The Bay of Mont-Saint-Michel

Facies, morphodynamics and Holocene evolution of a hypertidal coastal environment

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Excursion leaders
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The Bay of Mont-Saint-Michel

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Abstract. The aim of this 2-day field trip in the Bay of Mont-Saint-Michel, located between Normandy and Brittany (NW France), is to examine the different sedimentary environments, which compose this hypertidal coastal system: in the west, a tide-dominated wave-influenced embayment characterized by wide tidal flats, and bioclastic ridges; in the east, a tide-dominated estuary, with typical tidal facies, especially tidal rhythmites; in the north-east, a wave-dominated shoreline with sandspits bordering the high energy estuarine tidal channels. A spectacular reef made by worms develops on the rocky substrate outcropping in this northern entrance of the Bay. Hydrodynamics, sedimentary facies and sequences, Holocene infill and evolution will be discussed through field observations, sediment cores, VHR seismic and GPR data. The field trip includes a sightseeing tour of Mont-Saint-Michel, and an overview of Norman gastronomy!

Keywords. Tidal sedimentology, embayment, estuary, hydrodynamics, Holocene
General program of the field trip

**SUNDAY, OCTOBER 8**

**Tidal range:** 12.30 m (spring tide); **High tide:** 9:40 AM; **Low tide:** 5:00 PM

Northeastern sandy coast and Estuary

**STOP 1 – 10:00 am: Pointe de Champeaux**  
Geological context, hydrodynamic and morphosedimentary characteristics of the bay of Mont-Saint-Michel

**STOP 2 – 11:30 am: Sandspit in Dragey**  
Sediment dynamics of the northeastern sandy coast, Holocene infill

**STOP 3 – 2:00 pm: Retreating beach of St Jean le Thomas**  
Sediment dynamics of the northeastern sandy coast, Holocene infill

**STOP 4 – 3:30 pm: Hermelles reef in Champeaux**  
Conditions of settlement and structures of the reef

**STOP 5 – 5:00 pm: The inner estuary, from Pontaubault to Gué de l'Epine**  
Morphosedimentary organization, sedimentary facies and sequences in the inner estuary

**MONDAY, OCTOBER 9**

**Tidal range:** 11.5 m (spring tide); **High tide:** 10:20 AM; **Low tide:** 5:30 PM

Estuary and Western embayment

**STOP 6 – 9:30 am: Upstream along the Sée river estuary**  
Tidal bore observation, hydrosedimentary processes and sedimentary signatures

**STOP 7 – 11:00 am: The Mont Saint Michel**  
Tourism and restoration works of the maritime character of the Mont-Saint-Michel

**STOP 8 – 2:00 am: Vildé-Hirel**  
The embayment: tidal flats and shelly ridges  
Synthesis on the Holocene evolution of the Bay
Figure 1. Location of the different stops during the field trip (SPOT Image, February 28, 1999; Processing by J. Le Rhun & C. Bonnot-Courtois, UMR CNRS Prodige, EPHE).
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Morphosedimentary organization, sedimentary facies and sequences in the inner estuary
STOP 1. Pointe de Champeaux

Geological context, hydrodynamic and morphosedimentary characteristics of the bay of Mont-Saint-Michel

A nice panoramic view is offered on the whole Bay of Mont-Saint-Michel, from “la Pointe de Champeaux”, on top of the Massif of Carolles, one of the three main cadomian granitic batholites surrounding the bay (Fig. 2).

The Mont-Saint-Michel Bay (MSMB) belongs to the geological framework of the Armorican Massif (L’Homer et al., 1999). Its substrate is made of pre-cambrian sedimentary rocks (Brioverian turbiditic shales) and igneous rocks (Cadamian granites) (Fig. 2).

As most coastal landscapes around the English Channel, the morphology of the MSMB is a heritage of the plio-pleistocene glacio-eustatic fluctuations. During sea-level drops and lowstands, rivers incised the substrate and shaped the depression that was filled during subsequent rise and highstand. Since the regional subsidence is negligible, only the last post-glacial transgression is recorded into the infilling of the MSMB, the previous sea-level falls having reworked almost all older marine sediments (L’homer et al., 1999). The last post-glacial sea-level rise was very rapid (about 6 mm/year, Lambeck, 1997; L’ homer et al., 2002) and marine flooding already reached the most internal zones of the MSMB around 8000 yr B.P. (Fig. 3).

Figure 2. Simplified geological and sedimentological map of the Mont-Saint-Michel bay (after Laronneur and coll., 1989 ; L’Homer et al., 1999)
Around 7000 - 6000 yr B.P. the transgression slowed down significantly (3 mm to progressively 1 mm/yr, L'Homer et al., 2006, Fig. 4), allowing coastal wedge construction in general, and a rapid infilling of estuaries and embayments such as the MSMB (Fig. 5).

