Journal of Coastal Research	SI	51	63-76	West Palm Beach, Florida	Summer 2010

Geo-environmental Characterization of the Kwinte Bank

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ABSTRACT

A detailed geomorphological and sedimentological study has been performed at a tidal sandbank, which has been dredged during 30 years. Localised intensive aggregate extraction created a depression in the central part of the sandbank, upon which the Government decided to close this section of the bank for further exploitation. Multibeam and side-scan sonar technology was used to survey the bank, in combination with extensive ground-truthing. Automated seabed classification was performed, but showed no direct correlation with the mean grain-size; the primary drivers influencing the classification being the sorting of the sediments, the presence of shells and of fine sediments. Very-high resolution seismics revealed the internal architecture of the bank. In the central depression, the upper unit is locally severely dredged.

The central depression is characterized by distinct morphosedimentary facies, compared to the western and eastern part of the bank and the Kwinte swale, adjacent of it. The difference between the western and the eastern part is essentially due to different tidal current characteristics, each having their particular sedimentation-erosion patterns. These processes seem to be rather stable, though the evolution of the sediments in the central depression shows similarities with the Kwinte swale sediment evolution.

Since the depression is somewhat oblique to the normal crestline, it now forms an open transport pathway from the swale up to the crest of the sandbank. This led to a canalization of the flood current which is witnessed mostly by the northwards and faster progression of bedforms. Because of the difference in sediment characteristics between the dredged material and the present-day supply of sand, it is unlikely that natural processes will be able to counterbalance the severe dredging activities.

Moreover, the presence of the central depression is located close to the kink of the sand bank, which is influenced by a high-energy hydrodynamic regime. Its presence could intensify the current action in this area and could enhance the evolution of the bank.

ADDITIONAL INDEX WORDS: *North Sea, sandbank, acoustic imagery, seabed classification, dredging.*

INTRODUCTION

Numerous subtidal sandbanks and dunes (*senso* Ashley, 1990) cover the sea floor of the English Channel and the Belgian Continental Shelf. Some of these sandbanks are exploited or are located near navigation channels; as such, their dynamics and formation have given rise to numerous studies (e.g. Caston, 1981; Caston and Stride, 1970; Deleu *et al.*, 2004; Eisma, Jansen, and Van Weering, 1979; Houbolt, 1968; Kirby and Oele, 1975; Laban and Schüttenhelm, 1981; Le Bot *et al.*, 2000; Le Bot and Trentesaux, 2004; Stride, 1988; Trentesaux *et al.*, 1994; Van Lancker and Jacobs, 2000; Vincent, Stolk and Porter, 1998; and Williams *et al.*, 2000).

Off the Belgian coast, some parts of the sandbanks are dredged intensively. The exploitation of marine sand began in 1976 and, from 1979 onwards, the extraction activities have been monitored. The annual extraction evolved gradually, from 370,000 m^3, in 1979, to 1,700,000_m^3, in the middle of the 1990's. In 2001, the extraction exceeded 1,900,000 m^3; however, the last 2 years, the production has stabilized around 1,600,000 m^3 (Degrendele *et al.*, this volume).

One of the sandbanks, the Kwinte Bank, has been exploited intensively. In fact, two areas, located on this bank, represent 25 % of the total extraction on the Belgian continental shelf. One of these areas corresponds to the "central depression" (Degrendele *et al.*, this volume); it has a depth of 5 m, is 700 m wide and 1 km long, and is located in water depth at around 10-15 m MLLWS (Mean Lowest Low Water at Springs) (Figure 1.). Since February 2003, the marine aggregate extraction has been prohibited at this particular location, because of the creation of a more than 5 m depth formation, for a duration of 3 years, allowing a potential recovery of the area.

The closure of the depression has led to increased effort to study the environmental impact of sand extraction activities. The aim of this paper is the geo-environmental characterisation of the central depression. Since the dredging occurred

DOI: 10.2112 / SI51-006.1 received 15 January 2007; accepted in revision 27 March 2008.

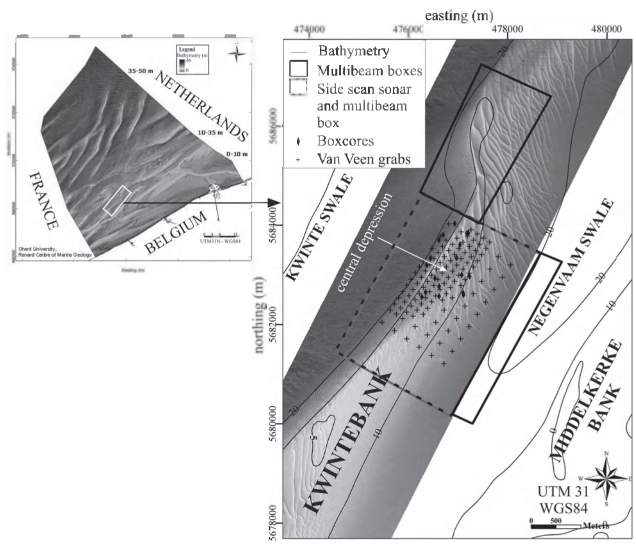

Figure 1. Location of the Kwinte Bank and the different measurement and sampling areas. Left: Bathymetric map of the Belgian continental shelf (Renard Centre of Marine Geology, Ghent University). Right: Bathymetry of the Kwinte Bank (Fund for Sand Extraction), and location of the presented geophysical and sedimentological measurements.

near the crest of the bank, it was important to evaluate whether this had an effect on the morphosedimentary behaviour of the different parts of the sandbank. Knowledge was needed on the grain-size distributions in the area, both from a (re)source perspective, as well as for the evaluation of the sedimentary material in transport. The study of the morphology focuses on the bedforms and the effects dredging have upon these. Indirectly, the study of the sedimentary environment can provide indications of what extent the extraction has altered the sediment transport pattern. The results allow having a first impression of the possible regeneration of the depression, after its closure for extraction.

The study is based on the results of high-resolution acoustic tools, such as side-scan sonar and multibeam. Manual and automated seabed classification was performed; these were calibrated with sediment samples (boxcores and Van Veen grabs) and video imagery. Conclusions are drawn on the performance of those techniques related to the characterization of the true nature of the seafloor. Very-high resolution seismics were used to estimate to what level of the bank the extraction took place. Moreover, it provides an estimate of the resource potential and its homogeneity.

ENVIRONMENTAL SETTING

General Morphology and Sedimentology

The Flemish Banks are oriented obliquely, in relation to the maximum tidal currents (De Moor and Lanckneus, 1990). The Kwinte Bank, one of the Flemish Banks, is a SW-NE oriented tidal sandbank (Figure 1.). The sandbank has a height of about 17 m, a length of about 15 km, a width varying from about 2 km in the southern part to about 1 km in the northern part; it shows an offshore "kink" over its middle part. The minimum water depth is close to -5 m MLLWS, in the southern part of the bank where the bathymetric profiles show a smooth morphology. Most of the sandbank is covered with large to very-large dunes (*senso* Ashley, 1990) with a wavelength of several hundreds of metres, a crest length of several tens of metres and a height varying between 1 and 7 m. In the northern part, very-large dunes are found in areas where the minimum depth is about -8 m MLLWS. Large dunes are present also in the middle part of the bank; their height can reach 2.5 m. The minimum depth, in the swales around the bank, is of the order of -22 m MLLWS. The cross-section of the sandbank is clearly asymmetrical, with the steeper side (slope up to 5 %) facing the NW (De Moor, 1985; De Moor, 1986; and Lanckneus *et al.*, 1989). The gentle eastern slope of the bank can reach ~2 to 3%.

Along the western slope of the sandbank, the sediments coarsen towards the north, from about 240 µm up to 400 µm. Generally, the eastern flank is finer-grained with values around 200 µm in the south (Lanckneus, 1989).

