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A LITHOFACIES CLASSIFICATION AS A TOOL IN THE RECONSTRUCTION OF THE PLEISTOCENE DEPOSITIONAL ENVIRONMENTS IN THE WESTERN COASTAL PLAIN (BELGIUM)

Frieda BOGEMANS & Cecile BAETEMAN

SERVICE GEOLOGIQUE DE BELGIQUE
BELGISCHE GEOLOGISCHE DIENST

Geological Survey
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Rue Jenner 13 - 1000 Bruxelles
Jennerstraat 13 - 1000 Brussel

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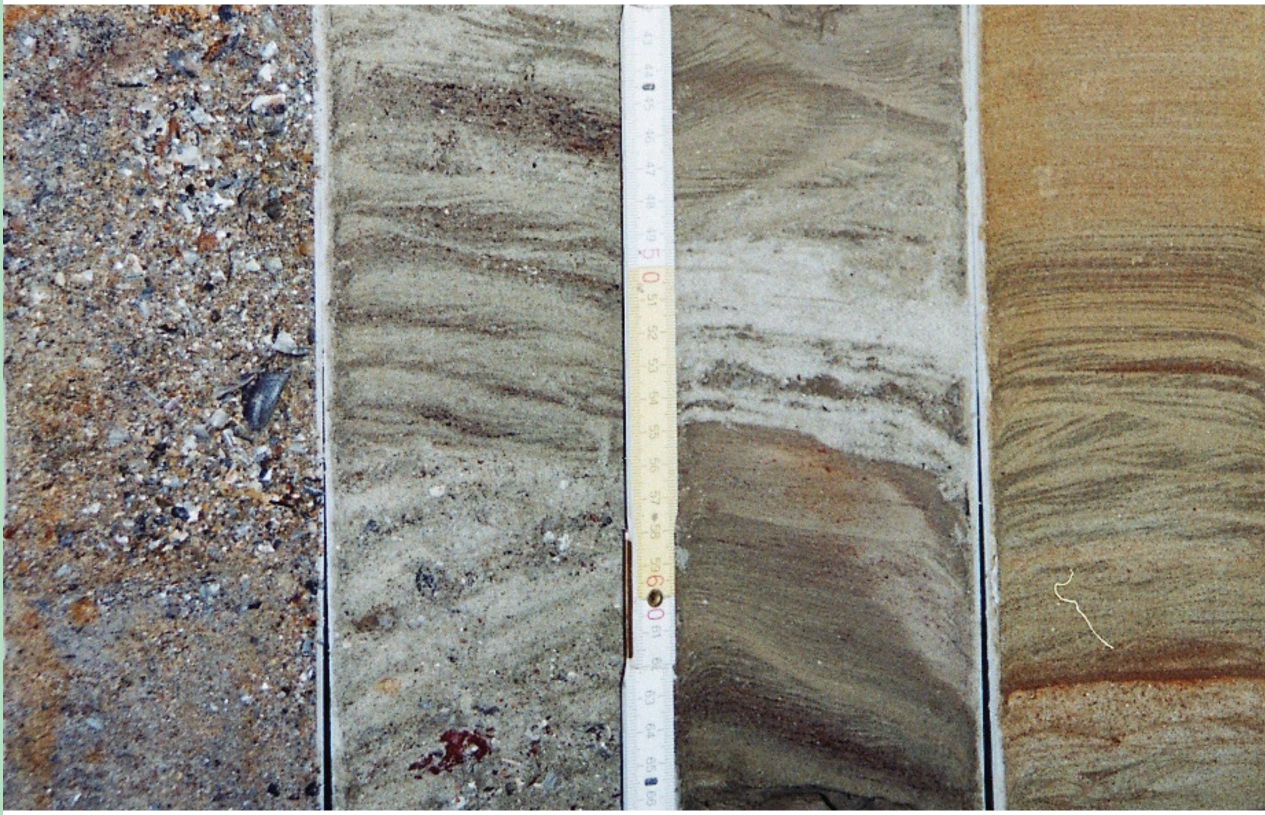

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A lithofacies classification as a tool in the reconstruction of the Pleistocene depositional environments in the Western Coastal Plain (Belgium)

Frieda BOGEMANS & Cecile BAETEMAN

Royal Belgian Institute of Natural Sciences
Operational Direction Earth & History of Life
Jennerstraat 13 – B-1000 Brussels
frieda.bogemans@naturalsciences.be; cecile.baeteman@naturalsciences.be

Synthesis of a Geological Survey project
'Updating the Quaternary database of the Geological Survey of Belgium'

34 pages, 8 figures, 8 tables, 23 photoplates

Cover illustration: Core Nieuwpoort 2 (36W145): basal part of the Pleistocene sequence showing the rapid vertical changes in lithology and sedimentary characteristics. The photograph covers the sediments at a depth between 25 – 26m (left part on the photograph); 23 - 24m; 22 - 23m and 20 - 21m below surface.