Since that time of highstand sea-level or at least of very slow transgression, the different coastal environments composing the present-day landscape of the MSMB developed and evolved, each under the influence of specific geomorphological, hydrodynamic and sediment supply conditions.

![Figure 3. Paleogeographical reconstruction of the Mont-Saint-Michel bay during the main stages of its Holocene evolution (after Morzadec-Kerfourn, 1974; 1975, in Bonnot et al., 2002 and in Larsonneur, 1989)]
Figure 4. Reconstruction of the Holocene relative sea-level fluctuations in the Mont-Saint-Michel bay. Before 6500 yr BP, the rate is of about 10 mm/yr and then decreased to 3 to 1 mm/yr (After L’Homer et al. 2006).

Figure 5. Schematic cross-section of the Holocene coastal wedge preserved below the Dol marshes (After L’hommer et al., 2002). This reconstruction mainly based on drillholes into the Dol Marshes shows the passage from a vertical aggradation to a progradation at around 6500 yr BP, i.e. when rise in sea-level slowed down.
**STOP 2 and STOP 3. Dragey and Saint Jean-Le-Thomas beaches**

*Sediment dynamics of the northeastern sandy coast, Holocene infill.*

The northeastern littoral of the MSMB is represented by a sandy coastline that experiences some spectacular and contrasted processes of erosion (coastline retreat) and sedimentation (coastline progradation) (Fig. 6).

Studies performed by comparing aerial photos since 1947 have demonstrated that the beach at Saint Jean-le-Thomas locality has retreated of about 200 m while, southward, at the Bec d’Andaine or Dragey sites, beaches advanced of about the same value (Compain et al., 1988).

These evolution and coastline organization are mainly related to wave action and sediment supply distribution.

**Figure 6.** The different landscapes and morphosedimentary units of the NE shoreline of the Bay of Mont-Saint-Michel (Aerial Photo © IGN 1999) (in Tessier et al., 2006).
The NE entrance of the MSMB is exposed to prevailing W to NW swells that induce severe erosion at Saint Jean-le-Thomas. The eroded sand material is transported southward by the littoral drift until Dragey and Bec d'Andaine localities where it is fixed as sandspits.

The sand spits isolate from the open sea energy sheltered depressions or ponds that are invaded only by spring tides, and are filled by fine-grained tidal facies evolving progressively to salt marsh deposits.

Northward, at Saint Jean-le-Thomas, the high energy swell action induces a severe beach and dune (barrier) retreat. The process produces a wave ravinement surface eroding older back-barrier sediment successions that deposited when the barrier was located more offshore than the present-day one. This barrier began to construct some 6500 y. ago, when the rise in sea level slowed down significantly. Since that period, sea level rose slowly and the barrier has retreated until its present-day position.

The NE littoral of the MSMB can be considered as a wave-dominated environment. However, its evolution is significantly influenced by the tidal dynamics of the adjacent estuary since the main estuarine channel borders the coastline. When the channel migrates northward and tends to approach the shore, the Bec d'Andaine and Dragey sand spits experience erosion due to tidal ravinement processes.

These different aspects of the NE littoral evolution and functioning are summarized on Fig. 6. Stops 2 and 3 also offer the opportunity to discuss about the Holocene sedimentary infill of the MSMB. In the framework of Isabelle Billeaud's PhD work (I. Billeaud, 2007, Univ. Caen), some 50 vibrocores and 600 km of VHR seismic profiles were acquired, that allowed reconstructing the Holocene infill architecture (Billeaud et al., 2007; Tessier et al., 2010) (Plate 1), as well as demonstrating that Holocene rapid climate changes have significantly impacted the dynamic of infill of this hypertidal environment (Billeaud et al., 2009; Tessier et al., 2012) (Plate 2).
Plate 1
Reconstruction of the Holocene sedimentary infill
(all figures in Tessier et al., 2010 and after Billeaud, 2007)

Examples of seismic lines and cores acquired in the embayment, on the mudflat of Cancale (above – Hriel 10) and on the sandflat of Cherrueix (below – Cherru 2). Seismic data in the illustrate that the HST (Ub4) is an aggradational depositional unit, with locally internal erosional surfaces (Hriel 10). In both sectors, the TST (Ub3) is represented by bioclastic sands and locally migrating bedforms such as dunes or banks. Cores and 14C dating demonstrate that the passage from the TST to the HST occurred around 6500 y BP.

