Complex tide- and wind-driven dune dynamics in the Eastern English Channel. Migration and internal architecture.

Y. Ferret, S. Le Bot & R. Lafite
Morphodynamique Continentale et Côtière, Université de Rouen, CNRS, Mont Saint Aignan, France.

T. Garlan
SHOM, Brest, France.

B. Tessier
Morphodynamique Continentale et Côtière. Université de Caen, CNRS, Caen, France.

ABSTRACT: In the Eastern English Channel, off the Bay of Somme, large dune dynamics is studied thanks to bathymetric and seismic data. In this area, the dynamics of the sedimentary prism of Picardy occurs mainly in dune fields. At the pluri-decennial time scale, dune movements are toward the East, in the direction of residual tidal currents (2-4m.y^{-1}). At the pluri-annual time scale, dune migration is also eastwards but mean speeds are higher (8m.y^{-1}), implying that tide is not the only hydrodynamic agent influencing dune dynamics. Dune internal architecture reveals a superposition of units with opposite progradation direction (eastward and westward). This architecture is typical of mixed environments, influenced by tides and storm events. Laterally, dune morphology (height) influences the internal structure (variation in the thickness of the West progradation unit). Internal architecture of tidal sandbanks strongly differs: only East progradation units are observed. It seems that hydro-sedimentary processes differ above and on dunes and sandbanks.

1. INTRODUCTION

On sediment starved continental shelves (low sediment supply and low subsidence) such as the English Channel, conditions are generally not in favour of sedimentary record. A high-energy hydrodynamism also contributes to the difficulty of record. In the Eastern English Channel, the sedimentary prism of Picardy, located off the Bay of Somme, constitutes an exceptional site where sediments are preserved. In this area, sedimentary bedforms (e.g. very large dunes) can be considered as sedimentary archives that enable to achieve a greater understanding of seabed sediment dynamics.

In the English Channel and the North Sea, many authors observed fields of submarine dunes which display lengths of several hundreds of meters and amplitudes exceeding 10 m (Dewez, 1988; Le Bot, 2001; Idier et al., 2002; Le Bot & Trentesaux, 2004). Dunes dynamics is controlled by various forcings such as the tide and the wind-driven currents. The footprint of the different hydrodynamic agents is recorded into the internal architecture of dunes. The tidal currents play a predominant role in dune structuring and dynamics, and influence strongly the internal structure of these sedimentary features (Allen, 1980). Winds are also an important hydrodynamic agent. Le Bot and Trentesaux (2004) noted that storm events can modify strongly dune dynamics and make their internal structure complex.

These mobile sedimentary features can make the navigation potentially hazardous. To ensure navigation safety, assumed by the Hydrographic and Oceanographic Office of the French Navy (SHOM), a regular monitoring of seabed bathymetry is necessary in order to have a better understanding of dune dynamics.

This paper aims to study the evolution of the sedimentary prism of Picardy through dune dynamics, on different time intervals (pluri-annual, to pluri-decennial time scales). We will try to characterize the role of the hydrodynamic agents on dune dynamics and to analyse how it is recorded in the internal architectures of dunes and tidal sandbanks.

