Geological Field Trips and Maps

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The Bay of Mont Saint Michel. Sedimentary facies, morphodynamics and Holocene evolution of a hypertidal coastal system

Field trip organized for the Tidalites 2012 Conference (Caen, France) and the International Meeting of Sedimentology 2017 (Toulouse, France).

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Cover page Figure: Shelly bank on the upper sandflat of the western embayment (photo © D. Mouazé).

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Abstract

The aim of this 3-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 (a tide-dominated, wave-influenced embayment, a tide-dominated estuary, a wave-dominated sandy shoreline). Hydrodynamics, sedimentary facies, and sequences, Holocene infill, and evolution will be discussed through field observations, sediment cores, very high resolution seismic, and ground-penetrating radar data. The field trip includes a sightseeing tour of Mont-Saint-Michel and an overview of Norman gastronomy.

Keywords

NW France, The Channel, Hypertidal system, Embayment, Estuary, Sedimentology, Modern processes, Holocene infilling.

Program Summary (see Fig. 1 for location)

Day 1 – The western embayment			
Departure from Caen: 09:00			
Stop 1	10:30 – 12:00	Mont Dol: the Holocene frame of the Bay and of the field trip	
Stop 2	12:30 – 14:30	Pointe du Grouin: rocky entrance of the Bay	Picnic
Stop 3	15:00 – 17:30	Hirel - Vildé area: mixed flat and shelly banks	
Return to the Hotel at 18:00		Dinner at 20:00	

Day 2 – The embayment/estuary transition and tide-dominated inner estuary			
Departure from the Hotel: 07:30			
Stop 4	08:00 – 10:30	The Mont-Saint-Michel (tourism, management operation)	
Stop 5	11:00 – 14:00	Chapelle Ste Anne: sandflat and litho-bioclastic banks	Picnic
Stop 6	14:30 – 17:30	Gué de l'Epine – Pontaubault: Inner estuary	
Return to the Hotel at 18:00		Dinner at 20:00	

Day 3 – The northeastern wave-dominated coastline			
Departure from the Hotel at 07:45 (with all the luggage)			
Stop 7	08:30 – 09:30	Grouin du Sud: Tidal bore passage	
Stop 8	10:00 – 12:00	Dragey: wave-dominated sandy barrier and back-barrier system	
Stop 9	12:30 – 14:30	Saint-Jean-Le-Thomas: Holocene evolution	Picnic
Stop 10	15:00 – 17:00	The Champeaux *Hermelle* reef (polychaete bioherm)	
Departure for Caen around 17:30 (arrival in Caen around 19:00)			

Safety

Warning against:

- Natural risks due to quicksands, soft mud areas: do not walk alone on the tidal flats but stay with the group.
- Risks due to road traffic and tourist season: watch out when the bus stops along heavy traffic roads and keep always with you valuable personal items.

Emergency contact number: 112

Hospitals

CENTRE HOSPITALIER d’Avranches-Granville (+33 2 33 91 50 00).

Accommodations

Hôtel Patton, place Patton, Avranches, +33 233 48 52 52
Hôtel de la Croix d’Or, 83 Rue de la Constitution, +33 233 58 04 88

Fig. 1 - Location of the different stops during the field trip (Image 2013-10-30: Collection SPOT6_2013_FRANCE-ORTHO_IGN-MS, Distribution Airbus Defense & GEOSUD). Numbers (1 to 10) refer to stop numbers. Av.: Avranches; MSM: Mont-Saint-Michel; MD: Mont-Dol.

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General geological, hydrodynamical and morphosedimentary frame of the Mont-Saint-Michel Bay

The Mont-Saint-Michel Bay (MSMB) is located in the western part of Europe, along the coastline of France facing the Channel. It is a 500 km² coastal embayment developed at the junction between the Cotentin Peninsula, oriented N-S, and the Brittany coast, oriented E-W (Fig. 1). The MSMB belongs to the geological frame of the Armorican Massif (e.g., L'Homer et al., 1999). Its substrate is made of Neoproterozoic metasedimentary rocks (Brioverian turbiditic shales) and migmatites, and Ediacaran plutonic igneous rocks (granodiorite) (Fig. 2).

The MSMB, as part of the Channel, has a semi-diurnal tidal regime. The formation of a standing tidal wave along the Cotentin Peninsula gives rise in this area to a hypertidal range (according to the classification of Archer, 2013) reaching up to 15 m in the MSMB during the highest spring tides (Larsonneur, 1994). Mean neap tide and mean spring tide ranges are of the order of 5-6 m and 10-11 m respectively. Powerful tidal currents are associated with these hypertidal conditions, especially into the tidal channels of the eastern part where alternating flood and ebb tidal currents, up to 3 m/s, are measured. In the western part, currents are generally weaker (1 m/s) and of giratory type (Larsonneur, 1994; Bonnot-Courtois et al., 2002). Wave climate is of relatively low energy, as the MSMB is protected from the prevailing western to northern storms by the Saint-Malo Peninsula (Fig. 2). Off the MSMB, Hs (Significant wave height) is less than 0.5 m for 70 % of the waves (Ehrhold, 1999). However, during severe storms, waves can penetrate into the MSMB, mostly affecting the northeastern coast (Larsonneur, 1994).

Three rivers flow into the MSMB in the eastern area (the Couesnon, the Sée, and the Sélune). They are minor rivers with very low water discharge (8 to 15 m^3/s) and their sediment load can be considered as almost negligible at present. As a consequence, sediments that fill the MSMB are almost exclusively originating from the marine domain. Moreover, it is mixed siliciclastic-carbonate sediment composed of at least 50% of bioclastic carbonates (Larsonneur, 1994).

According to the relative influence of tidal currents, waves, and fluvial dynamics, the MSMB is divided into three main morphosedimentary environments (Caline, 1982) (Fig. 2): 1) a **tide-dominated, wave-influenced embayment** in the West, characterised by very extensive tidal flats. Mudflats develop in the westernmost sector, sheltered behind the Saint-Malo Peninsula, while sand flats extend eastward where tidal and wave energy is higher (Caline, 1982). Along the southern coast of the embayment, storm wave action during high tides induces the construction of shelly banks (or «cheniers») on the upper tidal flat. They form a low elevation coastal barrier between the tidal flats and the salt marshes; 2) **a tide-dominated estuary** that occupies the eastern corner of the Bay, formed at the outlet of the three rivers. It is a vast sandy to muddy channel-and-shoal system. Very high-energy alternative tidal currents dominantly control sedimentary processes and channel migration in this area; 3) a **wave-dominated sandy coastline** to the northeast, composed of sand beaches and aeolian dunes (sand spits/coastal barrier).

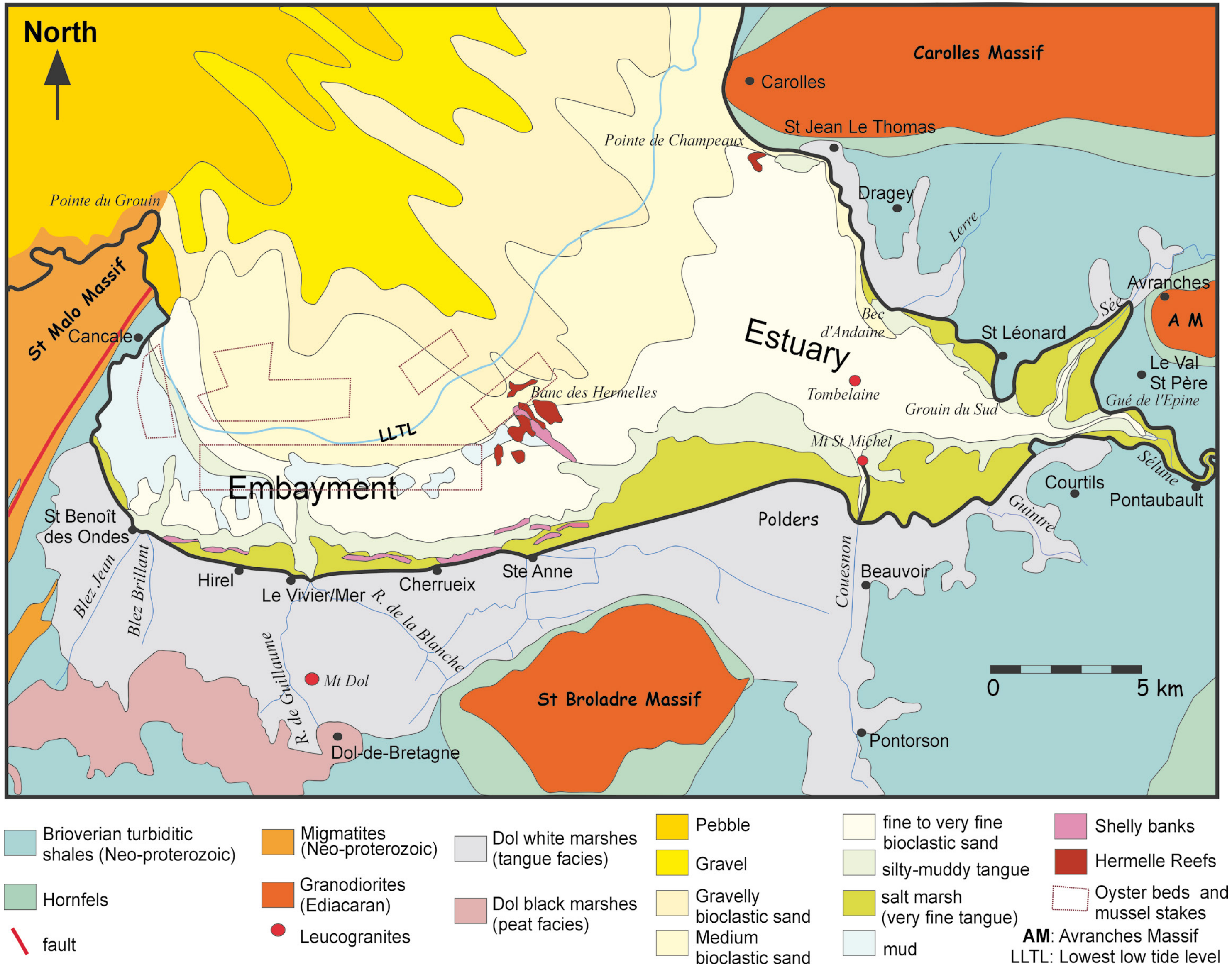

Fig. 2 - Simplified geological and sedimentological map of the Mont-Saint-Michel bay (after Larsonneur, 1989; L'Homer et al., 1999a).

Day 1 – The western embayment

Stop 1. Mont-Dol. The Holocene frame of Mont-Saint-Michel Bay

As the Mont-Saint-Michel and Tombelaine, the Mont-Dol is one of the Cadomian leucogranite intrusions that rise above the bay (Fig. 2). But contrary to the Mont-Saint-Michel and Tombelaine, which are still situated in a marine environment, the Mont-Dol is located in the middle of the Dol marshes. A nice panoramic view is offered on the whole bay from this point.

Like most coastal landscapes around the Channel, the morphology of the MSMB is a heritage of the Plio-Pleistocene glacio-eustatic fluctuations. Because the regional subsidence is negligible, only the last post-glacial transgression is recorded into the infilling of the MSMB, the previous sea-level fall having reworked almost all older marine sediments (L'Homer et al., 1999a, b). 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 cal BP (Fig. 3). Around 6500 cal BP the transgression slowed down significantly (3 mm/yr to progressively 1 mm/yr), allowing coastal wedge construction in general, and a rapid infilling of estuaries and embayments such as the MSMB (Fig. 4). Since that time of highstand sea-level or at

