

Architecture and long term evolution of a tidal sandbank: The Middelkerke Bank (southern North Sea)

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Abstract

The internal structure of the Middelkerke Bank (one of the Flemish Banks located in the southern North Sea off the coast of Oostende, Belgium) has been studied in the framework of the Marine Science and Technology (MAST) program co-funded by the European Community. A dense grid of high and very high resolution seismic profiles has been used, as well as several vibrocorings. Seven major seismic units can be identified in the Quaternary sediments, bounded by major discontinuities correlated across the whole study area. The lower units clearly appear as being deposited during periods of relative low sea level (channel infillings, shoreface, estuarine and/or ebb-tidal delta deposits). The present shape of the bank results partly from recent erosional processes, reworking the underlying deposits. Thus, the lower part of the bank as a morphological feature does not consist of "offshore tidal sands". The master bedding of the upper part of the bank consists of inclined reflectors, dipping at an angle of about 5° in the same direction as the bank's "steep" face. These reflectors, very similar to those described by Houbolt (1968), are interpreted as being the result of alternating periods of deposition and erosion related to the episodic combination of tidal currents and storms.

1. Background

Since the pioneering work by Houbolt (1968) in the Southern Bight of the North Sea, very little progress has been made in the recognition of the internal structure of tidal sand banks (also called "tidal sand ridges" by some authors), mainly because of technical difficulties encountered while investigating such deposits. The seismic records of this author indicated that the master bedding of the Well Bank and of the Smith Knoll consisted

of inclined reflectors parallel to the steeper face of the bank, with a dip of about 5°. Short cores evidenced that these surfaces bounded smaller sets of cross bedding (with angles of dip up to 32°), related to the migration of superimposed dunes, moving down—or parallel to—the "lee" side of the bank.

Based on morphological studies, a more speculative—but not very different—structure was proposed by McCave and Langhorne (1982) for the Haisborough Sand, also in the southern North

Sea. Taking into account the presence of smaller and more symmetrical bedforms along the crest of the sandbank, these authors proposed a model of structure where the large-scale (about 2 m high) cross-strata were overlain by interbedded flat bedding and medium-scale cross-strata (0.1–0.5 m thick sets). As in the Houbolt's model, all primary bedding planes (master bedding) were dipping at less than 5°.

More recently, a model based on short cores and current measurements has been proposed for the Moreton Sandbank (eastern Australia) by Harris et al. (1992). The main difference with the Houbolt's model is that, because of relatively weak tidal currents, foreset beds are preserved only on the crest of the sandbank, while sand is mainly bioturbated in other locations.

Another important result of the investigations by Houbolt (1968) was that the sand banks were found to rest on an essentially flat surface, which strongly supported a purely hydrodynamical origin of formation (as discussed by many authors: Caston, 1972; Pingree and Maddock, 1979; Belderson et al., 1982; Huthnance, 1982a,b; Pattiaratchi and Collins, 1987; Hulscher et al., 1993). Similar observations were reported from the Kwintebank (southern North Sea) (De Moor, 1989) or from tidal sand "ridges" of the continental shelf of western Canada (Moslow et al., 1989) and of the southwest Florida inner shelf (Davis et al., 1993). Similar observations were also reported for "moribund" sand banks (banks considered to have formed during the early Holocene) of the Celtic Sea (Bouysse et al., 1976), of the East China Sea (Yang and Sun, 1988) and of the North Sea (Davis and Balson, 1992). In contrast, the Zeeland banks in the southern North Sea appeared to be at least partly created by sand accumulation around a pre-existing sediment body (Houbolt, 1968; Laban and Schüttenhelm, 1981), as well as the banks located in the approaches to the Thames estuary (D'Olier, 1981) or some "ridges" of the Southern Yellow Sea (Yang, 1989).

From this limited information, it finally appears that two main types of tidal sand banks can be recognized from a stratigraphical point of views.

(1) Sand banks resting on a flat surface, where bank buildup is only related to a convergent

pattern of sand transport. In that case, the whole bank consists of Holocene deposits (early Holocene in the case of the "moribund" sand banks of the outer shelf, late Holocene in the case of active sand banks of estuarine or inner shelf environments.

(2) Sand banks whose core consists of eroded fluvial or estuarine sediments (of early Holocene age in the case of inner shelf sand banks, of Pleistocene age in the case of outer shelf "moribund" sand banks), or of erosive bedrock morphology.

In both cases, formation and maintenance of the bank require physical processes at the origin of convergent pattern of sand transport, like in the stability models of Huthnance (1982a,b).

2. Methods

2.1. Geophysics

The geophysical data set was acquired during four cruises, conducted between December 1990 and June 1992, with the research vessels *Belgica* and *Le Suroît*. The Belgian SYLEDIS chain was employed for accurate (about 3 m) positioning during each cruise. In order to obtain a sufficiently dense coverage of the study area a pseudo 3-D seismic grid was dimensioned, consisting of 72 transverse profiles with a spacing of 200 m and 6 longitudinal intersecting profiles. In addition, the northern termination of the bank was studied with more detail, 16 profiles 100 m apart being run. The grid covered a total area of 16 by 7 km, and comprised the entire Middelkerke bank and its surrounding swales as well as the seaward flank of the Oostende Bank (Fig. 1). The two main seismic sources used for the surveys were a 300 J Centipede sparker and an EDO 515A sub-bottom profiler working at 2.5 kHz. A total of 470 km of sparker profiles and of 350 km of 2.5 kHz sub-bottom profiles were recorded, both in analog and digital modes.

