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NORTH SEA

TERTIARY AND QUATERNARY GEOLOGY OF THE BELGIAN CONTINENTAL SHELF

S. LE BOT, V. VAN LANCKER, S. DELEU, M. DE BATIST, J.P.HENRIET

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S. Le Bot, V. Van Lancker, S. Deleu, M. De Batist, J.P. Henriet

Adresses of authors:

Renard Centre of Marine Geology (RCMG)

Ghent University
Department of Geology and Soil Sciences
Krijgslaan 281, S 8
B-9000 Gent
Belgium

Tel: +32 (0)9 264 45 89
Fax: +32 (0)9 264 49 67

E-mails: Sophie.Lebot@UGent.be
Vera.Vanlancker@UGent.be
Samuel.Deleu@UGent.be

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Rue de la Science 8
Wetenschapsstraat 8
B-1000 Brussels
Belgium
Tel: +32 (0)2 238 34 11 - Fax: +32 (0)2 230 59 12
http://www.belspo.be

Contact persons:
David Cox (coxd@belspo.be - Tel: +32 (0)2 238 34 03)
Anne Fierens (fier@belspo.be - Tel: +32 (0)2 238 36 60)

Introductory note

A synthesis of the geology of the Belgian continental shelf is here presented. The main part of this document is dedicated to the review of the lithostratigraphy, geotechnical properties, geometry and distribution of the Tertiary and Quaternary deposits.

The data compilation, review and assessment have been conducted from the numerous existing studies and large data sets, available offshore, but also onland when offshore data were scarce or lacking. Three main projects have enabled to collect the offshore data: (1) the project "Seismic stratigraphy, Southern Bight, North Sea" (RCMG, City of London Polytechnic/NERC, University of Caen/CNRS) ; (2) the project "Seismisch onderzoek op het Belgisch Continentaal Plat. Eerste faze. Ontginningszone 2" (MEZ/Administratie van het Mijnwezen, RCMG) ; (3) the project "Studie oppervlaktelaag van het Belgisch Continentaal Plat. Seismisch prospectie sector B" (MEZ/Belgian Geological Survey-BGD, RCMG). Data consist mainly of seismic profiles (16,000 km), cores (79) and cone penetration tests (CPTs, 177). All the data have been digitised and integrated in appropriate georeferenced softwares. Synthetic integrated maps and tables have been produced, aimed to provide the end-users with clear and directly usable information.

This synthesis has been conducted in the framework of the project "Optimal Offshore Wind Energy Developments in Belgium", financed by the Belgian federal government (Federal Office for Scientific, Technical and Cultural Affairs). This project is in keeping with the part I project network "Production patterns and sustainable consumption" of the PADD II program. Objectives of this project consisted in providing recommendations for the selection of sites that are convenient with respect to the stability of offshore wind structures and the minimisation of geo-environmental impacts.

Contents

INTRODUCTION: PRESENT-DAY SEABED SEDIMENTS[1]

Seabed morphology

General seabed morphology

Apart from major bedforms, the seabed of the Belgian continental shelf is gently dipping from 0 to 50m in the more offshore parts of the shelf (figure 1). In the coastal zone (10-20 km wide), depths range between 0 and 15 m. The median part, including the Zeeland Ridges and the Hinder Banken, is 15 to 35 m deep. In the northern part, the seabed is flat, not covered with large bedforms, deepening from 35 to 50 m.

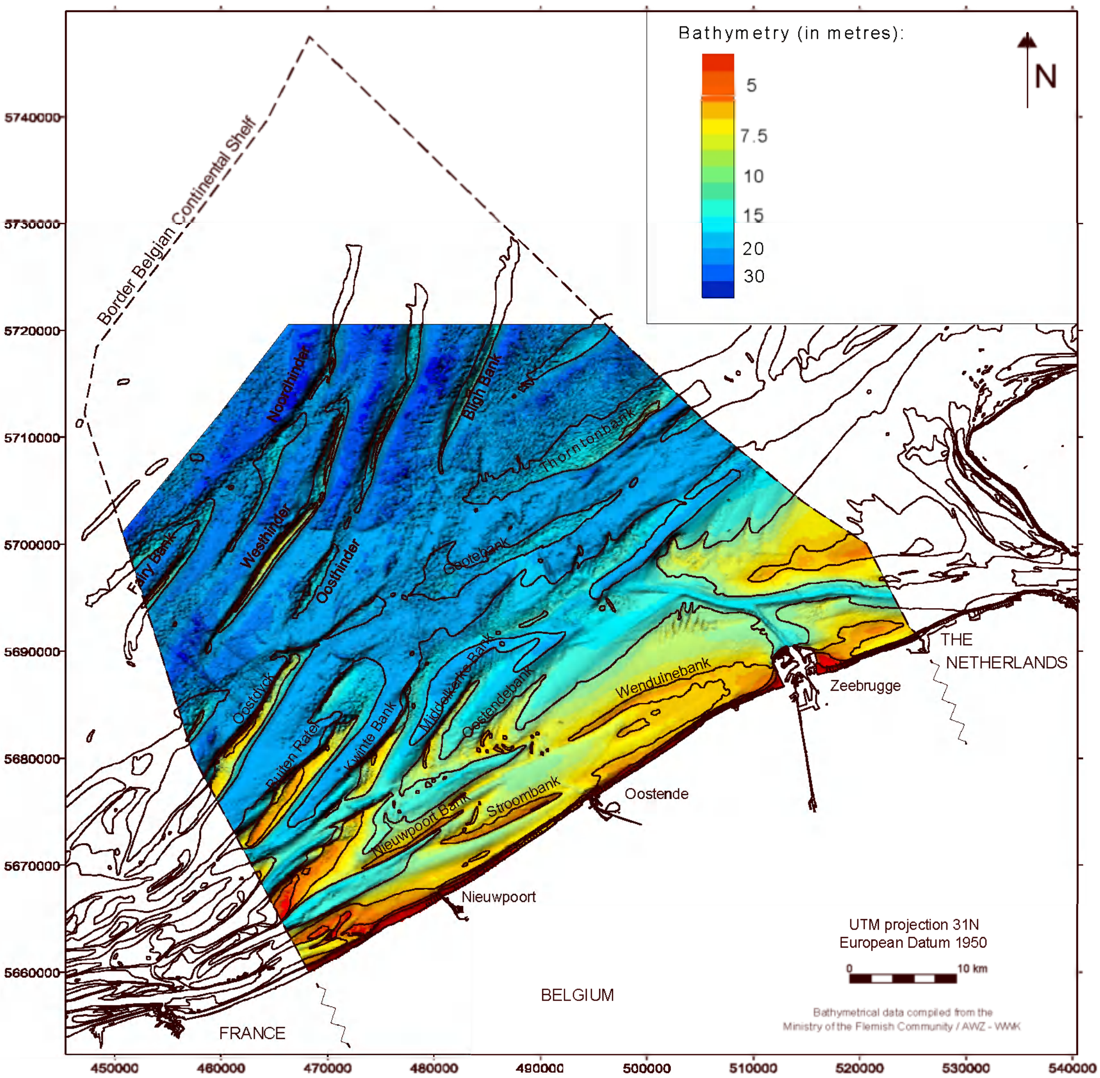


Figure 1: Pseudo 3D image of the topography of the Belgian continental shelf based on single-beam echosounder data (compiled from the Ministry of the Flemish Community AWZ-WWK Zeebrugge) (After Lanckneus et al., 2001).

[1] Reference is made to the results of the PPS Science policy project 'BUDGET' which gives an overview and critical analysis of all data relevant for the study of the natural sand transport on the Belgian continental shelf (Lanckneus et al., 2001).

Bedforms

Sandbanks and dunes, as defined by Ashley (1990), are the main and larger bedforms observed on the Belgian continental shelf. Sandbanks are the named, largest elongated features visible on figure 1 ; the "rough" areas correspond to dune fields.

Sandbanks are arranged in several groups: the Coastal sandbanks and the Zeeland Ridges are oriented ENE-WSW, the Flemish sandbanks are about NE-SW, and the Hinder sandbanks elongate NNE-SSW. These features are up to 30 m high, culminating only a few metres below the sea surface, several tens of kilometres long and several kilometres wide. A zoom on the Flemish Banks is presented (Middelkerke Bank, Kwinte Bank, Buiten Ratel) on figure 2, which corresponds to an excerpt from the map realised in the framework of the project BUDGET (Lanckneus et al., 2001).

Generally, sandbanks are covered with dune structures, except for most of the Coastal Banks. These dunes are mostly in the range of 2 to 4 m and often increasing in height towards the top zone. The long flank of the sandbanks is often characterised by an amalgamation of dunes which are often larger than dunes occurring along the steep slope. Again, the non-linear parts of sandbanks (kink areas) are the most complex, and are often covered with the largest dunes. Generally, the highest dunes are observed at the northern extremity of the Flemish Banks (up to 8 m) and in the northern part of the Hinder Banks region. Closer to the coast, the sandbanks are generally devoid of bedforms.

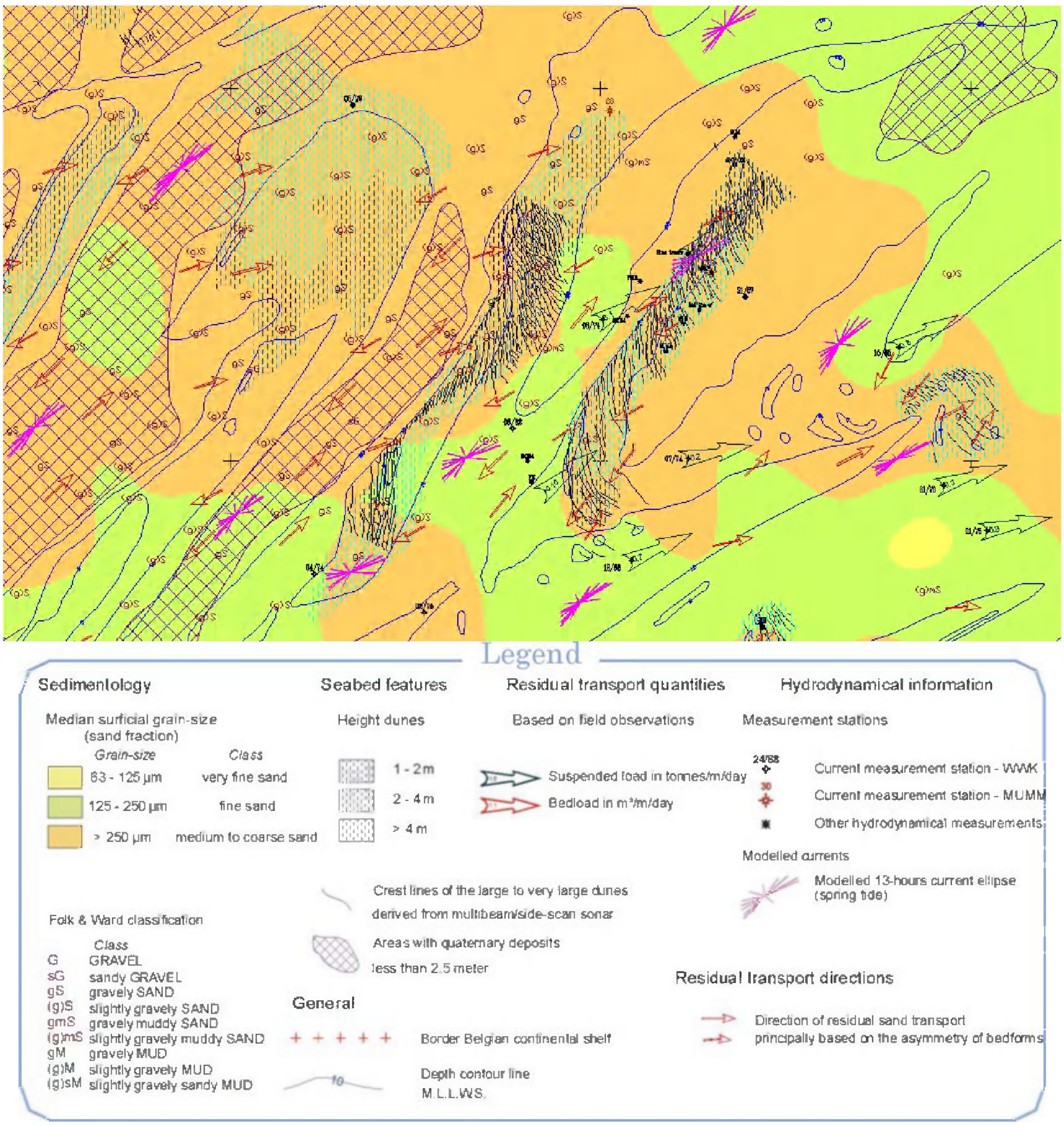


Figure 2: Morpho- and sediment-dynamic compilation. Excerpt from the BUDGET map (After Lanckneus et al., 2001).

Fields of large dunes also occur at the western extremity of the Goote Bank and in the northern part of the area of the Hinder Banks where they were abundantly observed in the swales between sandbanks (up to 11 m) (Deleu, 2001). Closer to the coast, their occurrence is merely restricted. Still, high dunes up to more than 2 m are often found in the shallowest areas. Areas with an indication of the dune heights, divided in classes of 1-2 m, 2-4 m and more than 4 m, have been delineated and reported on figure 3, which results in a compilation of the maps of the project BUDGET (Lanckneus et al., 2001) and of van Alphen & Damoiseaux (1989).

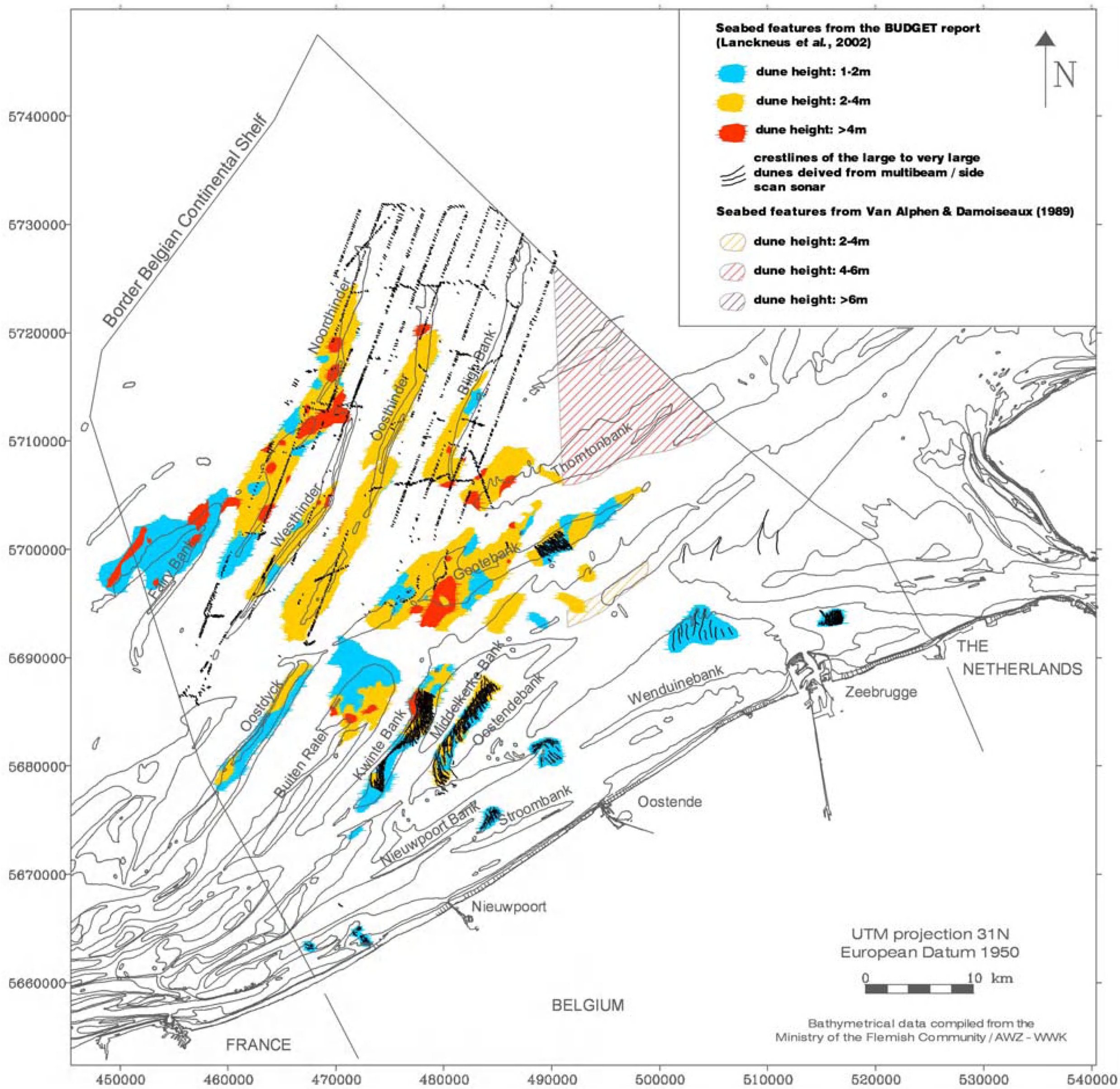


Figure 3: Dune areas with various height ranges (compilation from Lanckneus et al., 2001 and Van Alphen & Damoiseaux, 1989). The available information is largely restricted to the sandbank areas.

Bedform dynamics

The occurrence and morphology of the sandbanks as a whole has generally not drastically changed over the last 200 years. Movements are only located within the area of sandbanks themselves and especially towards their summits. Generally sandbanks witness a major stability and this at least since 1800 (e.g. the Flemish Banks, Van Cauwenberghe, 1966, 1971, table 1).

However, the morphological units under the influence of the Westerschelde estuary, as well as small recently formed sandbanks, tend to be more dynamic. Not included in the analysis are the Hinder Banken and the Zeeland Ridges. Research on kink areas of sandbanks do reveal a much more complex morphological behaviour than linear parts of sandbanks (Deleu, 2002).

Table 1: Stability of the major sandbank-swale systems, from east to west (description from Van Cauwenberghe 1966, 1971).

morphological unit	dynamics (from Van Cauwenberghe 1966, 1971)
Wandelaar	not enough reliable data to trace its evolution
Akkaert Bank	not enough reliable data to trace its evolution
Wielingen West	the general geometry has been subdued to major changes as a whole or partly; in the period 1959-1968, a certain narrowing takes place; this was also the case, but more pronounced in the period 1866-1870
Wenduine Bank	stable in the period 1800-1968
Ravelingen	recent in origin, it became part of larger existing sandbanks
Oostendebank	stable in the period 1800-1968
Middelkerkebank	stable in the period 1800-1968
Negenvaam	major stability since the period 1924-1929
Kwintebank	stable in the period 1800-1968
Kwinte	major stability since the period 1924-1929
Grote Rede	the general geometry has been subdued to major changes; the situation in the period 1959-1968 resembles that of 1901-1903
Kleine Rede	the general geometry has been subdued to major changes; the situation in the period 1959-1968 resembles that of 1901-1903
Stroombank	major stability since the period 1879-1882; previously they showed an S-shaped movement of 300 to 350 m
rechtstreekse kil'	entrance navigation channel towards Oostende; an anthropogenically induced channel through the Stroombank due to dredging works and hence gradually increased in depth
Baland Bank	recent in origin, it became part of larger existing sandbanks
Noordoostpas	stable in the period 1800-1968
Nieuwpoort Bank	major stability since the period 1879-1882; previously they showed an S-shaped movement of 300 to 350 m
Noordpas	major stability since the period 1901-1903
Westdiep	major stability since the period 1879-1882
Smal Bank	the general geometry has been subdued to major changes;the movements are especially located at its SW end which has broadened and was subdued to a NNE displacement
Den Oever	the general geometry has been subdued to major changes; see Van Cauwenberghe 1971
Potje	the general geometry has been subdued to major changes as a whole or partly; subdued to a NE displacement
Trapegeer	the general geometry has been subdued to major changes; see Van Cauwenberghe 1971
Broers Bank	the general geometry has been subdued to major changes; see Van Cauwenberghe 1971
Zuydcoote pas	the general geometry has been subdued to major changes as a whole or partly; subdued to a NE displacement
Hills Bank	the general geometry has been subdued to major changes; subdued to a NE displacement; the connection Breed Bank - Hills Bank has also known a SW movement under the influence of an ebb and flood parabola of which the ebb overruled the flood
Braek Bank	major stability since the period 1866-1870
Snouw Bank	stable in the period 1800-1968
Passe de l'Ouest	stable from the period 1901-1903 onwards

morphological unit	dynamics (from Van Cauwenberghe 1966, 1971)
Mardyck Bank	major stability since the period 1932-1939; before that, the bank showed a significant movement of +/- 2 km to the E
Fosse de Mardyck	the general geometry has been subdued to major changes as a whole or partly; since the period 1866-1870, it is 500 m closer to the coast and has an eastwards displacement
Breed Bank	stable in the period 1800-1968; still the bank tend to broaden and was subdued to a NNE movement (at least for the period up till 1968)
Binnen Ratel Bank	stable from the period 1901-1903 onwards; the shallow triangular part was previously subdued to movements
Buiten Ratel	stable from the period 1932-1939 onwards; a SE movement of the SW side of the sandbank only occurs in the period 1932-1939
Dyck Bank	the general geometry has been subdued to major changes as a whole or partly; since 1866-1870 the bank is decreased in surface at its NE where it tends to rotate counterclockwise, possibly under the influence of local changes in the current
Oost Dyck	stable from the period 1932-1939 onwards; only the SW part of the sandbank was previously subdued to a SE movement (in period 1879-1882 and 1901-1903); the sandbank itself is very stable
In-Ruytingen Bank	not enough reliable data to trace its evolution
Out-Ruytingen Bank	not enough reliable data to trace its evolution
Bergues Bank	not enough reliable data to trace its evolution

Based on time-series of observations, the following conclusions can be drawn on the behaviour of large dunes on the Belgian continental shelf (Lanckneus et al., 2001): (1) nearly all large dunes present an asymmetry (ebb- or flood dominated) that is subject to inversions ; (2) the height of all dunes oscillates around a particular value through time ; the height can be lowered by heavy weather ; (3) the large dunes are subject to oscillatory movements (up to 20 m) resulting , however, in minor net migration rates ; (4) displacement of the large dunes can occur in the direction of the steep slope or of the long flank, since the asymmetry of a large dune do not always show the direction of the short-term sediment transport. Dunes observed on kink areas are also more migrating than on the linear parts of the banks.

TERTIARY AND QUATERNARY DEPOSITS

On the Belgian continental shelf, the substratum is composed of solid layers of various ages. The Paleozoic basement is found at a depth of some 250 m near the French border to 450 m near the Dutch border. It is a relatively stable continental block called the London-Brabant Massif which was only flooded since Late Cretaceous times. During this period was deposited a chalk layer the thickness of which ranges from a minimum of 50 m between Nieuwpoort and Oostende and increase rapidly offshore to a maximum of 220 m in the area of the Hinder Banks. The chalk top lays at a depth of some 150 to 350 m, increasing to the NE (De Batist, 1989). The Palaeogene deposits (Tertiary) composed the upper part of the substratum. They outcrop locally on the seabed under a discontinuous cover of Quaternary sediments. These layers were mainly deposited during the Thanetian (started some 57 Ma) to Rupelian period (ended 30 Ma ago ; Haq et al., 1987). The top of these deposits is located at depth increasing in an offshore direction from some 10 to 60 m and features a thickness of 110 to 280 m, increasing toward the E-NE (De Batist, 1989). These solid layers are covered by sediments of Quaternary age.

1 Data and methodology

Internal layers are investigated by combining lithostratigraphical and geometrical information gathered from direct and indirect measuring systems.

1.1 Seismic data

Seismic data allow to determine the geometry (distribution and internal architecture) of geological layers. The high resolution reflection seismic method is based on acoustic wave propagation. The data consist of profiles corresponding to 2D vertical acoustic images. These images show reflectors corresponding to areas where an acoustic impedance contrast exists, induced by a contrast of compaction, internal pattern and/or sediment or rock nature.

Sediment geometries, identified from seismograms, can be interpreted according to seismo-stratigraphical principles (Vail et al. 1979) that allow a discrimination into depositional sequences. These are further investigated according to their seismic facies and can indicate the depositional environments. It needs emphasis that seismo-stratigraphical boundaries merely have a chronostratigraphical meaning and can not necessarily be interpreted in lithostratigraphical terms (Vail et al. 1979). Moreover, lateral alternations in lithofacies within a layer do not necessarily give rise to a seismo-stratigraphical boundary.

Since 1978, a dense and regular high-resolution reflection seismic grid with a total length of about 16,000 km has been acquired by the Renard Centre of Marine Geology (RCMG) on the Belgian continental shelf and the adjacent French, Dutch and UK sectors (between 51°-52° N and 2°-3.5° E) with a variety of different seismic tools (figure 4).

1.2 Coring information

Cores represent true 1D vertical data that can provide the lithological and micropalaeontological data required to determine the lithostratigraphic characteristics of the deposits. These information complement the geometrical and geotechnical information, obtained from the respective interpretation of extensive seismic data and cone penetration tests.

There is only limited core information (figure 4, see precise location in Annex 1). Among the 79 available cores, only 37 cored reach the Tertiary substratum of the Belgian continental shelf. Generally, they are no longer than 10m, exception made of some cores (e.g. RGD-N1262/B1 which has a length of 61.8m). Cores have been acquired by:
(1) the Rijks Geologische Dienst (RGD, NL) in the 1970's and 1980's. Most of the RGD cores are Geodoff drillings and are more or less equally partitioned over the Belgian continental shelf,
(2) the Belgisch Geologische Dienst (BGD), on the whole Belgian continental shelf,
(3) the OSIRIS Survey (NL).
Extra core information is available on the Oostdyck sandbank (ODB-B2) and near the Paardenmarkt (BKR-2/A B22).
Here, cores allow to recognise the different geological units.

Detailed lithostratigraphic information from 4 nearshore BGD boreholes (GR1, SWB, SEWB and VR1) were available and have already been correlated with seismic information (Jacobs & Sevens, 1993; Jacobs & De Batist, 1996). In the framework of this project, information from 33 cores, drilled offshore in the upper part of the substratum, has been integrated: for each core, a litholog was available, most of the cores were already interpreted in terms of stratigraphy, the others have been interpreted during the project period through a correlation with the seismic information. Some typical lithologs are reported in Annex 2, and core lithology is described in Annexes 3 and 5 .

A large variety of analysis realised on cores provide valuable indications on deposit ages (e.g. microfossil analysis such as palynomorphs) and deposit nature (e.g. grain-size and sedimentary facies analysis), which allowed the complete section to be correlated with equivalent sediment series onshore and, next, to establish the lithostratigraphy of offshore seismic units.

1.3 Cone Penetration Tests

Cone penetration tests (CPT's) correspond to 1D vertical measurements that provide quantitative data of various geotechnical parameters. A CPT is carried out by pushing statically a conus into the ground. Cone resistance (q_c in MPa) and, sometimes, total friction (Q_{st} in kN) are then measured. The correlation of CPT's parameters and coring data can enable to evaluate the lithological and geotechnical characteristics of geological units.

Almost all available CPT's have been realised onland, exception made of measurements taken near the harbour of Zeebrugge and discussed by Depret (1981), and the four CPT's acquired in offshore locations in the Quaternary deposits (1 in the Westhinder sandbank, 3 in the Oostdyck sandbank) (figure 4).

The onland and offshore CPT's were mostly acquired by the department of Geotechnics (Ministry of the Flemish Community) and made available by DOV (Databank Ondergrond Vlaanderen). Data were twofold: CPT's recorded before 1980 were only available on paper sheets, whereas the most recent CPT's were available as PDF files, converted by DOV and consultable on their website (dov.vlaanderen.be). In the Zeebrugge's area, 68 CPT's have been reported by Depret (1981) from which 37 penetrate deeper than 30m and 65 deeper than 20m.

Given the huge quantity of onland CPT's, the ones, interpreted and integrated in the framework of this project (165), have been selected on the basis of the following factors: (1) CPT's with available stratigraphic interpretations, delivered by DOV, were first considered; (2) it was necessary that the location of the CPT's would not be too far from the coast. For this reason only the geological chart numbers 4, 5, 11 and 12 (Jacobs et al., 1993, 1996, 1999a, 1999b, 2002) were taken into consideration; (3) the purpose was to represent every unit, thus CPT's were also chosen as a function of their position (see location on figure 4); (4) as many CPT's were only very shallow, only those penetrating deeper than 25m were studied; (5) preference was given to CPT's which penetrate into Tertiary deposits.

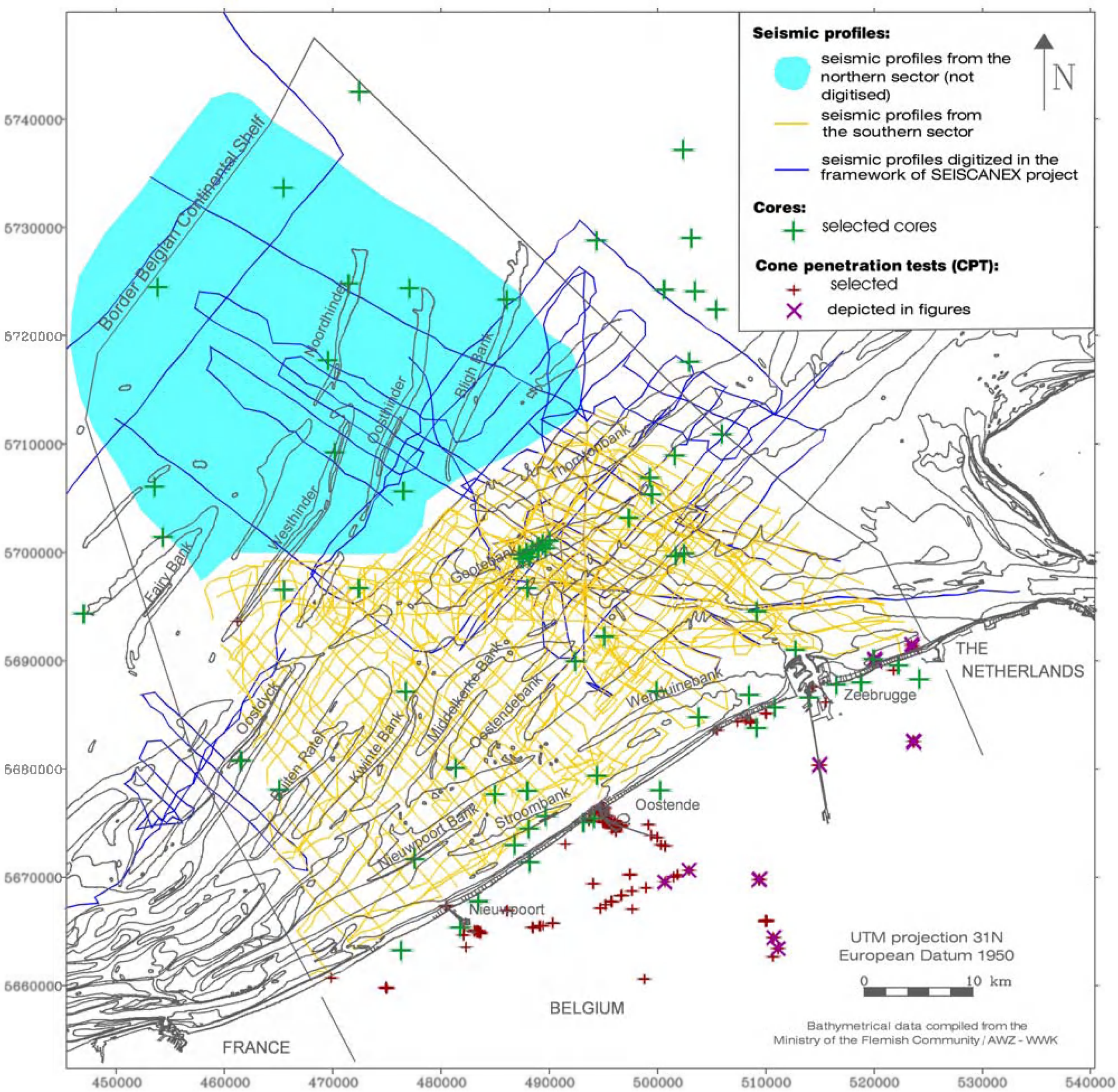


Figure 4: Location of available seismic profiles, cores and cone penetration tests. Seismic data have been provided by RCMG (Ghent University), boreholes and cores by the Belgian (BGD) and Dutch (TNO-NITG) Geological Surveys and CPT's by the Department of Geotechnics (Ministry of the Flemish Community, Databank Ondergrond Vlaanderen).