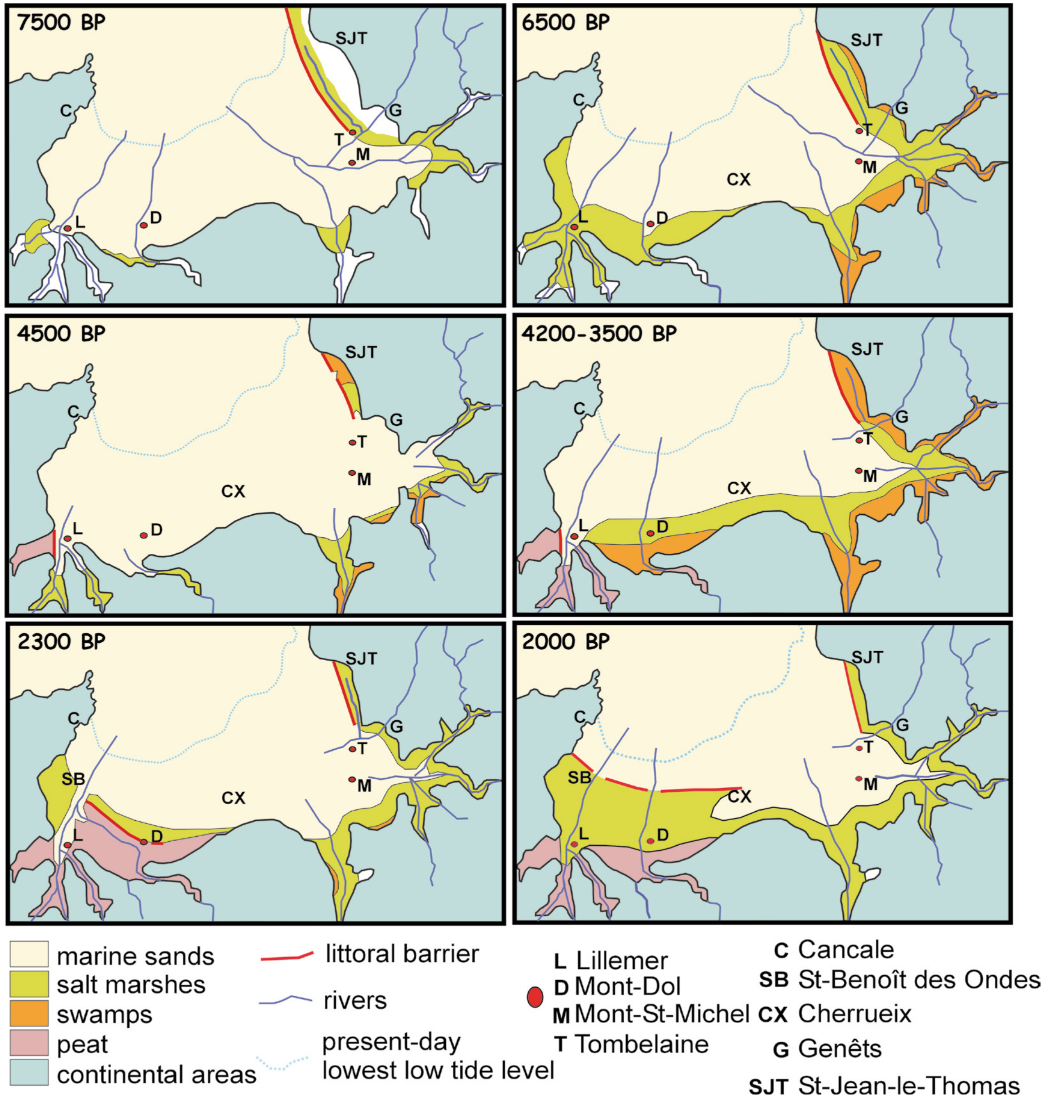

Fig. 3 - Palaeogeographical reconstruction of the Mont-Saint-Michel bay during the main stages of its Holocene evolution (after Morzadec-Kerfourn, 1975, 2002; Clet-Pellerin et al., 1981; in Larsonneur, 1989 and in Bonnot-Courtois et al., 2002).

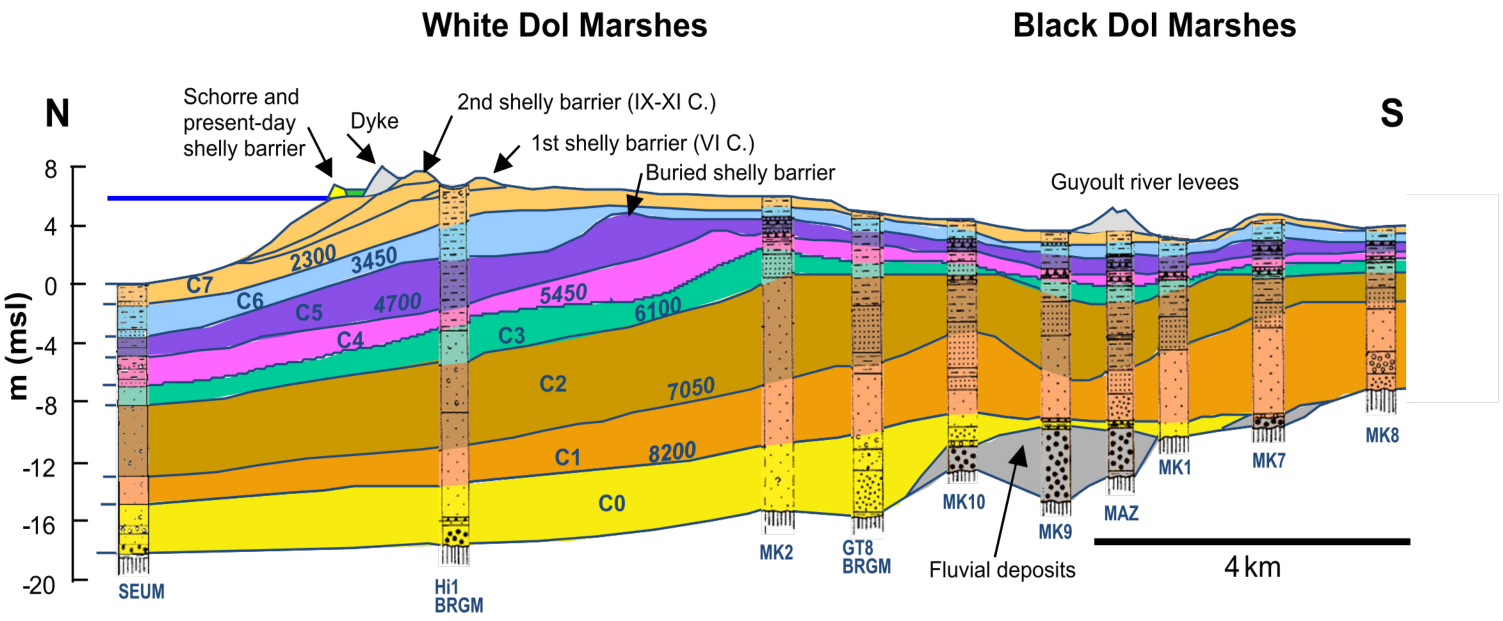

Fig. 4 - Schematic cross-section of the Holocene coastal wedge preserved below the Dol marshes (in Bonnot-Courtois et al., 2002). This reconstruction, mainly based on drill holes into the Dol marshes, shows the passage from vertical aggradation to a progradation at around 6500 cal BP, i.e., when sea-level rise slowed down. C0 to C7: successive sediment sets (distinguished with different colors). *8200*, *7050*, *6100*, *5450*, *4700*, *3450*, *2300* : years BP.

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, hydrodynamical, and sediment supply conditions.

Stop 2. The Pointe du Grouin. Western rocky coastline, tidal current patterns

“La Pointe du Grouin”, located at the northwestern extremity of the MSMB provides a panoramic view of the whole bay, especially on the western rocky coastline and the western embayment (Fig. 5A, B). This area is characterised by powerful tidal currents during the ebb “flushing” due to the effect of narrowing between La Pointe du Grouin and l’Ile des Landes (Fig. 5B). Tidal current velocity exceeds 1 m/s during mean spring tides. The embayment, stretching from Cancale to Cherrueix, is subject to moderate tidal currents, of giratory type in the westernmost part (Cancale bay) which is protected from dominant NW to W waves by «La Pointe du Grouin».
The Cancale bay is characterised by the presence of extensive oyster beds (Fig. 5C) settled on the lower and middle mud flat since the beginning of the 20th century. From Château Richeux westward, the coastline is outlined by the Dyke of Brittany stretching over almost 20 km. It was constructed during the 11th century on a natural coastal barrier to shelter the Dol marshes from marine submersions. Along the southern coast of the

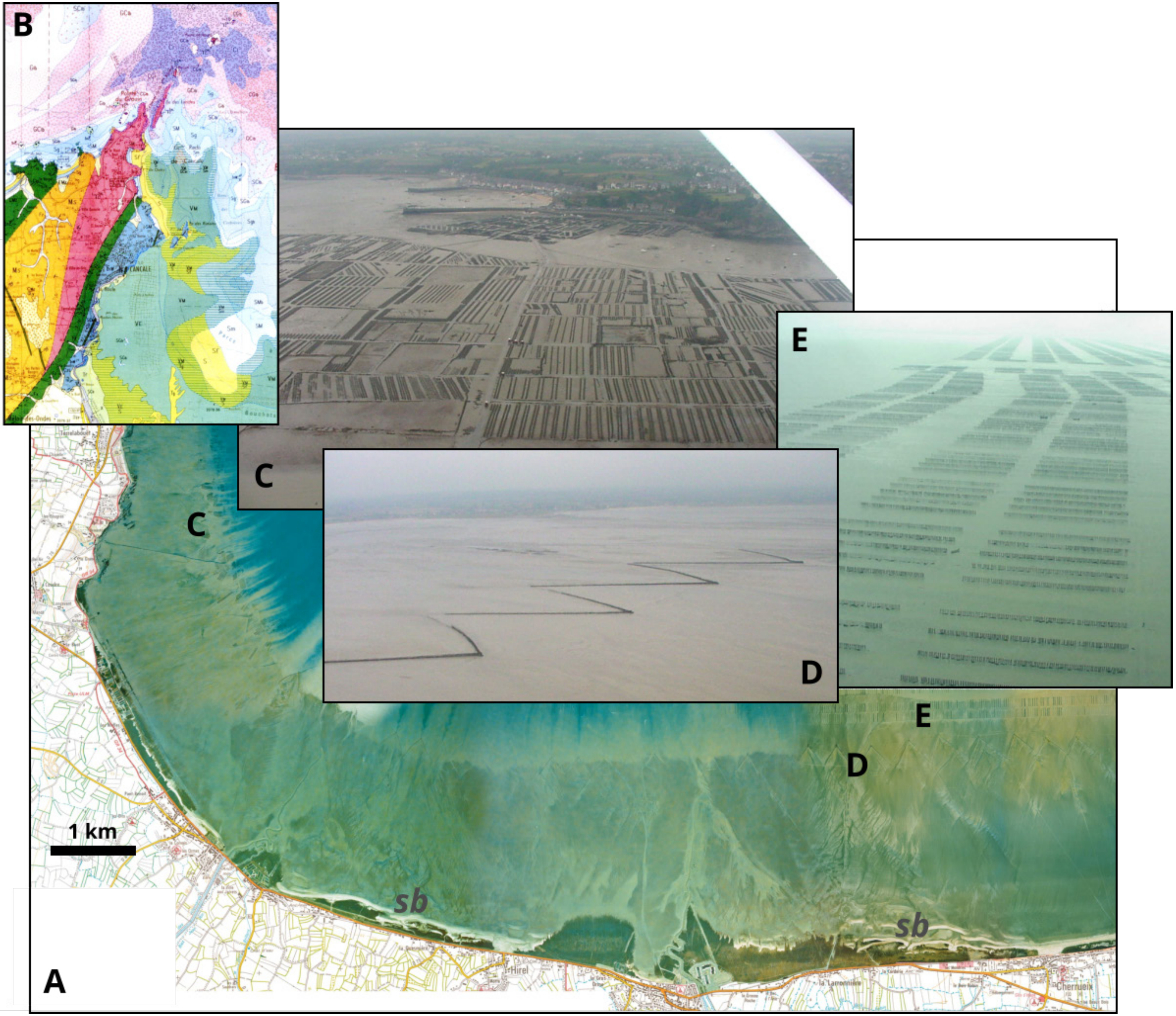

Fig. 5 - The Western embayment of the MSMB. A) Composite aerial photograph (IGN, 1996) superimposed on the 1/25 000 IGN topographic map (A. Dréau). B) Geological map (1/50 000, BRGM, L'Homer et al., 1999a) of the "Pointe du Grouin" area. The impact of the hydrodynamic regime on sediment distribution is highlighted by the sharp contact between the thin sheet of reworked coarse-grained relic deposits to the North (the Western offshore entrance of MSMB) and the thick muddy and sandy deposits in the South (Bay of Cancale). C), D), E) Aerial photographs (by C. Bonnot-Courtois) of respectively, the oyster beds in the Bay of Cancale, some of the old fishing grounds, part of the mussel farms. sb: upper intertidal shelly banks at Hirel – Vildé (Stop 3) and Cherrueix).

embayment, the upper tidal flat is marked by numerous shelly ridges concentrated in four sectors, respectively from west to east: Saint-Benoît-des-Ondes, Vildé-Hirel (Stop 3), Cherrueix and Chapelle Sainte-Anne (cf. Day 2, Stop 5).

The intermediate and lower parts of the tidal flat are occupied by two types of human installations: traditional fishing grounds (Fig. 5D) and mussel farms (Fig. 5E) arranged in regular lines parallel to the coastline.

Stop 3. Hirel-Vildé area. Shelly banks and mixed flat

As mentioned previously, the upper tidal flat of the southern embayment is outlined by numerous shelly ridges (Fig. 5A) that form and migrate progressively onshore under the action of wave and swash action. They are concentrated along four sectors from west to east: Saint-Benoît-des-Ondes, Vildé-Hirel, Cherrueix and Chapelle Sainte-Anne.

Stop 3 is dedicated to the Hirel-Vildé sector. Two main aspects dealing with the shelly banks are discussed: 1) the general morphological characteristics and dynamics of migration of the banks based on the works by Bonnot-Courtois et al. (2004) and Bonnot-Courtois (2012) (Fig. 6); 2) the hydrosedimentary processes of construction, internal architecture, and factors of evolution of the banks based on Pierre Weill's Ph.D works (2010) and Weill et al. (2010, 2012, 2013) (Fig. 7).

Three morphological types of shell banks can be distinguished (Fig. 6A): 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 (Bonnot-Courtois et al., 2007b; Bonnot-Courtois, 2012). The comparison of successive aerial photographs since 1940 allows specifying the dynamics of migration along the flat of the different types of banks (Fig. 6B). In the Hirel-Vildé area, it appears that: the dynamics of migration is regular and similar for tidal flat banks having the same origin on the mid flat, and migration rate slowed down around 1980. Since that moment, banks are almost stabilised; the rate of migration of the tidal flat banks decreases from 50-80 m/yr on the mid-flat to less than 10 m/yr 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/yr. The oldest banks, anchored into the salt marshes, are almost totally stabilised. This dynamic of migration is partly controlled by the annual rate of submersion of the banks by tides (Fig. 6B), since sedimentary processes for bank migration are active only during high tides (Bonnot-Courtois et al., 2004; Weill et al., 2012, 2013; Tessier et al., 2019).