Hydrodynamics and Sediment Transport Pattern

The hydrodynamics around the Kwinte Bank are characterized by semi-diurnal tides of a macrotidal range (4-5 m at springs). The average tidal movement corresponds to an elongated current ellipse, with a southwest-northeast axis. The flood peak and ebb peak currents are oriented towards the northeast and the southwest respectively. These tidal currents are rotating counter clockwise around the Kwinte Bank (Caston, 1972; De Moor, 1986; Houbolt, 1968; and Lanckneus *et al.*, 1989). The velocity of the surface peak currents reaches up to 2 knots (1 m/s) and the flood is the dominant current (De Moor, 1986; and Van Cauwenberghe, 1981).

The direction of sand transport is linked with the tidal currents. On the western part of the bank, the flood transports sand towards the northeast (Garel, this volume). On the eastern part of the bank, the ebb is dominant and transports the sand towards the southwest. The Kwinte Bank receives sand from both adjacent swales, coming from opposite directions, provoking sand up-piling towards the central parts; still the vertical growth is limited by wave and storm action (Caston, 1972; Lanckneus *et al.*, 1989; and Van Veen, 1936). The steep western slope is generally regarded erosional, by the action of the strong flood currents whereas the gentle slope can be considered as an accumulating area (De Moor, 1985; Lanckneus *et al.*, 1989; and Vlaeminck, Gullentops, and Houthuys, 1985).

Geological Background

The Tertiary substratum underneath the Kwinte Bank is composed of compact clay of the Kortrijk Formation (for an overview, see Le Bot *et al.*, 2005) and is locally eroded in the swale, west of the Kwinte Bank. The Quaternary geology of the sandbanks is best studied along the Middelkerke Bank, located adjacent to the Kwinte Bank. Detailed studies showed that this sandbank is composed of seven units, each having a particular lithological composition Trentesaux *et al.*, 1993; Trentesaux, Stolk, and Berné, 1999). A comparison of the present-day morphology with the top Tertiary erosion surface provides a rough volume estimation of 300×10^6 m^3 for the total Kwinte Bank.

METHODOLOGY

Multibeam and Side-scan Sonar

Acoustic measurements were undertaken in June 2003 (23-27/06/2003) (RV *Belgica* campaign ST0317; report www.mumm.ac.be). A Kongsberg Simrad EM1002S multibeam echosounder was used; this transducer produces 111 beams, arrayed over an arc of 150° and uses two frequencies, 93 and 98 kHz (Kongsberg Simrad, 1999-2001a). The multibeam imagery provides two datasets: the bathymetry allows a description of the morphology of the seabed and, especially, the bedforms; the backscatter provides an estimate of the nature of the sea floor, influenced mainly by sediment texture. The datasets were processed with different software packages: Neptune (Kongsberg Simrad, 1999-2001b), for the data correction and cleaning; Poseidon (Kongsberg Simrad, 1999-2001c), for the correction and mosaicing of the backscatter data and Triton (Kongsberg Simrad, 1999-2001d), for the automated seabed classification. The latter is a multivariate classification of backscatter values and uses different statistical parameters such as standard deviation, pace, quantile and contrast.

The side-scan sonar, a Geoacoustics model 159D, was deployed at the same time as the multibeam data. This would allow a complementary characterization of the bedforms and the nature of the sea floor. Only the 410 kHz frequency was recorded; no interference occurred with the frequency of the multibeam. The side-scan sonar data were processed with the Isis software (Triton Elics). As detailed full-coverage multibeam data of the area already existed, (Fund for Sand Extraction), it was preferred to space the tracklines according to the side-scan sonar coverage, being far larger than the one of multibeam.

Sediment Sampling

During the June 2003 campaign, 17 boxcores were taken to calibrate the side-scan sonar and the multibeam imagery. Three months later (September 2003), a larger area was covered by 120 Van Veen grab samples with a gridding of 150 m inside the depression and 300 m outside it. This area was sampled again in February 2004, October 2004 and February

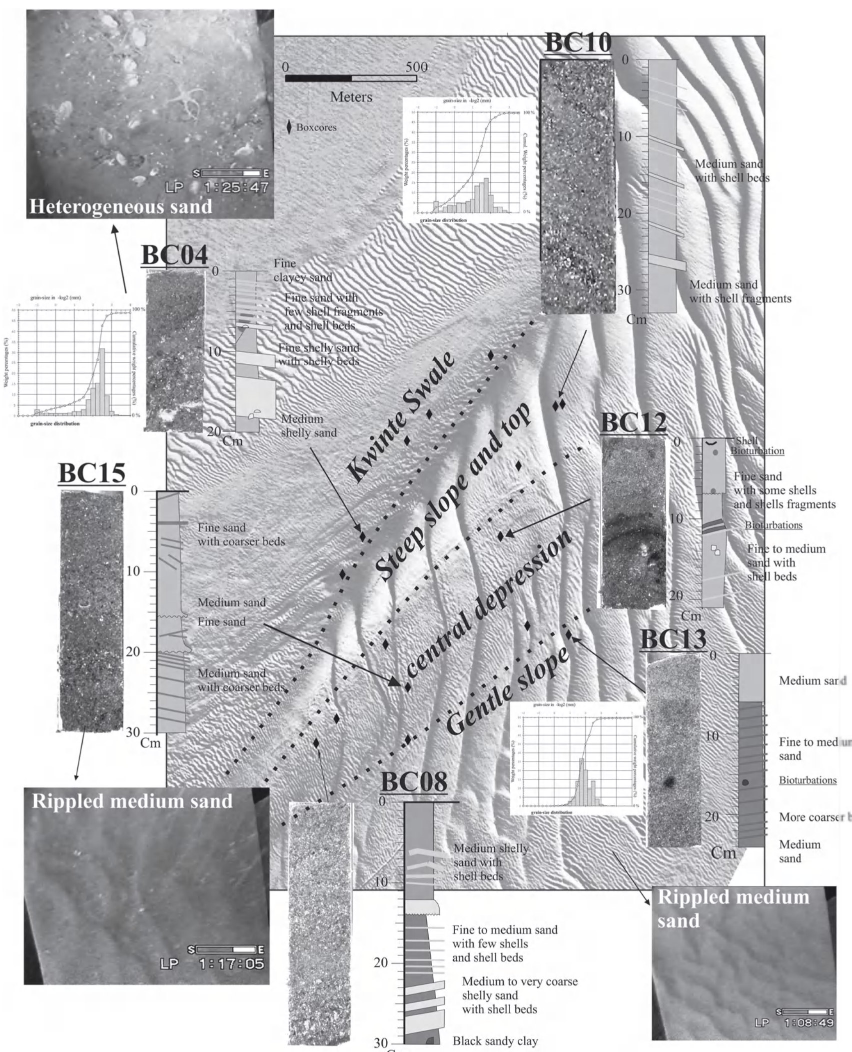

Figure 2. Boxcore interpretation and video imagery (June 2003), in relation to various parts of the sandbank.

