Internal Structure of Shoreface Banks Revealed by High-Resolution Seismic Reflection in a Macrotidal Environment (Dunkerque Area, Northern France)

Bernadette Tessier†**, Corinne Corbau†, Hervé Chamley†, Jean-Paul Auffret‡

† Université de Lille 1
Laboratoire de Sédimentologie et Géodynamique
UMR 8577 CNRS
59 655 Villeneuve d’Ascq
Cedex, France
corinne.corbau@univ-lille1.fr,
Herve.Chamley@univ-lille1.fr

‡ Université de Caen
Laboratoire de Géologie Marine
Esplanade de la Paix,
14 032 Caen Cedex, France
auffret@geo.unicauen.fr

ABSTRACT


The large-scale internal structure of shoreface banks located off Dunkerque (N France) in the Southern Bight of the North Sea is imaged in a very-high-resolution seismic reflection study. An interpretation is proposed of the processes controlling the construction and migration of these banks located in a macrotidal coastal environment.

The Dunkerque coastal system is characterized by strong, coast-parallel, tidal currents, and northerly moderate storms. The banks are coast-parallel and almost emergent during low-water spring tides. Their length, width and maximum height reach 8 km, 1.5 km and 12 m respectively. They have an asymmetrical profile with a steeper flank dipping either landward or seaward. Bathymetric investigations show that some parts of the banks migrate actively landward, while others tend to elongate or to migrate seaward. The steeper flank indicates the direction of the dominant migration. Seismic data reveal one main feature: the reflectors observed beneath the landward flank dip landward, and the reflectors observed beneath the seaward flank dip seaward. This large-scale internal structure conforms with the bank morphology and reflects the present-day migration mechanisms.

According to bathymetric, hydrodynamic and seismic data, the landward migration component is induced by northern storm wave action and the longshore/seaward component is tide-controlled. Seismic data show that this migration pattern was occasionally reversed, some parts of the banks that presently migrate longshore having migrated landward at an earlier time (and vice versa). The predominance of storm-induced landward migration over tide-induced longshore migration (and the reverse) is related to water depth and surrounding seabed morphology evolution. The banks are thought to be recent sedimentary features of a few centuries. They represent very active sand bodies the migration of which induces significant morphodynamic modifications of the coastal system, especially of the beach domain to which they tend to attach.

ADDITIONAL INDEX WORDS: Shoreface banks, tidal sand banks, high-resolution seismics, bathymetry, macrotidal environment, storm waves, N France.

INTRODUCTION

Many continental shelves are characterized by elongated sandbanks, the construction and migration dynamics of which are controlled either by storms (storm-generated ridges) or by tidal currents (tide-dominated banks) (Belderson, 1986). Tide-dominated banks were extensively studied (e.g. Houbolt, 1968; Caston, 1972; Davis et al., 1993; Berne et al., 1994; Park and Lee, 1994), especially in the North Sea and English Channel. The formation and maintenance of linear tidal bodies are still a matter of discussion but most interpretations and models proposed so far state they are initiated and constructed by residual circulation resulting from an interaction between tidal currents, bottom friction and Coriolis force (Zimmerman, 1981; Huthnance, 1982a, b; see review in Pattiaratchi and Collins, 1987). When they reach an equilibrium stage with ambient hydrodynamical conditions, these banks represent closed systems that get a relatively high state of morphological stability, their shape tending to slowly elongate in the direction of the dominant tidal current (Huthnance, 1982b). However this is not necessarily the case for banks located very close to the shore. The macrotidal coastal system of Dunkerque (N France) is characterized by the presence of shore-parallel banks located in the shoreface domain and that locally migrate very actively onshore (Corbau et al., 1993).
The internal structure and the migration mechanisms of such very shallow banks are still poorly documented, mainly because of the technical difficulties to perform high-quality seismic investigations and vibro-coring. The present paper aims to provide and discuss the results of a high-resolution seismic study which has been performed on the shoreface banks of Dunkerque. Although it has not been possible during the survey to collect cores and get extensive sedimentological information, the seismic data combined with the results of previous bathymetric investigation allow us to interpret the different processes that have participated in the construction and migration of coastal sedimentary bodies in a macrotidal environment. The different formation stages are discussed as well as their evolution with respect to adjacent areas and especially the beach.

**STUDY AREA**

The Dunkerque coastline is located in northern France, a few tens of kilometres from the Belgian border. It is orientated WSW-ENE and opens toward the Southern Bight of the North Sea, close to Dover Straits (Figure 1).