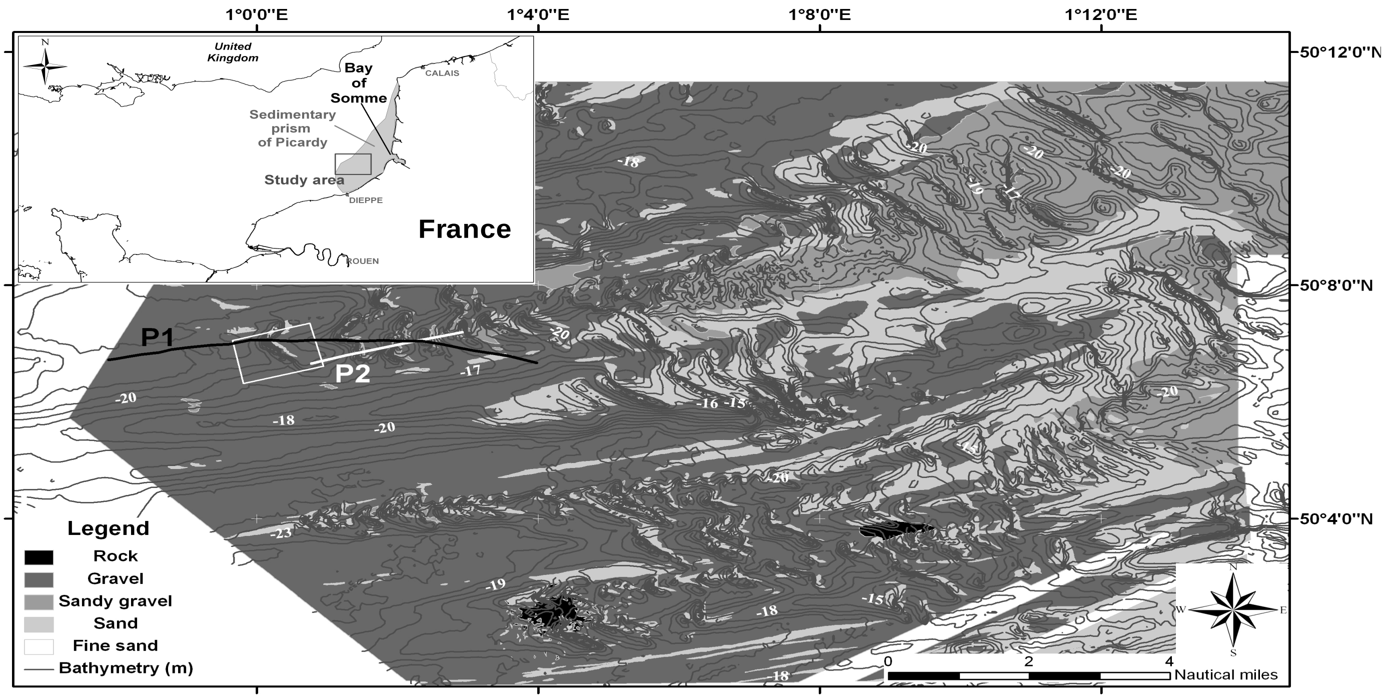

Figure 1. Location and bathymetry of the study area in the Eastern English Channel. Seabed nature resulting from sonar imagery interpretation (SHOM data). Location of profiles P1 (black line) and P2 (white line), and seismic data (white box) studied in the paper.

2 STUDY AREA

The study area is located in the Eastern English Channel, 4 to 20 nautical miles off the French coast of Normandy, West the Bay of Somme (fig. 1). The water depths range from 10 to 30 m.

In the study area, tides and winds are the main hydrodynamic agents. The area is characterised by semi-diurnal tides and megatidal conditions. The mean neap and spring tidal ranges are respectively 4.9 m and 8.5 m but can exceed 10 m during exceptional spring tides (SHOM, 1968). The maximum flood current speed is higher than the one reached during the ebb. In mean spring tide, the speed of flood and ebb surface currents reach respectively 0.9 and 0.6 m.s^{-1} (SHOM, 1968). Numerical modelling studies indicate a tidal residual component in the direction of the flood, towards the North Sea (Salomon & Breton, 1991, 1993; Bailly du Bois & Dumas, 2005). The wind can also be an important hydrodynamic agent. It generates waves and can induce a non-negligible bottom friction. The most frequent and strongest waves appear in winter time. They mainly come from West to North-West and also from South-west (Augris et al., 2004). Mean waves regime are 5 to 6 m in amplitude and 5 to 7 s in period.

The study area is located on the Western border of the sedimentary prism of Picardy, built during the last glacial-interglacial cycle. It is one of the few sites where sediments are preserved, in the context of low sediment supply of the English Channel. The study area is interesting to study the dynamics and the building stages of the prism. In the study area, an important diversity of sedimentary bedforms can be clearly identified. The zone corresponds to a nice morpho-sedimentary gradient (Fig. 1). In the western part, the seabed is flat and is composed of relict gravels whereas in the eastern part we observe tidal sandbanks, covered with dunes. In between sandy deposits and bedforms occur gradually sand ribbons, isolated barchans and fields of linear dunes from West to East. .

In this paper, only very large dunes are considered. They display heights between 3 and 9 m, and wavelengths ranging from 300 to approximately 1000 m. A specific dunes field has been selected on the western border of the sedimentary prism of Picardy.

3 DATA AND METHODS

In this paper, bathymetric and seismic tools are used to study the evolution of the western border of the sedimentary prism and dune dynamics.

3.1 *Bathymetric data*

The bathymetric dataset corresponds to three surveys realised in 1937, 1993 and 2006. The data from 1937 correspond to lead soundings realised by the SHOM, and were digitized for the purpose of the study. It is obvious that this survey method is less accurate than the recent geophysical methods. Nevertheless, taking corrections brought and uncertainties into account, the error margin of this type of measurements is about 10 m for position (see details of calculation in Chaumillon et al., 2002) and about 0.6 m for depth. The data from 1993 were acquired by the SHOM thanks to a single-beam echosounder. The 1937 and 1993 surveys display a good coverage, with profiles spacing respectively about 300 to 600 m and 100 m. They are detailed enough to be suitable for the study of the evolution and dynamics of the western border of the prism and of some fields of very large dunes. In 2006, only 3 single-beam echosounder profiles have been realized during the ALBATR06 survey.