Table 1. *Summary of the major sedimentological characteristics of the four environments (September 2003) (the mean value (M) and the range (R) for each environment inside the sampling area, are indicated).*

Environment	Mean grain-size	Sorting	Skewness	Carbonate content
East part (gentle slope)	Fine to medium sand (M: 281 µm, 188-489 µm)	Well to moderately-well (M: 0.59 ϕ, R: 0.27-1.69 ϕ)	Low values (M: -0.18, R: -0.77 - +0.13)	Low (M: 13%, R: 7-27 %)
Central depression	Fine to coarse sand (M: 303 µm, R: 205-552 µm)	Moderate to poor (M: 0.72 ϕ, R: 0.35-1.57 µm)	Variable (M: -0.26, R: -0.64 - +0.26)	Variable (9-31%)
West flank (northern large to very-large dunes, top and steep slope)	Coarse sand (M: 541 µm, R:229-1219 µm)	Poor (M: 1.04 ϕ, R: 0.50-1.69 ϕ)	Very variable (M: -0.21, R: -0.70 - +0.29)	High (> 40%)
Kwinte swale	Fine sand (M: 268 µm, R: 206-461 µm)	Poor (M: 0.92 ϕ, R: 0.48-1.68 ϕ)	Variable (M: -0.39, R: -0.76 - +0.01)	Low (M: 14%, R: 8-21%)

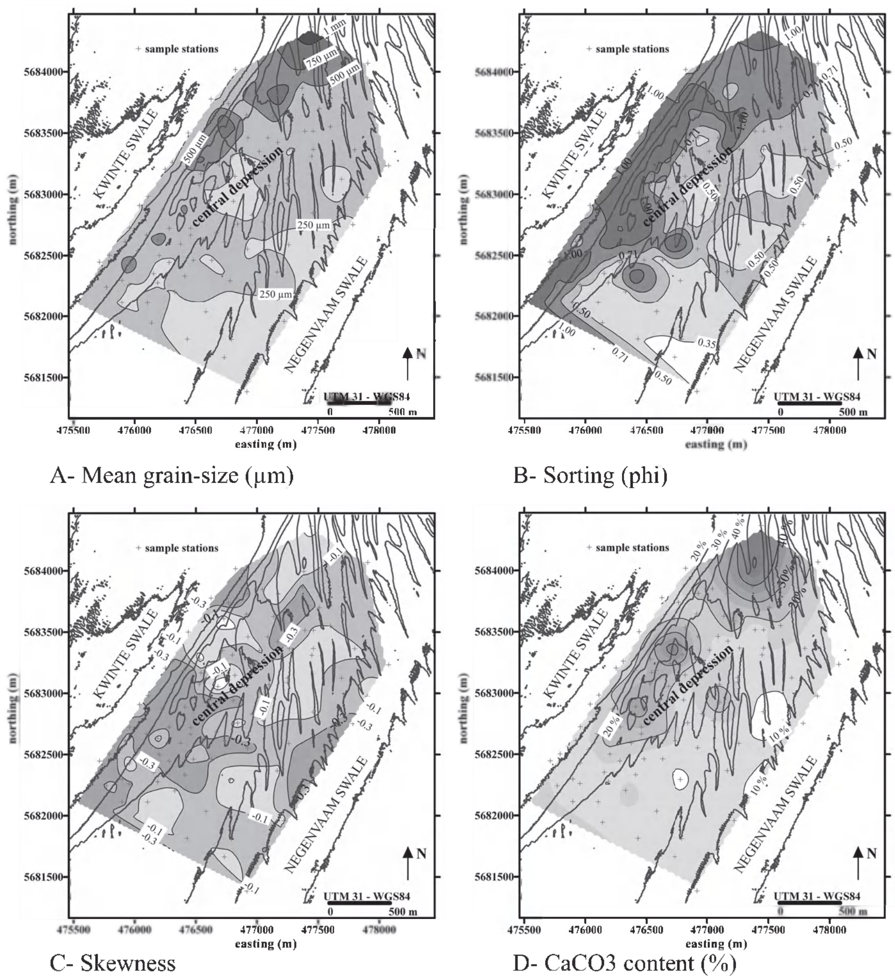

Figure 3. Sedimentological parameters obtained from the Van Veen grab samples (September 2003): A- Mean grain-size: fine sand (light grey) to coarse sand (dark grey), B- Sorting: well-sorted (light grey) to poorly-sorted (dark grey), C- Skewness: enrichment in fine grains (white) to enrichment in coarse grains (dark grey), D- Carbonate content: low values in light grey and high values in dark grey.

2005 (RV *Zeeleeuw*, RV *Belgica*; reports at www.vliz.be and www.mumm.ac.be, respectively).

The boxcores were taken to validate the relationship between the acoustic measurements and the true sedimentary character of the sea floor and become acquainted with the factors controlling the definition of the acoustically-derived seabed classes. Boxcoring permits sampling of the first 20-50 cm of the subsurface. The boxcore content was first described and photographed, after which 2 sub-cores were taken to analyse the stratification and the grain-size of each vertical sub-section. Sediments were sieved on a rack of 2 mm to 75 µm with a ¼ phi interval to permit detailed analysis. The final results were treated statistically according to FOLK and WARD (1957); this allowed obtaining the most relevant sedimentological parameters, such as mean grain-size, sorting and skewness. The calcium carbonate content was determined through calcimetry. Sediment grain-size fractions were classified according to the Wentworth scale (WENTWORTH, 1922).

On the larger grid framework, Van Veen grabs were collected. The positions of the samples were defined on the basis of a 300 m grid along a transversal section over the sandbank and a 150 m grid including the central depression. From each grab, a bag of about 1.5 kg was taken. In the laboratory, the bulk sample was split; the grain-size analyses were similar to those applied to the boxcore samples.

Video Recording

In June 2003, video sequences were obtained at the same locations as the boxcores. The system used was a Simrad underwater video camera, mounted on a small frame. Samples of the video imagery were taken using the Hollywood Pinnacle software.

Seismics

During the June 2003 campaign, a boomer (IKB Seistec boomer/receiver) was used to investigate the internal architecture of the sandbank. Boomer sources combine high frequencies with a broad spectrum and a good repeatability, and seem to offer a good compromise between resolution and penetration (main frequency ~4 kHz with a range of 0.7-7 kHz, a resolution of 20 cm and a penetration of 10–20 m). However, the quality of the data is highly weather dependent. The digital recording

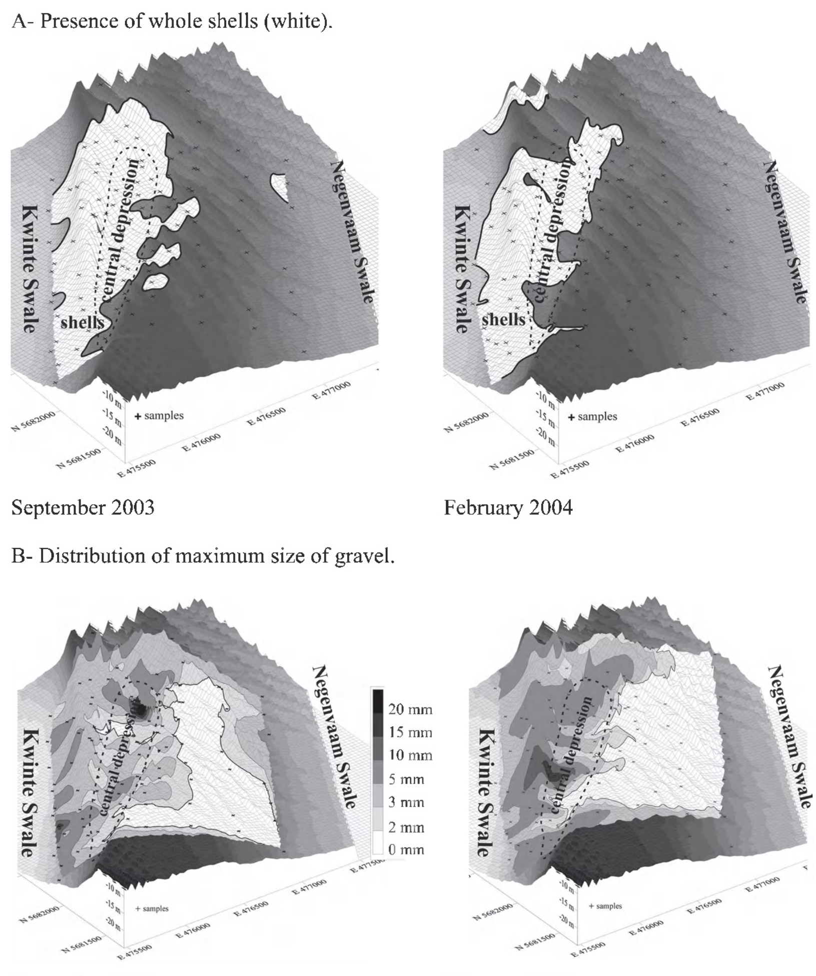

Figure 4. Distribution of the coarse fraction. Sedimentological information is wrapped onto a 3D bathymetry map. Crosses correspond to the sampling stations. A- Presence of whole shells (unbroken). They are only present along the western slope and in the central depression. B- Distribution of the maximum size of gravel.