The shoreface domain is characterized by a succession of bank alignments and channels roughly parallel to the coastline (Figure 1B). These banks belong to the group of the Flemish Banks (HouBOLT, 1968), (Figure 1A). The two banks investigated, called the Snow Bank and the Braek Bank, constitute the most proximal alignment and are separated from the lower foreshore by the access channel to Dunkerque harbours (Figure 1B).

The coastal area of Dunkerque is subject to tides the range of which reaches 5.2 m during spring tides and 3.4 m during neap tides, forming a dominantly macrotidal environment. Current measurements indicate the reversing nature of the tidal currents, with a fairly flat tidal ellipse almost parallel to the coastline (Vicaire, 1991). Vector directions are 60°–90° and 225°–270° for flood and ebb respectively, and the duration of the tidal curve is almost symmetrical. Current velocity measurements performed in all bank sectors indicate higher values during the flood than during the ebb. In the channel to the North of the Snow Bank, 3 m above the seabottom, maximum flood velocities during mean tides range from 80 to 100 cm/s and maximum ebb velocities from 70 to 85 cm/s (Vicaire, 1991). Near-surface measurements indicate that flood and ebb velocities during spring tides reach up to 150 cm/s and 135 cm/s respectively, and rarely exceed 50 cm/s during neap tides. The general dominance of the flood over the ebb determines a net sediment transport toward the ENE.

The most frequent winds blow from SW and NE, the stronger originating from NE to NW. The higher wind speeds at
tain values of 80 km/h and are recorded during autumn and winter for NNE winds. Predominant storm waves have a north to northwesterly fetch. Statistical analyses of wave measurements made approximately 2.5 km off the Snouw Bank (BONNEFILLE et al., 1971) indicate a period range of 5 to 12 s (maximum frequency between 6 and 9 s). Maximum wave heights rarely exceed 6 m and more than 50% are lower than 1.2 m. However, 10-year and 100-year wave heights can reach up to 8 and 10 m, respectively.

These hydrodynamical characteristics define the study area as a mixed environment influenced by both strong tidal currents parallel to the shore and moderate northerly storms.

METHODS

The seismic survey was performed using the 2.5 kHz EDO Western sub-bottom profiler of GENAVIR/IFREMER on board of the INSU/CNRS vessel Sepia 2. BERNÉ et al. (1988) used the same sensor system for revealing the internal structure of sand waves from a deeper area off western France. The vertical resolution provided by this seismic device is of 0.5 m. The sub-bottom profiler was maintained at about 50 cm below the water surface. Shooting rate was of 125 ms. Positioning was given by a differential GPS with an accuracy of a few meters. Twenty four transverse profiles were shot with a spacing of about 400 m. Two profiles parallel to the crest were also run (Figure 2). Data were recorded only in analog mode (paper output) on a Dowty graphic recorder. Bathymetric profiles were acquired simultaneously with seismic lines using a high-frequency Furuno 881 echosounder. Because of the poor quality of the seismic data on longitudinal profiles due to weather conditions, the results and discussion will mainly focus on transverse profiles.

BANK MORPHOLOGY AND SURFICIAL SEDIMENT CHARACTERISTICS

The Snouw and Braek banks have a depth relative to mean sea-level that varies from 18 m in the adjacent channels to 3 m above their crest; during lower low water stages the crests are almost emergent. The two banks have an average length of 8 km and a width of about 1–1.5 km. Their maximum height relative to the surrounding sea-bottom ranges from 12 to 15 m. Their transverse profile is asymmetric with a steeper flank dipping toward the coast (Figures 2, 3), except for the eastern part of the Braek Bank where the asymmetry is reversed (Figures 2, 4). The eastern end of the Snouw Bank is almost symmetrical. The banks display a very gentle relief because of their very low flank slopes relative to the width. Slope angles measured on the bathymetric profiles range from 2–4° for the steeper flank to 1–3° for the gentle flank. However the external (seaward) steeper slope of the eastern part of the Braek Bank locally reaches up to 10°. The summit of the banks is usually characterized by a long and flat-topped crest devoid of any dunes. The only megaripples observed on side scan sonar images (VICAIRE, 1991) and bathymetric profiles (CORBAU, 1995 and this study) are scattered on the bank area. The best developed megaripples occur in the deeper parts of the western termination of the Snouw bank. All these bedforms are flood-dominated.