Analysis of reflector terminations (erosional truncation, onlap, downlap) allowed identification of the boundaries of the seismic units. Unconformity depths were checked at the numer-

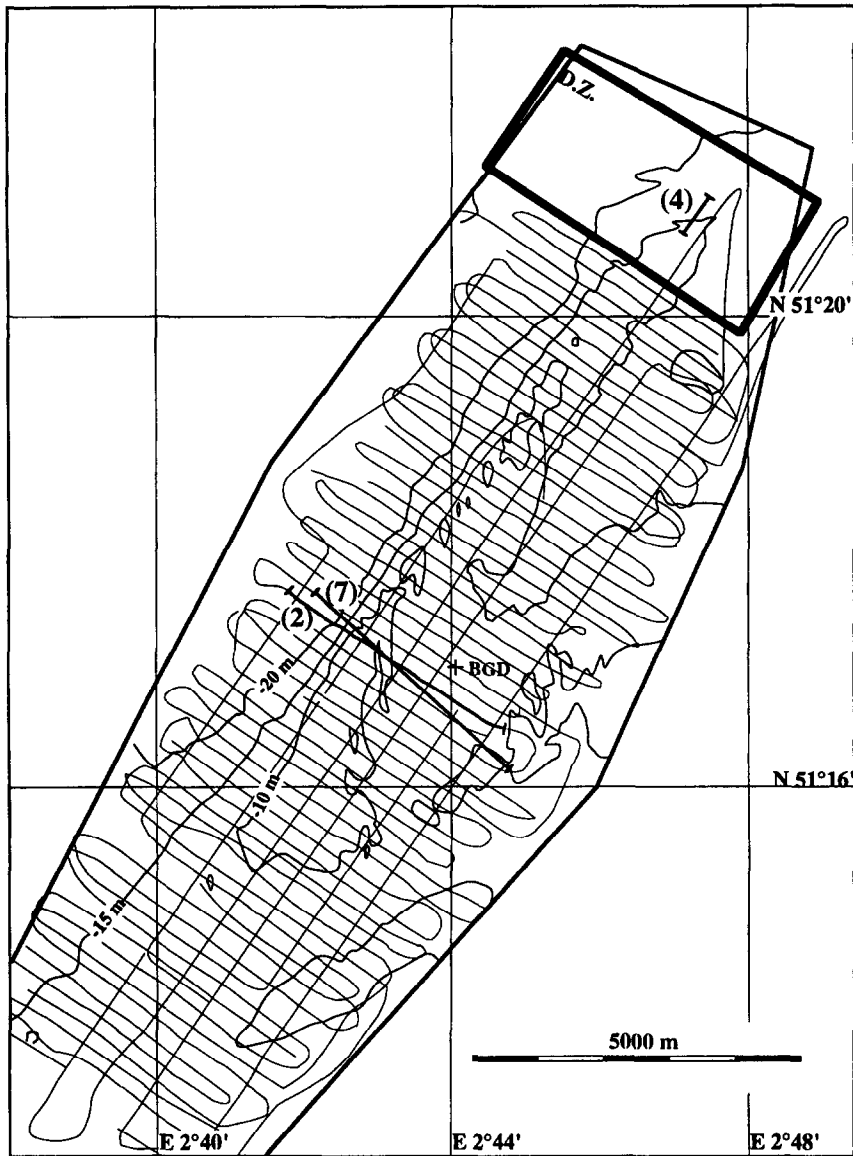


Fig. 1. Location of geophysical survey lines. *D.Z.* = detailed zone with 100 m spaced seismic lines; (2), (4) and (7) are the positions of Figs. 2, 4 and 7; and *BGD* = position of the borehole.

ous tie-points. The main interpreted reflectors were manually digitized and fed into a database allowing calculation of time–depth converted and re-scaled line-drawings (based on a sound velocity in sand of 1700 m/s). Eventually, these data were transferred to the GEOFOX system (Verschuren, 1992). The system allows interactive triangulation of the reflector points and generation of smoothed

gridded surfaces, which may be visualized either as contoured maps, perspective views or fence diagrams.

2.2. Coring

One borehole drilled by the Belgian Geological Survey (Baeteman and Maenhout van Lemberge,

1989) in the adjacent Uitdiep Swale, as well as several vibrocores acquired by the University of Utrecht in the framework of this MAST project, provide a “ground-truth” for the interpretation of the seismic units. The vibrocores were obtained with the “Triflip” vibrocorer, designed and constructed by the Geological Survey of the Netherlands (Hoogendoorn and Kluwen, 1990). The vibrocores were opened on board and lacquer peels were made by the pouring method (Bouma, 1969).

3. Results

3.1. Seismo-stratigraphic interpretation

Hierarchy of bounding surfaces

The combined use of sparker and sub-bottom profiles allows one to distinguish a hierarchy of bounding surfaces, in the sense of Brookfield (1977). Within the Middelkerke Bank study area, four main reflector categories are distinguished on the base of geometrical characteristics:

- the major unconformity at the top of the Tertiary deposits;
- major bounding surfaces within Quaternary deposits;
- medium bounding surfaces; and
- minor bounding surfaces, mainly observed in the upper layers where the sub-bottom profiler provides a good resolution.

The unconformity at the top of the Tertiary deposits is strongly apparent on most profiles. It represents the erosional boundary and significant stratigraphic hiatus between the Eocene Kortrijk Formation or “Ieper Clay” and the overlying Quaternary deposits (De Batist et al., 1989). This boundary is an angular unconformity, slightly dipping (0.005%) towards the north and characterized by incisions or depressions. Its average depth ranges between –12.5 m (MLLWS) in the southern part of the bank and –37.5 m in the incisions. These appear to line up in a bifurcating NW–SE and W–E trending channel system, located underneath the central and northern parts of the bank. Previous studies (Mostaert et al.,

1989; Liu et al., 1992) attribute this channel system to the Oostende Valley complex.

