# THE QUATERNARY GEOLOGICAL EVOLUTION OF THE BELGIAN CONTINENTAL SHELF, SOUTHERN NORTH SEA

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## Introduction

Since the end of the 70's and beginning of the 80's, the Quaternary cover of Belgian Continental shelf (BCS) has been intensively surveyed in the framework of several national and international projects. This resulted in one of the densest regional seismic grids of the world. These high-resolution reflection seismic profiles are available in the data files of the Renard Centre of Marine Geology (RCMG). In addition, an extensive series of cores and core descriptions have been acquired over the years and are stored in the repository of the Geological Survey of Belgium (GSB). Previous analyses of these datasets, however, focused mostly on a single sandbank or a distinct sub-area of the BCS. For each of the sandbanks and sub-areas a new, local stratigraphy and interpretation was proposed in these studies. So, notwithstanding the amount of information available, the data were never processed or interpreted in an integrated, coherent and BCS-wide way. With respect to the Quaternary deposits, the BCS had thus remained one of the last unmapped and unknown areas of Belgium.
One of the key reasons for this is that the Quaternary cover on the BCS is very patchy and discontinuous, mostly shaped into isolated sandbanks by past and modern tidal currents. It has a maximum thickness of only 45 m, and is on average even less than 10 m thick. This thin, fragmented record has made it so difficult to produce a coherent reconstruction of the Quaternary evolution of the BCS, especially at times when only analogue data were available.
So, in the present digital era, the main goal of the presented study was to archive, integrate and (re-interpret all existing datasets – seismics as well as cores – in order to develop for the very first time a common stratigraphy for the Quaternary deposits on the BCS and a genetic model for the Quaternary geological evolution of the area.

## Development of a Quaternary evolutionary model

In order to be able to correlate the complex Quaternary structure of one sandbank to another, the old, paper seismic recordings had to be translated into a digital format. Almost 30 years after their acquisition, more than 4000 km of high-resolution seismic profiles were scanned, converted into digital 'SEG-Y' format, and integrated with 1300 km of modern, digitally acquired seismic data, and with more than 600 core descriptions.

Seven seismic units were identified in the Quaternary deposits on the BCS. They are bounded by erosional unconformities. After calibration of the seismic characteristics with the core data, these seismic units could be assigned a lithological meaning and be interpreted in terms of depositional environment. The erosional surfaces represent important phases in the Quaternary sea-level evolution or changes in the sedimentary dynamics in response to it.
A valley incised in the Paleogene subsurface offshore Oostende, i.e. the Ostend Valley, is filled with three seismic units (U1-U2-U3). They represent three successive phases in the transgressive estuarine infilling during a relative sea-level rise. The infill is truncated at the sea bed by a ravinement surface formed by shoreface erosion and marine planation during marine transgression. On top of this regional erosional surface lies a fourth seismic unit (U4) representing tidal-flat deposits, which developed behind a coastal barrier in a back-barrier environment. On top of this unit, separated by another erosional surface, lies a fifth seismic unit (U5), which represents three parallel storm-generated sand ridges. A sixth seismic unit (U6) is interpreted as nearshore deposits consisting of reworked material of former tidal-flat deposits. The seventh, uppermost seismic unit (U7) represents mainly the recent tidal sandbanks and inter-sandbank swale sediments.

As no unreworked datable material was recognised in the available cores, it has thus far not been possible to obtain reliable absolute ages for these seismic units. The time of incision and the age range of the Ostend Valley fill had to be inferred from indirect evidence, such as the depositional depth of the seismic units and the marine transgressive surface in comparison with known relative sea-level curves (Denys and Baeteman, 1995, Siddall *et al.*, 2006). The connection to the Flemish Valley on land gave a maximum age for the Ostend Valley time of incision. For reconstructing the

Holocene evolution of the BCS, the link was made with the evolutionary history of the western Coastal Plain (Baeteman, 1999; Baeteman and Declercq, 2002; Baeteman, 2004, 2005ab). Holocene geological and archaeological reconstructions of Zeeland (The Netherlands) (Vos and van Heeringen, 1997) and historical coastline reconstructions of the Western Scheldt area (Coornaert, 1989; Augustyn, 1995; Termote, 2006) have also been taken into account. All these clues have been put together as in a giant jigsaw puzzle, to come to a comprehensive model for the Quaternary history of the BCS, which is presented in paleo-reconstructions.