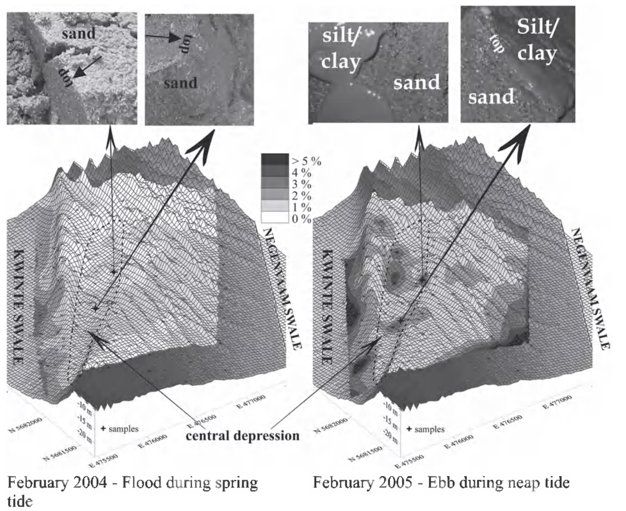

Figure 5. Distribution of the fine-grained sediments (< 75 µm), incorporated within a 3D bathymetric map. Crosses correspond to the sampling stations. In February 2004, the samples have been taken during the flood; there is no mud on the top. In February 2005, the samples have been taken during the ebb; a fine layer of mud is present on the top of the samples. Top: photos of the samples.

allowed a further processing, including a.o. bandpass filtering, age scaling, deconvolution and swell filtering. Small-scale seismic units and their boundaries were identified. The locations of the measurements are shown on Figure 1.

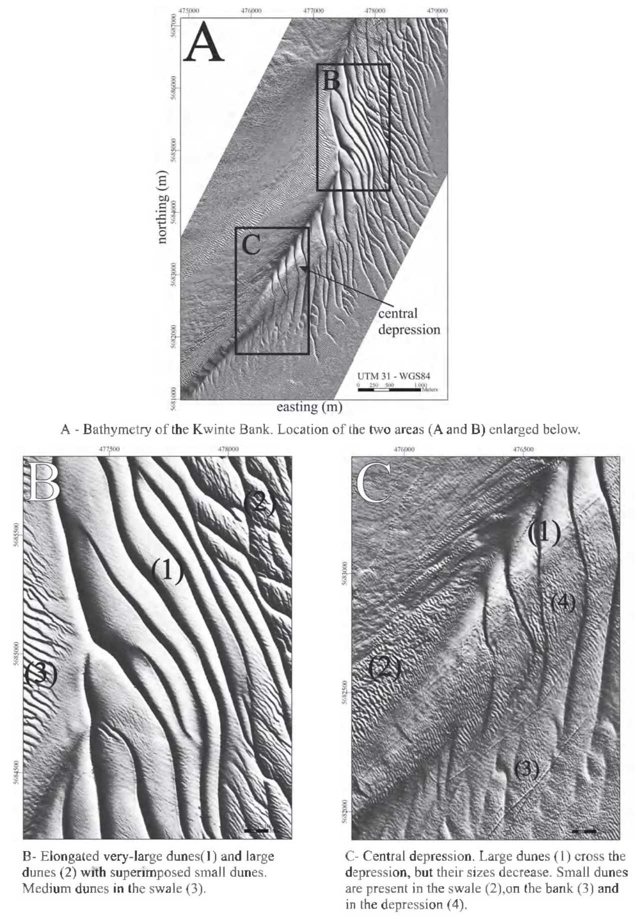

Figure 6. Bedforms on the Kwinte Bank. Bathymetry of the Kwinte Bank (A), the kink in the bank (B) and the central depression (C).

RESULTS

Sedimentological Characterization, Derived from Boxcoring, Van Veen Grabs and Video Imagery

Samples from the boxcores (June 2003; Figure 2., Annex 1) and from the Van Veen grabs (September 2003; Figure 3.) show the same sediment characteristics and allow to distinguish four lithofacies along the central part of the bank (locations indicated on Figure 2).

Each of these lithofacies has specific characteristics of mean grain-size, sorting, skewness and carbonate content (Table 1) and can be described as follows (east to west):

1) The eastern, gentle slope of the sandbank is characterised by well-sorted, fine to medium sands (mean grain-size of 281 µm). South and north of this central area, the sediments become, respectively, finer (+/- 190 µm) and coarser (+/- 300 µm). The skewness is characterised by low values, indicating a low enrichment in very coarse or very fine sediments. The carbonate content is generally reduced to 15%, whilst no important internal structures can be observed in the boxcores. The video imagery shows small dunes with sediments comprising some shells and shell fragments. No organisms are visible. No big differences of sediment occur between the gentle slope and the western boundary of the Negenvaam swale.

2) The central depression, caused by dredging, is a heterogeneous area. The sorting is variable and the sand is fine to coarse. The internal structure of the upper sediment layer shows shell beds of a few millimetres thick. In fact, this facies is intermediate between facies observed on the western steep slope and along the gentle eastern slope. The first facies is found, for example, near the southern extremity of the depression and comprises a large number of shelly beds (Figure 2.). Towards the gentle slope, the facies becomes more homogeneous. Skewness is the sediment parameter that clearly distinguishes the depression from the gentle and steep slope: it shows a lower mean value than along other areas of the sandbank. Generally, the skewness is negative, but some positive values (enrichment in very-fine sediments) can be found at some places. The carbonate content lies between 10 and 35 %. Video imagery showed shell fragments and complete shells, in the troughs, between the small dunes. The crests of the dunes were devoid of shells.

3) The western border of the central depression and the steep slope of the sandbank, are characterized by poorly sorted sediments. Large shell fragment layers of several centimetres thick occur at the base and are covered with an alternation of finer sand and shell beds of several millimetres thick. Generally, the skewness is negative, but low positive values also occur. The sand is coarse to very coarse and the carbonate content can exceed 40 %. The video imagery shows shell fragments and complete shells, mainly in the troughs of the

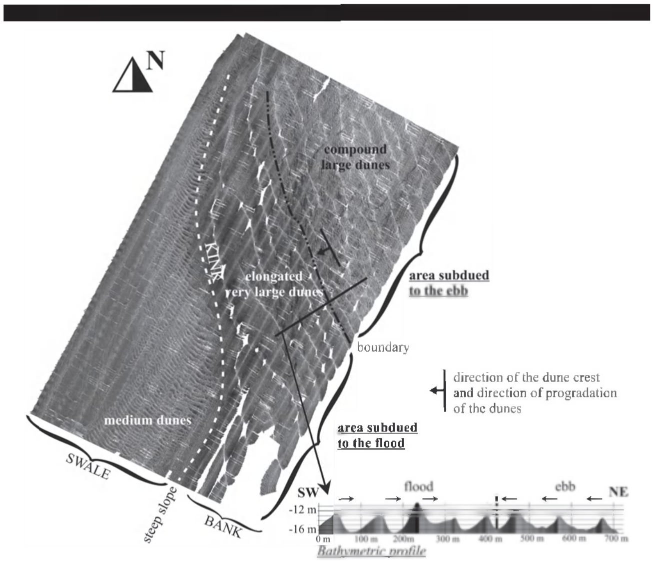

Figure 7. Multibeam backscatter of the "kink" area of the Kwinte Bank. Location of the area is shown on Figure 8.

small dunes. Generally, epibenthic fauna and, in particular, *Echinodermata* are observed (e.g. starfish, brittle stars, and uncovered sea urchin tests).