Surficial sediments of the Snouw and Braek banks consist of well-sorted fine to medium lithoclastic sand (mean grain-size based on about 20 grab samples: 125 to 315 μm; dominant mode: 250 μm, VICAIRE, 1991; CORBAU, 1995). Finer sands are usually located on the eastern part of each bank. Grain-size, current and wave data provide the basis for estimating conditions of surficial sediment motion using classical formulae (e.g. KOMAR, 1976; MIGNOT, 1977; MILLER et al., 1977). During spring tides, both flood and ebb current velocities are sufficient for inducing sediment motion and transport over the banks. By contrast, during neap tides, tidal current-induced transport is very restricted, especially during the ebb, with a near-surface velocity that rarely exceeds 50 cm/s. Calculation of orbital velocities over the seafloor for wave conditions of relatively moderate energy (with wave height $H = 1$ m and period $T = 6$ s) suggests that...
sediment motion is likely to occur over the banks in a water depth of 5 m (and less). For common fairweather conditions \((H < 0.5 \text{ m and } T = 4 \text{ s})\), sediment motion under wave action occurs in water depths less than 3 m.

According to these observations and considering (i) the fine to medium sand over the banks, (ii) the very shallow depth of the area, and (iii) the wave conditions that prevail during storms, surficial sediment motion must be very dynamic over the banks and is likely to result predominantly from a combination of tidal currents and wave action.

**SEISMIC RESULTS**

Five main kinds of seismic reflectors are identified on the transverse profiles and display the following characteristics (Figures 3 to 11):

The most basal reflector R1 is planar and continuous, and dips gently seaward \((< 0.5^\circ)\). Beneath the most landward part of the banks, R1 is locally overlain by another planar reflector which seems to represent the bank migration surface (Figure 5, profiles 9 to 18). Some inclined reflectors locally occur between these two planar reflectors (Figure 5, profiles 13 to 17, and Figure 6). We define this group of reflectors as the "basal reflector complex" (BRC). Below the seaward part of the banks, only the first basal reflector R1 is identified. In some places it is hardly differentiated from the migration surface of the bank. However it generally represents a well defined planar surface which almost merges with the sea floor in the channel off the banks (Figure 7).

Reflectors R2 are located between the flanks in the core of the banks. They exist on most profiles, except in the eastern part of the Snouw Bank (Figure 5, profiles 9 to 15). They are almost planar and generally discontinuous. Their slope is very low \((< 1^\circ)\) and dips seaward \((e.g.\text{ on profile 8, Figure 8})\) or landward. The relationship between R2 and the basal reflector complex or R1, not easy to observe because the contact is usually hidden by the first multiple, appears to be conformable (Figure 5, profiles 12 to 18, and Figure 6).

Reflectors R3 are associated with the external (seaward) flank of the banks. In common with this flank, they dip seaward and their slope is fairly conformal with that of the flank, or locally steeper (Figures 3, 4, 7). R3 are continuous and downlap tangentially the basal reflector R1. Their upper ter-

---

**Figure 3. Example of seismic profile and its interpretation (Profile 8—central part of the Snouw Bank). R1 to R4: Reflector types (see text for description). Vertical scale is given in two-way travel time with 20 ms = 16 m assuming a velocity of 1600 m/s (Vertical exaggeration: about \(\times 4\)).**
Internal Structure of Shoreface Banks

mination is usually tangential with the surface of the external flank. These geometric characteristics confer to R3 a sigmoidal shape (Figure 5, e.g. profiles 8, 11, 14, 15, 22). However the reflectors R3 reaching the bank surface at the flat-topped crest (i.e. between the flanks) always display a truncated toplap.

Reflectors R4 are associated with the internal (coastward) flank of the banks and dip coastward. They are continuous and their slope conforms with that of the flank (Figures 3, 4). Their lower termination is tangential to the basal reflector complex as with R3, but their toplap is truncated by the surface of the banks. They never display a sigmoidal shape. The contact between the reflectors R2 located in the core of the banks, and reflectors R3 and R4 associated with the flanks, looks often erosional (e.g. between R2 and R4 on profile 20, Figure 8) but locally the slope angles of R3/R4 and R2 are similar and no obvious erosional contact is evidenced.

Longitudinal seismic profiles provide evidence that reflectors R3 and R4 generally dip gently eastward.

Reflectors R5 are surficial and almost entirely restricted to the shallow channel between the two banks. They have a gentle channelized shape (Figure 5, profiles 12 to 15, Figure 9) and delineate an elongated seismic unit parallel to the bank axis.

This internal organization is valid in the case of a coastward asymmetry of the banks, i.e. with a gentle external flank and a steeper internal one (e.g. Figure 3, profile 8). In the eastern part of the Braek Bank where the asymmetry is reversed, i.e. seaward, the internal organization is roughly similar but the reflectors R3, although they are in that case associated with the steeper flank, still display a sigmoidal shape beneath the flank. In contrast, although the reflectors R4 are related to the gentle flank, their upper termination is still truncated (e.g. Figure 4, profile 23).

