are:

(1) Unit $U_S1$ corresponds to a large, rounded shape, poorly reflective facies (4.5×3 km) lying directly upon U0. Its upper unconformity displays typical morphology of sandwaves (Boythroyd and Hubbard, 1975; Dalrymple et al., 1978; Amos and King, 1984) equivalent to very large subaqueous dunes (Ashley, 1990), with wavelengths ranging between 150 and 400 m and amplitude ranging between 2 and 5 m. In the northern part of the sandbody, sandwave lee sides dip shoreward (eastward) indicating that they are flood-dominated (seismic profile Mi71, Fig. 7), while in the southern part, sandwave lee sides dip seaward (westward) indicating that they are ebb-dominated (seismic profile Mi 20, Fig. 7). Smooth crested sandwaves are also observed as shown on eastern part of the seismic profiles Mi 20 and 71 (Fig. 7).

(2) Unit $U_S2$ fills the troughs between the shallowest sandwave crests and covers entirely the deepest sandwaves (Fig. 7 and 8). The maximum thickness of $U_S2$ ranges from 2 to 3 m. Internal geometry displays parallel and horizontal reflectors. Locally, sandwaves are not covered by $U_S2$ unit (e.g. western part of seismic profile Mi20,

Fig. 7). They are characterized by a regular wavelength of about 150 m.

*4.3.2. Coring results, radiocarbon dating and correlation with seismic profile*

One vibrocore collected 200 m from seismic profile Mi20 and 50 m from seismic profile Mi59, is presented (VK64, Figs. 4, 7, 8 and 9). Two lithofacies are distinguished (Table 1). From bottom to top, they are:

(1) Facies Fs2b consists of coarse orange sand and gravel (94%) with fine sand (2%) and mud (4%). It extends from −145 to −75 cm and correlates with $U_S1$. An intact mollusc shell (Dentalium), collected at 1.10 m sediment depth in core VK 64, gave an age of 5260±30 years BP (Poz-4783).

(2) Facies Fs3a consists of black and grey mud (86%) fine sand (12%) and medium sand (3%). It extends from −75 to 0 cm and correlates with $U_S2$. An intact lamellibranch shell (undetermined species), collected at 0.4 m depth in core VK 64, gave an age of 1230±30 years BP (Poz-4782).

## 5. Discussion

Based on the results presented here, different kinds of sandbodies have been described: (1) two elongated nearshore sandbanks, one located around −2 m, the other around −6 m below low tide sea level; and (2) one deeper rounded sandbody topped by sandwave fields. Both of these sandbody types are buried by mud.

### *5.1. Factors of sandbody preservation*

The three study sites display similarities with respect to seismic and sedimentary facies succession with sand within the basal seismic unit (buried sandbodies corresponding to facies Fs2a and b) and muddier sediments within the upper sheet drape seismic unit (facies Fs3a and b). This sedimentary evolution is very sharp, and is therefore assumed to be associated to important environment changes. First, the fining upward succession indicates a decrease in hydrodynamic energy with time and/or an increase in suspended matter supply. Both bathymetric subtraction map, in the Rade des Trousses, and radiocarbon dates at the base of the mud drape, in the Rade des Trousses and upon the BSW, indicate the mud drapes ($U_T4$ and $U_S2$) has been mainly deposited during the last millenium. Because of the similarities in terms of configuration, sedimentary facies, and radiocarbon dates, the mud drapes observed on the RTBSB, BBSB and BSW are believed to record a similar period of time. Following this hypothesis, the environmental change recorded by this mud drape, is necessarily recent (approximately the last millennium) and does not correspond to long-term environmental evolution. Consequently, such preservation is probably not related to the last major sea level change, i.e. the transition between the early Holocene rapid sea level rise and the late Holocene slow sea level rise that occurred around 6000 BP (rate of sea level rise changes from 7 to 1 mm year$^{-1}$, Lambeck, 1997). At the time scale of the last millennium, major environmental changes include: (1) secular rise in sea level (Wöppelmann, 1997); (2) climate changes (Leroy-Ladurie, 1967; Lamarche, 1974; Dansgaad et al., 1975; Bernabo, 1981); (3) anthropogenic factors, including reclamation of intertidal areas and subsequent seaward migration of the shoreline (Pawlowski, 1998; Camuzard, 2000 and Fig. 1).

