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Geomorphological and hydrodynamic forcing of sedimentary bedforms - Example of Gulf of Morbihan (South Brittany, Bay of Biscay)

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ABSTRACT

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The late Quaternary sedimentary architecture of the *Golfe de Morbihan*, a bedrock-controlled lagoonal basin with low sediment supply, was studied by applying an approach based on high-resolution seismic stratigraphy. The present-day environment is characterized by a wave-dominated regime and also shows some local tidal influence. Indeed, the *Gulf of Morbihan* is connected to the *Bay of Quiberon* by a narrow tidal pass (rocky sill) where the surface tidal currents reach velocities of up to 2.2 m/s during the flood and 1.8 m/s during the ebb. Wave influence is reduced and confined in the eastern part (inner zone) of the gulf. Flood and ebb tidal currents constrained by basement highs cause a separation between gravel, sand and mud particles. The channel-fill architecture is strongly dependent on tidal current velocity and the geomorphological setting. In the western part of the gulf (outer zone), near the tidal pass, erosion and sediment transport processes are enhanced along the axis of the tidal channel, because of the increased velocity of tidal currents. The outer tidal channel is scoured and the strong currents transport sand (lithic and biolithic fragments) and gravels, which are later deposited along the channel margins. In the central part of the gulf, the hydrodynamic conditions are of slightly weaker energy, and infilling takes places along the axes of the tidal channel, with sedimentation being dominated by a moderate to low-energy regime with fine sands and muds. The channel-fill architecture is composed of lateral-accretion bedding and small elongate tidal bars. In the eastern part of the gulf, tidal currents are very weak, and tidal channels are mainly filled with muddy facies, containing fluid muds in the channel bottom.

ADDITIONAL INDEX WORDS: *bedrock control, hydrodynamic conditions, sand and tidal bars*

INTRODUCTION

The evolution and distribution of ancient and present-day coastal systems have been greatly influenced worldwide by the geomorphological heritage and the Quaternary variations in sea-level. On several occasions, marine transgressions advanced along valleys incised during lowstands. The hydrodynamic variations generated during high- or lowstands shifted the sediments and contributed to the erosion of sandy, muddy and rocky shores. This led to gradual geomorphological changes in both coast line and substratum. Numerous articles have been published worldwide over the past 20 years concerning the stratigraphic geology and infilling of incised valleys (Allen & Posamentier, 1993; Dalrymple *et al.*, 1992; Zaitlin *et al.*, 1994). On the Atlantic seaboard, several studies, conducted in the 1990s and during the first decade of this century, have clarified the infilling patterns of the "fossil" valleys leading out onto the continental plateau (Proust *et al.*, 2001; Lericolais *et al.*, 2001; Fénies & Lericolais, 2005; Menier *et al.*, 2006; Chaumillon *et al.*, 2006; Thinon *et al.*, 2009, Menier *et al.*, 2010, Tessier *et al.*, 2010, Paquet *et al.*, 2010). Since then, new very-high-resolution seismic data have been acquired in more sheltered environments, less exposed to the action of physical elements such as waves and wind. In the present study, we are concerned with the system of the Gulf of Morbihan (GM), which communicates with the open sea via a narrow sill, 900 m wide and 30 m deep (Figures 1 and 2). The GM includes a network of incised valleys which extends into the *Baie de Quiberon* (Menier *et al.*, 2010) and which are controlled by the orientation of the main structural and lithological features. The incisions are located in the central zone of the GM, between the two main islands, the "*Ile aux Moines* » and the « *Ile d'Arz* » (Figure. 1). These valleys are narrower than those identified in the *Bay of Quiberon* (Menier *et al.*, 2006, Menier *et al.*, 2010), with widths ranging from 100 to 1000 m. A transverse section reveals varied morphological features: round-bottomed V-shaped valleys, flat-bottomed and steep-sided valleys, and valleys with stepped terraces. The reconstruction of longitudinal profiles also reveals major discontinuities characterized by the presence of topographic sills. The latter are thought to be due to the reactivation of Cadomian and Hercynian fractures, or related to lithological contrasts, or a combination of both (Menier, 2004, Menier *et al.*, 2006).