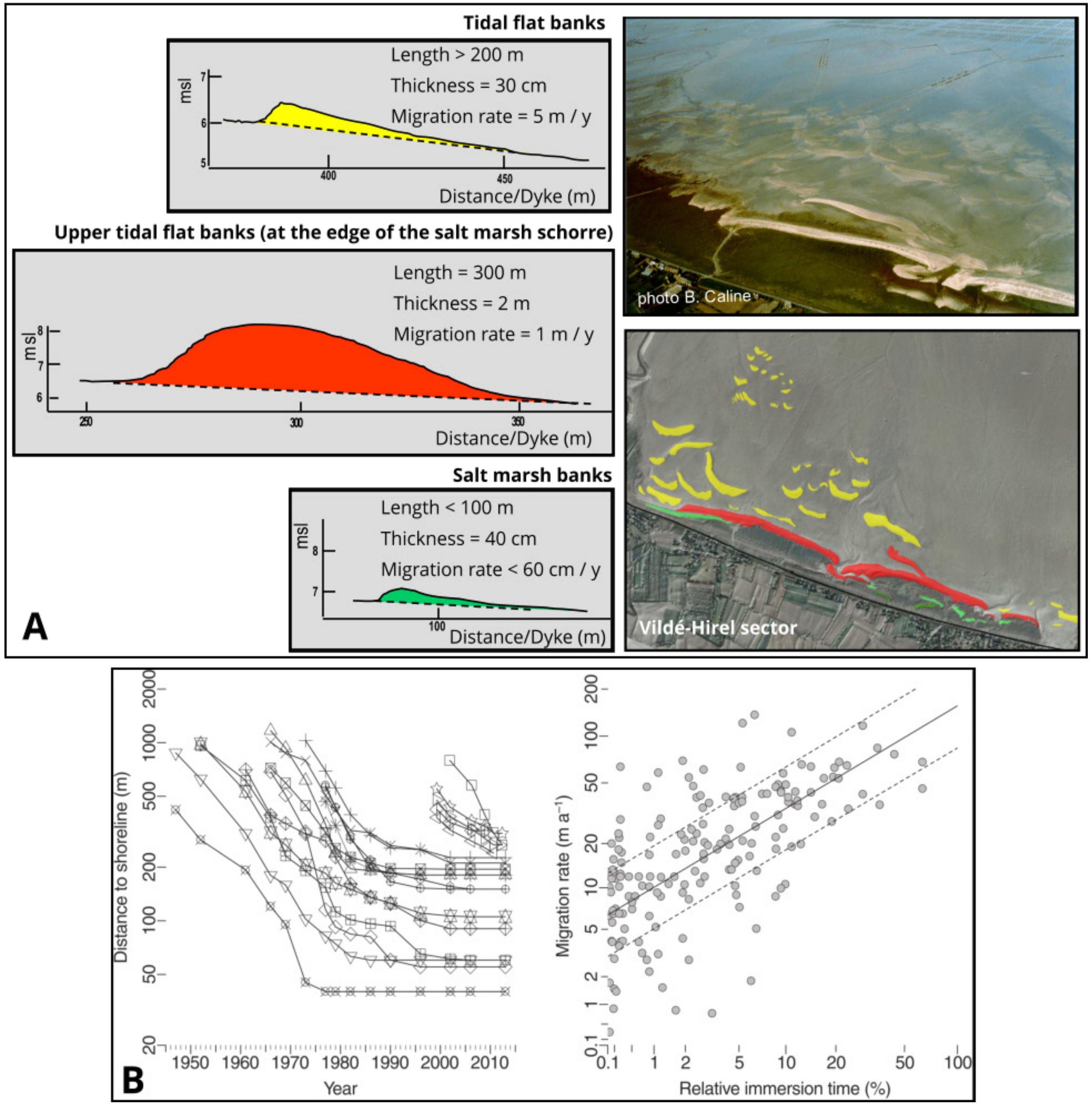

Fig. 6 - Shelly banks A) the three main morphological types of banks. B) Cross-shore migration of shelly ridges tracked on aerial photographs (data from 1947 to 2006 in Bonnot-Courtois, 2012) and bank migration rate as a function of relative immersion time (Tessier et al., 2019).

Fieldworks and flume experiments have been conducted on the upper tidal flat banks, also defined as shelly ridges, to understand the hydrodynamic and sedimentary processes involved in their evolution and their internal architecture (Weill, 2010; Weill et al., 2010, 2012, 2013). The study included ground-penetrating radar (GPR) survey, trenching, computed tomography (Scanner), porosity and permeability measurements on cores, and wave flume modelling.

The main processes that result in the 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 (Fig. 7A). From GPR profiles, 3 stages of beach ridge evolution have been identified (Weill et al. 2012): A) early transgressive, B) late transgressive, and C) progradational stages (Fig. 7B). The evolution and internal architecture of the shelly ridges are closely related to the level of tidal flooding during high spring tides.

Shelly 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, was calculated. It oscillates between 160 and 270 h of flooding per year, following 4.4 and 18.6-yr tidal (cf. Fig. 7D). Among the main factors influencing shelly ridge development (wave activity, tidal dynamics, sediment supply), spring tide level is the parameter that shows more variability on a multi-decadal time scale. It is thus supposed to have a major influence on the overall system dynamics.

Flume experiments were conducted with natural sediment sampled in the MSMB (Weill et al., 2013). Constant wave

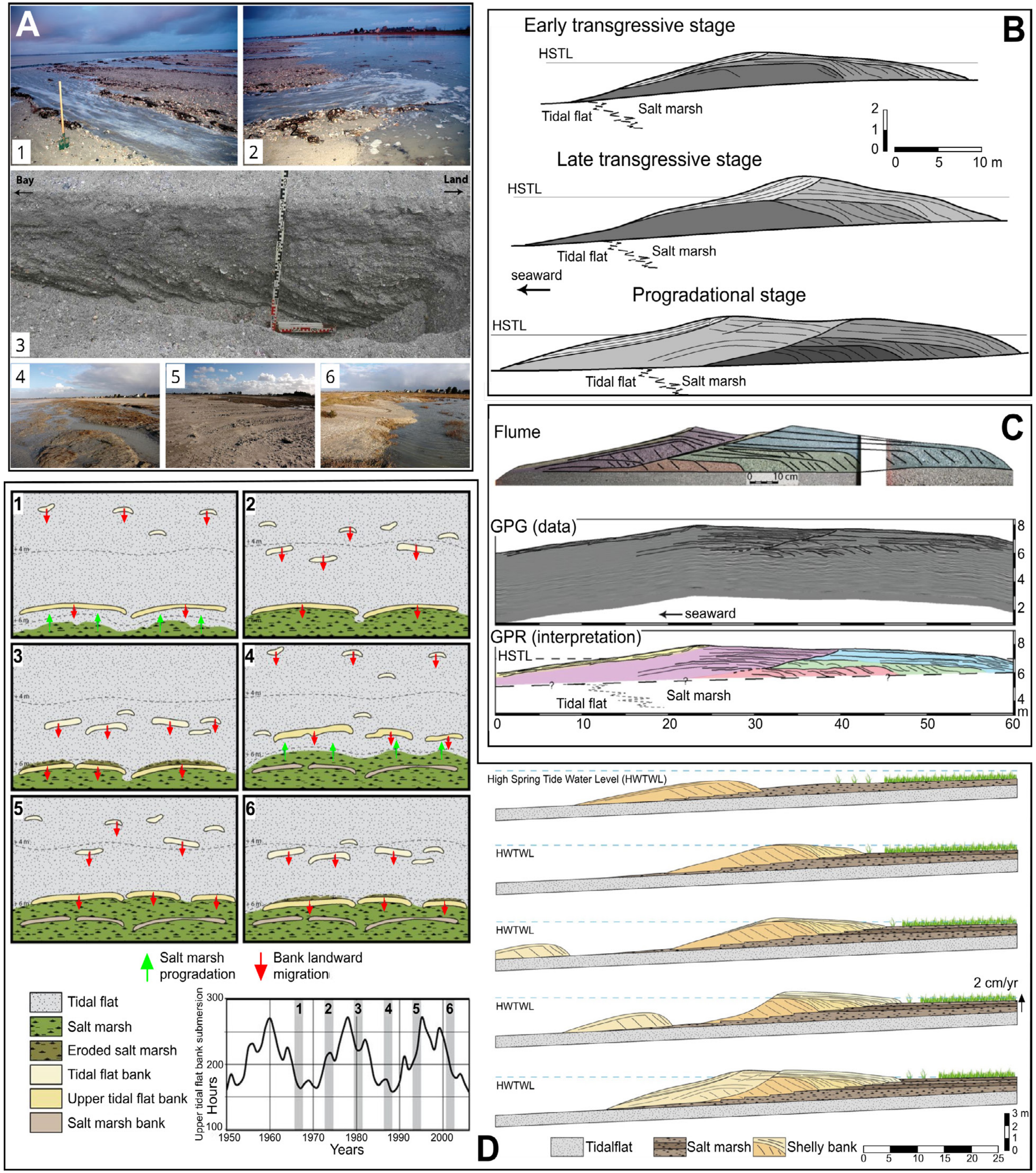

Fig. 7 - Hydrosedimentary processes, internal geometry, factors of evolution of shelly banks. A) A- Overwash flowing along ridge backslope. B- Overwash pouring in the flooded salt marsh. C- Trench along a washover lobe showing high-angle landward-inclined foreset strata (sub-aqueous sedimentation) overlay 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. B) The three main stages of shelly bank evolution based on ground-penetrating radar (GPR) data (Weill et al., 2012). C) Comparison of the architecture of experimental shelly ridge (flume) with the architecture observed in the field (GPR data/interpretation) for the progradational stage. D) Model of the shelly ridges construction and evolution influenced by low-frequency tidal level fluctuations (Weill et al., 2013).

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 structures observed in GPR profiles have been reproduced in the flume (Fig. 7C), suggesting that tidal flooding level is a major forcing parameter that controls beach ridges construction and evolution. Extreme wave climate might be important as well, in conjunction with high tidal flooding levels (Weill et al., 2012; Tessier et al., 2019).

Based on field data and flume modelling results, a depositional model of the beach ridges influenced by low-frequency tidal level fluctuation is proposed (Fig. 7D). Periods of a low frequency of high spring tide flooding (troughs of 18.6-yr cycles) allow the stabilisation of shell banks lower on the tidal flat. It creates favourable conditions for salt marsh progradation. Periods of a high frequency of high spring tide 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) and activities. Recent experimental works performed on the transport of bioclasts derived from mollusc shells contained into the shelly ridges clearly demonstrate differences in behaviour depending on mollusc species (Rieux et al., 2019). Shellfish farming, especially oyster farming, began during the 19th century in the western embayment, and extensive shellfish farming activities started in the 1950s (Bonnot-Courtois, 2012). Shell quantities and types have thus changed significantly during the 20th century compared with previous times, probably with positive consequences on shelly barrier stability (Tessier et al., 2019).

Day 2 – The embayment/estuary transition and tide-dominated inner estuary

Stop 4. The Mont-Saint-Michel. Tourism and environmental management operation to restore the maritime character of the Mont-Saint-Michel

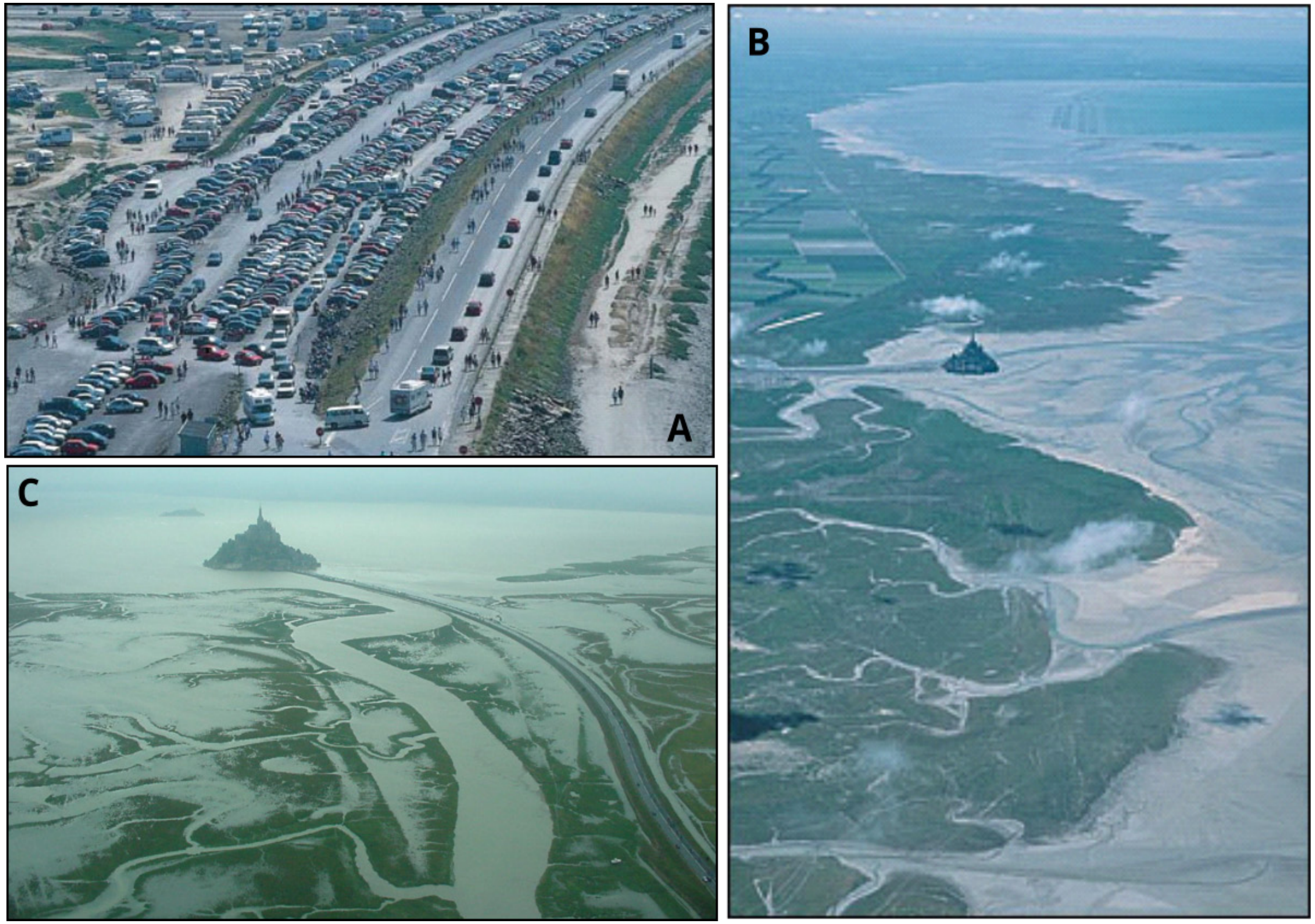

Fig. 8 - The Mont-Saint-Michel, a very busy touristic site (A) and a progressively "continentalized" environment (B). The Mont-Saint-Michel during high spring tide (C). Because of sediment accumulation around Mont, this spectacle was becoming increasingly rare. Photos in http://www.projetmontsaintmichel.fr.