From a general point of view, the transition between the external flank marked by the seaward dipping reflectors R3, and the internal flank marked by the landward dipping reflectors R4, does not display the same pattern from West to East. In the central part of the Snouw Bank (Figure 5, profiles 8 to 12; Figure 10), reflectors R4 clearly truncate reflectors R3, whereas in the eastern part of the Braek Bank this relation is reversed (Figure 5, profiles 22 to 24; Figure 11). The eastern termination of the Snouw Bank only displays reflectors R3. In the other parts of the banks the transition
Figure 5. Internal structure of the Snouw and Braek Banks reconstructed from the transverse seismic profile interpretation (simplified). Scales are indicative.
between R3 and R4 is separated by reflectors R2 that outcrop at bank surface (Figure 5, profiles 1 to 7 and 16 to 17).

The most significant characteristics of the large-scale internal organization of the two shoreface banks investigated may be summarized as follows. The internal structure mainly conforms to the bank morphology with landward dipping reflectors located beneath the internal flank and seaward dipping reflectors under the external flank. These reflectors R3 and R4 are locally underlain by deeper reflectors (R2), which constitute a core in the banks. Finally all these reflectors R2, R3 and R4 rest through a conformable or tangential contact on a basal planar surface (R1 or “basal reflector complex”).

**INTERPRETATION OF THE LARGE-SCALE INTERNAL STRUCTURE OF THE BANKS**

**Origin of the Banks**

The banks are constructed on a planar surface which almost crops out at the sea-floor outside of the bank area, and rests on the regional substrate represented by the Ypresian clayey Formation (DE BATIST et al., 1989; VICAIRe, 1991). This planar surface is attributed to the regionally well-known Holocene transgressive surface that is commonly described beneath the sandbanks in the Southern North Sea (HOUBOLT, 1968; LABAN and SCHUTTENHELM, 1981; DAVIS and BALSON, 1992; VAN DE MEENE, 1994; COLLINS et al., 1995). In the...
English Channel and Dover Strait, this surface outcrops in the areas where the sandy cover is absent and is represented by a pebble lag (Beck et al., 1991; Vicaire, 1991). The “basal reflector complex” that constitutes the lowest unit of the Snouw and Braek banks in their landward part is thought to represent the early transgressive stage of sedimentation. In absence of any success so far in coring these sandbanks it is hazardous to postulate the sedimentological nature of this unit. Note that a basal unit has also been described in some shoreface banks of the Dutch coast and has been attributed to lagoonal or nearshore deposits (van de Meene, 1994). Similar succession is also documented by Ashley et al. (1991) in linear sand ridges located on the New Jersey inner shelf.

The flanks have developed on each side of the bank inner core. According to its relief above the basal reflector and to its internal reflectors, this core is interpreted as the residual part of previous banks. In view of the Dunkerque coast configuration it is unlikely that it represents part of an ebb tidal delta such as in the model proposed by McBride and Moslow (1991) to explain shoreface ridge development along the U.S. States Atlantic inner shelf. More or less complex cores have been described in most sandbanks of the Southern North Sea and Northern English Channel (D’Oliver, 1981; Laban and Schüttenhelm, 1981; Berne et al., 1994). Their ages range from Pleistocene to Holocene. The Snouw and Braek bank core is assumed to be Holocene but this should be checked by direct dating which implies successful coring of these shallow sand bodies.

Mechanisms of Migration

The seismic data show that the present-day bank morphology results from an accretion along the two flanks. Several bathymetric investigations have been performed in the study area in order to obtain information about the pattern and rate of bank migration since the last century (Le Petit and Leroy, 1977; Clique, 1986; Corbau et al., 1993). The western part of the banks migrates actively toward the South, i.e. landward, at a rate approaching 5 m/year, whereas their eastern part tends to migrate slowly toward the NE, i.e. almost seaward, or simply to extend toward the ENE. The bank asymmetry, with the steeper flank either landward or seaward, is therefore indicative of the recent to present-day migration pattern. We therefore conclude that the reflectors R3 and R4, that are respectively associated with the seaward and landward flanks of the banks, reflect the sedimentary processes controlling this present-day migration.

However, the geometrical relationships existing between the reflectors R3 and R4 show that the two flanks do not evolve simultaneously. According to these geometrical relationships and to bathymetric observations, it is inferred that the flanks accreting at present time are i) the internal flank of the western part of the banks, migrating landward, and ii) the external flank of their eastern part, migrating toward the NE or elongating.