Secular rise in sea level since 1820 is in the order of 0.2 m (Wöppelmann, 1997) and mean sea level rise rate during the late Holocene is around 1 mm year$^{-1}$ (Lambeck, 1997). We assume that such a moderate rise (about 1 m since 1000 years) cannot induce the sharp sedimentary change we observe in the studied estuaries.

In terms of climate change, the dates of 1230±30 and 850±40 BP above the base of the mud drape suggests that it could correspond to the transition between the cold period of the Dark Age (400–900 AD) and the Medieval warm period (900–1400 AD; Bernabo, 1981; Lamarche, 1974; Leroy-Ladurie, 1967). Usually warmer periods are associated with higher rain fall and more frequent floods leading to increasing estuarine mud supply. Lesueur et al. (1996) showed that estuarine mud output has clearly increased regionally on the adjacent shelf over the past 2000 years partly because of climate change. Therefore, the occurrence of the mud drape in our studied area may, in part, be related to the general frame of this climate-induced increase in fine grained sediment supply.

Anthropogenic perturbations are, however, believed to be the most important factor for explaining the observed sedimentation change. Human activity during the last millennium, in the studied area, has mainly consisted of land reclamation: maximum seaward shoreline advance is up to 70 km during the last 2000 years and is located eastward of the Pertuis Breton (Fig. 1). This dramatic increase of land reclamation is assumed to have strongly influenced the hydrodynamics and related sedimentation. It is commonly shown that at the present time, infilling and shoreline progradation within bays and estuaries leads to a decrease in tidal prism resulting, in turn, to positive feedback and sedimentation increase (Pendon et al., 1998, Van der Wal et al., 2002). On the other hand, reclamation of intertidal flats and marshes induce expulsion of suspended matter to the outer parts of estuaries, which correspond to the studied areas. The mud drape described in this study shows similarities with the lithological succession of the Gironde shelf mud fields (Lesueur and Tastet, 1994; Lesueur et al., 1996). The Marennes-Oléron bay receive suspended matter originating from the Gironde estuary (Castaing, 1981; Gonzalez et al., 1991; Froidefond et al., 1998). We conclude that there could be a link between the genesis of the detached mud prism deposited on the inner shelf and the observed change in sedimentation of the studied estuaries. We propose that, in addition to suspended matter sedimentation increase derived from both the Gironde estuary and the small rivers flowing in the studied estuaries, land reclamation and related decrease in tidal prism have also induced a decrease in tidal currents, which can also result in deposition of finer sediments (Fig. 10).

### 5.2. Origin and evolution of sandbodies

The three selected examples of sandbodies are located at various water depths and seismic evidence illustrates variations in their morphology and internal architecture. We propose to explain these variations in relation to Holocene sea level change.

The southern part of the RTBSB is buried by the mud drape and is therefore older than 850±40 BP. The northern part of the RTBSB has been partly deposited during the last two centuries (Figs. 2 and 3) and corresponds to the nearshore prolongation of a coast, which has experienced progradation during the same period of time (Fig. 2). This shoreline progradation is associated with sand spit building (Fig. 2), indicating that the sand infilling this northwestern part of the Marennes-Oléron bay is partly driven by littoral drift processes. Thus we propose that the RTBSB corresponds to a millenial time scale increase in sand deposition in response to both littoral drift and tidal current transport and reflects a stage of coastal progradation and estuary infill (Chaumillon et al., 2003). The RTBSB flat upper surface is close to the present-day low tide ($-3$ to $-1$ m) and is indicative of present-day sea level and of an equilibrium between sediment supply and tidal/wave regime. We thus postulate that the RTBSB is a good analogue of progradational coastal wedges recording sea level stillstands (Darigo and Osborne, 1986; Van Wagoner et al., 1988; Boyd et al., 1989; Tesson et al., 1993; Gensous et al., 1993; Rabineau et al., 1998).