Seven major bounding surfaces have been identified within the Quaternary deposits. They represent unconformities and/or distinct seismic facies boundaries which can be easily identified on the seismic records and followed over large (>1 km) distances. These reflectors ($U_{1,b}$ – $U_{7,b}$) correspond respectively to the lower boundaries of seven seismic units, called U_1 (bottom) to U_7 (top). An example of an analog record and interpreted line-drawing showing the seven seismic units is given in Fig. 2.

Reflectors $U_{1,b}$ and $U_{2,b}$ are erosional surfaces cutting across Tertiary deposits. They form the base of channel-fill units U_1 and U_2 , restricted to the northern and central part of the bank, where the study area intersects with the Oostende valley complex. In some locations, $U_{2,b}$ is also eroding U_{1b} .

Reflector $U_{3,b}$ is a quasi-horizontal surface cutting across U_2 , U_1 or even the Tertiary deposits. It is restricted to the central part of the bank.

Reflector $U_{4,b}$ is a very high-amplitude reflector that occurs throughout the entire area. It is quasi-horizontal and cuts across underlying surfaces (including the basal unconformity). It is not truncated by overlying unconformities.

Reflector $U_{5,b}$ has a low reflectivity and is only observed in a restricted area in between the Middelkerke Bank and the Oostende bank.

Reflector $U_{6,b}$ has a very strong reflectivity. It can be observed in the southern part of the Middelkerke Bank as well as in large parts of the Oostende Bank. It locally outcrops in the Uitdiep Swale. In a NE–SW direction, it is slightly concave upward.

Reflector $U_{7,b}$ is strongly undulating and occurs in the entire Middelkerke Bank and in parts of the Oostende Bank. It outcrops in the Uitdiep and Negenvaam Swales, except in the southern part of the study area. It displays a convex upward shape in the NE–SW direction. In many cases, it represents the lower bounding surface of large scale overlying inclined reflectors (medium bounding surfaces, see below). Within U_7 , a sub-horizontal reflector is observed on some profiles, but its lateral extent is too low to permit any correlation.

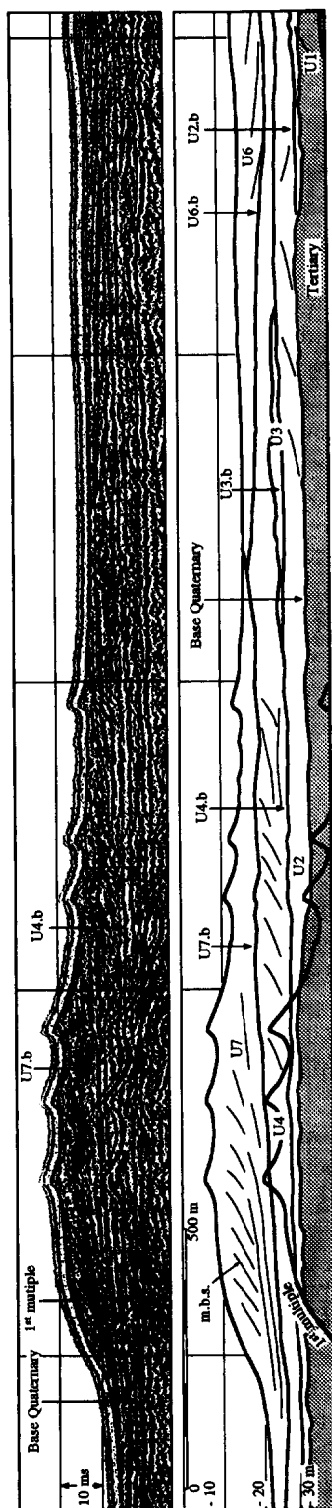


Fig. 2. Analog record and interpreted line-drawing showing the seven seismic units bounded by major bounding surfaces; *m.b.s.* = medium bounding surface.

Ten selected line-drawings across the bank, illustrating its complex internal structure and lateral variability, are presented in Fig. 3.

Medium bounding surfaces within unit 7 have limited lateral extent (less than 1 km), preventing any correlation across several profiles. They are inclined reflectors dipping at an angle of less than 5° in the same direction as the bank “steep” slope (towards the northwest, Fig. 2).

Minor bounding surfaces (Fig. 4) are “reactivation surfaces” in the sense of McCabe and Jones (1977) (“inclined reflectors within a cross-bed set which separate adjacent foresets with similar orientations and truncate the lower foreset laminae”). They have very low lateral extent and are only observed on the sub-bottom profiler records. These surfaces characterize the internal structure of the large dunes covering the Middelkerke Bank, as well as some lower parts of U₇. In the latter case, they are bounded either by medium or major bounding surfaces. Their angle of dip ranges between 10° and 15°. Between these surfaces, steep (>15°) reflectors are observed.

Characteristics of the major seismic units

The main seismostratigraphic characteristics of each of the seven major seismic units (i.e. units bounded by major bounding surfaces) are summarized in Fig. 5. The external form of these units, although probably largely modified by erosional processes, clearly exhibits an evolution through time from a channel fill shape (units U₁ and U₂) to a lens or bank shape (units U₄ to U₇).

Unit 1 consists of transparent channel fill deposits, without any internal reflectors.

Unit 2 is also a channel fill deposit, but it is restricted to the Uitdiep and Oostende Bank areas. It displays few internal reflectors, parallel to the base of the unit.