Location of seismic lines (~ 600 km) and vibrocores (~50, 7 m long) collected in the MSMB

Above the bedrock, two depositional units are identified:

The TST is made of aggradational fine-grained facies in the estuarine domain, while it is composed of high energy coarse-grained deposits into the embayment.

The HST into the estuary is represented by a sand-dominated tidal channel-and-shoal belt, whereas into the embayment, it is an aggradational unit, consistent with the present-day tidal flat landscape.
Examples of seismic lines and cores collected into the estuary. The HST is composed of 2 units: an upper unit (Ue5) containing multiple erosional surfaces (estuarine channels), and that progressively pinches up seaward. It rests through an erosional surface (tidal ravinement) on a seaward progradational unit (Ue4) interpreted as the bottomset termination of the estuarine body. The TST is made of an aggradational unit composed of fine-grained deposits that produce biogenic gas.

Synthetic cross-sections illustrating the main geometrical patterns of the MSMB sedimentary infilling.

The HST represents the main unit of the infilling of the MSMB. It is composed of aggrading tidal flats in the embayment, and of aggrading / wandering channel-and-shoal body in the estuary. This body, fed exclusively by marine source, translates progressively seaward, as the estuary fills. Because of the shallowness of the bedrock compared to the deepness of the tidal ravinement, the HST occupies most of the initial accommodation into the estuary.
Plate 2

Holocene rapid climate change impacts
(all figures in Billeaud et al., 2009)

Cores and seismic lines acquired in the MSMB, illustrating the different types of records of Holocene climate changes into the HST: storm-dominated facies in the sandflat successions into the embayment; barrier destruction phases along the NE shoreline; tidal incisions into the mudflat of the embayment induced by barrier destruction; storm-generated erosional flat surfaces into subtidal banks.

The records of periodic environmental changes are preserved into the HST deposits of the MSMB sedimentary infill. 14C dating demonstrates these changes can be correlated at the scale of the bay. They are attributed, in all cases, to storm impacts, which occur with a millennial time-scale periodicity. Four to five significant changes occurred. The time of these climatic crises was ~5500-5800, 4000-4500, ~3000, 1000-1200 yr B.P. and matches the time of the Bond’s events.
STOP 4. The Hermelles reef

Conditions of settlement and structures of the reef

At two places in the Bay of Mont-Saint-Michel, bioconstructions made by polychaete worms develop on the margins of the estuarine system in the lower intertidal area. The best developed and known reef, called the “Banc des Hermelles” is located about 4 km off the Chapelle Sainte-Anne at the transition between the estuarine domain and the embayment (cf. Fig. 2). The second reef is implanted on the rocky flat at the foot of Champeaux cliff (cf. photos below), in the north of the Bay, at the junction between the estuarine entrance and the open marine domain. This reef is easily accessible at low tide and, although of less extension than the “Banc des Hermelles”, displays very spectacular shapes and development.

The “Hermelles”, or *Sabellaria alveolata*, are gregarious and sedentary annelid polychaete that construct massive reefs made of contiguous arenaceous tubes 5 to 10 mm in diameter. The reefs constitute arborescent structures reaching up to 1.2 m above the floor. Densities are very high (15,000 to 60,000 individuals/m²).

The settlement of the juvenile polychaete requires a hard or sufficiently stable substrate. In the case of Champeaux, the reef naturally settles on the outcropping rocky substrate as well as on the walls of ancient permanent fishing. The nature of the substrate supporting the so-called “Banc des Hermelles” is not clearly defined. It is probably constituted by natural oyster beds.

For more information about the dynamics and behaviour of *Sabellaria alveolata* reefs (including those of the Bay of Mont-Saint-Michel) see Dubois et al. (2003) as well as Lecornu et al. (2016) and references therein.
STOP 5. From Gué de l’Épine to Pontaubault

Morphosedimentary organization, sedimentary facies and sequences in the inner estuary

The Stop 5 is in fact composed of 2 main stops between Gué de l’Épine and Pontaubault. This portion belongs to the inner estuary (Fig. 7A). It is located on the right bank of the Sélune river where the estuarine system is made up of a single channel, bordered by the slikke and schorre domains which extend over a width of about 1 km (this portion of the estuary corresponds to the straight-to-meandering fluvio-tidal transitory domain of the morphosedimentary model for tide-dominated estuary by Dalrymple et al. (1990), Fig. 7B).

Some 1-2 km downstream, the estuary consists in a vast area of sandy-silty slikke covered by a dense network of tidal channels bordered by megaripples (the braided tidal system according Dalrymple’s model, Fig. 7B).