1.4 Methodology

In previous studies, "events and trends" have been identified and correlated in northern Belgium from seismic sections and outcrops. Offshore seismic facies have been tentatively matched with onshore lithofacies.

On the shelf, lithological and geotechnical observations are scarse, since difficult to realise from a technical point of view: cored wells and CPT's are merely confined to nearshore locations, and allow only punctually to determine precisely the lithology and geotechnical properties of units. Onshore lithology and geotechnical properties of the geological deposits comes from detailed and precise observations from relevant onshore outcrops. When no or scarse offshore data exist, the assessment of the lithological and geotechnical characteristics of offshore layers can be made by extrapolating onshore information to their corresponding offshore units.

2 Palaeogene deposits

2.1 Previous works

A first attempt to investigate the geology offshore Belgium in detail was undertaken by Bastin (1974). The study of De Batist & Henriet (1995), of which some preliminary results have already been presented by Henriet et al. (1989a, b) and De Batist et al. (1989), represents the first comprehensive investigation of the stratigraphy and structural setting of the Belgian continental shelf. A fine-scale, seismo-stratigraphical model for the Palaeogene was formulated by De Batist (1989) and De Batist and Henriet (1995). A sedimentation model has been proposed by Jacobs & De Batist (1996). It is complementary to the palaeomorphologic studies of Mostaert et al. (1989) and Liu et al. (1992, 1993), and to the lithostratigraphic investigations of Jacobs et al. (1990) and Jacobs & Sevens (1993). The present knowledge of the onland Palaeogene lithostratigraphy was summarized by Maréchal and Laga (1988) and Laga et al. (2001) with contributions from various authors.

2.2 Seismic stratigraphy

Detailed seismic interpretation following Mitchum et al. (1977), allowed De Batist (1989) and De Batist and Henriet (1995) to identify 8 seismo-stratigraphical units and a number of subunits within the Belgian offshore Palaeogene succession using geometry and facies characteristics.

Erosional truncation and valley incisions are common features at the top of the units. Most of the units have a pronounced sheet-like shape, with planar dipping boundaries at their base and top, and show only minor thickness variations. Each unit is also characterized by a distinct seismic facies and/or by typical facies variations, indicative for the depositional environment and its evolution.

The major seismo-stratigraphical units have been labelled with a character-digit symbol, indicating their most probable chronostratigraphical position: Y1 to Y5 from Ypresian age, L1 and L2 from Lutetian age, B1 from Bartonian age and P1 from Priabonian.

The main seismo-stratigraphical characteristics of these units are listed in table 2 and have been compiled into a synoptic seismic and schematic type section, constructed as a composite or 'collage' of several seismogram sections acquired with comparable source signatures (figure 5).

Table 2: Seismostratigraphical characteristics of the 11 Palaeogene units in the offshore Belgian continental shelf and surroundings (after De Batist and Henriet, 1995).

Unit	Nature of base	Nature of top	Seismic facies (sound velocity in m/s)	Geometry	Thick-ness
R2	conformity	erosional truncation, channel incision	very regularly banded pattern of continuous, parallel high- to medium-amplitude reflectors (1650 m/s)	Base: planar dipping Top: strongly incised and channelized	0 – 60 m
R1	discrete downlap	discrete truncation	irregular and laterally discontinuous facies composed of subparallel to wavy reflectors with variable amplitude (1700 m/s)	Base and top: planar dipping	+/- 35 m
P1	discrete onlap	discrete truncation	Vertical succession of 2 seismic facies subunits (1700 m/s): 2: homogeneous pattern of continuous, parallel, low- to medium amplitude reflectors 1: continuous, parallel, draping reflectors of varying amplitude	Base and top: planar dipping Unit: divergent to NE	40 – 90 m
B1	conformity	conformity	Vertical succession of 7 distinctive and laterally very continuous seismic facies subunits (1580 m/s): 7: reflection free with a low-amplitude, discontinuous, draping ondulating reflectors 6: ondulating, medium-amplitude, draping reflectors 5: reflection free 4: convex, lob-shaped mounds of medium-amplitude, prograding, hummocky reflectors 3: reflection free 2: oblique reflectors ; progradating (shingled) reflector on top 1: regular set of continuous, parallel, high-frequent reflectors	Base and top: planar dipping Unit: thickening to N and NE	45-60 m
L2	not known	not known	not known	Unit: very thin, locally distributed patchy deposit	not known
L1	conformity	tectonically influenced truncation	Vertical succession of 2 seismic facies subunits (1700 m/s): 2: discontinuous, parallel to subparallel reflectors of variable amplitude : towards the top 2 to 3 discontinuous, subparallel, very high-amplitude reflectors 1: 2 continuous high-amplitude parallel reflectors, and 1 discontinuous, low-amplitude reflector at base	Base and top: planar dipping	25-30 m
Y5	downlap	truncation and toplap	3 seismic facies subunits of local area extent (1700 m/s): 3: low-amplitude, parallel reflectors 2: parallel-oblique clinoforms 1: reflection-free	Base and top: planar dipping Unit: wedge shape, pinching out towards N	0-17 m
Y4	downlap	truncation	3 SE prograding infilling subunits with sigmoidal to parallel oblique clinoforms of variable amplitude (Y4.a, Y4.b, Y4.c) (1700 m/s)	Base: linear channelized Top: planar dipping Unit: channel-fill shape	10 km wide, N70° orientation c: 0-25 m b: 0-20m a: 0-21 m
Y3	discrete downlap	truncation	low-amplitude, discontinuous, parallel reflectors or parallel-oblique clinoforms (1600 m/s)	Base: planar dipping Top: planar dipping (locally channelized)	0 - 25 m
Y2	downlap	truncation	reflection-free or very low-amplitude, parallel-oblique, prograding clinoforms (1750 m/s)	base and top: planar dipping	+/- 30 m
Y1	conformity	discrete truncation	homogeneous seismic facies of low-amplitude, discontinuous parallel reflectors affected by intraformational deformations (1620 m/s): 3 : undisplaced, faulted blocks with alternately tilting and downwarping bedding terminations 2: major tilted blocks, convolute structures with broad synclines and cusps anticline, diapers 1: block-faulting, tilted and bent blocks, randomly dipping fault planes	base and top: planar dipping Unit: thickening to NE	150-180 m

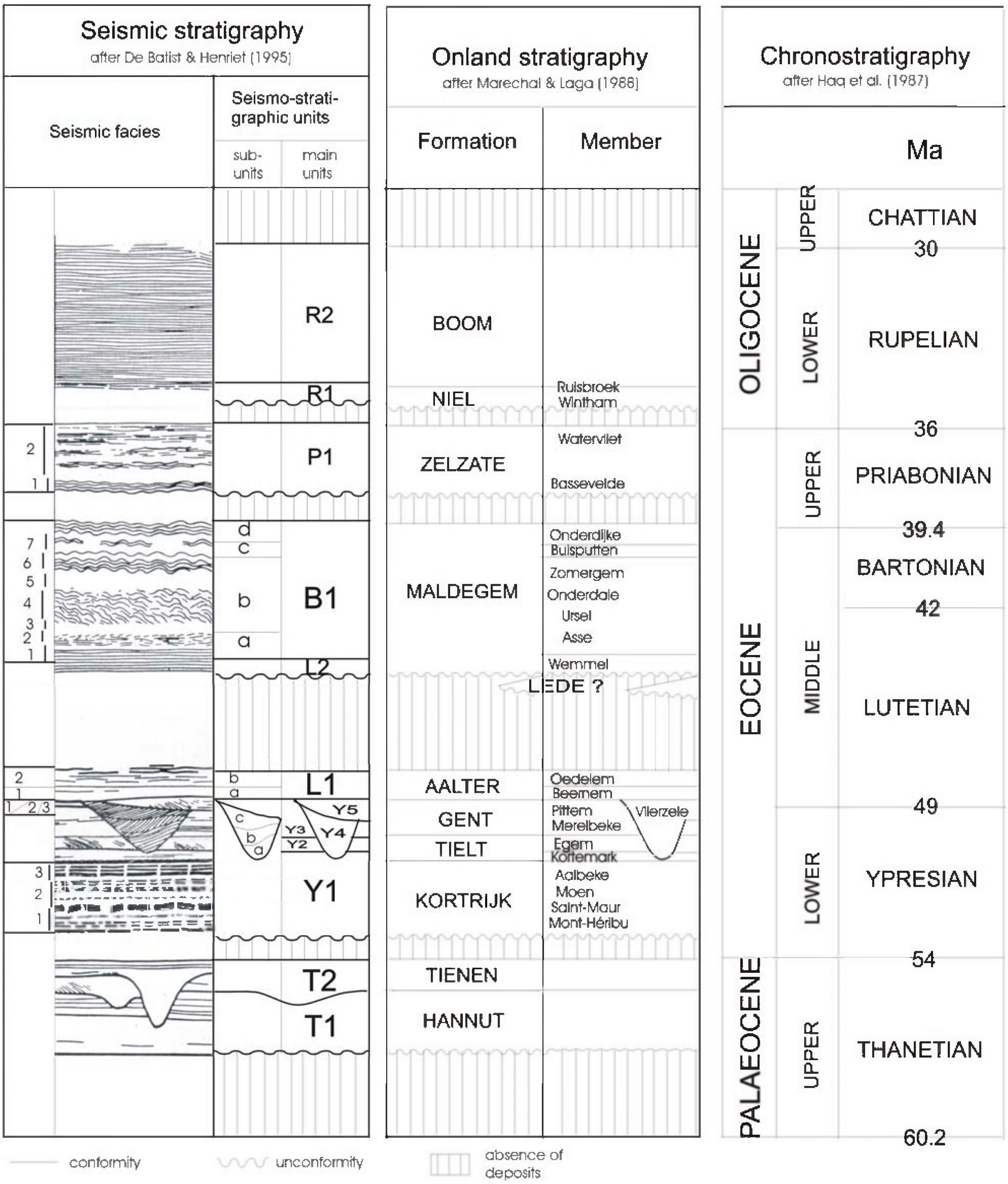


Figure 5: Synthesis of seismostratigraphy and onland stratigraphy (modified from Jacobs & De Batist, 1996; complements from Maréchal et al., 1986).

2.3 Nature of deposits

2.3.1 Previous works

Knowledge of the lithology of offshore solid deposits is not very detailed, in particular towards the most offshore part of the Belgian continental shelf where only few wells are available. The synthesis on the litho-stratigraphy of all seismic facies units has been established by De Batist (1989), De Batist and Henriet (1995) and Jacobs and De Batist (1996) by realising a correlation between seismic data and offshore boreholes, offshore cores and onshore outcrops. Seismic unit facies and their morphological expression at outcrops and subcrops were also analysed (De Batist, 1989). The knowledge of the offshore lithology of the seismic units was based on 4 shallow cored boreholes drilled near the Belgian coast, containing a nearly continuous, 200 m thick sediment succession of Eocene age, described in detail by Jacobs and Sevens (1993a) and Jacobs (1995b). Unfortunately, integration of these data with the seismic information has not been straightforward: 3 of the boreholes were located in shallow water areas, characterised on the seismic profiles by acoustic blanking due to superficial gas, and only borehole VR1 can be tied directly to the seismic data (see figure 4).

2.3.2 Problematics

When lithological information is sparse, the most reliable methodology consists of considering that each seismic unit has a homogeneous lithology: the lithology known from onshore observations and punctual wells can be applied offshore to the whole seismic unit. However, attention needs to be paid to the fact that unit boundaries are: (1) offshore: chronological and do not necessary depend on lithology ; (2) onshore: based on lithological criteria.

These remarks are of specific interest as most of the Palaeogene units of the Belgian Basin are characterized by rapid, wholescale lateral facies changes, inherent to the marginal position of the area within the North Sea Basin, as it was concluded by Jacobs & De Batist (1996) by using sequential stratigraphy method. Marginal environments (table 3) are submitted to a strong variability of sediment sources and deposit processes, inducing a possible rapid change in the sediment nature and pattern (lithology) in the across-margin (onshore-offshore) direction. Globally it can be said that deposits become finer in the offshore direction and coarser in coastal environments, but no more detailed conclusions can be drawn on the lithology, and local morphologies can induce modifications of this pattern.

Table 3: Depositional environments of the Tertiary units of the Belgian continental shelf (after Jacobs & De Batist, 1996).

Seismic units	Depositional environment
P1	shallow marine and barrier-protected lagoonal, wash-over and tidal flat environments (onland: Steurbaut, 1986 ; Jacobs & Sevens, 1993)
B1	central to outer shelf environment (20 to 50 m water depth) (onland: distal deltaic environment, Jacobs & Sevens, 1993)
L2	transgressive lag deposit overlying a ravinement surface
L1	very shallow marine environment (strong variations) (onland: tidal flats, lagoons ; Jacobs et al., 1990, Jacobs & Sevens, 1993)
Y5	lagoon towards mouthbar or crevasse splay in a deltaic to intertidal environment (onland: tidal ridge system, Houthuys & Gullentops, 1988 ; cross-bedded sands)
Y4	eroded and then infilled depression (channel or basin ?) (onland: tidal ridge system, Houthuys & Gullentops, 1988 ; cross-bedded sands)
Y3	nearshore mudshelf (15 – 30 m) with delta influence (top of Merelbeke clay) and tide influence (Pittem Member) (nearshore: offshore sand-shoal deposits, Jacobs & Sevens, 1993)
Y2	deltaic origin deposits with a southern sediment supply (onland: offshore mud-flat deposits, Jacobs & Sevens, 1993)
Y1	mud-shelf environment below storm-wave base (Jacob & Sevens, 1993)

2.3.3 New data and interpretations

2.3.3.1 Lithostratigraphy

New offshore cores (33) have been interpreted in terms of lithostratigraphy (Annex 3). New insights have been drawn on the lithology of offshore Palaeogene units, and also on the lateral variability of the lithology within each unit (table 4). The lithology of deposits can also be determined using the cone resistance values obtained from CPT's (figure 6 and Annexe 4). This parameter allows to clearly define pure sand and pure clay. The values with absolute certainty for clays are below 2 MPa whereas for sands the values are higher than 15 MPa. Although, most of the cone resistance values are in-between both limits (tables 5 and 6, figure 6 and Annexe 4), given raise to difficulties to characterize sediments, they can provide very valuable lithological information when correlated with coring information.

Y1 and Y4 units and the Ursel, Zomergem and Onderdijke Members of B1 are made of clay. The Buisputten Member of unit B1 is made of sand. The majority of units is made of a mixture of sand and clay, often evolving laterally: clayey sands (Wemmel and Asse Members of unit B1, Beernem Members of unit L1), sandy clay (Y3). Y2 and evolve from a sandy to clayey nature from onland towards offshore. The Oedelem Member is described as a clayey sand unit onland, but displays a vertical rapid alternation of clayey and sandy units towards offshore. The sandy clay Pittem Member of Y3 unit contains numerous mud drapes and rythmic interlayered bedding. Y4.a unit displays a fining of sand (medium coarse to fine) towards offshore, and the Y4.b unit displays an increasing amount of silt in this direction. The units displaying important lateral variability of the lithology (L1-Oedelem, Y5, Y2) concern sediments deposited in a very coastal environment where rapid changes of sedimentary sources and processes occur (table 3).

Table 4: Lithology of the Palaeogene geological units. Synthesis of available information.

Main Unit	Subunit	Lithological description	Lithological spatial variability
P1 (Zelzate F.)	no subunit	coastal zone: Bassevelde sands Member: strongly bioturbated clayey fine sands with mottled texture and containing carbonised plant remains, with 1 bioturbated intercalated sandy clay layer (Jacobs & De Batist, 1996) / offshore: stiff and slightly sandy, green grey clay (known till 5 m depth)	no specific noticeable spatial trend (evolution towards a more clayey sediment ?)
B1 (Maldegem F.)	Onderdijke M.	clay (Jacobs & De Batist, 1996) / offshore (this study): stiff to very heavy clay, with various amounts of silt and sand	no specific spatial trend
	Buisputten M.	sand	
	Zomergem M.	strongly bioturbated blue-green clay	
	Onderdale M.	moderately clayey sands	
	Ursel M.	blue-grey bioturbated massive clay with pyrite concretions	
	Asse M.	bioturbated clayey sands and sandy clays	
	Wemmel M.	grey glauconitic, slightly clayey fine sands with 2 continuous calcarenite horizons	
L2 (Lede F. ?)	no subunit	onland (Mourlon, 1873 and Fobe, 1988 ; in Laga et al., 2001): calcareous and glauconifereous, fine sand. The base is formed by a pebble layer with reworked elements from older deposits. 3 layers of sandy limestone or calcareous sandstone are observed.	no offshore information
L1 (Aalter F.)	Oedelem M.	coastal zone (Jacobs & De Batist, 1996): grey-green glauconitic fine sands to clayey sands, with bioturbation and fossil abundance. At the top, a number of discontinuous subparallel very high amplitude reflectors correlate with calcareous sandstone beds reported in the Zeebrugge area (Depret, 1983) / offshore (this study): very stiff to hard, silty, locally slightly sandy clay (known till 40 m depth), surmounted by a slightly silty fine sand layer (11 m thick) ; at the top (2 to 3.5 m thick) very hard to very stiff clay, with (in some places) alternating layers of sandy silty clay and clayey silty sand	evolution from sandy to clayey sediments towards offshore
	Beernem M.	grey-green bioturbated glauconitic clayey fine sands (Jacobs & De Batist, 1996)	no offshore information
Y5 (upper part of Gentbrugge F.)	no subunit	onshore (Houthuys, 1990): cross-bedded sands with several layers of sandstones / coastal zone (Jacobs & De Batist, 1996): green glauconitic fine sands with low angle parallel lamination, thin brown sand laminae and a brown clayey matrix / offshore (this study) (only the upper 10 cm are known): clay with a low amount of very-fine sand	evolving from cross-bedded sands to clay: sediment fining towards offshore
Y4 (upper part of Gentbrugge F.)	generality	onland: occurrence of several layers of sandstones	
	Y4.c	- compact clay to loam (this study, known till 1.15 m depth) - several layers of sandstones (known onland)	no specific data trend
	Y4.b	- brittle to compact clay to loam. In some places, low amount of shell fragments, gravel and micas (this study, known till 3.2 m depth) - several layers of sandstones (known onland)	increasing amount of silt
	Y4.a	compact clay containing a high amount of silt and sand, and some shell fragments (this study, only the 1st m known)	fining of sand (medium coarse to fine) towards offshore
Y3 (lower part of Gentbrugge F.)	Pittem M.	bioturbated sandy clay with mud drapes, rhythmic interlayered bedding, shell clasts and local silica cementations (Jacobs & De Batist, 1996)	no specific trend identified
	Merelbeke M.	strongly bioturbated silty clay with thin laminae, heavily burrowed at the top (Jacobs & De Batist, 1996)	
Y2 (Egem M. from Tielt F.	no subunit	- onland (Geets, 1988a ; Steurbaut, 1998): very-fine sands - coastal zone (Jacobs & De Batits, 1996): sharp-based, glauconitic, bioturbated fine sands with low-angle cross-bedding and fine laminations, ripples and flaser lamination (mud drapes) - offshore: olive-grey, stiff, sandy loam to silty clay	evolution from cross-bedded fine sands to silty clay: sediment fining towards offshore
Y1 (lower part of Tielt F. and Kortrijk F.)	Kortemark M. (Tielt F.)	centimetric, fining upward, yellowish, silty sand laminae that consist almost entirely of early-diagenetic authigenic siderite in a poor clay matrix (Jacobs & De Batist, 1996)	no spatial trend identified
	Kortrijk F.	mostly made of a massive, very heavy and hard, green-grey clay which displays a vertical texture change from a disturbed (bioturbation) and random orientation of clay particles, towards a preferential orientation, undisturbed at the base but laminated towards the top. 1 dark organic rich clay layer with very well parallel-oriented clay particles (Jacobs & De Batist, 1996). 4 fining upward clayey litho-units can be identified ; they are capped by a sandy clay unit and by a silty to fine-sandy clay unit (Jacobs et al., 1990 ; Jacobs & Sevens, 1993a, Jacobs, 1995b)	no spatial trend identified

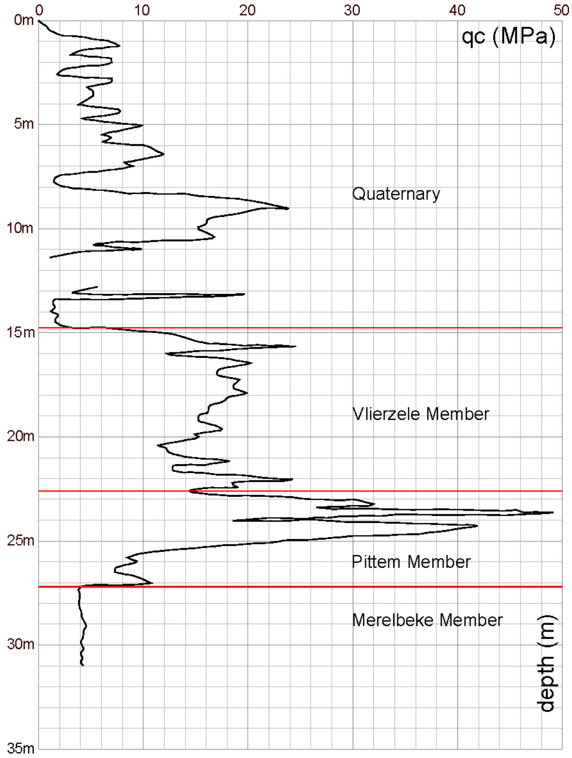
2.3.3.2 *Geotechnical properties*

Some geotechnical properties of Palaeogene units have been derived from onland CPT's profiles (figure 6). Characteristics of the cone resistance parameter (qc) have been synthetised for every Tertiary unit from the interpretation of 165 selected CPT's (table 5). Synthetic typical values of the cone resistance parameter have been compiled from the new geological maps of Flanders (Jacobs et al., 1993, 1996, 1999a, 1999b, 2002) (table 6). In the latter table cone resistance values are not normalized to depth, but each set of values can be considered as typical of the values which can be found in the limited area of each map.

The Tertiary members consisting of clay have consistently lower values which remain more or less constant over the whole unit. Other members consisting of sand or a mixture of sand and clay often show no uniform pattern (see lithological informations from table 4). The Onderdale, Oedelem, Vlierzele, Pittem and Egem Members display a large variety of cone resistance values, which underlines the heterogeneity of these deposits, whereas the Onderdijke, Zomergem, Ursel, Asse, Merelbeke and Kortemark Members consist in more homogeneous units. It was not possible to determine the lateral variability of the geotechnical properties of units with full certainty.

Table 5: Characteristics of the cone resistance parameter q_c within the Tertiary solid deposits and the Quaternary sediments. Compilation obtained from onland CPT's.

Onderdijke Mb (Fm of Maldegem)	number of CPT's: 2
Homogeneous graph with constant values around 5. Sharp transition between the upper lying Quaternary (lower part displays high values) and this member (low values). Sharp transition towards the lower lying Buisputten Member which has higher values.	
Buisputten Mb (Fm of Maldegem)	number of CPT's: 1
Sharp transition from the lower lying Onderdijke Member (low values) towards the Buisputten Member which has high values.	
Zomergem Mb (Fm of Maldegem)	number of CPT's: 2
Homogeneous graph with constant values, mostly 4. Soft transition between the upper lying Quaternary and this member, but sharp transition towards the lower lying Onderdale Member.	
Onderdale Mb (Fm of Maldegem)	number of CPT's: 2
Very irregular pattern. Sharp contact with the upper lying Zomergem Member which has somewhat lower values.	
Ursel Mb (Fm of Maldegem)	number of CPT's: 7
Homogeneous graph with constant values, mostly 4. Sharp transition between the upper lying Quaternary, which displays high values, and this member.	
Oedelem Mb (Fm of Aalter)	number of CPT's: 4
Very irregular pattern. The transition from Quaternary to the lower lying Oedelem Member is often characterized by a small decline. At the bottom of the CPT's within this member, there is a sharp rise.	
Vlierzele Mb (Fm of Gent)	number of CPT's: 5
Very irregular pattern. Sharp contact with the upper lying Zomergem Member which has somewhat lower values.	
Pittem Mb (Fm of Gent)	number of CPT's: 2
Very irregular pattern. Both CPT's show a positive peak with some little negative peaks in between. The overall values are higher than the upper lying Vlierzele Member and the lower lying Merelbeke Member.	
Merelbeke Mb (Fm of Gent)	number of CPT's: 16
Homogeneous graph with constant values (mostly 2). Sharp transition between the Quaternary, which displays high values, and this member. Gradual transition towards the Egem Member, lying below, which has higher values. Somewhat higher values towards the bottom of this member.	
Egem Mb (Fm of Tielt)	number of CPT's: 32
Irregular to very irregular pattern with short high and low peaks. When the Kortemark Member (lower values) lies beneath, there is a soft to sharp transition from lower (Kortemark Member) to higher values (Egem Member). When the Merelbeke or Pittem Member (lower values) lies above, there is a sharp transition between both, from lower (Egem Member) to higher values (Merelbeke or Pittem Member).	
Kortemark Mb (Fm of Tielt)	number of CPT's: 92
Homogeneous graph with constant values, mostly 3 or 4. Most abundant Tertiary unit. Sharp transition between the upper lying Quaternary which has high values and this member (low values).	



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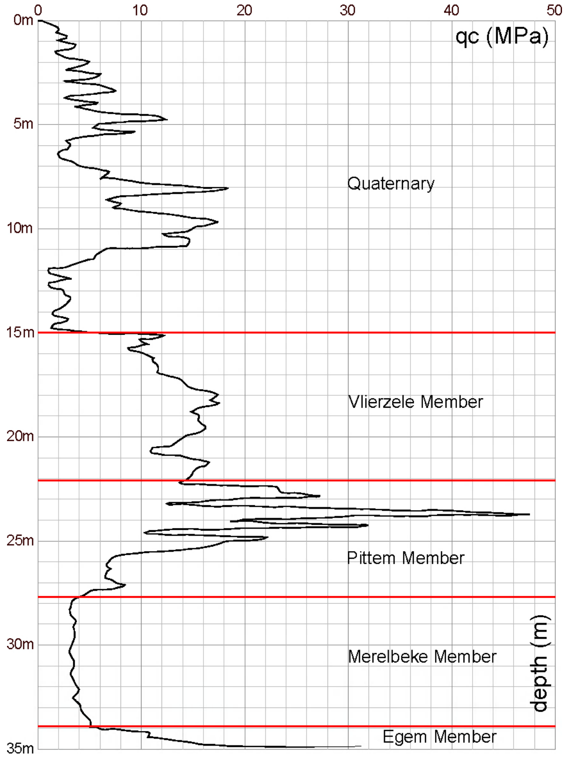

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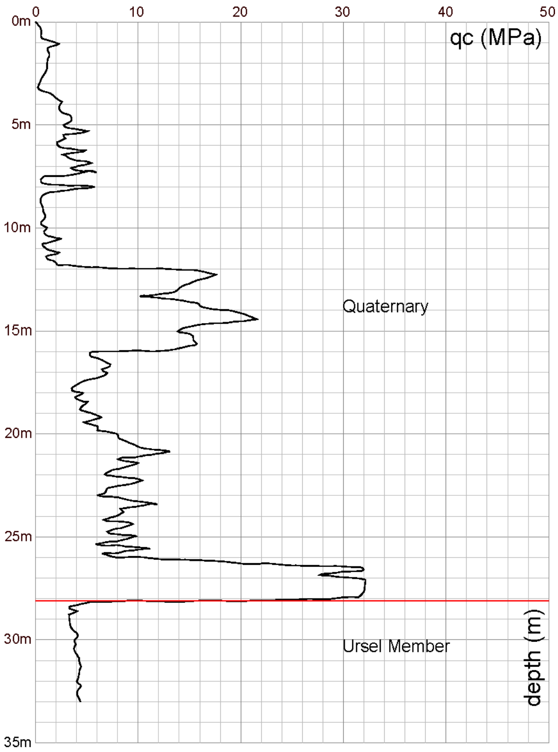

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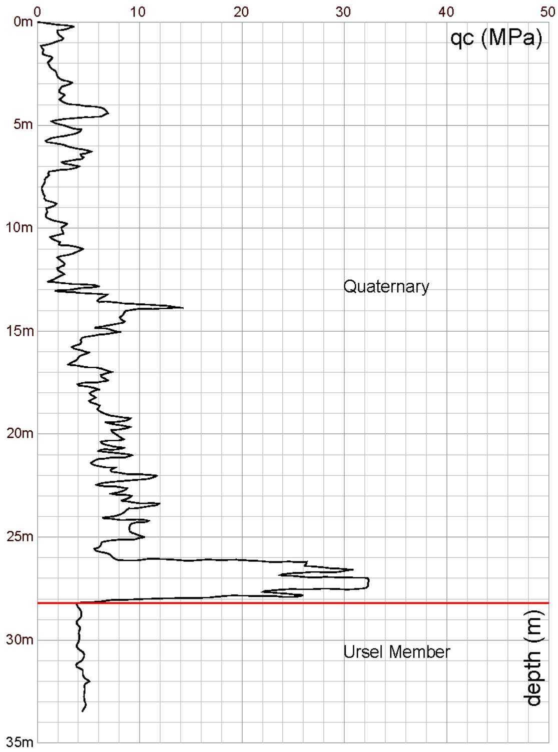

CPT 6617-72/600 nr VI
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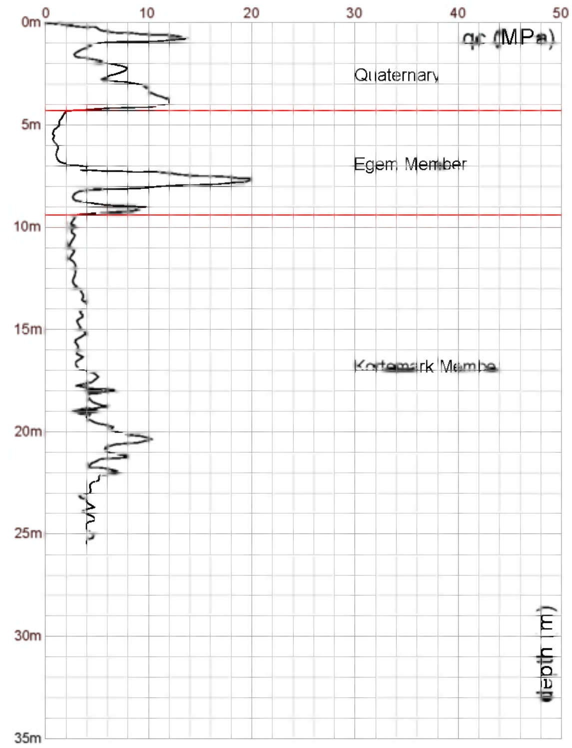
Figure 6: Onland CPT's profiles typical of the Tertiary solid units typical: q_c values (source: Databank Ondergrond Vlaanderen). The name and location of every CPT are given in UTM coordinates (zone 31).