Offshore from Southern Brittany, the infilling of incised valleys usually involves two sedimentary sequences. The sedimentary environment of the basal sequence seems to correspond to braided fluviatile deposits, laid down during the Saalian and/or Elsterian lowstands, or even before (Proust *et al.*, 2001, Menier *et al.*, 2006, Menier *et al.*, 2010). This basal sequence is overlain by a younger sequence of deposits, related to meandering fluviatile and estuarine environments of unknown age, developing later into an open marine facies dated as Holocene (Proust *et al.*, 2001, Menier *et al.*, 2010, Sorrel *et al.*, 2010).

The analysis presented here is focused on the final infilling stage, using a combined approach which includes seismic data (this study), a morphobathymetric survey (Pastol *et al.*, 2007) and sedimentological studies (Menier and Dubois, 2011) of the Gulf of Morbihan. The present study shows the essential role of basement roof morphology in controlling the acceleration of currents, which influences the sedimentary architecture (Heap and Nichols, 1997; Lobo *et al.*, 2003) as well as the distribution of deposits along the rocky coasts of South Brittany, which are characterized by low sediment supply (Menier *et al.*, 2010).

STUDIED AREA

The *Gulf of Morbihan* is a steep topographic depression which forms a water body with an area of 11,500 ha and a shoreline of 250 km, opening out to the sea through the 900-m wide sill at Port Navalo. The offshore and onshore substratum is mainly composed of igneous and metamorphic rocks, emplaced during the Hercynian orogeny. Inland, we note the absence of a Mesozoic sedimentary cover, in contrast with the presence of a Cenozoic sedimentary succession in the northern and eastern parts of the gulf (Brault *et al.*, 2001). The GM is characterized by the considerable number of islands, 37 according to the French IGN (*Institut Géographique National*). The two largest islands are the *Ile aux Moines* and the *Ile d'Arz* (Figure 1). In the GM, almost all the valley fills are post-glacial (Perez-Belmonte, 2008).

Hydrodynamic modelling has been used to study the powerful tidal currents which run through the Gulf of Morbihan (Marcos *et al.* 1996). At the GM entrance, the current can reach a velocity of 2.2 m/s during ebb tides and 1.8 m/s during flood tides. Tides in the Gulf appear to vary considerably, both in time and space. The further away from the entrance, the lower the tidal range: it is of the order of 5 m at the GM entrance, but only 4 m near Vannes and 3 m at the level of the *Ile Bailleron*. Hence, the tides are hypersynchronous, a characteristic feature of tide-dominated environments (Dalrymple and Choi, 2006), while the attenuation of the tidal pulse is due to local geomorphology (Marcaillou *et al.* 1996).

As a result of these very specific hydrodynamic conditions, morphobathymetric features show a very uneven relief, with depths ranging from more than 30 m at the gulf entrance to less than 1 m in the western sub-basin, thus emphasizing the gradual attenuation of tidal currents towards the east.

More specifically, three morphobathymetric sub-basins can be distinguished: i) an inner zone, east of the *Ile d'Arz*, which is sheltered from currents and where incision depth does not exceed 1 to 2 m; ii) a medium zone, where channel depths can reach 10 m and a width of 50 m; iii) an outer zone, located between the *Ile aux Moines* and the entrance of the gulf, where tidal currents are strong (Fig. 3; Perez-Belmonte, 2008). The gulf is contains a complex network of tidal channels, oriented according to the two principal Armorican structural trends, N 160° and N 40°, where the development of infilling mainly depends on the last glacial cycle (Perez-Belmonte, 2008).

The most modern superficial sedimentary mantle has been the object of a recent publication (Menier and Dubois, 2011). In the external basin, the channel beds are mainly rocky, sometimes covered by a thin layer of coarse deposits. In the medial sub-basin, channel beds are mainly composed of a mixture of sand and silt, which changes to mud in the more lateral channels (Fig. 2).

METHODS

The present study analyses a combination of morphobathymetric data (Pastol et al., 2007), sedimentary data (Menier and Dubois, 2011) and HR/VHR seismic data (Figure 2). The morpho-bathymetry data used here are available from the Hydrographic and Oceanographic Service of the French Navy (S.H.O.M), and are derived from the multibeam data compiled in the framework of the Litto3D project. We used these morphobathymetric data to create a Digital Terrain Model (DTM) for the GM, with a 1m resolution. Developed using Arcview®, a geographic information system software, this DTM provided us with detailed information on the rocky areas as well as the morphology of tidal channels, subtidal and intertidal mudflats and sandbanks (Figure 2; Menier and Dubois, 2011).