## The Quaternary geological evolution of the BCS

### *The Pleistocene evolution*

*Saalian glaciation*

During the maximum ice-sheet extent of the Saalian glaciation (MIS6; 200-130 ka ago) a large, proglacial ice lake formed between the Scandinavian and British ice in the central North Sea area, and a ridge north of the Dover Strait (Gibbard, 2007). The Rhine-Meuse system entered this proglacial lake that reached heights similar to the present mean sea-level (Busschers *et al.*, 2007), and formed a delta close to the present-day Dutch coastline. During the following deglaciation, at the end of the MIS6 ice age, the proglacial lake breached the ridge north of the Dover Strait and drained. With dropping base level, the Meuse deeply incised in the former proglacial Rhine-Meuse braidplain and sought its way south, towards the Dover Strait, forming the Offshore Platform and Offshore scarp on its way, i.e. prominent morphological features in the Top-Paleogene surface of the BCS. Most likely also the rivers of the Flemish Valley formed a delta entering the Saalian proglacial lake. In reaction to the dropping base level, these rivers started incising as well, moulding the eastern Coastal Valley and the Ostend Valley. When the meltwater outflow diminished, and only the deeper Axial Channel was still occupied as main drainage path, a small stream in the Ostend Valley extended towards the Axial Channel cutting through the former Meuse valley flank.

*Eemian interglacial*

During the Eemian (MIS5e; 130-110 ka ago) sea-level rise, the sea invaded the earlier incised valleys, which evolved into estuaries. Soon, the Ostend Valley evolved into a typically funnel-shaped tide-dominated estuary, consisting of an outer estuary, middle estuary and fluvial-tidal transition zone according to the model of Dalrymple and Choi (2007). Three seismic units (U1-U2-U3) represent the estuarine infilling of the Ostend Valley. They represent each time a more seaward section of the estuary, indicative of a landward migration of the estuarine environment. With rising sea level, the estuary continuously migrated further upstream the eastern Coastal Valley, which forms the connection between the Flemish and Ostend Valley. In the process of transgression, landward and laterally migrating tidal channels, coupled with wave action, eroded part of the more landward facies, and left tidal ravinement surfaces in between the seismic units.

Meanwhile, also the coastline migrated landward, and the upper surface of the estuarine infillings became truncated at the seabed by a ravinement surface formed by shoreface erosion and marine planation during marine transgression. By the time the Eemian relative sea level reached its maximum height, comparable to the present-day level, the coastline was situated 7 km inland of the present-day shoreline (near Brugge). In the Flemish Valley, the marine influence reached as far as 40 km inland into the low-lying tributaries (De Moor *et al.*, 1996), turning a large part of the Flemish Valley into an estuarine embayment. In both the eastern Coastal Plain and Flemish Valley, the final phase in the Eemian succession is represented by the development of exposed (open marine) tidal flats.

*Weichselian glaciation*

At the beginning of the Weichselian period (MIS 5d-5a; 110-75 ka ago)), sea level lowered due to ice-mass expansion, and soon the North Sea floor became dry land. In our regions the climate became relatively cold, but with a very high humidity (Verbruggen *et al.*, 1991), which induced an intense and deep fluvial incision, as no permafrost was established yet. In the Flemish Valley, the Eemian sediments were largely removed. In the former Ostend Valley area, the river incised down to -21 m MLLWS. During the Early Pleniglacial (MIS4; 75-60 ka ago), characterised by a very cold and humid periglacial climate, the thalwegs evolved into braided river systems. This continued during the milder Middle Pleniglacial (MIS3; 60-25 ka ago). During the Late Pleniglacial (MIS2; 25-10 ka ago), the climate evolved to very cold and dry circumstances with very restricted vegetation. Aeolian action took over and earlier deposited fluvial sediments were blown into cover sand ridges, gradually damming the Flemish Valley. The whole northward oriented braided drainage system of the Flemish Valley was forced to branch off eastward, along the Lower-Scheldt (De Moor and Van De Velde, 1995). Since then, the Ostend Valley was no longer connected to the Flemish Valley.

### *Holocene evolution*

*Initial flooding of the southern North Sea and formation of a coastal barrier*

During most of the Weichselian, the North Sea was dry land, but around 12,500 cal BP rising sea water entered the southern part of the North Sea again. Coastward sediment transport could not keep pace with the rapid rise in sea level and the relict landscape drowned rapidly (van der Molen and van Dijck, 2000). Microtidal conditions prevailed in most of the Southern Bight. In this early Holocene period, most likely an exposed tidal-flat environment developed in the Southern Bight. As groundwater level rose with sea level, the tidally flooded area was fringed by freshwater marshes in which peat accumulated, known as basal peat (Baeteman, 2004).