For the 1937 and 1993 surveys, a 50 m resolution digital elevation model (DEM) has been computed using geostatistical methods (variogram, krigging). The interpolation concerning the 1937 measurements required a particular attention due to the anisotropy in data spatial distribution. By comparing the successive DEMs, it is possible to analyse the global evolution of the study area (vertical precision about 1m). In particular, it is possible to locate areas in erosion or accretion. From the DEM of 1993 (best detailed coverage), bathymetric profiles, superimposed on the profiles of original data of 1937 and 2006, were extracted. By comparing bathymetric profiles, it is possible to quantify precisely dune migration and dune morphological changes.

3.2 *Seismic data*

A 3.5-kHz EDO-Western sub-bottom profiler has been deployed during the SISCOSAG survey (April 2007, 85 profiles, 330 km). It allowed a penetration of about ten meters enabling the dune bodies to be mostly insonified, with a vertical resolution of about 0.5 m. The data have been post-processed: shots have been stacked in order to reduce the noise due to the boat and the waves, and induced by the sediment coarseness. Moreover, this characteristic of the sediment made the validation of the data by coring impossible.

Interpretation of seismic data allows to analyse dune internal architecture and successive building steps.

4 BATHYMETRIC EVOLUTION

In order to analyse the morphological evolution of the study area, the bathymetry has been studied at pluridecennial and pluriannual time-scales. For each, DEMs and single profiles have been compared to get respectively the global evolution for the whole study area and dune morphodynamics.

4.1 *Pluridecennial evolution (the 1937-1993 period)*

4.1.1 *Global trends*

Figure 2 corresponds to a bathymetric differential map for the 1937-1993 period. Dark colours represent zones in accretion and light colours correspond to areas in erosion. White indicates stable areas, i.e. depth variations less than 1 m. Most of the area is stable on the 1937-1993 period. Tidal sandbanks outlines and inter-sandbank spaces do not show significant evolution. Evolution concerns mainly dune fields. N-NW / S-SE alternating bands of erosion and accretion underline dune migration. For some dune fields, in the western part, only erosion is observed on large distances (about several hundreds of meters), indicating a global migration of dune fields towards the East. This observation confirms the results obtained by Augris et al. (2004) concerning the eastward migration of the western border of the

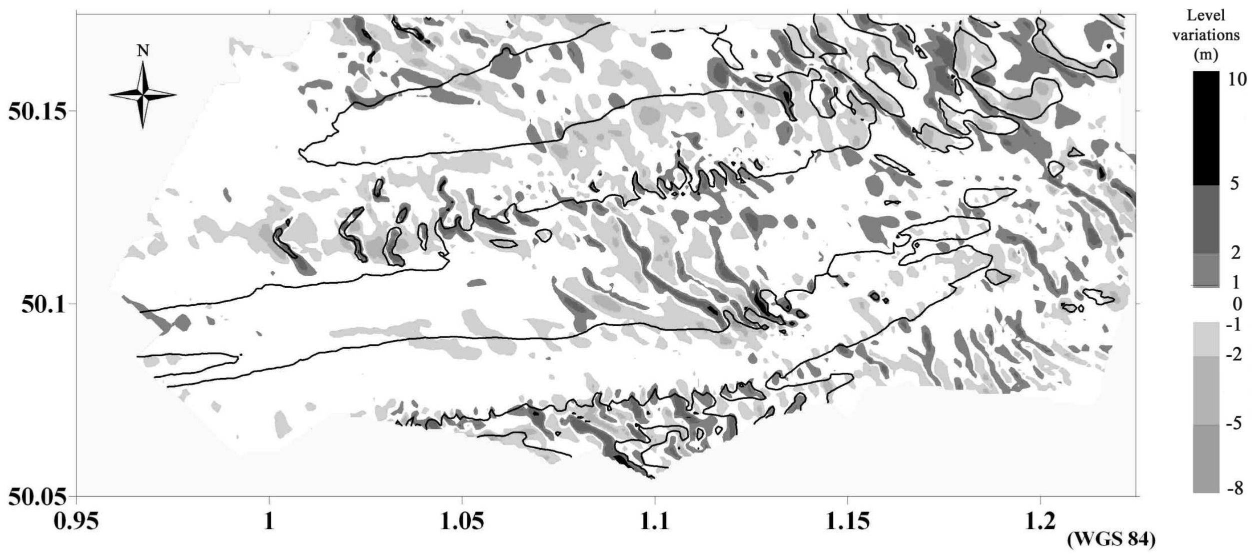

Figure 2. Evolution of the bathymetric of the study area between 1937 and 1993.The black line is the -20 m isobath from the 1993 survey (approximate baseline of tidal sandbanks)

Picardy sedimentary prism, globally in erosion.

4.1.2 *Dune morphodynamics*

Since evolution is mainly concentrated on dune fields, a detailed analysis of dune morphodynamics has been realised. One profile has been selected on the western border of the sedimentary prism of Picardy (P1 on Fig. 1) where barchans are observed.