The seismic profiles cover an area extending from the mouth of the Noyalo river to Auray river and also as far as the entrance of the *Gulf of Morbihan* (Figure 2). Data acquisition was carried out using an IKB-Seistec™ (VHR (very-high-resolution) profiler equipped with a boomer and a directional line-in-cone broadband seismic receiver (Simpkin and Davis, 1993). Recording of the data in real time was performed with the ELICS DELPH software, which also allowed acquisition with simultaneous positioning ensured by a DGPS (digital global positioning system).

Seismic data were then processed using the Unix Seismic

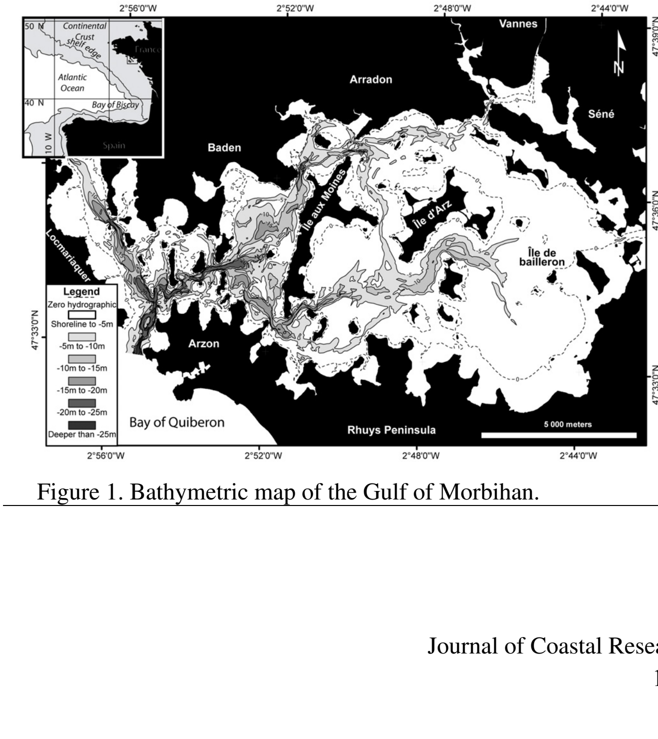

Figure 1. Bathymetric map of the Gulf of Morbihan.

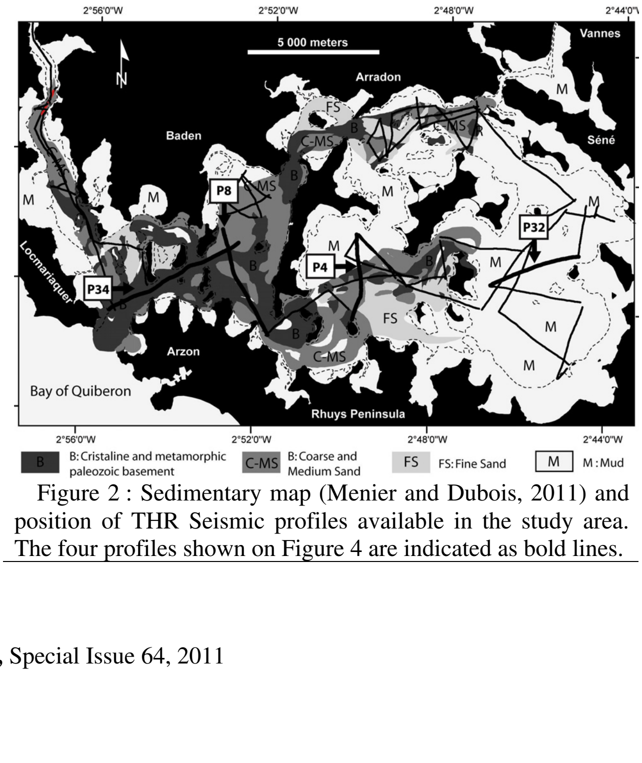

Figure 2 : Sedimentary map (Menier and Dubois, 2011) and position of THR Seismic profiles available in the study area. The four profiles shown on Figure 4 are indicated as bold lines.

software, notably to filter swell. The results of profile interpretation where then utilized by the Kogeo software. To estimate the thicknesses, a velocity of 1800 m/s was assumed for seismic wave propagation in the filling.