The Mont-Saint-Michel, with around 3 million visitors per year, is one of the major French touristic sites (Fig. 8A). 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 19th century (Fig. 9), rapid sediment and salt marsh accretion occur around the Mont-Saint-Michel (Fig. 8B), so that the attractive spectacle of the incoming tidal bore was becoming very rare (Fig. 8C).

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. The project advancement, as well

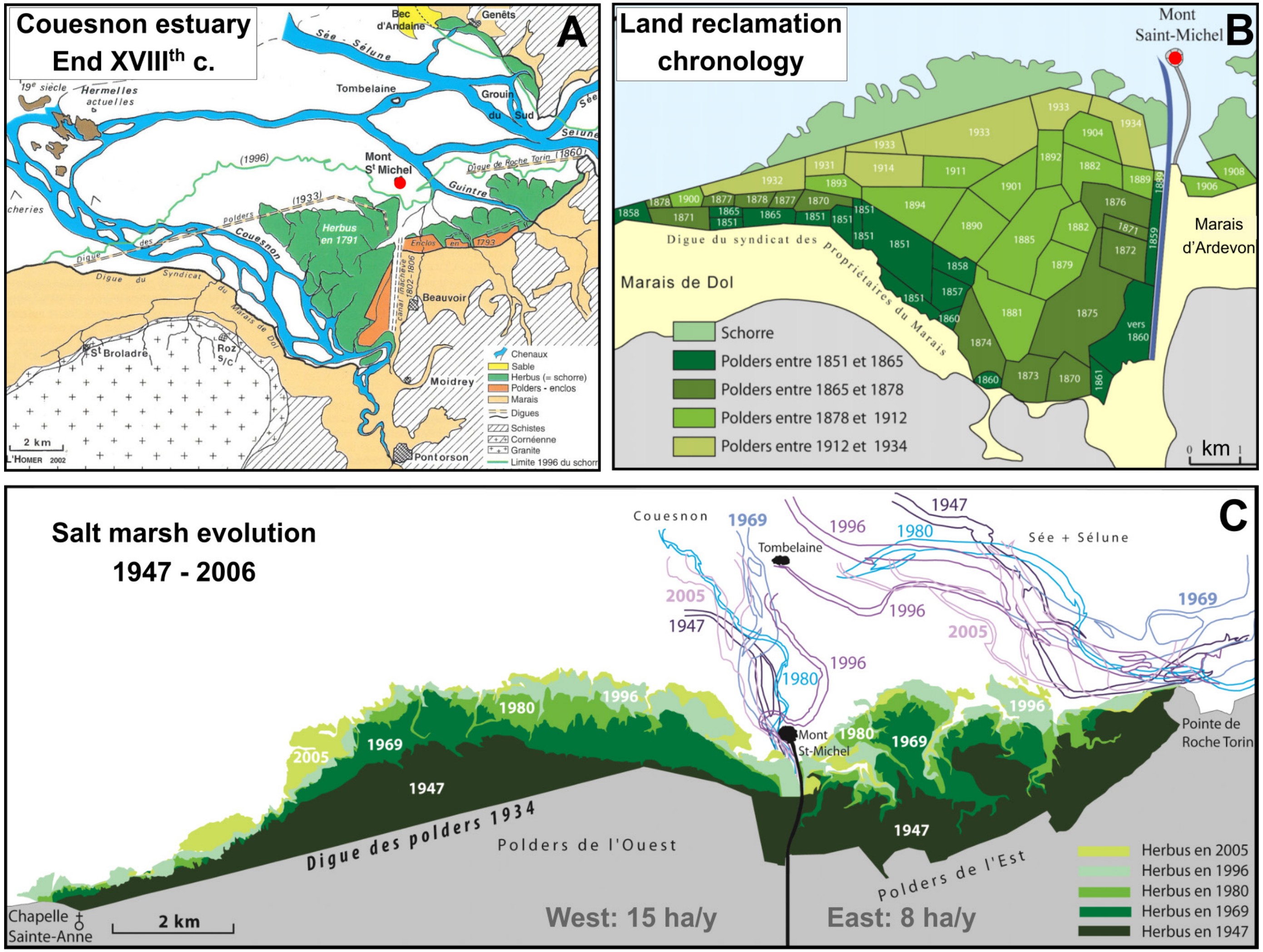

Fig. 9 - Evolution around the Mont-Saint-Michel since the 18th century. Before land reclamation operations, the Couesnon estuary was wider, with active migrating tidal channels (A). After unsuccessful attempts of land reclamation during the 18th century, the dyking of the Couesnon River was finally done to prevent its migration and land reclamation was achieved in the middle of the 20th century (B). Since that moment, salt marshes dramatically extended west and east of the Mont-Saint-Michel (C), leading to the project of restoration of the maritime character (after Bonnot-Courtois, 2012).

as the arising restoring operations that began in 2005 (Fig. 10), are described in detail on the following website: 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).

The main achievements of the project of restoration of the maritime character (in http://www.projetmontsaintmichel.fr/index.html) are (Fig. 10A): (**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 the 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

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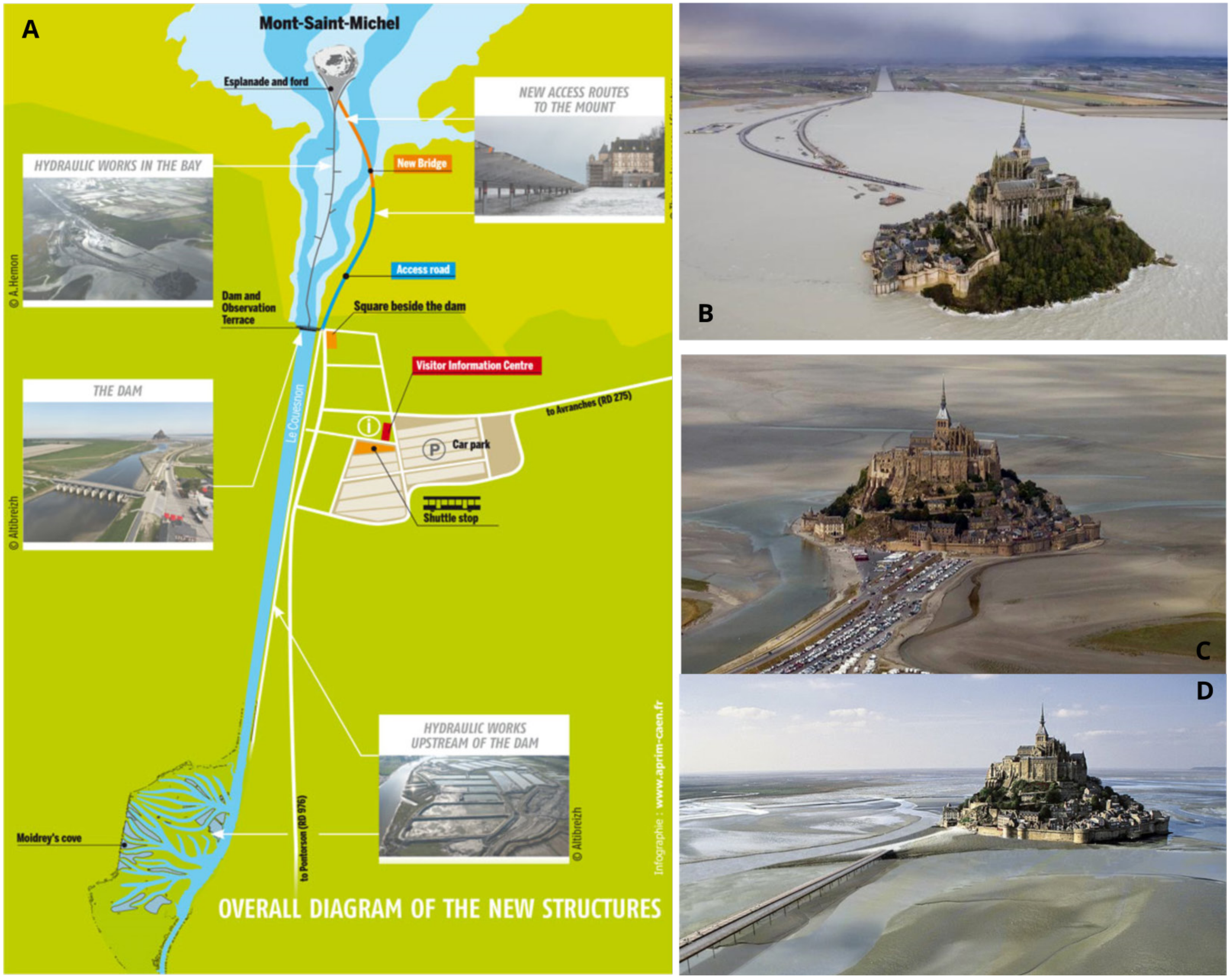

Fig. 10 - The project of restoration of the maritime character of the Mont Saint Michel. A) Diagram of the main operations planned to achieve the restoration (http://www.projetmontsaintmichel.fr). B) The Mont Saint Michel now during high spring tide (Photo ©Ouest-France). C) The Mont Saint Michel before and D) after the project (Photos© http://debates.coches.net/showthread.php?256648-El-Mont-Saint-Michel-se-convierte-en-una-isla-por-la-gran-marea).

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 (Fig. 10B). 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.

Stop 5. The Chapelle Sainte-Anne. Litho-bioclastic banks and sandflat at the embayment -estuary transition

In the centre of the MSMB, off “la Chapelle Ste-Anne” locality, at the transition between the embayment and the estuary, a spectacular bioconstruction made by annelids (*Sabellaria alveolata* or “*Hermelles*”) is settled on the lower tidal flat (Fig. 11). The reef system constitutes an area of important sediment storage, available for sandbank construction. The dynamics of shoreward migration of these banks is fairly similar to that of the banks of the Vildé-Hirel and Cherrueix areas. Migration rate can reach locally 100 m/yr on the mid flat. The

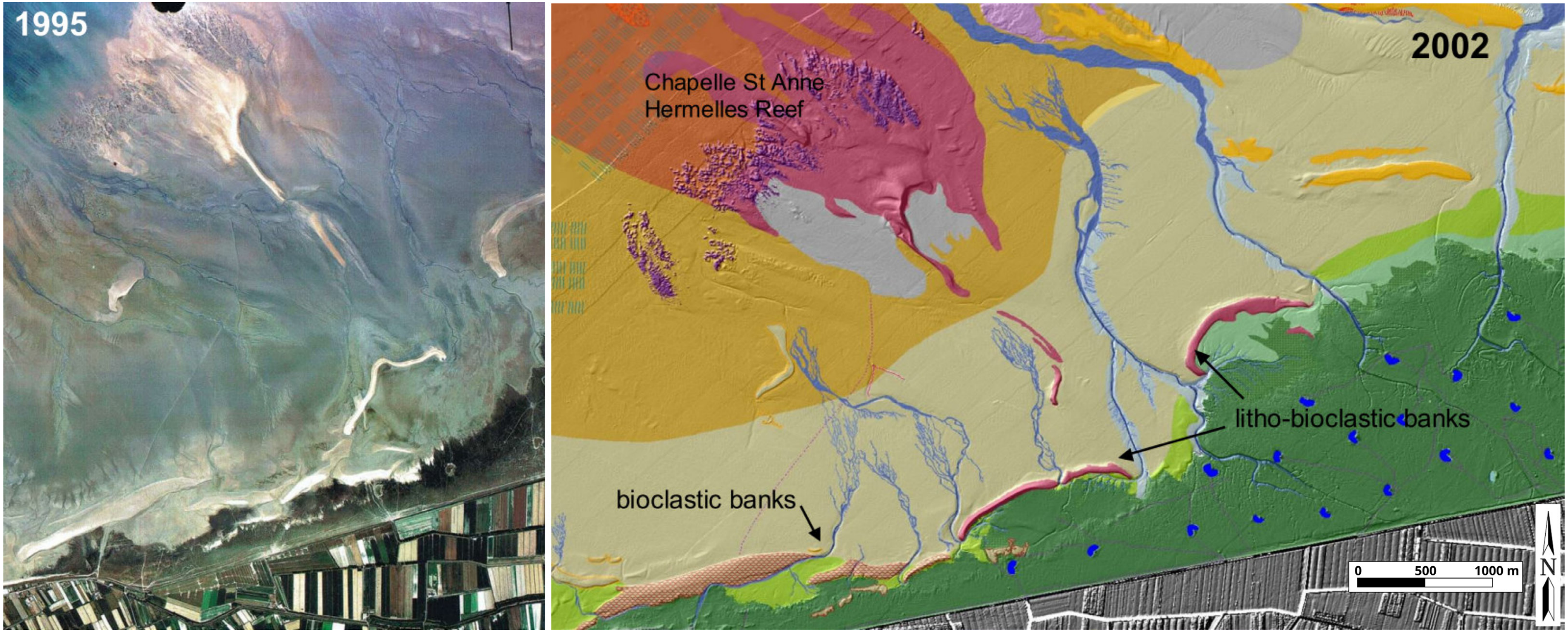

Fig. 11 - The litho-bioclastic banks of «La Chapelle Sainte-Anne». These banks are supplied by sediments that are reworked from the Annelid reef area, located on the lower sand flat. The relative lithoclast richness into the banks is due to the impoverishment in bioclasts, these latter being used for the reef construction (after Bonnot-Courtois et al., 2007a; Bonnot-Courtois, 2012).

banks that finally reach the upper tidal flat are composed of bioclasts (such as in the banks located westward, at Vildé-Hirel and Cherrueix localities), but are characterised also by a much higher content in lithoclasts. This is the result of the selection by the annelids of bioclastic particles for the reef construction so that the sand that is not trapped into the reef is enriched in lithoclastic elements.