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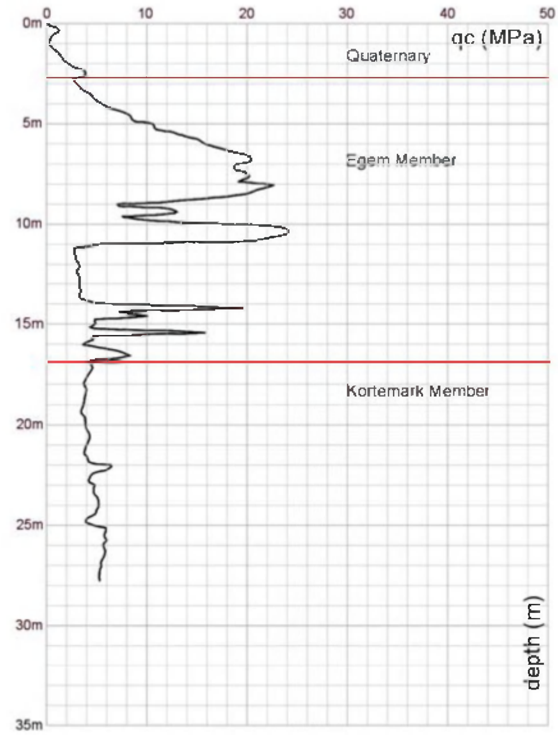

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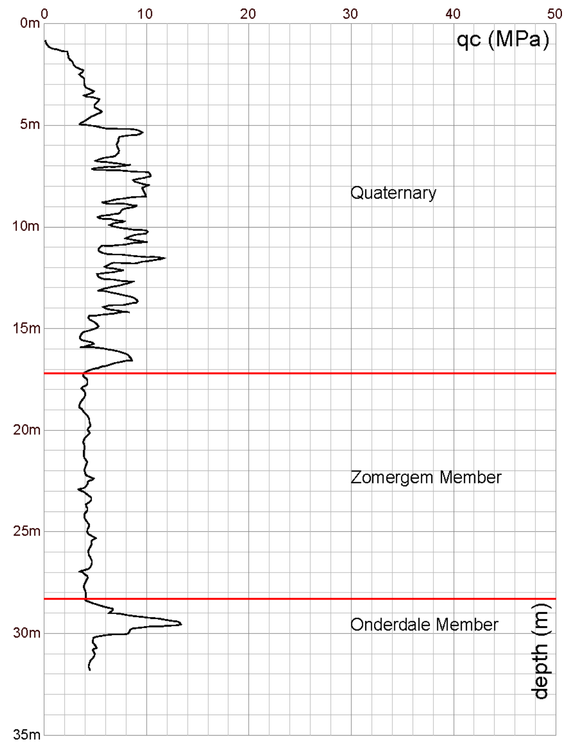

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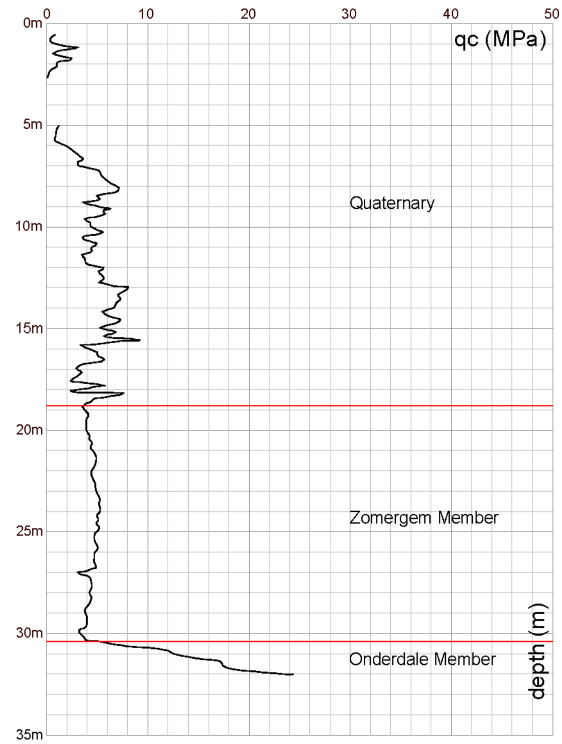
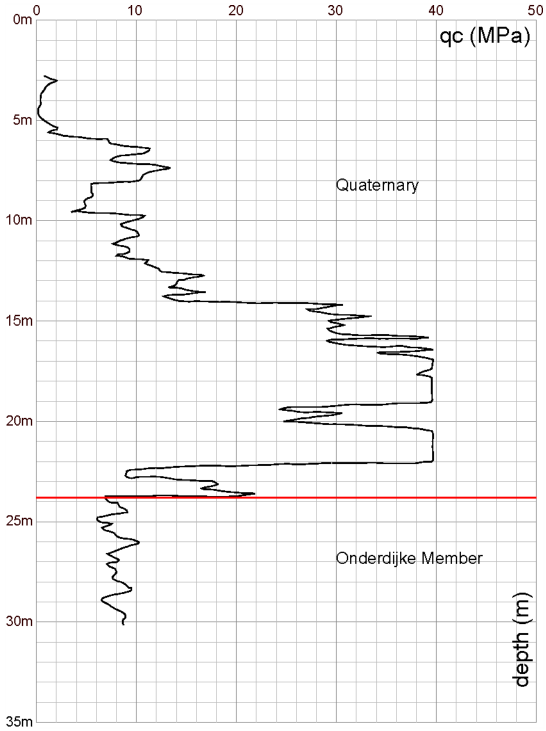


CPT 7508-78/215 nr LXXXVII
5689945N, 520056E

Figure 6: Onland CPT's profiles typical of the Tertiary solid units typical: q_c values (source: Databank Ondergrond Vlaanderen). The name and location of every CPT are given in UTM coordinates (zone 31).



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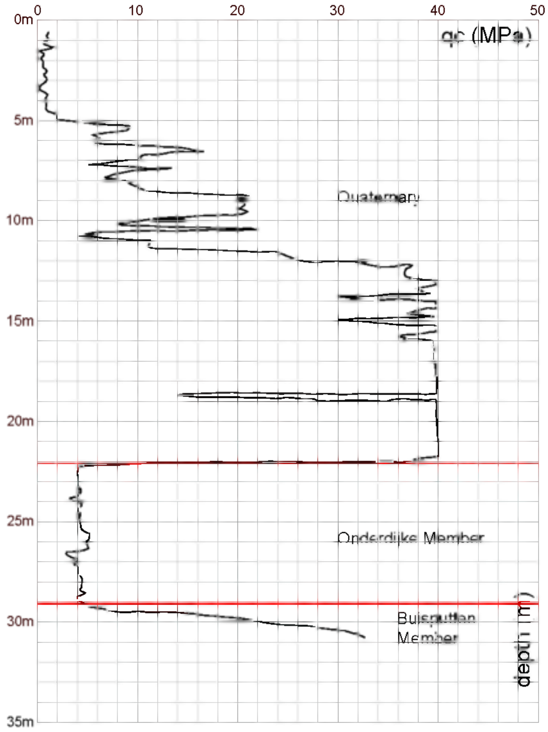

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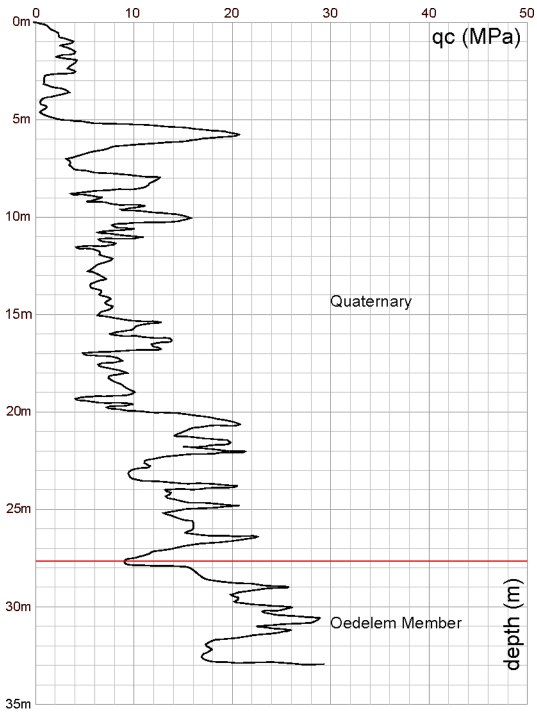

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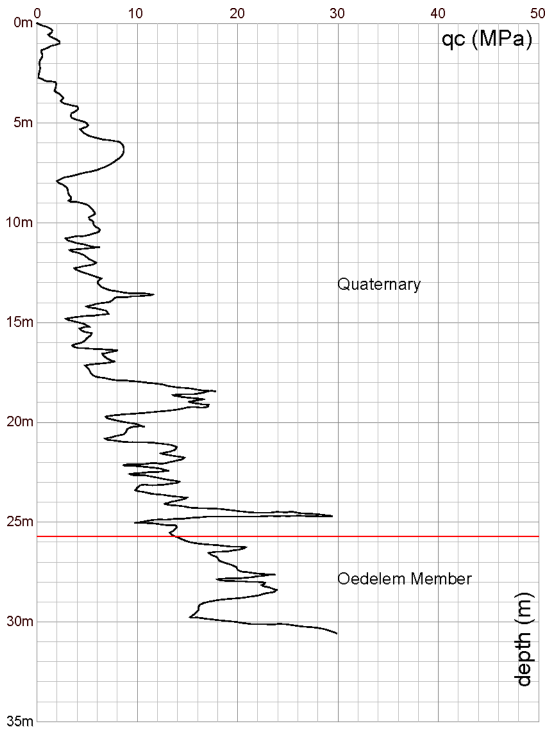

CPT 7407-78/182 nr VI
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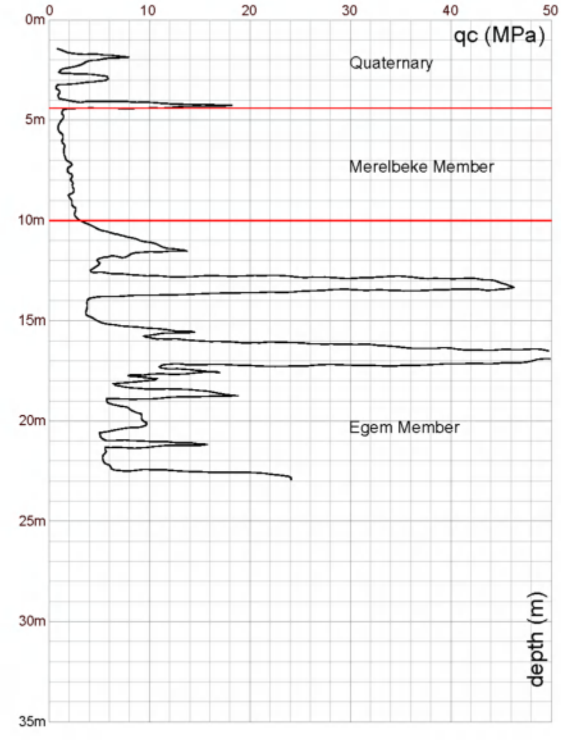
Figure 6: Onland CPT's profiles typical of the Tertiary solid units typical: q_c values (source: Databank Ondergrond Vlaanderen). The name and location of every CPT are given in UTM coordinates (zone 31).



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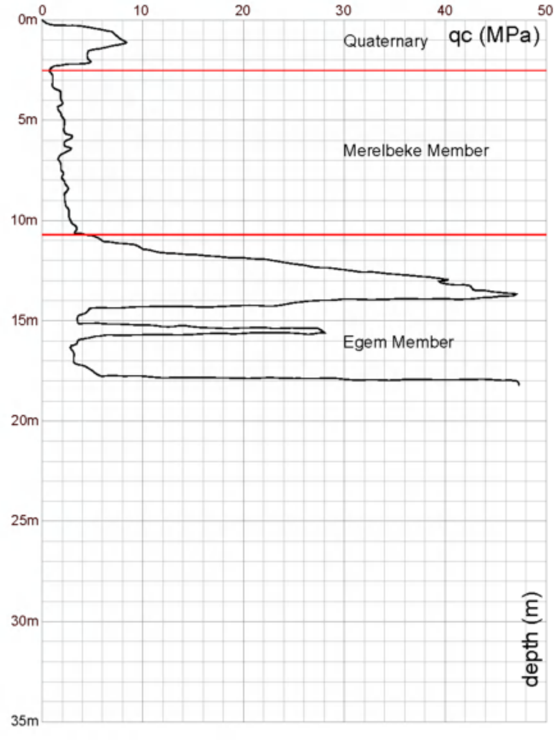


CPT 9750-91/140 nr I
5664407N, 510724E

Figure 6: Onland CPT's profiles typical of the Tertiary solid units typical: q_c values (source: Databank Ondergrond Vlaanderen). The name and location of every CPT are given in UTM coordinates (zone 31).

Table 6: Overview of the typical q_c values (10^3.kN/m^2) in the Tertiary solid units obtained from onland CPT's for 5 coastal regions (compilation from Jacobs et al., 1993, 1996, 1999a, 1999b, 2002).

Formation	Member		Blankenberge, West-Kapelle, Oostduin-Kerke, Oostende region (sheets 4-5-11-12)	Kortrijk region (sheet 29)	Tielt region (sheet 21)	Lokeren region (sheet 14)	Gent region (sheet 22)
Maldegem	Onderdijke		3-5			5	
	Buisputten					12	
	Zomergem		4-5			4	
	Onderdale					22	
	Ursel		5			4	2,5
	Asse					3	
	Wemmel					14	
Aalter	Oedelem		10-24			15	25
Gent	Vlierzele		>10		20,5	>50	18
	Pittem		10-30		6		7
	Merelbeke		4-6	4-6			2,5
Tielt	Egem	sand	15-25	10-20	9,5		13
		clay	4-5	4			6
	Kortemark		5	2-10	7		4,5

2.4 Distribution and geometry of the deposits

2.4.1 Subcrops of Palaeogene units and subunits

On the Belgian shelf the surface which truncates the sequence of Palaeogene strata coincides with the base of Quaternary deposits, except in the northeastern part, where the truncation surface coincides with the base of the Neogene deposits (Mostaert et al., 1989).

Palaeogene deposits are situated on top of the Late Cretaceous chalk and under the Quaternary deposits's base (see paragraph "Base of the Quaternary deposits"). These deposits are gently dipping (0.5–1°) towards the NNE. The Palaeogene units Y1 to P1 are superposed from WSW towards ENE, direction in which they subcrop successively (figure 7).

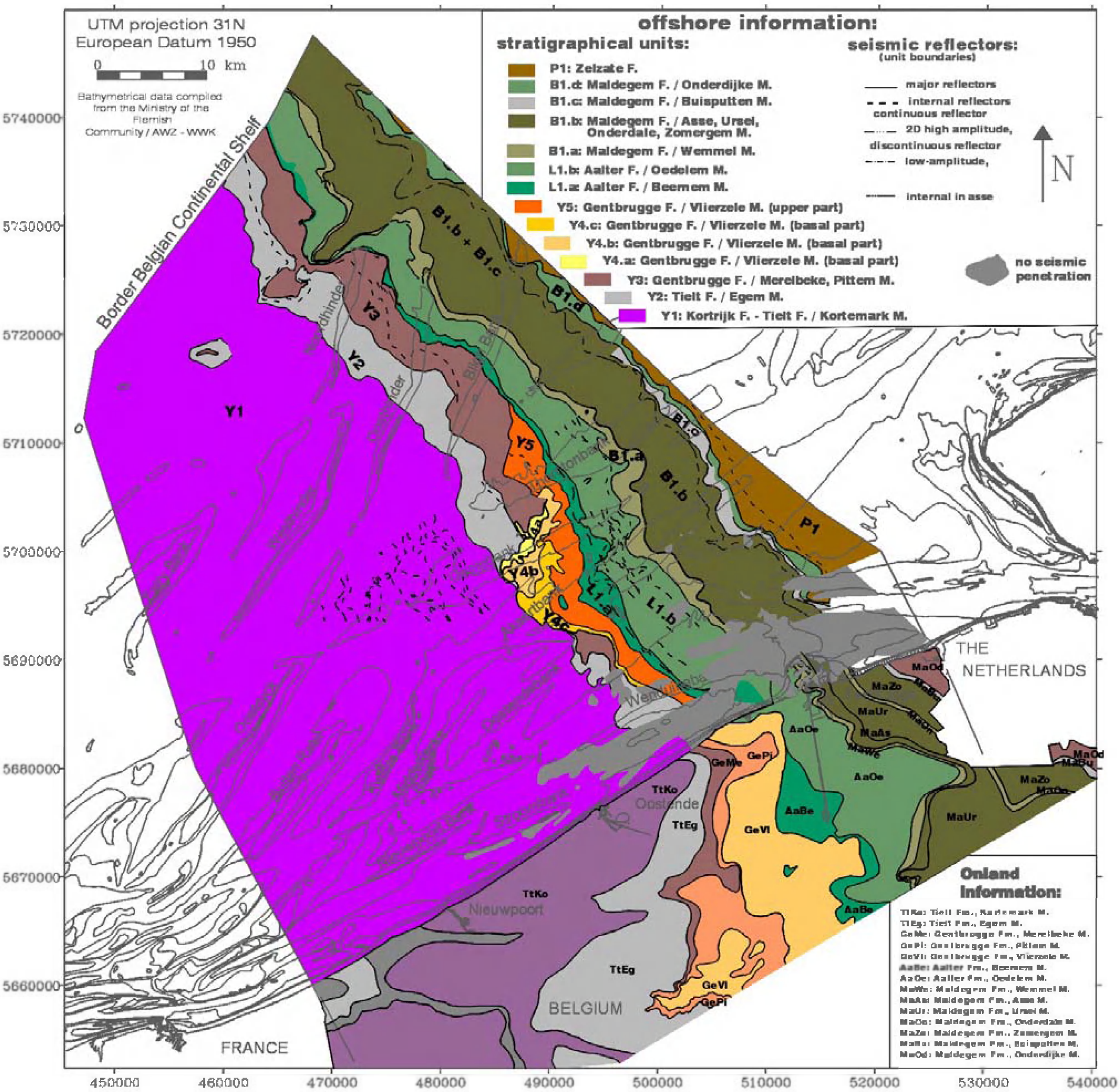


Figure 7: Subcrops of solid deposits (Tertiary) under the non-consolidated deposits (Quaternary) (offshore data: compilation after Maréchal et al., 1986, De Batist, 1989, De Batist & Henriet, 1995 / onland data: Jacobs et al., 2002).

Unit Y1 crops out in the major part (1/2 to 2/3) of the Belgian continental shelf, in its western part. This unit displays the largest thickness (150 to 180 m). Units Y2, Y3, L1, B1 and P1 crop out in the east 1/3 of the Belgian continental shelf along its whole width. Units Y2, Y3 and L1 display a maximum thickness of 30 m whereas units B1 and P1 have large respective thicknesses of 45-60 m and 40-90 m. Units Y4 and Y5 crop out in a restricted part of the shelf. Unit Y4 is located underneath the Akkaert Bank and the Goote Bank. It corresponds to an erosion / infilling stage, confined into a channel or erosional depression, trenched in units Y1 (uppermost layers), Y2 and Y3. Unit Y5 extends from the coast to the Thornton bank with a maximum thickness of 17 m. The strata relationships and geometries are illustrated by interpreted line-drawings of seismic sections (figure 8).

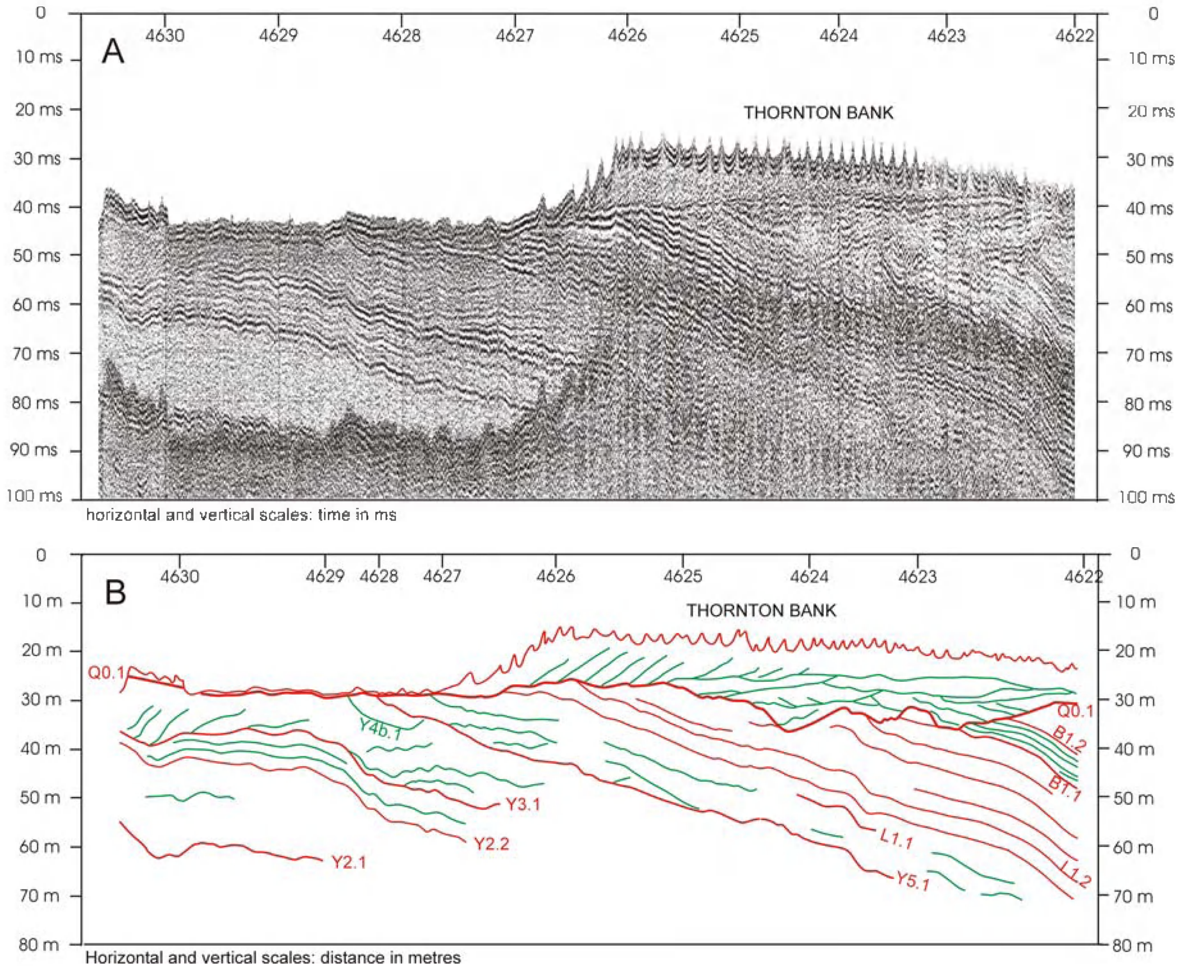


Figure 8: Geometry and relationships between solid units (Tertiary). Example of a seismic section (A) and its interpretation (B), realised above the Thorntonbank and orientated NE-SW (see location on C) (after Maréchal et al., 1986).

2.4.2 Unit thickness and extension

The thickness of the Tertiary deposits is highly variable from one unit to another, but quite constant within each unit. Maximum unit thicknesses are reported in table 2. Distributionpatterns are various from one unit to another, although some similarities can be drawn (figures 9-a, 9-b and 9-c).

The Y2 and Y3 units have a very similar extension (figure 9-a). To the North, they reach respective thicknesses of 30 and 20 m in the Noordhinder deformation zone. In this area the synclinal folds initiated during the folding phase that took place during the Meso-Cenozoicum transition (see the paragraph 2.5.1), constituted depressions where the sediments were preferentially trapped.

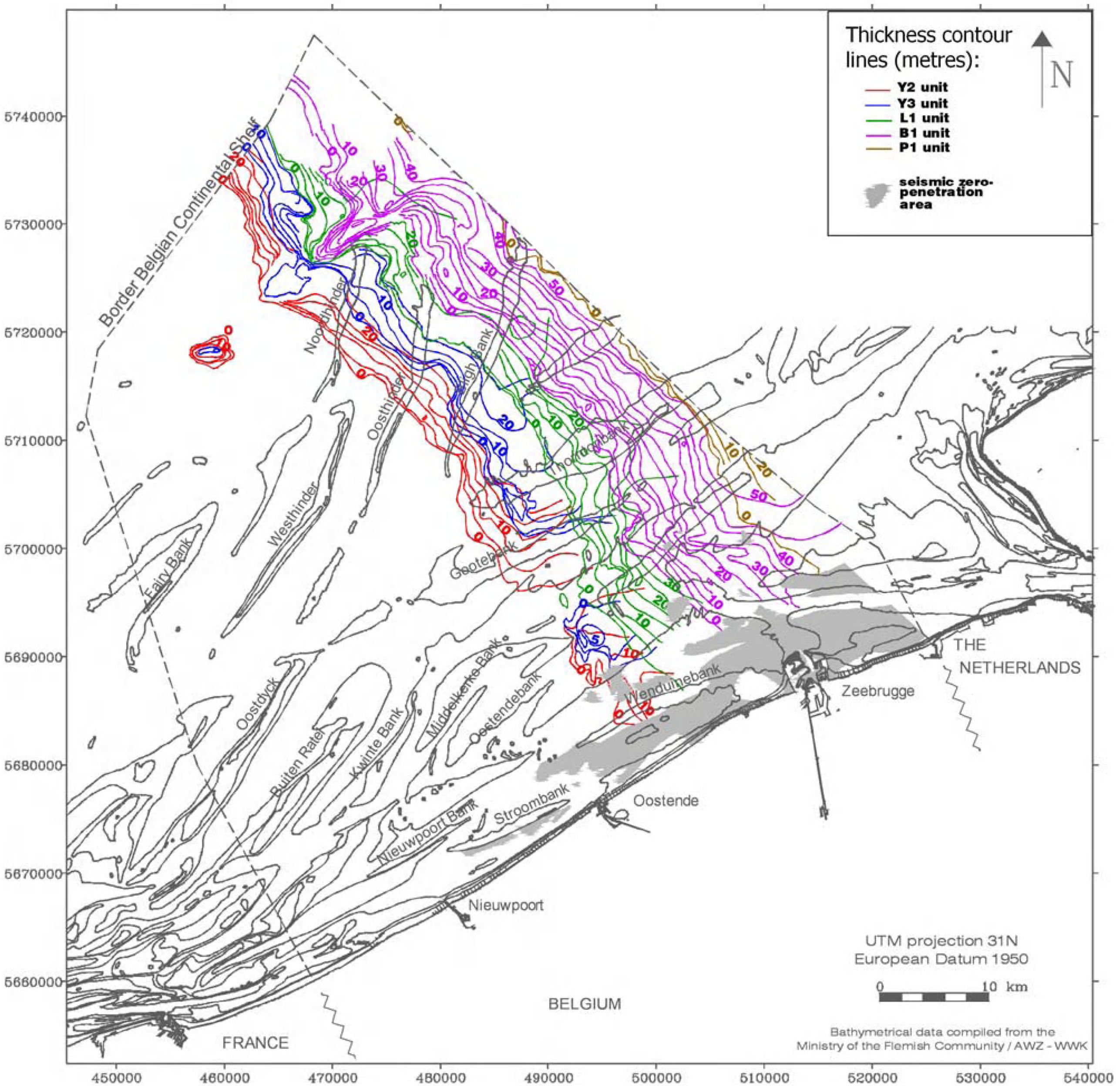


Figure 9-a: Thickness of the Y2, Y3, B1, L1 and P1 solid units (Tertiary) (after De Batist, 1989).

In the Hinder Banken, Y2 and Y3 units thicken gently to a maximum of 25 m, after which the Y3 unit thickens quickly from 0 to 10m in the area of the Gootebank. In the Akkaertbank area, Y2 and Y3 deposits are not observed: they have been completely eroded during the Y4a, b and c phases. To the south, up to the coast, the Y2 unit slowly thickens in the S-SE direction, till reaching 15 m in the area of the Wenduinebank, and the Y3 unit reaches not more than 10 m in the depressed, circular area located between the Akkaert Bank to the West, the Sierra Ventana to the East and the Wenduine Bank to the south.

The L1 unit reaches a maximum of 20-25 m from the northern Belgian continental shelf boundary to the Thorntonbank, and more than 30 m between the eastern extremity of the Goote Bank and the coast. From the Thornton Bank to the coast, the extension and thickness pattern of L1 coincides with this of Y5: the L1 0-m thick line coincides with the Y5 10 m-thick line. In the Noordhinder deformation zone, deposits become quickly very thick.

The thickness of the B1 unit displays a very homogeneous, regular pattern. B1 thickens gently to a maximum of 55 m, reached at the NE extremity of the Bligh Bank. In the Noordhinder deformation zone, deposits become also quickly very thick.

In the Belgian continental shelf area, the P1 unit appears from the coast to the Bligh Bank, thickening gently till a maximum of 20 m.

The Y4.A, Y4.B and Y4.C units are the less extended deposits (figure 9-b and 9–c).