Unit 3 clearly represents an intermediate depositional pattern, with a flattened morphology and internal reflectors dipping very gently (about 1°) towards the WNW. It is restricted to the central part of the study area. Its mean thickness is 5 m.

Unit 4 is present in the whole study area, including the adjacent swales and the Oostende Bank. It displays numerous internal reflectors, mainly dipping towards the north. Their angle of

dip amounts up to 5°. Its thickness does not depend on the depth of its lower boundary (U_{4,b}).

Unit 5 has a limited lateral extent (2 by 5 km) and is located underneath the central part of the present Oostende Bank. It has a lens shape, with elongation in the NE–SW direction. Its average thickness is about 2 m. There are few internal reflectors, gently dipping (less than 1°) in the southeastern direction.

Unit 6 also displays a lens shape in the NE–SW direction. Its large axis is oblique with respect to the present bank orientation. It is mainly developed in the southern part of the Middelkerke Bank, in the Uitdiep Swale and in the Oostende Bank. Several internal reflectors are present, dipping mainly towards the southeast at an angle of about 5°. Some of these reflectors have a sigmoidal shape, with tangential contacts with the lower seismic boundary (U_{6,b}).

Unit 7 corresponds to the present shape of the Middelkerke Bank. On several seismic lines, it could be subdivided into several sub-units, because of the existence of one or two sub-horizontal seismic reflectors cutting across the underlying deposits. However, the lateral extent of these reflectors is too small and does not allow any correlation across the bank. The characteristics of internal reflectors allows distinction of two zones (see Fig. 3): (1) In the northern part of the bank, where the asymmetry of the bank is well marked, internal reflectors are dipping towards the northwest at 1°–5°. (2) The southern part of the bank is characterized by sub-horizontal internal reflectors, onlapping against U_{7,b}.

3.2. Borehole and vibrocores correlations

Description of a complete Quaternary sequence

The borehole drilled by the Belgian Geological Survey in the adjacent Uitdiep Swale (location in Fig. 1) provides a “ground-truth” for the seismic interpretation. This drill-core, 13.75 m long, reaches the Tertiary substrate and allows correlation of five seismic units (U₁, U₂, U₃, U₄ and U₆). On basis of core descriptions, a lithological log has been drawn (Fig. 6).

Unit 1 is composed of coarse to medium poorly sorted grey sand, with few rounded flint pebbles

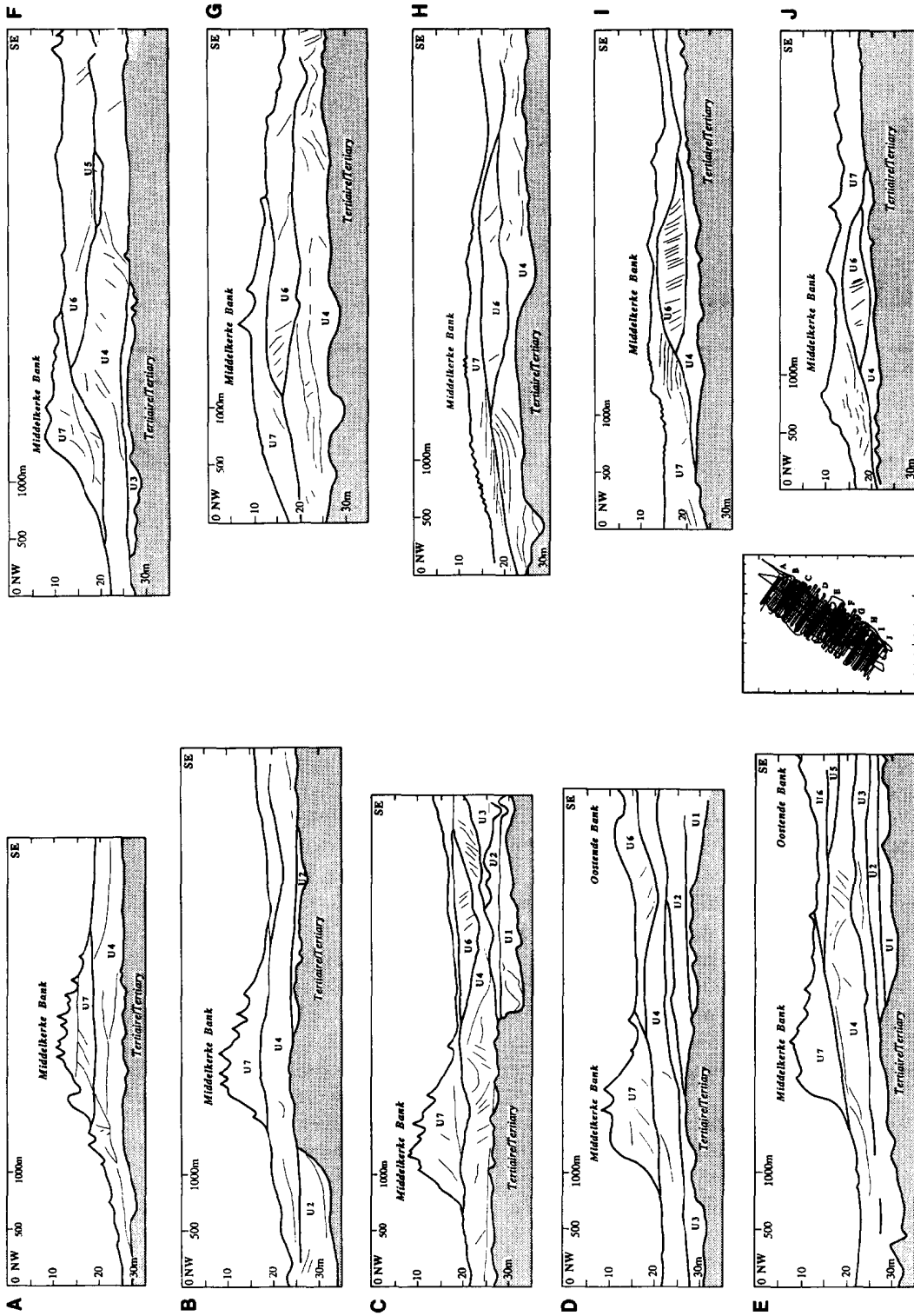


Fig. 3. Selected interpreted line-drawings from 10 sparker lines across the Middelerke Bank.

