8th International Conference on tidal Environments
Caen, France, July 31 – August 2

Pre-conference field trip

The Bay of Somme
A wave dominated, macrotidal estuary

(July 29-30, 2012)

Leaders

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With the sponsor of Oscar Savreux Quarry.

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General programme

Sunday, 29th July 2012
The Southern Bay. Following the gravels on their way North.

Tidal range: 5.65 m High tide at 08h37, 8.20 m Low tide at 15h53, 2.55 m

Stop 1: Ault
Introduction to the bay of Somme. Geological context.
Panorama on the chalk cliffs of Normandy, source of flint gravels.
Planning issues concerning the cliff retreat.

Stop 2: l'Amer du Sud. Cayeux-sur-Mer
Zone of gravel-spit high vulnerability.

Stop 3: Brighton-les-Bains.
Gravel spit evolution.

Stop 4: Pointe du Hourdel.
The modern end spit.
Changes in sedimentation rhythms
First view on the inner bay.

Stop 5: The Cap Hornu
The paleocliff and its foot sediments.
Sediments of the inner bay

Monday, 30th July 2012
The inner bay. Where the mud sticks to boots.

Tidal range: 6.30 m High tide at 09h55, 8.50 m Low tide at 17h00, 2.20 m

Stop 6: The seamen's chapel
Panorama of the bay at high tide from a Tertiary High.

Stop 7: Gravel quarries
Pleistocene evolution of the bay

Stop 8: Le Crotoy
How to slow down the sedimentation in the estuary?
The Northern end of the Bay

Stop 9: Le Crotoy -> Saint-Valery
Journey along the salt marshes
Use of the steam train to join the next stop

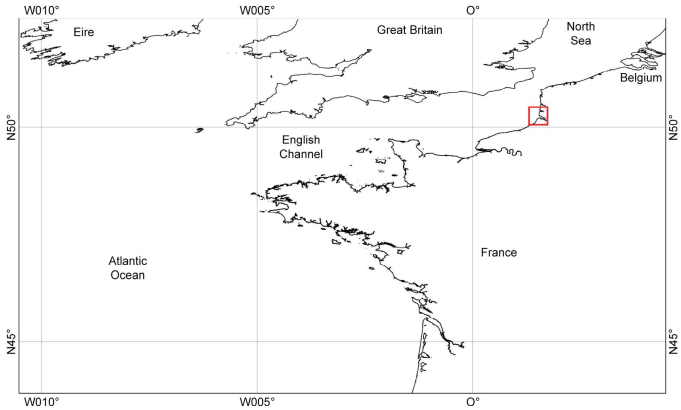
Stop 10: Saint-Valery
Inner-Bay sedimentation

Alain Trentesaux, Sophie LeBot and José Margotta have prepared this volume.

Abstract

The Somme Bay is a nice example of a macrotidal estuary developing characteristic and original features. The main objective of this field trip is to examine the modern sedimentation that occurs in the Bay of Somme as a function of the exposure to different hydrodynamic agents, such as waves, tides or river flows. As most of the European estuaries, this area is rapidly evolving, following a typical estuarine infill pattern (Chaumillon et al., 2010). In the context of eventual climatic changes and ecological realization, some environmental and planning issues will be also discussed.
The second objective consists in the presentation of the Holocene evolution of the Bay in relation with sea-level variations.
Two other field-trip guides can complete this booklet: Dupont et al., 1993, and Ducrotoy, 2004. The French Association of Sedimentologists (ASF) publishes both.

Stops



Road map displaying the proposed stops. IGN documents (www.geoportail.fr)
Red square: figure 1, next page.

1- Introduction

The Somme Bay is located in the North of France, in Picardy. It forms a vast embayment open to the NW in the Southern part of the coastal plain of Picardy (Figs. 1 and 2). The inner part of the estuary is continuously silted up and displays a mobile and fragile coast. Landscapes and sedimentary objects are very diverse: rapid changes of the estuarine channel courses, gravel bars to the South, sand beaches and dunes to the North. They are in front of a low-lying zone under the risk of flooding. Land reclamation has reinforced the natural accretion processes and led to deep modifications of environmental uses (e.g. fisheries or navigation).

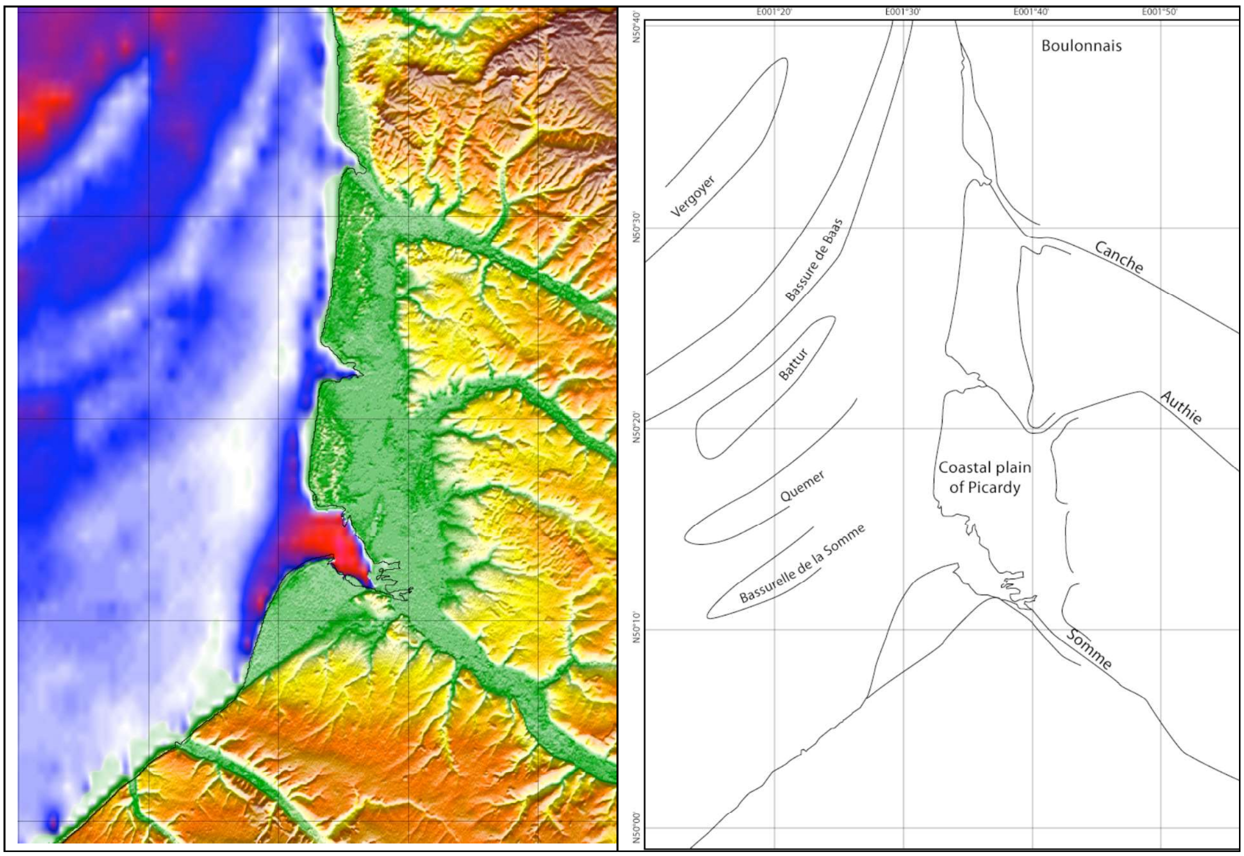


Figure 1. Digital Terrain Model of the coastal plain of Picardy. Distinction between the coastal plain in green and the relief from the Artois Chalk plateau is easily visible. Three main streams dissect the plain: the Somme, the Authie, and the Canche, respectively from South to North. The offshore zone displays some large 'tidal' sand banks. Topography from SRTM V4 (NASA, 2008) 90 m resolution. Bathymetry from ETOPO1 (NOAA, 2009) 1800 m resolution. Projection: Mercator, WGS84. Treatment: F. Graveleau, Géosystèmes, CNRS-Lille 1.

1.1- Geological framework

On a broad sense, the Bay of Somme is located in the Paris Basin North-western end. The Paris basin is intracratonic with a Mesozoic to Cenozoic infill history. The geological map displays three groups of terrains based on their age (Fig. 2). The substratum covering the entire zone consists in Cretaceous chalk. Outcrops display a wide range of chalks from Lower Turonian to Lower Santonian. The estuary lies on a large faulted syncline (van Vliet et al., 2000, Augris et al., 2004) at the origin of a large open bay that is filled with mostly marine sediments since the Cretaceous (Loarer, 1986).

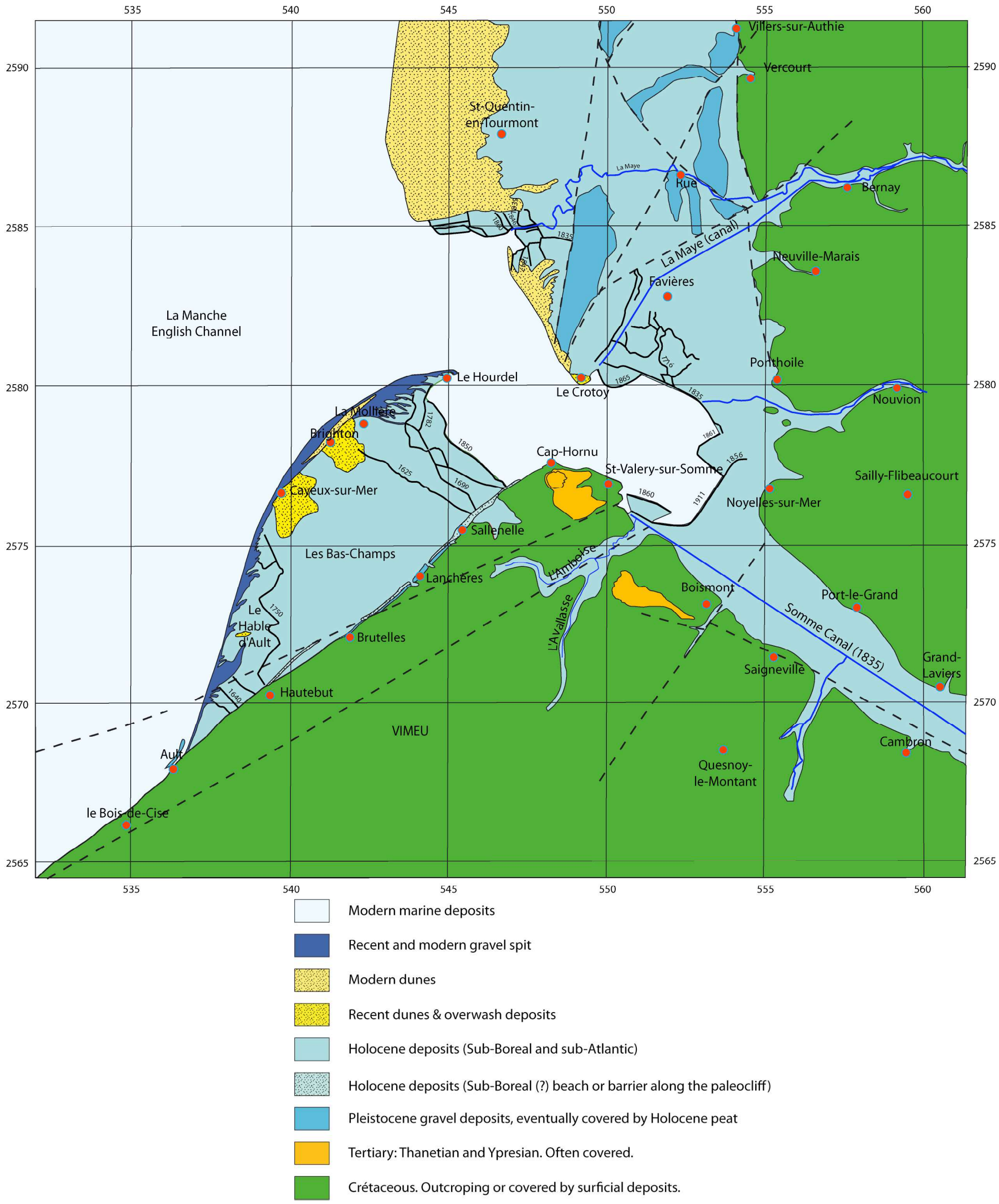


Figure 2. Geological sketch based on the two published geological map. (BRGM, 1981; 1985). Dashed lines refer to presumed faults or hypothetical Quaternary fault or flexure. Some dates have been reported along ancient seawalls.

Mesozoic rocks outcrop along the coast from Normandy (Le Havre) and constitute some well-know cliffs (Fig. 3). On a lithological point of view, except for Lower and Upper Turonian where the chalk is argillaceous, the chalk is pretty pure and displays a white colour. Flint layers are present throughout the series but their abundance is variable. The Cliff coast of Normandy ends at the southern extremity of the Bay of Somme. It continues as a paleocliff (ravines) separating the Artois plateau from the Pleistocene coastal plain.

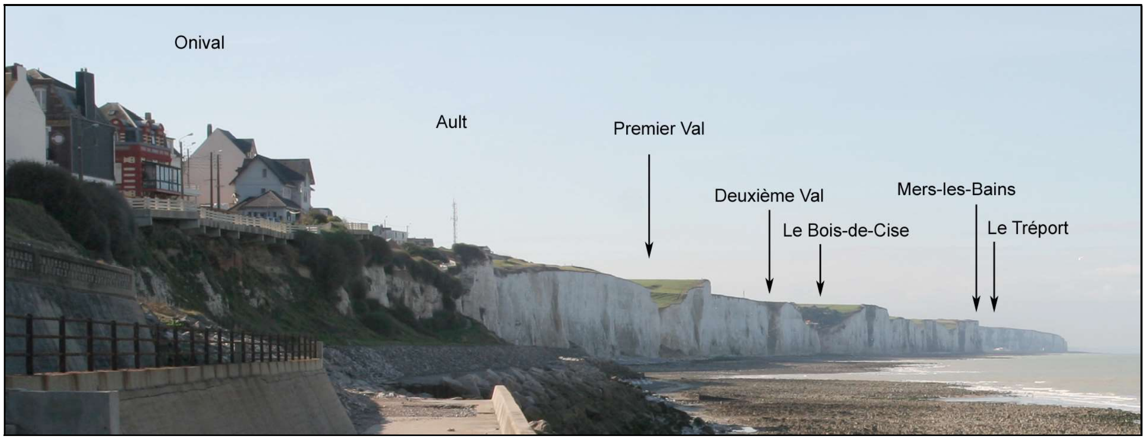


Figure 3. View from the beach of Onival toward the SW and displaying the active cliffs. On the shore appears the rocky platform. At the top of the cliffs, dry valleys appear. They are locally called 'val' or 'valeuse'.

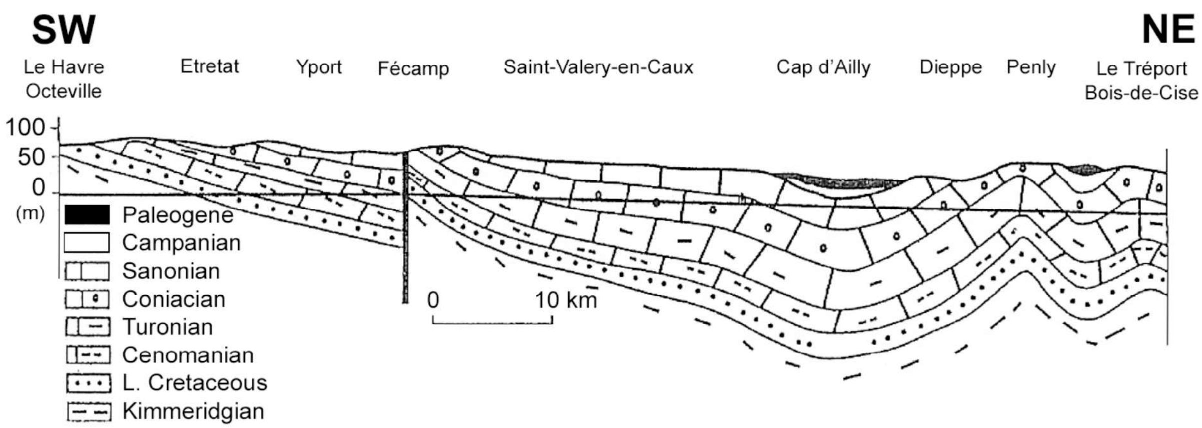


Figure 4. Simplified geologic section South of the Bay of Somme (Augris et al., 2004).

The second unit consists in Tertiary rocks well developed offshore. Inland it appears as witness buttes in the area of Saint-Valery. Around this locality, Thanetian sands and Lower Yresian sands, muds, silts and coquinas outcrop. These formations, characteristic of the Paris Basin, are mapped and described in Quesnel (1997) and Laignel et al. (2002).

The third unit is composed of Pleistocene deposits. These are of continental origin on the Plateau (e.g. loess; Lautridou, 1995), fluvial in the continental valleys, and mostly marine on the coastal zone. Ante-Holocene gravel bar formation and marine deposits will be further discussed in part 4.

1.2- Holocene context

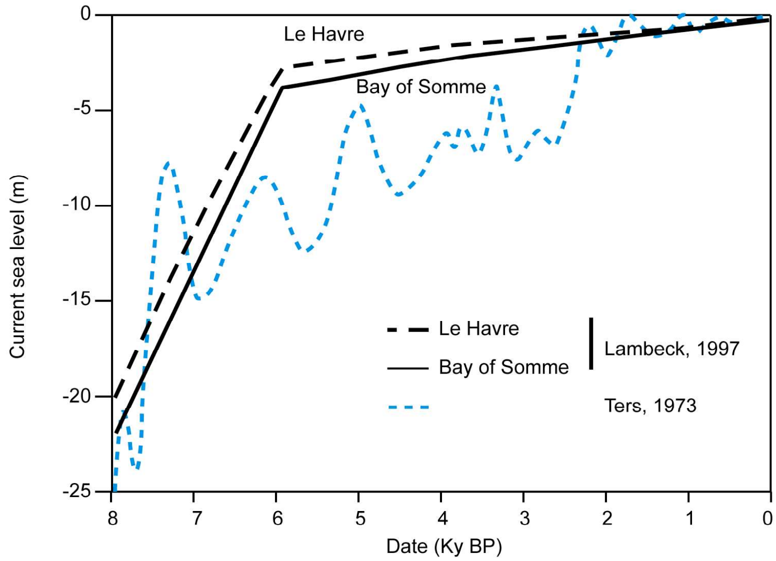


Figure 5. Sea-level evolution for the last 8 ka (Ters, 1973 and Lambeck, 1997)

Due to changes in sea-level (Fig. 5), the English Channel was strongly modified between glacial ages and interglacial stages, leaving a large fluvial plain between France and Great Britain. Different hypothesis have been proposed to explain how and when the opening of the Dover Strait occurred at each changes (Gupta et al., 2007, Destombes et al., 1975, Auffret et al., 1980, Lericolais et al., 2003.). One certainty is that a vast fluvial system was present at the place of the English Channel (See section 6). During low sea-level stages, the Somme was one among the many tributaries feeding this network.