The general morphology and asymmetric evolution of the two shoreface banks are consistent with their interpretation as classical linear tidal sandbanks (Caston, 1972; Kenyon et al., 1981), the migration dynamics of which result from the growth of ebb and flood channels. However this interpretation, which implies that the banks are in equilibrium with the regional tidal dynamics only, cannot be fully retained. The observed internal structure is incompatible with that of classical tide-dominated banks (e.g. Houbolt, 1968; Yang and Sun, 1988; Berne et al., 1994; Collins et al., 1995); moreover, instead of experiencing mainly a slow elongation as is usually the case for classical linear tidal bodies, the banks off Dunkerque are subject to both a slow elongation and a significant migration normal to their main axis and oriented onshore. As the surficial dynamics over the banks is necessarily controlled by the combined action of tidal currents and waves during moderate-energy wave conditions, it is likely that the northerly storms occurring in this macrotidal coastal environment severely affect the banks and therefore partly control their migration.
Table 1. The place of the Snoew and Braek banks in the classification of Belderson (1986). Arrows indicate the bank affinity with tidal or storm-generated bodies.

<table>
<thead>
<tr>
<th>Angle with coastline</th>
<th>Tidal sand banks</th>
<th>The Snoew and Braek Banks</th>
<th>Storm-generated ridges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>related to peak tidal current direction</td>
<td>&lt;= almost 0°</td>
<td>up to 60° (mode 35°-40°)</td>
</tr>
<tr>
<td>Sandwaves</td>
<td>abundant and semipermanent</td>
<td>absent =&gt;</td>
<td>rare to absent</td>
</tr>
<tr>
<td>Obliquity with main flow</td>
<td>0°-20° (generally 7°-15°)</td>
<td>&lt;= 0°</td>
<td>up to 60° (mode 35°-40°) with coast-parallel main flow</td>
</tr>
<tr>
<td>Height</td>
<td>up to 43 m (55 m for moribund banks)</td>
<td>&lt;= 10-15 m =&gt;</td>
<td>3-12 m (average 7 m)</td>
</tr>
<tr>
<td>Crests</td>
<td>frequently sharp (except where crests are near sea surface)</td>
<td>&lt;= smooth-crested =&gt;</td>
<td>smooth-crested</td>
</tr>
<tr>
<td>Slope angles</td>
<td>6° or less</td>
<td>1-4° =&gt;</td>
<td>2° or less</td>
</tr>
<tr>
<td>Spacing</td>
<td>2-30 km</td>
<td>&lt;= locally up to 10°</td>
<td>0.5-7 km</td>
</tr>
<tr>
<td>Length</td>
<td>up to 70 km</td>
<td>&lt;= 8-10 km =&gt;</td>
<td>up to 20 km</td>
</tr>
<tr>
<td>Internal structure</td>
<td>pervasive normal cross-stratification</td>
<td>almost conform to morphology</td>
<td></td>
</tr>
</tbody>
</table>

Considering the classification proposed by Belderson (1986), the Snoew and Braek banks belong strictly neither to the category of tidal sand banks, nor to that of storm-generated sand ridges (Table 1). In their size and generally low slope angles, the Snoew and Braek banks display a certain affinity with storm-generated ridges. Their flat-topped morphology can also be related to wave action. On the other hand, an affinity with tidal sandbanks is suggested by the locally high slope angles and the dominant shore-parallel orientation, which means that tidal currents play a key role in the general maintenance of these morphological features. Therefore, the construction and migration dynamics of the shoreface banks are thought to be controlled by a combination of longshore tidal processes and shore-normal storm-induced processes. Previous studies on shallow banks located in inner shelf, tidally-influenced environments have also appealed to a combination of tide and wave processes to explain the surficial sand dynamics (Houbolt, 1968; Caston, 1972; Stride, 1988; Houthuys et al., 1994; De Meene, 1994; Antia et al., 1995; De Meene et al., 1996), but none has documented the large-scale internal structure as evidence.

The reflector shape differs in the external and internal bank flanks. Beneath the external flank the reflectors R3 usually display a sigmoidal shape whereas beneath the internal flank the reflectors R4 systematically show truncated toplaps. This last characteristic reflects the action of high energy processes that lead to heavy erosional effects. In contrast, the sigmoidal shape of the reflectors R3 can be related to depositional processes of moderate energy allowing the preservation of tangential toplaps. These seismic data, associated with hydrodynamic conditions prevailing in the study area, suggest that storm wave action is partly responsible for the onshore migration of the internal flank whereas tidal dynamics dominate the external flank accretion toward the northeast.