The hydrodynamic of the inner estuary is controlled by tidal currents and in particular by the flood, faster than the ebb. The flood arrival is accompanied by a tidal bore - mascaret in French - (reaching about 80 cm during high spring tides) which spreads into the channel with a velocity in the order of 3-4 m/s.

Figure 7. Morphosedimentary map of the Mont-Saint-Michel estuarine system (A) with indication of the concordances with the model of Dalrymple (1990) for tide-dominated estuaries (B) (in Lanier & Tessier, 1998)
The bore reworks a high quantity of sediment as it passes, contributing in increasing considerably the turbidity of the penetrating water in the estuary (cf. Day 2 – Stop 6 – Plate 6 for more information on the hydrosedimentary characteristics of the tidal bore in the Mont-Saint-Michel estuary). Once the channel is filled, the flood overflows and sweeps progressively through the slikke, then the upper slikke if the tidal range is high enough. The velocity of the flood thus decreases very quickly and is only 0.5 m/s on average. The ebb is, as a rule, the subordinate current. Nevertheless, it is locally dominant assuming specific trajectories.

The migration of the straight-to-meandering fluvio-tidal transitory channel in time and space constitutes the main morpho-sedimentary process of Gué de l’Épine – Pontaubault area (cf. Fig. 9 for an example of cores collected in the meandering zone). This migration controls the dynamics of the point bars and the development of the banks associated to the channel, determining the distribution of the areas of sedimentation and erosion.

The inner estuary is characterized by a specific sediment called “tangue” (regional name), grey in colour, and generally described as a sandy to silty mud. Its mean grain size ranges from 0.03 to 0.09 mm. The tangue is a mixed silico-bioclastic sediment, containing about 50 % of biogenic carbonate represented by a fine-grained mixture of mollusca, foraminifera, ostracods, coccoliths and bryozoair fragments. The mineral fraction consists mainly of quartz, mica and heavy minerals. Due to its physico-chemical properties, linked to its composition, grain-size and texture, the tangue is a sediment that can be drained easily and compacts quickly. It has also thixotropic properties, making its reworking by tidal currents easy.

The tangue is therefore a mobile sediment, favourable to the formation and preservation of numerous figures and depositional structures. In cross section, the tangue displays a bedded appearance, made up of alternating layers, few millimetres to few centimetres thick, of sandy silt or muddy silt. Flaser-, wavy- and lenticular- bedding, as well as planar bedding of low energy, are the most represented beddings (Plate 3, photos 1, 2, 3). Climbing ripple bedding can also be frequent in short cut or levee position. Due to the tidal bore passage, freshly deposited tangue succession along tidal channel, can be deeply convoluted (Tessier & Terwindt, 1994; Tessier et al., 2017) (Plate 3, photos 4, 5, 6; cf. as well stop 6).

Microscop photo of a tangue sample showing the diversity of grain shapes and origins of this mixed silico-bioclastic silt-dominated sediment
Plate 3
Tidal facies in the inner estuary
Tidal beddings and tidal bore–induced deformations

The typical laminated aspect of the tangue in cross-sections. The tangue is constituted by the superposition of sand/mud couplets of varying thickness and shape.

Syn-sedimentary deformations in tangue deposits due to the tidal bore passage over the flat along the main estuarine channel (Grouin du Sud). (Tessier & Terwindt, 1994).
As wave activity is almost negligible, and thanks to the tangue occurrence and properties, the inner estuarine domain is the most favourable area in the MSMB to observe and analyse tidal facies and more specifically, tidal rhythmites (Plate 4).

In the lower intertidal area (lower slikke), in cross section, facies are quite homogenous represented by fine grained sand with occasional ripple cross bedding and upper flow planar bedding. Generally no rhythmicity can be observed at these low topographic levels on the edge of the active channel (Fig. 8, and Fig. 9 for example of cores). The energy is too high, inducing intense erosion processes, which prevent the record of the cyclic character of tidal dynamics.

Towards the upper intertidal (high slikke) and supratidal areas, the tangue facies become finer and the preservation of mud drapes increases. Flaser-, wavy - and lenticular beddings appear progressively. A high variety of beddings is well-preserved and tidal rhythmite facies are observable.