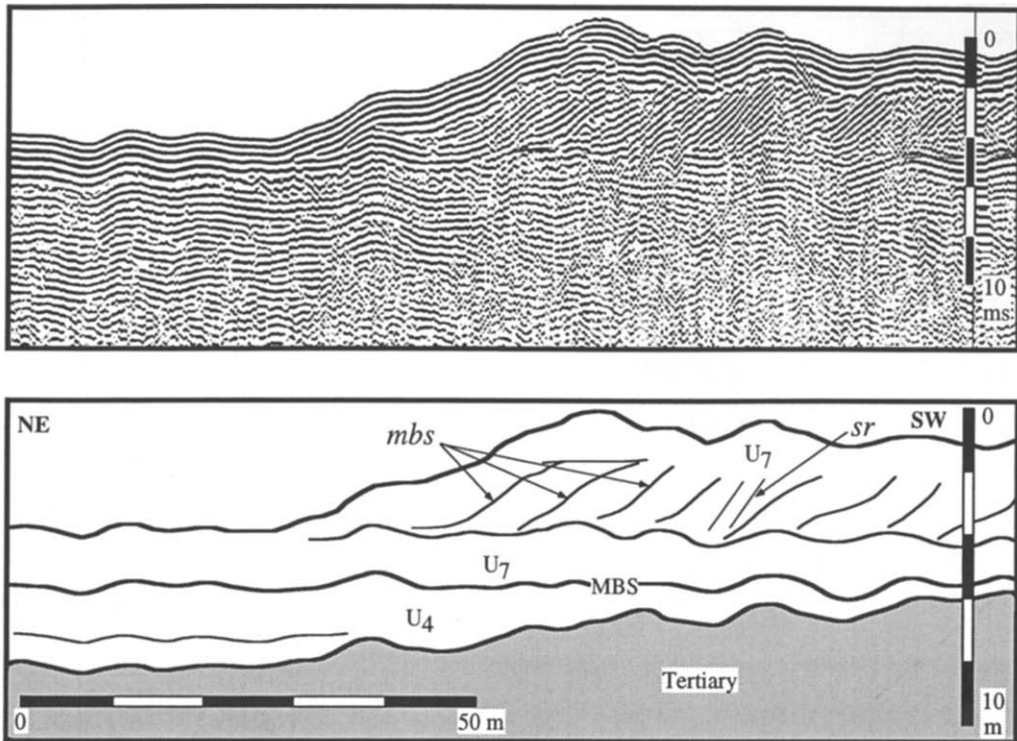


Fig. 4. Analog profile and line-drawing of a sub-bottom profile across the northern termination of the bank. *MBS*=Major Bounding Surface; *mbs*=minor bounding surface; and *sr*=steep reflectors.

and marcassite debris. Some shell debris (including an Eemian guide fossil: *Corbicula*) are also present, as well as some humic particles which occur either along some clay laminae or isolated within the sand.

Unit 2 corresponds to several lithological facies. Its lower part consists of clay deposits (continuous beds or mud clasts), mixed with organic debris. Between -11.90 and -11.25 m, oblique layers with fine grey sand and clay are present. The top of the unit is composed of medium grey sand in which some gravels (up to 3 cm in diameter) are present.

Unit 3, about 4 m thick at the borehole location, is mainly composed of homogeneous shelly medium brown–grey sand, into which the content of shells and shell debris increases upwards, while the clay fraction, which is very important at the base, decreases upwards through the core. Some flint pebbles are also present.

The major seismic bounding surface $U_{4,b}$, in

between U_3 and U_4 , corresponds to a good stratigraphic marker consisting of flint pebbles (some of these pebbles being up to 5 cm in diameter) overlying a sharp erosive contact.

Unit 4 consists of medium to fine grey sand, rich in shell debris and intensely cross-stratified. Some silt and clay layers are interstratified within the sand, especially in the lower part of Unit 4. Samples from some vibrocores (see below) reaching this unit indicate that very strong lateral facies variations exist within U_4 .

Unit 6 consists of fine, bioturbated yellow-brown to grey-brown medium to coarse shelly sand with some clay layers.

Unit 7 was not present at the borehole site.

Vibrocores profile across the bank

A set of 10 vibrocores was acquired across the bank along a seismic line previously recorded with the sub-bottom profiler (Fig. 7).

The core lengths range between 2.80 and 5.40

Unit	location and direction of internal reflectors	mean energy of the acoustic facies	external shape	maximum thickness
U 7		medium, low		13 m + dunes
U 6		medium		8 m + dunes
U 5		medium, high		5 m
U 4		high		14 m
U 3		low		7 m
U 2		medium		6 m
U 1		low		10 m

Fig. 5. Characteristics of the main seismic units in the Middlerkerke Bank area. The regional extension of each unit (within the adjacent swales and within the Oostende Bank) is represented by the squares: from left to right, the grids represent the Negenvaam Swale, the Middlerkerke Bank, The Uitdiep Swale and the Oostende Bank. The three horizontal divisions correspond to the northeastern, central and southwestern parts of the study area. Vertical lines correspond to the orientation of the Middlerkerke Bank axis.