Around 9500 cal BP, the North Sea was already sufficient in size to produce waves at its eastern shores capable of building a protective barrier behind which a complex of estuaries and tidal basins could develop (Beets and van der Spek, 2000; van der Molen and van Dijck, 2000), represented in seismic unit U4. Sand to fill the back-barrier basins was derived from the shoreface adjacent to the tidal inlets and from the ebb-tidal deltas. As insufficient sediment was supplied to the shoreface to compensate for this sediment loss, the shoreline was forced to recede (Beets and van der Spek, 2000), while eroding the underlying deposits and previous back-barrier sediments.

*Formation of storm-generated ridges from the transgressive sand sheet*

Several metres of sand covered the ravinement surface cut by the barrier retreat process, i.e. the Holocene transgressive sand sheet. From this sandy layer storm-generated or shoreface-connected ridges formed erosively under influence of storm and tidal forces which left a deep imprint in the U4 surface. On the basis of morphological evidence, the Goote and Akkaertbank most likely represent former shoreface-connected ridges, represented by seismic unit U7. Their position with respect to former coastlines suggests that these banks started forming around 9500 and 8900 cal BP, respectively. Shortly later, around 8400 cal BP at a more nearshore position, the sand ridges recognised in seismic unit U5 started developing. With further rising relative sea level, the ridges became detached, but continued growing upwards. On the basis of the preserved dimensions of the ridges, it is suggested that the most nearshore ridge developed until about 7000 cal BP.

*Coastal barrier stabilisation around 7500 cal BP*

Since the start of the flooding of the Southern North Sea, substantial volumes of sand were eroded from the bottom and transported toward the coast by the tidal asymmetry, aided by wave suspension (van der Molen and van Dijck, 2000; van der Molen and de Swart, 2001). Around 7500 cal BP, the rate of relative sea-level rise decreased resulting in a sand surplus and consequently in the upsilting of the back-barrier tidal basins and the onset of stabilisation of the coastal barrier and closing of the tidal inlets (Baeteman and Declercq, 2002). The retreating shoreline reached in the western Coastal Plain its maximal landward position and the barrier stabilised about 3 km inland of the present-day coastline (Baeteman, 2005a). Note that the barrier retreated more or less parallel with its former position, keeping a straight coastline, but with an angle to the present-day coastline, which caused the seemingly more landward position of the barrier in the western Coastal Plain. The upsilting of the back-barrier basins resulted in the evolution of salt marsh vegetation into reed growth (fresh water marsh), and consequently in peat accumulation (Baeteman,1999; Baeteman, 2004).

*Changing hydrodynamics and formation of tidal sandbanks around 7000 cal BP*

With further rising sea level, the tidal and current amplitudes kept increasing until 7000 cal BP. The larger water depths allowed the tide to propagate closer to the shore, changing the shoreward net sand-transport pattern from before 7000 cal BP to a pattern of along-shore transport. The sand supply to the coast decreased, which was enhanced by a decrease in the suspension of sand by wind waves as the sea became deeper (van der Molen and van Dijck, 2000). The decrease in the rate of relative sea-level rise after 7500 cal BP (Denys and Baeteman, 1995), could compensate the reduced sediment supply, resulting in the sand surplus and consequently in the silting up of the tidal basins as mentioned above (Baeteman, 1999, 2004).

From 7000 cal BP the tidal system became comparable to the present one (van der Molen and van Dijck, 2000). Most likely from this period onwards, when the outer and middle sand ridges of U5 reached their maximum preserved heights, the tidal sandbanks of the Flemish and Hinder Banks (represented by seismic unit U7) started to develop on top of these sand ridges. The Flemish and Hinder Banks formed simultaneously, as a response of the sea bed to a suitable hydraulic regime, and are not formed diachronously, as a response to shoreface retreat due to sea-level rise. Most of the material of which the U7 banks are built up, originates from local erosion of underlying sediments, which can be deduced from the often erosional character of the base of the banks and the presence of deeply incised swales in between them.