Evolution of the profile on the 1937-1993 period has been studied (Fig. 3). We can clearly recognize the different dunes between 1937 and 1993, named dunes A to D. The dunes display amplitude ranging

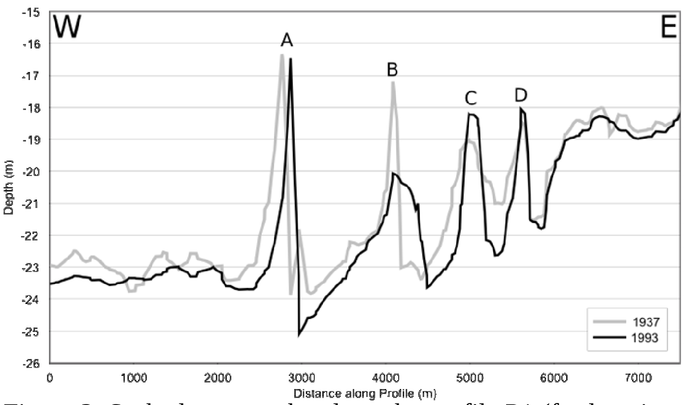

Figure 3. Seabed topography along the profile P1 (for location, see Fig. 1). Position of the seabed in 1937 and 1993 corresponds respectively to grey and black lines.

from 4 to approximately 8.5 m. Seabed is submitted to a global lowering, as clearly observed in-between dunes.

Dune morphology displays different evolutions. The shape of dune A did not really change into 56 years. Dunes C and D show a steepening of their flanks (width decrease) associated with an height increase, whereas dune B an important height decrease and width increase. Dunes C and D evolve towards a more active shape, whereas dune B evolves towards a less active one.

The dynamic of the dunes is complex on this pluri-decennial time-scale. Dune migration is different from one dune to another. Dune migration characteristics are presented in Table 1.

Dunes		A	B	C	D
Movement (m)	Crest	*102*	*0*	*0*	*0*
	Feet	*0* *105*	*-98* *303*	*96* *0*	*0* *0*
Migration speed (m.y^{-1})	Crest	*1.8*	*0*	*0*	*0*
	Feet	*0* *1.9*	*-1.8* *5.4*	*1.7* *0*	*0* *0*

Table 1. Dune displacements along profile P1, and corresponding mean migration speeds over the 1937–1993 period. The movement of dune crest and feet has been measured (western foot values are wrote above eastern ones). Positive and negative values correspond respectively to a displacement towards the East and the West.

Crest and western foot of dune A moved about a hundred meters towards the East, which corresponds to a mean migration speed of about 2 m.y^{-1}. The western foot of dune B migrates 98 m towards the West, its eastern foot moves of about 300 m toward the East and its crest does not move. The resultant migration, directed toward the East, is mainly due to a morphological reorganization. Crests and eastern feet of dunes C and D did not move between 1937 and 1993, whereas western foot of dune C move towards the East.

Except the dune D, each dune displays a migration component towards the East, even if the migration modality is not the same from one dune to another (dune crest or foot movement). The migration direction coincides with that of the residual tidal currents. This seems to indicate that tide is the dominant hydrodynamic agent responsible for dune migration on a pluri-decennial time-scale.

4.2 *Pluri-annual evolution (the 1993-2006 period)*

The weak bathymetrical coverage of the 2006 survey prevents from analyzing the global evolution of the study area over the 1993–2006 period. Only the evolution of the profile P2 has been studied for this period (Fig. 4). The location of this profile allows to analyse the dynamics of dunes B, C and D and to see if their behaviours are comparable on the medium- and long-terms.

Morphological modifications are observed but they are less important than on the pluri-decennial time-scale. The shape of dune B is similar in 1993 and 2006. Dune C height displays a decrease of about 1.5 meters and its flanks are gentler. The shapes of the other dunes (D, E and F) change only slightly into these 13 years (weak steepening of their flanks).

In term of dynamics, the dunes also show varied behaviours at this time-scale (Table 2).

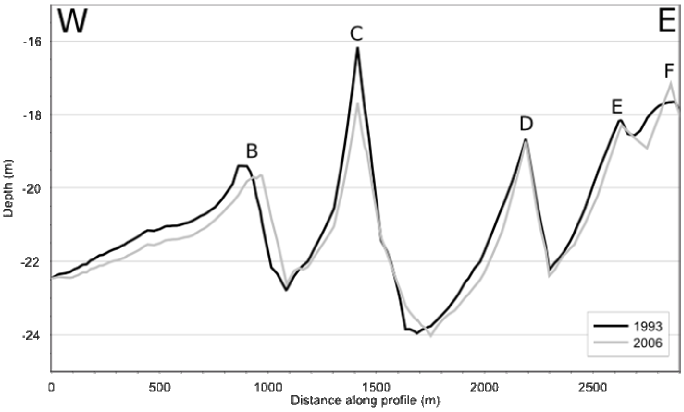

Figure 4. Seabed topography along the profile P2 (for location, see Fig. 1). Position of the seabed in 1993 and 2006 corresponds respectively to black and grey lines.