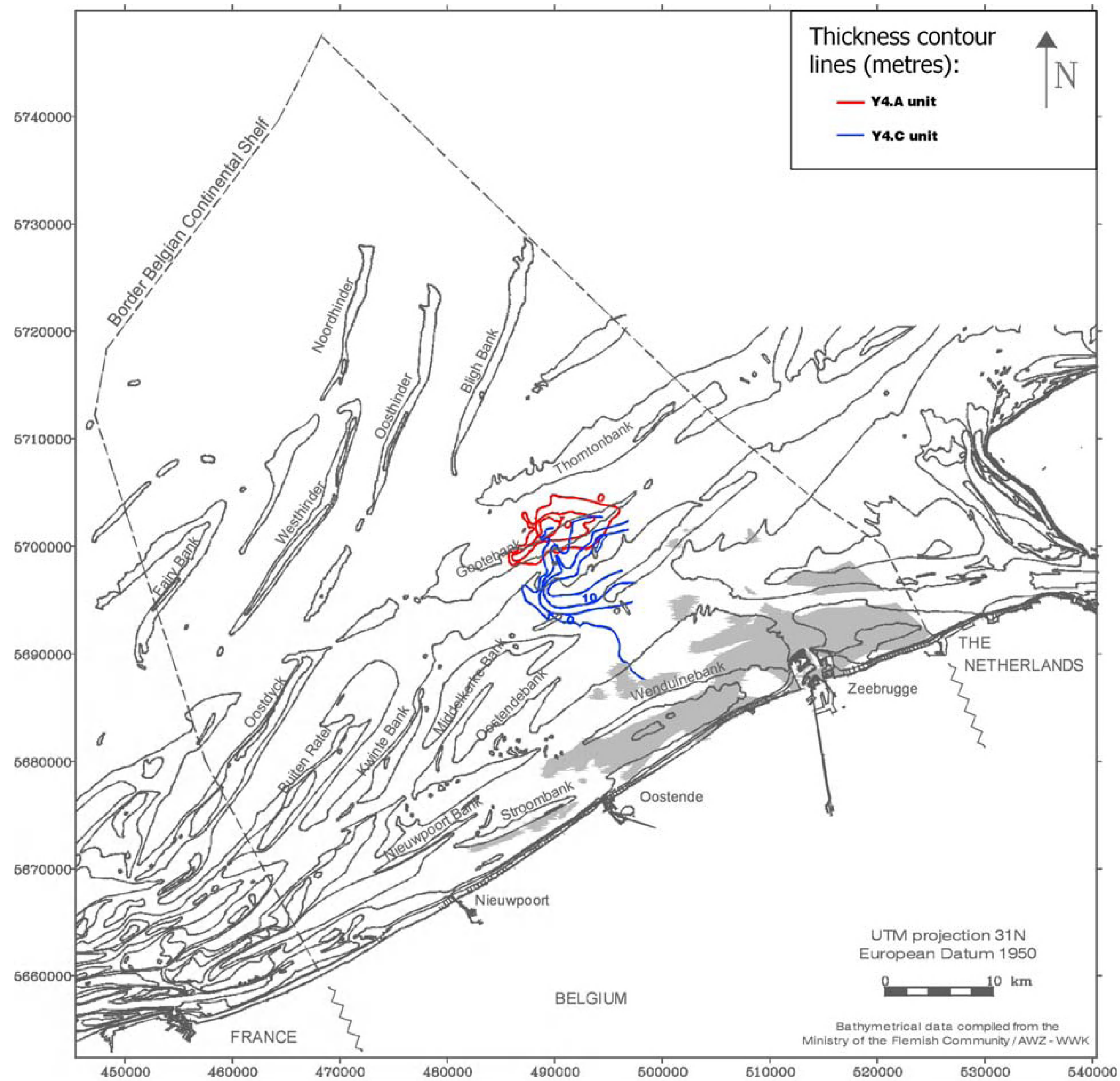


Figure 9-b: Thickness of the Y4.A and Y4.C solid units (Tertiary) (after De Batist, 1989).

The Y4.a unit, with a maximum thickness of 10 m, is confined to an ellipse-shaped area, located straight below the eastern part of the northern flank of the Gootebank. The Y4.b unit, with a maximum thickness of 15 m, is also confined to an ellipse-shaped area, but more extended to the south, from the Thornton Bank to the Akkaertbank. Its depocentre is located South of the present-day Gootebank. The Y4.c unit, with a maximum thickness of 20 m, is located more southerly, extending from the Gootebank to the Wenduinebank. Its depocenter is situated straight below the northern flank of the Akkaert Bank. They were deposited after complete erosion of the Y2 and Y3 units in this area.

The Y5 unit extends from the coast to the Bligh Bank (figure 9-c). It reaches a maximum thickness of 15 m between the Sierra Ventana and the Wenduinebank.

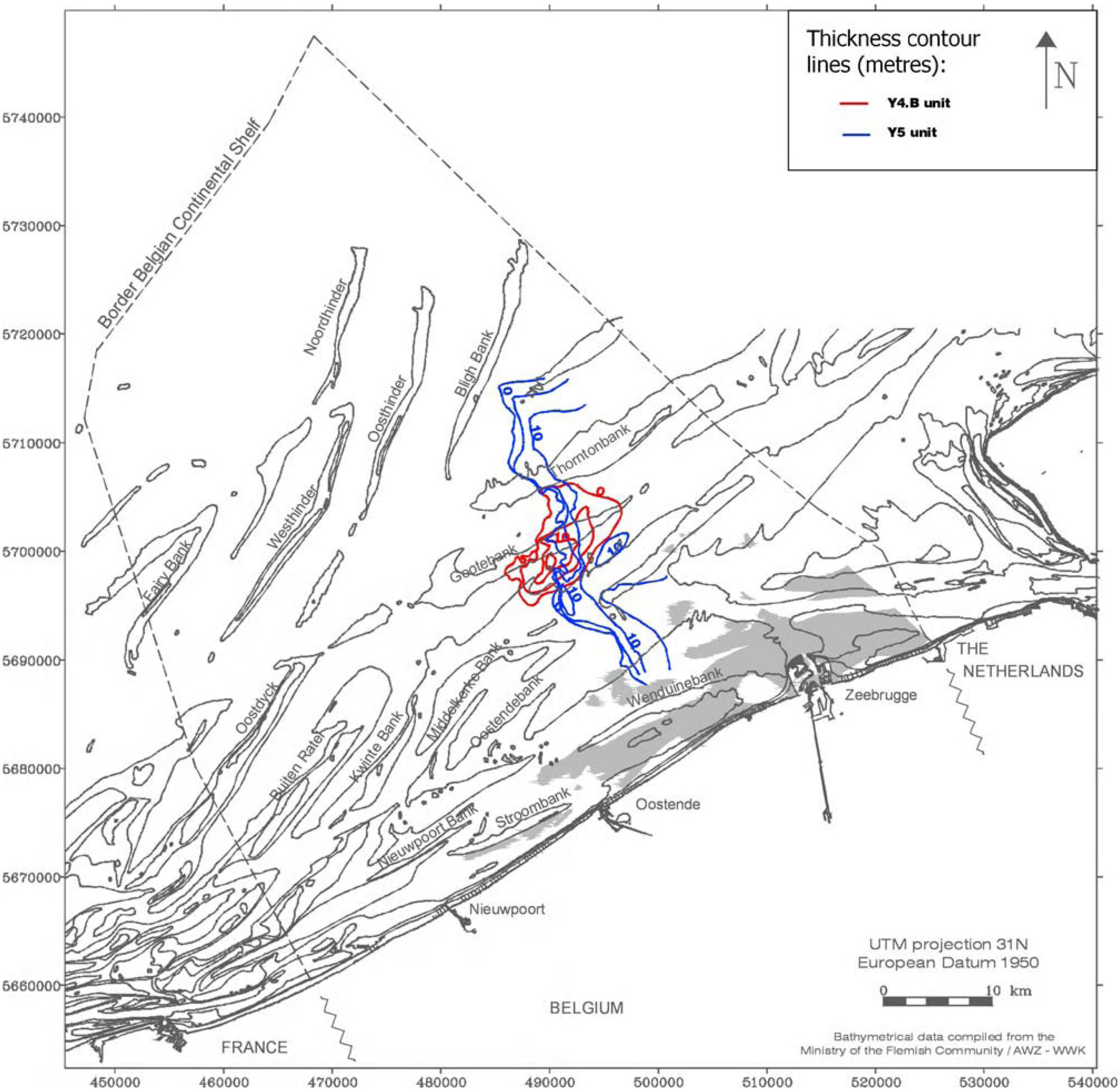


Figure 9-c: Thickness of the Y4.B and Y5 solid units (Tertiary) (after De Batist, 1989).

Thickness is a highly variable parameter within the different geological units, as well as extension of deposits. However, similarities can be drawn: in the Hinder Banks area, all the subcropping units (Y2, Y3, L1, B1, P1) display the same distribution pattern, whereas, in the southern part, 3 different groups can be distinguished (Y2 and Y3, Y4a, b and c, Y5, L1, B1 and P1).

2.5 Deformations

On the Belgian continental shelf, 2 different genetic types of deformations are encountered: (1) *basement induced deformations*: these have been created under influence of an external, regional tension field and consist essentially in folds and faults ; (2) *sediment-dynamical or-tectonical deformations*: these appear in specific units, due to changes in mechanical and rheological features of the sediments during compaction.

2.5.1 Basement induced deformations

Tectonic events are documented by synclinal folds and faults (Henriet et al., 1989b), which are associated with structural truncations at tectonically enhanced unconformities. Three structural anomalies exist in the Mesozoic and Cenozoic cover: these occur at the base of units T1, L2 and R1. Two folding phases have been recognised from seismic data (De Batist, 1989) (figure 10): the main phase has taken place after the Bartonian, the initial deformation phase between L1 and L2. Basement-induced deformations are concentrated in 2 zones, the Noordhinder and the Goote-Raan deformation zones. Nowadays, the above mentioned tectonic deformations are not active anymore.

2.5.1.1 Noordhinder deformation zone

* Description of the structures

This zone is situated north of the Noordhinder sandbank over a distance of 75 km. It is orientated N50°, perpendicularly to the strike of the London-Brabant Massif. Tectonic structures affecting the Tertiary cover consist of synclinal and anticlinal folds, faults and synclinal collapse features.

At the SW edge of the Northhinder zone, some regular alternating anticlinal and synclinal folds can be observed, influencing Cretaceous, Palaeocene and Eocene units. The most remarkable structures are 5 lineated synclinal depressions appearing in the Eocene cover. Some deep seismic profiles reveal that these 5 synclinal folds might be a kind of collapse structures. Their amplitude diminishes towards the NE. The 5 folds are elongated +/- N90° in a global "en echelon" pattern orientated N50° referred to the main tectonic direction. The southernmost SW syncline has a maximum amplitude of more than 150 m and a mean diameter of 5 km. Toward the East this syncline is bordered by a N180° orientated fault. Toward the north, it is bordered by an anticlinal fold or structural height, orientated N90°. The 3 central depressions have an amplitude ranging between 30-60 m and appear to be correlated over a distance of +/- 15 km into a complex, asymmetrical synclinal fold. The synclines southern side is bordered by a parallel fault. A pattern of numerous small faults can be explained by reactivation of fault structures in Y1. The most NE situated syncline is covered by the non-deformed R1 unit. The amplitude reaches a maximum of 20m. In the North the syncline is bordered by an anticline and a parallel fault, orientated N90°.

* Dating of the structures

The location and orientation of paleo relief forms found in T1 correspond well with the pattern of synclinal and anticlinal folds. This suggests a weak initial folding phase that took place during the transition Meso-Cenozoicum. At the same stratigraphic level, no discordance level is found in the 5 synclinal depressions. However on some profiles a weak erosion can be found at the top of L1, print of a Late Lutetian folding phase.

The most NE synclinal depression is completely covered by the non-deformed R1. This could mean that the main deformation phase for the Noordhinder zone is during the transition Priabonian-Rupelian.

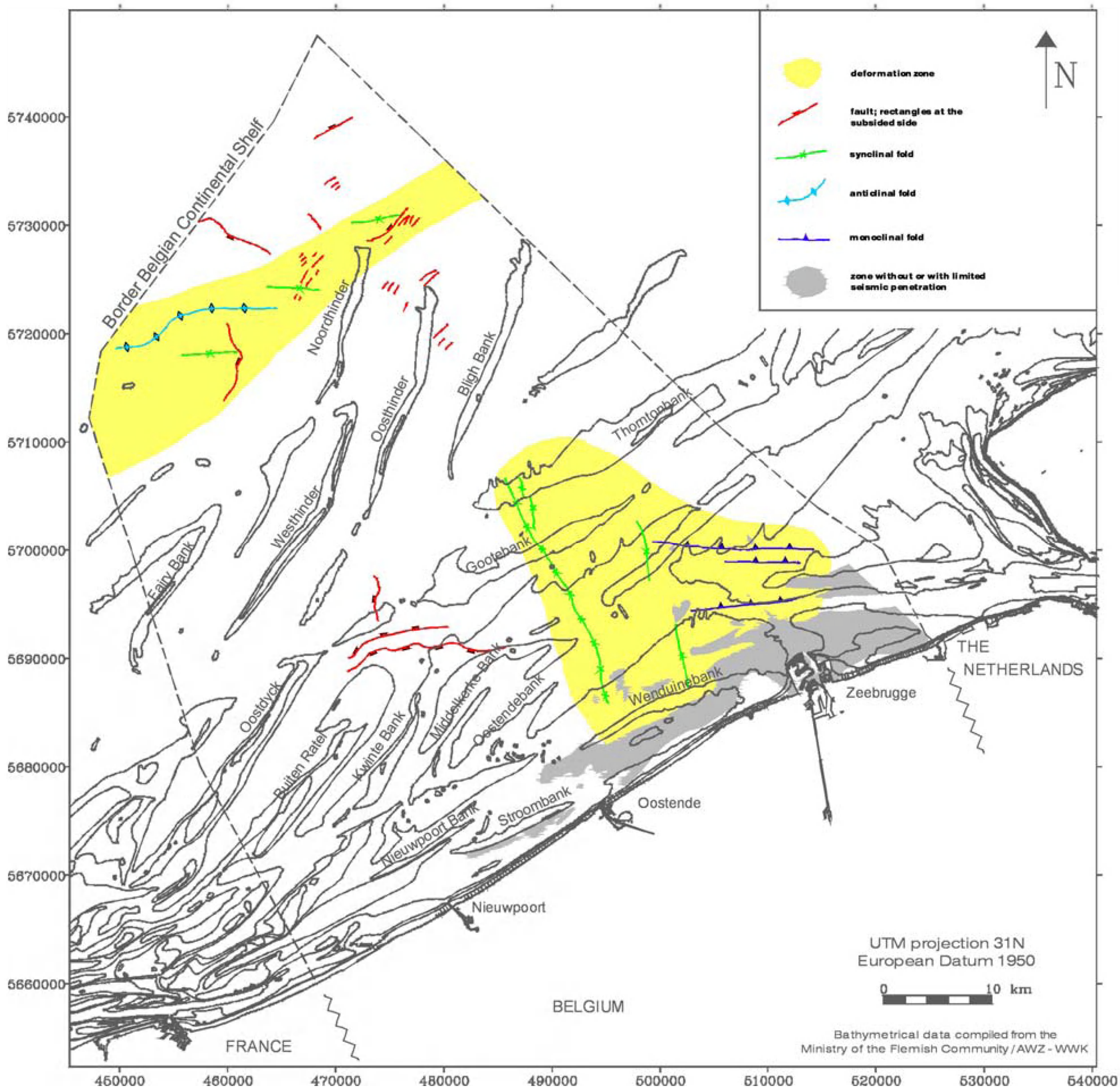


Figure 10: Basement induced deformations: deformation zones and features (after De Batist, 1989).

2.5.1.2 Goote-Raan deformation zone

* Description of the structures

This zone consists of 2 groups of synclinal and monoclinal folds with a maximum amplitude of 20m. Their orientations are respectively N150/160° and N90/100°. From some seismic profiles, it can be deduced that the folding, sometimes influencing the whole Eocene, is a consequence of the fault structures in the Cretaceous and Palaeocene. To the East some faults with a N60° orientation are found.

* Dating of the structures

In the East part, at the top of L1, a weak truncation is observed, which was created by a first weak deformation phase in Late Lutetian. The main folding phase has a post-Eocene age, that took place after the deposition of P1.

2.5.1.3 Regional, structural explanation

The appearance of at least 3 different deformation phases (Cretaceous-Palaeocene, Late-Lutetian, Eocene-Oligocene) does not mean that there is no correlation between the 3 deformation zones. The Noordhinder zone and the Gravelines zone can be a part of a large graben structure cutting through the London-Brabant Massif. This theory of a fault-zone through the Artois High and maybe even through the London-Brabant Massif has already been used to explain the opening in the Pleistocene of the Narrow of Calais.

2.5.1.4 Genetic analysis and tectonic reconstruction

The theory of a Cenozoic age of the big deformation structure seems rather not credible with reference to the rather "calm" stresses during the Tertiary and the rigidity of the London-Brabant Massif. The structure certainly originated as a possible reactivation of older faults in the Paleozoic basement. The "en échelon" orientation of folds in the Noordhinder zone suggests an important horizontal component in the reactivation movement of the proposed fault zone.

The configuration of the synclinal folds in the Noordhinder zone can be explained by 2 opposing tectonic reactivation processes: 'drape folds' as a consequence of a dextral horizontal movement or 'drag folds' in a sinistral movement regime. The interpretation of these folds as collapse structures above normally tilted blocks in the basement points to 'drape folds'. This hypothesis is however not consistent with the regional tension model for NW Europe (dextral reactivation).

2.5.2 Sediment-dynamical or -tectonical deformations

2.5.2.1 Ypresian

The best developed structures are observed in the Y1 clayey unit.

* Different deformation styles and their vertical zonation

In unit Y1 a wide range of intraformational 'sediment tectonic' deformations is found (described by Henriet et al., 1982, 1988, De Batist et al., 1989, Cameron et al., 1992). These deformations are due to the relaxation of temporary states of density inversion linked to undercompaction in the early burial history of the clayey-silty sediment.

12 different reference reflectors have been identified by Heldens (1983), and Henriet et al. (1982, 1988) and De Batist et al. (1989). Theses reflectors can be grouped in 3 large structural units:

(1) The lowest interval concerns the 25 m above the non-deformed base reflector Y1.1. It is characterised by intense block-faulting, tilted and bent blocks and randomly dipping fault planes. The higher from Y1.1, the higher the density of faults, the higher the fault height (about a few decimetres) (figure 11).

(2) The median interval is located between 25m and 70m above Y1 base. Deformations become more intense, evolving upwards from block-faulting to a sinusoidal structure: major tilted blocks, convolute structures with broad synclines and cusps anticlines, sometimes evolving to diapirs even up to the Quaternary basis. This unit is only visible on best quality seismic profiles.

(3) The upper interval consists of undisplaced, faulted blocks with alternately tilting and downwarping bedding terminations. The broken and tilted blocks are self-undeformed and greatly variable in length and fault height (variable due to their localisation).

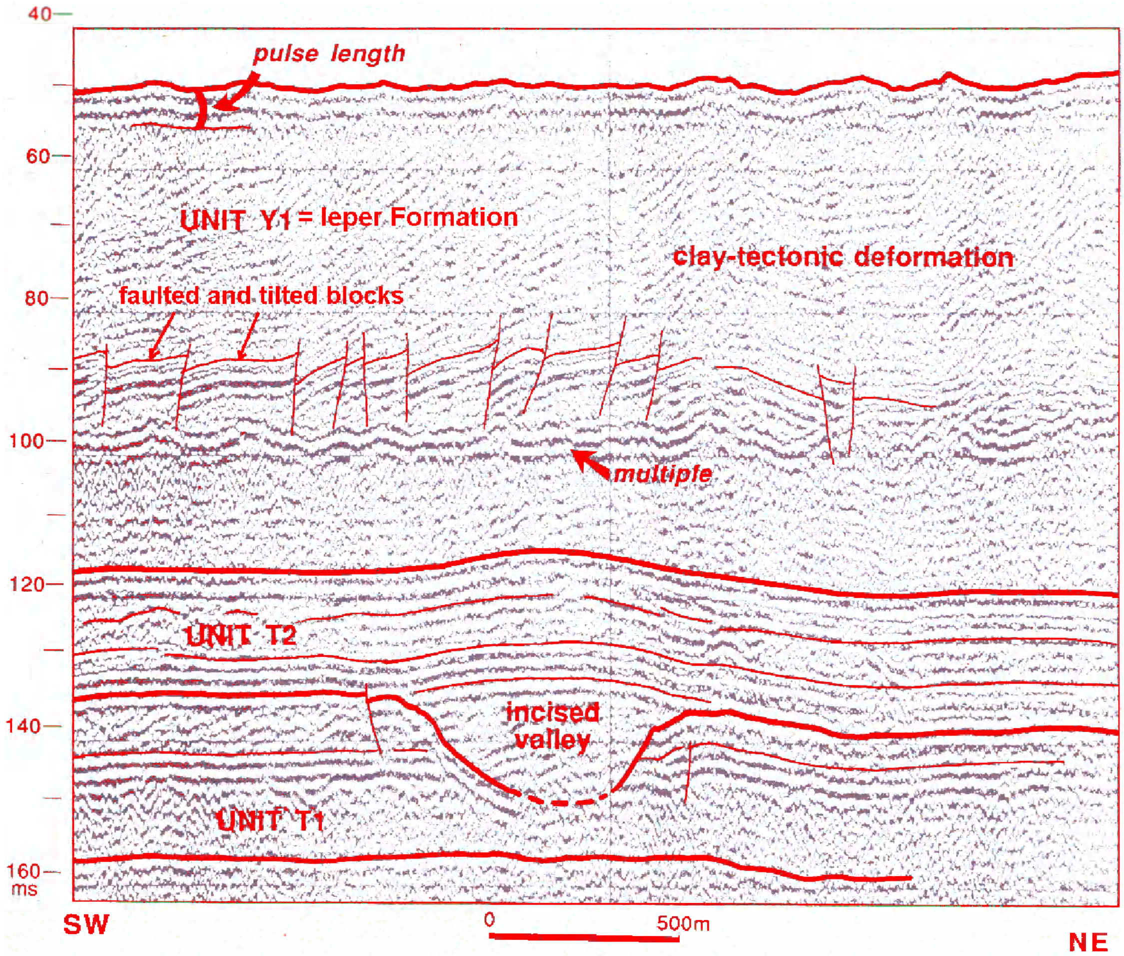


Figure 11: Faulted and tilted blocks due to clay tectonics in the Ieper Formation (after De Batist, 1989). In black: seismic data, in red: interpretation.

Next to this, several other subtypes are observed, e.g. broken blocks tilted in the direction of the apparent dip of the layers, faulted blocks not displaced relative to each other, only their edges are concerned by displacement.

These structure fade out in Y2, suggesting an early post-sedimentary origin of these structures, during deposition of Y2. Due to regional tectonic deformations, reactivation of some of the smaller deformation structures is possible.

* Regional zonation of deformation style

The appearance of the intraformational 'sediment tectonic' deformations (horizontal extension) have been mapped using seismic data (figure 12). 9 seismic facies have been distinguished on the basis of the distinct deformation styles encountered in Y1. However, only the upper tens of m can be studied, and difficulties have been encountered to correlate the tectonic structures of neighbouring profiles. These maps do not show a direct correlation between the outcrop pattern of the deformations and their type. Often the geographic localisation, more than the stratigraphic position, determines the type of structures:

More unsteady deformation styles are found in the south, whereas more steady styles exist in the North: to the north of the Noordhinder bank, no internal reflector is observed and diapirs correspond with incised paleovalleys.

* Land detections

On land also, several deformation structures have been reported in the London Clay Formation and the Ieper Formation, and clay diapirs around London. Most deformations in SW Flanders appear in the upper part of the Roubaix Member and the lower part of the Aalbeke Member, which can be correlated with the upper interval at sea.

2.5.2.2 Bartonian

The B1 unit presents certain forms of sediment dynamics, such as an undulation of the internal reflectors, especially in the upper units B1.6 and B1.7. These deformations fade out in the P1 unit. It is not clear whether the lobe-shaped reflection patterns of B1.4 are due to certain large sedimentary structures or due to post-sedimentary tectonic deformations.

Correlations of these deformations on the land are unknown.

2.5.2.3 Rupelian

In the Westerschelde the R2 unit is also characterised by tectonic deformations. They have a diapiric character and can appear at different levels throughout the Rupel Formation.

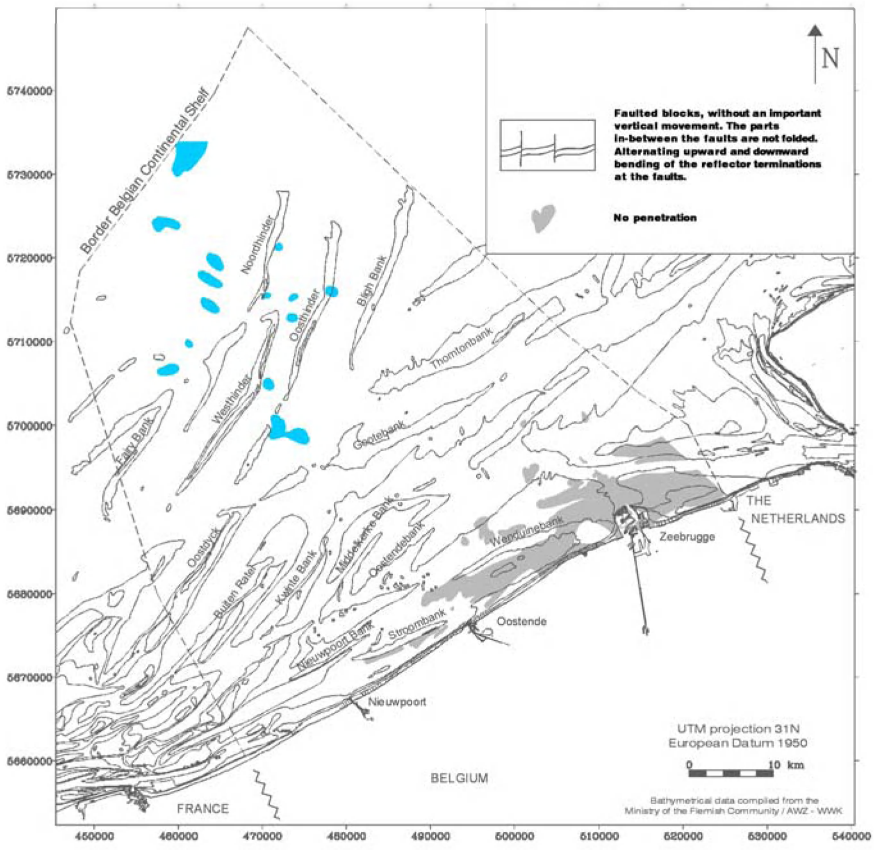


Figure 12: Distribution of the sediment tectonic deformation styles within the first upper metres of the depositional sequence Y1 (seismo-stratigraphic interpretation) (after De Batist, 1989). Top, right: schematic representation and description of the reported sediment tectonic deformation style.

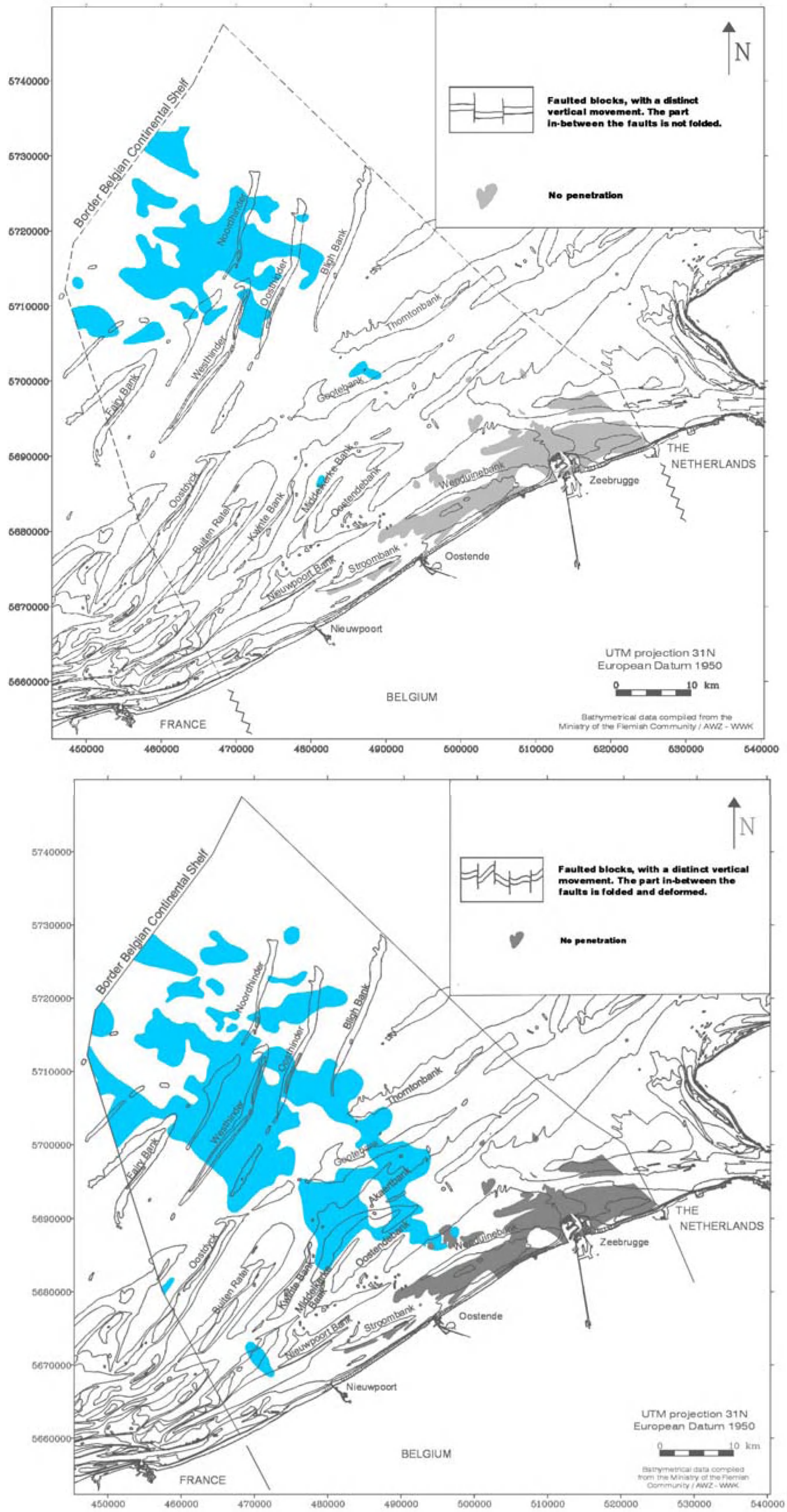
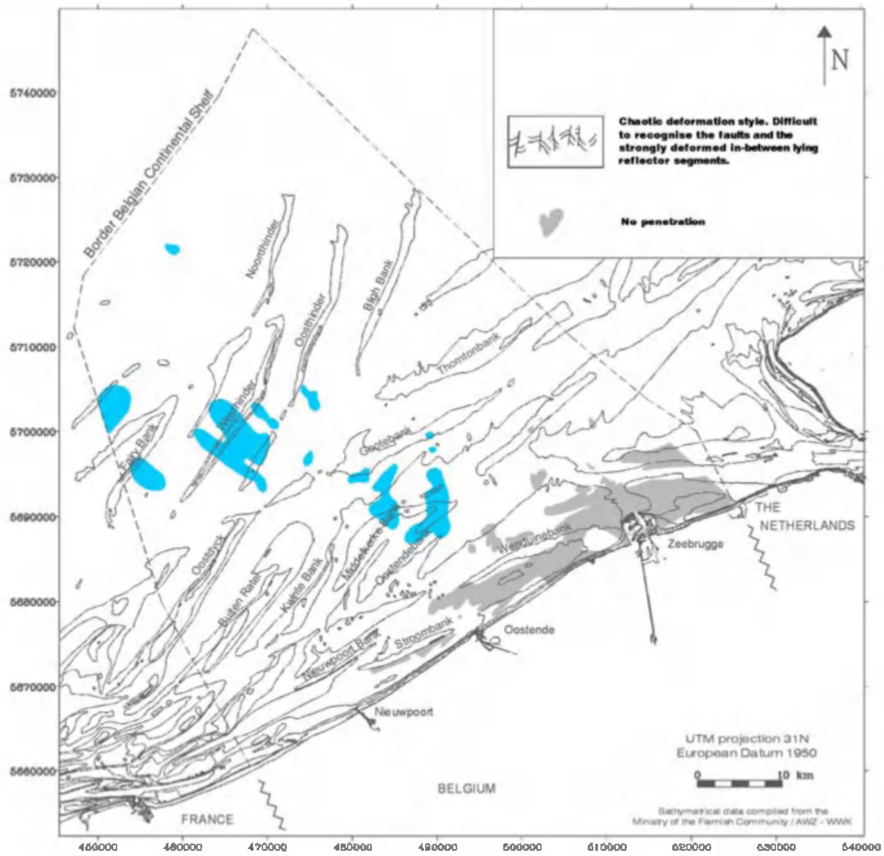


Figure 12: Distribution of the sediment tectonic deformation styles within the first upper metres of the depositional sequence Y1 (seismo-stratigraphic interpretation) (after De Batist, 1989). Top, right: schematic representation and description of the reported sediment tectonic deformation style.