Stop 6. "Gué de l'Épine - Pontaubault" area. Tidal facies and sequences of the inner estuarine environment

The Gué de l'Épine - Pontaubault area belongs to the inner estuary (Fig. 12A). 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* (intertidal) and *schorre* (supratidal) domains which extend over a width of about 1 km (this part 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. 12B). Some 1-2km downstream, the estuary consists of a vast area of sandy-silty *slikke* covered by a dense network of tidal channels bordered by megaripples (the braided tidal system according to Dalrymple et al., 1992; Fig. 12B).
The hydrodynamics 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 in height during high spring tides) which spreads into the

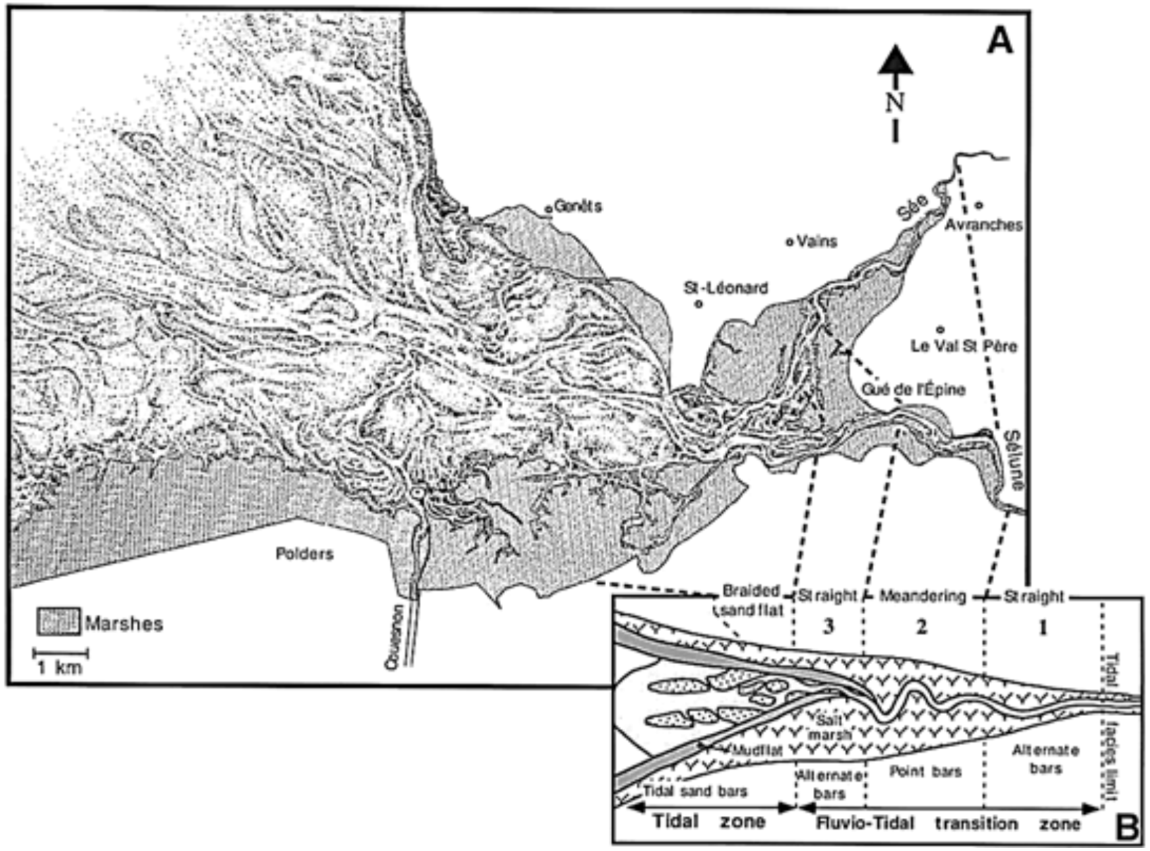

Fig. 12 - Morphosedimentary map of the estuarine system (A) with the indication of the concordances with the model proposed by Dalrymple et al. (1992) for tide-dominated estuaries (B) (in Lanier and Tessier, 1998).

channel with a velocity in the order of 3-4 m/s. The bore reworks a large quantity of sediment as it passes, contributing to increase considerably in the turbidity of the penetrating water in the estuary (Fig. 13). Based on field data, a model of suspended sediment concentration (SSC) evolution in the water column during and after the tidal bore passage is proposed, highlighting the following main processes (Mouazé et al., 2010; Furgerot et al., 2012a, 2012b, 2013, 2016a, 2016b; Furgerot, 2014): 1) 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; 2) an upward advection from this high concentration layer in the water column by positive vertical velocities (Vz ~ 0.5 m/s) and turbulence; 3) 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.

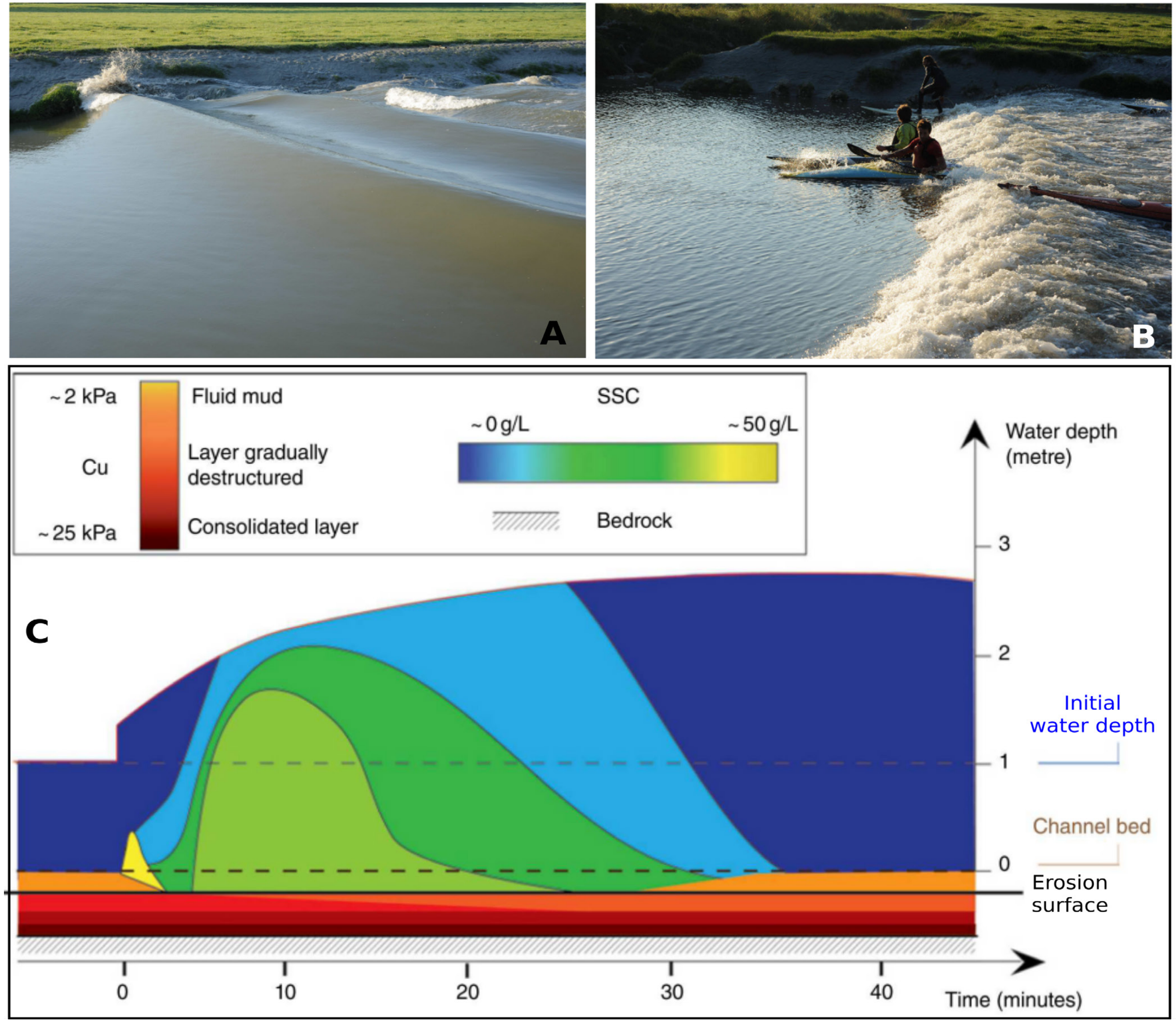

Fig. 13 - Tidal bore on the Sée river inner estuary (The Bateau locality). Depending on the channel cross-section and river water level, tidal bores range from undular (A) to breaking (B) types. C) Evolution of suspended sediment concentration during the passage of a tidal bore modelled on the basis of field data. The time axis starts at the passage of the tidal bore front (0 min) (Furgerot et al., 2016a).

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 inner estuary is characterised by specific sediment called "*tangue*" (regional name), grey in colour, and generally described as a sandy to silty mud (mean grain size 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 molluscs, foraminifera, ostracods, coccoliths, and bryozoan fragments. The mineral fraction consists mainly of quartz, mica, and heavy minerals. Due to its physicochemical properties, linked to its composition, grain size, and texture, the *tangue* can be drained easily and compacts quickly. It is also thixotropic, making its reworking by tidal currents easy. It is mobile sediment, favouring the formation and preservation of numerous figures and depositional structures. In cross-section, the *tangue* displays a bedded appearance, made up of alternating layers, a few millimetres to a 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 common beddings (Fig. 14A, B, C). Climbing ripple bedding can also be frequent in short cut or levee position (Lanier and Tessier, 1998). Due to the tidal bore passage, freshly deposited *tangue* succession along the tidal channel, can be deeply convoluted (Tessier and Terwindt, 1994; Tessier et al., 2017) (Fig. 14D, E).

As wave activity is almost negligible, and thanks to the *tangue* properties, the inner estuarine domain is the most favourable area in the MSMB to observe and analyse tidal facies and more specifically, tidal rhythmites (Fig. 15).

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 (Fig. 15A). No rhythmicity is observed at these low topographic levels on the edge of the active channel. 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.