The morphobathymetric and seismic data were supplemented by sedimentological data, acquired by sampling and coring during numerous campaigns between 2003 and 2009, which enabled us to map the superficial sedimentary formations (Figure 2). Core sample analysis allowed us to establish severals marker beds. AMS (Accelerator Mass Spectrometry) radiocarbon dating was carried out on intact shells and bulk sediments. Measurements were carried out by the Poznań Radiocarbon Laboratory (Poland) (Perez-Belmonte, 2008).

Seismic profile analysis consists of defining the properties (continuity, amplitude and frequency), configuration and termination of the reflectors, according to the conventional rules of seismic stratigraphy defined by Mitchum et al., (1977) and adopted by Menier *et al.* (2006 et 2010). The analysis of the facies and acoustic units in this area have already been the object of several publications (Proust *et al*., 2001; Menier, 2004; Menier *et al*., 2006; Menier et *al.*, 2010), so these aspects are not further detailed in the present study. To illustrate the Holocene infilling of incised valleys in the GM, four seismic profiles were selected (P04, P08, P32 and P34). They are located over on area from the mouth of the Noyalo river to the entrance of the GM (Figure. 4).

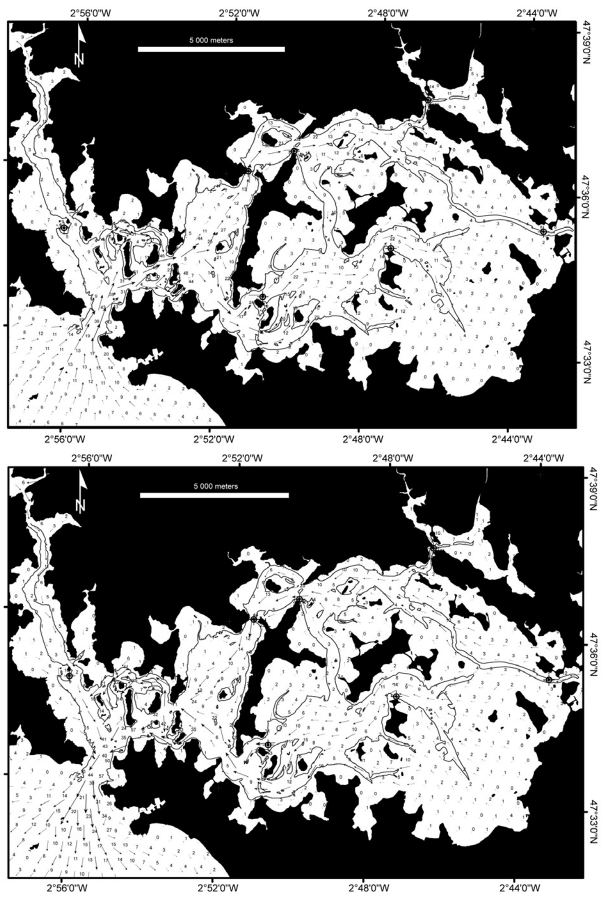

Figure 3. Map showing tidal current speed (cm/s) and tidal cirrent direction (A), two hours before high tide (coef 95) and (B) two hours after low tide (Coef 45), (Pastol *et al.*, 2007)

RESULTS

Analysis of the geophysical data allows us to distinguish several infilling units within the three sub-basins, which are described here one after the other. All these infilling units overlie a basal unit that corresponds to the seismic unit U0 (Figure 4). This acoustic basement is made up of faulted igneous and/or metamorphic rocks (Menier *et al.*, 2010).