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A LITHOFACIES CLASSIFICATION AS A TOOL IN THE RECONSTRUCTION OF THE PLEISTOCENE DEPOSITIONAL ENVIRONMENTS IN THE WESTERN COASTAL PLAIN (BELGIUM)

Frieda BOGEMANS & Cecile BAETEMAN

Abstract. This paper is the outcome of the project “Updating the Quaternary database of the Belgian Geological Survey”(November 2010 – March 2013). The objective of the project was to provide a useful and relatively quick method for borehole description and for the reconstruction of the depositional environment, applicable on the whole of the Quaternary deposits. The western coastal plain of Belgium has been selected as pilot area because of the existence of about 100 high-quality undisturbed mechanically-drilled cores recovering the whole Quaternary sediment succession until the Tertiary substratum. The investigation focuses on the Pleistocene deposits that hitherto have not been studied in detail; this in contrast to the Holocene deposits. Moreover, their existence is even hardly known. This study is made as a model study.

The first part of the paper illustrates step by step the procedure followed in order to reconstruct the depositional palaeo-environments. Much attention is paid to the definition of lithofacies as they are the basic tool in the reconstructural procedure. Because these lithofacies are so fundamental in particular for further use, most of them are illustrated with photographs. In a next step the lithofacies are combined into facies associations and sedimentary subenvironments are defined. The goal of the study, viz. the reconstruction of the environment, is obtained by combining the facies associations. These environments are then part of a larger entity namely the depositional system.

In the second part of the paper the application of the classification on the Pleistocene deposits in the Western Coastal Plain of Belgium is described and discussed.

Keywords: sequence architecture, shore-shelf, tidal flats, estuary, fluvial, Pleistocene, Belgium

1. Introduction

1.1. The need of geological knowledge

Environmental management and a well-balanced land-use planning must be considered with respect to the geological setting and the properties of the deposits in order to avoid environmental, technical and financial problems. The purpose of a land-use planning is to reduce to a minimum the negative impact on the natural environment at the occasion of the selection of sites or areas for e.g. extraction of raw material, agricultural activities, creation of dumping sites. This explains the increased use of subsurface data. Engineers are interested in the properties of the deposits for practical purposes such as subsurface constructions, large infrastructural works, development of building sites, and compaction of unconsolidated deposits. More recently, archaeologists need to interpret their findings within a context of palaeo-environmental change since the Convention of Malta requires a geo-archaeological survey before construction works. Such a survey is frequently carried out by archaeologists, geographers and engineers from consulting agencies who are not familiar with the (detailed) Quaternary setting of a particular area. Therefore, they have to rely on the existing database of borehole descriptions available in DOV (website https://dov.vlaanderen.be/dovweb/html/index.html) (see comments below).

However, borehole descriptions of Quaternary deposits are only useful when the data is organized into a clear and unambiguous stratigraphy. Quaternary deposits in particular show rapid vertical changes in lithology that, moreover, have restricted spatial distribution. The heterogeneity is the result of the responses of the natural systems to the complex relationship between the successive climate changes (with short-term episodicity), base-level changes, sedimentation and erosion processes, and not at the least, human activity for the more recent period.

The organization of the Quaternary deposits can only be performed with the understanding of the depositional history of an area. Therefore, knowledge of successive depositional palaeo-environments within a timeframe is required. The primary and basic elements to reconstruct the palaeo-environment are lithofacies based on texture, sedimentary structures and bedding characteristics, reflecting depositional processes on a regional scale. Once defined, the lithofacies are combined into lithofacies associations, also called assemblages, also named architectural elements by Miall (1985, 1996). Their correlation determines the depositional environment, basic element in the above-described application.