4) The sediments of the swale, west of the Kwinte Bank (Kwinte Swale), are poorly sorted, due to the presence of gravel and clayey or silty sediments, mixed with fine sand. The skewness is variable. The carbonate content is, generally, down to 20 %.

On an overall basis, the distribution of the coarse fraction (> 3 mm, mostly shells) is limited to the western part of the bank and the central depression (Figure 4.).

A fine layer of mud can appear on the top of the samples inside the central depression (Figure 5.). This occurs when the tidal current are very low in the central depression. This layer was sampled during ebb and slack-water time during a neap tide. So it is difficult to distinguish which condition, between ebb and neap tide, is the most important. During the flood, this layer disappears.

Large and Small-Scale Bedform Morphology

Results from the multibeam and side-scan sonar imagery

The four lithofacies, previously described correspond to particular morphological characteristics:

1) The gentle slope of the sandbank shows large sinuous dunes that amalgamate in some places. Small dunes cover their flanks (Figures 6. and 7.).

2) The contours of the central depression are well pronounced. Interestingly, the large dunes cross the central depression, but they are smaller than those outside the depression (Figure 6C.). The crests of the large dunes within the central depression are more diverted towards the north, than the crests on both sides of the depression, indicating a more rapid movement of the dunes in the depression area due to their smaller height.

3) The western part (steep slope and crest) shows elongated very-large dunes, generally without superimposed small dunes (within the accuracy of the device). In fact, there are two types of large to very-large dunes: (i) higher (up to 5 m) and elongated, located close to the Kwinte Swale (Figure 6B. (1)); (ii) more towards the north and east, belonging to the gentle slope and are smaller (around 2-3 m height) with superimposed smaller bedforms on their slope (compound large dunes) (Figure 6B. (2)).

4) Within the Kwinte Swale, erosional features from currents (furrows), oriented northeast-southwest, are located between two fields of small to medium dunes; these dunes have a southeast-northwest strike (Figure 6B. (3)). The first dune field extends towards the mouth of the central depression, whilst the second terminates on the part of the steep slope, where the offshore kink is present (see above). The crestline of this section of the bank consists of one elongated very-large dune structure.

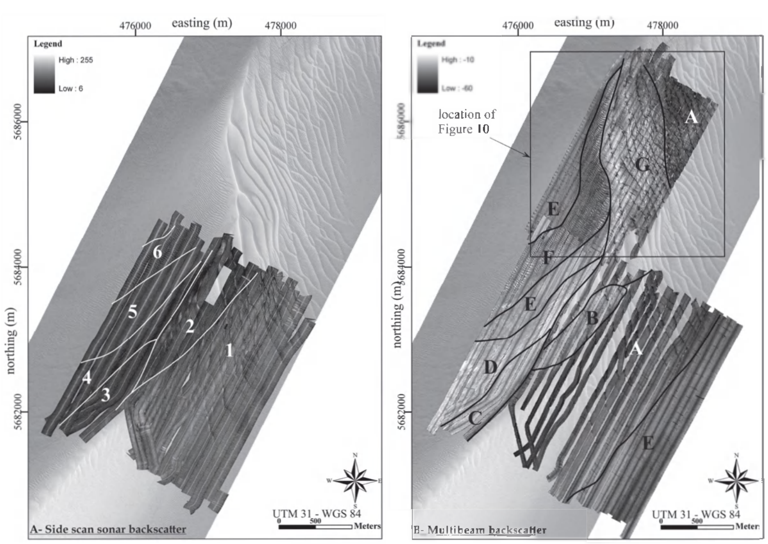

Figure 8. Comparison of the seabed classification, obtained from A- Side-scan sonar imagery and B- Multibeam backscatter. Five classes have been derived from the side-scan sonar imagery (1 to 5) and seven ones from the multibeam imagery (A to G). In the background: bathymetry of the Kwinte Bank.

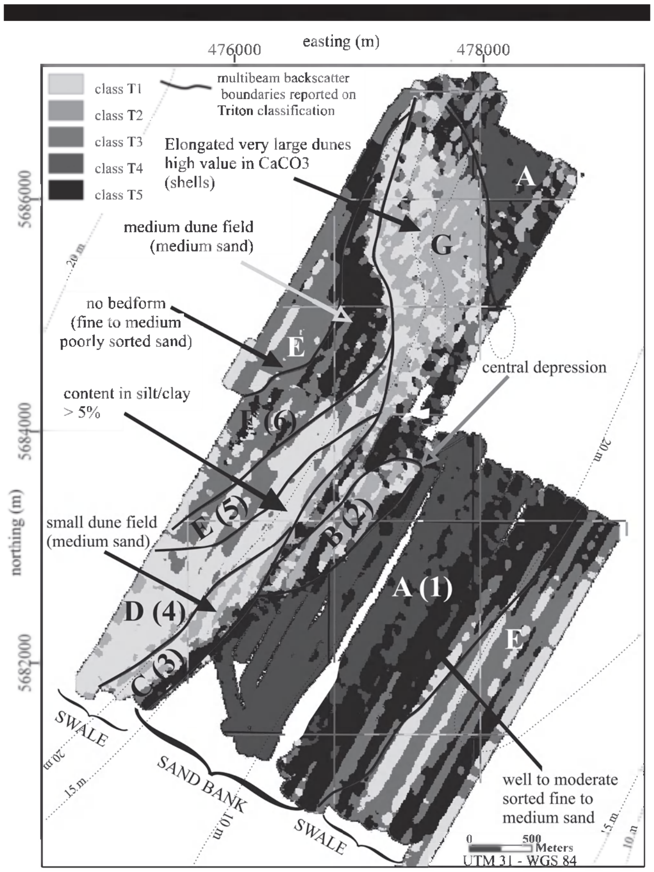

Figure 9. Triton automated seabed classification (Kongsberg Simrad) (classes T1 to T5). Comparison with the manual seabed classification (classes A to G).

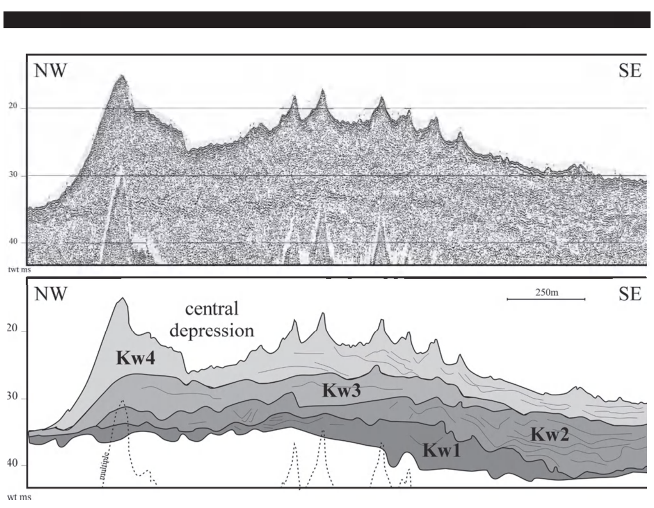

Figure 10. Seismic profile crossing the central depression. In the central depression, the extraction nearly affected the base of the youngest seismic unit Kw4.

Results from seabed classification

Multibeam and side-scan sonar data were used for the seabed classification (Figure 8.). The side-scan sonar imagery was interpreted, manually; this has led to the delineation of 6 classes (Figure 8A.), occurring from southeast to northwest (see below).