As a consequence, the western part of the two banks is presently forced to migrate onshore under the action of northerly storm waves, while their eastern part elongates and/or migrates offshore under the action of tidal currents. These processes can be described as follows (Figure 12):

1) During storm events, shoaling and breaking waves erode the very shallow back and crest of the banks. Sand is overwashed landward along the internal steeper flank causing its progradation. The predominant landward migration evidenced by bathymetric investigations indicates that most of the sand overwashed along the internal flank is deposited with a shore-normal component. However part of the material resuspended by storm waves is transported by tidal currents in a longshore direction, especially toward the ENE under the action of the dominant flood currents. This flood-induced transport explains why the banks tend to elongate.

Sand transport under storm action in the shoreface zone depends on many factors and is usually fairly difficult to predict in terms of vectors (Swift et al., 1981; Vincent, 1986; Wright et al., 1991). However, storm-induced onshore transport has been observed and described in detail by Vincent et al. (1983), and previously invoked to explain landward migration of some shoreface banks and shoals by sand overwashing (Swift et al., 1972; Shaw and Forbes, 1992). Moreover, shoreface ridges have been occasionally compared in terms of morphology with wave-built bars (Swift and Field, 1981), the landward displacement of which may occur during high wave activity (Davidson-Arnott and Greenwood, 1976) and storms (Greenwood and Mittler, 1984; Greenwood and Sherman, 1984; Greenwood and Osborne, 1991).

2) Tidal dynamics control the seaward flank accretion on the eastern parts of the banks toward the ENE to NE. This is presently opposed to the landward flank construction on their western parts under the storm wave action. Two main factors explain this local predominance of tidal currents over storm waves in the control of bank migration: these are water depth and sheltering from wave attack. Water depth is involved in the case of the eastern part of the Snoew Bank (Figure 5, profiles 13 to 15). This is the deepest part of the bank at the present time and tidal currents are considered to remain the dominant agent of transport. Moreover, the flood velocity is enhanced in the channel separating this eastern part of the Snoew Bank from the western part of the Braek Bank. According to seismic and bathymetric data, the
main construction component of this part of the Snouw is oriented toward the ENE, i.e. almost longshore and under the influence of flood. The dominance of longshore processes in the deepest areas is confirmed by the presence of the reflectors R5 essentially located in the channel separating the eastern end of the Snouw Bank and the western termination of the Braek Bank. They form a seismic unit the shape of which consists of an elongated trough pointing to a transport parallel to the bank.

Such a control by water depth on bank migration cannot be evoked for the eastern part of the Braek Bank, one of the shallowest zones of the area. On this evidence, wave-induced transport should be strong on this part of the bank, but we think that tidal currents are the main factors responsible for the northeasterward migration. In fact, another bank lies very close to and off the eastern part of the Braek Bank (the Smal Bank, Figure 1B). Its crest is just submerged during low tides, and it is even shallower than the Braek crest. During northerly storms, waves first break on the Smal bank, dissipating much of their energy before arriving at the eastern end of the Braek Bank. This explains why the action of tidal currents probably remains dominant in this area. This form of protection from wave attack behind sand bars has long been recognized in nearshore environments (e.g. DAVIS and FOX, 1972). As revealed by seismic and bathymetric profiles, the slopes of the seaward flank and associated reflectors R3 in the eastern part of the Braek are higher (up to 10°) than those of the seaward flank of the eastern part of the Snouw the accretion of which is interpreted to be also flood-controlled. This feature is thought to be the consequence of a higher asymmetry between flood and ebb velocities in the channel located north of the eastern end of the Braek Bank. On the bathymetric map (Figure 2), it can be seen that the eastern end of this channel is partially closed. The closing probably results from the landward overwashing of sand reworked from the crest of the Smal Bank during storm events. The velocity of ebb currents flowing from the ENE is necessarily reduced in this area.

**DISCUSSION**

**The Bank Construction Stages**

One of the most significant results of the seismic investigation is the evidence for occasional reversal of the migration pattern during the bank construction, i.e. the parts that are migrating landward at the present time were previously migrating longshore, and vice versa. Changes in water depth and protection against wave attack are assumed to be the cause of this inversion. The following scenario is proposed to explain the bank construction and evolution (Figure 13):

1. Under the action of longshore tidal currents, a classic linear tidal sandbank began to form, developing along a pre-existing relief (core). The flood current was already dominant, and the bank migrated slowly toward the NE to ENE.

2. As the bank grew and elongated, a flood channel formed obliquely to the bank elongation, according to the classic evolution proposed by CASTON (1972). This flood channel formation progressively led to the separation of the Snouw and Braek banks.

3. The two tidal banks continued to grow. When their crest reached a critical depth (about −3 m according to the present bathymetric data), storm waves became effective enough to
Waves obliterate the tidal transport, initiating landward migration. However tidal currents remained dominant in the flood channel built previously so that the eastern part of the Snouw Bank continued to elongate in the ENE to NE direction.