The BBSB displays similarity in terms of geometry with the RTBSB; it has an elongated shape and is parallel to the shoreline. Moreover, we note that the BBSB upper surface corresponds to a terrace-like feature, located between $-6$ and $-7$ m of water depth, which is also apparent in the northern part of the Pertuis Breton (Fig. 4). The upper part of BBSB is dated to 2965±30 BP, we thus assume that the BBSB is a remnant of coastal progradation recording a lower sea level stillstand. Coastal progradation during transgression is related to a decrease in the rate of sea level rise or stillstand (Darigo and Osborne, 1986; Van Wagoner et al., 1988; Boyd et al., 1989; Gensous et al., 1993; Hernandez-Molina et al., 1994; Somoza et al., 1997). Such a change in sea level rise seems to have occurred around 3000 years BP, on the French Atlantic coast, when mean sea level was around $-3$ m ($-6$ to $-7$ m relative to present-day mean sea level, 0 NGF, Ters, 1986).

Buried sandwaves are emplaced in a different setting. They are deeper and localised on a rounded shape sandbody. Their occurrence attests to the action of tidal currents below wave base. As revealed by seismic data, BSW shape is very similar to that of active dunes. This feature indicates that the sandwaves have not been reworked during the

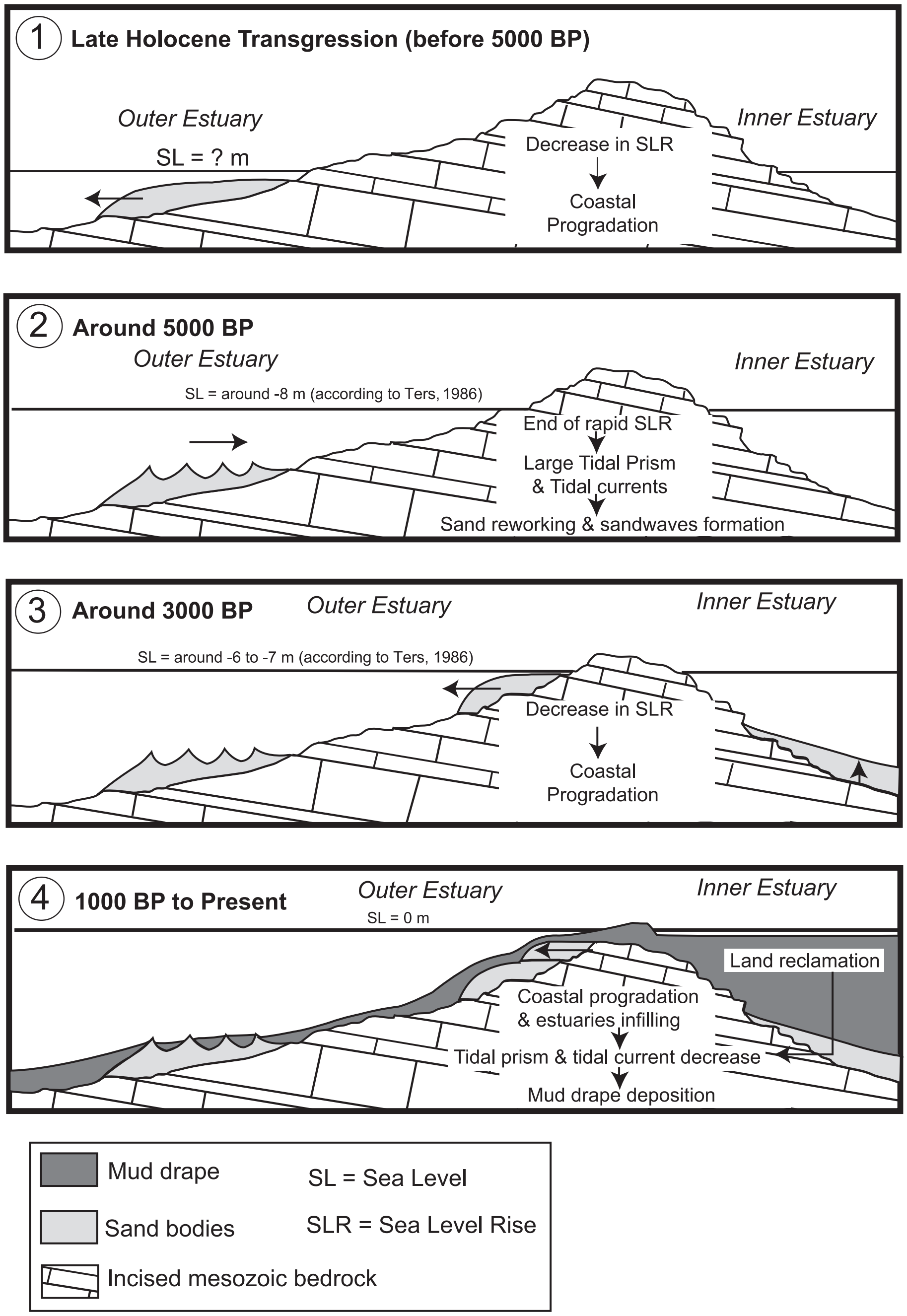



Fig. 10. A series of sketch illustrating the way of preservation of the three examples of sandbodies discussed in this paper. Deepest sandbodies (−6 and −17 m) are interpreted as remnants of lower sea levels, their stepping recording the Holocene transgression. The shallowest one (RTBSB) record shoreline progradation during the last centuries. All those sandbodies are buried under an estuarine mud drape emplaced during the last millenium. This drape is interpreted as the record of a major environmental change partly driven by human activities.

stage of burial, which mainly occurred during the last millenium, as revealed by radiocarbon dating (Fig. 2). The upper part of the sandbody, on the top of which the BSW are located, is dated to 5260±30 BP; indeed it would record an episode of sandbank reworking during the slowdown of the sea level rise, which occurred after 6000 BP (Lambeck, 1997). We assume that the sandbody, below the sandwaves, could have been deposited before this stage of sand reworking, during the early Holocene transgression.