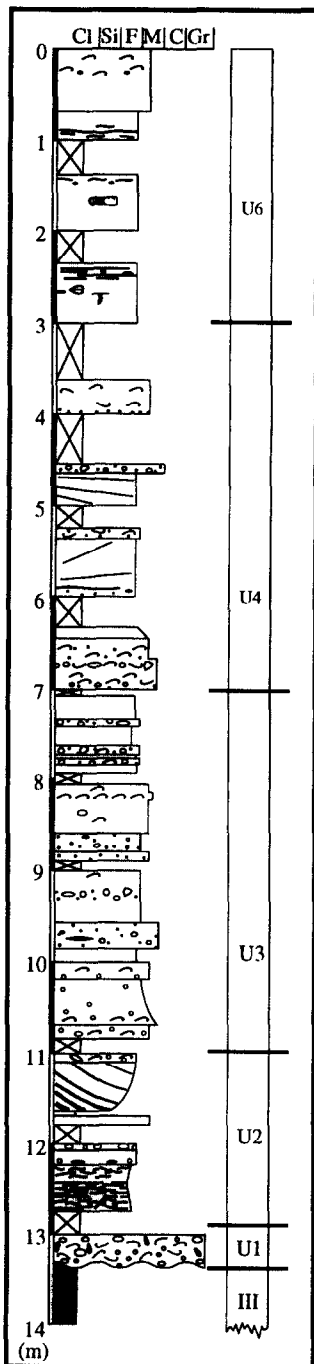


Fig. 6. Lithology of core no. 29 of the Belgian Geological Survey (Trentesaux, 1993, #650). The symbols are similar to those in Fig. 7. The scale to the right corresponds to the position of seismic units at the drilling point. × represents the parts of the borehole without sediment recovery.

m, for water depths between -6 and -18 m (MLLWS). The Middelkerke Bank, as well as the adjacent swales and the western termination of the Oostende Bank, have been sampled. Cores taken from U_7 and U_6 have a relatively homogeneous composition (fine to coarse sand) whereas those from the swales exhibit grain size changes, from clay to gravels.

Cores from U_7 (cores 22 to 25 and 21 pro parte) consist of fine to medium brown sands (125 – $250 \mu\text{m}$) with shells and shell debris and some flint pebbles up to 5 mm in diameter. The lower parts of cores 21, 22, 23 and 25 exhibit some large or medium-scale cross-stratification attributed to medium dunes/megaripples. These crossbeds are underlined by shell debris generally in a convex-up position. Few clay laminations are also preserved in between sand layers.

The major bounding surface between U_7 and U_4 is well correlated with a change in lithologic composition and sedimentary structures. Clay and silt deposits become more abundant in the cores sampled along the swales (20, 21, 26 and 27), while shell debris is less abundant. Within U_4 , sand layers mainly consist of fine grey sand, sometimes with thin laminations (upper plane bed?) or small-scale cross stratifications. However, core 19, supposedly taken from units 4, 5, and 6, does not exhibit any fine sediment. Furthermore, even in the case of cores taken about 100 m apart (e.g. cores 26 and 27), correlations between individual sedimentary units appear virtually impossible.

These observations indicate that, even within seismic units defined by well correlated bounding surfaces, strong lateral variations of the lithologic composition and sedimentary facies occur.

4. Discussion

4.1. Origin of minor bounding surfaces

Internal reflectors dipping at 10° – 15° in the same direction as the lee side of large tidal dunes have been described within dunes of the English Channel and of the French Atlantic shelf (Berné et al., 1988, 1991, 1993). As these surfaces have a very low lateral extent, positioning uncertainties