In cross-section, from upper intertidal to supratidal facies, two main types of tidal rhythmites (TR) are distinguished:

- 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. 15A). Different types of beddings form semi-lunar TR. The most frequent develops in planar bedding made up of sand- or mud-dominated, millimetric to centimetric couplets (Fig.15B). In the case of tidal bore occurrence, very thick couplets are generated in relation to high SSC (Fig.15C). In ripple bedding, the 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 (Fig.15D, E). Finally, semi-lunar TR are expressed quite frequently in climbing ripple bedding (Lanier and Tessier, 1998) in the ebb-dominated short-cut channels above point bars, or in flood levee facies (Fig. 15F, G);

- annual TR that record the highest equinoctial tides of the year (Fig. 15A). They are preserved

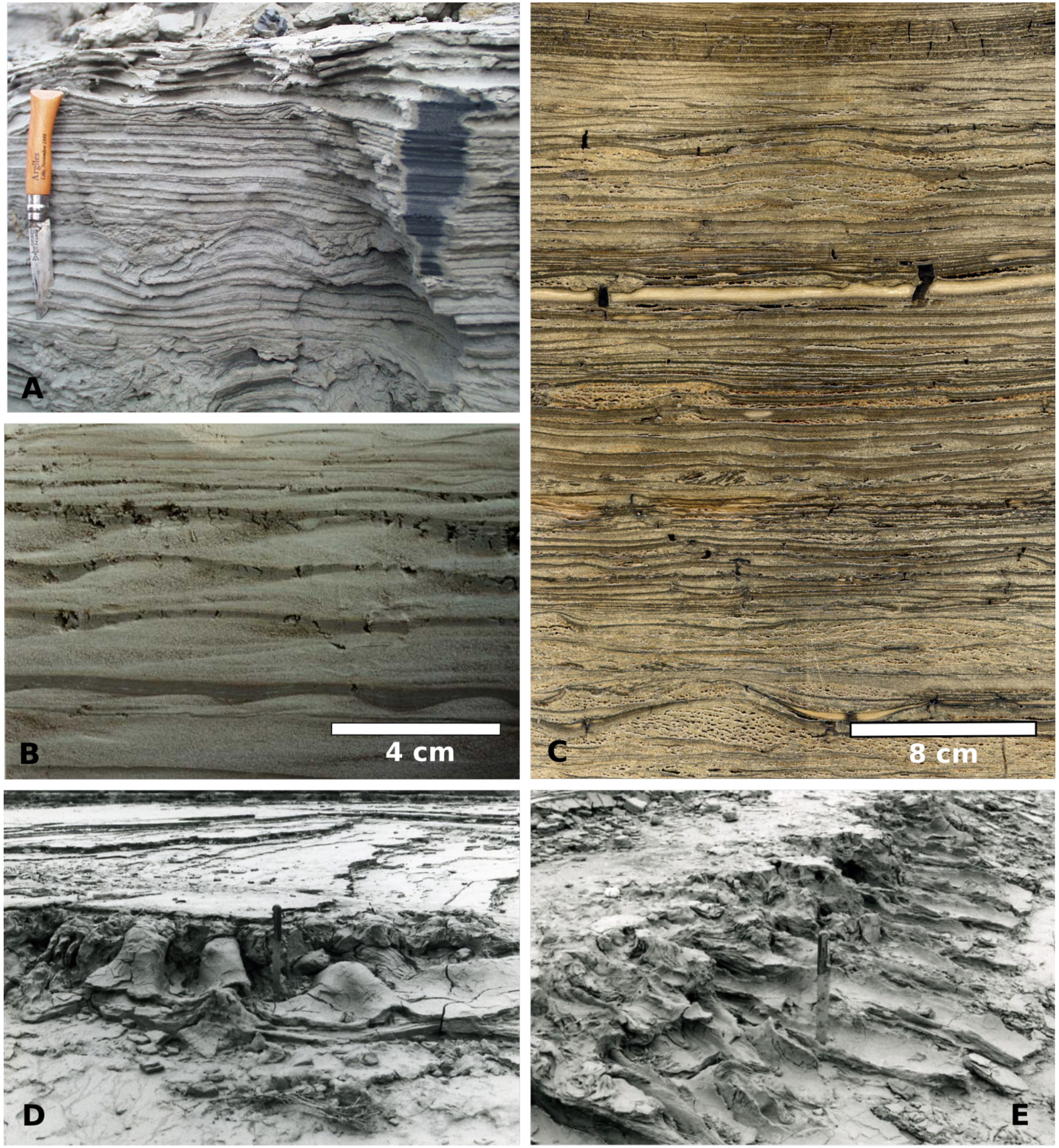

Fig. 14 - The *tangue*. A), B), C) Typical aspects of its beddings made of the superposition of “sand-mud” couplets of various shape and thickness. D), E) Deeply convoluted *tangue* deposits due to tidal bore passage.

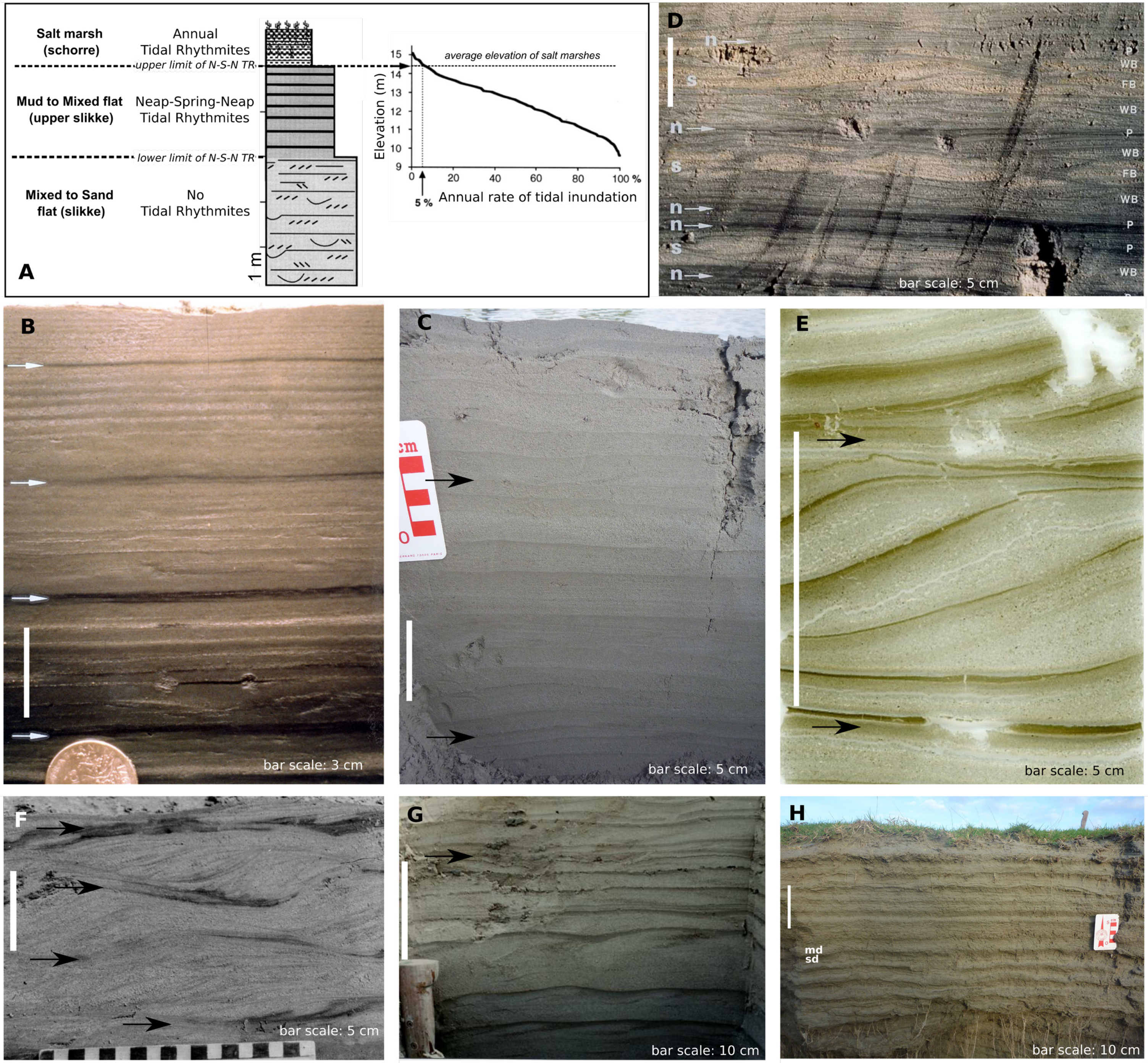

Fig. 15 - Tidal rhythmites (TR) in the inner estuary. A) Occurrence within an ideal tidal flat succession (Tessier, 1998). From B to G) examples of semi-lunar TR in planar (B, C) and ripple (D, E) beddings, including climbing ripple bedding (F, G). Note that (E) is a thin section. On all photographs, arrows indicate neap periods. H) Annual TR into supratidal deposits (salt marsh). sd, md for sand-dominated and mud-dominated couplets respectively. N-S-N TR: Neap-Spring-Neap Tidal Rhythmites.

exclusively in supratidal (salt marsh) facies and consist of a few cm-thick sequences made up of very thin (mm) tidal couplets (Fig. 15H). Annual sequences are formed by a succession of undisturbed sand-dominated couplets and mud-dominated couplets heavily disturbed by roots (respectively sd and md on Fig. 15H). The later (md) materialise 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.

Properties of the *tangue* do not only enhance the preservation of a great variety of tidal sedimentary structures but also allow the exceptional preservation of vertebrate tracks. Tidal sediments are considered the deposits which best preserve vertebrate tracks in modern and ancient sedimentary successions (Allen, 1997; Marty et al., 2009; Campos Soto et al., 2017). Therefore, the *tangue* offers an opportunity for understanding the sedimentary controls on the formation and preservation of vertebrate tracks in modern tidal settings. In a recent study (Campos-Soto et al., 2022), human tracks have been made during low tide in the upper intertidal flats in different areas of the MSMB (Fig. 16A-C). It has been observed that their morphology is strongly related to the water content of sediments, the sediments with moderate water content being the ones that allow the best definition of the shape and

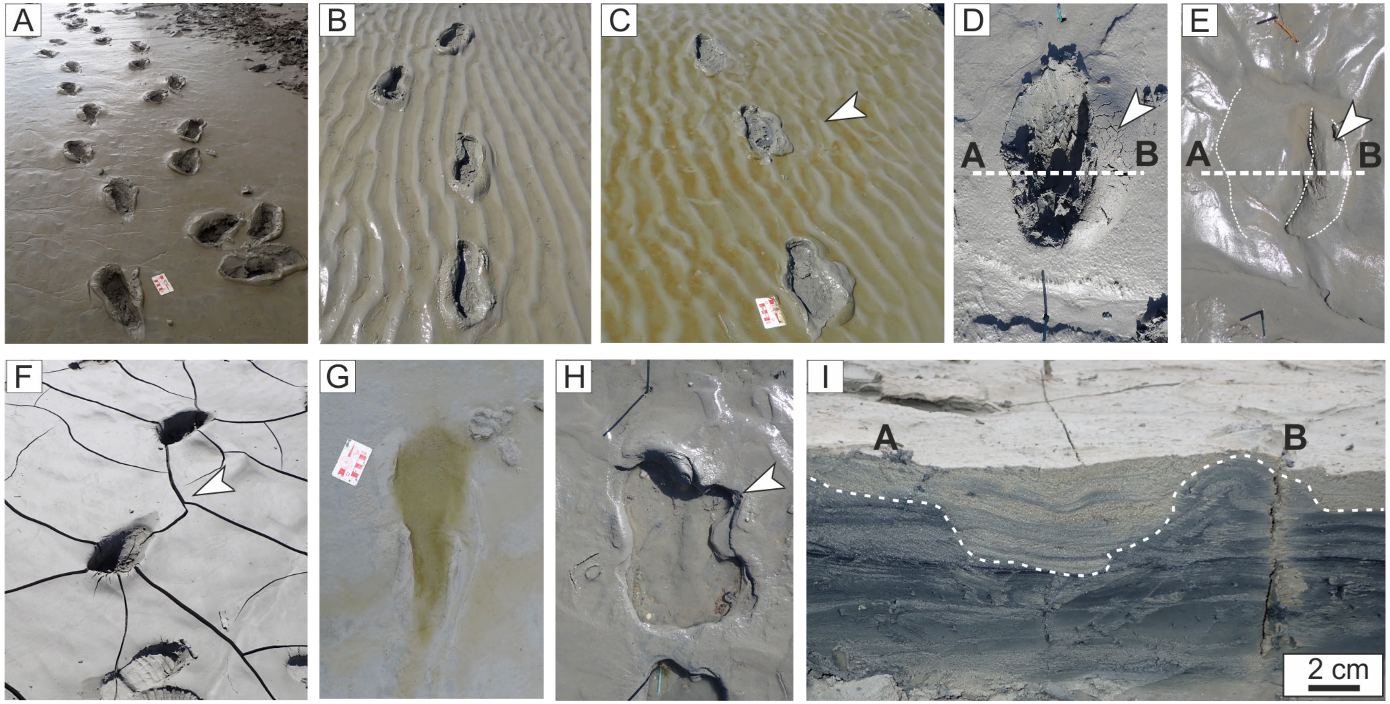

Fig. 16 - A-C) Human tracks made in the upper intertidal flats of the MSMB. In (C) tracks are made in a sediment colonised by microbial mats (white arrow). D-E) Track being monitored after several tides. The white arrow points to the position of the displacement rim located at the right part of the track. F) Sediment getting desiccated and consolidated after track-making, which led to the formation of large desiccation cracks (white arrow). G) Overgrowth of microbial mats in the inner part of a track. H) Track partially eroded by currents (white arrow). I) Cross-section of the track shown in Fig. D-E. The sediment underlying the track has been deformed and the track has been filled by new sediment (above the white dotted line).

the best preservation of the anatomical details, as previously reported in other modern tidal settings (Allen, 1997; Marty et al., 2009). The occurrence of microbial mats, which developed during the summer season, may also contribute to the preservation of the tracks (Fig. 16C), as previously observed in other modern examples (Marty et al., 2009). After track-making, tracks were monitored through the following spring and neap tides (Fig. 16D-E), which has allowed us to analyse the post-sedimentary processes that control their preservation. For example, the consolidation and desiccation of the track-bearing sediments (Fig. 16F) and the overgrowth of microbial mats in the inner part of tracks (Fig. 16G) are some of the processes that favour the preservation of the tracks, as similarly indicated in other studies (Marty et al., 2009). On the contrary, other processes, such as the erosion of currents, may prevent preservation (Fig. 16H). Once the tracks were completely covered by sediment, cross-sections were made in order to test if tracks were preserved after burial (Fig. 16I). This has allowed to study the infilling of the tracks and the deformation of the underlying sediments.