![Figure 8. Ideal facies succession in the internal estuary based on tidal rhythmite (TR) occurrence and evolution from lower intertidal (no TR), to upper intertidal (semi-lunar TR) and supratidal (annual TR) deposits (after Tessier, 1998)](image-url)
In cross-section, from upper intertidal to supratidal facies, two main types of tidal rhythmites (TR) are distinguished (Plate 4 and 5):

- **Semi-lunar TR** that record the neap-spring-neap tidal cycle of 14 days (Tessier, 1993). They are the best-developed TR and are essentially preserved in the upper intertidal deposits (Fig. 8). Different types of beddings form semi-lunar TR (Plate 4). The most frequent develop in planar bedding made up of sand- or mud-dominated, millimetric to centimetric doublets. In ripple bedding, neap/spring cycle is characterised by a variation in the thickness of the successive doublets, but also by an evolution in the type of bedding materialising the energy evolution during the semi-lunar cycle. Finally, semi-lunar TR are expressed quite frequently in climbing ripple bedding (Lanier & Tessier, 1998) in the ebb-dominated short-cut channels above point bars, or in flood levee facies (Plate 5, photos 1, 2, 3, 4).

- **Annual TR** that record the highest equinoctial tides of the year. They are preserved exclusively in supratidal (salt marsh) facies (Fig. 8) and consist in a few cm thick sequences made up of very thin (mm) tidal couplets (Plate 5, photos 5, 6, 7). Annual sequences are formed by a succession of undisturbed sand-dominated couplets and mud-dominated couplets heavily disturbed by roots. The later materialize the very low energy summer sedimentation of the marshes when grass develops, the sand dominated episode being related to the higher energy winter/spring sedimentation.
Figure 9. Vibrocores collected at Argennes-Pontaubault locality, in the lower to mid intertidal area of the meandering zone of the fluvio-tidal transitional channel that extends from Gué de l’Epine (downstream) to Pontaubault (upstream). Facies successions made of gravels and coarse sands and then sandy to silty tidal bedding are interpreted as the result of the channel migration and infilling (I. Billeaud, 2007, PhD Univ. Caen; Billeaud et al., 2007).
Plate 4
Tidal facies in the inner estuary. Semi-lunar tidal rhythmites

Examples of semi-lunar tidal rhythmites recorded in upper intertidal deposits of the inner estuary (arrows indicate neap tide stages (n) that correspond to a 5-6 days period of emersion. Spring tides (s) only are recorded. These examples illustrate TR recorded in planar-, wavy- and flaser-beddings (P, WB, FB) (in Tessier, 1993).
Plate 5
Tidal facies in the inner estuary
Semi-lunar and annual tidal rhythmites

Examples of semi-lunar tidal rhythmites (TR) recorded in upper intertidal deposits of the inner estuary. These examples illustrate TR recorded in Climbing-ripple beddings (n: neap tide stages; s: spring tides).
(1, 2: Flood-dominated facies of flood levees; 3, 4: ebb-dominated facies in short cut channels)
(After Lanier & Tessier, 1998)

Annual cycles recorded in salt marsh deposits of the inner estuary. Sand-dominated couplet succession (sd, light color - winter equinoctial tides) alternate with highly rooted mud-dominated succession (md, dark color - low energy summer deposition) (in Tessier, 1998).
Monday, October 9

Tidal range: 11.50 m (spring tide); High tide: 10:20 am; Low tide: 5:30 pm

Estuary and Western embayment

Stop 6 – 9:30 am: Upstream along the Sée river estuary

Tidal bore observation, hydrosedimentary processes and sedimentary signatures

Stop 7 – 11:00 am: The Mont Saint Michel

Tourism and restoration works of the maritime character of the Mont-Saint-Michel

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The embayment: tidal flats and shelly ridges

Synthesis on the Holocene evolution of the Bay
Upstream along the Sée river estuary

Tidal bore observation, hydrosedimentary processes and sedimentary signatures

The tidal bore is a common phenomenon observed in many estuaries around the world. All are hypersynchronous estuaries with low slope and tidal range exceeding, at least at their mouth, 6 m. Since a small decade, projects aiming in studying the hydrosedimentary processes induced by tidal bores emerge (e.g. Fan et al., 2012, 2014, Qiantang River, China; Bonneton et al., 201, Garonne River, France; Chanson et al., 2011, Garonne River, France; Mouazé et al., 2010, Sélune River, France).

In the MSMB research works were conducted between January 2011 to June 2014 in the framework of the ANR project “Mascaret” (http://mascaret.enscbp.fr/) involving the M2C Lab (CNRS/university of Caen). Part of the study was devoted to in situ measurements in order to better understand the processes involved in the formation of a tidal bore, and its impacts on sediment transport (Lucille Furgerot’s PhD work, M2C/Univ. Caen). The main measurement site, “Le Bateau”, was located in the inner estuary, along the Sée River, in a linear portion of the channel where tidal bores develop during every high spring tide period. Depending on the channel cross-section and river water level, tidal bores from undular to breaking type (photos) can develop in this segment of the River.