1.3- Physical, modern framework

1.3.1- Tidal conditions

The Somme Bay is located in the Eastern English Channel, where the tidal regime is macrotidal and semi-diurnal. The tidal range reaches 9-10 m in spring conditions. It is the second location for tidal range value; after the Mont-Saint-Michel Bay (See this volume), along the Eastern English Channel (Fig. 6) Tidal values vary therefore strongly between 4.52 and 5.58 m (IGN 69, Tab. 1).

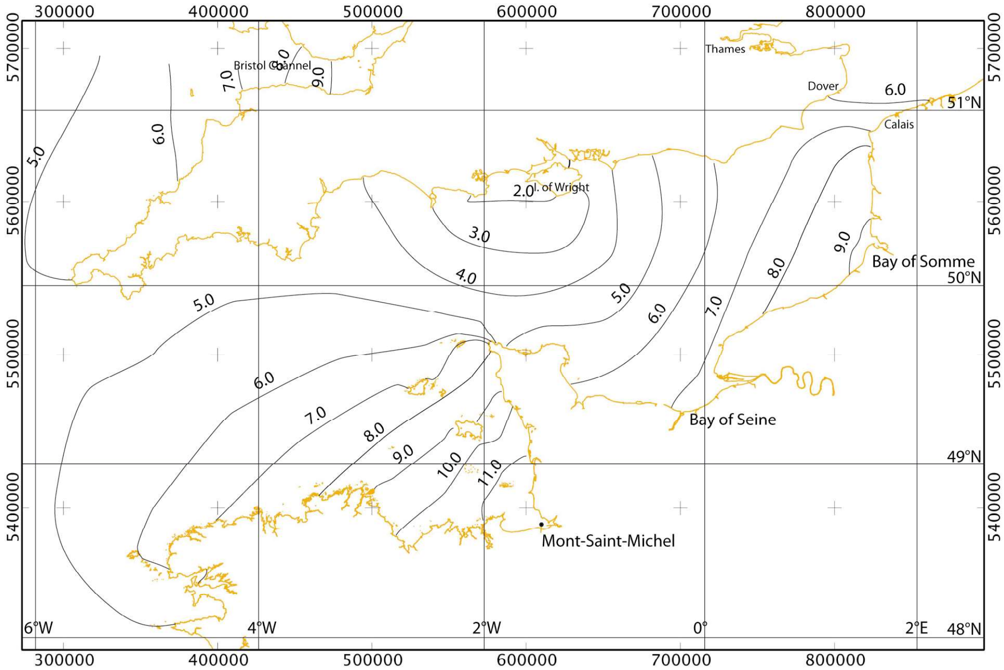


Figure 6. Mean spring tidal range along the English Channel. Data from Telemac model (EFDF-DRD, in SHOM, 2000).

Table 1. Characteristic tidal-levels at Cayeux (EPSHOM, 2001). *Coeff. (for coefficient) refers to a French tidal factor varying between 20 and 120.

	Coeff.*	Height (Nautical charts)	Height (IGN69)
Highest Astronomical Tide	-	10.55	5.58
Mean High Water Spring	95	9.85	4.88
Mean High Water Neap	45	8.00	3.03
Mean Water-Level	-	5.49	0.52
Mean Low Water Neap	45	2.95	-2.02
Mean Low Water Spring	95	1.20	-3.77
Lowest Astronomical Tide	-	0.45	-4.52

The tidal regime is flood-dominated (Fig. 7), although the flood effect tends to decrease due to the migration of the gravel spit toward the North that progressively closes the bay. The maximum current velocity measured offshore is lower than 1 $m.s^{-1}$ (Fig. 8). Tidal currents only increase when entering the bay (Fig. 9). The tidal cycle is strongly unbalanced: flood phase displays the maximal velocities, but only lasts 2 hours, whereas ebb phase lasts 5h45. Most of the bay is totally emerged during 4h30, and only the water flowing from the different rivers fill the inner channels of Le-Crotoy and Saint-Valery.

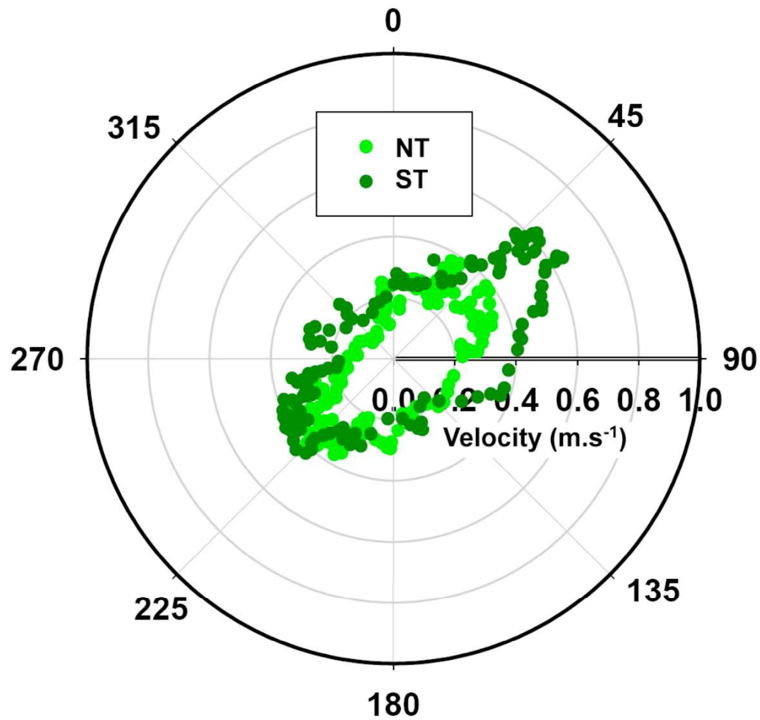


Figure 7. Averaged current rose measured between 2 m above the sea-floor and the surface offshore the Somme Bay at N50°09', E-001°17,5' (Ferret, 2011). NT refers to neap tides, ST to spring tides.

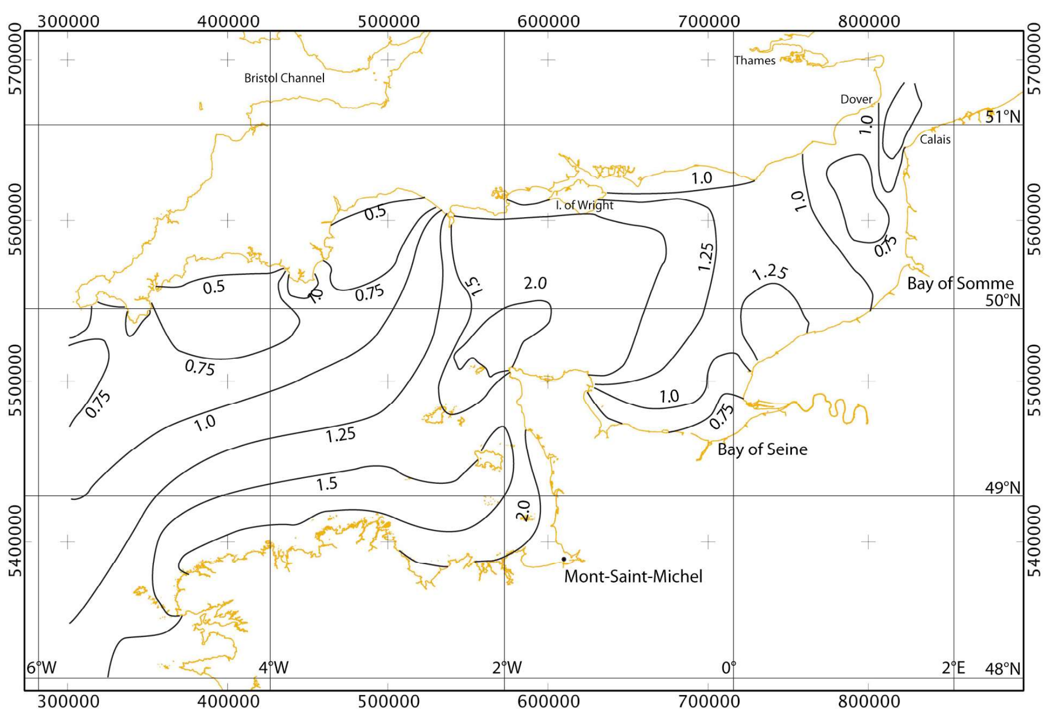


Figure 8. Maximum tidal current velocity in m.s^{-1} (from Larsonneur et al., 1982)

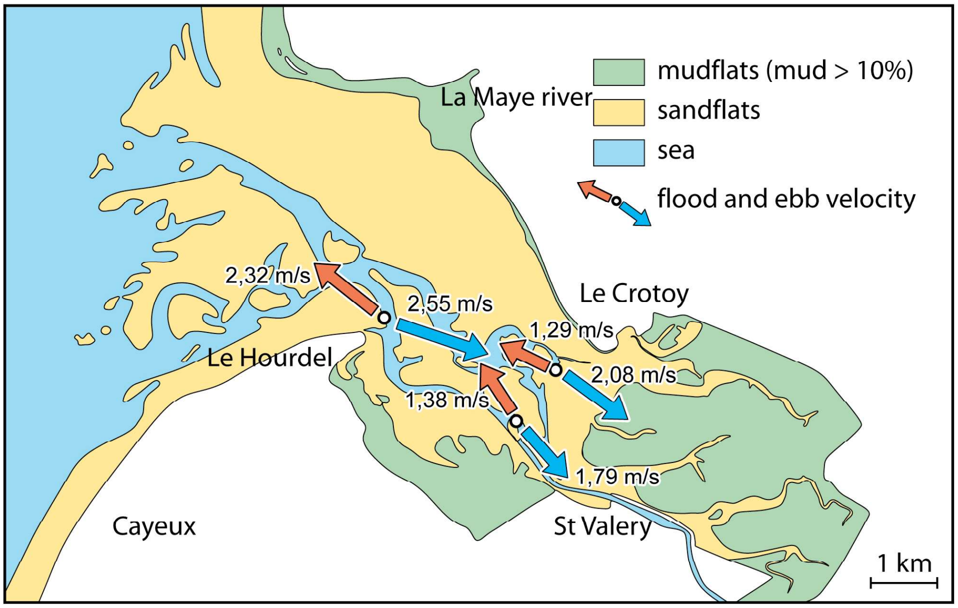


Figure 9. Flood and ebb currents in the Bay of Somme at low tide. Courtesy from François Baudin redrawn from diverse sources.

Fluvial discharge of the Somme River is low (5-60 $m^3.s^{-1}$, Dupont et al., 1993) with an annual mean around 32 $m^3.s^{-1}$ and does not counterbalance the flood dominance. The Somme is canalised between Saint-Valery and Abbeville, 15 km upstream and a sluice gate connect the river with the bay. Other small rivers only add 2.4 $m^3.s^{-1}$ to the estuary.

A tidal bore is sometimes observed (Fig. 10). Ancient documents seem to indicate that it was strong enough to help some vessels on their way to Abbeville in the XVIIth century (Cloquier, 2012), but nowadays, it is seldom observed and only helps canoe users in returning to Saint-Valery-sur-Somme from the Hourdel. Its position and occurrence strongly depends on tide conditions, but also on the movement of sand banks.

Figure 10. The tidal bore in front of the Jeanne d'Arc Quay. 10th September 2006. Picture: R. Grosléziat. The city of Le-Crotoy is visible in the distance.

1.3.2- Wind conditions

Local winds, generating wave agitation, dominantly Blow from west (50%, Fig. 11).

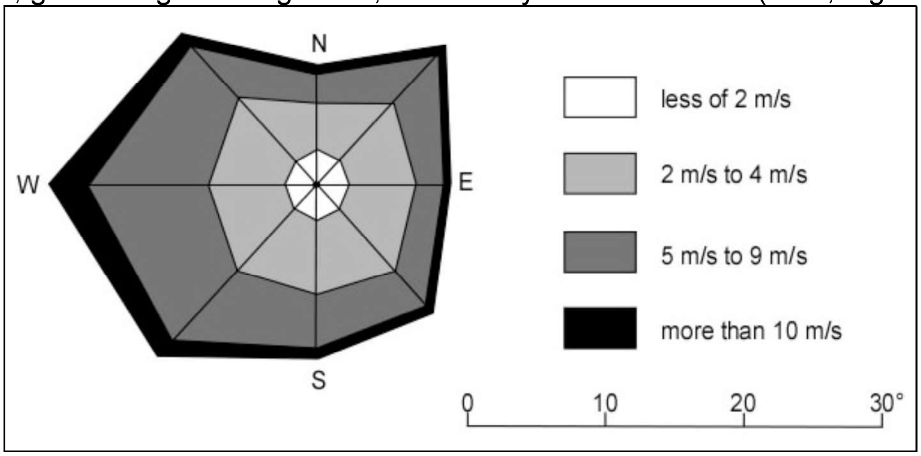


Figure 11. Wind rose measured at Abbeville (Clique et Lepetit, 1986).

1.3.3- Wave conditions

The Somme bay is concerned by a macrotidal regime, but waves act significantly due to high-energy wave conditions (Fig. 12). They first induce a strong littoral drift leading to the development of a gravel barrier at its mouth, on the southern part (Anthony and Héquette, 2007, Marion et al., 2009).

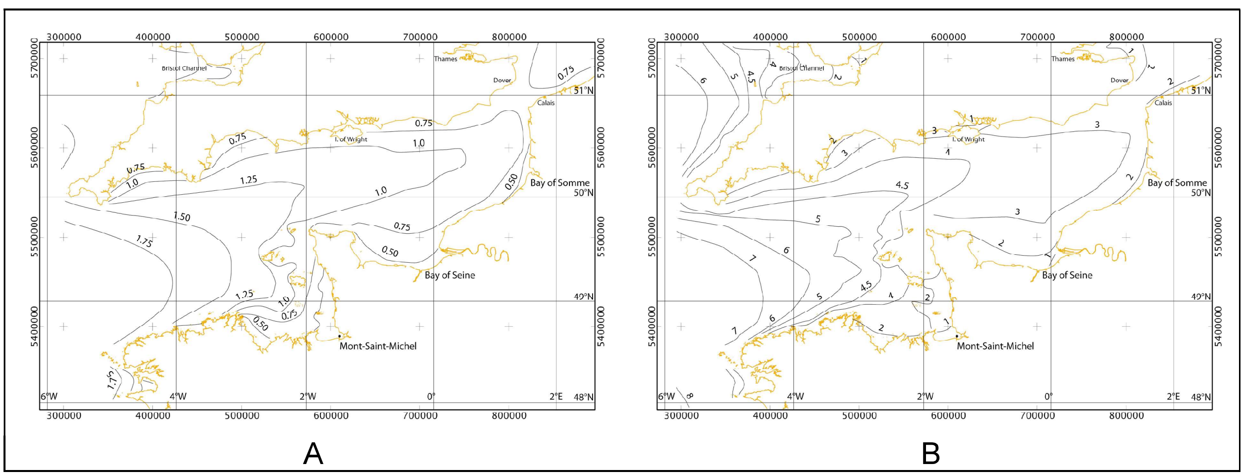


Figure 12. (Left) Mean of significant wave height and (Right) 99th wave-height percentile (Data from SHOM and Ifremer numerical models)

The local regime is characterized by low amplitude (< 1m) and short period (3-6 s) waves, mostly coming from the western sector (Fig. 13).

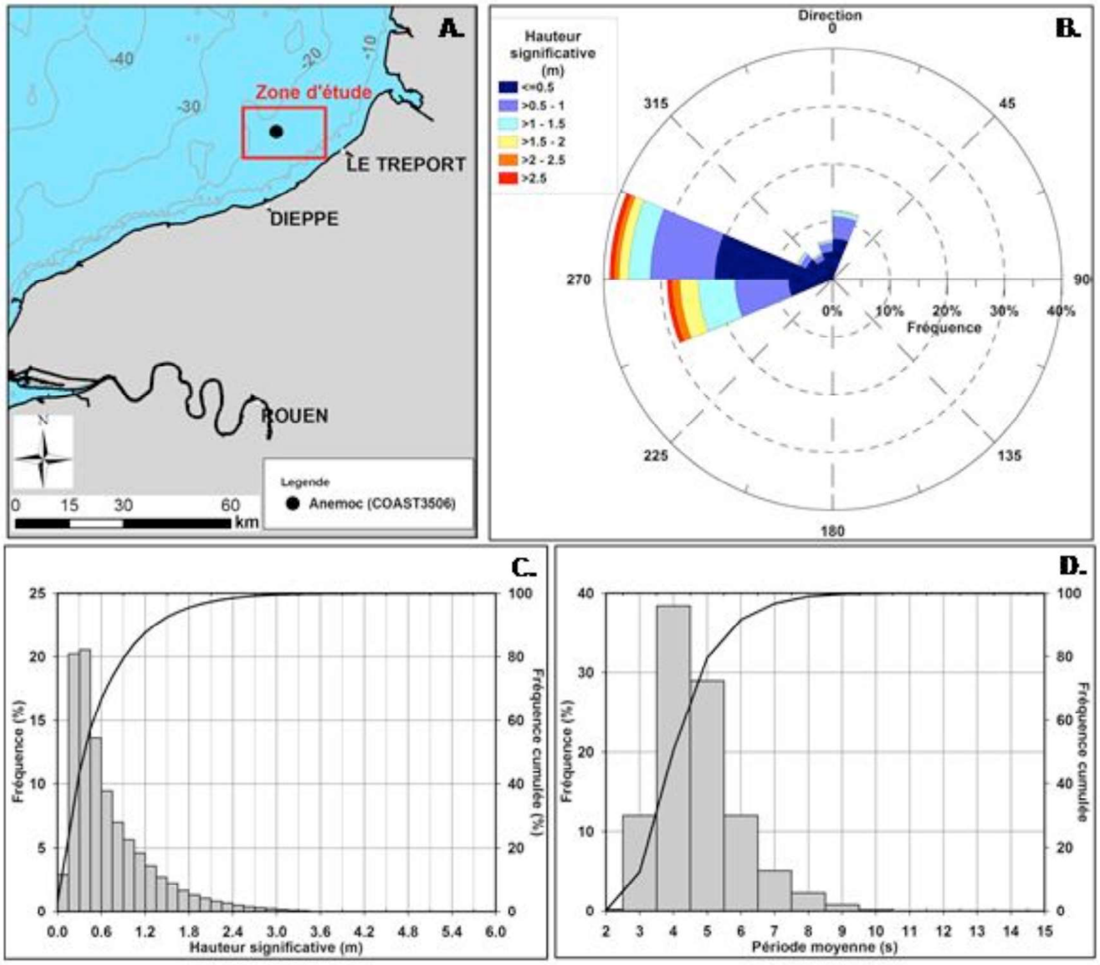


Figure 13: Wave regime offshore Dieppe on the period 1979-2002 (ANEMOC data, point Coast-3506). A. Location of the point Coast-3506 corresponding to the node of the analysed coastal grid; B. Wave frequency as a function of its provenance (hourly measurements); C. Histogram of the mean significant wave height; D. Histogram of the mean wave period (Ferret, 2011).