Day 3 – The northeastern wave-dominated coastline

Stop 7. The Grouin du Sud. Tidal bore and panoramic view on the transition between the outer and inner estuary

The "Grouin du Sud" offers one of the most beautiful panoramic views on the MSMB, especially onto the estuarine domain (Fig. 17A). The narrowing of the estuary from this point leads to an acceleration of tidal current velocities into the channels of the Sée and Sélune rivers. During spring tides, nice tidal bores may develop when the tidal channel configuration is favourable (Fig. 17B). Hence, the site can be an appropriate place to observe this spectacular tidal process (cf. Stop 6, Fig. 13 and associated text for more information about tidal bore).

Stops 8 and 9. Dragey and Saint Jean-Le-Thomas beaches. Wave-dominated coastline and Holocene infill reconstruction

The northeastern part of the MSMB is represented by a sandy coastline that experiences spectacular and contrasting processes of erosion (coastline retreat) and sedimentation (coastline progradation). Comparison of aerial photos since 1947 demonstrates that the beach at Saint Jean-le-Thomas locality has retreated of a few hundreds of meters while, southward, at the Bec d'Andaine

Fig. 17 - The Grouin du Sud offers one of the most beautiful panoramic views on the MSMB (A, Photo in: http://www.projetmontsaintmichel.fr). During favorable conditions, tidal bores can develop into the main channel (B) that goes along the Grouin du Sud (Photo: B. Tessier, Oct. 2010).

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or Dragey sites, beaches advanced of about the same value (Compain et al., 1988; Auffret, 1999).

These different aspects of the NE coastline evolution and functioning are summarised in Fig. 18. They are mainly related to wave action and sediment supply distribution. The NE entrance of the MSMB is exposed to prevailing W to NW waves inducing severe erosion at St-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 sand spits (Fig. 18A). The sand spits isolate from wave dynamics sheltered depressions or ponds that are invaded only during high spring tides and filled by fine-grained tidal facies evolving progressively to salt marsh deposits. Northward, at Saint-Jean-le-Thomas, the high energy wave action induces a severe beach and dune (barrier) retreat. The process produces a wave ravinement surface (U4 in Fig. 18A) eroding older back-barrier sediment successions that deposited when the barrier was located more offshore than the present-day one (Fig. 18B). It is worth noting that the wave ravinement reveals an ancient (4000 cal BP) human occupation surface with remains of fishing grounds and bovid imprints (Billard et al., 2003). The barrier began to construct some 6500 years ago when

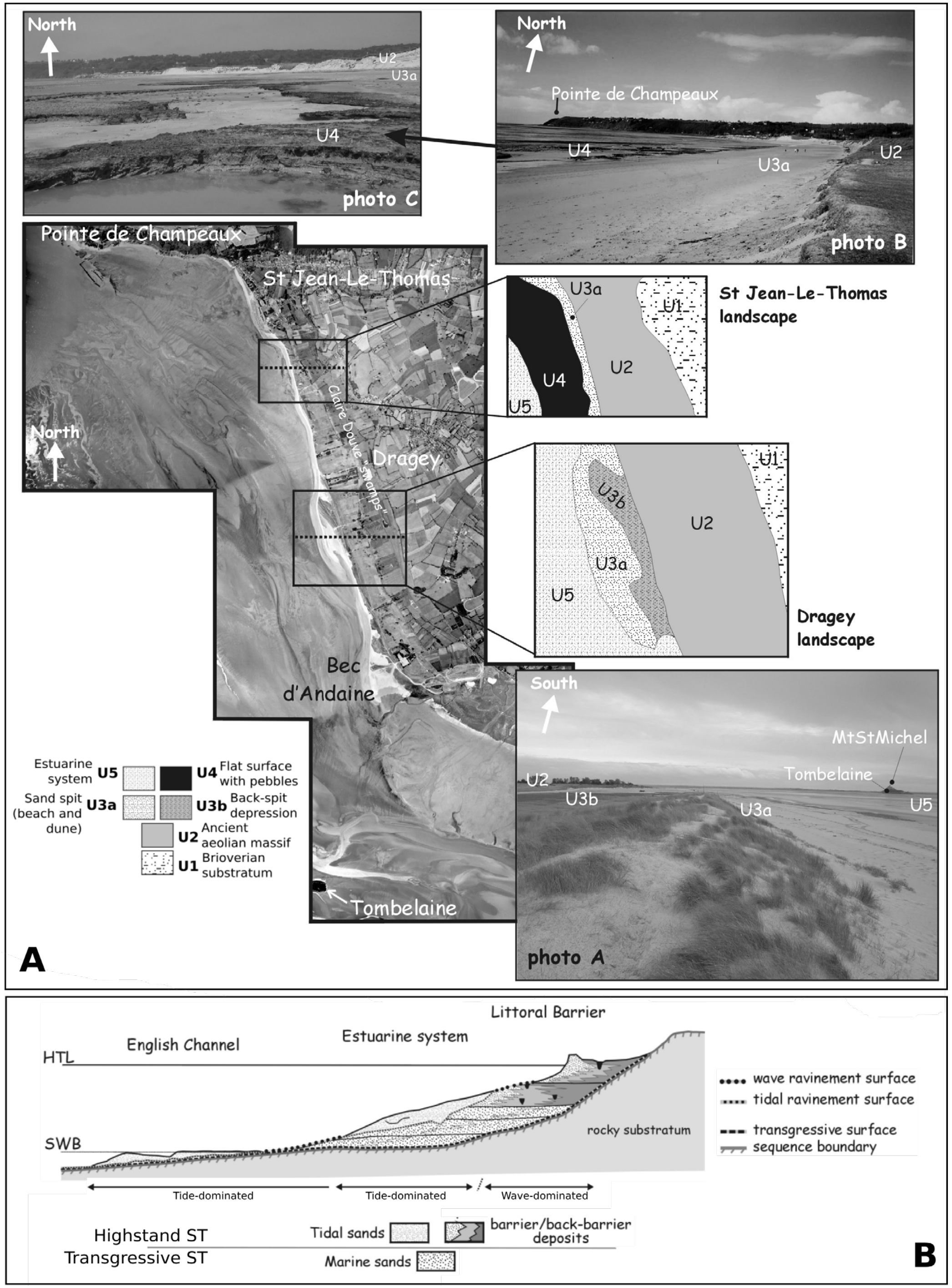

Fig. 18 - The NE shoreline of the Bay of Mont-Saint-Michel (Aerial Photo © IGN 1999) (Tessier et al., 2006). A) Organisation of the landscapes and morphosedimentary units; B) Reconstruction of the coastal wedge.

the sea level rise slowed down significantly. Since that period, the 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 (Fig. 18B).

Stops 8 and 9 offer also the opportunity to discuss the Holocene sedimentary infill of the MSMB. In the framework of Isabelle Billeaud's Ph.D. works (Billeaud, 2007), 50 vibrocores (7 m long on average) and about 600 km of very high-resolution seismic profiles were acquired (Fig. 19), that allowed reconstructing the Holocene infill architecture (Billeaud et al., 2007; Tessier et al., 2010; Fig. 20). The data demonstrate as well that the Holocene rapid climate changes (RCC) have significantly impacted the dynamic of infilling of this hypertidal environment (Billeaud et al., 2009; Tessier, 2012; Tessier et al., 2012; Fig. 21).

Seismic and core data allow distinguishing two main depositional systems, a transgressive and a highstand system tracts (TST, HST). The maximum flooding surface (MFS) between the two is dated at around 6500 year BP. The TST is poorly developed and rests directly on the bedrock (Brioverian substrate) in most of the area (Fig. 20). It is represented by aggradational fine-grained facies in the estuarine domain, producing biogenic gas (Ue3 in Fig. 19D), while it is composed of high-energy coarse-grained deposits into the embayment (Ub3 in Fig. 19B, C). The HST represents the main part of the sedimentary infill (Fig. 20). Into the embayment, the HST is an aggradational unit, consistent with the present-day tidal flat landscape (Ub4 in Fig. 19B, C). In the estuary, it corresponds to a sand-dominated tidal channel-and-shoal unit that progressively pinches up seaward (Ue5 in Fig. 19D). The base of this unit is marked by an erosional surface (tidal ravinement) truncating a seaward progradational unit interpreted as the bottomset termination of the estuarine body (Ue4 in Fig. 19D). The estuarine HST is fed exclusively by marine source and 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 inner estuary (Fig. 20).

Going further in the reconstruction of the Holocene infill, core (Fig. 21A) and seismic (Fig. 21B) data show that the signatures of periodic environmental changes are preserved into the HST deposits. ^{14}C dating demonstrates that these changes can be correlated at the scale of the whole bay (Fig. 21C). They are attributed, in all cases, to the impact of enhanced storm dynamics, which occurred with a millennial time-scale periodicity. Four to five significant changes occurred. The time of these climatic crises was ca. 5500-5800, 4000-4500, 3000, 1000-1200 cal BP and matches the time of the Bond's events (Billeaud et al., 2009; Sorrel et al., 2012).

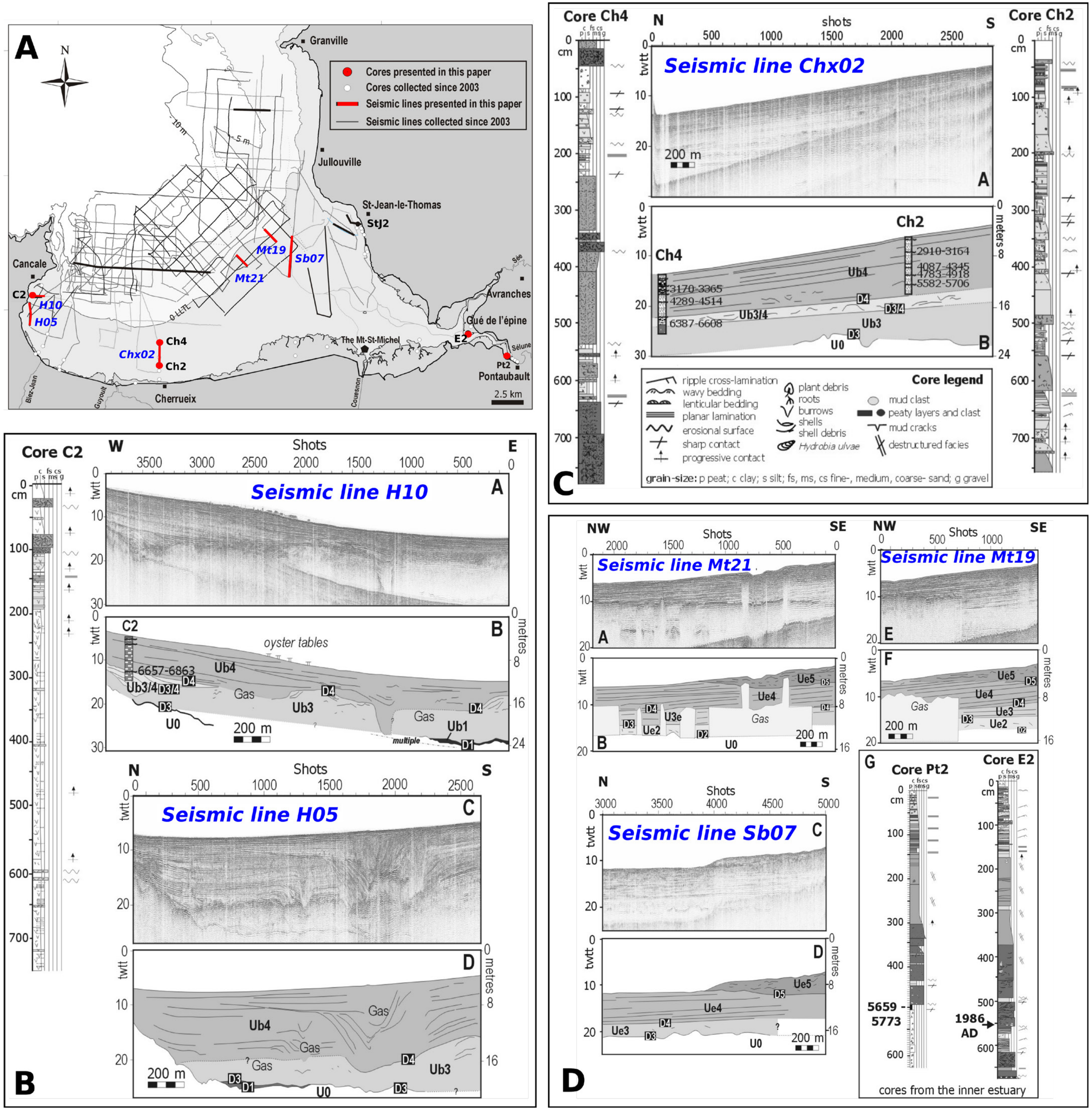

Fig. 19 - Examples of very high-resolution seismic lines (raw and interpreted) and vibrocores acquired in the MSMB. A) Location map of the data (Lines and cores on B, C, D are indicated in red). B) From the mudflat in the embayment - Cancale Bay. C) From the sandflat in the embayment – Cherrueix. D) From the external (seismic lines) and internal (cores) estuary. Data from Billeaud (2007), figures in Tessier et al. (2010). All ages are in Cal. yr. BP. Uxn: Seismic Units and Dx: discontinuities as defined in Billeaud (2007) and Tessier et al. (2010).