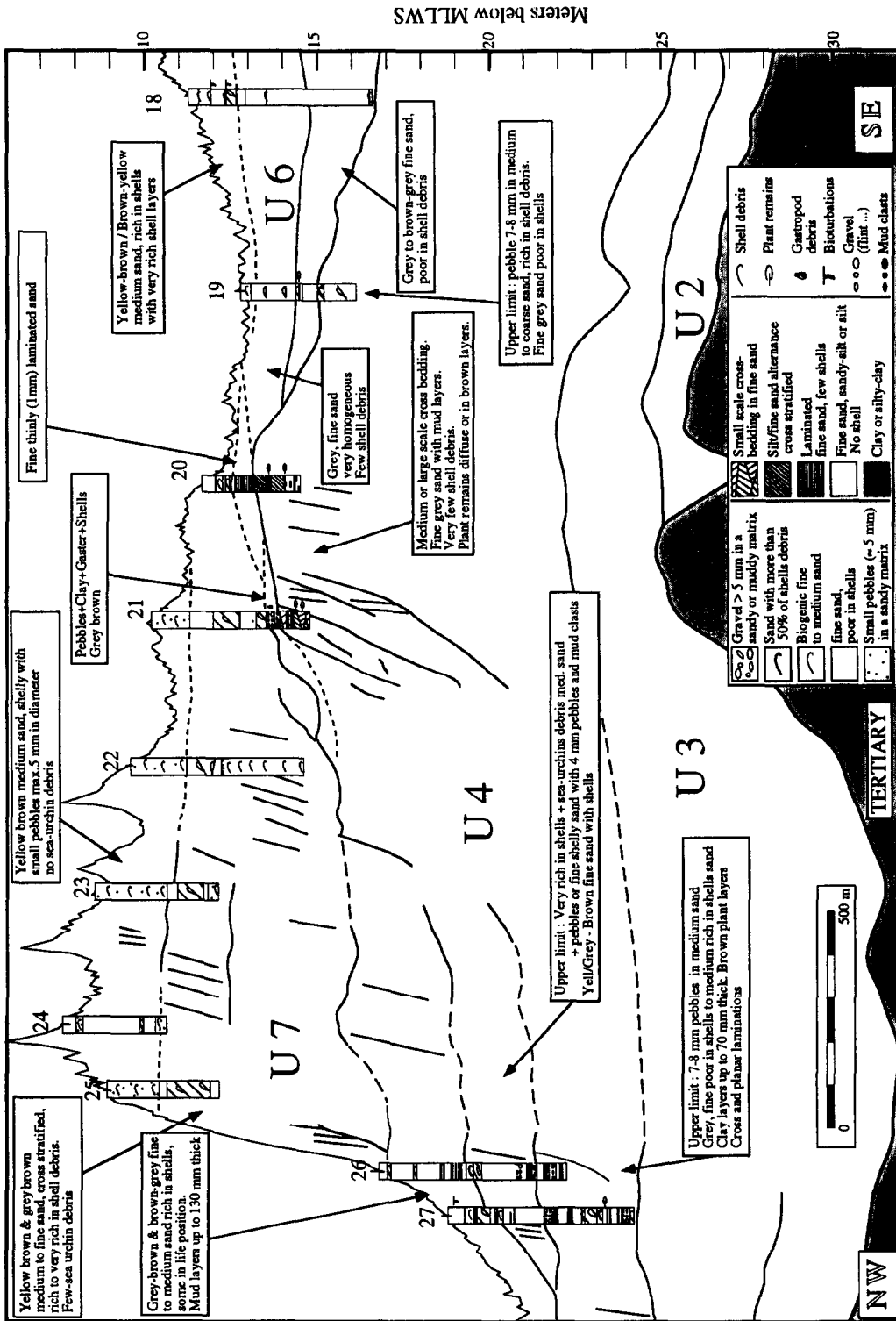


Fig. 7. Simplified core logs along a seismic profile across the Middelkerke Bank (location in Fig. 1).

and the time between seismic and coring operations do not permit a direct comparison of seismic and core data sets. However, samples from U₇ indicate that this unit is composed of homogeneous sand with some coarse layers consisting of shells and pebbles, up to 5 mm in diameter, generally less than 1 cm thick. Two processes may be at the origin of such layers:

(1) The downclimbing of small dunes (megaripples) could be at the origin of some “inclined cross-beddings” as described within intertidal dunes of the Bay of Fundy (Dalrymple, 1984). Small dunes are present all over the bank (Trentesaux, 1993), however, the size of cross beds deposited by such bedforms is an order of magnitude smaller than the resolution of our seismic equipment.

(2) Fluctuation of velocity and asymmetry of the bedforms is at the origin of compound cross-bedding, as shown by Rubin (1987, figs. 22 and 58). In the case of the Middelkerke Bank, the main episodic process which could be at the origin of such fluctuations is the combined effect of tidal currents, wind-driven currents and waves during storms. Several studies have shown that tidal bedforms could change—or even reverse—in response to changes in the wave and/or wind driven current direction and magnitudes (Terwindt, 1971; Hine, 1977; Field et al., 1981; Langhorne, 1982; Swift, 1985; Harris, 1989, 1991). Because of the relatively small water depth, the Middelkerke Bank is especially sensitive to such processes, as shown by comparison of hydrographic surveys which clearly indicate that storms result in a “rounding” of the shape of large dunes, while dune migration mainly occurs during fair weather periods (Houthuys et al., 1994-this volume).

In between some of these minor bounding surfaces, some steep ($>15^\circ$) reflectors are observed. Because of hyperbolae generally associated with such features, it is difficult to draw conclusions about the origin of these reflectors, but preferential orientations of these artifacts strongly suggest that they are produced by steep reflectors (like foreset beds dipping at the angle of repose) rather than to “point reflectors”. Furthermore, it must be pointed out that these steep reflectors match very well with large-scale cross-beds observed along

several cores. One explanation for this correlation is that the cross-beds are frequently underlined by shells or shell debris which could be at the origin of sufficient impedance contrasts for creating seismic reflections, as already mentioned for dunes on the Atlantic shelf (Berné et al., 1991).

4.2. Origin of medium bounding surfaces

Structures similar to the inclined reflectors forming the medium bounding surfaces were described by Houbolt (1968) within the Well Bank and Smith Knoll in the North Sea. However, cores from unit 7 indicate that the medium bounding surfaces could correspond to some coarse layers (consisting of shells and pebbles), rather than to mud layers as observed within the Well Bank or to differences in density. Two mechanisms may explain the origin of these surfaces.

(1) Migration of large dunes with a positive angle of climb. The medium bounding surfaces gently dipping toward the northwest could be related to the migration of large dunes moving obliquely with respect to the bank axis. In the case of a positive angle of climb, these dunes would deposit sets bounded by coarse lags related to the scouring effect which occurs at the bottom of the lee side of the dunes. The vibrocores show that these layers are relatively thin, thus probably only the thickest coarse lags could be detected on the seismic records.

(2) Alternating phases of erosion and deposition along the steep flank of the bank. Very accurate hydrographic surveys before and after a storm indicate a net post-storm sedimentation (up to 25 cm locally) over the northwestern flank of the bank (Houthuys et al., 1994-this volume, #643). Even if the mechanisms of long-term evolution of the bank are not clear, these results suggest that the “master bedding” of the bank could be the result of alternating periods of deposition and erosion (controlled by the combination of wave activity and wind-driven and tidal currents). Each coarse layer could correspond to the beginning of a storm period, which was subsequently covered by finer sediment eroded from the top of the bank and deposited along the flank. However, grading is not clearly observed within the cores.