(4) The storm-induced landward migration may finally lead to a progressive suturing of the banks to the foreshore. Similar phenomena occurred in the XVIIth Century on another bank in the same study area (CORBAU et al., 1995). By contrast the eastern part of the Braek remains sheltered from wave attack by the surrounding bank growth, allowing replacement of the landward storm-induced migration by a new stage of tide-induced displacement toward the NE.

The Sedimentological Nature of the Banks

The foregoing interpretations should be checked by core data. Unfortunately this is technically very difficult and has not been achieved so far. However, the combination of hydrodynamic measurements, surficial bedforms and seismic data provides reliable indications on the successive lithofacies contained in the banks and, more specifically, on the successive seismic reflectors identified.

Most of the sediment probably consists of fine- to medium-grained sand comparable to the surface sand. This is deduced from the quality of the seismic data provided by the 2.5 KHz sub-bottom profiler. This seismic tool has an acoustic signal the energy of which does not allow a deep penetration in coarse-grained material. As the penetration is good through the reflectors R3 and R4 of the banks, we postulate that these reflectors do not consist of shell- or gravel-lags. By contrast, none reflections can be observed beneath the basal reflector R1, suggesting that the seismic signal does not penetrate this surface. This indicates the coarse-grained nature of R1 and thus reinforces the interpretation that this reflector constitutes the pebbly Holocene transgressive surface. With regard to the sedimentary facies and bedding within the banks, the facies present within the reflectors R3 ("tide-dominated" seaward flank) are inferred to be partly represented by tidal dune cross-bedding although these bedforms are rare at the bank surface. Such facies are probably preserved as well within the reflectors R4 ("storm-dominated" landward flank), but there it is likely that most primary sedimentary structures reflect the combined action of tidal currents and waves as described by VAN DE MEENE et al. (1996) in shoreface banks off the Netherlands coast. Finally, in view of the epi-sodic sand motion, we postulate that reflectors R3 and R4 incorporate periods of nondeposition or of very low sedimentation and transport rates. R3 and R4 may represent the interface between very fine-grained sediment and/or a bioturbated surface (low rate of deposition/transport) and coarser sand deposits (high rate of deposition/transport). It is nevertheless unlikely that clay drapes like those described in some linear tidal sandbanks (e.g. HOURT, 1968) occur in the internal facies of the Snouw and Braek banks since their mean water depth is frequently above the fairweather wave base.

The Age of the Banks

As revealed by the seismic data, the banks contain an inner core representing the initial bank, on each side of which the flanks developed. In the absence of direct dating, the age of the core and of the subsequent flank construction has not been determined.

We presently envisage two main hypotheses for the age of the core: (1) The initial banks were constructed during the first major transgressive stage of the Holocene sea-level rise, i.e. before 4000 BP; (2) The present-day banks are very recent sedimentary features, and the initial bank construction is related to the minor transgressive pulsation that occurred after 1500 BP. Let us consider each of these possibilities.

(1) Stratigraphic investigations in the Dunkerque coastal plain led to the identification of two main transgressive stages during the Holocene sea-level rise (SOMME, 1979): the Calais stage from 8000 BP to about 4000 BP, and the Dunkerque stage from 2500 BP until now. These two stages are represented in the Flemish coastal plain succession by two marine formations separated by a peat layer dated from 3500-3400 BP. In the marine domain, the Calais and Dunkerque stage deposits have been correlated with two formations identified in some sandbanks of the North Sea; these banks contain a core of Atlantic age (older than 5000 BP) overlain by sand deposits called "the Young sands" (OELF, 1969; VICAIRe, 1991; VAN DE MEENE, 1994), which postdate 2000 BP. We do not know if these two formations exist in the Snouw and Braek banks off Dunkerque. The new seismic data presented herein are nevertheless consistent with the possibility that the core of the two banks belongs to the Calais stage.

(2) Recent bathymetric investigations made off Calais, about 30 km WSW of Dunkerque on a shoreface bank morphologically similar to the Snouw and Braek banks, show that this bank developed no more than 100 years ago, and subsequently grew and migrated landward (GARLAN, 1990). In addition, the merging of a shoreface bank to the foreshore during the XVIIth Century has been reported in the Dunkerque area (see CORBAU et al., 1993). This suggests that the
shoreface off Dunkerque may have been affected by considerable morphological change in recent historical times. Therefore, we cannot exclude the possibility that the Snouw and Braek banks are recent (historical) sedimentary bodies, although they were already identified as individual banks on bathymetric maps of the XVIIth Century. Stratigraphic studies performed on the Dunkerque stage successions have shown that this stage comprises three transgressive pulsations, the last one being post-medieval (Xth Century). As a consequence, the inner core of the Snouw and Braek banks might represent the residue of banks that developed during the pre-medieval period of the Dunkerque stage.