All the dunes have migrated toward the East. Only the crest of dune B moved about a hundred of meters, which corresponds to a mean migration speed of 8.3 $m.y^{-1}$. The movements of dunes C, D, E and F are restricted to their feet, with values of migration speed varying between 4.6 and 8.8 $m.y^{-1}$.

Dunes		**B**	**C**	**D**	**E**	**F**
Movement (m)	Crest	*108*	*0*	*0*	*0*	*0*
	Feet	-	*0*	*64*	*0*	*60*
		0	*115*	*0*	*60*	-
Migration speed ($m.y^{-1}$)	Crest	*8.3*	*0*	*0*	*0*	*0*
	Feet	-	*0*	*4.9*	*0*	*4.6*
		0	*8.8*	*0*	*4.6*	*0*

Table 2. Dune displacements along the profile P2, and corresponding mean migration speeds over the 1993-2006 period. For explanation on the value significance, see the legend of Tab.1.

4.3 *Discussion*

The migration speeds recorded on this pluri-annual time-scale are about 2 to 4 times higher than those obtained on the pluri-decennial scale. The tide action being constant in the time, this observation implies that it is not the exclusive forcing agent, playing a role in dune dynamics. Tidal currents are probably prevalent on the long-term, but on the medium time-scale, dune movements are influenced by another hydrodynamic agent, which has a higher sediment transport capacity (or potential), and/or exerts probably in various directions. This phenomenon could explain the complexity of dunes morphodynamics.

5 INTERNAL ARCHITECTURE. EXAMPLE OF DUNE A.

Many studies have shown that the footprint of the different hydrodynamic agents is recorded into the internal architecture of dunes (Allen, 1980 ; Dalrymple, 1984 ; Berné et al., 1988 ; Berné et al., 1993 ; Le Bot & Trentesaux, 2004).

5.1 *Vertical architecture*

The analysis of dune structures reveals a hierarchy of discontinuities of three different types: first-, second- and third-order reflectors (noted 1, 2 and 3 on Fig. 5). The first-order reflectors are subhorizontal to horizontal reflectors. At dune basis, they correspond to the progradation mark of the dune above the gravel pavement. In the summital part, they can be attributed to the progradational surface of superimposed small dunes which migrate faster than the host dune (e.g. Le Bot & Trentesaux, 2004). Second- and third order reflectors are inclined and both interpreted as erosive structures. The third-order reflectors are steeper than the second ones. According to Berné et al. (1988), the 3d-order results from the alternation of avalanche phases and sandy rainfalls (i.e. alternation of different granulometric natures).

The organisation of these discontinuities defines a complex dune internal architecture. On figure 5, 3 main units, delimited by 2d order discontinuities, can be observed. Their direction of progradation is opposite: oriented toward the East at the dune basis and summit and toward the West in between (grey unit on Fig. 5).

In dunes occuring in mixed environments, several authors observed similar discontinuities and internal architectures. Berné et al. (1993) observed them in environments dominated by tide and fluviatil discharge. Berné et al. (1988) and Le Bot & Trentesaux (2004) described similar structures in environments where tidal currents and wind-driven currents are prevalent. These authors interpret 2d-order discontinuities as erosive structures due to storm events, and the opposite progradation units as deposits during these high energy events. In the study area, where water depths range from 10 to 30 m, winds and storms could explain the observed internal structures.

5.2 *Lateral architecture*

In order to study the lateral variability of dune internal architecture, we interpreted 5 seismic sections from different parts of dune A (Fig. 6).

All the sections show the complex internal structure described above. The three types of reflectors, and the 3 units with opposite progradation direction

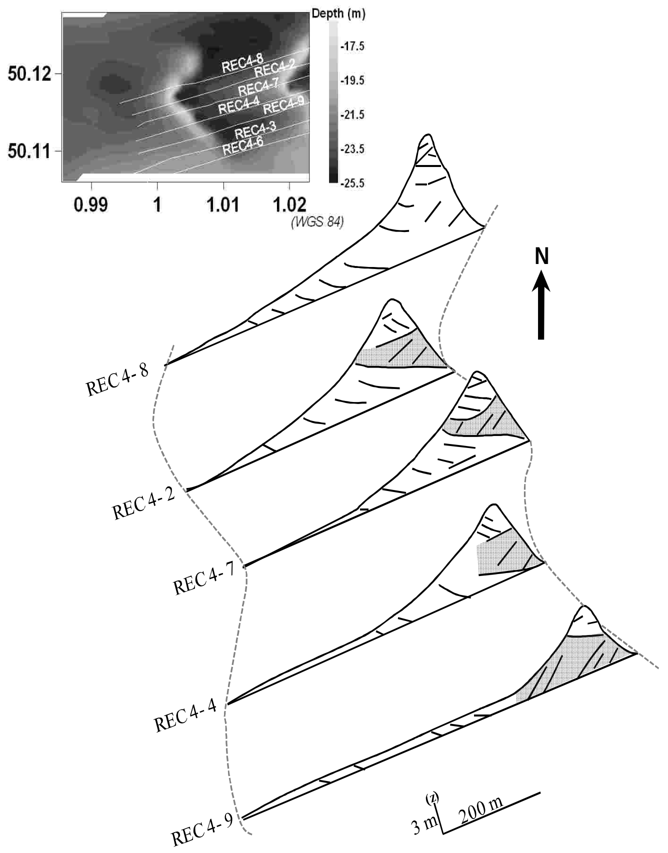

Figure 6. Schematic map of internal structure of different parts of dune A. Tear lines correspond to the dune feet. Top: Location and names of seismic profiles.