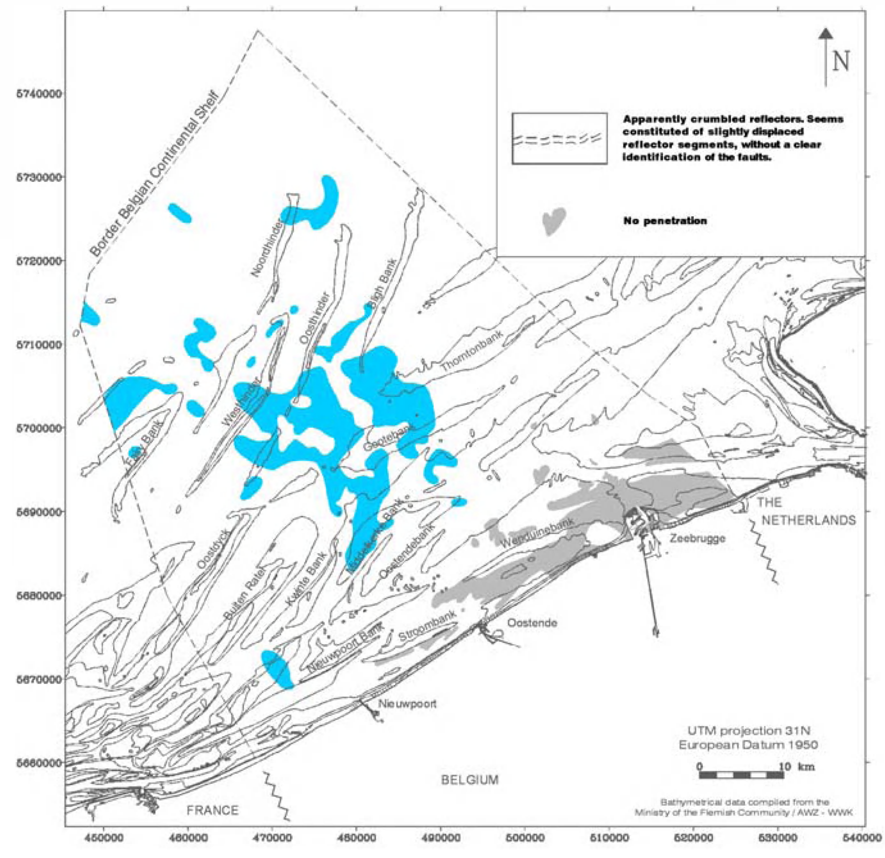
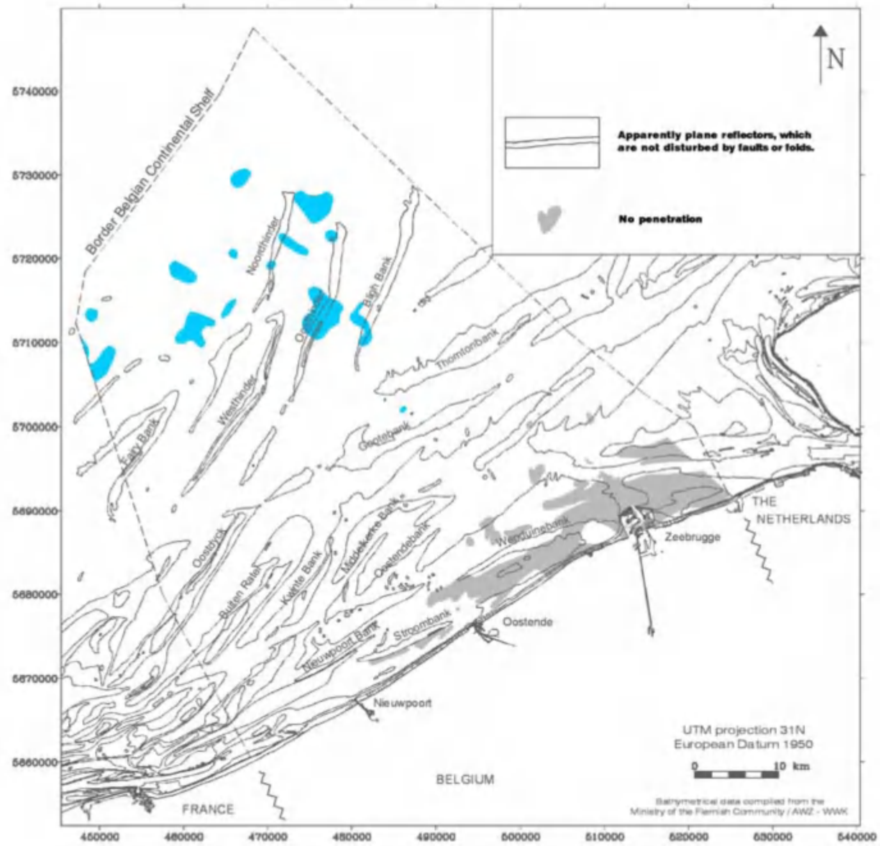


Figure 12: Distribution of the sediment tectonic deformation styles within the first upper metres of the depositional sequence Y1 (seismo-stratigraphic interpretation) (after De Batist, 1989). Top, right: schematic representation and description of the reported sediment tectonic deformation style.



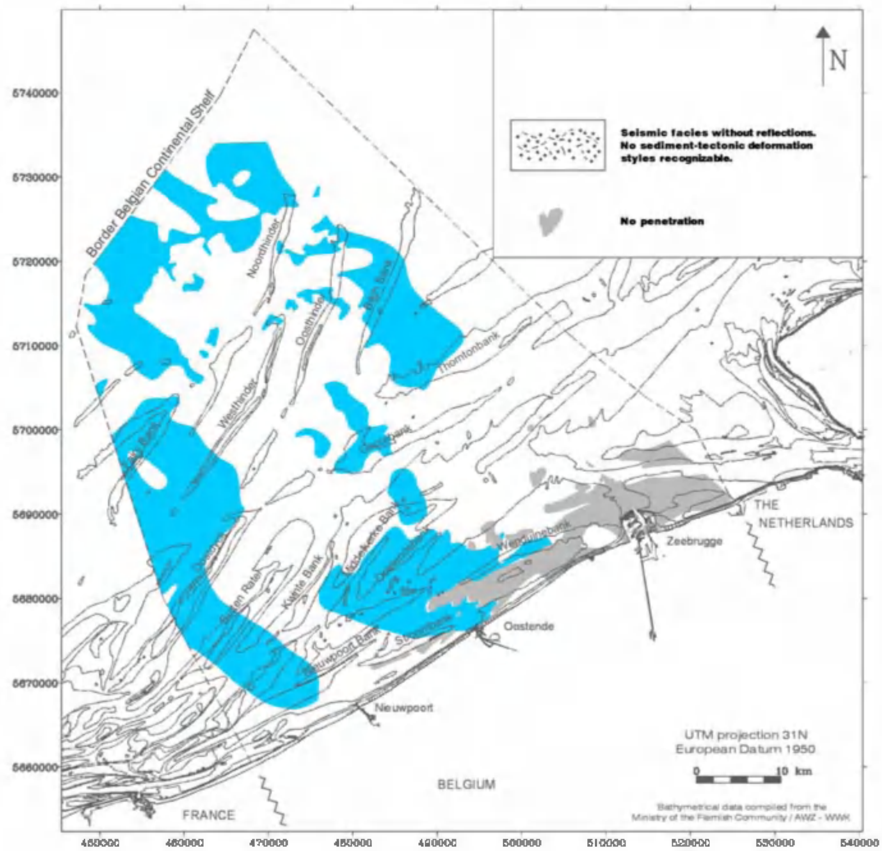
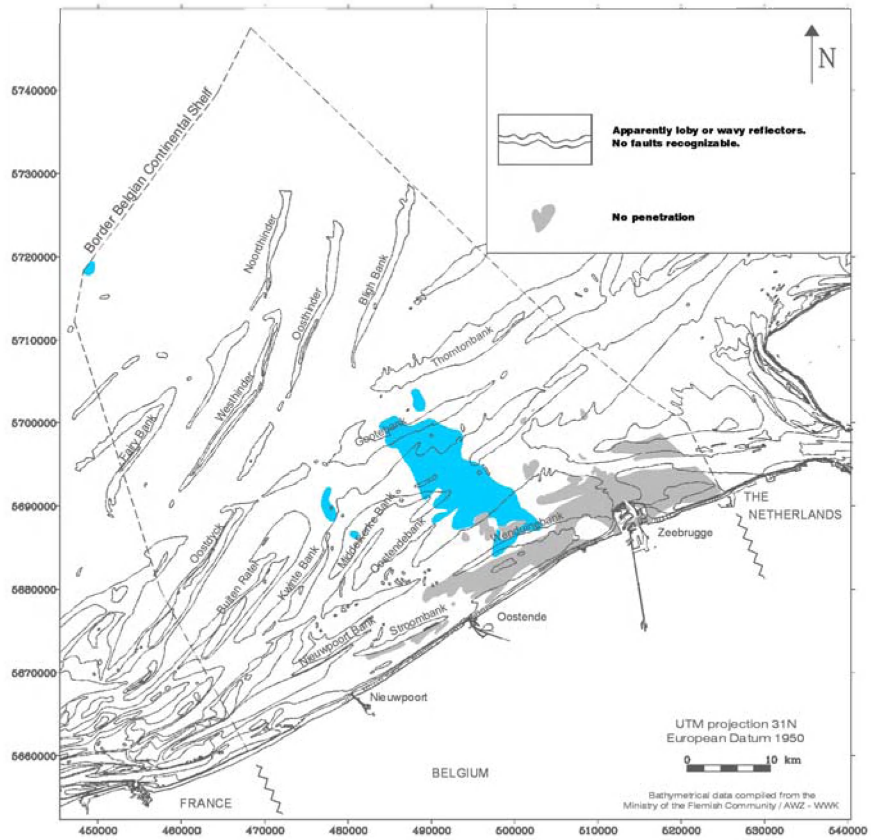


Figure 12: Distribution of the sediment tectonic deformation styles within the first upper metres of the depositional sequence Y1 (seismo-stratigraphic interpretation) (after De Batist, 1989). Top, right: schematic representation and description of the reported sediment tectonic deformation style.



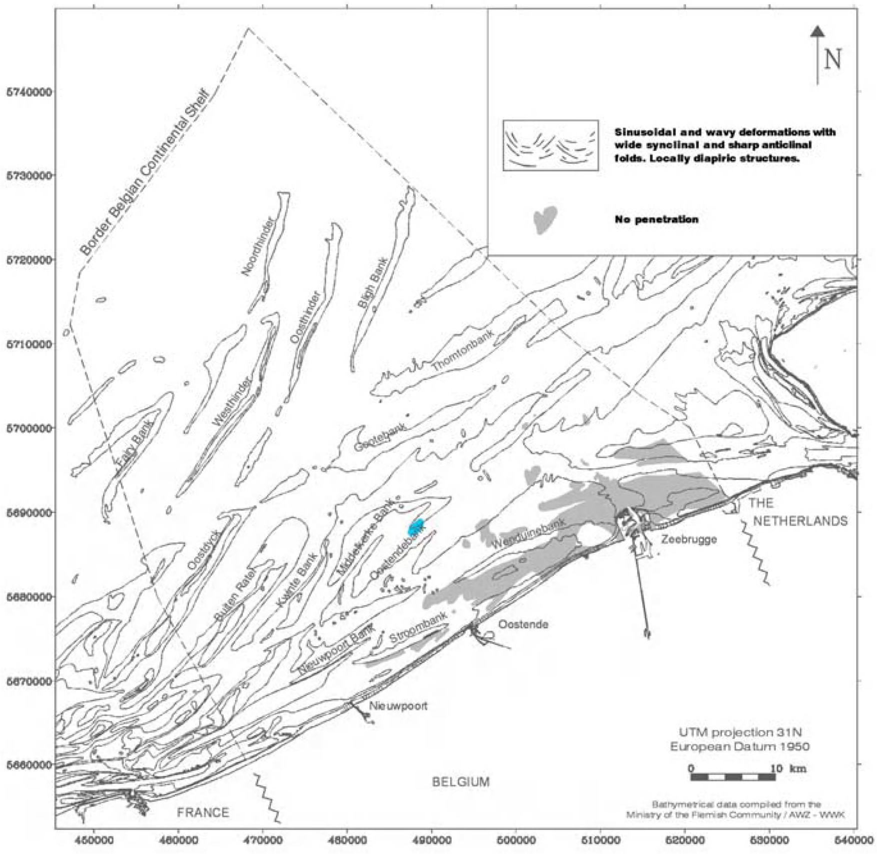


Figure 12: Distribution of the sediment tectonic deformation styles within the first upper metres of the depositional sequence Y1 (seismo-stratigraphic interpretation) (after De Batist, 1989). Top, right: schematic representation and description of the reported sediment tectonic deformation style.

3 Quaternary sediments

Quaternary deposits are regarded as non-cemented sediments. A part of them is relict, but the other part is currently mobile under the tidal current action.

The Quaternary in the study area is characterized by a laterally as well as vertically complex and heterogeneous facies assemblage. Quaternary deposits occur in individual morphological subunits characterised by a very distinct stratigraphical build-up and lithological complexity (Bastin, 1974 ; Eisma et al., 1979). The extension of the Quaternary deposits is known but their lateral correlation is difficult to establish.

3.1 Depositional history

Most of the preserved Quaternary sediments has been deposited during the Holocene flooding of the Southern North Sea (Flandrian transgression) which has started some 10,000 years ago. These sediments form the present-day tidal sandbanks and dunes. Nevertheless, although weakly extended, some thick deposits originate from the Pleistocene period.

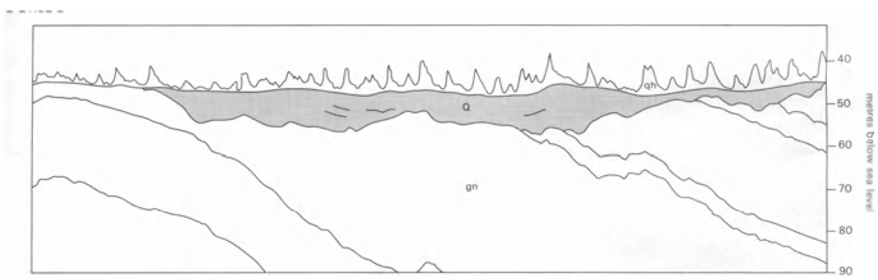
3.1.1 The Pleistocene deposits

The Pleistocene period is characterized by the succession of numerous glacial and interglacial stages. During interglacial stages, large budgets of sediments were carried out into the southern North Sea Basin by large rivers such as the Thames, Meuse and the Rhine. On the Belgian continental shelf, most of the Pleistocene sediments originate from the discharge of the Rhine-Meuse system and the Flemish Valley (Houbolt, 1968).

Only few sediments are considered of Pleistocene age. One reason is the important sediment reworking during the Holocene. Another reason is the lack of coring information in these deposits. The supposed Pleistocene deposits consist mainly of infilling of scour hollows and palaeovalleys, burrowed in the top of Palaeogene deposits. Some other thinner deposits can be mentioned: a series of marine deposits in the coastal plain near the Belgian-French border (Sommé, 1974; Paepe et al., 1981) and along the eastern Belgian–Dutch border (Balson et al., 1992), marine tidal flat deposits (Oostende Formation) in both the middle and eastern coastal plains, reaching 9 m in thickness (Kirby & Oele, 1975), channel deposits observed in the north-western part of the Belgian shelf (Balson et al., 1992) (figure 13).

SW

51°43.91′N
2°21.32′E



NE

51°58.00′N
3°59.33′E

Horizontal scale: 1:50.000 Vertical exaggeration: x50

Figure 13: Pleistocene channel deposits (interpreted seismic profile) (Balson et al., 1992). Q: Pleistocene deposits, gn: Tertiary deposits.

3.1.2 The Holocene deposits

The Holocene started 10,000 years ago and represents the current interglacial period. The Holocene is characterized by a sharp sea level rise, called the Flandrian transgression.

During the Holocene, the coastal plain was subjected to marine, freshwater and terrestrial conditions. Towards the seaward part of the coastal plain, only marine and brackish clastic sediments have been deposited that are in some places overlying a basal peat layer (Baeteman & Van Strijdonck, 1989). In coastal areas the formation of the basal peat is due to groundwater level rise associated with the sea level rise. The basal and also the intercalated peat layers are lacking in the very seaward area, where also the Pleistocene deposits are almost completely eroded (Baeteman & Denys, 1997) and/or reworked into tidal flat sands, estuarine sandbanks and beach deposits as during each precedent Quaternary flooding. The Holocene development of the Belgian coastal plain is characterised by a rapid infilling following the rate of sea-level rise and the morphology of the Pleistocene substratum (Baeteman & Denys, 1997). Changing conditions in the most silted-up parts of the former Pleistocene valleys induced local peat growth on the tidal flat sediments, whereas in the rest of the plain mudflats and salt marshes developed. Finally, during the last part of the Holocene, a repeated reworking and removing of the fine-grained material led to the deposition of the so-called Young Sands on top of the tidal flat deposits (Oele & Schüttenhelm, 1979 ; Jelgersma et al., 1977 ; Jansen et al., 1979). These sands took part in the upbuilding of the sandbanks, and have also been shaped into nearly planar beds, megaripples and dunes by recent tidal currents (Eisma et al., 1979).

3.2 Nature of deposits

3.2.1 Lithology

3.2.1.1 Generalities

According to coring data, the Quaternary sediments consist essentially of sand. Each of the 32 cores contains a lot of sand (Annex 4, table a). More precisely, in the upper few metres, sand is generally encountered and sometimes, underneath, shelly layers (around 0.1-1 m thick / 6 cores), gravely layers (around 1.5-3 m thick / 4 cores) or clayey layers (around 0.1-1.5 m thick / 7) are intercalated within the sandy ones. Quaternary sediments are heterogeneous as displayed in the pattern of CPT's data (66).

3.2.1.2 The Pleistocene sediments

According to coring information, the assumed Pleistocene sediments seem to consist mainly of sands, essentially medium coarse to very coarse (210-420 µm) (13 cores; Annex 4, table b). Only 1 core contains flint gravels.

In the northern part of the Belgian shelf, the channel deposits consist in a complex of sands, silts and muds. According to Van Den Broeke (1984), the Eemian interglacial remnants observed in the present-day offshore area are characterised by shelly coarse sands. Salt marsh clay and peat appear in the present-day coastal plain and coincide with the landward area of Eemian marine influence at the climate maximum.

Along the Belgian-Dutch border, the Eemian deposits (Eem Formation) consist predominantly of medium-grained sand locally with clay laminae and some gravel (Balson et al., 1992).

3.2.1.3 The Holocene sediments

On the Belgian continental shelf, 27 cores have been drilled through the Holocene sediments (Annex 4, table c). Holocene sediments merely consist of sands (25 cores) but also clay (3 cores) and gravels (2 cores) are found. Sands are mainly medium coarse, yellow-brown, rounded angular to angular rounded. Gravels consist mainly in flints and also in shells fragments. The ODB-B1 core has been taken in the Oostdyk Bank: it reveals a complex pattern of several metres-thick sandy layers alternating with gravelly ones (1.5-3 m). From CPT's realised in the Oostdyck and Westhinder sandbanks, the cone resistance displays a rapid alternation of high and low peak values which indicate a huge vertical sediment heterogeneity.

3.2.2 Geotechnical properties

Geotechnical parameters of Quaternary deposits, measured along 138 CPT's profiles (66 onland, 68 nearshore, 4 offshore), show heterogeneous patterns which cannot be generalized (see figure 6), whereas it was mostly possible for Tertiary deposits. These observations emphasize the lithological heterogeneity of Quaternary deposits.

3.3 Main depositional features

The main Quaternary depositional features consist of Pleistocene scour hollow infillings and Holocene tidal sandbanks (figure 14).

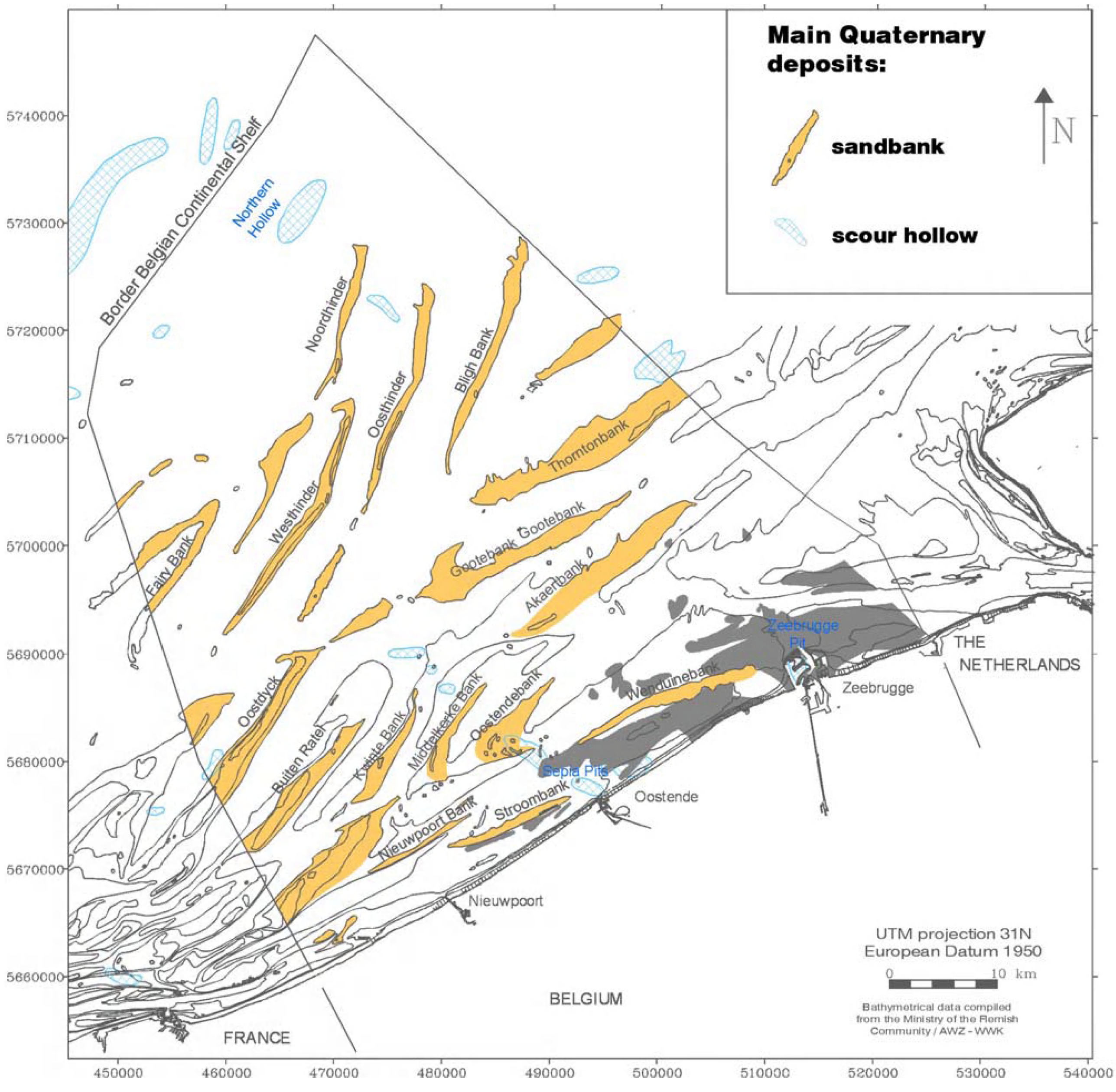


Figure 14: Main Quaternary depositional features (after Liu et al., 1993).

3.3.1 Pleistocene scour hollows

On the Belgian continental shelf, scour hollows are thought to have formed by tidal scouring and fluvial erosion (Liu, 1990 ; Liu et al., 1993). The remainders of the hollows are incised into the top of the Palaeogene deposits. The hollows were most likely formed during phases of Late Pleistocene sea-level rise and most of them have been filled by Late Pleistocene marine sediments. The scour hollows occur essentially within fluvial paleovalleys, mainly within the Ostend Valley and the Axial Channel (see figure 21).

3.3.1.1 Sepia Pits

The nearshore part of the Ostend Valley contains the so-called Sepia Pits 1, 2 and 3 (Mostaert et al., 1989 ; Liu, 1990) with respective depths of 52.5, 47.5 and 60 m, and widths of 3 km and 3.5 km. They have been cut 20 m or more below the valley base. All three hollows are assumed to be filled with deposits of Late Eemian age. The Sepia Pit 1 has a V-shaped profile and is buried beneath the Ostend bank (figure 15), whereas the Sepia Pit 2 has a more irregular profile. To the northwest of the Sepia Pits, a number of 5-10 m depth hollows are scoured into the Ypresian clay. These hollows are U-shaped in cross-section and are partly overlain by the Kwinte Bank.

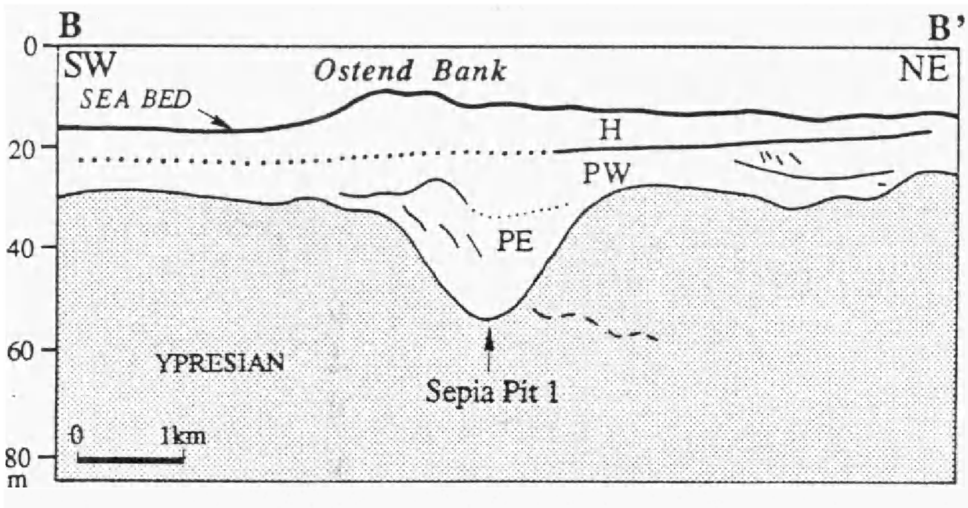


Figure 15: Sepia Pit 1 scour hollow: interpreted seismic profile (Liu et al., 1993). PE: Eemian, PW: Weichselian, H: Holocene. Depths are in metres.

3.3.1.2 Northern Hollow

The Northern Hollow has been identified within the Northern Valley (see location on figure 21). It has an incised depth of 15 m and an asymmetric profile, indicative of a differential erosion phenomena.

3.3.1.3 Zeebrugge Pit

Located offshore Zeebrugge, this NE trending shaped pit has been cut 10 m below the valley base. It is marked by 3 infilling stages which can be dated from bottom to top as Eemian, Weichselian and Middle Holocene (Henriet et al., 1978).

3.3.2 Holocene tidal sandbanks

3.3.2.1 Architecture: seismic units

The Quaternary upbuilding of some of the sandbanks on the Belgian continental shelf has mainly been characterised from seismic investigations. Still, fundamental research is needed to reconstruct the genesis of the sandbanks and to enhance the predictability of the occurrence of Quaternary deposits. Figure 16 gives a conceptual overview of the depositional sequences of the Quaternary of parts of some sandbanks. Note that the names of each depositional sequence include an annotation of the area as it is not clear how the Quaternary sequences found in the sandbanks laterally correlate. More detailed information can be found in Maréchal & Henriet (1986).

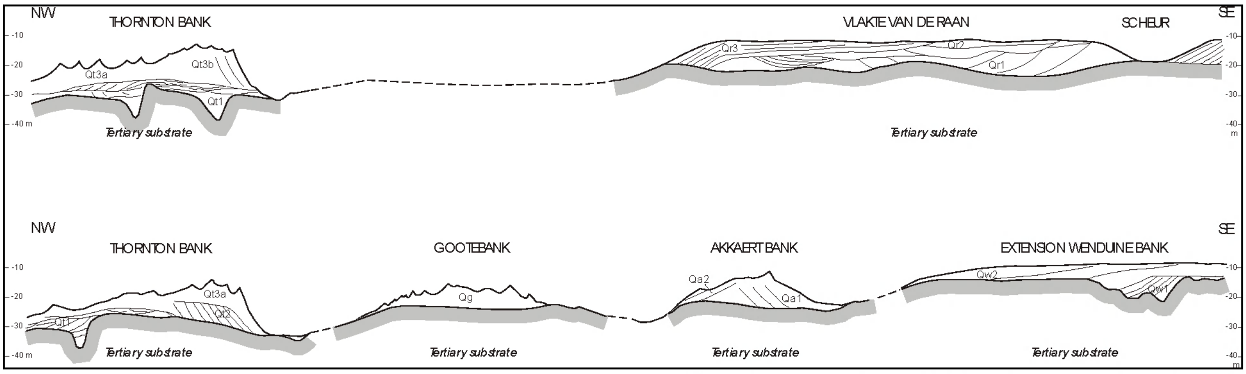


Figure 16: Conceptual overview of the depositional sequences of the Quaternary of parts of some sandbanks (Maréchal et al., 1986). Interpreted seismic profiles. Qt, Qr, Qg, Qa, Qw: Quaternary deposits related to respectively Thornton Bank, Vlakte van de Raan, Gootebank, Akkaert Bank, Wenduine Bank.

** Thornton Bank*

The most complex sandbank is the Thornton Bank, of which the Quaternary is characterised by at least 3 depositional sequences. Qt1 represents a complex channel infill facies; its thickness is highly variable and can amount up to 10 m. Qt2 mostly occurs directly on the substratum where Qt1 is absent. Its thickness is maximally 8 m and has only been observed at the southeast end of the Thornton Bank. The Qt3 series is more complex and consists of Qt3a corresponding to a reflection free facies and Qt3b representative of prograding clinoforms. These series are representative for the upper Quaternary sediments and are strongly varying in thickness.

** The Gootebank*

It has only a limited Quaternary cover as it is located on a broad Tertiary ridge. From a seismo-stratigraphical point of view, it can not be subdivided. Qg is mainly characterised by the presence of dune structures.

** Akkaert Bank*

The Quaternary of the Akkaert Bank is somewhat more complex ; 2 depositonal sequences can be distinguished. Qa1 is representative of prograding clinoforms; its thickness is around 10 m and is present in most of the bank. Qa2 corresponds with a faintly dipping parallel seismic facies. This series occurs only locally.