Table 2. Wave characteristics offshore the coast of Normandy at Paluel and Penly.

	Paluel	**Penly**
H_{max}:	80 cm	60 cm
$H_{1/3}$:	40 cm	35 cm
H_{mean}:	30 cm	25 cm
T_{max}:	8-9 s	6-7 s
T_{mean}:	6-7 s	5-6 s
Annual wave height:	5.6 m	4.1 m
Decennial wave height:	7.6 m	5.6 m
Centennial wave height:	9.6 m	7.3 m

Paluel and Penly are 44 and 32 km southward along the coast. The measurement points were located in about 15 and 10 m water depth (marine charts), respectively.

2 – The modern gravel spit

The characteristic that makes the Somme Bay different from the other Picardy estuaries is the presence of a long spit made of gravels while other are made of sands. This gravel spit started to form 2 500 years B.P (Dupont, 1981). In this section we'll discuss the source of these gravels, the spit dynamics, and some management problems linked to the spit. Stops 2, 3, and 4, along the 15.5 km-long spit will follow the gravel course due to residual wave action from their source along the Normandy cliff to the Northern end.

2.1- The source

The Somme estuary corresponds to the Northern end of the cliffs of Normandy (Fig. 14).

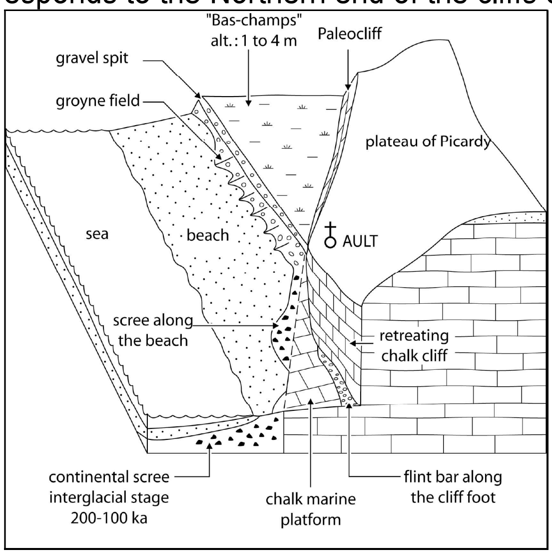


Figure 14. Sketch of the zone close to Ault where the retreating chalk cliff evolves in a paleocliff due to a longshore gravel spit. This spit isolates some lowlands, often reclaimed, locally called "bas-champs" that are under the level of spring high tides.

Figure 15. The cliff, shore platform, and pebble beach system from Haute-Normandy (Costa et al., 2002).

The Normandy cliffs are made of Cretaceous chalks characterized by their more or less high content of flint layers, especially high in Coniacian (8-13.5%), Santonian (10-16%), and Campanian (13.5-14.5%) layers (Laignel, 2003). Flints constitutes the source of the gravels: cliff retreat by marine action leads to landslides of cliff faces (Fig. 15). Blocks of chalk are quickly destroyed by the see in a couple of weeks (or months) but flints resists and are shaped in rounded gravels. Along this littoral, they are made of 98% of silica. On average, flint layers represent about 1 to 2% of the total rock volume. The cliff erosion feeds the gravel transport. Around Ault-Onival, the cliffs are made of Upper Turonian to Lower Santonian chalks (Fig. 16).

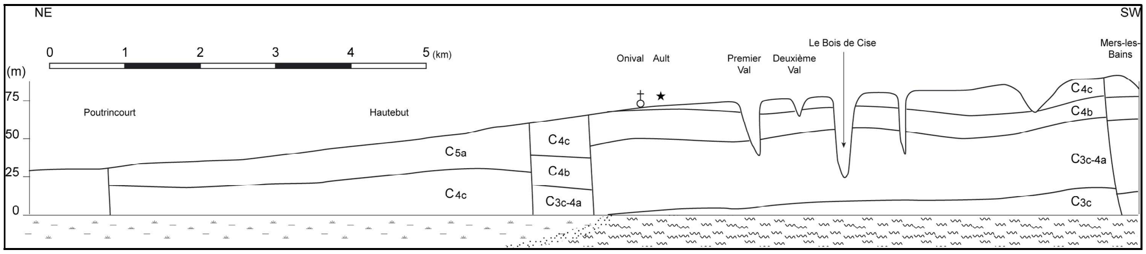


Figure 16. Synthetic geological cross-section along the nick-points located at the top of the cliff or paleocliff. Data drawn from the Geological map (BRGM, 1985). No indication of superficial deposits. The topographic profile does not take into account the profile along the coast, but the location of the highest nick-point. From Onival, Northward, the cliff is located inland and consists in a paleocliff. Vertical exaggeration: x20.
C3c: White or yellowish chalk with isolated or layered flints. Upper Turonian. C3c-4a: Chalk rich in flints. Latest Turonian and Lower Coniacian. C4b: White or yellowish, locally silicified chalk with rare flints. Middle Coniacian. C4c: White chalk with few flint layers. Upper Coniacian. C5a: White chalk with rare and small flints. Lower Santonian.

2.2- The gravel budget

The evolution of the gravel spit strongly depends on equilibrium between (i) gravel delivery from the chalk cliffs along the littoral of Seine-Maritime, from Antifer (Le Havre) to Ault, and (ii) the Northward gravel movement along the shore. If one of these two components is modified, the subtle equilibrium is broken and the gravel spit can grow or thin. This was the case along the Holocene, but has been strongly affected by human occupation along the shore, and often on the shore itself.

2.2.1- Incomes - Cliff-retreat rates

Mean cliff retreat is in the order of 0.21 m.yr-1 between Antifer and Ault on the 1966-1995 period (Costa, 2000; Costa et al., 2001). However, there is an important spatial variability of the cliff retreat rates (Fig. 17). The cliff evolution rhythm is strongly controlled by the lithology of the chalk (Costa et al., 2002) and also by the presence of obstacles such as harbour jetties, large landslides…

Close to the gravel spit, between Le Tréport and Ault, the shore retreat has been evaluated to 18 cm.year^{-1} on average. This retreat releases 2000 m^3 of gravel each year (Tab. 3).

Table 3. Annual gravel production along different sections of the Normandy coast (volume data from LCHF, 1986).

Zone	Length of coast (Km)	Annual production (m^3)	Annual production (m^3.km-1)
Antifer - Fécamp	38	6 100	160
Fécamp - Dieppe	55	10 400	190
Dieppe – Le Tréport	25	1 100	44
Le Tréport - Ault	7	2 000	285

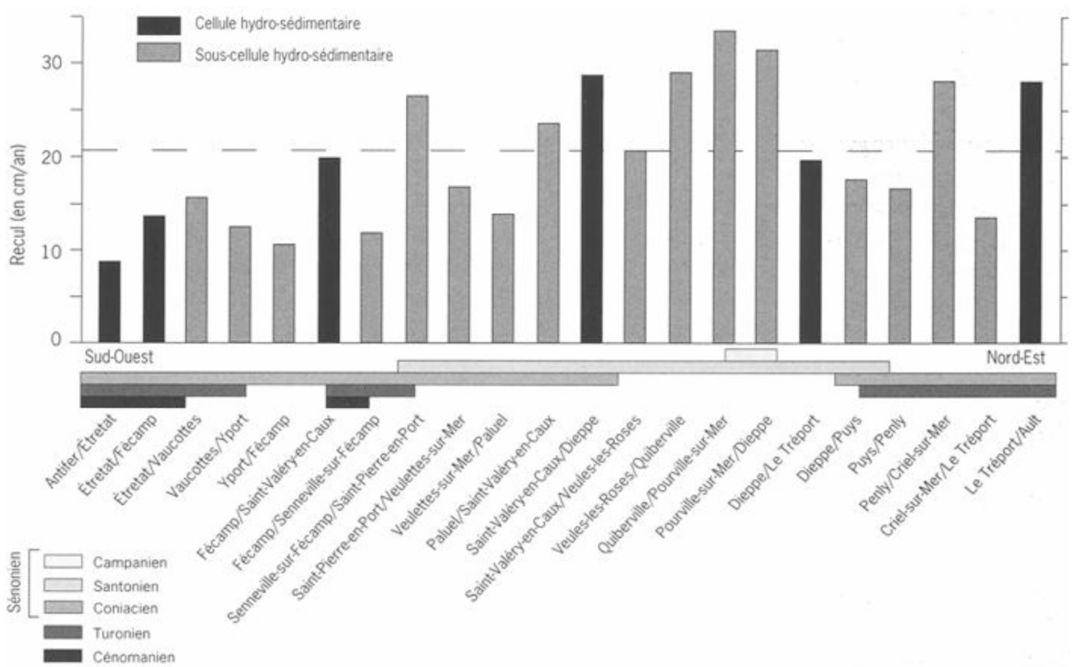


Figure 17. Cliff retreat rates by hydro-sedimentary cells (black) and sub-cells (grey). Horizontal bars inform on the stratigraphy of the chalk cliffs (Costa et al., 2000).

2.2.2- Outcome – Gravel extractions

From ages, gravel has been extracted along the shore to be used for house constructing or as road stones. These extractions remove gravels from the littoral budget and could have significant impact on the shore evolution. From the XXIst Century, this work decreased, and is now only located in strongly accreting zones. Gravel extraction on the beach itself is now restricted to manual collection for specific industrial use of the most rounded gravels (Fig. 18).

A B

Figure 18. Gravel exploitation. A. Gravel collection in the early days of the XXth century (in Bastide et al., 2010). B. Hand-made flint-stone gravel collection for industrial use. Picture: June 2010. Ancient cane baskets handled between the knees are still in use.

2.2.3- Gravel budget evolution along the shore

Gravel transit is directed eastward along the littoral of Seine-Maritime and Somme, from Antifer to Le Hourdel (Fig. 19)). Gravel budget has been estimated at the feet of the chalk cliffs and at the river mouths (LCHF, 1972; LCHF-BRGM, 1987). Except the low intake from retreating cliffs and official shingle extractions, these results allow establishing the main evolution pattern of the gravel budget along the coast (Costa, 1997). These studies suggest a generalized decrease of shingle beaches between Fécamp and Le Tréport. Several harbours and nuclear plant jetties especially disrupt the gravel transit and keep gravels on the western upstream-drift side of the jetties (Fig. 19 and 20).

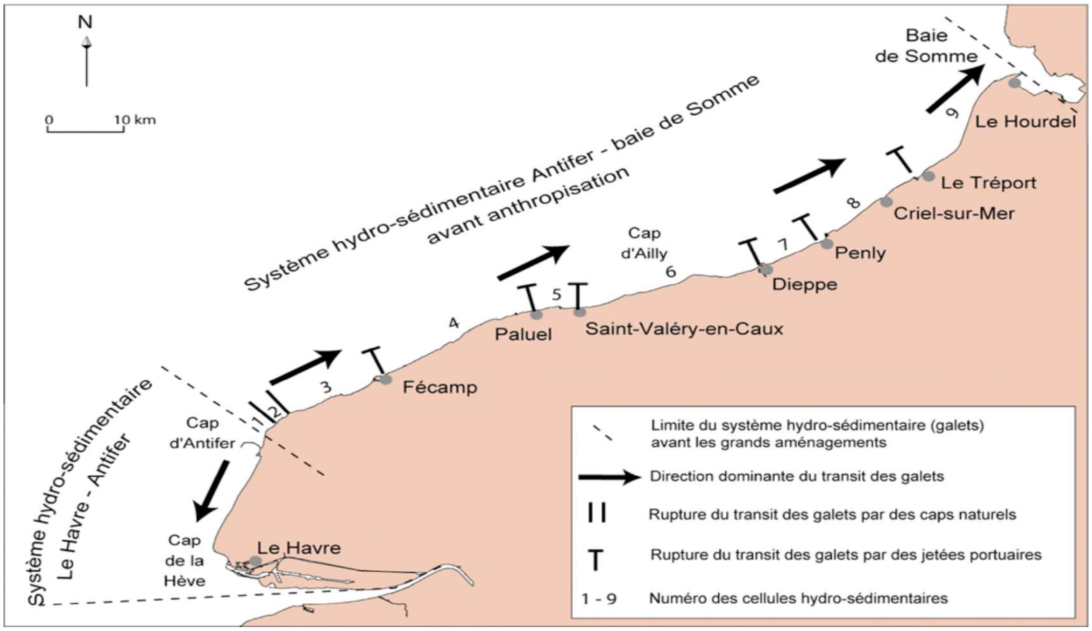


Figure 19. Direction of the resulting transit of gravels and sedimentary cells along the littoral of Seine-Maritime (Augris et al., 2004). Arrows: dominant direction of the gravel transit. Rupture in gravel transit by: (i) natural capes (double line), or (ii) harbour jetties ("T" symbol). 1-9: number of the hydro-sedimentary cells.

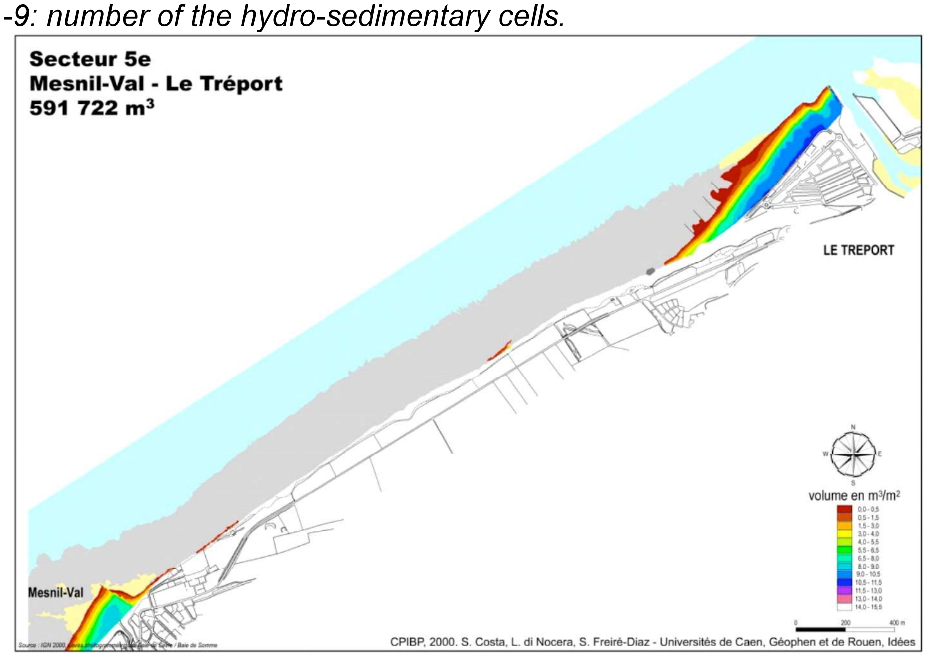


Figure 20. Volume of gravel along the shore between Mesnil-Val and Le Tréport (Costa et al., 2000).

2.3- Gravel spit migration

The gravel spit is characterised by various longitudinal dynamics, function of gradients in the littoral drift, typical of "open" spits (Orford et *al.*, 2002; Anthony, 2009). Several studies have contributed to characterize and quantify the secular to decennial dynamics of the gravel spit (Briquet, 1930; Dallery, 1955; Costa, 1997; Dolique, 1998; Costa et al., 2000; Bastide, 2011; Fig. 21). Two spots are favourable to illustrate how the sand spit is moving north. The Northern end offers a scenic point on the Bay. The other point, between Ault and the end, is located at Brighton-les-Bains. At this locality the active gravel spit is bordered by a series of ancient ridges.