The inner sub-basin contains two infilling units [U4a & b], separated by an erosive surface and preserved within a 350-m-wide incised valley with a maximum depth of 10 m. The deposits of the U4b unit broadly overlap from the valley. Most reflectors display a parallel configuration with an aggrading geometry. These acoustic features were interpreted as corresponding to fine and medium-grained tidal deposits, representative of a low-energy environment such as that of a bay head. Drill cores yield a date of 4910 yrs cal BP for the base of these tidal flats (Perez-Belmonte, 2008). The central sub-basin exhibits 4 infilling units in a valley approximately 800 m wide with an incision depth of 18 m. A thin basal unit (U1), of small extent, is visible on the basement roof. This unit is made up of reflectors with a chaotic to prograding configuration, only preserved in certain minor depressions. This infilling unit is interpreted as being composed of lowstand fluvio-estuarine deposits similar to those found in the south-Armorican coastal domain (Proust *et al.*, 2001, Perez-Belmonte, 2008, Menier *et al.*, 2006, Menier *et al.*, 2010). It is covered by two units (U3 and U4) with a complex configuration, in which a parallel oblique pattern is combined with the two main geometries tangential oblique and sigmoidal oblique. The tangential oblique geometry forms a lateral filling with a channelling structure, and can therefore be interpreted as representing lateral beach accretion ridges (point bars). The sigmoid oblique geometry shows a regular prograding configuration which is interpreted as an expression of the progradation of sandbars separating the tidal channels (Figure 4). In the lower energy sectors, laterally to the main valley, we note the presence of the U4a unit.

The outer sub-basin contains infilling units U1, U2, U3 & U5 in a valley that is 1,000 m wide and 25 m deep. The U2 and U3 units, only preserved on the glacial shoulders of the main valley, are capped by an uppermost infilling unit (U5), where the reflectors are highly oblique. The steep dip of the reflectors and the very rugged topography (Figure 4) are indicative of a higher energy depositional environment. These deposits correspond to high-energy tidal dunes (Berné, 1999). The centre of the valley is devoid of sediment, which confirms the high- energy conditions that prevailed in this sub-basin (Figure 4).

DISCUSSION

The preserved morphosedimentary features encountered in the three sub-basins (or zones) are due to numerous controlling factors which influence the superficial and internal nature of the deposits, as well as their spatial development according to bathymetry, geomorphological features, hydrodynamic energy regime (tidal currents) and the eventual reworking of sediments (Heap and Nichols, 1997; Lobo *et al.*, 2003). During lowstands, transport processes (by-passing) were probably predominant. During these periods of sub-aerial emergence, erosional processes predominated in these narrow valleys rather than fluvio-estuarine sedimentation. This interpretation is backed up by the poor preservation and the thinness of the lowstand deposits. During post-glacial transgression, tidal erosion processes seem to have been intense, leading to topographic depressions and migration of sandy and silty-clay deposits towards the continent.