Various measurements into about 35 tidal bores were performed using ADV and ADCP (current velocities), CTD (temperature, salinity), OBS and direct sampling (suspended sediment concentration - SSC). The measurements evidence primarily that tidal bores are made of successive fronts: 1) a tidal wave front (the bore itself), 2) a turbidity front, arriving about ten seconds after the bore, and 3) a salted water front recorded 3 to 16 mn after the bore.

A model of SSC evolution in the water column during and after the tidal bore passage is proposed, highlighting the following main processes (Furgerot et al., 2013a, 2016a; 2016b):

- An important sediment resuspension, due to highly sheared flow during the bore passage, resulting in a 10 cm thick fluid mud layer with concentration values up to 53.5 g/L, created on the channel bed as the bore is propagating;
- an upward advection from this high concentration layer in the water column by positive vertical velocities (Vz ~ 0.5 m/s) and turbulence;
- a homogenisation of SSC in the water column. The sediment is maintained in suspension due to sufficient horizontal velocity of flow and is transported upstream.
According to the few studies published until now on tidal bore-induced facies within inner estuarine tidal channel infilling successions, two main signatures only can be reported (Tessier et al., 2017) (Fig. 11): 1) Soft Sediment Deformations (SSD) due to over-pressure linked to sudden water elevation, high shear stress and vertical velocity acceleration below tidal bore front and secondary waves. SSD may be present throughout the channel infill succession, except generally in the uppermost part. Tidal bore-induced SSD are only described in modern facies; 2) Tidal bore couplet (TBC) formed by an erosional surface overlain by draping massive sands, and related the reworking of sediment bottom at the tidal bore passage. TBC were first described in the ancient (Martinius and Gowland, 2011; then Fielding and Jöckel, 2015). Studies in modern estuaries (e.g. Fan et al., 2012; 2014; Tessier et al., 2017) demonstrate that TBC evolve towards tidal bore sequences (TBS) from tidal channel bottom (subtidal to low intertidal facies) to tidal channel bank (low to mid intertidal facies). Finally, in mid to upper intertidal facies, the occurrence of thicker-than-average tidal rhythmites (Fig. 12), reflecting higher-than-averaged suspended sediment concentration, are considered as well as a signature of tidal bore dynamics.

Figure 10. Evolution of suspended sediment concentration during the passage of a tidal bore modelled on the basis of field data (ASM, direct water sampling) collected in the inner estuary of the Sée River. Time axis starts at the passage of the tidal bore front (0 min) (Furgerot et al., 2016a)
Figure 11. Schematic distribution of tidal bore sedimentary signatures that can be preserved in a tidal channel infilling succession, from tidal bore couplets (TBCs) within subtidal facies to tidal bore sequences (TBSs) within low to mid intertidal facies. Very high SSC due to tidal bores produce thicker-than-average tidal rhythmites (TTA-TRs) preserved in mid to upper intertidal facies. Tidal bore-induced soft sediment deformations (SSDs) can be present throughout the succession, except in the upper intertidal part. LTL Low tide level, HSTL high spring tidal level (Tessier et al. 2017)

Figure 12. Thicker-than-average middle to upper intertidal rhythmites attributed to high suspended sediment concentration induced by tidal bores (Tessier et al., 2017): A) thick tidal rhythmites including complete tidal bore sequences as tidal couplets (Sélune River inner estuary, Bay of Mt. St. Michel; coin for scale: 1cm); B) tidal rhythmites made of thick planar bedded sand-dominated tidal couplets (flood tidal levee, Sée River inner estuary, Bay of Mt. St. Michel). C) For comparison, typical averaged thick tidal rhythmites (Sélune River inner estuary, Bay of Mt. St. Michel; Tessier, 1993). Arrows on all photos Neap tide period (emersion a few days long).
STOP 7. The Mont-Saint-Michel

Tourism and restoration works of the maritime character of the Mont-Saint-Michel

The Mont-Saint-Michel, with about 3 million visitors per year, is one of the major French touristic sites. In addition to the elegant gothic abbey settled on top of the granitic mount, the tides that surround regularly the site constitute the main attraction. However, due to the natural infilling of the estuary, dramatically enhanced by land reclamation since the XIXth century, rapid sediment and salt marsh accretion occur around the Mont-Saint-Michel (Fig. 13), so that the attractive spectacle of the incoming tidal bore were becoming very rare.

In order to restore the maritime character of the Mont-Saint-Michel, a research project was initiated in 1995, including hydrodynamical and sedimentological studies, numerical and physical models (Fig. 14). The project advancement, as well as the arising restoring operations that began in 2005 (Fig. 15), are described in detail on the following web site:

http://www.projetmontsaintmichel.fr

(official web site of the "syndicat mixte Baie du Mont Saint Michel" for the restoration of the maritime character of the Mont-Saint-Michel).