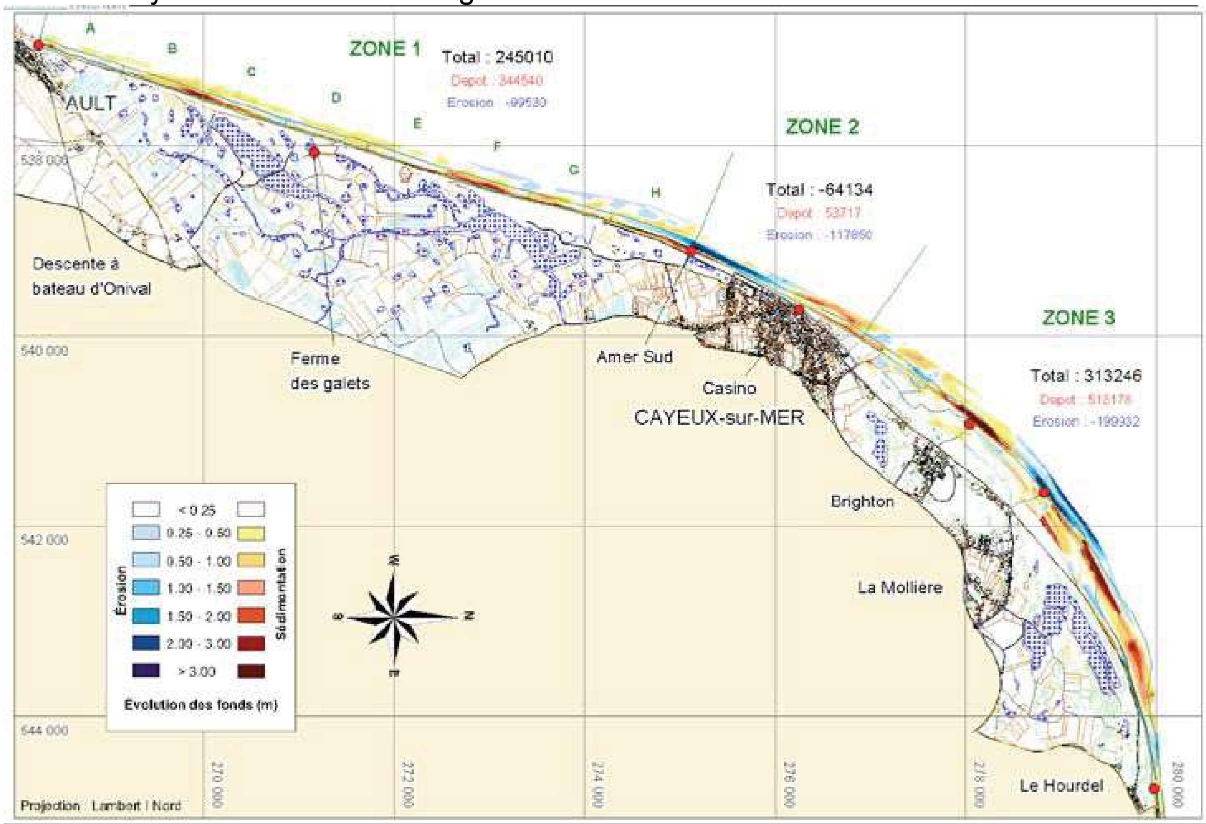


Figure 21. Volumetric balance of the gravel spit for the 05/1994 – 10/2001 period (Bastide, 2011).

2.3.1- Le Hourdel. The final spit

The end of the spit is rapidly evolving. The city of Le Hourdel moved to the coast during the XVIIIth century as some fishing vessels started to stop there, maybe due to increasing silting of the inner bay. Thanks to this occupation, many maps are available and have been compared (Fig. 22 and 23). They allow following quite accurately the evolution of the final spit. Nowadays, the spit migration is evaluated to 2 m.year^{-1}, and the gravel budget reaching the extremity of the spit is estimated to 4.000 m^3.year^{-1} (Bastide, 2011).

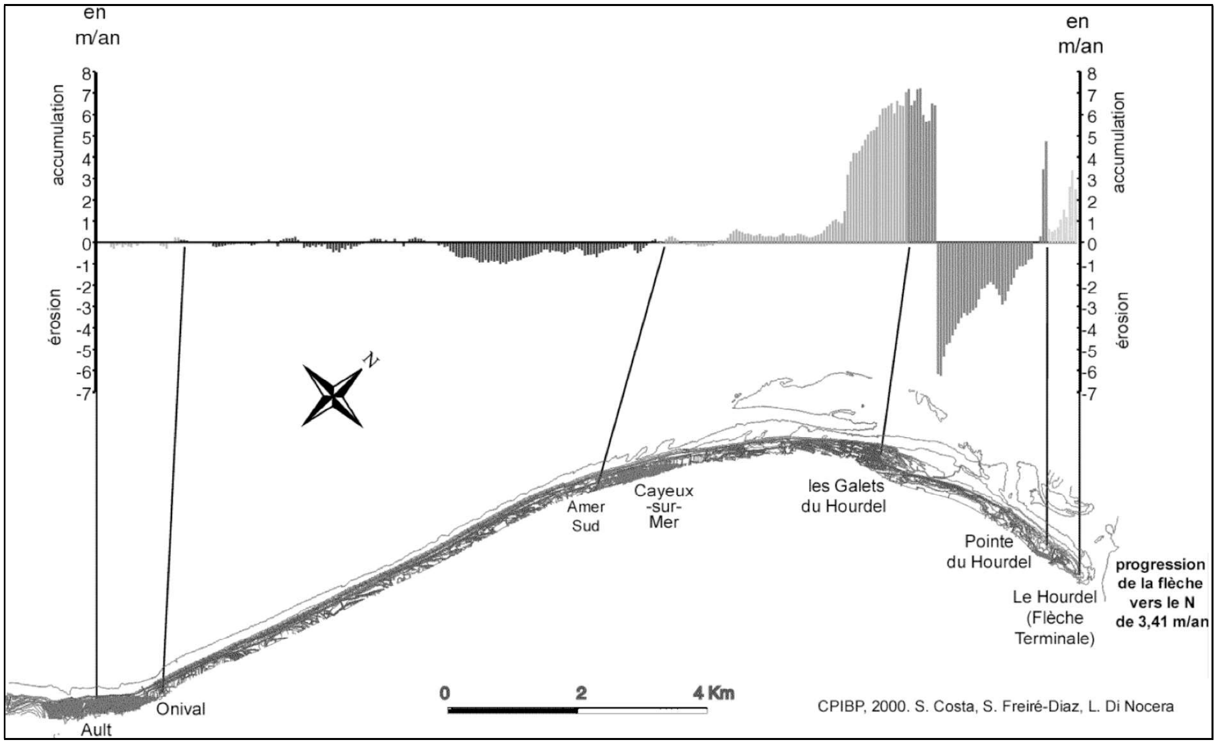


Figure 22. Coastline dynamics on the 1961-65/1999 period, between Ault and the Hourdel every 50 m (Costa et al., 2000).

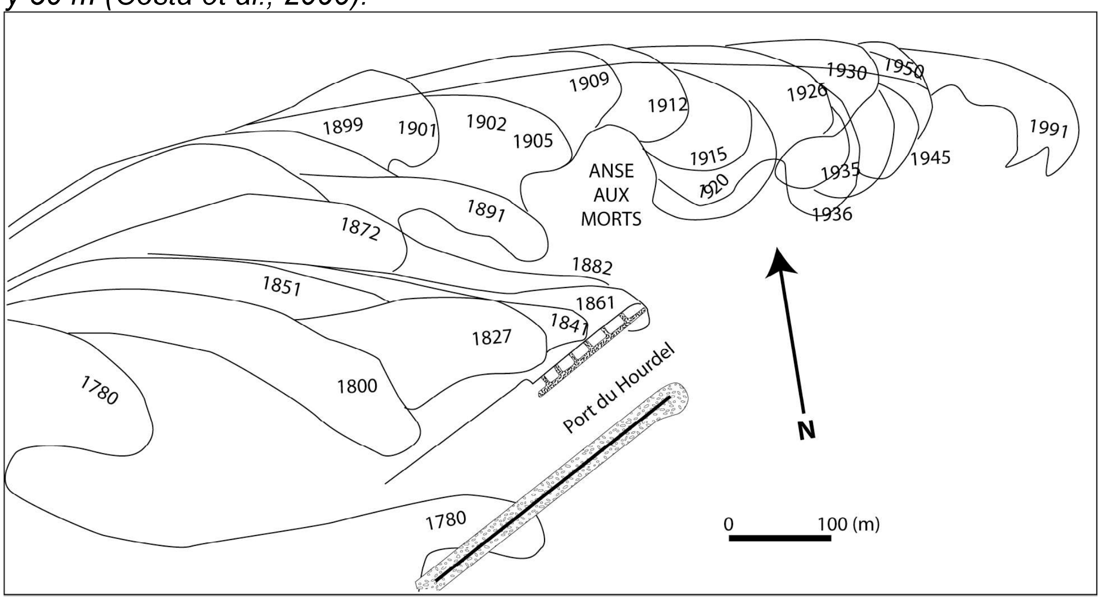


Figure 23. Two hundred years of evolution of the final spit. Work from diverse sources (Dallery, 1955 and Dolique, 1991) and partly based on photogrammetric data.

2.3.2- Brighton-les-Bains

Close to the lighthouse, a small track is perpendicular to the shore and crosses first a dune, then a series of gravel ridges. At that place, the movement of the gravel bar is exceptionally high, with advance rates reaching 120 m.year^{-1} (Fig. 24; SOGREAH, 2005).
Different geomorphologic features allow understanding the evolution of the gravel spit in a context of high gravel income: hooks, overwash deposits, silting in the runnel, dune installation, plant evolution… A cross-section illustrates how this place evolved recently (Fig. 25).

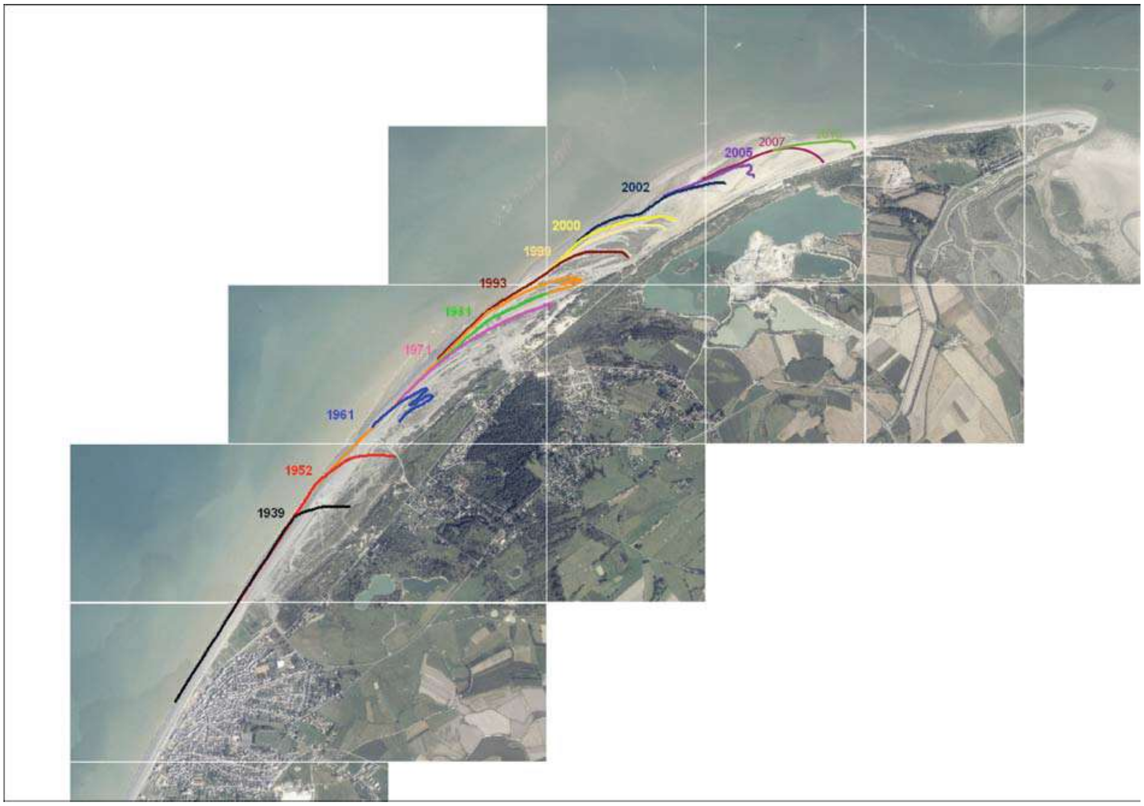


Figure 24. Evolution of the gravel spit North of Cayeux-sur-Mer between La Mollière and Le Hourdel between 1939 and 2005 (SOGREAH, 2005, Bastide, 2011). Aerial photograph © ORTHOLITTORALE 2000

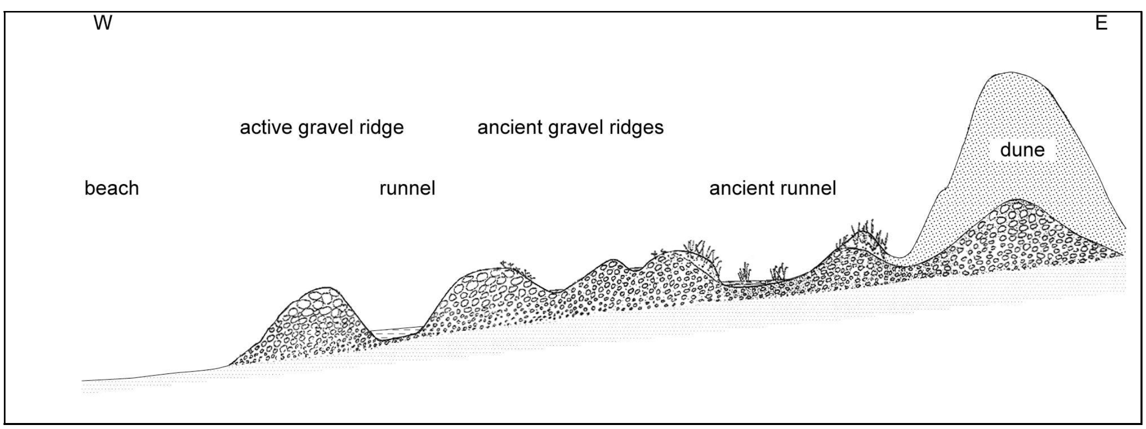


Figure 25. Cross-section around the Brighton lighthouse. (From Wiber, 1980)

2.3.3- Gravel migration rates

Even if the final position of the spit allows evaluating a NE-prograding velocity, the movement of individual gravel is still poorly known. This is however important for management reasons, especially in low-budget areas such as South from Cayeux-sur-Mer. Different experiments were conducted along the shore to measure the current and wave fields and to follow individual gravels (Fig. 26).

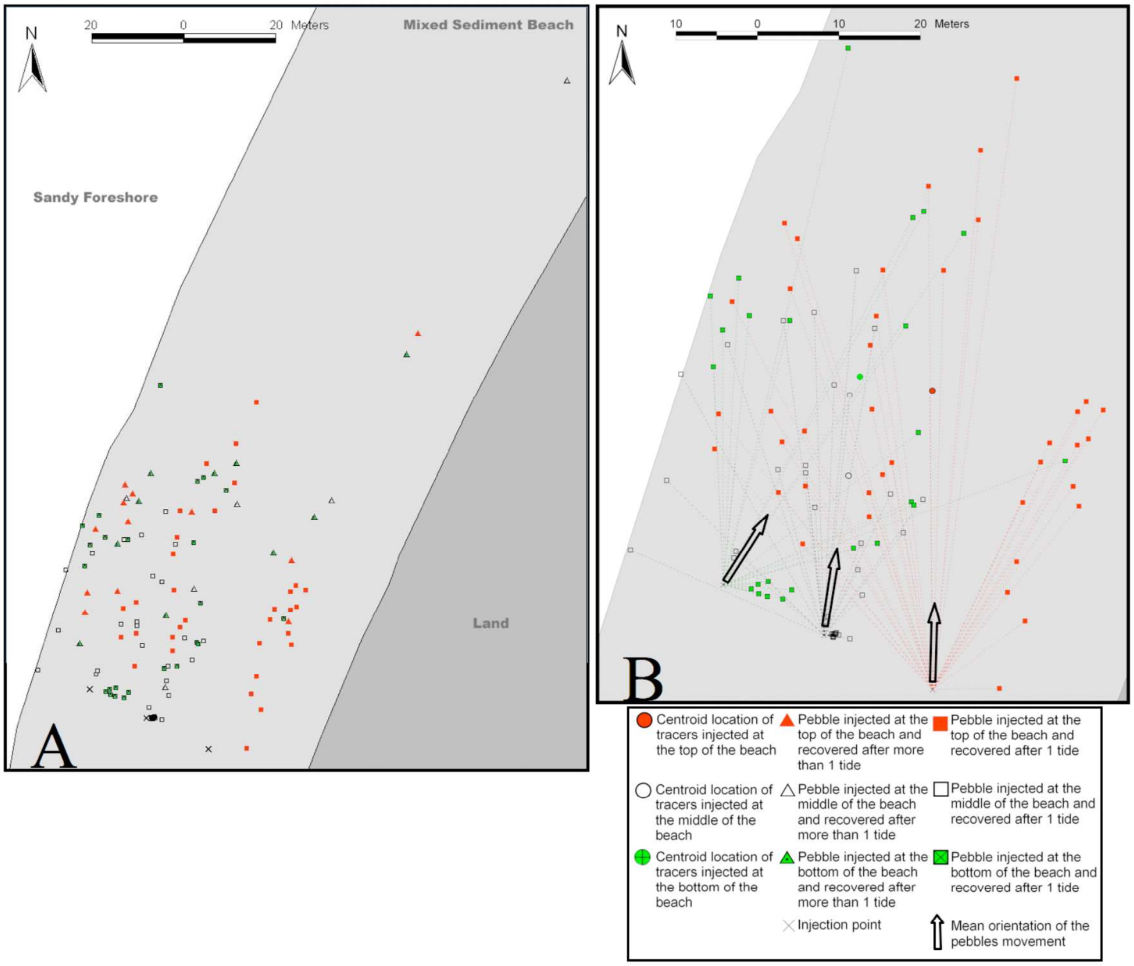


Figure 26. Movement of tracer pebbles deployed on the 8th of November 2005 close to the city of Cayeux-sur-Mer. A. Scattering observed over the whole survey period. B. Scattering observed after one tide (J. Curoy et al., U. Sussex, personal communication).

For this experiments it can be noticed that the movement of pebbles depends on their location at different levels of the bar. Material coming from the upper part tends to migrate seaward and further downdrift than the other parts of the beach. This is interpreted as linked to a continuous swash action from the high tide to the low tide (Curoy et al., U. Sussex, Pers. Comm.). Pebbles from the lower beach migrate upward, although alongshore transportation dominates. It is suggested that these movements are explained by the combined effect of groundwater flow, swash flow and breaking-wave action. Pebbles from the middle part of the beach move hanks to the same processes, but tend to migrate down the beach. For all situations, the alongshore drift is significantly greater than cross-shore movements.

2.4- Human impacts related to the gravel spit evolution

The gravel spit constitutes a natural protection against submersion for the polders of the 'Bas-Champs'. Part of its recent evolution seems to be strongly linked to human impacts along the shore both at the source of the gravel bar, and along its way North. Around Onival, a resort station developed in the early 1900's (Fig. 27). A casino was built on a natural riprap at the foot of the cliff (Fig. 28). This cliff was then eroded following the general cliff retreat characterizing the Normandy coast and the casino disappeared.