are recognised. Nevertheless, lateral variability is observed: the thickness of the opposite progradation unit (in grey when the unit is clearly delimited, on Fig. 6) decreases from the South to the North. For each profile, the thickness of these units is measured where it is maximal. It ranges from 3.3 m thick in the northern part (profile REC 4-2, Fig. 6) to about 4 m in southern part (profile REC 4-9, Fig. 6). On profile REC 4-9, this thickness is underestimated because an important part of the unit top is eroded. Without erosional processes, internal variability along the dune A would have been more important.

Several parameters can explain lateral variability in dune migration and architecture: bathymetry (influence on current speeds), grain size (influence on sediment transport capacity; Ernstsen et al., 2004), dune morphology (height and width).

In the study area, we do not have enough sediment data to characterize dune lateral granulometric variability.

In order to determine if bathymetry is an important factor controlling dune structure, we measured the depth of basal part of the westward progradation unit, for each seismic section (when it was clearly visible). This depth corresponds to the limit action depth of storm-driven currents. Depth of the basal surface of this unit does not really change laterally (values vary from about -24 m to -25 m). The influence of dune morphology has been also studied. Dune A shows different height and width according to the seismic section observed (Fig. 6): the dune height decreases from North (more than 8 m on profile REC 4-2) to South (5.6 m on profile REC 4-9). This height decrease coincides with an increase in westward progradation unit thickness. For the same quantity of transported sediment, the higher the dune dimensions are, the thicker the resulting deposit unit is. In dune A, this phenomenon seems to strongly influence the internal architecture and can explain the lateral variability.

5.3 *Comparison between dune and tidal sandbank*

The study area corresponds to a remarkable morphosedimentary gradient constituted, in particular, of

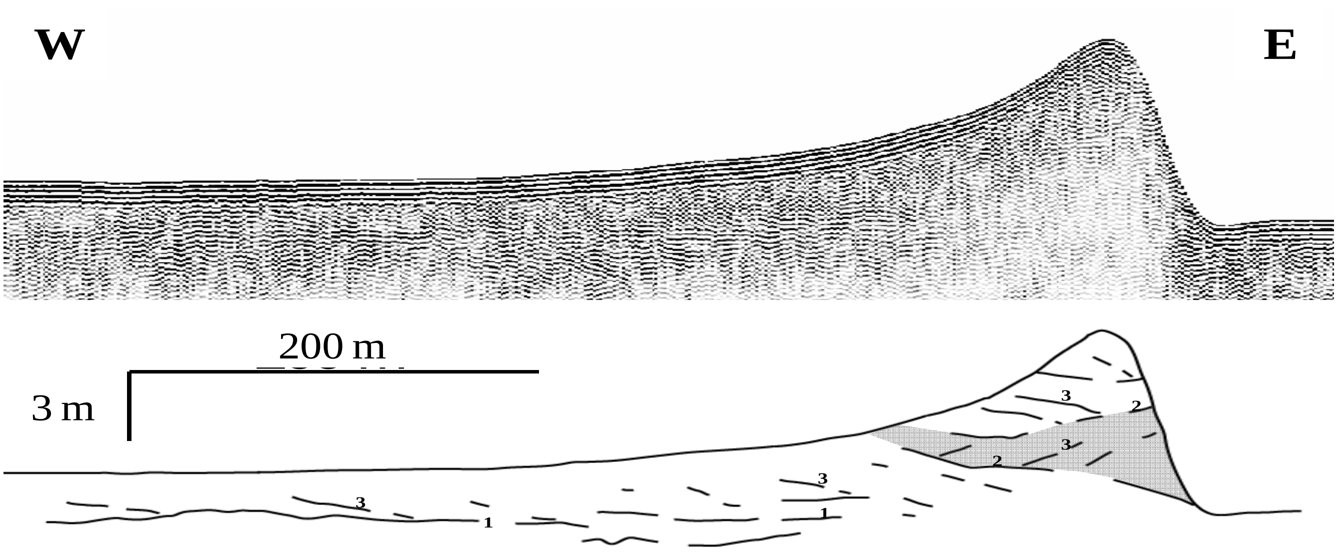

Figure 5. W-E seismic section perpendicular to the crest of dune A (profile REC 4-7, located on figure 6) and the interpretation.