** Vlakte van de Raan*

Along the 'Vlakte van de Raan' also 3 depositional sequences can be characterised. A first series (Qr1) is directly deposited on the Tertiary substrate and consists of channel infill up to 10 m thick. These bears similarities with the lateral migrating and filled tidal gullies of the coastal plain (Mostaert, 1985). The second Qr2 series is relatively thin and consists of a wavy, discontinuous prograding layering. The upper deposional sequence Qr3 is maximally 5 m thick and occurs at the most offshore part of the 'Vlakte van de Raan'. The reflectors gradually dip to the NW.

** The Middelkerke Bank*

The Middelkerke bank has been intensively studied during the MAST projects (De Moor and Lanckneus, 1993 ; Trentesaux, 1993 ; Trentesaux et al., 1994 ; Berné et al., 1994 ; Heyse & De

Moor, 1996 ; Trentesaux et al., 1999) using high and very high resolution seismics (800 km of profiles) and vibrocoring (65 cores). The sandbank was shown to be not merely a piling of sand, but a result of different well-distinct evolutionary phases of erosion and deposition.

- Seismo-stratigraphy of the Middelkerke Bank

Seven seismostratigraphic units, chronologically labelled U1 to U7, have been identified within the Quaternary deposits (figure 17). Subunits can be determined in seismic units U4 (2) and U7 (3).

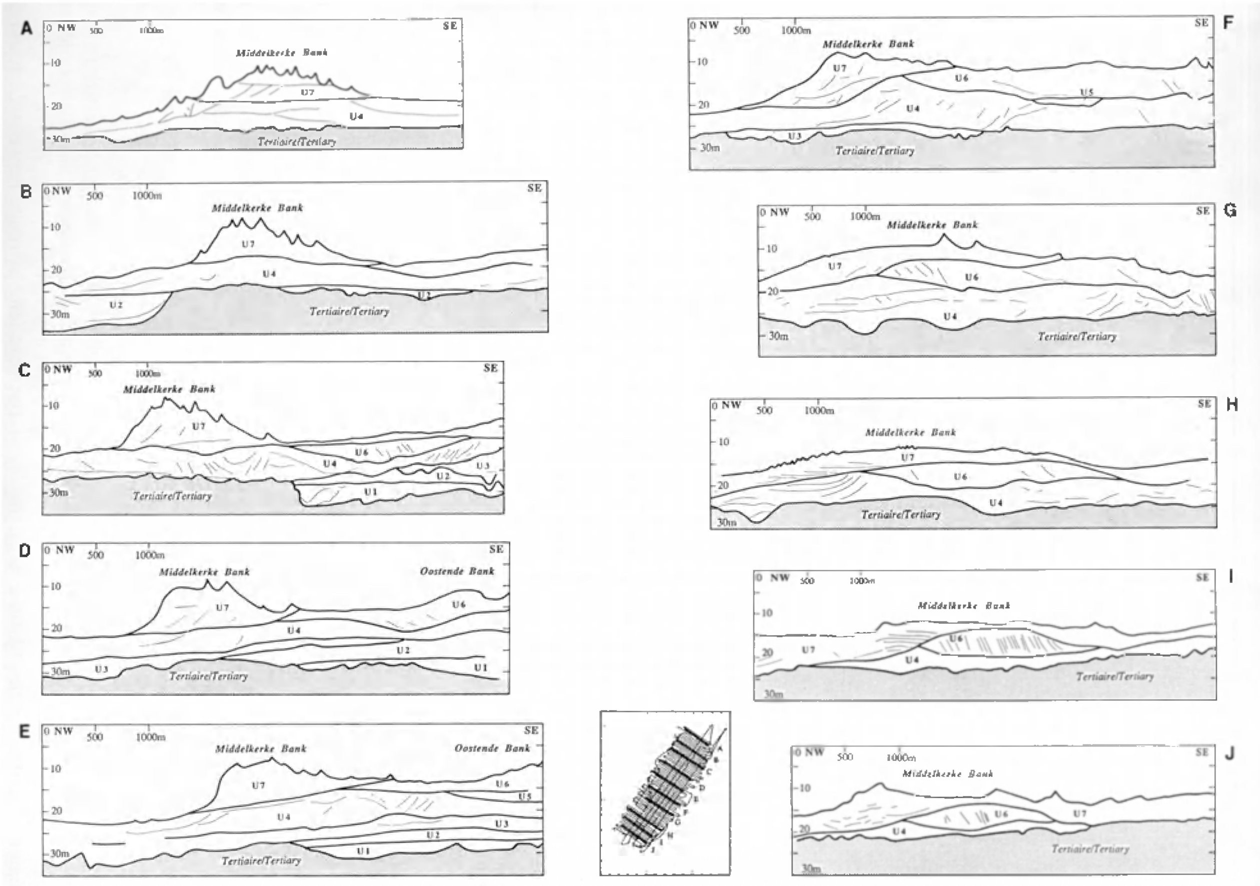


Figure 17: Seismic units composing the internal structure of the Middelkerke Bank (selected interpreted seismic sections from A to J) (Berné et al., 1994).

- Lithology of the Middelkerke Bank

Subsequently, the sediments involved can be very diverse in nature. Sediments range from clay to gravel and the shell content from about 0 to more than 50 % of the total sediment. In cores, 11 sedimentary facies have been distinguished according to their grain-size, nature of components, sedimentary structure, bioturbation and colors (figure 18). A high variability of sedimentary facies is observed: (1) vertically, the transition between facies is often sharp. Most cores show an upward coarsening trend, associated with a change of sediment colour from grey to beige. There is also an upward simplification of the sediment structure which is less complicated and less variable than in the lowest levels ; (2) laterally, there is a clear opposition in sedimentary facies between the flanks (fine, grey, clayey and variable sand) and the top of the bank (coarser sediments, beige in color, rich in shell debris and spatially more constant).

- Comparison of seismic and lithologal limits of the Middelkerke Bank

Most seismic reflectors correspond to changes in sedimentary facies, grain-size and density. Nevertheless, some reflectors cannot be associated with any change in lithology, whereas strong lithologic contrasts are not linked with any seismic discontinuity. Seismo- and litho-stratigraphic information for the Middelkerke Bank is reported in table 7. On this sandbank, only the upper sediment cover (7 to 13 m thick) is representative of the present hydrodynamic regime (Trentesaux, 1993 ; Berné et al., 1994 ; Trentesaux et al., 1999).

Table 7: Compilation of the seismo- and lithostratigraphic information of the Middelkerke Bank (data from Trentesaux, 1993).

Unit	Distribution	Age	Lithology
at the base	scouring of channels	Weichselian	-
U1	channels overlaying the Tertiary clay	Late Boreal (8200 – 7900 BP)	coarse flint gravels associated with marcassite and humic debris. The shells correspond to marine animals.
U2	valley infilling	limit between Boreal and Atlantic stage (8100 – 7900 BP)	wavy and flaser bedding with an alternation of sandy and muddy layers / oblique alternate layers of sand and mud (large dune progradation)
U3	sand sheet	Atlantic	base: clean white, well-sorted sand / end: coarse flint gravel layers
U4	all over the study area thick sand sheet	Calais Formation (7800 – 6700 BP)	3 facies associations, containing all the facies defined, often intercalated: (A) fine grey, silty and muddy sands, mud and gravel ; (B) medium to fine grey sands, poor in shell debris with few mud clasts and gravels ; (C) different sedimentary facies with frequent vertical change
U5	lens shape on a small sector	?	grey brown fine sand, poor in shell debris
U6	lens shape elongated in a NE-SW direction	?	medium sand, poor in shell debris
U7	most of the study area	present-day	grey brown or beige, fine to coarse sand. High amount of small gravels and shell debris, low amount of clay and plant remains

** The Kwinte Bank*

Preliminary investigations showed that the sandbank is composed of large planar layers of Holocene marine sediments, which cover a lower core of planar units (De Moor, 1986). A core revealed these sediments to be perimarine and having an early Holocene to Pleistocene age. These sediments rest on the Ypresian clay.

** The Western Coastal Banks*

De Maeyer et al. (1985) and Wartel (1989) have studied the Quaternary of the western coastal banks. De Maeyer et al. (1985) focused on the internal structures of the Nieuwpoort Bank. These authors distinguished small to occasionnally large gullies presumably of pre-Holocene to Holocene age that were incised in the stiff clayey deposits of the Ypresian. Subsequently, sand, gravel and mud pebbles are found of which the latter are associated with erosional forces exerted on the clay layers. This sequence, in total 1 m thick, is overlain by a 60 cm thick shell layer. The occurrence of gravel and the random orientation of the shells indicate a highly energetic environment, presumably nearshore or beach. Moreover, the characteristics of the overlying sediments being composed of alternating sand and clay beds or laminae sometimes in combination with concave upwards oriented shells, suggest deposition in an intertidal environment.

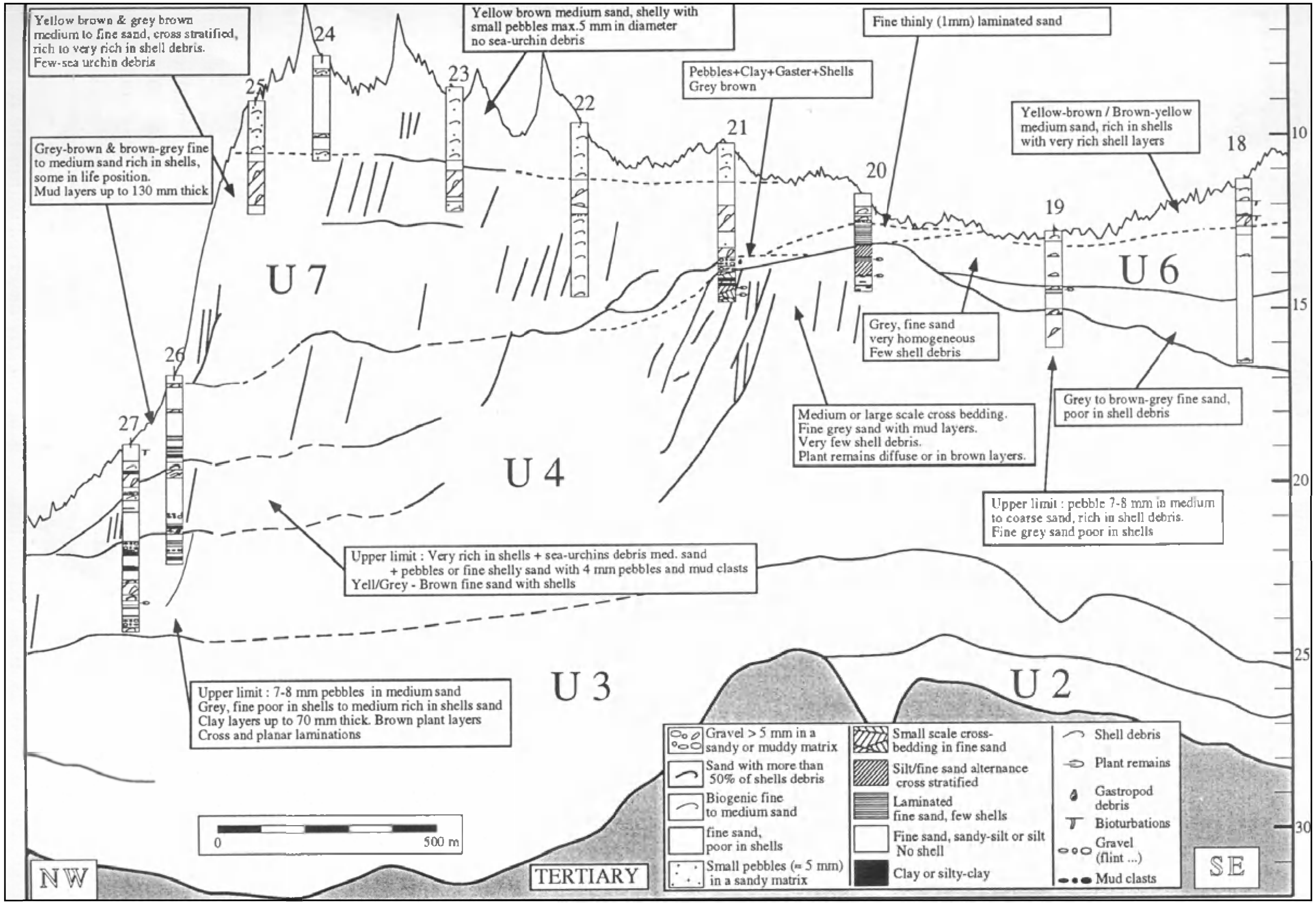


Figure 18: Correlation between the nature (simplified core logs) and the internal structure (seismic units U2 to U7) across the Middelkerke Bank (Berné et al., 1994). Depth in metres below MLLWS.

The tidal flat deposits are overlain by larger sediment bodies which lack however any stratification. Grain-size analysis of a core sampled in a sediment body north of the Nieuwpoort Bank reveals a relatively uniform grain-size distribution, mainly composed of fine sands comparable to the present day situation. The uppermost layer represents active marine deposits.

3.3.2.2 Geotechnical properties

In the Westhinder sandbank, where a 16 m-long CPT has been realised (figure 19-a), the cone resistance displays more or less constant values at depths higher than 6 m, indicating merely a vertical homogeneous sediment distribution. The values of the angle of internal friction (Φ) display a continuous decline from 45° at the top to 30° at the base of the Quaternary layer.

In the Oostdyck sandbank, the cone resistance presents a very irregular pattern (figures 19-b, 19-c and 19-d). The angle of internal friction (Φ) displays a progressive decrease from 40° at the top to 30° at the base of the Quaternary layer.

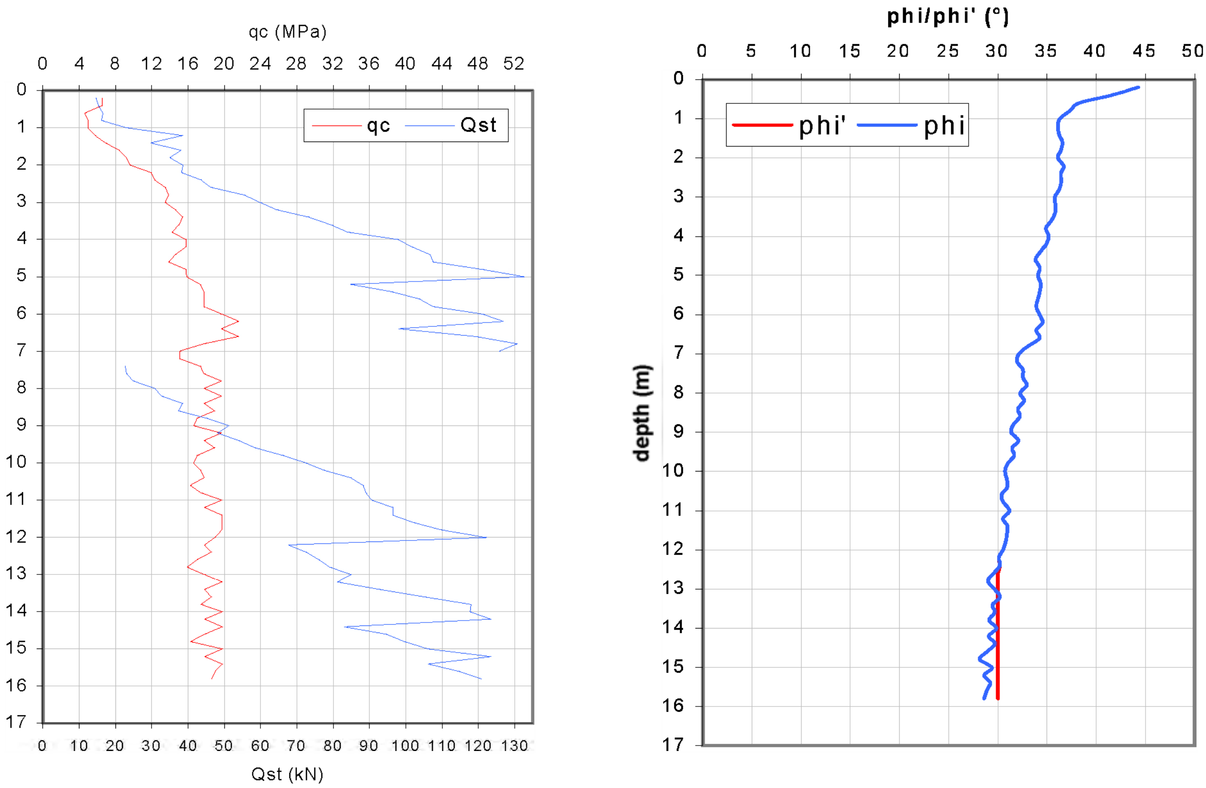


Figure 19-a: CPT on the Westhinder Bank (localisation UTM 31: 5693498N, 461191E) (Rijksinstituut voor Grondmechanica, 1988). q_c, Q_{st}, φ and φ' values.

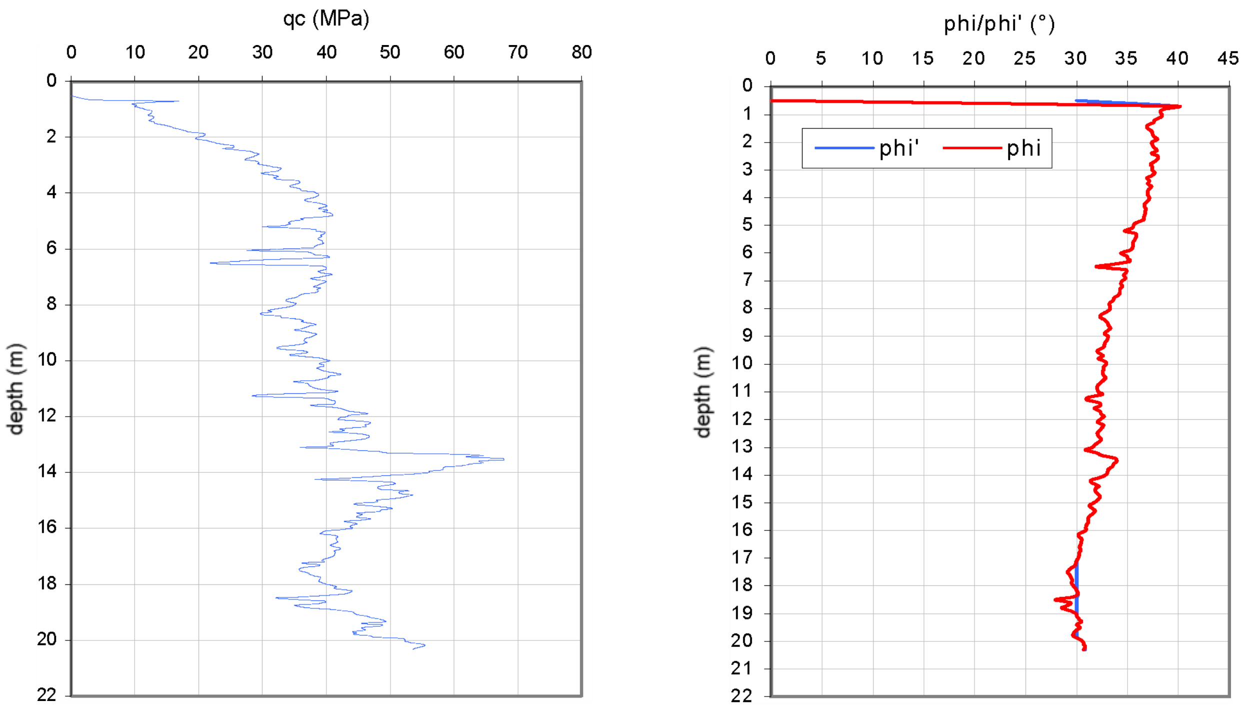


Figure 19-b: CPT ODB-S1 realised on the Oostdyck Bank (localisation UTM 31: 5680825N, 461550E) (Ministerie van de Vlaamse Gemeenschap-DLI, AOSO-Afdeling Geotechniek, 1999). q_c, φ and φ' values.

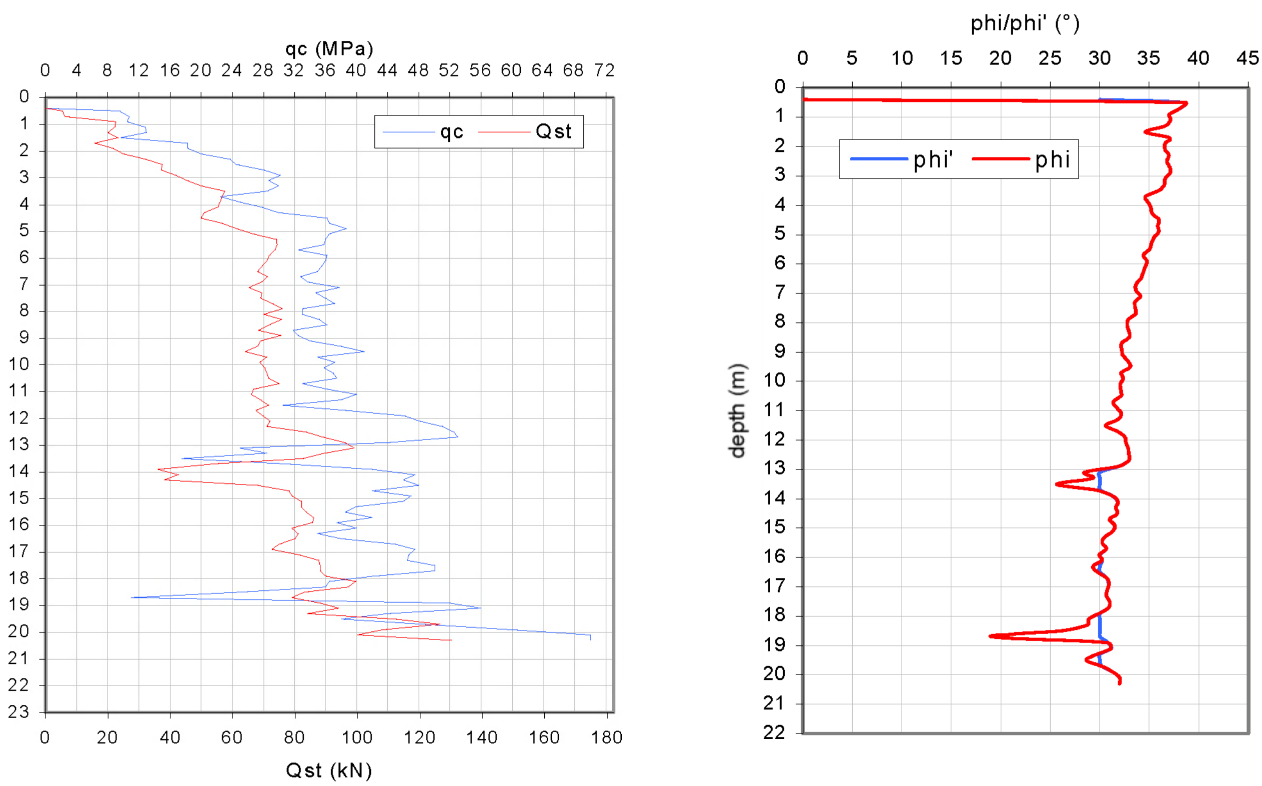


Figure 19-c: CPT ODB-S2 realised on the Oostdyck Bank (localisation UTM 31: 5680750N, 461550E) (Ministerie van de Vlaamse Gemeenschap-DLI, AOSO-Afdeling Geotechniek, 1999). q_c, Q_{st}, φ and φ' values.

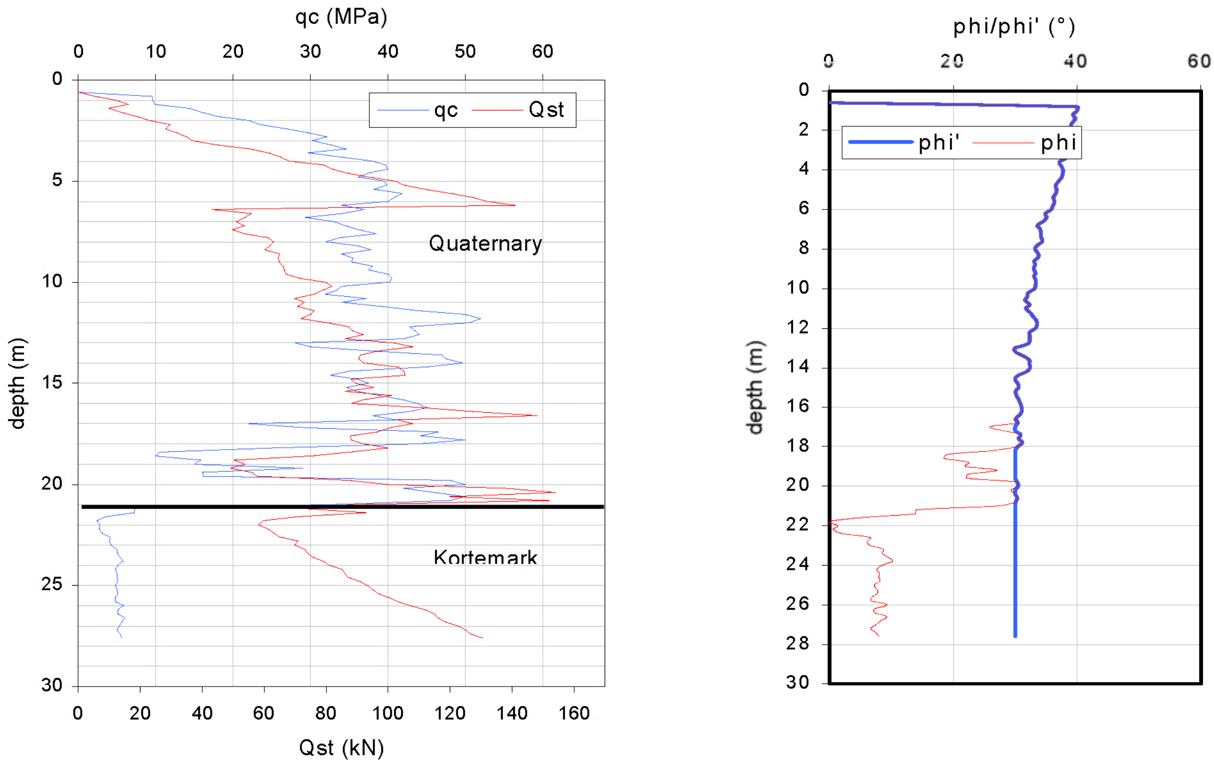


Figure 19-d: CPT ODB-S3 realised on the Oostdyck Bank (localisation UTM 31: 5680730N, 461464E) (Ministerie van de Vlaamse Gemeenschap-DLI, AOSO-Afdeling Geotechniek, 1999). q_c, Q_{st}, φ and φ' values.

3.4 Distribution and geometry of deposits

3.4.1 Base of the Quaternary deposits

This surface is situated at some 12.5 to 60 m deep, respectively from the coast towards offshore areas (figure 20). Along the eastern part of the present-day coastal plain, the surface lays at least at a depth of 20 to 30 m below the surface (-15 to –20 m TAW). In the sector of the Coastal Banks, Flemish Banks and Zeeland Ridges, the base of the Quaternary deposits dips progressively from 12.5 to 35 m in the offshore direction. Further offshore, this surface deepens in a less progressive way, from 35 to 45 m in a NE direction in the area of the Hinder Banks and in a NW direction further offshore.

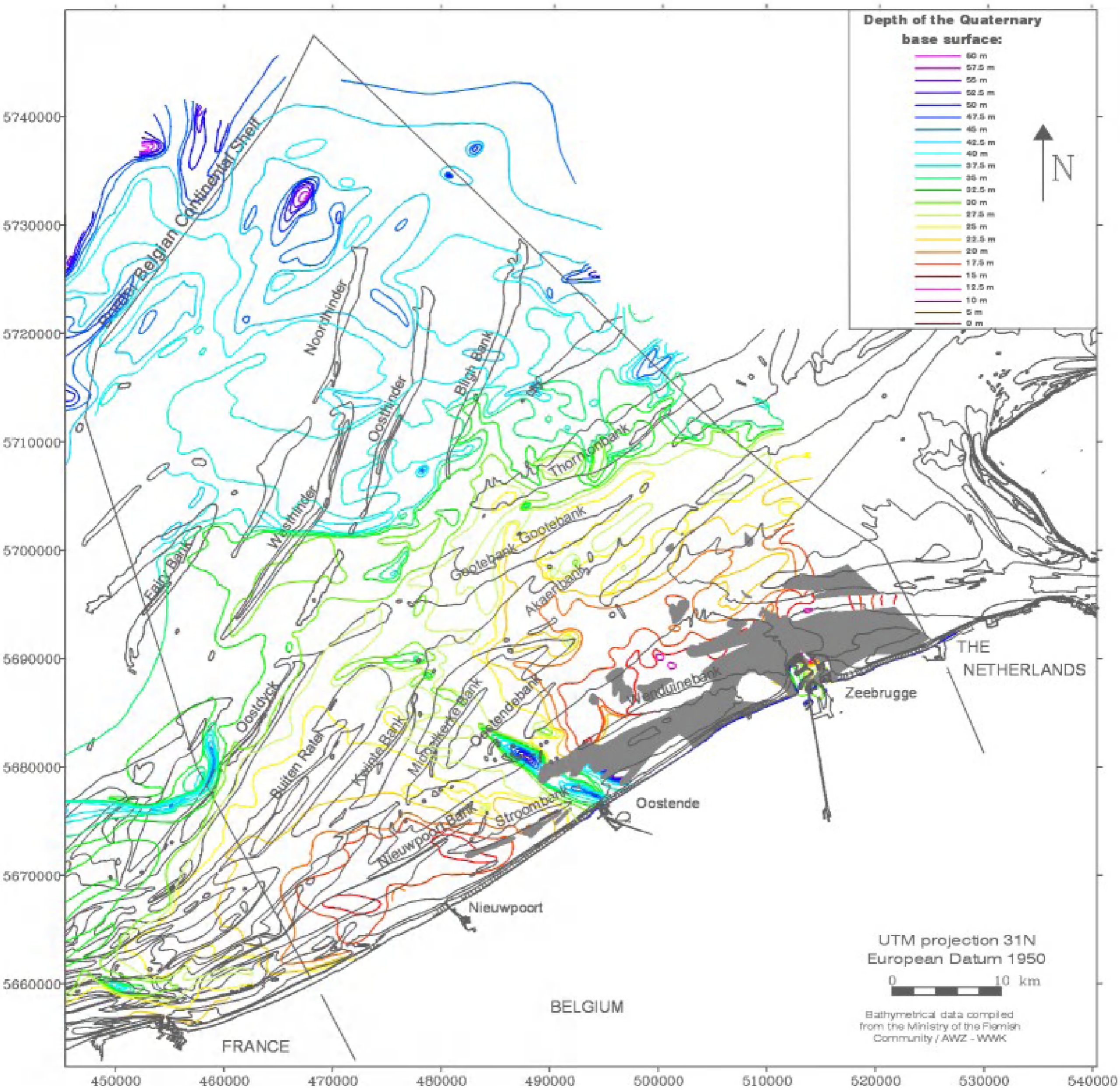


Figure 20: Depth (contour lines) of the Quaternary base surface (After Liu, 1990). Reference level is the mean lowest low water-level at spring tide.