Differences in sandbody morphology and internal architecture, revealed by our seismic studies, indicate that they record different processes. Both bathymetric data and radiocarbon dating show that they have been built during different periods of time (Fig. 10). Since the mud drape, lying upon those sandbodies, has been mainly emplaced during the last millennium, the boundary between the sandbody and the mud drape is not an isochron. It would represent a period of time ranging from decades to millenia. The southern RTBSB has been emplaced slightly before the mud drape and the northern RTBSB has been emplaced during mud drape deposition, indicating that the sand to mud transition record a very short period of time. Radiocarbon dates of BBSB and BSW indicate that they have been emplaced at the end of the Holocene transgression, indeed their upper unconformity may represent a few thousand years of non-deposition. In terms of stratigraphy, this major sedimentary change does not only record the transition from transgressive to highstand parasequences (BSW and BBSB), but also sedimentary facies change within highstand estuary infill.

## 6. Conclusion

VHR seismic studies constrained by vibrocores and repetitive bathymetric surveys document the occurrence of buried sandbodies in mixed tide-and-wave estuarine systems of the French Atlantic coast. Buried sandbodies are located at various water depth and include (1) a very shallow water elongated nearshore sandbody, emplaced during the last millenium; (2) a −6 to −7 m deep, elongated nearshore sandbody probably emplaced around 3000 BP; (3) a sandwave field lying around −17 m of water depth on top of a large, rounded sandbody that was probably emplaced around 5000 BP. Deepest sandbodies (−6 and −17 m) are interpreted as remnants of lower sea levels, their stepping recording the Holocene transgression. All those sandbodies are buried under an estuarine mud drape. This drape is interpreted as the record of a major environmental change that occurred during the last millenium. We propose that this environmental change is mainly related to human activities, more precisely to dramatic land reclamation resulting in both a decrease of tidal prism and tidal current energy and an increase of mud deposition upon sand bodies.

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