The present study aims to contribute to a better organization of the Pleistocene deposits in the western coastal plain of Belgium by applying this methodology which facilitates the reconstruction of the depositional palaeo-environments. Numerous high-quality undisturbed mechanically-drilled cores are available in the western coastal plain which recover the whole Quaternary sediment succession until the Tertiary substratum. The Holocene deposits of these cores have been investigated in detail for the purpose of mapping and palaeogeographical reconstructions (e.g. Baeteman, 1999, 2004; Baeteman & Declercq, 2002). The investigation of the Pleistocene deposits was restricted to a plane lithological description without further stratigraphical and/or environmental interpretation. The distinction between the Holocene and Pleistocene parts is based on distinct differences in colour, lithology, carbonate content and degree of consolidation. Furthermore in some cores the boundary is apparent by the presence of the (Holocene) basal peat with associated humic horizon and sometimes a podzol.

1.2. Geography of the study area

The study area covers the western coastal plain and its immediate surroundings (Fig. 1). It extends from the border with France to Oostende in the north, and from Reninge to Merkem and up to Diksmuide in the south. The coastal area is drained by the IJzer, a river with his source in France, and its tributaries the Kemmelbeek and Sint Jansbeek, which have their source on Belgian territory (Fig. 2). The SW-NE running coastline is remarkably straight. The coastal plain is separated from the sea by a dune belt that, in several places, is strongly reduced or destroyed by housing projects. Because of embankments, the coastal plain is nowadays a low-lying flat artificial landscape or polder with sluices, ditches and canals at an elevation ranging between +1 and +5m TAW[1], which actually is below high water level as TAW refers to the mean lowest water spring. The plain is protected from inundations by the remaining dunes and seawalls at some locations. The present-day landscape is the result of a continuous infilling process directed by the sea-level rise during the Holocene (Baeteman, 1999). Hence, the present-day landscape masks the presence of Pleistocene coastal and fluvial deposits in its subsoil.

The topography of the surrounding area with outcropping Pleistocene deposits is undulating and forms several "plateaus". The so-called plateau of Izenberge borders the coastal plain in the southwest with an elevation between +7.5 and +17.5m TAW (Fig. 3).