The Quaternary base is affected by numerous and various morphological features (Liu et al., 1992) (figure 21):

- Scarps, slope breaks, cuestas and valleys are observed. They have been induced by differential erosion of the Tertiary deposits underneath.
- Several deep depressions also affect the Quaternary base. They correspond to scour hollows, burrowed during the Pleistocene (see paragraph 4.3.1). Most of them are observed in the northernmost part of the continental shelf (e.g. the Northern Hollow located north of the Noordhinder Bank, extends between 45 and 60 m under the seabed). The larger ones correspond to the Sepia Pits, located near the coast, off Oostende and Bredene. They are NNW elongated and extends from 30 m depth at the top to 57.5 m at the base.

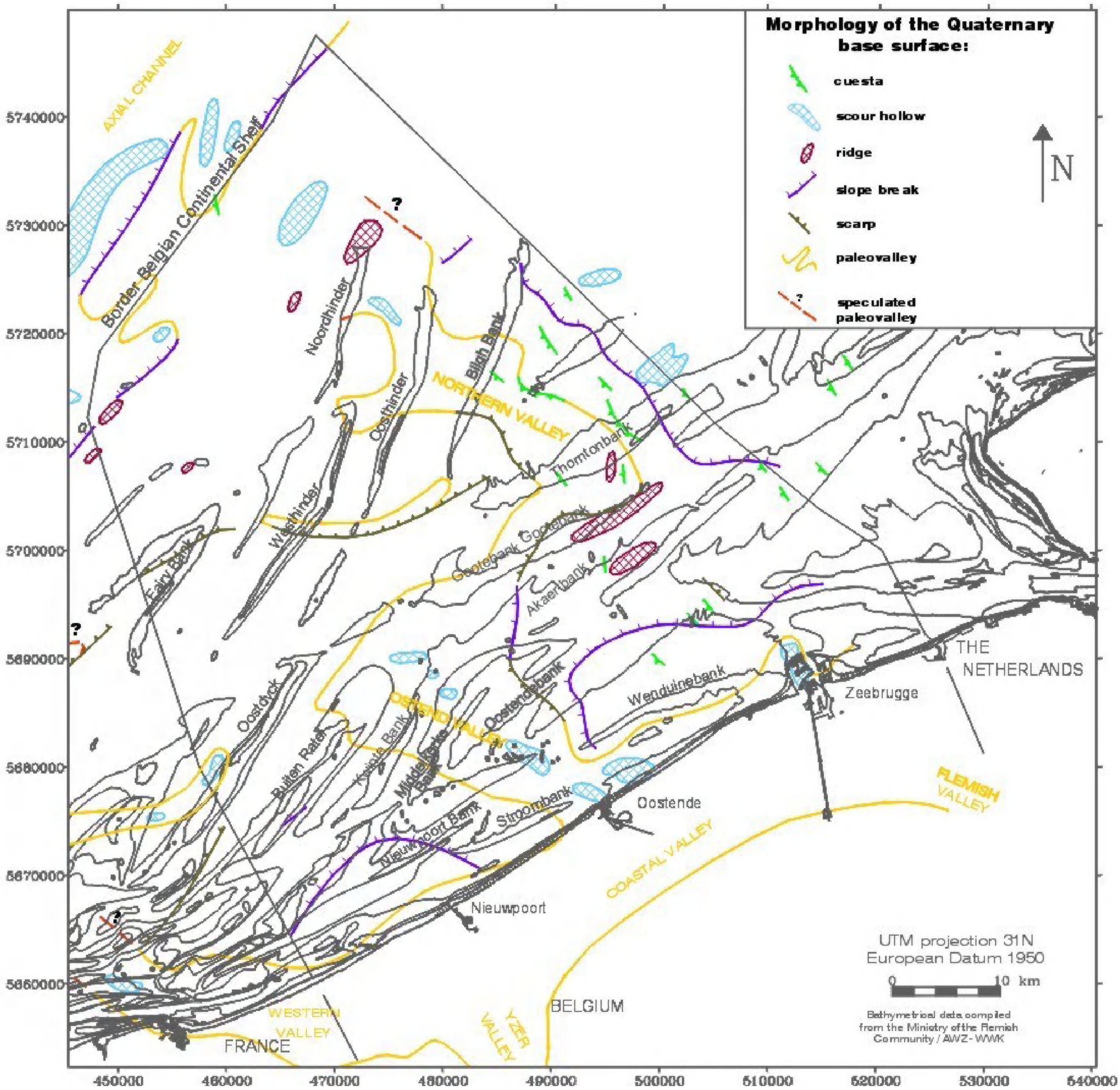


Figure 21: Morphological features observed at the Quaternary base surface (After Liu, 1990 and Liu et al. 1992).

3.4.2 Depth of the Top Eemian

The top of the Eemian deposits has been tentatively recognised in the sector of the Hinder Banks mainly on the basis of seismic interpretations (Van Den Broeke, 1984) (figure 22).

This surface is located at 25 to 42.5 m depth. In the northeastern part, the reliefs visible on this surface consist of long, streamlined bulges and depressions with more or less the same strike as the overlying sandbanks: the Hinder Banks (Oosthinder, Westhinder, Bligh Bank), the Thornton Bank and the Zeeland Ridges. In the southwest, an unsteady pattern of altitude lines, revealing a succession of unsteady bulges and depressions is observed.

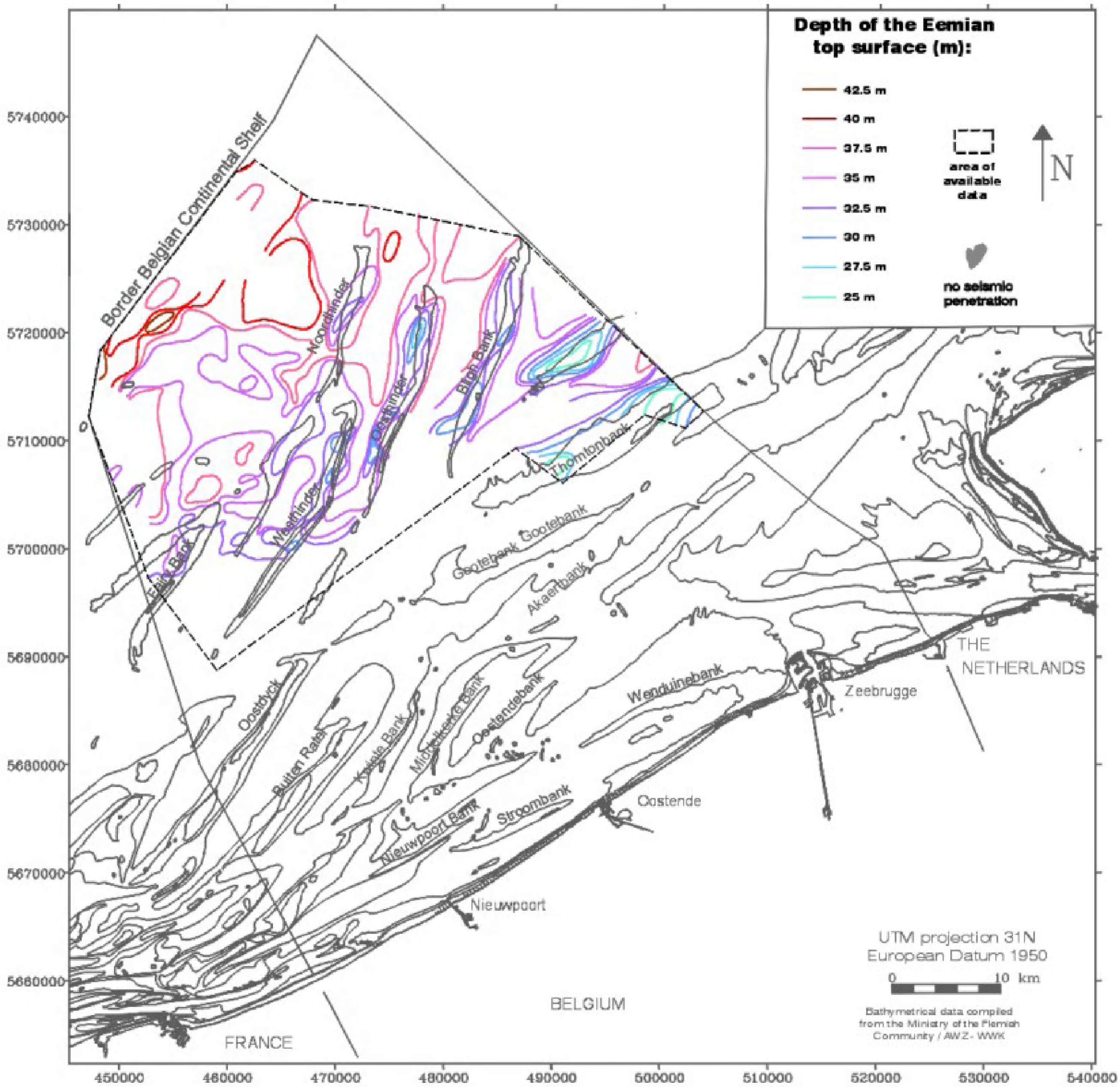


Figure 22: Depth of the Eemian top surface recognised in the area of the Hinder Banken (Van den Broeke, 1984). No interpretation is available outside the Hinder Banken area.

3.4.3 Thickness of the Quaternary deposits

The Quaternary deposits are generally thinner offshore: they range in thickness from a few metres to 50 metres (figure 23).

Locally, Tertiary strata are exposed at the seabed. For example, to the south and northeast of the Goote Bank, no Quaternary deposits are found, and in the Westdiep swale and west of the Kwinte Bank, the Tertiary deposits can even be eroded by the present-day hydrodynamic regime.

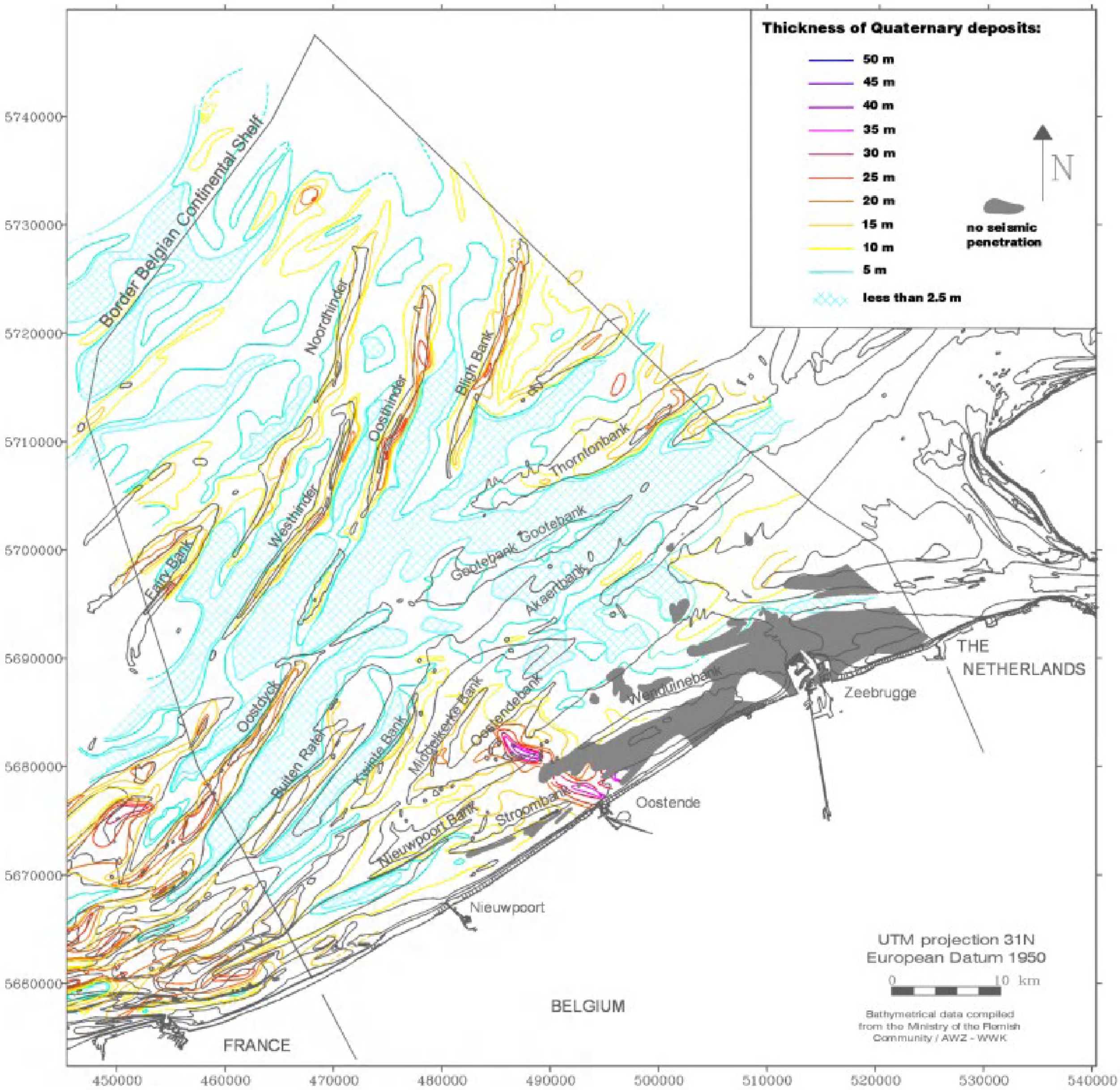


Figure 23: Thickness of Quaternary sediments (after Liu, 1990).

In most of the swales of the Belgian continental shelf, the thickness of the Quaternary is between 0 and 10 m, and mostly less than 2.5 m (Maréchal & Henriet, 1983, 1986). For example, swale areas of the southern part of the Hinder Bank Region are characterized by a thin Quaternary cover often consisting of a gravelly floor.

The larger thicknesses are reached along the tidal Holocene sandbanks (up to 30 m) and in Pleistocene scour hollows (20 to 50 m thick off Oostende and Bredene, 10 to 25 m at the NNE of the Noordhinder Bank). The major difference between Pleistocene (Eemian) and Holocene sequences concerns the areal and vertical distribution pattern of the sedimentary units (Mostaert & De Moor, 1989). These differences come from the location of the margin and the prevailing paleorelief during both periods (e.g. the most southern margin of open Eemian conditions was more southward than that of Holocene conditions). Therefore, Eemian deposits are more important in the coastal plain, contrary to the continental shelf where Holocene deposits are most abundant. In the northern part of the shelf, the thickness of Eemian deposits was found to be 8m at the Noordhinder Bank (core 81MK60), 4 m on the Oosthinder bank (core 80GD142). The appearance of an Eemian sequence is also clear on the Blighbank. On the Dutch continental shelf, north of the Zeeland ridges, the Eemian sequence was found to be 5 m thick (core 77MK38).

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List of tables

ANNEXES

Annex 1

Available cores: name and location

Data have been provided by the Belgian (BGD) and the Dutch (TNO-NITG) Geological Surveys.

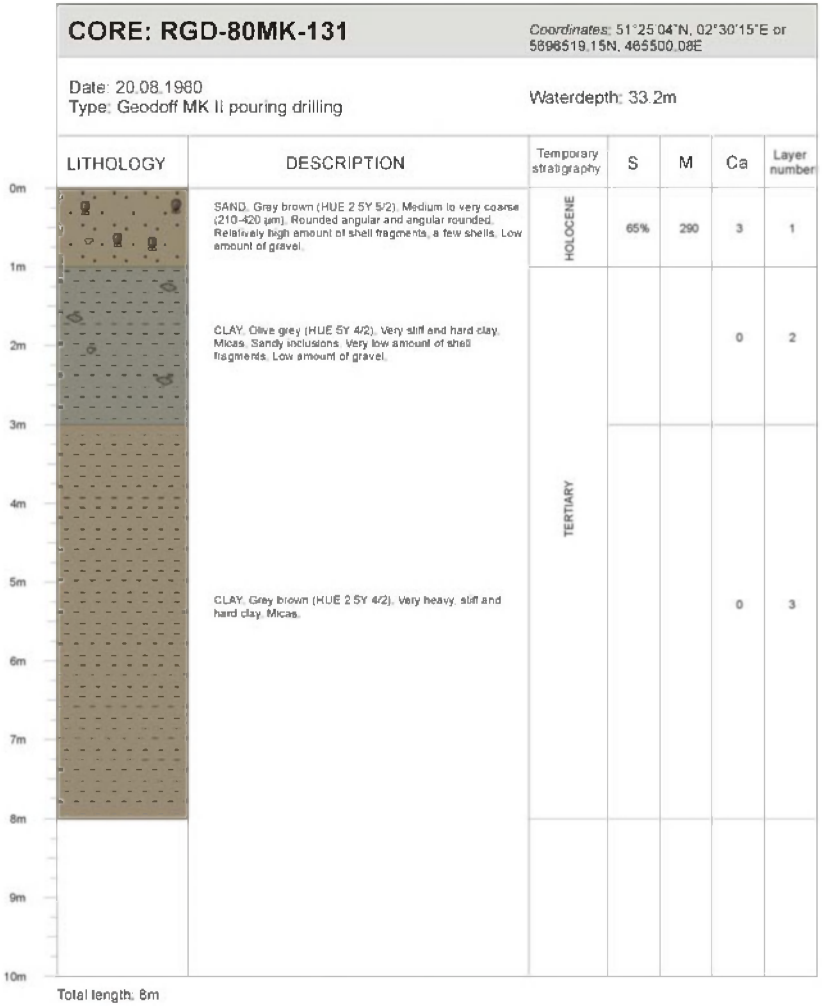
Core name	UTM 31-e ED50	UTM 31-n ED50
RGD-69/T79	497338	5703169
RGD-69/T137	503458	5724085
RGD-70/H30	495070	5692203
RGD-73/GD12	472455	5742511
RGD-73/GS9	502357	5737152
RGD-73/GS12	494338	5728752
RGD-76/H36	501580	5708915
RGD-77/MK37	505913	5710895
RGD-77/MK38	502924	5717565
RGD-77/MK39	505420	5722387
RGD-77/MK61	500596	5724238
RGD-77/MK62	503090	5728997
RGD-78/H5	476758	5687126
RGD-78/H6	484974	5677642
RGD-78/H8	481319	5680063
RGD-78/H9	488088	5674482
RGD-78/H10	486785	5672972
RGD-78/H11	486785	5672972
RGD-78/H14	477561	5671645
RGD-79/H32	499267	5706875
RGD-80/MK123	488479	5751964
RGD-80/MK124	464414	5750471
RGD-80/MK125	465445	5733625
RGD-80/MK126	453836	5724449
RGD-80/MK127	442183	5715238
RGD-80/MK128	442107	5696639
RGD-80/MK130	453533	5706037
RGD-80/MK131	465500	5696519
RGD-80/MK132	499903	5687165
RGD-80/MK133	487961	5677973
RGD-80/MK136	465085	5678078
RGD-80/GD138	487985	5696664
RGD-80/GD139	499460	5705331
RGD-81/MK71	447009	5694330
RGD-N1262/B1	486088	5723299
BGD-10E/30	510802	5685669
BGD-10E/46	509121	5683775
BGD-11E/48	522225	5689562
BGD-11E/138	524146	5688273
BGD-21E/41	494100	5675430

Core name	UTM 31-e ED50	UTM 31-n ED50
BGD-21E/121	488178	5671362
BGD-21E/122	493133	5675060
BGD-35E/142	476319	5663247
BGD-11W/88	513993	5686567
BGD-11W/160	518772	5687972
BGD-11W/170	516486	5687779
BGD-22W/276	500233	5678021
BGD-35E/142	476319	5663247
BGD-36W/94	481751	5665357
BGD-36W/118	483450	5667761
DBGD-86/SB1	489666	5675622
DBGD-86/GR1	503764	5684769
DBGD-86/3/SWB	494407	5679377
DBGD-86/4SEWB	508419	5686814
RGD-81/MK72	454320	5701396
RGD-82/MK180	470172	5709187
RGD-69/HT5	472416	5696662
RGD-80/GD141	476534	5705632
RGD-81/MK60	471455	5724782
RGD-80/GD142	477062	5724352
RGD-81/MK73	469549	5717718
BKR-2/A B32	519921	5690139
ODB-B1	461575	5680746
ODB-B2	461464	5680739
B85a	512709	5690967
B158	492408	5689924
B65ab	509144	5694543
B65a	509144	5694543
GII193	501653	5699655
GII192	502448	5699867
G222a	487215	5699771
G220	487889	5699937
G221	488154	5699540
G214	489378	5700748
G216	488969	5700542
G215	489675	5700341
G223	487538	5699390
G218	488402	5700190
G212	489985	5701050

Annex 2

Lithostratigraphic interpretation obtained from cores. Examples of typical cores drilled in various Tertiary units.

Name and location (geographic and UTM 31) of cores are given, and the interpretation for the Tertiary unit (left, bottom) (sources: Dutch Geological Survey, TNO-NITG).



Kortemark Member (Y1)

Egem Member (Y1)

CORE: RGD-80MK-125

Coordinates: 51°45'05"N, 2°29'58"E or 5733624.84N, 465445E

Date: 18.08.1980
Type: -

Waterdepth: 38.5m

DESCRIPTION	Temporary stratigraphy	S	M	Ca	Layer number
SAND. Green brown (HUE 2.5Y 5/4). Very to extremely coarse (300-2000 µm). Angular rounded and rounded. High amount of shell fragments. Low amount of gravel, silex, cristalline.	HOLOCENE	65%	440	3-4	1
SAND. Grey brown (HUE 2.5Y 5/2). Very to extremely coarse (300-2000 µm). Rounded angular and rounded. High amount of shell fragments. Low amount of gravel, silex, quartz, cristalline.	PLEISTOCENE (EEMIAN)	65%	400	3	2
SAND. Grey (HUE 10YR 6/1). Very to extremely coarse (300-2000 µm). Angular and angular rounded. Low amount of shell fragments. Low amount of gravel, silex, sandstone, quartzite.		65%	400	2	3
SAND. Grey (HUE 10YR 6/1). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. Low amount of shell fragments. Low amount of gravel, cristalline, granite, quartzite.		65%	290	2	4
SAND. Grey (HUE 10YR 6/1). Very to extremely coarse. High amount of shell fragments. Low amount of gravel content, silex, quartz, sandstone.		65%	400	2	5
SAND. Green grey (HUE 5Y 5/2). Medium fine and medium coarse (150-300 µm). Rounded angular and angular rounded. Very low amount of shell fragments. Low amount of gravel, silex.		65%	200	2	6
SAND. Grey (HUE 10YR 6/1). Very to extremely coarse. High amount of shell fragments. Low amount of gravel, silex, quartz, sandstone.		65%	400	2	7
SAND. Green (HUE 5Y 4/3). Extremely fine (63-105 µm). Angular. Silty and high amount of clay. Traces of shell fragments. *REMARK. At the bottom of the core: green clay, strongly enriched with sand. Strongly silty, loamy material. Stiff. Ca=0. Tertiary*		>70%	100	1-2	8

Total length: 10m

Merelbeke/Pittem Member (Y3)

CORE: RGD-80GD-138

Coordinates: 51° 25' 12", 02° 49' 38" or 5696663.7N, 487985.46E

Date: 28.08.1980
Type: Geodoff pouring drilling

Waterdepth: 22.6m

DESCRIPTION	Temporary stratigraphy	S	M	Ca	Layer number
SAND. Olive grey (HUE 2.5Y 4/4). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. Low amount of shell fragments and shells. Low amount of gravel. Relatively high amount of loam fragments (>8%), relatively plastic.	HOLOCENE	65%	290	3	1
LOAM. Olive grey (HUE 5Y 5/2). Crumbly, very stiff material. Micas. Relatively high amount of hard material. Traces of shell fragments. Low amount of gravel.	TERTIARY			3	2

Total length: 4.2m

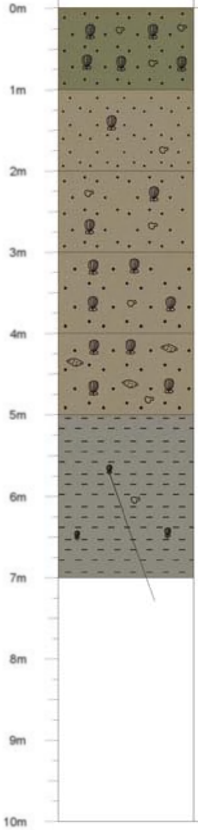
Vlierzele Member (Y4b)

CORE: RGD-80GD-142

Coordinates: 51°40'07"N, 02°40'07"E or 5724351.72N, 477062.09E

Date: 29.08.1980
Type: Geodoff pouring drilling

Waterdepth: 39m



DESCRIPTION	Temporary stratigraphy	S	M	Ca	Layer number
SAND. Olive brown (HUE 2.5Y 5/4). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments. Some gravel, fine and very coarse.	HOLOCENE	65%	310	4	1
SAND. Grey brown (HUE 2.5Y 5/2). Medium fine to medium coarse (150-300 µm). Rounded angular and angular rounded. Low amount of shell fragments. Low amount of gravel.	PLEISTOCENE (EEMIAN)	>70%	200	3	2
SAND. Grey brown (HUE 2.5Y 5/2). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. Low amount of weathered shell fragments.		65%	290	1	3
SAND. Grey brown (HUE 2.5Y 5/2). Very to extremely coarse (300-2000 µm). Rounded angular and angular rounded. High amount of weathered shell fragments. Low amount of gravel.		65%	400	2	4
SAND. Grey brown (HUE 2.5Y 5/2). Very to extremely coarse (300-2000 µm). Rounded angular and angular rounded. High amount of weathered shell fragments. Low amount of gravel. Some clay pieces, olive grey (HUE 5Y 4/2), stiff material.				0	5
CLAY. Olive grey (HUE 5Y 4/2). Medium to very heavy material. Very hard, stiff. Micas. Some weathered, very fine shell fragments. A few small gravel fragments.	TERTIARY (EOCENE)				6

Total length: 7m

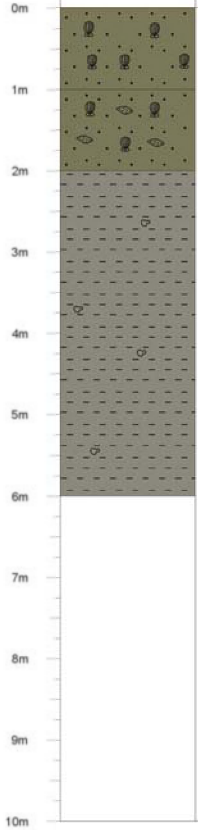
Oedelem Member (L1b)

CORE: RGD-80GD-139

Coordinates: 51°29'53"N, 02°59'32"E or 5705330.64N, 499460.07E

Date: 28.08.1980
Type: Geodoff MK II pouring drilling

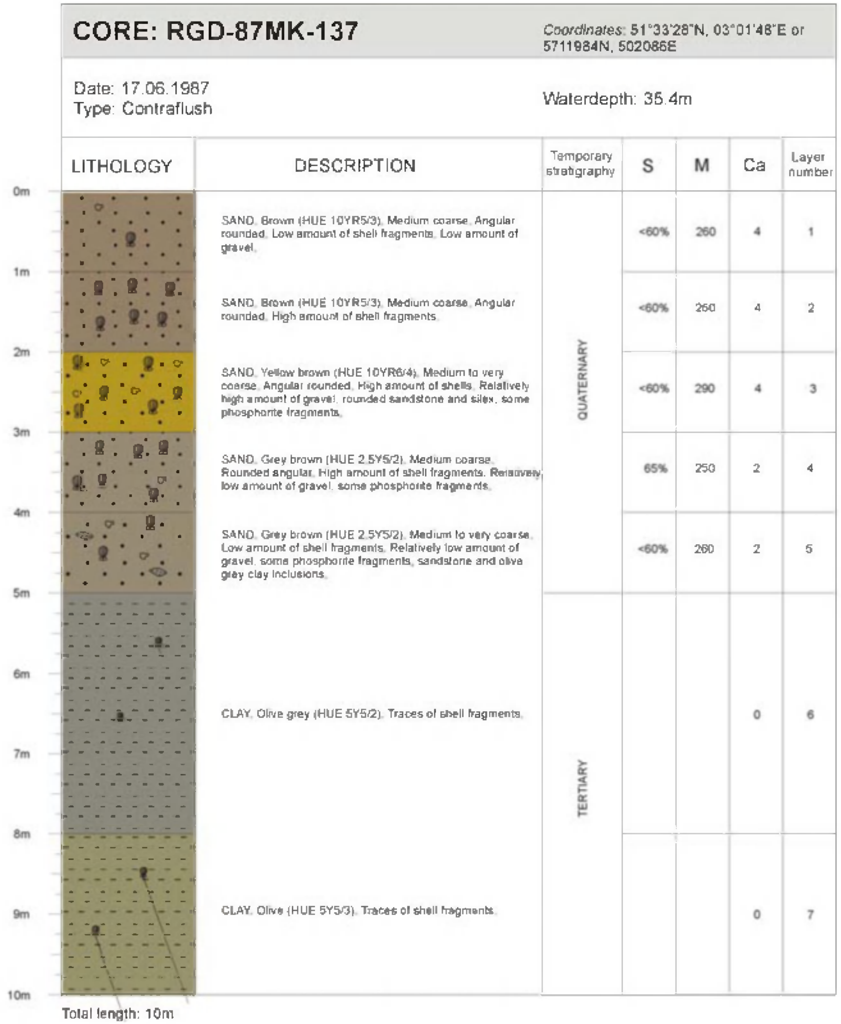
Waterdepth: 26.7m



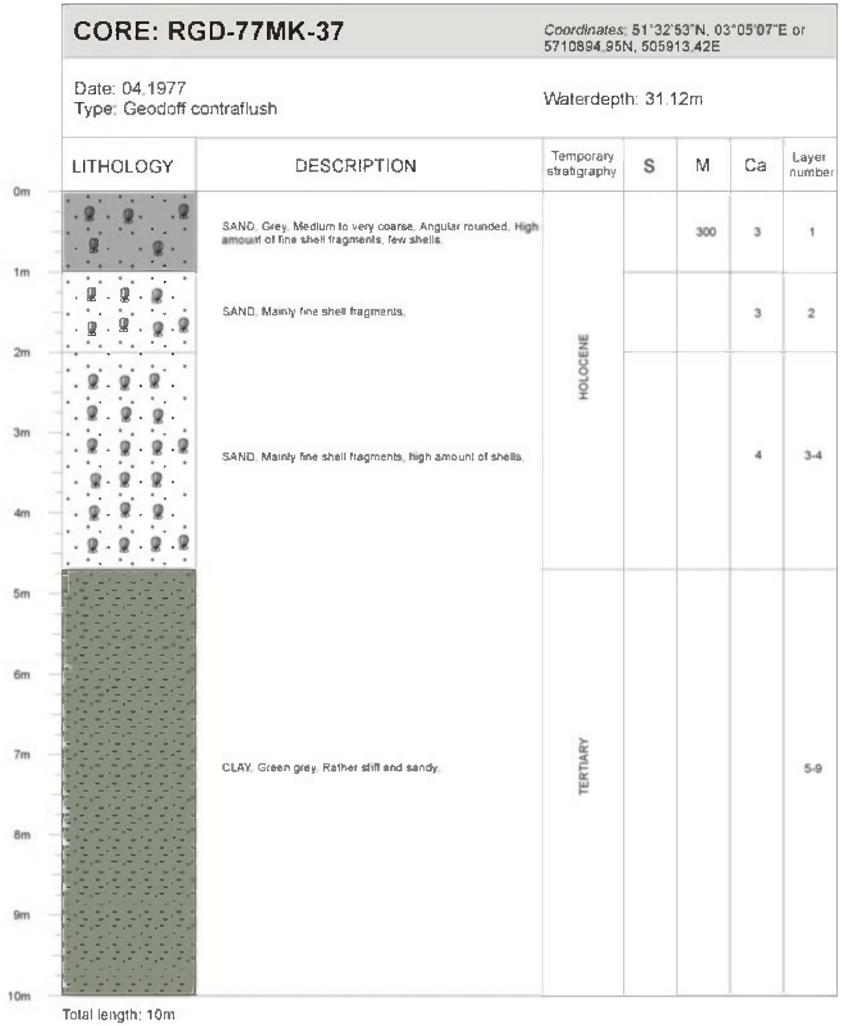
DESCRIPTION	Temporary stratigraphy	S	M	Ca	Layer number
SAND. Olive brown (HUE 2.5Y 4/4). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments.	HOLOCENE	65%	290	3	1
SAND. Olive brown (HUE 2.5Y 4/4). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments. Some clay inclusions. Light, plastic clay.		65%	290	3	2
CLAY. Olive grey (HUE 5Y 5/3). Very heavy, hard, stiff material. A few gravels, silex.	TERTIARY			0	3

Total length: 6m

Asse/Ursel/Onderdale/Zomergem Member (B1b)



Buisputten Member (B1c)



Zelzate Member (P1)

Annex 3

Synthesis of the existing information concerning the lithology of the Palaeogene units. Onland and coastal cores.