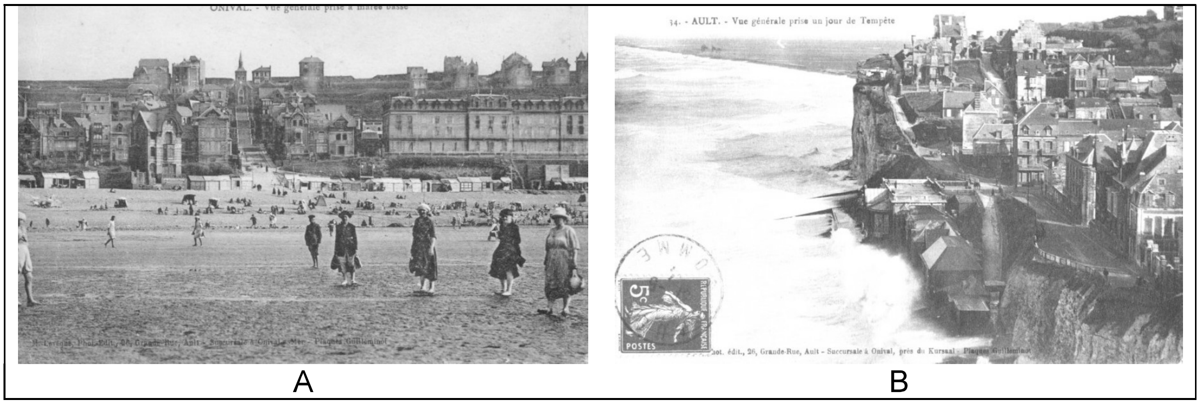


Figure 27. Two postcards from the early 1900's. A. The beach of Onival. The church and some houses are still visible. B. The cliff at Ault. The casino 'on the beach' and most of the front-row houses have been destroyed.

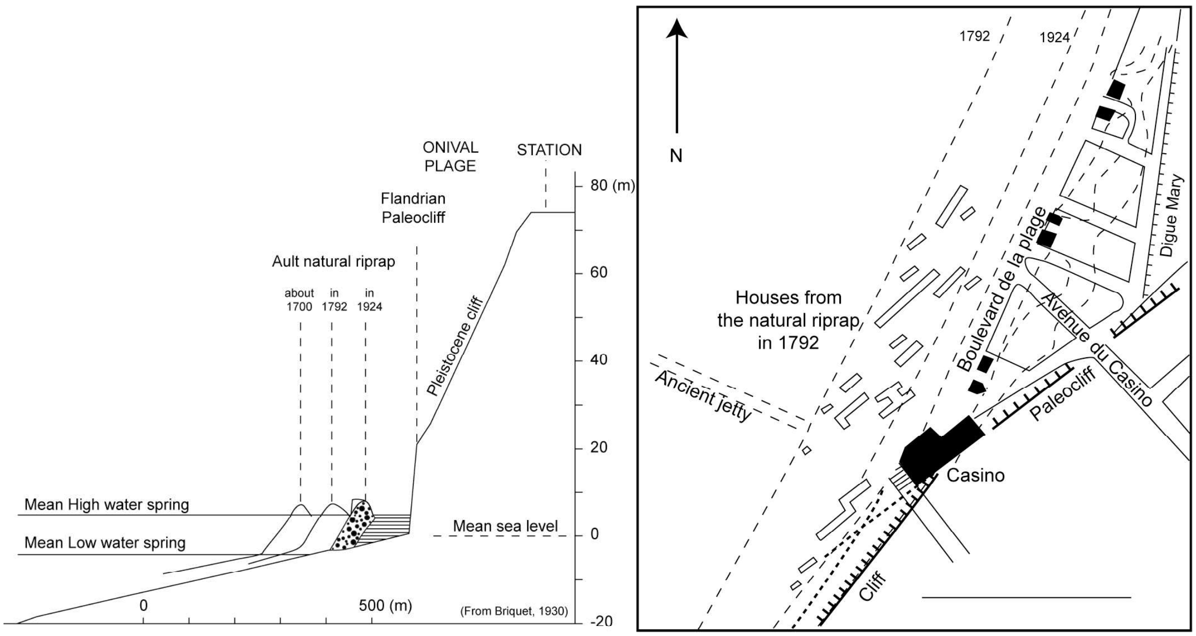


Figure 28. In the 30's, there was still a platform at the foot of the Flandreau cliff at the foot of which a casino was present. A gravel bar acting like a natural riprap protected this platform. (Drawing adapted from Briquet, 1930). The drawing indicates a series of houses on this platform and indicates they were still present in 1792. Some papers indicate that they were destroyed during a severe storm in 1579 or 1583. There is also an ancient map from 1667 displaying windmills and houses.

From 1835, different series of groynes were installed at the foot of the cliff, but also along the spit to limit the gravel drift and help protecting the shore (See e.g. Dallery, 1955, and later works).

At some places, such as Onival, heavy solutions were decided and built between 1981 and 1986 (DREAL, 2011) to protect the cliff from sea undermining, but also aerial erosion due to continental-water seepage (Fig. 29).

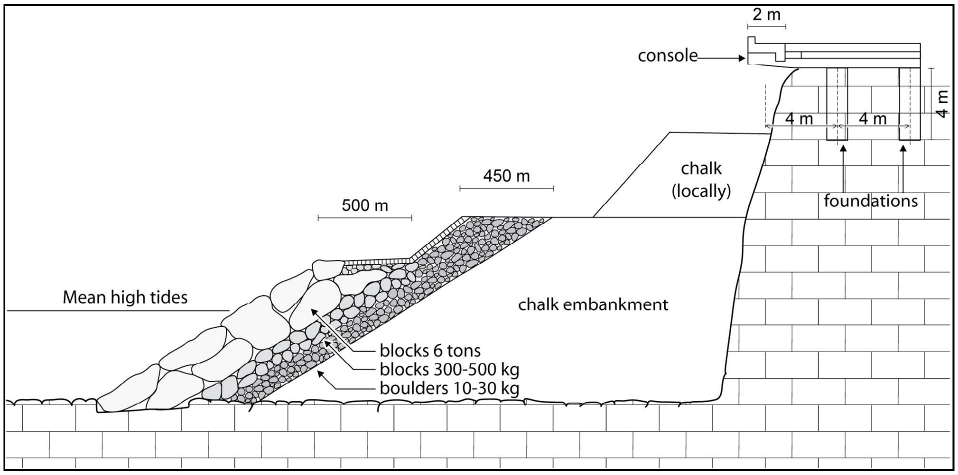


Figure 29. Last coastal defence built in the 70's and regularly maintained at Onival. DDE document.

The decrease of the gravel budget, observed since 2 centuries, has lead to the erosion of the spit in some places (e.g. Cayeux) (Costa, 1997; Costa et al., 2000). The gravel spit has been strongly comforted by groynes and spikes at the beginning of the 80's between Ault and Le Cayeux, in order to limit spit erosion and protect the area of the Bas-Champs from marine submersion. In strong relation with human constructions, the gravel spit can be divided in 3 sectors displaying a contrasted dynamics, from its proximal area, close to the gravel source to its distal area at the entrance of the Somme Bay: (1) the sector between Ault-Onival and the South of Cayeux-sur-Mer, with 83 spikes, built to trap the gravels, in response to an important erosion (0.1 to 1.8 $m.yr^{-1}$ on the 1800-1991 period; Dolique 1998), (2) the sector of Cayeux-sur-Mer, in erosion, where frequent nourishments are conducted to avoid spit rupture and make possible an artificial gravel transit, and (3) the sector of Brighton-Le Hourdel, in progradation (150 m between 1780 and 1930; Briquet, 1930), where gravel extractions are still active (e.g. 'Silmer' and 'Delarue' concessions).

3- Intertidal sedimentation

In the bay of Somme, the sedimentation is driven by sediment budget, strongly linked to sea level rise and, much later, human influence. Modern intertidal sedimentation can only be seen on a quite limited area compared to the ancient size of the Bay of Somme. This is due to long-term continuous infill of the estuary as for many estuaries along the English Channel (Tessier et al., 2011). Land reclamations (embankments, polders) reinforce the natural accretion process (Bastide, 2011). The infilling then leads to important modifications of environment uses (e.g. fisheries, navigation).

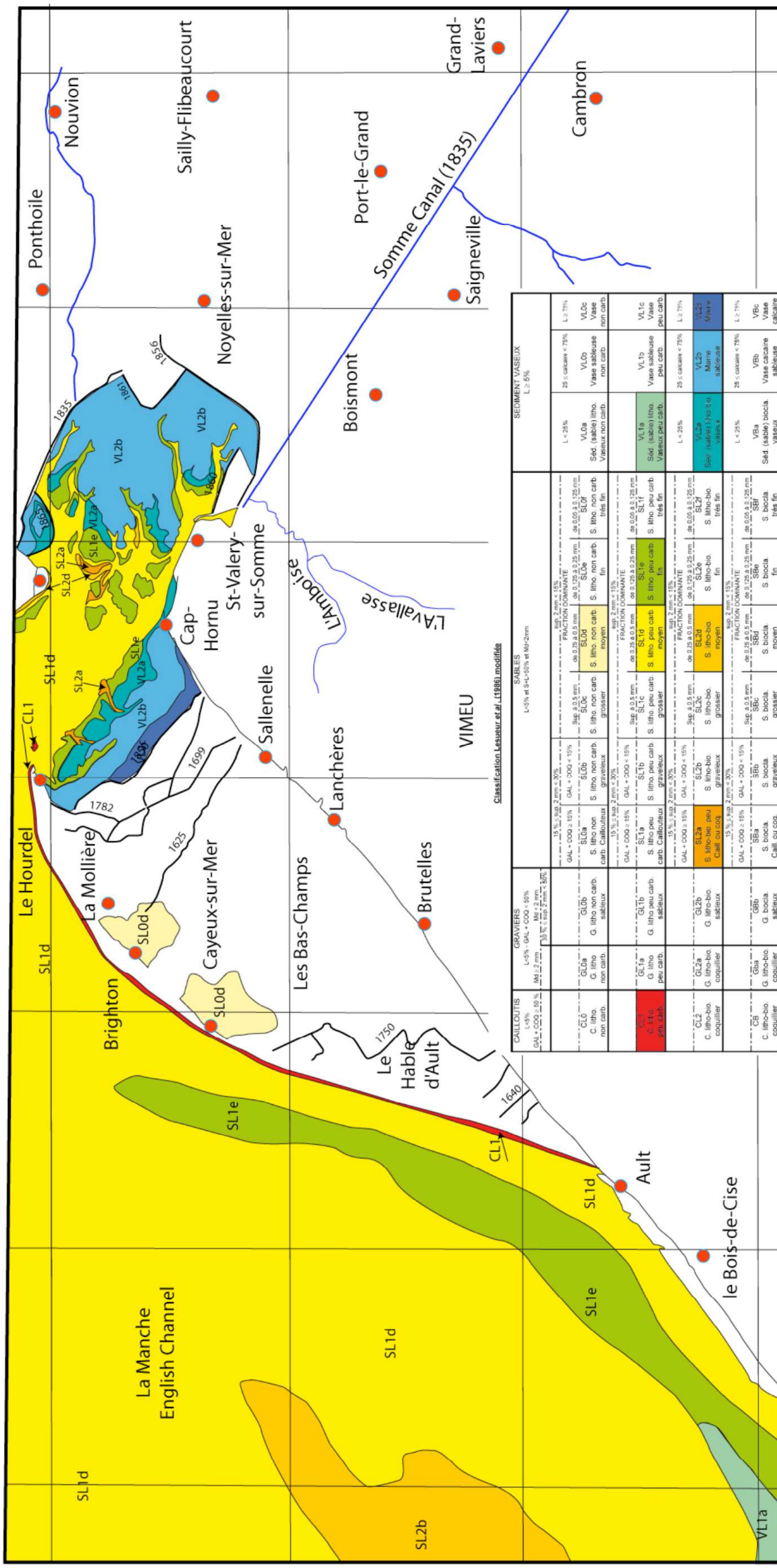
3.1- Modern sedimentation

Recent sedimentation has been intensively studied in the 80's (e.g. Dupont and Homeril, 1980), but then the attention decreased replaced by management-oriented studies due to the high vulnerability of the coast (see sections 5).

The Somme estuary is macrotidal, but wave-dominated due to high energy wave conditions, the resulting strong littoral drift leading to the development of the gravel spit

(see part 2). The Somme Bay (Fig. 30) is almost exclusively filled with sands of marine origin (Dupont, 1981) and bioclasts from endemic benthic production (Desprez et al., 1998). Sedimentation rate in the Somme estuary is about 700 000 $m^3.yr^{-1}$ corresponding to a mean seabed elevation between 1.3 and 1.8 $cm.yr^{-1}$ (Verger, 2005; Bastide, 2011). These rates are similar to those recorded in the Authie estuary tens km further North (0.71-1.6 $cm.yr^{-1}$; Marion, 2007).
Dupont summarized the influence of tides and waves on the sedimentation in the Bay (1981). Tidal currents are responsible for the formation of an ebb delta protecting the inner estuary (Figs 31 and 32). Fine sands penetrate the estuary as sandy layers associated to flood-channelized currents. Flood dominance favours the infill pattern and the construction of sandy bodies at high topographic levels. Waves contribute to the protection of the internal estuarine domains by edifying littoral spits and swash bars at high altitudes. In internal estuarine domains, decantation of suspended sediment operates on the rapidly prograding salt marshes (schorres; Fig. 33), but also on the mixed flats (slikke) in sheltered areas (e.g. Mollières d'Aval to the South). In the estuary, a grain size fining trend is observed from open-sea sites to sheltered sites, due to various exposure degrees to tide and wave action. This is shown in the sedimentation in *Spartina* and *Halimione* communities observed on the low marsh (between slikke and schorre) flooded by mean tides and on the mid-marsh flooded by spring tides for 3 different sites in the Bay (Le Bot et al., 2012).
At Le Hourdel, intertidal modern sedimentation can be seen on both inner and outer estuary sides (Fig. 33). On the seaward side, small to medium dunes (Fig. 34) cover the intertidal areas, while south-eastward, fine sedimentation occurs. The total energy rapidly decreases and is at the origin of most of the fine sedimentation.

Figure 30. Surface sediments based on their grain-size and $CaCO_3$ content. Data from BRGM, 1985. Classification according to Larsonneur et al., 1978. From left to right, the mean gain-size decreases. From top to bottom, the $CaCO_3$ content increases. CL1 (red): lithoclastic gravels. SL2a (dark orange): litho- and bio-clastic sand bearing between 15 and 30% of gravels. SL2d (orange): litho- and bio-clastic medium sand. SL1d (dark yellow): lithoclastic medium sand poor in carbonate. SL0d (pale yellow): lithoclastic medium sand free of carbonate. SL1e (yellowish green): lithoclastic fine sand poor in carbonate. VL1a (green): muddy lithoclastic sand poor in carbonate. VL2a (blue green): muddy litho- and bio-clastic sand. VL2b (blue): sandy marl. VL2b: marl.


La Manche
English Channel
Le Hourdel
La Mollière
Cayeux-sur-Mer
Brighton
Les Bas-Champs
Le Hable d'Ault
Ault
le Bois-de-Cise
Brutelles
Lanchères
Sallenelle
Cap-Hornu
St-Valery-sur-Somme
L'Amboise
L'Avalasse
VIMEU
Boismont
Port-le-Grand
Somme Canal (1835)
Saigneville
Noyelles-sur-Mer
Ponthoile
Nouvion
Sailly-Flibeaucourt
Cambron
Grand-Laviers
SL1d
SL1e
SL2b
VL1a
SL0d
CL1
SL2a
SL2d
VL2a
VL2b
1640
1750
1625
1782
1699
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Classification Lesueur et al. (1986) modifiée

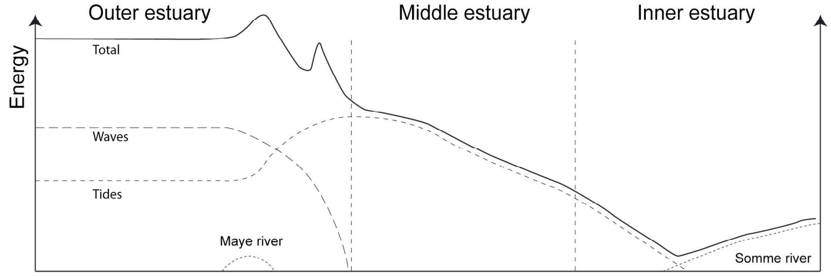


Figure 31. Energy diagram in the Bay of Somme. Partly from Dolique, 1998. This figure can be compared with fig. 32.