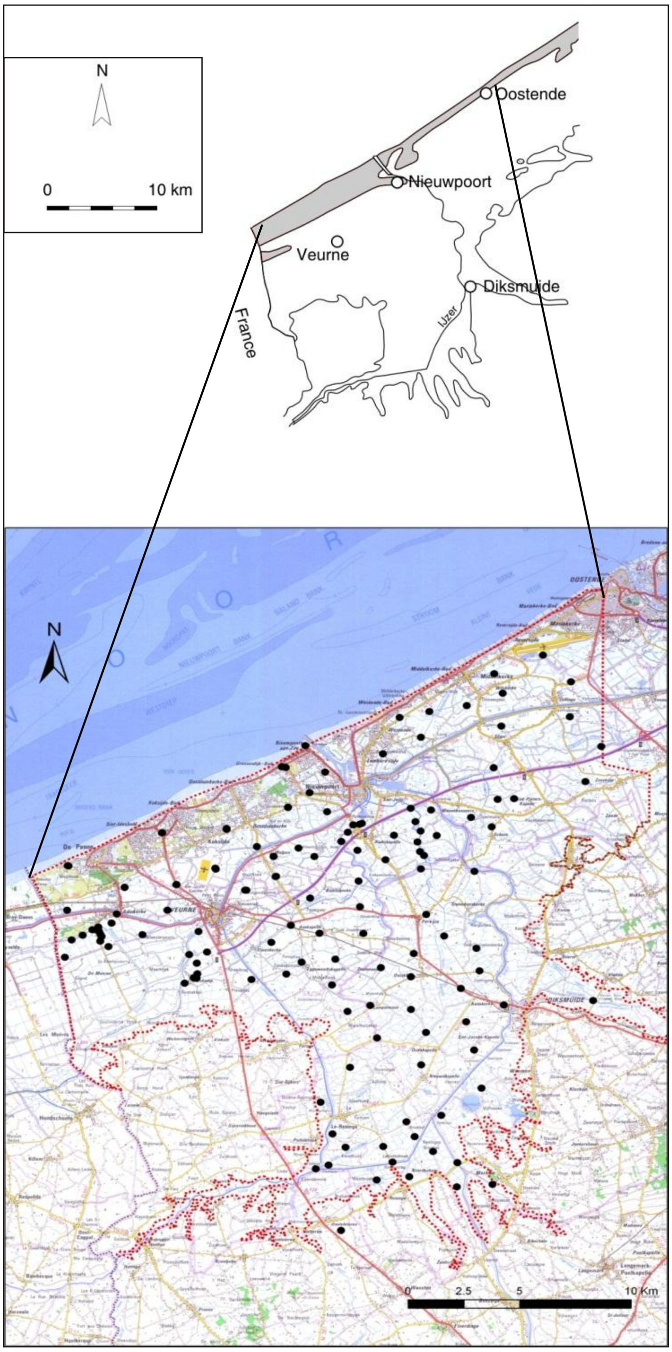

Figure 1. Location of the study area with indication of the mechanically-drilled cores.

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[1] TAW: The Belgian ordnance datum refers to mean lowest water spring, i.e. about 2 m below mean sea level.

Figure 2. The river IJzer and its main tributaries.

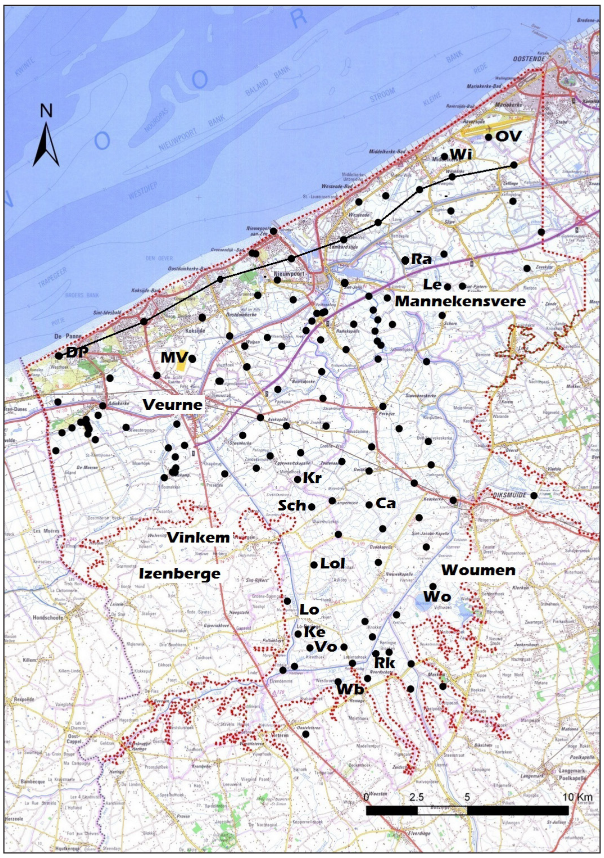

Figure 3. Map with the location of the drillings and places referred to in the text. MV: Militair Vliegveld (35E151), Wi: Wilskerke (21E222), Rv: Rattevalle (36W168), DP: De Panne (35W164), Lol: Lollege (51W138), Vo: 't Vosje (66W122), Ke: Kellen (66W135), Le: Leeuwenhof (36E132), Rk: Rattekot (66W139), We: Westbroek (66W140), Kr: Kruisabele (51W136), Sch: Schaap (51W137), Ca: Cayenne (51W148), Wo: Woumen (51E162), OV: Oostende Vliegveld (21E221). The position of cross-section (Fig. 8) is indicated.

1.3. Historical background of the interpretation of borings in the archives of the Geological Survey of Belgium

At the very beginning of the Geological Survey of Belgium, geologists like Rutot, Mourlon, (end of the 19th and beginning of the 20th century) provided beside a chronostratigraphic interpretation of the Quaternary deposits also a genetic one on the level of depositional systems. However, they incorporated these specifications on the geological map only as points; the Quaternary deposits were not integrated in the graphic representation that a geological map is.

Later on, borehole descriptions consisted only of colour and grain-size description. At few occasions, the Quaternary was subdivided into Pleistocene and Holocene. It is evident that this kind of interpretation is useless for any kind of application.