– Class 1: represented by large dunes, superimposed with small dunes and a low to moderate reflectivity (gentle slope);
– Class 2: the same large to very-large dune structures, but the reflectivity is stronger (central depression and along the crest of the western part of the sandbank);
– Class 3: small to medium dunes, with a moderate to strong reflectivity (swale, dune field);
– Class 4: furrows with a moderate reflectivity (swale);
– Class 5: devoid of bedforms and a moderate reflectivity (swale);
– Class 6: field of small to medium dunes within the swale.

A seabed classification has been performed on the multibeam backscatter data (Figure 8B.). Similarly, as for the side-scan sonar backscatter, these data are also a function of several parameters such as seabed sediment type, roughness and bedforms. No large differences were detected between the side-scan sonar and the multibeam backscatter. Seven classes were distinguished manually from the multibeam backscatter data (see below).

– Class A: same bedform pattern as Class 1 (see above) (gentle slope), corresponding to large dunes, superimposed with small dunes; a low reflectivity is observed;
– Class B: central depression and similar to Class 2 (see above). It displays a higher reflectivity than the gentle slope;
– Classes C and F: the small to medium dune fields of the swale (classes 3 and 6, see above), with a higher reflectivity for Class C;
– Class D: the furrows of Class 4 (swale, see above), a high reflectivity is observed;
– Class E: different from Class 5 (swale, see above), also a high reflectivity is seen;
– Class G: the elongated very-large dunes, being a part of Class 2 (western part: steep slope and crest of the sandbank, see above) with a reflectivity somewhat lower than the ones of Classes C, D and E.

The automated seabed classification, based on the multibeam backscatter data, allowed discriminating 5 classes (Figure 9.). Classes T1, T2 and T3 are located mainly in the Kwinte swale, and correlate well with the Classes C, D and E, based on a manual interpretation of the multibeam backscatter data. Classes T1 and T2 are, also, found on the elongated very-large dunes (class G). Classes T4 and T5 are situated in particular on the gentle slope of the sandbank (Class A) and along a dune field in the Kwinte Swale (Class F). The central depression is covered mainly with Class T2 and somewhat by the Classes T1, T3 and T4.

Internal Structure of the Bank

The present investigation only focussed on the area around the central depression. The interpretation of the seismic profiles allowed for the discrimination of four units (Kw1-4) (Figure 10.). The oldest ones, Kw1 and Kw2, are bounded by erosive reflectors with medium to good conti-

Table 2. *Correlation between the backscatter, the sea-floor classification and the sedimentological and morphological characteristics.*

Sediment type		**High silt content (> 5 %)**	**High carbonate content**	**Fine to medium well-sorted sand (sandbank)**	**Poorly-sorted, fine to medium sand (swale)**
Morphology (bedforms)		Small dunes, furrows	Elongated very large dunes	Compound large dunes	No bedforms
Backscatter	Classes	C-D	G	A	E
	Values	High	High	Low	Medium
Automated sea-floor classification		T1	T2	T4-T5	T3
Side-scan sonar		3-4	Outside the area	1	5

nuity. The internal structure of Kw1 is composed of some high-amplitude and low discontinuity reflectors. Kw2 shows channel-shaped structures, alternating with more linear reflectors. Kw3 has a bank-shaped form and presents some reflectors parallel to its slopes. Kw4 corresponds to the bank itself. It is covered by dune structures and smaller bedforms. This unit is about 5 to 7 m thick. In this paper, only the relevance of the data with respect to the impact of aggregate extraction is discussed.

DISCUSSION

Methodologies - Interrelationship of the Acoustic Techniques

The backscatter data from a 95-98 kHz multibeam echosounder, such as the EM1002, can provide an estimate of the nature of the surficial sediments. For a muddy seabed, the signal is strongly absorbed and the values of the backscatter are low. On a rocky or gravelly seafloor, the signal is strongly reflected and the values of the backscatter are high. A flat seabed or areas with well-sorted sediments reflect less the signal than a rough seabed or than poorly-sorted sediments. Other factors contributing to the value of the backscatter relate mainly to sediment compaction and bioturbation (e. g. Ferrini and Flood, 2006; Hughes Clarke *et al.*, 1997; and Nitsche *et al.*, 2004).

For the present datasets, the multibeam backscatter data range between –40 and –10 dB. This range appears to depend, at a first approximation, upon the sea floor roughness (the presence of small bedforms), sorting and presence of shell. Variations in these three parameters correlate well with the backscatter differences. Coarse sediment is found in the swale where the reflectivity is generally high (Classes C, D and E) and on the elongated very-large dunes (Class G), whereas finer sediments are found on the gentle slope (Class A), and on the fields of the small to medium dunes (Class F), where the reflectivity is low.

This pattern corresponds on the side-scan sonar imagery to the low reflectivity of Class 1 and the higher reflectivity of Classes 2 and 3 and 4.

Although, the reflectivity of the multibeam correlates approximately with the mean grain-size, the results of the sea floor classification (Triton) do not exactly represent this particular parameter. The results show that the Triton automated seabed classification is more sensitive to the content in shells, in fine sediment (Classes T1 and T3) and in the sorting: for example, the difference between Classes T3 and T4-T5 representing fine to medium sand, but poor and well-sorted sand respectively. Classes T1 and T2 represent the coarsest sediments.

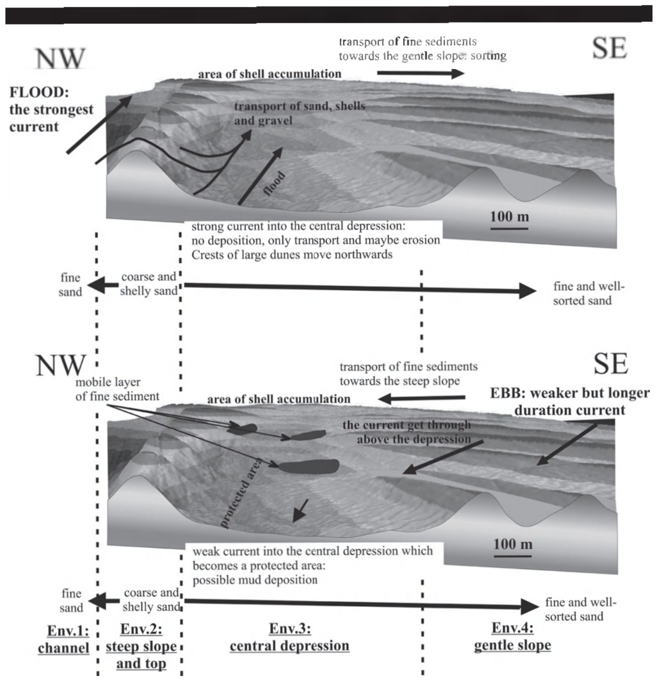

Figure 11. Conceptual model of the sedimentary dynamics associated with the central depression of the Kwinte Bank during flood (top) and ebb (bottom) tide. Env. = environment.

In summary, Classes A/T4-T5 correspond to fine to medium well-sorted sand. However, problems appear with the other classes corresponding to moderate and poorly sorted sand. For example Classes C and D/T1-T2 contain a mixture of fine sand, gravel and silt. They show acoustic characteristics similar to those of Class G, formed by coarse shelly sand. In fact, Class T1 seems to be more sensitive to the silt content and Class T2 to the carbonate content. Class T3, found within both of the swales (Class E) corresponds probably to fine to medium poorly sorted sand (Ceuleneer and Lauwaert, 1987). The different classes and their possible interpretation are summarised in Table 2.

The results of the sea floor classification delineate the region of the central depression as being composed of heterogeneous sediments. This is in accordance to the sedimentological results, based on sampling. The carbonate content is generally less than 20 %. The higher reflectivity of the central depression is also influenced by a more compact nature of the sediments. Whether, this is due to an early compaction decreasing the porosity, a somewhat stronger current action or perhaps the extensive dredging that exposed more consolidated sediment remains to be investigated.