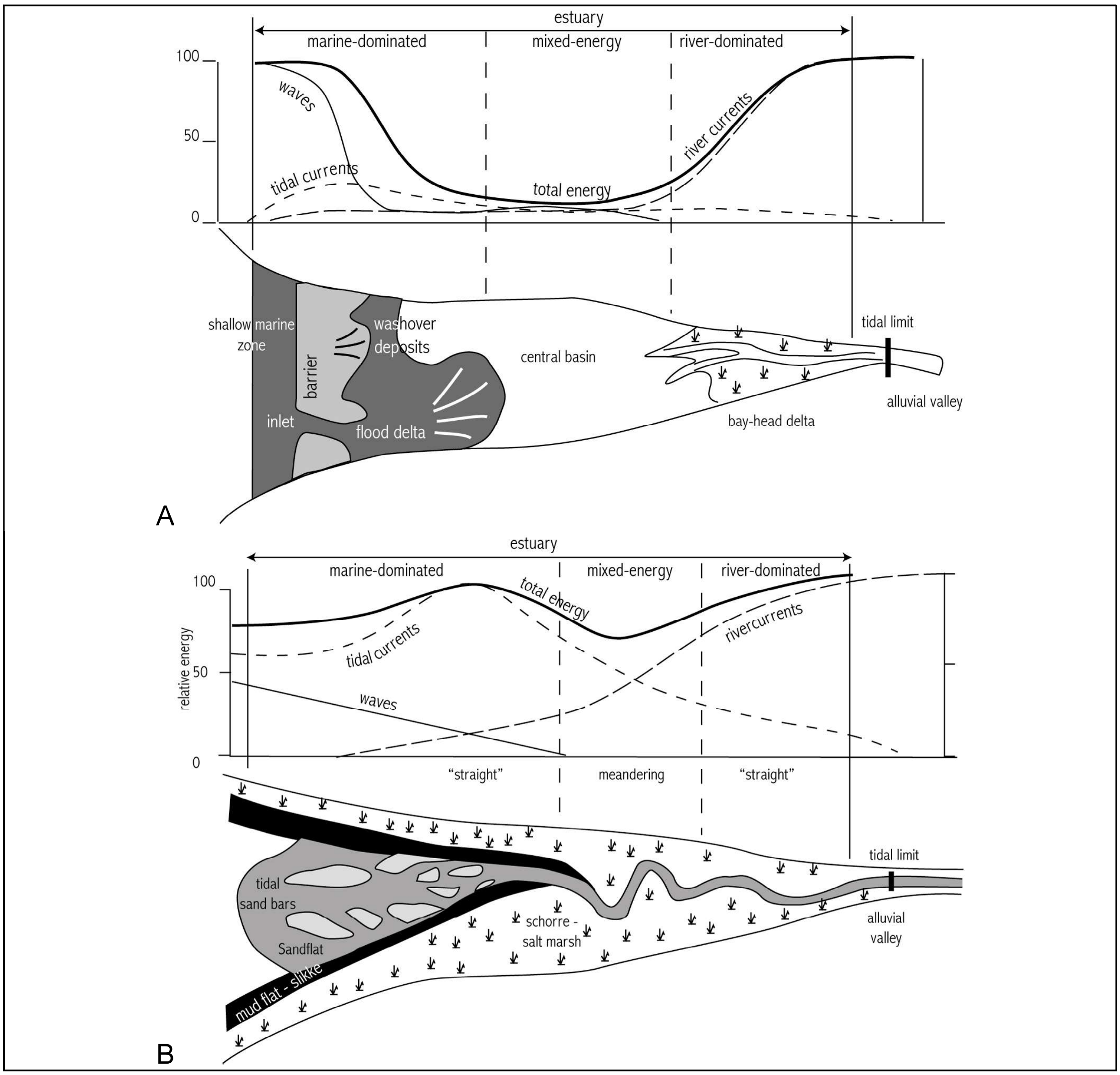


Figure 32. Distribution of energy types and morphological components of an idealised A) wave-dominated, and B) tide-dominated estuary (From Dalrymple et al., 1992).

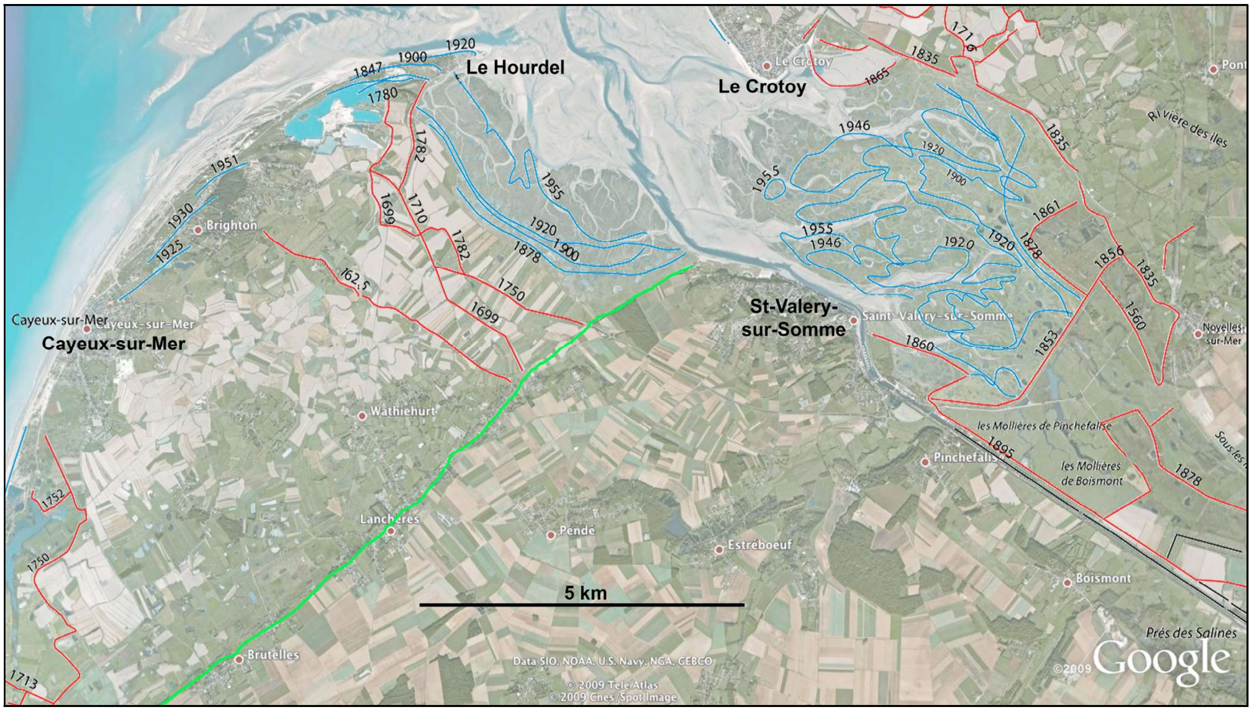


Figure 33. Central part of the Bay of Somme. In red, dated dykes. In blue, vegetated area evolution. In green, Paleocliff. In black, Abbeville-St-Valery-sur-Somme canal. Base map: Google Earth. Image date: Dec. 2007.

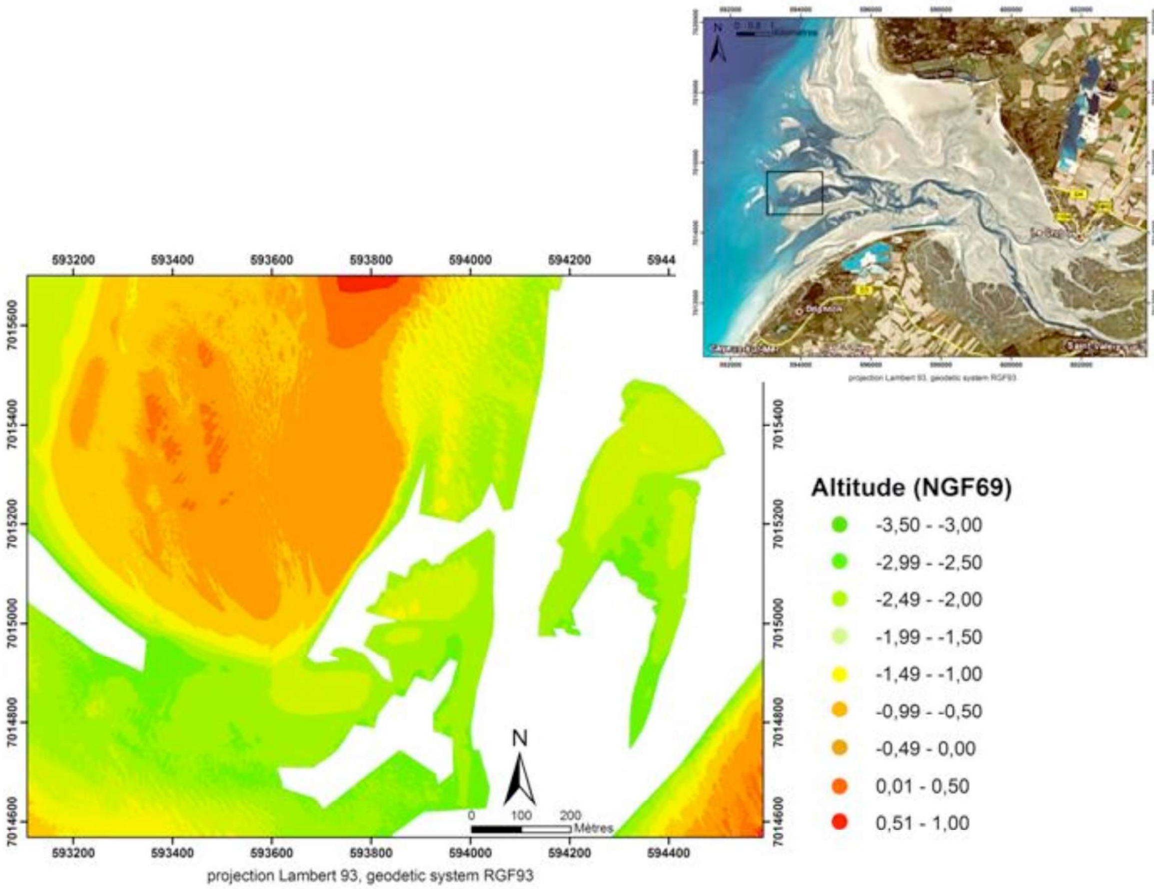


Figure 34. Topography of the channel area, in the external part of the Bay. DTM from LIDAR data (data source: operational team CLAREC, CNRS-UCBN, 28 September 2011). Up, right picture from Google Maps.

3-2. Long-term evolution

A series of coring were done in the Bas-champs allowing reconstructing the shore movements from 7 500 BP (Fig. 35).

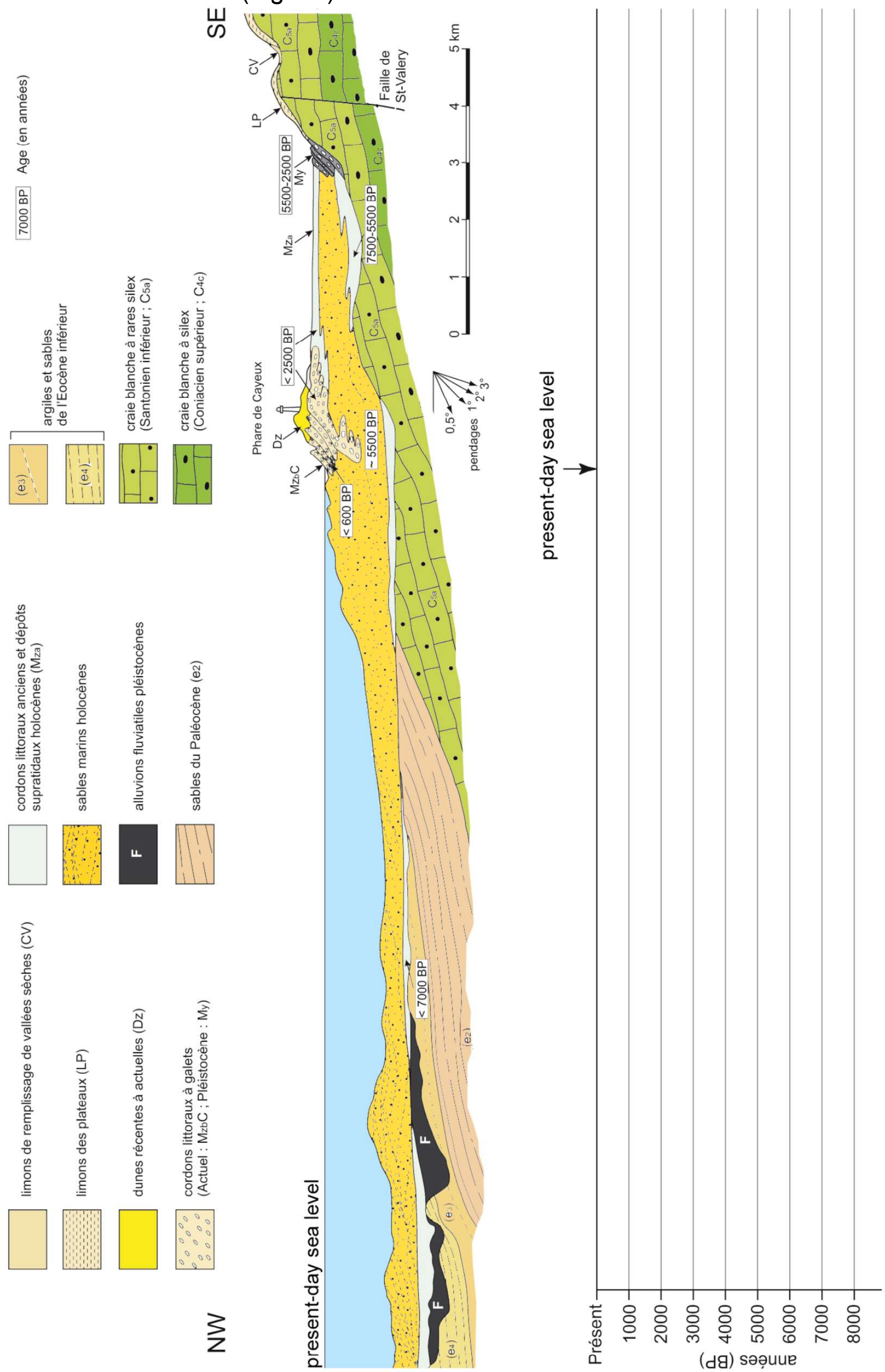


Figure 35. Cross section of the Bas-champs by the Cayeux lighthouse (BRGM, 1985).

3.3- Man-influenced coastal evolution

From the Middle Ages, for agriculture needs, man influenced the evolution of the coast in building embankments on the upper intertidal zone. This was done all along the Picardy coastal plain (Fig. 36), deeply modifying the landscape, closing the smallest estuaries. Works have been attested from the XIIth century in the bay of Authie, while in the bay of Somme the earliest embankments are from the mid XVIIth century. In the left bank of bay of Somme, thanks to continuing silting up, embankments were done in the southernmost part of the bay, and on its northern part on both side of a line linking Cayeux-sur-Mer to the paleocliff (Fig. 37). To the South, the objective was to reclaim the Hable d'Ault, a former estuary that regularly opened through ages. To the North, the embankments followed the gravel-spit evolution in its way North. On the right bank of the Somme embankments also occurred between St Valery-sur-Mer and Le Crotoy, but also around the Maye river (Fig. 36).

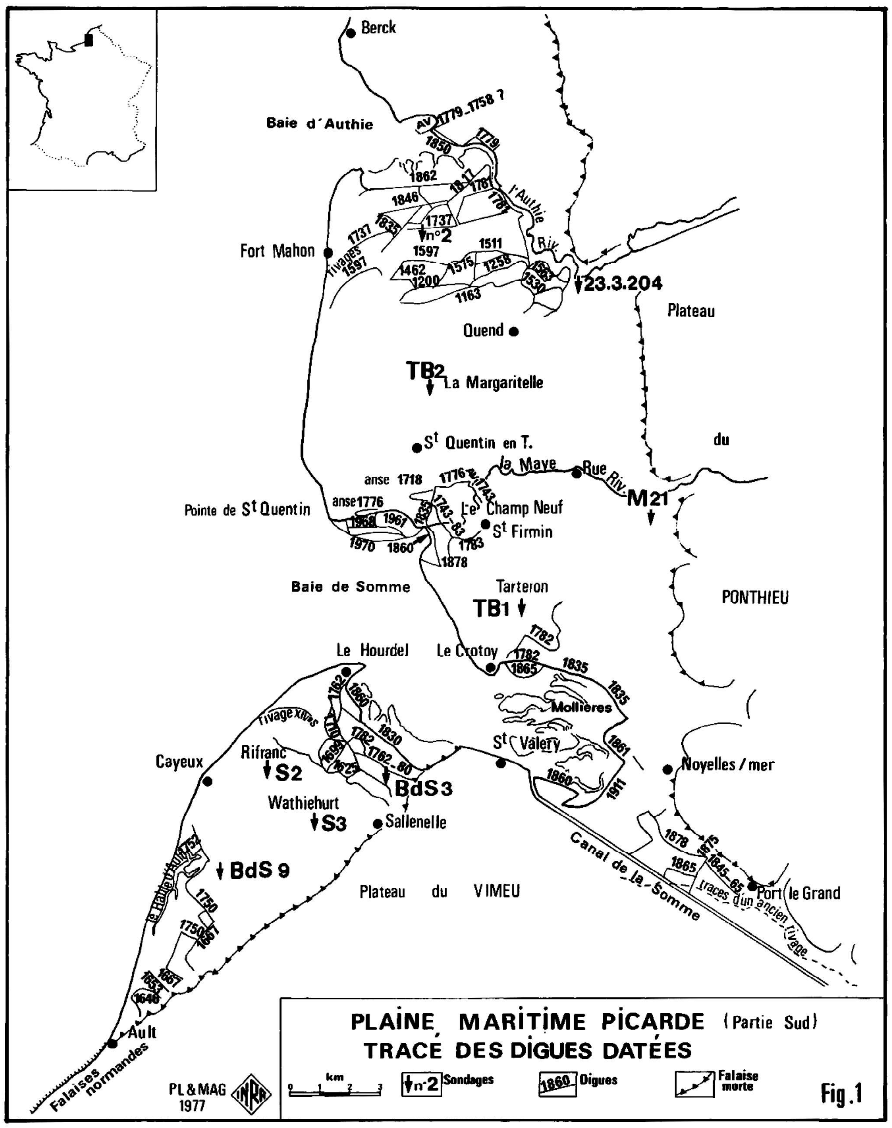


Figure 36. Embankment evolution in the Southern Picardy coastal plain (Lefevre, 1977).