Two aspects of the Mont-Saint-Michel: a very busy touristic site (top) and a progressively "continentalized" environment (right). Photos in http://www.projetmontsaintmichel.fr
Figure 13. Evolution around the Mont-Saint-Michel since the XVIII\textsuperscript{th} century. Before land reclamation operations, the Couesnon estuary was wider. After unsuccessful attempts of reclamation during the XVIII\textsuperscript{th}, the dyking of the Couesnon River was finally done to prevent estuarine channel migration and polder destruction. Land reclamation was achieved in the middle of the XX\textsuperscript{th} century. Since that moment, salt marshes extended dramatically west and east of the Mt-St-Michel, leading to the recent works performed in order to restore the maritime character (after Bonnot-Courtois, 2012).
Main achievements of the projet
(in [http://www.projetmontsaintmichel.fr/index.html](http://www.projetmontsaintmichel.fr/index.html))

- **2009** - The construction of the dam over the Couesnon (officially launched in June 2006), is complete. The dam is the cornerstone of the project’s hydraulic aspect, and its functioning began to remove sand from around the Mt St Michel in May 2009. The public service delegation for visitor parking and transport was also awarded at the start of autumn 2009.

- **2010-2011** - Start of the reception work (landscaped car park, reception and service buildings) and access work for the Mont (pedestrian footbridge and causeway from 2011) enabling a completely new approach to the site. Start of the hydraulic developments upstream and downstream of the dam (2011-2015) which will restore the Couesnon’s hydraulic capacity to move sediment away from the site.

- **2012** - The new car park on the continent and the public transport shuttles are commissioned to bring visitors to the Mont.

- **2014** - The pedestrian footbridge is open to visitors, pedestrians and shuttles, but also logistics (outside busy periods) and the Mont’s permanent security services.

- **2015** - More symbolically still, the operation is completed with the destruction of the causeway which brings visitors from the continent to the Mont since 1879. The works to restore the maritime character of the Mont-Saint-Michel are then complete. It will then take a few years for a wide strand to form around the site and for the Mont to regain its full maritime landscape for many years to come.
Figure 15. Diagram of the main operations planned to achieve the restoration of the maritime character of the Mont-Saint-Michel (http://www.projetmontsaintmichel.fr)

The Mont-Saint-Michel at high spring tide in 2015. The pedestrian footbridge is complete, the old causeway is in course of destruction (Photo © Ouest-France)

The Mont-Saint-Michel before and after the restoration works of its maritime character (Photo © http://debates.coches.net/showthread.php?256648-El-Mont-Saint-Michel-se-convierte-en-una-Isla-por-la-gran-marea)
STOP 8. Vildé Hirel

The embayment: tidal flats and shelly ridges

A huge embayment occupies the western part of the Mont Saint Michel bay and is characterised by extended tidal flats (Fig. 16).

The upper tidal flat is outlined by numerous shelly ridges that form and migrate progressively onshore under the action of swell and swash action. They are concentrated along four sectors from west to east: Saint-Benoît des Ondes, Vildé-Hirel, Cherrueix and Chapelle Sainte-Anne.

Figure 16. The Western embayment: composite aerial photograph (IGN, 1996) superimposed on the 1/25 000 IGN topographic map (A. Dréau). The photograph, taken at mid-ebb, displays particularly well some of the main features that characterize the western embayment:

The oyster beds of the Bay of Cancale (OY), part of the mussel farms (MF), the old fishing grounds (FG), and the upper intertidal shell banks (SB) at Hirel – Vildé (Stop 8) and Cherrueix (Aerial oblique photos C. Bonnot-Courtois).
Two main aspects dealing with the shell ridges are discussed during Stop 8:

1) The general morphological characteristics and dynamics of migration of the banks based on recent lidar data and the works by Bonnot-Courtois et al., 2004; Bonnot-Courtois, 2012 (Plate 6).


Aerial photos of the shell banks in the Hirel-Vildé sector
Three morphological types of shell banks can be distinguished: tidal flat banks, upper tidal flat banks and salt marsh banks (Bonnot-Courtois et al., 2004). Lidar data acquired in 2002 allowed defining accurately the altitude of the banks and by this way determining their dynamics with respect to tidal submersion (Lidar, 2002, © Fondation TOTAL et Ifremer, in Bonnot et al., 2007b, Bonnot-Courtois, 2012).