Considering these two hypotheses we postulate then that the Snouw and Braek banks could be of either millenial- or centennial-order age. The pattern of migration some 100 years ago was probably similar to that observed today, the bathymetric maps of the end of the XIXth Century showing no evidence of extensive morphological changes relative to the present-day configuration. Differences are more important when comparing older maps. By comparing the rate of bank migration deduced from bathymetric data (1 to 5 m/year, CORBAU et al., 1993) and the migration distance deduced on seismic profiles from reflectors R3 and R4 (a few hundreds of meters), a centennial-period could be reasonably deduced as the time-scale for the evolution of these shoreface banks, provided that a comparable migration rate prevailed over that time. Then, the Snouw and Braek banks are thought to be relatively recent bodies. If this is the case, their inner core is probably much younger than the Calais stage (> 4000 BP), the residual deposits of which might be represented by the basal reflector complex preserved beneath the most landward part of the banks.

Future Evolution and Environmental Implications

Whatever the exact age of the Snouw and Braek banks, their present-day construction and migration dynamics are related to the present high sea-level stillstand. As long as the sea-level and sediment supply conditions do not change significantly, the storm-induced landward migration should continue and progressively lead to the attachment of some parts of the banks to the adjacent foreshore. Such suturing, as has occurred already in the study area (CORBAU et al., 1993), should contribute to the natural nourishment of beach systems by providing an additional sand supply. In turn, if the rate of sea-level rise increases and/or the bank sediment supply decreases, this natural evolution could change, tidal currents tending probably to become dominant again over wave action. Sediment for bank maintenance is likely to be supplied from the adjacent bank areas located offshore and upstream to the dominant flood current. Extensive dredging and/or establishment of coastal protection devices in these areas could induce a deficit in bank sediment supply. Such human activities, especially linked to harbour and industry developments, are widespread along the Dunkerque coast but it remains difficult to estimate their direct impact on the functioning of the shoreface banks. It is worth noting however that the navigational channel that separates the Snouw and Braek banks from the foreshore is constantly dredged. Such activity prevents their suturing to the foreshore and in this way could be responsible for beach erosion.

CONCLUSION

This paper presents and discusses the large-scale internal structure of two shoreface banks (the Snouw and the Braek) located in the macrotidal environment of the Southern Bight of the North Sea. The study is documented through high-resolution seismic reflection data combined with results of bathymetric investigations and hydrodynamic measurements in the shoreface domain of the Dunkerque area, northernmost France.

1. Since the early stages of evolution, the bank construction and migration have been controlled both by tidal currents that induce their elongation and ensure their shore-parallel morphological maintenance, and by frontal storm waves that force some parts of the banks to migrate actively landward. Such banks should thus be defined as mixed “tide- and storm-generated” banks.

2. As revealed by changes in the geometric relations between tide- and storm-generated seismic reflectors, the pattern of migration was occasionally reversed during bank construction, depending on the predominance of tidal dynamics over that of storm wave action, and vice versa. This inversion is due to water depth changes over the banks as well as to the occasional development of surrounding banks, each of them experiencing a specific evolution, sheltering the more coastal banks against wave attack.

3. Although no direct dating evidence is available, the shoreface banks studied off Dunkerque are considered as probable recent sedimentary bodies, the construction of which began only a few centuries ago. The development of these banks is, thus, related to the present-day high sea-level stillstand. As long as the sea-level conditions do not change and/or the bank sediment supply does not decrease, storm-induced landward migration should lead to the bank suturing to the foreshore. Therefore, the dynamics of such very shallow shoreface banks potentially contribute to the natural nourishment of the beach system. In areas where beaches tend to retreat as is the case along the coastal system of Dunkerque, human activities (such as extensive dredging) that modify sediment supply have thus to be carefully controlled in order to minimize coastal and seabed instability.

ACKNOWLEDGEMENTS

GENAVIR/IFREMER is thanked for providing seismic equipment and technical assistance during the sea survey, as well as the crews of Sepia 2. We are indebted to Chris Vincent, Serge Berné and Joost H.J. Terwindt for their useful and constructive comments. Thanks are also due to Dr. Donald L. Forbes and an anonymous referee for their critical comments which much improved the final text.

LITERATURE CITED


Publication of the International Association of Sedimentologists, 5, 361–383.