The second process is more plausible since large dunes are not developed over the “steep” flank of the bank and because no example of dunes migrating with a positive angle of climb is observed in the study area. In any event, preservation of inclined reflectors requires *in both cases* a net deposition along the northwestern flank of the bank. The bank height is relatively constant because of permanent reworking of its upper part during storms, while the southeastern flank of the bank is mainly characterized by erosion (toplap terminations), which implies a net migration of the bank. Finally, it may be concluded that the orientation of inclined reflectors within the Middelkerke, can be used as an indicator of the long-term movement of the bank, as already proposed by Stride et al. (1982) for the Well Bank.

As to the sub-horizontal reflector observed within U_7 on some profiles (Figs. 3A,D and 5), the most likely mechanism is the scouring effect of large dunes migrating over the top of the bank.

4.3. Architecture of the Middelkerke Bank

A comparison of seismic profiles across the Middelkerke Bank (Fig. 3) shows a strong difference between the “offshore” and the “onshore” parts of the bank, as well as between its northwestern and southeastern flanks.

To the northeast, where the bank is relatively symmetrical in cross section, it rests on a relatively flat surface with medium or minor bounding surfaces downlapping over U_4 .

In the central part of the bank, a strong asymmetry develops, the “steep” flank of the bank facing towards the northwest. The Negenvaam Swale, to the northwest of the Bank, is up to 8 m deeper than the Uitdiep Swale, to the southeast. The bounding surface at the base of U_7 ($U_{7,b}$) becomes inclined towards the northwest. It is a well-defined erosional surface.

Further landward, the asymmetry of the bank disappears and internal reflectors within U_7 are onlapping against the underlying deposits.

These observations suggest that deposition is not the only process at the origin of the present shape of the Middelkerke Bank. The angle of dip of $U_{7,b}$ towards the supposed direction of migra-

tion of the bank and the clear erosional nature of $U_{7,b}$, cutting across underlying medium bounding surfaces, suggest that the formation of the Middelkerke Bank is associated with erosion of adjacent deposits, at least in its central part. This hypothesis is in agreement with the different physical models of sand bank maintenance, where the convergence of sediment toward the bank crest requires winowing of the adjacent swales (Houbolt, 1968; Pingree and Maddock, 1979; Zimmerman, 1981; Huthnance, 1982a,b).

As a result, the external morphology of the bank does not match its internal structure: Unit 4, which corresponds to the lower part of the bank, probably consists of estuarine or tidal flat deposits, rather than of offshore tidal sands. This suggests that the major bounding surface between U_7 and U_4 (or between U_6 and U_4) would be the main ravinement surface produced by the shoreface retreat during the Holocene sea-level rise. The lithological succession displayed by the borehole is similar to several examples from the East Coast of the U.S.A. as synthesized by Nummedal and Swift (1987). However, the lack of absolute dating prevents determining whether the last lowstand unconformity corresponds to the top of unit 3 or to the major unconformity at the base of Quaternary deposits. The second hypothesis is more likely because most of the Pleistocene deposits off the Belgian coast have been completely reworked during the last transgression (Jelgersma et al., 1979; Paepe and Baeteman, 1979). In that case, U_1 would be late Weichselian to early Holocene in age, as the valley fills of the Dutch coast (C. Laban, pers. commun., 1994). In this case, the top of unit 3 could represent a first (higher order?) ravinement surface associated with the Holocene transgression.

The difference in asymmetry between the offshore termination and the central part of the bank could correspond to a change in the net bedload transport direction. In the northern part of the bank, the orientation of steep reflectors within U_7 (calculated from two apparent directions along perpendicular profiles), as well as the polarity of the small and large dunes, indicate a net bedload transport towards the east or the east-northeast (flood direction). This suggests that the bedload

parting zone between a flood dominated zone, located in the axis of the Southern Bight, and an ebb-dominated zone further to the south, could be slightly further to the south than as mapped by Kenyon et al. (1981).

5. Conclusions

Compared to some relatively simple sand banks such as the Well Bank, the Middelkerke Bank represents a complex assemblage of depositional units, related to processes whose time scale probably ranges from 10^{-6} to 10^3 years, corresponding to the hierarchical subdivisions 1 to 7 in the terminology of Miall (1991). The present shape of the bank appears to be the result—at least partly—of erosional processes, reworking underlying deposits. As a result, the lower units of the bank do not consist of offshore tidal sands, but more likely of ebb-tidal delta or tidal flat deposits. The major bounding surface between the two units is interpreted as a ravinement surface produced by shoreface retreat.

The mechanism at the origin of the master bedding of the bank (medium bounding surfaces within U_7) is believed to be alternating phases of erosion and deposition, with net deposition, along the “steep” flank (NW) of the bank. Thus, the northwestern orientation of these reflectors is supposed to be indicative of the long-term migration of the bank. Uncertainties in positioning of former hydrographic surveys does not permit determination as to whether or not this process is still active.

Relatively steep reflectors (dipping at angles up to 15°) within the upper part of the bank are interpreted as “reactivation surfaces” within the large dunes. These surfaces are attributed to the “rounding” effect of storms rather than to semi-diurnal reversal of the tidal current as proposed by Allen (1980).

A precise chrono-stratigraphic framework is required for deciphering the time scales of processes at the origin of the different surfaces and sequences identified. Biostratigraphic analysis, radiocarbon dating, as well as comparison of the stacking patterns of the different sedimentary units with available curves of Quaternary sea-level fluctua-

tions will be undertaken in a near future in order to shed some light on the remaining questions.

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