Morphosedimentary map of the upper tidal flat and banks in the Vildé-Hirel area (sedimento-logical data combined with lidar data.)
The comparison of successive aerial photographs since the 1940s allows specifying the dynamic of migration along the flat of the different types of banks. In the Hirel-Videl area, it appears that:

- The dynamic of migration is regular and similar for tidal flat banks having the same origin on the mid-flat;
- Migration rate slowed down around 1980. From that moment, banks are almost stabilized;
- The rate of migration of the tidal flat banks decreases from 50-80 m/y on the mid-flat to less than 10 m/y on the upper flat. When the banks reach the uppermost flat, their thickness increases and their migration rate slows down to only a few m/y. The oldest banks, anchored into the salt marshes, are almost totally stabilized;
- This dynamic of migration is partly controlled by the annual rate of submersion of the bank by tides, since sedimentary processes for bank migration are active only during high tides.
Extensive field work and flume experiments have been conducted on the upper tidal flat banks, also defined as beach ridges, to understand the hydrodynamic and sedimentary processes involved in their evolution and their internal architecture. The study included ground-penetrating radar (GPR) survey, trenching, CT-Scan, porosity and permeability measurements on cores, and wave flume modelling.

The main processes that results in the beach ridges landward migration and construction are i) wave breaking and swash currents acting on the foreshore, and ii) overwash events that flow on the ridge backslope and pour in the flooded back-barrier.

A- Overwash flowing along ridge backslope. B- Overwash pouring in flooded salt marsh. C- Trench along a washover lobe showing high-angle landward-inclined foreset strata (sub-aqueous sedimentation) overlay by low-angle landward-inclined washover sheets (sub-aerial sedimentation). D- Eroded salt marsh deposit at the toe of beach ridge. E- Washover run-off channels on the ridge backslope. F- Washover lobes covering the salt marsh.
From GPR profiles, 3 stages of beach ridge evolution have been identified (Weill et al. 2012): A) Early transgressive, B) late transgressive, and C) progradationnal stages. The evolution and internal architecture of the beach ridges are closely related to the level of tidal flooding during high spring tides (HST). Washover foresets are deposited as long as overwash occurs and pours in the flooded salt marsh. If ridge backslope is over-extended, overwash infiltrates before it reaches the salt marsh. Aggradation occurs on the backslope in the form of washover sheets. When vertical accretion prevent overwash to occur, beach ridges extend bayward by ridge ammalgamation in a progradational pattern.

Beach ridges are activated only a few hours at high spring tides. Annual cumulated time of flooding exceeding 6 m above m.s.l., which corresponds to the level of beach ridge activation, is calculated. It oscillates between 160 and 270 h of flooding per year, following 4.4 and 18.6-yr tidal cycles (bold black curve).

Numbers of storms that occurred per year during HST flooding are represented in light grey bars. It displays some variability and a global increase on the 1950-2000 period. Among other factors influencing beach ridge development (wave activity, sediment supply...), spring tide level is the parameter that shows the more variability on a multi-decadal time scale. It is thus supposed to have a major influence on the overall system dynamics. Tidal channels in the estuary also seems to be influenced by these low-frequency tidal cycles (Levoy et al. 2017).
Flume experiments were conducted with natural sediment sampled in the field (Weill et al., 2013). Constant wave parameters were used, and low-frequency water level fluctuations were generated to mimic the variations in the frequency and intensity of high spring tide flooding. Most of the landform morphologies and internal structure observed in GPR profiles have been reproduced in the flume. As low-frequency water level fluctuation was the only variable parameter in the experiment, it suggests that it is the main forcing parameter that controls beach ridges construction and evolution.

Based on field data and flume modeling results, a depositional model of the beach ridges influenced by low-frequency tidal level fluctuation is proposed. Periods of low frequency of HST flooding (troughs of 18.6-yr cycles) allow the stabilization of shell banks lower on the tidal flat. It creates favorable conditions for salt marsh progradation. Periods of high frequency of HST flooding (peaks of 18.6-yr cycles) trigger major reworking and landward migration of beach ridges by overwash events. 4.4-yr tidal cycles may be responsible for the formation of individual washover units. Of course, other parameters are involved in the process, such as storm wave activity, sediment supply, biological productivity, and human infrastructures (dykes).


supply and climate changes (The examples of the Seine estuary and the Mont-Saint-Michel Bay, English Channel, NW France). *Sedimentary Geology*, 279, 62-73.


The different tidal cycles over a 2-year period from the semi-diurnal cycle (low tide/high tide/low tide) until the semi-annual cycle (183 days: solstice/equinox/solstice). Tidal range is expressed (in France) as tide coefficient.

It is a relative value, identical at all given sites for a given moment (although the real value could be very different).
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