Interpretation of the Four Lithofacies

Around the central depression, four lithofacies were identified, each with its specific sedimentological and morphological characteristics. The findings and their integration with the governing hydrodynamic characteristics are shown in Figure 11.

The Kwinte Swale

Heterogeneous sediments, composed of fine to medium sand containing a considerable amount of shells and epibenthic fauna, form the Kwinte Swale. The silt content, often higher than 5 %, together with coarse gravel was sampled on the seabed. This distribution pattern appears to be rather stable, except for some sporadic high-energy events. Previous studies (Ceuleneer and Lauwaert, 1987) have indicated that the values of the clay and gravel contents within the swales between the Flemish banks can be high and the admixture results in the occurrence of poorly sorted sand. Strong currents can lead to the formation of erosional furrows, eroding the underlying Tertiary clay and pre-Holocene stones (essentially flints). Under high-energy events, these can be transported towards the banks. Moreover, as the banks are oblique (up to 20°) to the tidal ellipses, sediments that are eroded in the swale are transported towards the bank. With sufficient sand available, dune fields form in specific areas.

Western part of the sandbank, steep slope and crest

Heterogeneous medium to coarse shelly sand characterizes the sediments of the elongated very-large dunes along the western part of the sandbank. The strong currents in this area, generally, provoke erosion along the steep slope. The erosional nature of this steep slope is clearly shown when erosion and deposition areas are modelled (Brière *et al.*, this volume; and Van den Eynde *et al.*, this volume). The strong currents on the steep slope (Van den Eynde *et al.*, this volume) allow an active transport of shells and coarse material, which is probably common along the erosive western flank. This transport appears to extend up to the depression, showed by the coarse fraction pathway (Figure 4.). The eastern flank of the central depression seems to form a boundary for the progression of the coarse fractions. Moreover, the transport process likely destroys the shells. They finish up accumulating on the northern elongated very-large dunes, where the shell fragment size is quite homogeneous.

The central depression

The central depression shows patches of fine- to coarse-grained sediments; as such it is an intermediate area between the heterogeneous and poorly-sorted sands of the western flank and the fine- and well-sorted sands of the gentle slope. Before dredging, it is likely to have been associated with similar sedimentation as along the western side (Bonne, 2003; Vanosmael *et al.*, 1982), since the area was a former crestline of the Kwinte Bank. Noteworthy, are the very-large dunes that are clearly lower in height in the depression than outside of it, though the strike of the dunes is continuous from the western part up to the eastern part. From time-series of multibeam imagery (Degrendele *et al.*, this volume), it has been shown that in the depression, the dune sections have a higher rate of mobility.

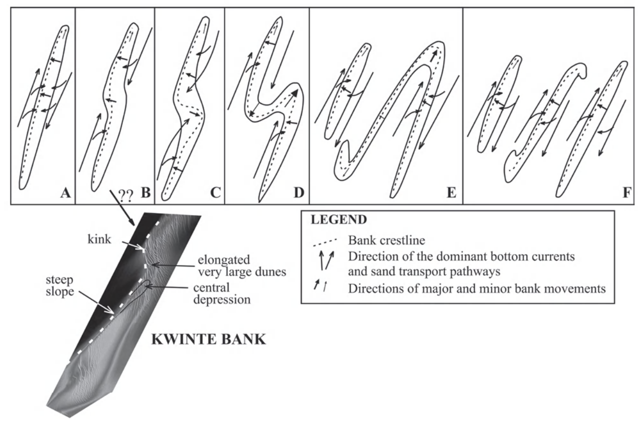

Figure 12. Caston's hypothesis on the evolution of the Norfolk Bank (Caston, 1972) adapted to the Flemish Banks. The morphology of the Kwinte Bank is similar to Stage B condition. A: single bank, B: formation of a kink on the steep slope, C: enlargement of this kink under tidal current action, D: setting of two sandbanks, E: continuation of the process with the initiation of a third sandbank, and E: three sandbanks.

This may allow an easier passage of the currents (Figure 11.) and hence, an increased erosion potential might be expected in this area. Degrendele *et al.* (this volume) observed a deepening of 0.8 m between 1999 and 2003 and erosion processes are still evidenced from hydrodynamic measurements and modelling (Garel, this volume; Brière *et al.*, this volume). However, Degrendele *et al.* (this volume) indicate also that the erosion in the depression appears to have ceased and that the top volume of the sandbank is stable again, since the closure of the depression.

The regeneration of the depression is however problematic, at least on the short-term. From the time-series in sediment sampling and from the subsequent multibeam soundings (Degrendele *et al.*, this volume), no evidence of a significant sedimentation after the cessation of dredging is observed. According to the main sediment transport direction, a southern provenance would be most favourable. Still, if the depression is to be refilled with coarse sand, as was originally the case, there is only a limited availability of this fraction to the south. The only evidence found, is the trapping of shelly material in the depression, likely originating from the coarser western slope of the bank and hence transported with the flood current. Figure 11. also shows the possible trapping of silty sediments in the depression, most probably occurring under ebb and neap tide conditions. If both processes would be continuous over time, this might be a first, but very slow initial stage for a further regeneration of the area.

Eastern part

Finally, opposite to the western part, the gentle slope of the bank is composed of homogeneous fine to medium sand. The large dunes are smaller and are covered with small dunes. The gentle slope is merely subdued to the ebb current. The boundary between the influence of the flood and of the ebb is visible on the multibeam backscatter imagery (Figure 7.); this area corresponds to a bed load convergence zone (e.g. HARRIS *et al.*, 1995).

Evolution of the Sandbank

Several authors have attempted to explain the maintenance of the North Sea sandbanks and mainly attributed this to the convergence phenomena of tidal currents (CASTON, 1972; LANCKNEUS *et al.*, 1989; and VAN VEEN, 1936). Investigations concerned with the Kwinte Bank have agreed upon the volume equilibrium, but they have not explained the evolution of the offshore "kink", located within the middle part of the bank, just to the north of the central depression. This kink is covered with the highest very large dunes; its evolution and current pattern suggests a strong hydrodynamic regime (VAN DEN EYNDE *et al.*, this volume). Previously, CASTON (1972) has explained the presence of such a feature in the Norfolk Banks (Figure 12.) where six stages have been described which could lead to the formation of two new banks. The initial linear tidal bank (Stage A) becomes sinuous under the action of the tidal currents. The sinuosity increases with the formation of a kink (Stages B and C) until there is the development of a double curve (Stage D), associated with the ebb and flood channels. The new channels lengthen considerably, until they break through the sandbanks at the location of the kink (Stage E). The parabolic terminal banks leave gaps at the extremities of the channel. The final stage (Stage F) reveals the creation of three banks, out of a single bank.

This hypothesis might be applied to the Flemish Banks for the reasons:

(1) The Norfolk Banks are under a hydrodynamic regime which is very similar to that of the Flemish Banks;

(2) Some of the Flemish Banks show some of the intermediate stages, as presented by CASTON (1972). For example, the Middelkerke Bank and the Oostende Bank have reached Stage D and the Buiten Ratel reveals a kink, resembling the middle bank shown on Stages E and F.

The Kwinte Bank appears to be similar to Stage B, as described for the Norfolk Banks. The formation of the kink is probably due to an increase in the currents and the bottom shear stress at this particular location (WILLIAMS *et al.*, 2000) being responsible for the formation of the elongated very-large dunes (Class G of the multibeam data set) and the medium dune field observed at the base of the sandbank (Class 6 of the side-scan sonar imagery and Class F of the multibeam imagery; Figure 7.). In Figure 7., it can be seen also that the wavelength of the elongated very-large dunes decreased towards the northeast. The small bedforms located further eastwards, have a north-south orientation and appear to be mainly formed by the ebb current. In conclusion, in this area of the kink, there is a convergence of strong forces, provoking instability of the sandbank. DELEU *et al.* (2004) found the same conclusions for the Westhinder kink area, located to the north.