very large dunes and tidal sandbanks (Fig. 1). Many studies have been dedicated to the analysis of the internal architecture of tidal sandbanks (e.g. Berné et al., 1994; Tessier et al., 1997). However, transitions between internal structures of dunes and sandbanks have not been studied. In the study area sediment transport is controlled by tide- and wind-driven mechanisms. Dune internal architecture and their dynamics clearly display non-tidal characteristics (opposite progradation unit, oscillating migration). . The seismic section REC 4-3 (located on Fig. 6) has been realized on the northern border of a tidal sandbank, located 2 hundreds of meters south to dune A. Its interpretation allows to recognize the tidal sandbank internal architecture (Fig. 7).

Only first- and third-order reflectors are observed in the tidal sandbank. They delimit several progradation units oriented toward the East and never show an inversion of progradation direction, contrary to dune. The first-order reflector in the summital part is very long and seems to be representative of an active dynamic of small superimposed dunes. The migration of these superimposed features could have erased the significant westward progradation reflectors, preventing it from observation. Since the western border of the Picardy sedimentary prism, where the tidal sandbank is observed, is stable on the long term period (Fig. 2), this implies that West progradation unit has never been deposited.

It seems that tide-and wind-driven current action is recorded in different ways in internal architectures of dunes and tidal sandbanks. It is probable that hydro-sedimentary processes differ above on dunes and sandbanks, in spite of their proximity. Varying parameters need to be determined in the future.

6 CONCLUSION

In the Eastern English Channel, the sedimentary prism of Picardy, located off the Bay of Somme, is one of the exceptional sites where sediments is preserved. To study the evolution of its western border, bathymetric and seismic data have been used to analyse, on the pluri-decennial to pluri-annual time scales, the dynamics of dunes, which are the most widespread bedforms in the area. The following conclusions have been noted:

1) On the 1937-1993 period, the western border of the sedimentary prism is in erosion This confirms the erosion trend observed by Augris et al. (2004) for the whole prism on the long-term. Sediment dynamics is mainly concentrated in dune fields.

2) Dune dynamics is complex. Dune movement and their evolutions display different behaviours. On the pluri-decennial time-scale (1937-1993 period), dune residual movements are toward the East (mean migration speed of about 2 to $4 m.y^{-1}$). It coincides with the direction of the residual tidal currents. This indicates that dune dynamics is mainly controlled by the tide on the long-term.

3) On a pluri-annual time-scale (1993-2006 period), all studied dunes have migrated toward the East, with higher mean migration speeds than on the long-term (values can reach more of $8 m.y^{-1}$). This observation implies that tide is not the only hydrodynamic agent controlling dune dynamics.

4) Dune internal architecture reveals a complex superposition of units with reflectors having opposite (East or West) progradation direction. This architecture is similar to those observed by Berné et al. (1988) and Le Bot & Trentesaux (2004) in mixed environments, influenced by tides, winds and storm events. The occurrence of a West progradation unit has to be related to the action of wind-driven currents. This indicates that wind-driven currents, when

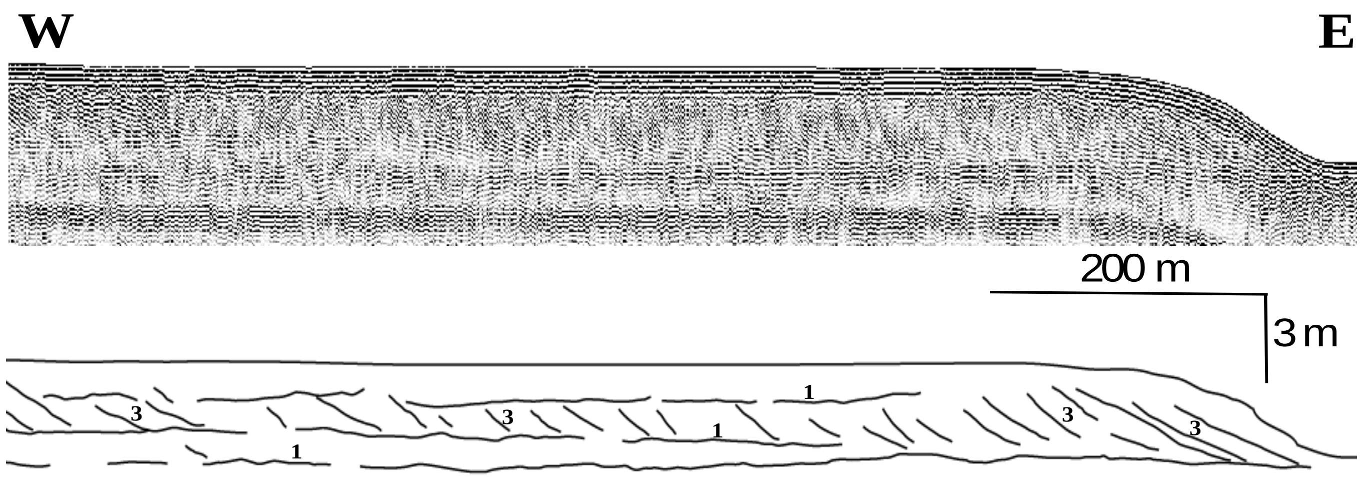

Figure 7. W-E seismic section of the north border of tidal sandbank (profile REC 4-3, located on figure 6) and the interpretation.

are important, can control dune dynamics.