(sources:Belgian and Dutch Geological Surveys, BGD-RGD)

Tertiary formation	Cores	Depth (m)	Lithology	Sand content (%)	Mean grain-size (µm)	General + spatial trends (from SE toward NW)
P1	RGD-77/MK37	10	4.7 to 10 m: CLAY. Green grey. Rather stiff and sandy.			CLAY. Rather stiff and sandy. Green grey.
B1 / Asse to Zomergem	B65a	3.15	2.1 to 3.15 m: CLAY			CLAY. Evolving from stiff to very heavy. Amount of silt and sand in various amounts within the unit (no marked spatial trend).
	B65ab	3.6	2.65 to 3.6 m: CLAY. Granular.			
	GII192	3.4	2.05 to 3.4 m: CLAY. Low amount of silt			
	GII193	1.4	0.8 to 1.4 m: CLAY. Stiff. Low amount of silt. Traces of sand.			
	RGD-80/GD139	6	2 to 6 m: CLAY. Olive-grey (HUE5Y 5/3). Very heavy, hard, stiff material. A few gravels, flints.			
	RGD-79/H32	0.65	0.15 to 0.65 m: CLAY. Green-grey (HU5Y 5/2 or 6/2). Very stiff.			
	RGD-76/H36	0.7	0.2 to 0.7 m: CLAY. Blue-green. Very hard. Containing glauconite.			
	RGD-N1262/B1	61.8	16.7 to 40.5 m: CLAY. Contains silt. Very stiff to hard. Olive-grey (HUE5Y 4/2).			
	RGD-73/GD12	2.9	2.33 to 2.9 m: CLAY. Green-grey. Very stiff. Granular. Contains sand and small lenses of FeS.			
	RGD-80/MK124 ? (outside BCP)	6.3	1 to 4 m: CLAY. Olive-grey (HUE5Y 4/2). Very heavy stiff material. Low amount of shell fragments. Some sand inclusions. Micas. 4 to 6.3 m: CLAY. Olive-grey (HUE5Y 4/2). Very heavy stiff material. Some stiff material. Micas.			
	BKR-2/A-B32: 16 to 28 m = Eocene: Bartonian / Zomergem ?? 28 to 40 m = Eocene: Lutetian / Assian = Asse to Onderdale ?	40	16 to 17 m: CLAY. Grey-green. Contains fine sand and silt. 17 to 25 m: CLAY. Grey-green. 25 to 26.5 m: CLAY. Grey-green. Contains fine sand 26.5 to 28 m: CLAY. Grey-green. Contains fine sand. Contains micas. 28 to 32.5 m: CLAY. Grey-green. 32.5 to 35 m: CLAY. Grey-green. Contains fine sand 35 to 40 m: CLAY. Grey-green.			
L1 / Oedelem	RGD-69/T79	0.42	0.07 to 0.13 m: CLAY. Brown, viscous. Shells and shell fragments. 0.13 to 0.42 m: CLAY. Grey. Very stiff.			3 layers:

	RGD-N1262/B1	61.8	40.5 to 44 m: alternating layers ofCLAY (very sandy, silty) and SAND (very clayey, silty). 44 to 55 m: SAND. Fine, slightly silty. Olive-grey (HUE5Y 4/2). Some clay inclusions at the bottom. 55 to 61.8 m: CLAY. Silty, locally slightly sandy. Very stiff to hard. Olive-grey (HUE5Y 4/2). Remark: Base Bartoon suggested to be located at 40.5 m depth	> 70	80	(1) Base: CLAY. Very stiff to hard. Silty, locally slightly sandy. Olive-grey. (2) SAND (11 m thick). Fine, slightly silty. Some clay inclusions at the bottom. Olive-grey. (3) CLAY (3.5 m thick). Very hard to very stiff. Some fine shell fragments and fine gravels. In some places, alternating layers of sandy, silty clay and clayey, silty sand. Grey to olive-grey.
	RGD-80/GD142	7	5 to 7 m: CLAY. Olive grey (HUE5Y 4/2). Medium to very heavy material. Very hard, stiff material. Micas. Some weathered, very-fine shell fragments. A few small gravel fragments.			
Y5	G216	5.3	5.2 to 5.3 m: CLAY. Low amount of very-fine sand.			CLAY. Low amount of very-fine sand.
	G212	3.55	3.45 to 3.55 m: CLAY			
Y4c	G214 (Tertiary? dubious)	4.15	3 to 4.15 m: CLAY. Compacted. High amount of silt.			CLAY to LOAM. Compact. High amount of silt Low amount of very-fine sand and shells.
	G215	4.7	2.65 to 2.7 m: CLAY. Compacted.			
	G216	5.3	5.15 to 5.2 m: CLAY. High amount of fine sand and silt. Low amount of shells.			
Y4b	G221	2	1.9 to 2 m: CLAY. High amount of silt and fine sand. Low amount of shell fragments.			CLAY to LOAM. Brittle to compact. High amount of silt (and fine sand). Low amount to traces of shell fragments. In some places, low amount of gravel and micas.
	G223	2.7	2.5 to 2.7 m: CLAY. Compact.			
	RGD-80/GD138	4.2	1 to 4.2 m: LOAM. Olive-grey (HUE5Y 5/2). Brittle but very stiff. Micas. A lot of hard material. Traces of shell fragments. Low amount of gravel.			
Y4a	G218	1.3	1.1 to 1.3 m: CLAY. Compact with high amount of silt and medium coarse sand, low amount of shell fragments.			CLAY. Compact. High amount of silt and sand (evolving from medium coarse to fine towards NW) Low amount of shell fragments.
	G220	3.15	2.2 to 3.15 m: CLAY. Compact. High amount of silt and fine sand. Low amount of shell fragments.			
	G222a (Tertiary, Quaternary ?)	0.8	0.2 to 0.8 m: SILT. High amount of compact clay and medium fine sand. Low amount of shell fragments.			
Y3	RGD-70/H30 (Y3 or Y4c ?)	0.35	0.23 to 0.35 m: CLAY. Green grey. Very stiff. High amount of sand.			CLAY. Stiff. High amount of sand. Contains silt. Green to green grey.
	RGD-80/MK125	10	At the bottom of the core: green clay, strongly enriched in sand. Strongly silty, loamy material. Stiff			
Y2	RGD-80/MK132	7	4 to 5 m: LOAM. Olive grey (HUE5Y 4/2). Stiff material, very sandy. Low amount of shell fragments. Poor in gravel content (shell fragments). 5 to 7 m: LOAM. Olive colored (HUE5Y 4/3). Stiff material, strongly sandy. Micas. Possible traces of shell fragments.			LOAM. Stiff. Very sandy. Low amount of shell fragments. Olive grey.
	B158	4.75	3.75 to 4.75 m: CLAY. Granular texture.			
Y1	RGD-80/MK136	6	4 to 5 m: CLAY. Dark-brown (HUE10YR 3/3). Light soft clay. High amount of shell fragments. Low amount of gravel 5 to 6 m: CLAY. Dark brown (HUE10YR 3/3). Heavy clay. Micas. 1 shell fragment.			1st seven metres: CLAY. 2 distinct layers: (1) base: CLAY: composed of very heavy, stiff, hard clay
	ODB-B1	25	22.3 to 25 m: CLAY. Grey. Plastic. Some stones and sand.			

	RGD-80/MK131	8	1 to 3 m: CLAY. Olive grey (HUE5Y 4/2). Very stiff and hard clay. Micas, sandy inclusions. Very low amount of shell fragments. Poor in gravel content 3 to 8 m: CLAY. Grey brown (HUE2.5Y 4/2). Very heavy, stiff and hard clay. Micas			grey brown to dark brown (2) top: CLAY: thickness seems to increase from 1 to 3 m composed of light soft clay evolving into plastic and then stiff and very hard. dark brown to olive grey
	RGD-69/HT5	0.9	0.4 to 0.9 m: CLAY. Grey. Moderately viscous. At the top, some flints.			
	RGD-80/MK126	7.8	5 to 7.8 m: CLAY. Brown grey (HUE2.5Y 4/2). Very heavy, stiff material. Contains some pyrite pellets			

Annex 4

Synthesis of the existing information concerning the lithology of Quaternary deposits (a), Pleistocene (b) and Holocene (c) deposits.

(sources:Belgian and Dutch Geological Surveys, BGD-RGD)

Table a: Quaternary units (undistinguished Quaternary) of the Belgian continental shelf: synthesis of existing information concerning the lithology derived from offshore cores.

Core:	**Core depth (m):**	**Lithology:**	**Sand content (%):**	**d50 (µm)**
ODB-B1	25	0 to 1.5 m: SAND. Coarse with shells. Brown-white. 1.5 to 9.5 m: SAND, Fine. Grey 9.5 to 11.5 m: SAND. Fine with shells. Grey-white. 11.5 to 16.5 m: SAND. Coarse with shells. Brown-white. 16.5 to 18 m: GRAVEL. Fine with sand. Brown-white. 18 to 18.7 m: SAND. Coarse with gravel. Brown-white. 18.7 to 22.3 m: GRAVEL. Coarse with sand. Grey-white.		
ODB-B2	10	0 to 2 m: SAND. Coarse with shells. Brown-white. 2 to 10 m: SAND. Coarse with shells. Grey-white.		
B158	4.75	0 to 3.75 m: SAND. Medium coarse. Traces of shell fragments.		290
G220	3.15	0 to 1.3 m: SAND. Medium coarse. Low amount of shell fragments. 1.3 to 2.2 m: SHELLS. High to very high amount of medium coarse sand. Low amount of fine gravel.		255
G222a	0.8	0 to 0.1 m: SAND. Medium fine. High amount of silt. Low amount of shell fragments. 0.1 to 0.2 m: SHELLS. High amount of medium fine sand. Low amount of silt. 1 stone		
G221	2	0 to 0.9 m: SAND. Medium coarse. Low amount of shell fragments. 0.9 to 1.5 m: SAND. Medium coarse. High amount of shell fragments 1.5 to 1.8 m: SHELLS. Low amount of medium coarse sand.		
G223	2.7	0 to 2.3 m: SAND. Medium coarse. Low amount of silt and shell fragments. 2.3 to 2.5 m: SHELL FRAGMENTS. High amount of gravel. Low amount of clay and silt.		285
G214	4.15	0 to 0.55 m: SAND. Medium coarse. High to very high amount of shell fragments. Traces of fine gravel and silt. 0.55 to 2.8 m: SAND. Medium coarse. Traces of silt and shell fragments. 2.8 to 2.95 m: GRAVEL. High amount of shells and medium coarse sand.		255
G215	4.7	0 to 4.65 m: SAND. Medium coarse. Low amount of shell fragments. Traces of silt.		280
G216	5.3	0 to 5 m: SAND. Medium coarse. Low amount of shell fragments. Traces of silt. 5 to 5.15 m: GRAVEL. High amount of fine sand and shells. Low amount of silt.		260
G212	3.55	0 to 2.15 m: SAND. Medium coarse. Low amount of shell fragments. Traces of silt. 2.15 to 3.35 m: SAND. Medium coarse. Low to very low amount of shell fragments. Traces of silt. 3.35 to 3.45 m: GRAVEL (stones). Low amount of medium coarse sand and clay.		
B65a	3.15	0 to 0.2 m: SAND. Medium fine. Low amount of silt (stratified, layered). Low amount of shell fragments and gravel. 2 stones. 0.2 to 1.45 m: SAND. Medium fine. Low amount of silt and shell fragments. Stone at 1.3 m. 1.45 to 2 m: SAND. Medium fine. Low amount of shells and silt. 2 to 2.1 m: SAND. Medium coarse. High amount of shells. Low amount of gravel and silt.		180 (the whole layer)

B65ab	3.6	0 to 2.3 m: SAND. Medium fine. Low amount of silt and shell fragments. 2.3 to 2.5 m: SAND. Medium fine. High amount of shell fragments. 2.5 to 2.65 m: SHELLS. High amount of fine gravel and low amount of medium fine sand.		
GII192	3.4	0 to 0.35 m: SAND. Medium coarse. High amount of silt and shell fragments. Low amount of clay. 0.35 to 0.7 m: SAND. Medium coarse. High amount of shells and silt. 0.7 to 1.85 m: SAND. Medium coarse. Low to high amount of shells. Traces of silt. 1.85 to 2.05 m: SAND. Medium fine. High amount of clay. Low amount of shells and silt.		285 285 320
GII193	1.4	0 to 0.5 m: SAND. Medium coarse. High amount of shells and clay. Low amount of silt (layered). 0.5 to 0.8 m: SHELL FRAGMENTS AND SAND. Medium coarse. Low amount of clay and silt.		
G218	1.3	0 to 0.45 m: SAND. Medium coarse with shells. 0.45 to 1.1 m: SAND. Medium coarse with a low amount of shell fragments.		
RGD-78/H5	0.15	2 layers of SAND (0 to 0.1 m). 1 layer of CLAY (0.1 to 0.15 m)		180
RGD-78/H6	3.9	3 layers of SAND 1 layer of CLAY 4 layers of SAND 1 layer of CLAY 1 layer of SAND		200 125 to 210 125
RGD-78/H7	3.82	6 layers of SAND.		210, 300, 160, 150, 210, 180
RGD-78/H8	3.56	8 layers of SAND (0 to 1.98 m) 1 layer of CLAY (1.98 to 2.09 m) 3 layers of SAND (2.09 to 3.56 m)		105 to 210 130 to 210
RGD-78/H9	2.35	2 layers: CLAY (0 to 1.49 m) 2 layers: SAND (1.49 to 2.35 m)		 180
RGD-78/H10	1.29	SAND (4 distinct layers) 2 peat layers at the bottom of the core (12 and 21 cm thick)		130 to 420
RGD-78/H11	0.96	2 layers of SAND (0 to 0.34 m, 0.34 to 0.41 m). Very fine. Grey. Rounded angular. Very fine shell fragments. 1 layer of CLAY (0.41 to 0.5 m). Grey. Very stiff. Some lenses of grey medium fine sand. 3 layers of SAND (0.5 to 0.53 m, 0.53 to 0.62 m, 0.62 to 0.79 m). Light grey to grey. Medium to very coarse. Angular rounded to rounded. High amount of shell fragments. 2 layers of PEAT (0.79 to 0.91 m, 0.91 to 0.96 m). Contains some clay and some sand.		130 230 to 420
RGD-78/H12	1.0	3 layers of SAND		180, 180, 350
RGD-78/H13	1	4 layers of SAND (0 to 0.2 m, 0.2 to 0.7 m, 0.7 to 0.92 m, 0.92 to 1 m). Yellow grey at the base, becoming yellow brown upwards.		200, 180, 420, 180
RGD-78/H14	1.81	3 layers SAND (0 to 1.55 m + 1.62 to 1.81 m). CLAY (1.55 to 1.62 m).		180 to 190
RGD-78/H15	1.63	SAND. Yellow grey. Medium fine. Angular rounded. High amount of shell fragments. Contains silt arranged in bands.		
RGD-78/H16	3.2	2 layers of SAND (0 to 0.13 m, 0.13 to 3.2 m)		210, 180
RGD-78/H17	0.1	SAND. Yellow-brown. Medium coarse. Contains silt. Low amount of gravel and shells.		250
RGD-80/MK133	10	4 layers of SAND (0 to 1 m, 1 to 2 m, 2 to 6 m, 6 to 10 m)	> 65	155, 155, 100, 155
RGD-N1262/B1	61.8	0 to 16.7 m: SAND. Medium to fine. Loose to very dense with increasing depth. Dark greyish brown to grey downwards (HUE2.5Y 4/2 HUE2.5Y 5/0). Locally many shell fragments and layers. Some small clay/silt layers and clay inclusions.	65	155 (base) to 220

BKR-2/A-B32	40	0 to 1 m: CLAY. Black. Some shells, mussels. 1 to 1.5 m: CLAY. Black. Contains sand. 1.5 to 2 m: CLAY. Black. Some flint. 2 to 13.5 m: SAND. Fine. Dark grey. Some fine shell fragments. Few clay fragments. 13.5 to 16 m: SAND. Fine. Dark grey. Some fine shell fragments. Some clay fragments.		

Table b: Pleistocene units of the Belgian continental shelf: compilation of the new lithological information derived from offshore cores.

Pleistocene stratigraphy:	**Core:**	**Depth (m):**	**Lithology:**	**Sand content (%):**	**Mean grain-size (µm):**
Not specified	RGD-69 /T137 (outside BCP)	2.26	Pleistocene (2.16 to 2.26 m): GRAVEL. Mainly flints.		
Eemian (?)	RGD77/MK39 (outside BCP)	8.3	Pleistocene (6 to 8.3 m): 3 layers of SAND. Grey. Very coarse. Angular rounded and rounded. High amount of shell fragments.		350 to 375
Eemian	RGD-77/MK38	10	5 to 6 m: SAND. Grey. Medium coarse. Angular rounded. High amount of shells. One flint. 6 to 7 m: SAND. Grey. Very coarse. Angular rounded. Traces of shell fragments. 7 to 8.5 m: SAND. Grey. Medium coarse. Angular rounded. Traces of shell fragments. 8.5 to 9 m: SAND. Grey. Medium coarse. Angular rounded with some coarser grains. High amount of shell fragments. Some gravels, granite, crystalline, flints,… 9 to 10 m: SAND. Grey. Medium coarse. Angular rounded. High amount of shells. Some gravels, quartz, quartzite,…		350 255 255 255 255
Eemian	RGD-77/MK61 (outside BCP)	10	Pleistocene (9 to 12 m): SAND. Grey. Medium to very coarse. Angular rounded and rounded. High amount of shell fragments. Small clay pebbles and gravels.	60	350
Eemian (?)	RGD-80/GD140	8	1 to 8 m: 4 layers of SAND (1 to 2 m, 2 to 4, 4 to 7 m, 7 to 8 m). Angular Rounded and rounded angular. At the base and top: medium coarse to very coarse (210-420 µm) ; middle: medium fine to medium coarse (150-300 µm). Amount of shell fragments decreases from base to top.	65	310, 200, 220, 310
Eemian (?)	RGD-80/GD141	6	2 layers of SAND (4 to 5 m, 5 to 6 m). Olive brown (HUE2.5Y 5/4). Medium coarse to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shells, shell fragments. Few small gravel at the base.	65	310
Eemian	RGD-80/GD142	7	1 to 2 m: SAND. Grey brown (HUE2.5Y 5/2). Medium fine to medium coarse (150-300 µm). Rounded angular and angular rounded. Low amount of shell fragments, gravel. 2 to 3 m: SAND. Grey brown (HUE2.5Y 5/2). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. Low amount of weathered shell fragments. 3 to 4 m: SAND. Grey brown (HUE2.5Y 5/2). Very to extremely coarse (300-2000 µm). Rounded angular and angular rounded. High amount of weathered shell fragments. Low amount of gravel. 4 to 5 m: SAND. Grey brown (HUE2.5Y 5/2). Very to extremely coarse (300-2000 µm). Rounded angular and angular rounded. High amount of weathered shell fragments. Low amount of gravel. Some clay pieces, olive grey (HUE5Y 4/2), stiff material.	> 70 65 65	200 290 400
Eemian	RGD-80/MK125	10	1 to 2 m: SAND. Green brown (HUE2.5Y 5/4). Very to extremely coarse (300-2000 mm). Angular rounded and rounded. High amount of shell fragments. Low amount of gravel, flints, cristalline 2 to 4 m: SAND. Grey brown (HUE2.5Y 5/2). Very to extremely coarse (300-2000 mm). Rounded angular and rounded. High amount of shell fragments. Low amount of gravel, flints, quartz, cristalline 4 to 5 m: SAND. Grey (HUE10YR 6/1). Very to extremely coarse (300-2000 mm). Angular and angular	65 65	440 400

			rounded. Low amount of shell fragments. Low amount of gravel, flints, sandstone, quartzite. 5 to 6 m: SAND. Grey (HUE10YR 6/1). Medium to very coarse (210-420 mm). Rounded angular and angular rounded. Low amount of shell fragments. Low amount of gravel, cristalline, granite, quartzite. 6 to 7 m: SAND. Grey (HUE10YR 6/1). Very to extremely coarse.. High amount of shell fragments. Low amount of gravel, flints, sandstone, quartz. 7 to 8 m: SAND. Green grey (HUE5YR 5/2). Medium fine and medium coarse (150-300 mm). Rounded angular and angular rounded. Very low amount of shell fragments. Low amount of gravel, flints. 8 to 9 m: SAND. Grey (HUE10YR 6/1). Very to extremely coarse. High amount of shell fragments. Low amount of gravel content, flints, quartz, sandstones. 9 to 10 m: SAND. Green (HUE5Y 4/3). Extremely fine (63-105 µm). Angular. Silty and high amount of clay. Traces of shell fragments.	65 65 65 65 65 > 70	400 290 400 200 400 100
Eemian	RGD-80/MK126	7.8	2 to 5 m: SAND. Brown yellow (HUE10YR 6/6). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments, some shells. Some gravel, flint, quartzite, sandstone.	65	310
Eemian	RGD-80/MK127	8	4 to 6 m: SAND. Grey brown (HUE10YR 5/2). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments, a few shells. Poor in gravel content. 6 to 7 m: SAND. Grey brown (HUE10YR 5/2). Medium fine and medium coarse (150-300 µm). Rounded angular and angular rounded. A few shell fragments. Poor in gravel content. 1 clay inclusion. 7 to 8 m: SAND. Brown (HUE10YR 5/2). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments, a few shells. Poor in gravel content.	< 60 < 60 < 60	310 220 290
Eemian	RGD-80/MK132	7	3 to 4 m: SAND. Olive grey (HUE5Y 5/2). Medium fine and medium coarse. Angular and rounded angular. Low amount of shell fragments. Poor in gravel content.	> 70	200
Not specified	RGD-80/MK136	6	3 to 4 m: SAND. Grey (HUE5Y 5/1). Very fine to extremely fine (63-150 µm). Rounded angular and angular rounded. Very high amount of shell fragments, traces of shells. Low amount of gravels.	65	110
Eemian (?)	RGD-81/MK60	10	Pleistocene (2 to 10 m): 4 layers of SAND. Green-grey. Medium fine to very coarse. Rounded angular and angular rounded. Low amount of shell fragments.	65	220 to 310

Table c: Holocene deposits of the Belgian continental shelf: compilation of the new lithological information derived from offshore cores.

Core:	**Depth (m):**	**Lithology:**	**Sand content (%):**	**Mean grain-size (µm):**
RGD-69 /T137 (outside BCP)	2.26	0 to 0.03 m: CLAY 0.03 to 2.16 m: SAND, yellow-brown, medium fine to medium coarse. Shell fragments, contains silt		
RGD-73/GD12	2.9	0 to 1 m: SAND. Yellow-brown. Medium coarse. Low amount of shell fragments. 1 to 1.8 m: SAND. Yellow-brown. Medium coarse. Low amount of shell fragments and gravel.		

		1.8 to 2.33 m: SAND. Yellow-grey. Medium fine. High amount of shell fragments and shells. Low amount of gravel.		
RGD-73/GS12 (outside BCP)	5	5 layers of SAND (0 to 2.3 m, 2.3 to 3.5 m, 3.5 to 4 m, 4 to 5 m). Yellow-grey. Medium coarse. Increasing amount of shell fragments towards the top.		
RGD-76/H36	0.7	CLAY. Brown-yellow. Stratified with layers of sand. Low amount of shells and gravel.		
RGD77/MK39 (outside the BCP)	8.3	0 to 6 m: 5 layers of SAND. Yellow-brown to light grey. Very coarse. Angular rounded and rounded. High amount of shell fragments.		350 to 375
RGD-77/MK61 (outside BCP)	10	0 to 9 m: 9 layers of SAND (1 m thick each). Light grey to grey. At the top, very coarse sand becoming finer towards the base.	60 to 65	255 to 375
RGD-80/MK136	6	0 to 3 m: 3 layers of SAND (each 1 m thick). Yellow-brown (HUE10YR 5/4). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments. Amount of shells and gravel: low at the base and not existant towards the top.	< 65	310 (base) to 290
RGD-80/MK131	8	0 to 1 m: 1 layer of SAND. Grey brown (HUE2.5Y 5/2). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. Relatively high amount of shell fragments. Few shells. Poor in gravel content, some silex.	65	290
RGD-69/HT5	0.9	0 to 0.2 m: SAND. Brown-yellow. Medium fine to medium coarse. Fine, small gravel: mainly flints, also shell and shell fragments. 0.2 to 0.4 m: GRAVEL and STONES (especially flints). Mixed with medium coarse sand, shells and shell fragments.		
RGD-80/MK126	7.8	0 to 1 m: SAND. Brown yellow (HUE10YR 6/6). Medium to very coarse (210-410 mm). Rounded angular and angular rounded. High amount of shell fragments. Few shells. Low amount of gravel. 1 to 2 m: SAND. Brown yellow (HUE10YR 6/6). Medium to very coarse (210-410 mm). Rounded angular and angular rounded. High amount of shell fragments. Few shells. Some gravel, flints, quartzite, sandstones.	65 65	310 310
RGD-80/MK132	7	0 to 2 m: SAND. Olive grey (HUE5Y 5/2). Very to medium fine (105-210 µm). Angular and rounded angular. Low amount of shell fragments. A few possible undermined clayfragments. 2 to 3 m: CLAY. Olive grey (HUE5Y 4/2). Light, weak material, very silty and sandy Low amount of shell fragments. Poor in gravel content.	65	145
RGD-70/H 30	0.35	0 to 0.23 m: SAND. Yellow brown. Medium fine to medium coarse. Contains silt and shell fragments.		
RGD-80/MK125	10	0 to 2 m: SAND. Green brown (HUE2.5Y 5/4). Very to extremely coarse (300-2000 µm). Angular rounded and rounded. High amount of shell fragments. Low amount of gravel, flints, crystallines.	65	440
RGD-80/GD138	4.2	0 to 1 m: SAND. Olive grey (HUE2.5Y 4/4. Medium to very coarse (210-420 µm). Angular rounded and rounded angular. Some shell fragments, some shells. Low amount of gravel, a few medium coarse gravels (flints).	65	290
RGD-69/T79	0.42	0 to 0.07 m: GRAVEL and STONES. Especially flints, shell fragments and shells. Low amount of medium fine sand.		
RGD-80/GD142	7	0 to 1 m: SAND. Olive brown (HUE2.5y 5/4). Medium to very coarse (210-420 µm). Rounded angular to angular rounded. High amount of shell fragments. Some gravel, fine and very coarse.	65	310
RGD-80/GD139	6	0 to 1 m: SAND. Olive brown (HUE2.5Y 4/4). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. High amount of shell fragments.	65	290
RGD-79/H32	0.65	SAND. Yellow-brown (HUE10YR 6/4). Medium fine to medium coarse (150–300 µm). Rounded angular and angular rounded. High amount of shell fragments. Low amount of shells and gravel.	65	200
RGD-80/GD140	8	0 to 1 m: SAND. Yellow-brown (HUE10YR 5/4). Medium to very coarse (210 – 420 µm). Rounded angular and angular rounded. Low amount of shell fragments and shells.	65	310
RGD-80/GD141	6	3 layers of SAND (0 to 2 m, 2 to 3 m, 3 to 4 m). Olive brown (HUE2.5Y 5/4). Medium coarse to very coarse (150-420 µm). Rounded angular and angular rounded. Increasing amount of shell fragments towards the top.	65	290 to 310
RGD-80/MK124	6.3	0 to 1 m: SAND. Grey-brown (HUE5Y 5/2). Medium to very coarse (210-420 µm). Rounded angular and angular rounded. Some silty and loamy material. High amount of shell fragments. High amount of gravel (flints, quartzites, quartz, crystalline)	65	310
RGD-80/MK130	10	5 layers of SAND (0 to 1 m, 1 to 6 m, 6 to 7 m, 7 to 9 m, 9 to 10 m)	< 65	220 to 310
RGD-81/MK60	10	0 to 2 m: 2 layers of SAND. Brown. Medium to very coarse. Rounded angular and angular rounded. High amount of	65	290

		shell fragments. Few shells.		
RGD-81/MK72	10	0 to 7 m: SAND. Brown (HUE10YR 5/3). Medium coarse to very coarse (210 – 420 µm). Rounded angular and angular rounded. High amount of shell fragments. Traces of glauconite. 7 to 10 m: SAND. Grey (HUE5Y 5/1). Medium to very coarse (210 – 420 µm). Rounded angular and angular rounded. High amount of shell fragments and shells. Low amount of gravel.	65 < 60	310 310
RGD-81/MK73	10	0 to 1 m: SAND. Brown (HUE10YR 5/3). Medium to very coarse (210 – 420 µm). Rounded angular and angular rounded. Low amount of shell fragments. Traces of micas, glauconite. 1 to 7 m: SAND. Green-grey (HUE5Y 5/2). Medium coarse to very coarse (210 –420 µm). Rounded angular and angular. Low amount of shell fragments. 7 to 8 m: SAND. Green-grey (HUE5Y 5/2). Medium coarse to very coarse (210 –420 µm). Rounded angular and angular. Low amount of shell fragments. Some gravels: flints, quartz. 8 to 12 m: SAND. Green-grey (HUE5Y 5/2). Medium coarse to very coarse (210 –420 µm). Rounded angular and angular. Low amount of shell fragments. Some gravels: flints, quartz. Traces of wood fragments.	65 65 65	310 290 310
RGD-82/MK180	10	6 layers of SAND (0 to 2 m, 2 to 3 m, 3 to 5 m, 5 to 6 m, 6 to 7 m, 7 to 10 m)	> 65	290 to 310
RGD-77/MK37	10	0 to 1 m: SAND. Grey. Medium to very coarse. Angular rounded. High amount of fine shell fragments. Few shells. 1 to 2 m: SAND. Mainly fine shell fragments. 2 to 4.7 m: SAND. Mainly fine shell fragments, high amount of shells.	-	300