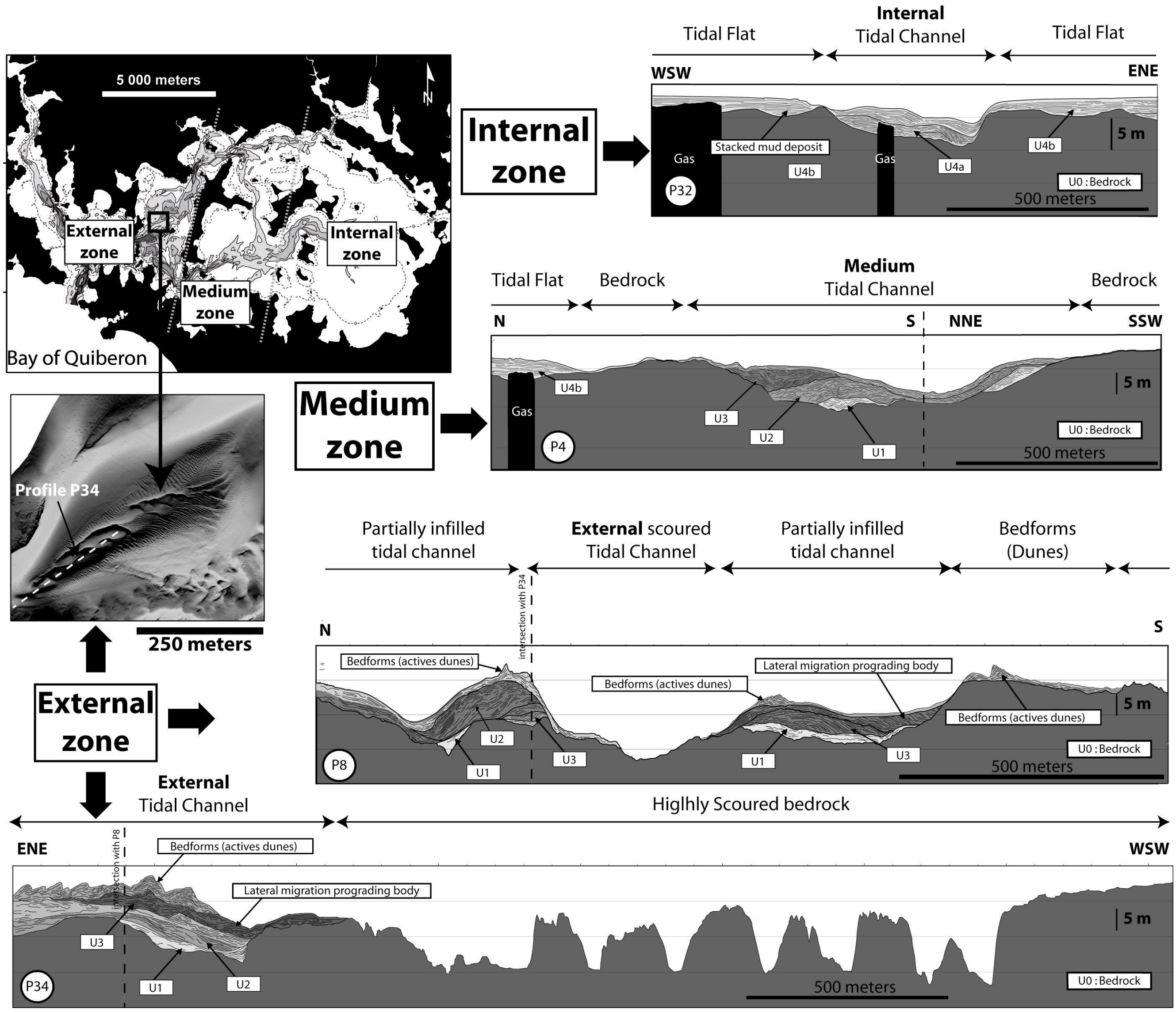

Figure 4. Seismic interpretations of P32, P4, P8, P34 seismic profiles showing the whole organization of the main seismic units in the Gulf of Morbihan.

At the river mouths, channels are over deepened and scoured. Deposits are only visible on the channel margins, and their facies are characteristic of tidal dune fields. These dunes are asymmetrical and display a highly heterogeneous morphology. Episodes of maximum flooding reinforced the currents and led to the emplacement of coarse- and medium-grained deposits, such as found in the central zone, both in the channels and at their margins. In the internal sector, deposits were laid down over a wide area with weak tidal currents. In this sheltered environment, less exposed to wave and wind action, sedimentation of tidal flat deposits occurred over a vast area (Figures 2 and 4).

CONCLUSION

This study illustrates the record of the main post-glacial and recent depositional sequences that were remobilized in a system dominated by tidal influences and low sediment supply. The sediment distribution depends on the tidal currents, which are themselves strongly influenced by the very rugged geomorphological setting. The *Gulf of Morbihan* could be considered as a succession of three small basins, separated to the west by the *Ile aux Moines* and to the east by the *Ile d'Arz* (Figure 1). The depth of these basins decreases towards the east. They are separated by topographic sills, which we interpret as resulting from the Quaternary reactivation of old Hercynian faults (Bonnet *et al.*, 2000; Menier *et al.*, 2006; Perez-Belmonte, 2008; Menier *et al.*, 2010). In the western part (inner zone), channels are devoid of sediment, except at their margins, where several generations of tidal sandbars have developed (Berné, 1999; Dalrymple and Choi, 2006). The most recent dunes show sharp ridges, which are maintained by the very strong tidal currents (Figure 4). In the central basin, tidal currents are weaker in the channels. Sediments are medium to fine grained, forming longitudinal bodies oriented parallel to the direction of the strongest currents. The internal geometry of the channel fill in the central zone results from the stacking of channel levee systems, which grade horizontally into lateral accretion bars. Finally, within the inner zone, the hydrodynamic regime is of much lower energy. Extensive sedimentary units, composed of vertically accreted depositional sequences dominated by muds, are developed in sub-tidal and intertidal environments.

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