5) The lateral variability of dune internal architecture can be related to the variability of its morphology (height and width in particular).

6) The internal architecture of a tidal sandbank differs strongly from the neighbour dune architecture. This tends to show that hydro-sedimentary processes differ above and on dunes and sandbanks.

ACKNOWLEDGMENTS

This study is supported by the Hydrographic and Oceanographic Service of the French Navy (SHOM) and the Regional Council of Haute-Normandie.

The authors would like to thank the team of the RV "Côte d'Aquitaine" (INSU CNRS) and the SHOM for providing bathymetric data.

REFERENCES

Allen, J.R.L., 1980. Sand waves: a model of origin and internal structure. *Sediment. Geol. 26,* pp. 281– 328.

Augris C., Clabaut P., Costa S., Gourmelon F. & Latteux B., 2004. Evolution morpho-sédimentaire du domaine littoral et marin de la Seine-Maritime. *IFREMER (Ed.),* 159p.

Bailly du Bois P. & Dumas F. 2005. Fast hydrodynamic model for medium- and long-term dispersion in seawater in the English Channel and Southern North Sea, qualitative and quantitative validation by radionuclide tracers. *Ocean Modelling (9).* pp. 169-210.

Berné S., Auffret J.P., Walker P., 1988. Internal structure of subtidal sand waves revealed by high-resolution seismic reflection. *Sedimentology 35,* pp.5 –20.

Berné S., Castaing P., LeDrezen E. & Lericolais G., 1993. Morphology, Internal structure and reversal of asymmetry of large subtidal dunes in the entrance to Gironde estuary (France). *J. Sediment. Petrol. 63,* pp. 780-793.

Berné S., Trentesaux A., Stolk A., Missiaen T. & de Batist M., 1994. Architecture and long term evolution of a tidal sandbank: the Middlekerke Bank (southern North Sea). *Marine Geology 121,* pp. 57-72.

Chaumillon E., Gillet H., Weber N. & Tesson M. 2002. Evolution temporelle et architecture interne d'un banc sableux estuarien : la Longe de Boyard (littoral atlantique, France). *C.R. Geoscience 334.* p. 119 – 126.

Dalrymple R.W., 1984. Morphology and internal structure of sandwaves in the Bay of Fundy. *Sedimentology 31,* pp. 365– 382.

Dewez S. 1988. Sédimentation et dynamique en Manche Orientale (de la Baie d'Authie au cap d'Alprech). *PhD Thesis,* University of Lille Flandres-Artois. 256 p.

Ernstsen V.B., Noormet R., Winter C., Bartholomä A., Flemming B.W. & Bartholdy J., 2004. Development of subaqueous barchan dunes due to lateral grain size variability. *In : Hulscher J.M.H., Garlan T. & Idier D. (Eds), Marine Sandwave and River Dune Dynamics, International Workshop. Enschede (Pays-Bas).* pp. 80-87.

Idier D., Ehrhold A. & Garlan T., 2002. Morphodynamique d'une dune sous-marine du détroit du Pas de Calais. *Comptes Rendus Géosciences* (334). pp. 1079-1085.

Le Bot S., 2001. Morphodynamique de dunes sous-marines sous influence des marées et des tempêtes. Processus hydro-sédimentaires et enregistrement. Exemple du Pas de Calais. *PhD Thesis,* University of Lille. 300p.

Le Bot S. & Trentesaux A. 2004. Types of internal structure and external morphology of submarine dunes under the influence of tide- and wind-driven processes (dover strait, northern france). *Marine Geology* (211) pp. 143-168.

Salomon J.C & Breton M. 1991. Courants résiduels de marée dans la Manche. *Oceanologica Acta. Proceedings of the International Colloquium on the environment of epicontinental seas, Lille, vol. Sp. n°11.* pp. 47-53.

Salomon J.C. & Breton M., 1993. An atlas of long-term currents in the Channel. *Oceanologica Acta* (16), 5-6. pp. 439-448.

Tessier B., Corbau C., Chamley H. & Auffret J.P., 1997. Internal structure of shoreface banks revealed by high-resolution reflection in a macrotidal environment (Dunkerque area, northern France). *Journal of Coastal Research 15,* pp. 593-606.

SHOM, 1968. Courants de marée dans la Manche et sur les côtes françaises de l'Atlantique, n° 550.