*Coastal barrier progradation from 6800-5000 cal BP*

Between 6800 and 6000 cal BP, the relative sea-level rise lost its driving force (Baeteman and Declercq, 2002; Baeteman, 2005a). The relative sea-level rise decreased, so that even the reduced

sediment supply exceeded the created accommodation space, inducing the coastal barrier to prograde. In spite of a second slow-down in the relative sea-level rise, around 5500 cal BP, the barrier did not continue prograding, but stabilised. At that time in the west, the barrier had extended seaward of the modern coastline. In the east, the barrier had migrated seaward over the previous developed nearshore storm-generated ridge. The sediment deficiency responsible for the stabilisation of the barrier is due to a further reduction in sediment supply from offshore to the shoreface. The formation of the tidal sandbanks since 7000 cal BP might have played a role in this.
Meanwhile, since 6400 cal BP, periods of peat growth lasted longer and the lateral extension of freshwater marshes became more widespread (Baeteman and Declercq, 2002; Baeteman, 2008). Between 5500 and 4500 cal BP, almost the entire coastal plain had changed into a freshwater marsh with peat accumulation, the so-called surface peat (Baeteman, 1999; Beets and van der Spek, 2000).

*Renewed expansion of the tidal environment and barrier retreat from 2800 cal BP to 1200 cal BP (750 AD)*
After 2000-3000 years of uninterrupted peat growth (Baeteman and Declercq, 2002; Baeteman, 2008), a tidal system was again installed in the back-barrier area. This was not the result of a sea-level rise, since the sea level still rose with the same strongly reduced trend as during the peat growth. Re-entrance of the tidal system was probably induced by the cleaning of older channels due to an increased rainfall related to a climatic change around 2800 cal BP (Baeteman, 2005b). Due to compaction of the peat and collapse of the channel banks, a lowering of the ground level occurred, which induced an increase of the tidal prism of the tidal channels and consequently, deep vertical incision. Part of the sediment needed to fill the deep incised channels came from the eroding shoreface, which resulted in a landward migration of the coastline.
Around1400-1200 cal BP (550-750 AD), the newly formed channels came in infilling phase, and the major part of the plain evolved again in a supra-tidal environment. As sediment was no longer needed for the further infilling of the remaining tidal channels, the barrier retreat slowed down or even stopped, and did not retreat much further. When the receding barrier stabilised, the shoreline coincided with the present-day coastline in the west, but in the east the coastline was still located at about 10 km from the present coastline, forming the seaward boundary of the island 'Wulpen'.

*Human induced barrier retreat in early 15th century*
The final phase of the barrier retreat up to the present-day coastline, was a consequence of human intervention. Mismanagement of the dunes, dikes and embankments led to the inundation of the isle of Wulpen and losses of large areas of Zeeland during the storm surges in the early 15th century. This caused irreversible hydrographical changes in the mouth of the Western Scheldt. Due to these changes in the hydraulic regime and the consequently stronger tidal currents near the entrance of the widened Western Scheldt, the original – natural – and storm-induced shoreface ravinement surface was deepened, until an equilibrium was reached under the new hydraulic regime. This did not happen though until the middle of the 16th century, as it was then still possible to trace the contours of the drowned island (Augustyn, 1995), while the equilibrium surface adjusting to the renewed hydrographic situation reached a depth of -12 m before it was covered with sediments. So at least after the middle of the 16th century, the eroded, high-organic muddy sediments (of former back-barrier deposits) could settle, alternated with sandy storm layers, i.e. seismic unit U6.

*Formation of the Coastal Banks*
After the deposition of seismic unit U6, the Coastal Banks (seismic unit U7) started developing on top of it. On the basis of morphological evidence these banks represent shoreface-connected ridges. They developed simultaneously though, as a response of the sea bed to a suitable hydraulic regime of wave (storms) and tide, and not in relation to a retreating shoreline as the coastline had already reached the present-day position by the time they could form.

## Conclusion
Despite the very thin and fragmented Quaternary record without any datable material, a comprehensive geological evolutionary model could be reconstructed for the entire Belgian Continental Shelf for the very first time. As the BCS appears more often in the news nowadays, on issues such as the construction of offshore windmill parks or requests for extending sand and gravel extractions permits, reliable knowledge of the nature and composition of the shallow subsurface of the BCS, which is closely related to its geological evolution, is truly indispensable. A thorough knowledge of the sedimentology, structure and evolution of the shallow subsurface is essential, not only for practical applications but also for biological and ecological investigations in the North Sea, as the seafloor forms a crucial part of the North Sea ecosystem. Finally, the knowledge of the development of former estuaries and the natural evolution of past coastlines can help to assess future coastline migrations in the light of further sea-level rise.

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