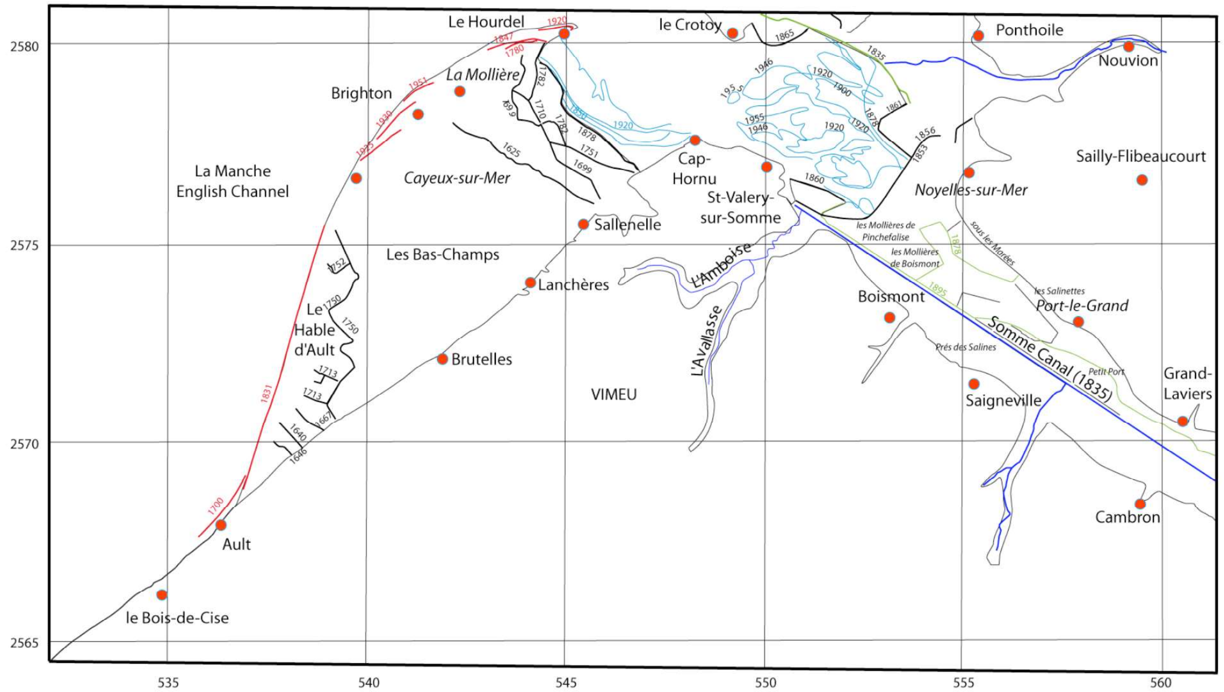


Figure 37. Significant lines indicative of shore evolution. In red, gravel spit location. In blue, shorre/slikke limit with dates, in black, main embankments. In italics, some villages or locations have been distinguished to illustrate a former maritime influence, e.g. Port-le-Grand (large harbour), les-Salinettes or Prés-des-Salines that refer to salt occurrences.

4– Ante-Holocene gravel spit evidences

Fossil gravel spits outcrop on the Northern side of the Somme. They correspond to a series of small hills clearly visible in the topography. These relative elevations have often been chosen to establish some cities from Gallo-Roman time (Gosselet, 1906). The city of Rue was an important trade city in the Middle Ages. The sea was still along its walls in the XIIth century. From the XVth Century largest vessel were not able to reach the harbour that disappeared during the XVIIth Century.

The gravel relief were especially visible prior to the gravel extraction (Fig. 38) as on modern maps these 10-metres high hills have been transformed either on quarries or in recreation lakes after exploitation. Cities of Quend or Rue are still on these remaining hills.

Figure 38. Topographical map drawn from the IGN 1:80 000 map. Recognition of dated element such as sea walls and groins indicate that the map could have been surveyed between the XIXth and XXth century. Geological information has been overlain from the geological map (BRGM, 1981). In blue, My: Rue Formation (Gravels) in beige: hillslope and underlying terrains. It combines CLP: hillslope loams, LPS: sandy-clayish red loams bearing flint pebbles, and C4C: White Chalk with flint of Upper Coniacian age not detailed on this figure.

The gravel spit rests on a white chalk (craie) marine abrasion platform (Fig. 39). Some reliefs seem to characterize the surface of the platform. Diverse interpretations have been proposed to explain the changes in altitude and in orientation of these gravel spits. The presence of faults or flexure is mostly accepted, but some erosive processes could be evocated.

The maximum altitude is at +13 m NGF with a water level at about +4 m NGF. The base of the gravel spit close to -8m NGF.

The sediment is composed of quartz sand and flint gravels. Cretaceous fossils are seldom observed as gravels. Exotic rocks such as diorites, pink granites, metamorphic rocks or sedimentary rocks can be observed. Up to 4 m wide blocks of Tertiary sandstones can be found in the lowermost intervals. It is thought that these last elements were transported on ice rafts during ice breaking up. Other exotic rocks are similar to some observed along the coast of Brittany (further South) or Boulonnais (to the North) (Petit, 1959). The gravel deposits are free of shells (Briquet, 1930), probably due to decalcification processes.

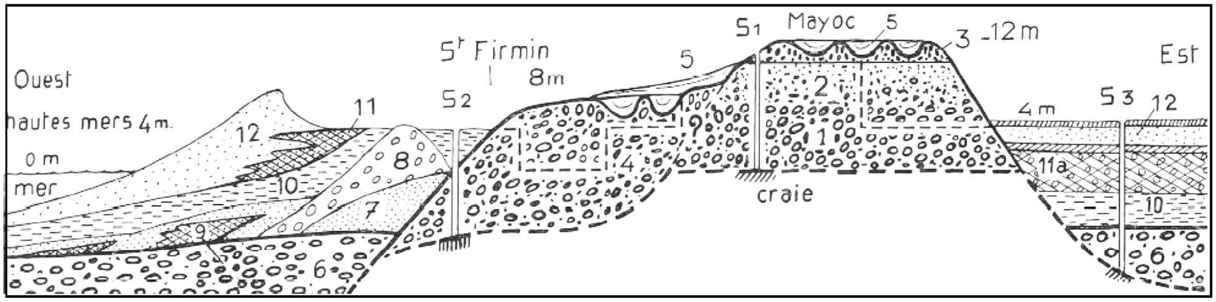


Figure 39. Cross section in the Northern end of the Le-Crotoy gravel bar. This interpretation proposes a multiphase setting for the bank and separates the group in two (St Firmin and Mayoc) individual bars (Agache et al., 1963).

Pebbles are usually organised in horizontal or slightly (2 to 5°) SE-ward dipping beds (Fig. 40-A). Stratification is made of an alternation or more or less sandy intervals. The uppermost part of the spits consists in finer sediment and often present some evidences of cryoturbation such a loem-filled ice wedges (Fig. 40-B).

A B

Figure 40. Typical views of the fossil gravel bar at Oscar Savreux quarry. A. Layering in the Pleistocene gravel spit. B. Loem-filled ice wedge at the top of the gravel formation. Total thickness of this picture is about 2 m.

Further west, some miles offshore Dieppe, ancient gravel spit (16 km long, 4 km wide) is also observed (Claveleau, 2007). It is made of 3 sediment bodies; each one composed of several prograding units and is interpreted as being of Pleistocene age. Its geometry is similar to what is observed in the quarries.

5– Environmental considerations

The low-lying area back from the gravel spit is fragile. Despite many attempts to consolidate it by gravel imports or groyne constructions from late XIXth century, some places are often subject to breaches that lead to land inundations (Fig. 41). On this picture, four successive submersions are distinguished.

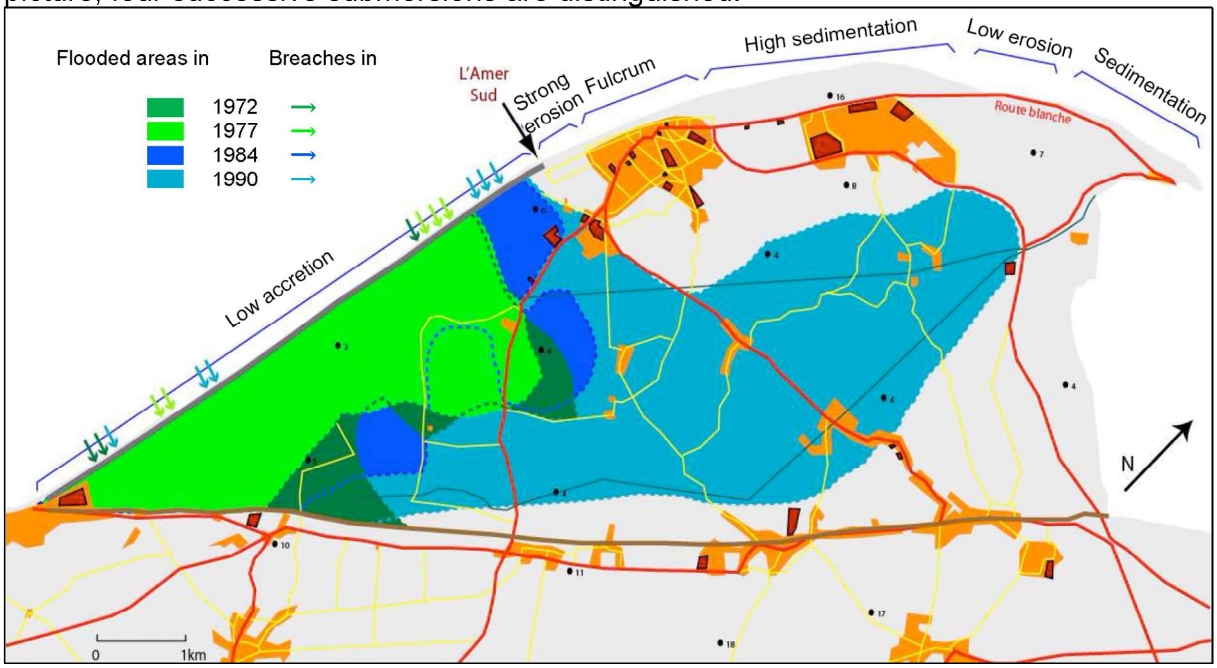


Figure 41. The Bas-champs of Picardy. Areas that were submerged by floods in 1972, 1977, 1984, and 1990 (Carel, 2009). The data used by Carel are from Costa, 1997, Dolique, 2004, and Creocean, 2005.

Many issues deal with the gravel budget along the spit. To help protecting the shore a lorry noria feed the gravel spit at its weakest positions, between groynes and at the Amer-Sud. Gravels are taken either from the final spit or from local quarries.

The other problem that the Somme bay has to face with is the continuous silting up. It leads to strong reduction of the intertidal zone (Fig. 42-A) and reduces the possibilities for boats to join their harbour. Biggest one moved to further deepest harbour out of the Bay, while being replaced by smaller units and recreation vessels. One possibility to reduce sedimentation and leave an open access to harbour is to re-open ancient reclaimed areas locally called polders as in the Netherlands. This is the case close to the final spit in the Ferme-de-la-Caroline polder (Fig. 42-A). In opening this area, and removing a huge amount of sediment, one can expect, on a very long-term basis, to recreate a more open area and maintain the access to Le Hourdel harbour (Fig. 42-B). In this configuration, dykes would be consolidated to protect the population.

Such a scenario could be difficult to accept for a population that continuously increased its acquisition of intertidal areas but is encouraged by most local authorities. A second project of reclaimed-area reopening is planned to the South at Le Hable d'Ault, as continuous gravel-spit feeding is too expensive compared to the local possibilities. This gravel spit was definitely closed in 1752 by a gravel dyke, the Digue-du-grand-barrement, but is often submerged and need to be repaired. A politic of controlled of the coastline could be more economic than a politic of strict maintenance, but is sometimes facing local lobbies.

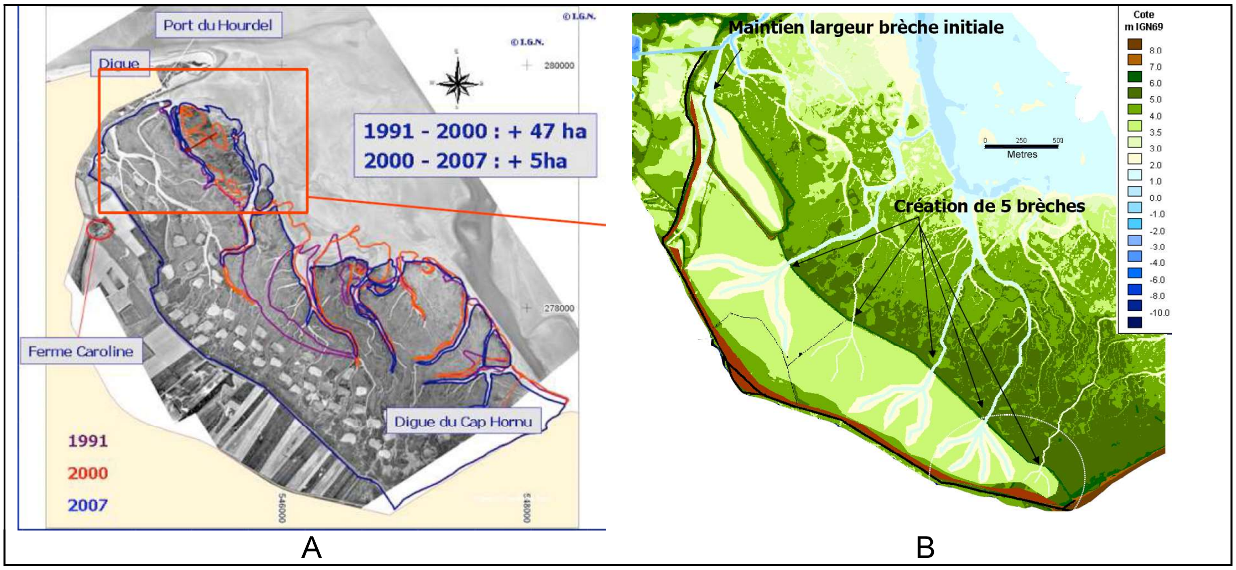


Figure 42. A. Evolution of the intertidal zone close to the harbour of Le Hourdel between 1991 and 2007. Lines correspond to the altitude of 4.1 m. they mark the limit between the vegetated schorre (salt marshes) and the non-vegetated slikke (mixed-flats). B. Digital terrain model on a very long-term basis after opening the Caroline farm polder to the North, and the possibility to open 5 new breaches.

During this excursion, we'll visit an area on the other side of the bay, close to Le Crotoy. A 50 ha basin has been opened to the sea to flush the sediment that is silting up in the harbour. Despite a certain efficiency to maintain water in the harbour very high sedimentation rate occurs in the basin that need to be often dredged. On average, 30 m^3 are deposited at each tide and more than one million m^3 were dredged between 1973 and 1982. In 1993, 800 000 extra m^3 were dredged again (Dupont et al., 1993).

6– Marine geology

Offshore the Somme Bay, the coarse seabed of the Eastern English Channel is covered with a thick cover made of a sand and gravels mixture. Its construction results from the Holocene transgression (Auffret *et al.*, 1980; Dewez, 1988). This wedge is moulded by a series of tidal sand-banks, generally covered with dunes. Tidal sandbanks are parallel to the coast, although some tend to connect the shallow area when the orientation of the coastline suddenly changes in the surroundings of Ault and the gravel spit (Figs. 43 and 45). Very large dunes display heights between 4 and 10.5 m and wavelengths between 250 and 1800 m (Ferret et al., 2010; Ferret, 2011; Fig. 44). Dune migration rate is not very high, varying between 0.8 ± 0.25 $m.yr^{-1}$and 6.6 ± 0.7 $m.yr^{-1}$. Sediment transport and dune residual movements are toward the East, in the direction of the dominant flood, but small waves may reverse sediment transport direction to the West and slow down (and even reverse) dune migration. Sediments of the sedimentary wedge of Picardy partly supply the Somme Bay, even though fluxes and budgets are not yet known.

The area is also characterized by a well-developed paleovalley system (Fig. 44) that drained main rivers and the now coastal rivers. A complete network was first drawn by Auffret et al. (1980) and was refined in its shape (Auffret & Alduc, 1982), in its stratigraphy (e.g. Lericolais et al., 2003) or in the history of its origin (Gupta et al., 2007).

Recently shot seismic profiles offer the possibility to describe the architecture of coastal tidal sand banks, but also to reconstruct the paleochannel network in an area that is close to the coast, where seismic profiling is less efficient due to rapid income of the first multiple (Fig. 46, 47, and 48; Trentesaux et al., 2011). Careful analyses of the 200m-spaced profiles allow defining a series of surfaces mostly dipping offshore and sometimes incised by ancient small or larger streams. The Somme paleovalley is well expressed in the South of the study area, while, in the North a strange meandering channel occurs (Fig. 49). This valley is not in front of the Authie River at its present-day location, but could correspond to an ancient stream combining waters from the Authie and further-south smaller coastal rivers.

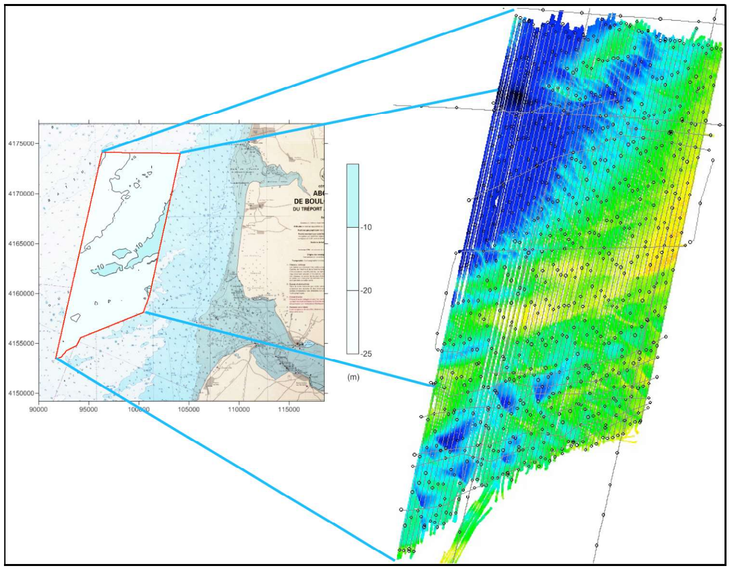


Figure 43. Bathymetry offshore the Somme Bay. The end of a sandbank, the Quemer, is clearly visible in yellow. Its asymmetry, the steepest flank facing the coast, is also visible. Dunes of different heights cover the bank and surrounding areas. Courtesy from Laure Simplet, 2010, Ifremer.