The presence of the central depression, close to the kink, could intensify the current action; this could enhance the evolution of the bank. However, the modelling studies (BRIÈRE *et al.*, this volume) showed that dredged areas are rather insignificant at geological time-scales. Moreover, within existing sandbank groups in the southern North Sea, there might not be enough accommodation space to allow a repartitioning of the bank.

Different Seismic Units of the Banks

From the interpretation of the seismic profiles, the formation of the central part of the Kwinte Bank seems to have occurred in four main phases, separated by three major erosional surfaces. Correlation of the results with the detailed seismic investigations and ground-truthing of the adjacent Middelkerke Bank (TRENTESAUX *et al.*, 1993; and TRENTESAUX, STOLK, and BERNÉ, 1999), suggests that the four units, Kw1-4, are Upper Quaternary in age and have a varying lithological composition. High-amplitude reflectors, likely indicating a coarse sedimentation, characterize the oldest unit and likely reflect the infill of a fluviatile channel. Kw2 is more complex; its geological history merely reflects a channel-barrier facies with an alternation of channels and barriers. This may be related to a marsh, a lagoon or a back-barrier system of a coastal plain and indicates that the sedimentation is rather heterogeneous (TRENTESAUX, STOLK, and BERNÉ, 1999). Kw3 has a sandbank-shaped facies; hence its sedimentation is likely sandy and more homogeneous in nature. Kw4 is the actual tidal sandbank facies, maintained by the present-day hydrodynamic regime. In the central depression, this unit is almost dredged completely.

These results confirm that the sandbank is not a homogeneous piling-up of sand and that not all units are *per se* sandy in nature. It is clear that detailed information is needed on the internal structure of the bank, if adequate resource calculations are to be made. From an environmental perspective, it seems only recommended to dredge the upper subsurface layer, as only these sediments may be renewed by the present-day hydrodynamic regime.

CONCLUSIONS

A detailed geomorphological and sedimentological study has been performed on a tidal sandbank that has been dredged during 30 years. The marine aggregate extraction has led to a depression, in the former crestline of the bank, of up to 5 m. From this, the Government closed down the area for further exploitation.

High-resolution acoustics were used, as also seabed classification tools. Multibeam and side-scan sonar backscatter showed similar results. Automated seabed classification, based on multibeam backscatter, showed no direct correlation with the mean grain-size. The primary drivers were merely the sorting of the sediments, the presence of shells and of fine sediments. Very-high resolution seismics allowed studying the upper 20 m of the sandbank and showed the presence of various seismic units. Of these, only the upper unit is representative of the present-day hydrodynamic regime; this unit is nearly completely dredged along the central depression.

The central depression was clearly distinguished from the morpho-sedimentary environment, characterizing the western and eastern part of the bank and the swale. The differentiation between the western and the eastern part is essentially due to different tidal current characteristics that lead to different erosion-sedimentation processes. These processes seem to be rather stable as each subenvironment had similar overall grain-size characteristics over a period of two years. Within a subenvironment, some evolutionary trends could be distinguished and could be related to seasonal variation. Of note is the evolution of the sediments within the central depression as this was similar to the evolution witnessed for the swale sediments, hence significantly different from what would be expected from a former crestline of a sandbank. The interplay of the flood and ebb current is as follows: (a) The flood is a stronger, but of a shorter duration. It erodes and transports the sediments in bulk, without efficiently sorting it. At such, it induces a resuspension and subsequent sedimentation of coarse sediments, poorly sorted and with high carbonate content. These sediments are transported into the depression and accumulate locally; (b) the ebb tide is weaker, but of longer duration than the flood. It erodes with difficulty the sediments, but its long duration permits an improved sorting of the fine to medium sand fraction. There is no supply in shells, as these are only observed along the western part of the bank.

The presence of the central depression has several influences. It is located along a part of the bank, that is generally dynamic in nature and its position is close to a kink in the sandbank. This could have a positive effect: the high amount of transported sediment could enable a levelling out of the depth differences. However, kink areas are mostly less stable in nature; as such, initial erosion might be accelerated in such areas. The depth of the central depression should allow a trapping of sediment. However, the depression is somewhat oblique to the normal crestline; as such, it now forms an open transport pathway from the swale up to the crest of the sandbank. This has led to a canalization of the flood current; this is witnessed by a decreasing height of the dunes and the fact that the occurrence of shells is restricted to the depression and need to be brought in by the flood. The lower height of the large dunes cannot slow down the current and erosion and transport of sediment is increased. These phenomena likely prevent any significant regeneration of the depression.

If the depression is to regenerate, it will likely need a refill in coarse material, similar to its original sedimentary deposits. However, the present-day hydrodynamic regime is not able to supply this fraction, nor are there any nearby sources that could govern this supply. Nevertheless, there is a constant supply in shells, originating from the western steep slope. Moreover, time windows exist during which fine sediments can settle down. If the shells would be able to trap the finer sediments, this might be a first initiation of a further regeneration.

The major problem for the regeneration of the central depression remains the lack of coarser-grained material that is needed as a basis for a further infilling. As these fractions are not regularly transported, it is unlikely that the natural processes will be able to counterbalance the severe dredging activities. If, from a management perspective, the central depression needs to be restored, it might be envisaged to supply the depression with a basic layer of coarse sediments or shells from, for example, the wastes of the dredged material around this area. This would likely permit a more important trap of sediments and thus initiate a further infill of this depression.

ACKNOWLEDGEMENTS

This study is contained within the research objectives of the projects MAREBASSE (Management, Research and Budgeting of Aggregates in Shelf seas related to End-users, Belgian Science Policy, Contract EV/18A) and EU-MARSAND (European Marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction, EC Contract HPRN-CT-2002-00222). Time-series of sediment samplings were collected in the framework of the Belgian Science Policy project SPEEK (EV/02/38A). The authors warmly thank Wendy Bonne, Samuel Deleu and Els Verfaillie for their help. The Management Unit of the Mathematical Model of the North Sea and the Scheldt Estuary (MUMM) provided ship-time, on board the RV *Belgica*. The Flemish Institute of the Sea (VLIZ) granted shiptime on the RV *Zeeleeuw*. The captain and officers are acknowledged for their flexibility and assistance, during the campaigns. The consultancy firm Magelas was responsible for the side-scan sonar recordings.

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Annex 1

Sedimentological parameters of the boxcores, as shown in Figure 2.

Boxcores	Position	Sample depth (cm from the top)	Mean grain-size (μm)	Sorting (ϕ)	Skewness	$CaCO_3$ %	Mode
BC4	Steep slope-swale	1	236	0.65	-0.50	11	unimodal
		3	255	0.82	-0.59	12	unimodal
		17	498	1.28	-0.17	23	bimodal
BC10	Top	6	466	0.81	-0.31	11	unimodal
		22	423	0.58	-0.30	20	unimodal
		32	442	1.07	-0.17	20	bimodal
BC8	Top-central depression	6	500	1.17	-0.07	31	bimodal
		14	537	1.12	-0.07	38	bimodal
		17	325	0.97	-0.48	13	unimodal
		25	799	1.04	0.41	34	bimodal
BC12	Central depression	6	265	0.46	0	11	unimodal
		11	226	0.44	-0.08	12	unimodal
		13	270	0.55	-0.04	16	bimodal
		20	250	0.59	0.01	19	bimodal
BC15	Central depression	3	253	0.52	-1.04	14	unimodal
		12	318	0.68	-0.14	9	unimodal
		17	284	0.60	-0.11	15	bimodal
		20	385	0.83	-0.20	27	bimodal
		28	353	0.71	-0.10	8	
BC13	Gentle slope	4	282	0.47	0.15	1	unimodal
		12	276	0.47	0.1	7	unimodal
		23	310	0.63	-0.1	11	unimodal