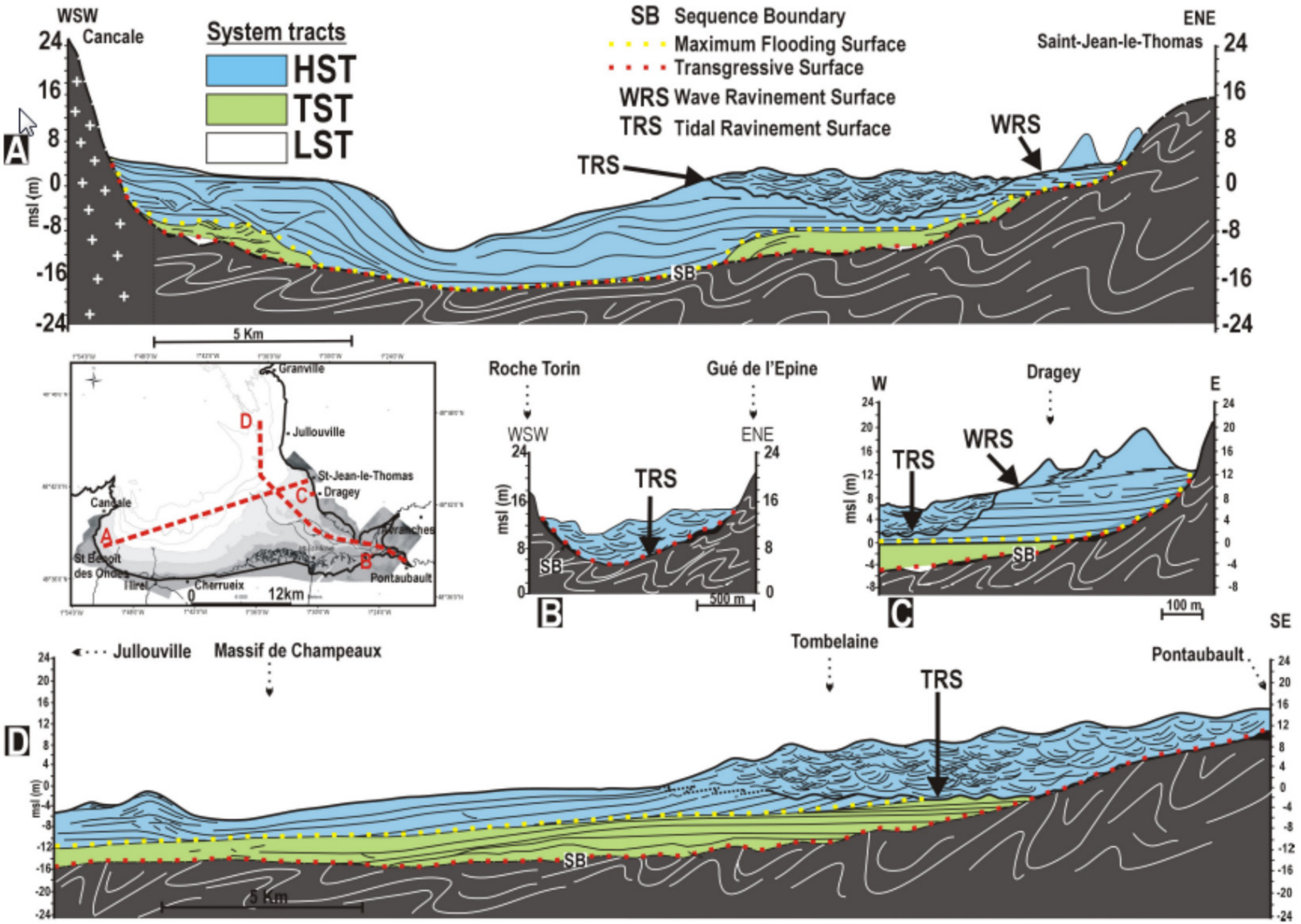

Fig. 20 - Synthetic cross-sections illustrating the main geometrical patterns of the MSMB sedimentary infilling (Billeaud, 2007; Tessier et al., 2010).

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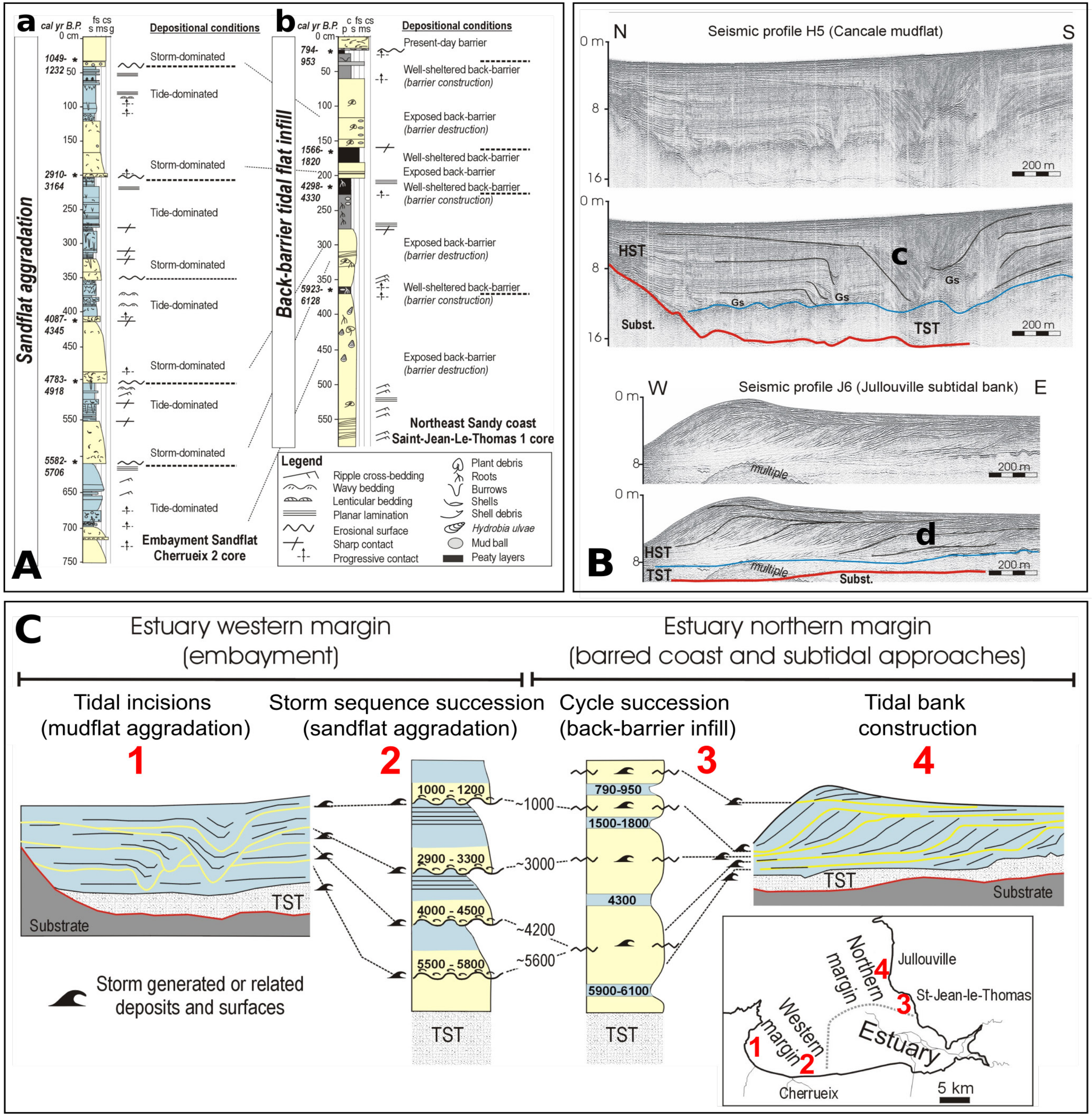

Fig. 21 - Holocene rapid climate changes as recorded into the MSMB sediment infill. A) As storm-dominated facies in the sandflat successions into the embayment (a) and barrier destruction phases along the NE shoreline (b). B) As tidal incisions (c) into the mudflat of the embayment induced by barrier destruction (seismic line H5) and storm-generated erosional flat surfaces (d) into subtidal banks (seismic line J8). C) The time of these changes matches those of the "Bond's Events" (in Billeaud et al., 2009). TST: Transgressive System Tract; HST: Highstand System Tract; Subst: rocky substrate; Gs: gas.

Stop 10. Champeaux rocky flat. The "*Hermelles*" (polychaete worms) 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, 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. Stop 5). The second reef is implanted on the rocky flat at the foot of the Champeaux cliff (Fig. 22), in the North of the Bay, at the junction between the estuarine entrance and the open marine domain. This

Fig. 22 - The "*hermelles*" (*Sabellaria alveolata*) reef at the foot of the Champeaux cliff. A) General view at mid-tide. B), C) Arborescent and tabular structures. D), E) Closer views of the "*hermelles*" tube entrances (D) and vertical coalescence and superposition (E) (Photos B. Tessier) (scale bars on B, C, E: about 10 cm).

reef is easily accessible at low tide and, although of smaller extension than the "*Banc des Hermelles*", displays very spectacular shapes and development.

The "*hermelles*", or *Sabellaria alveolata*, are gregarious and sedentary annelid polychaete worms that construct massive reefs made of contiguous arenaceous tubes 5 to 10 mm in diameter. The reefs constitute arborescent and tabular structures (Figs 22, 23) reaching up to 1.2 m above the floor. Densities are very high (15,000 to 60,000 individuals/m^2).

The settlement of juvenile individuals requires a hard or sufficiently stable substrate. In the case of Champeaux, the bioherm naturally settles on the outcropping rocky substrate as well as on the walls of ancient permanent fishing grounds (Fig. 23). The nature of the substrate supporting the so-called "*Banc des Hermelles*" is not clearly defined. It is probably constituted by natural oyster beds.

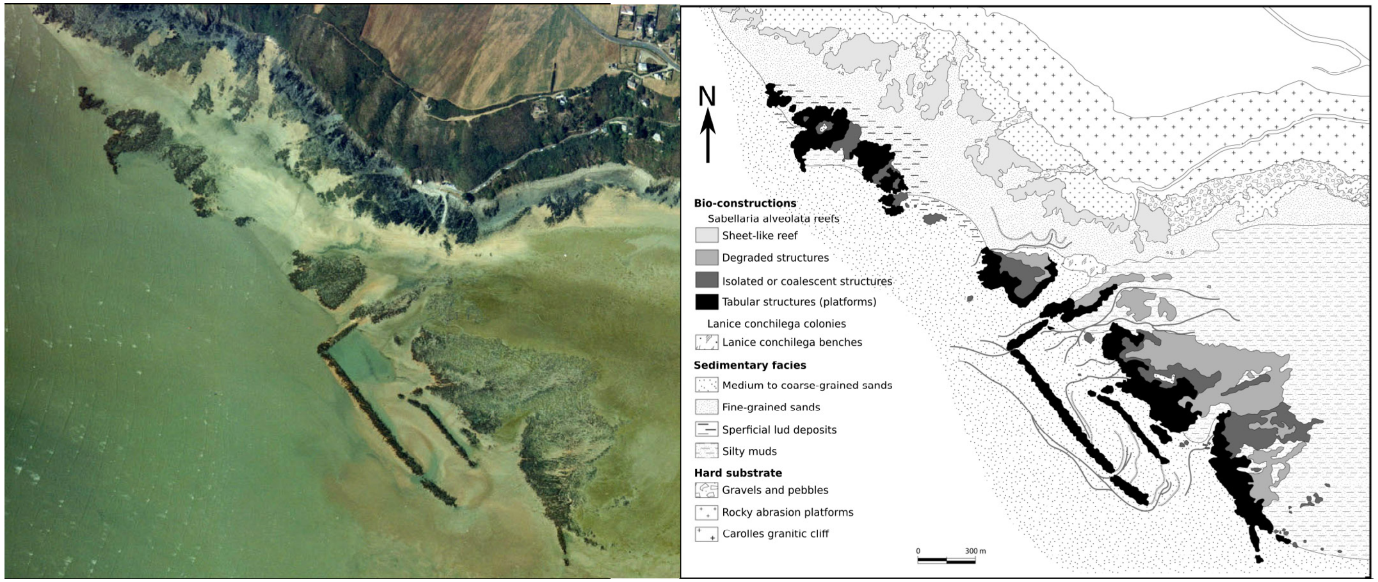

Fig. 23 - Distribution of the "*hermelles*" reef structures and of associated sedimentary facies at Champeaux locality (aerial photograph ©IGN, 1999; Map ©Bonnot-Courtois C. and Dubois S.). Note the triangle shape of the main reef, settled on an old stone fishing ground.

Acknowledgments

The data provided in this booklet has been collected for several decades of researches. Among the most recent investigations dealing with the sedimentary processes, facies, and infilling of the MSMB and led by the CNRS M2C Lab, we can cite the Ph.D. works of Isabelle Billeaud (2007, University of Caen) funded by the French Ministry of Research, Pierre Weill (2010, University of Caen) funded by the Basse Normandie Region, Lucille Furgerot (2014) funded by the ANR "Mascaret", Alissia Rieux (2018) funded by the Normandie Region and the DDTM35, the post-doctorate works of Sonia Campos Soto (2021), funded by the University of Caen Normandie, with the support of the project PGC2018-094034-B-C21 of the Spanish Ministry of Science, Innovation and Universities and in collaboration with Maria Isabel Benito, Complutense University of Madrid, Isabel Emma Quijada, University of Oviedo and Pablo Suarez Gonzalez, Complutense University of Madrid. We thank Prof. Andrea Zanchi, the Editor-in-Chief as well as Angelo Cipriani and Diego Pieruccioni, Editorial Managers of Geological Field Trips and Maps, and two anonymous reviewers for helping to improve the content of the booklet.

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