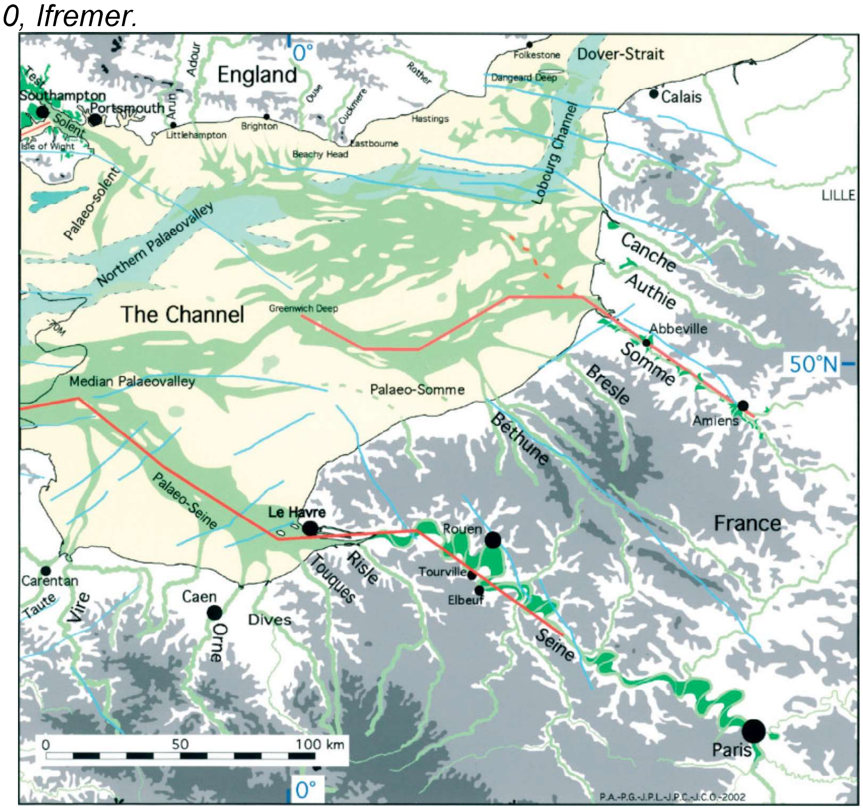


Figure 44. Map displaying the valley and offshore paleovalley system in the Eastern English Channel (Antoine et al., 2007).

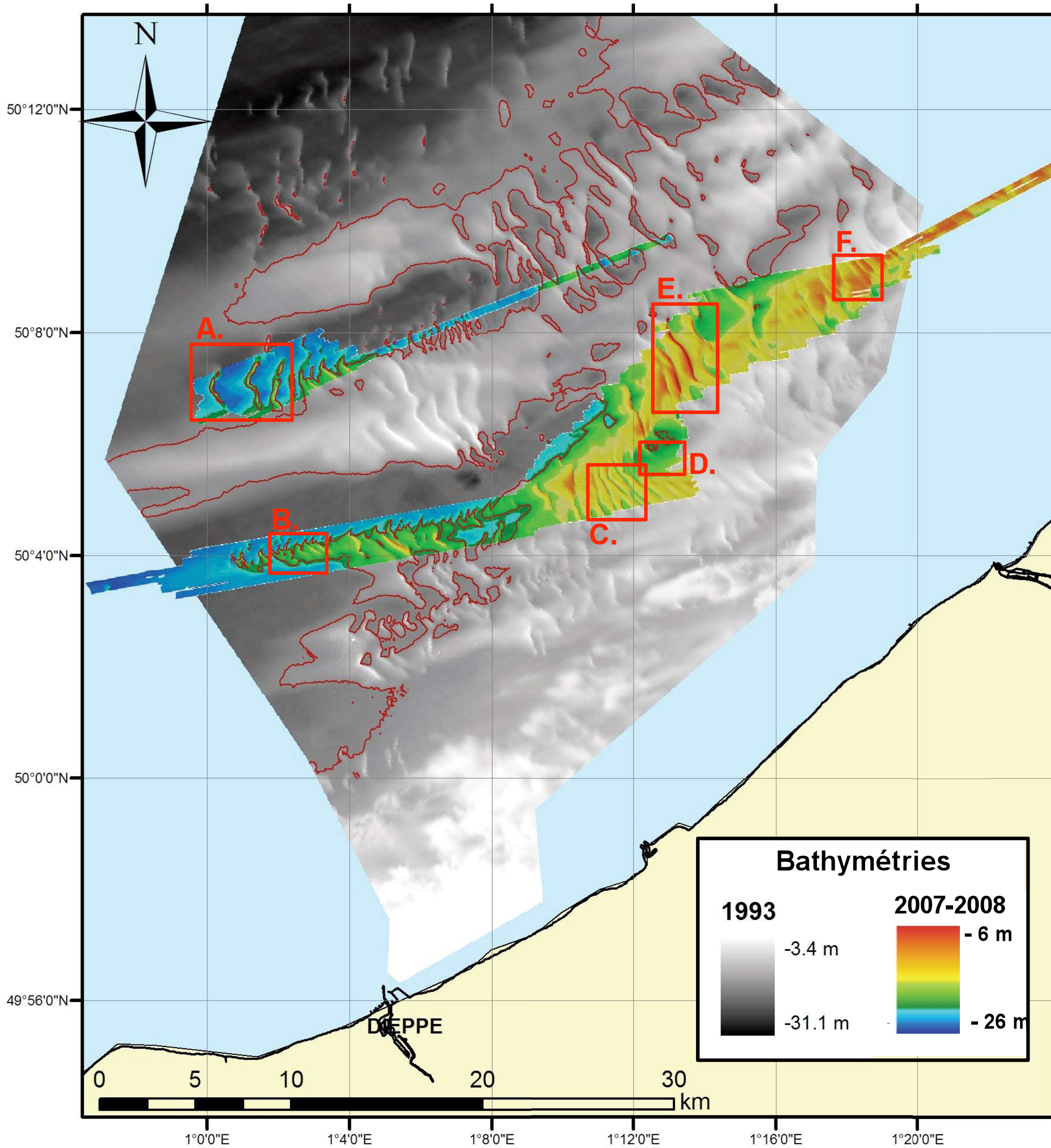
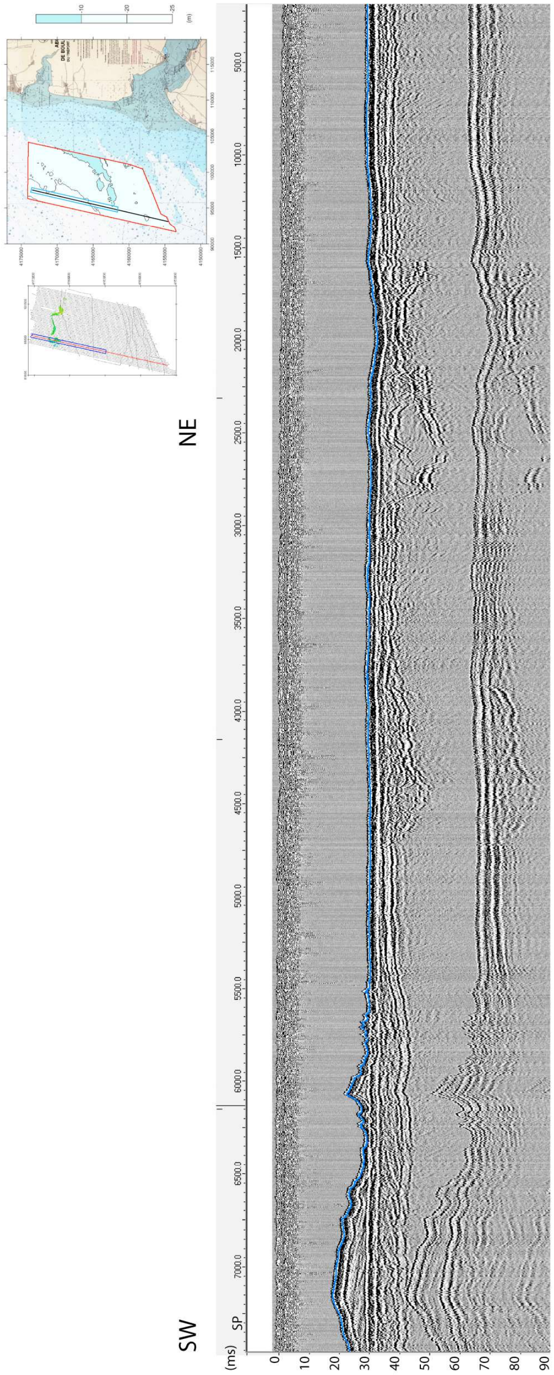


Figure 45. Bathymetry offshore Dieppe and Le Tréport (Northern harbour; Ferret, 2011). Single and multibeam data acquired respectively in 1993 (data source: SHOM) and 2007-2008. The red line corresponds to -20 m and underlines the tidal sandbank boundaries.



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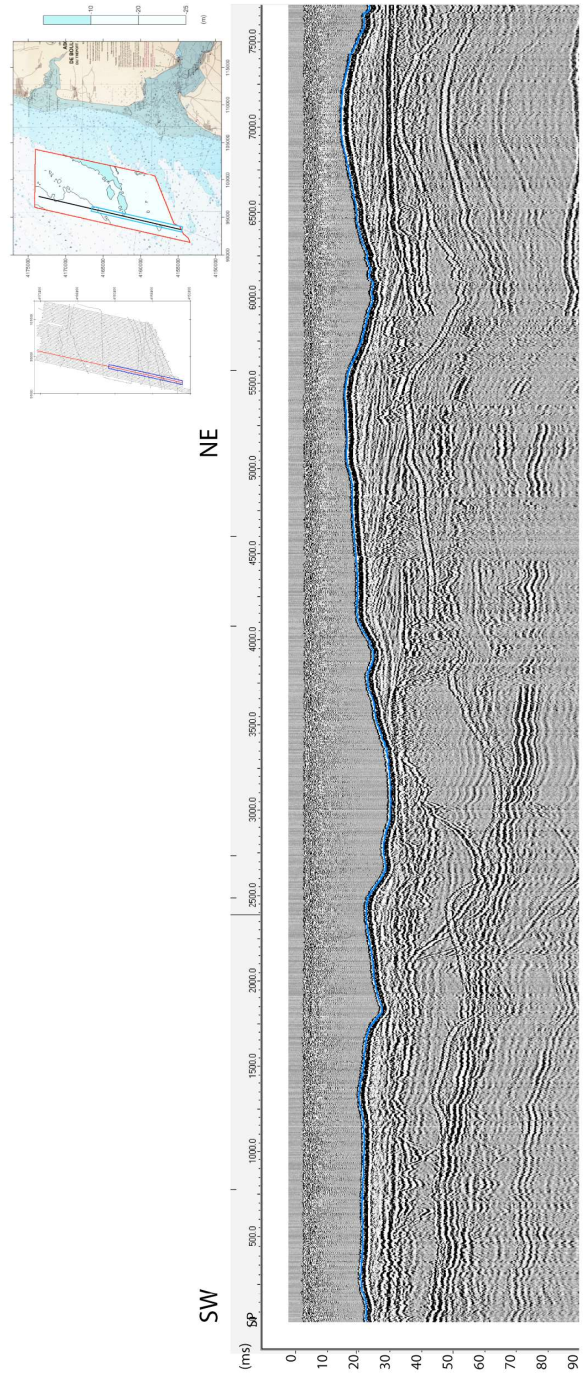

B

Figures 46 and 47. High-resolution sparker seismic profiles shot offshore the Somme estuary. Depths have been corrected from tide-related sea level. A. Profile 124 displays a series of three small incisions that are not in front or the Somme nor the Authie at their present-day locations. B. Profile 123 displays a deep incision related to the Somme valley. The South-dipping reflector corresponds to the Top Cretaceous. Gas, probably of biogenic origin, seems to be trapped in the sandbanks on the east side of the profile.

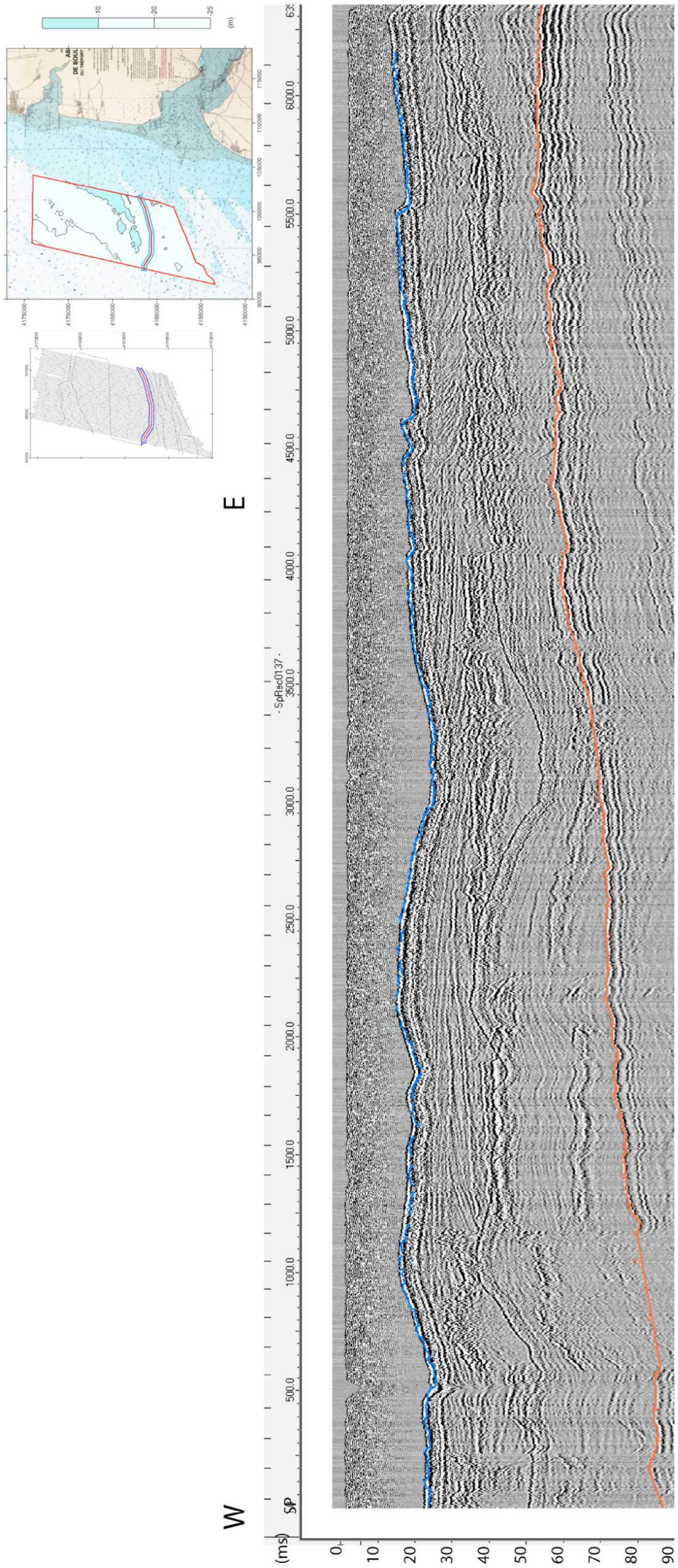

Figure 48. High-resolution sparker seismic profile 137 shot offshore the Somme estuary. The top Cretaceous surface in orange is dipping toward the centre of the Dieppe Basin. The uppermost part of the profile shows inclined bedding related to the upper Quaternary structure of the offshore banks.

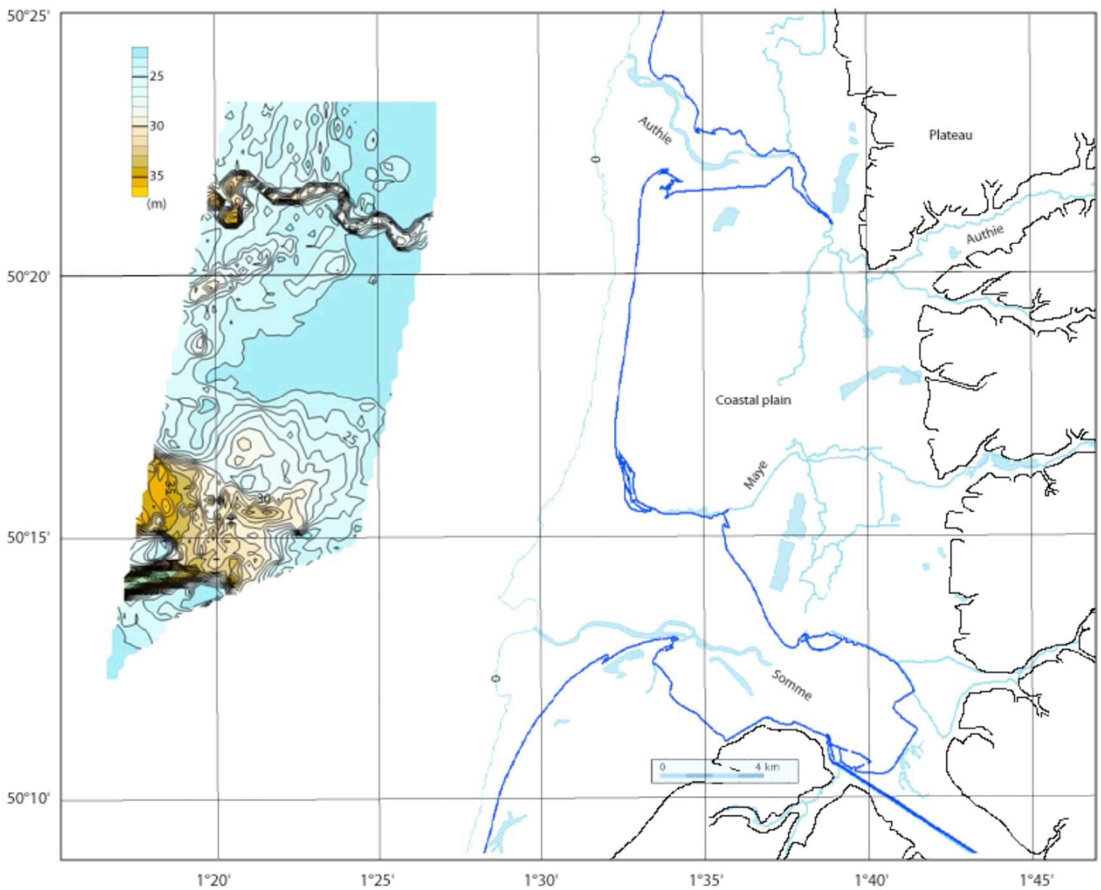

Figure 49. Bathymetry of the top-Tertiary surface offshore the Somme River (Lassue, 2010).

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Seals at low tide on a mixed flat. A colony of a few hundreds seals are present in the bay and its vicinity throughout the year. Notice some linear traces ending where the seals are resting. Picture: Les Editions Gaud, Syndicat Mixte Baie de Somme – Grand Littoral Picard.