When in 1993 the Flemish Government decided to produce Quaternary geological maps of Flanders (on a scale of 1/50 000) the borehole descriptions were reconsidered. However, it must be mentioned that the work had to be carried out on the basis of the existing data. The latter actually were largely the archives of the Geological Survey. Together with the production of the maps, all data used were integrated into a database. With the exception of a few maps, the work was carried out by the Universities of Brussel, Gent and Leuven. These geological maps were not traditional geological maps but profile type maps on which not only the lateral extension of the deposits were visualised but also the entire vertical sequence of the Quaternary deposits in analogy with the profile type map of the Holocene deposits. The lithological properties of the deposits formed the basic mapping element. However, each institute was free to define the mapping units, which resulted in non-conformity between the different institutes. Even within the same institute identical deposits were differently interpreted when another geologist made the map. A positive aspect, however, was that the Quaternary deposits were subdivided into lithological units. The difficulty of non-conformity was overcome by translating all mapping units used in the past into a unique DOV code (Bogemans, 2005). Simultaneously an overview profile type map of the Quaternary deposits on a scale of 1/200 000 was made (Bogemans, 2005).

Apart from the non-conformity, a more fundamental problem arose because the Quaternary geological mapping was carried out within a strict and limited timeframe. For the mappers it was an impossible task to (re)define and (re) interpret all data, especially in areas with a complex setting. Such problems are for example encountered in areas where Holocene and Pleistocene fluvial and tidal deposits are present in the subsoil. This is the case in the present study area. The knowledge about the erosional/depositional mechanisms and the interaction between the different environments is not sufficiently understood, a knowledge that nevertheless can be useful in the near future to predict, among other things, the effects of climate changes on the modifications of the natural environment.

2. Lithofacies classification

2.1. Introduction

It is a known fact that facies analysis is one of the most important elements in the sedimentological study of sedimentary deposits. But because every place and each environment is unique it is necessary to introduce a classification based on a series of common basic properties so that the comparison and integration of data on a regional scale is possible. In the fluvial sedimentology a general classification of lithofacies, for the greatest part based on the work of Miall, is already commonly used (for an overview see Miall, 1985, 1996). Using the basic criteria of the classification of Miall an attempt is made to introduce a classification for sediments present in areas where marine-continental environments intersect.

Grain size is the basic criterion in defining the lithofacies. In the framework of this study four groups are introduced:

- Mud (unconsolidated sediment with grain size smaller than sand; sand particles form an insignificant part – Collinson & Thompson, 1984.)
- Sand (63µm – 2mm)
- Gravel (mainly consisting of shell remains of > 2mm)
- An alternation of 2 or more grain sizes.

To cover all environments extra lithofacies are introduced like peat-dominated ones and those made up of a heterogenic grain-size distribution. To reduce the number of lithofacies per core, small entities like small sedimentation cycles are merged.

Within these groups a subdivision is made on bases of primary sedimentary structures, or the lack of it, the presence or absence of bioturbations, deformation structures, and the existence of calcium carbonate or organic matter (remains of fauna and/or flora).

As a lithofacies reflects the general characteristics of the deposits, one has to go back to the original description when making a detailed palaeo-environmental study (Tables 1-5, Photoplates 1-23).

In order to reduce the number of lithofacies some of the introduced codes are already lithofacies assemblages (set of lithofacies) according to the definition of Miall (1985, 1996). Examples are the ‘F’ facies and S3 facies. Within the S3 facies different types of stratifications are integrated. As undisturbed cores provide us only 2D information (the 5cm perpendicular to the core width is not enough to give information about the 3rd dimension), the identification of certain types of stratification was not possible (for example the differentiation between planar and trough cross stratification). In the description and interpretation that was made for each undisturbed core the identification of the sedimentary structures is therefore restricted to large scale cross stratification (S3c), small scale cross lamination (S3sc), horizontal lamination/stratification (S3h) and herringbone cross stratification (S3he) (Collinson et al., 2006). The problem concerning S3he relates to the fact that the core intervals of 1m were taken without orientation so that the identification of the presence of a bidirectional flow remained an isolated observation per interval, making the linkage over the whole core impossible. Besides, the non-orientation of the cores obstruct the reconstruction of palaeo-flows.

Table 1. Facies classification of the mud-dominated deposits.

Code	Description
M1 (photo 1)	Massive mud consisting of clay, possible enriched with silt. Vegetation fragments are observed, some of them in situ. Patches of sand sized sediments are possible.
M2 (photo 1)	Mud with intercalations of coarser sediments. These intercalations are present as discontinuous and continuous laminae, deposited along horizontal and oblique surfaces. The so called lenticular bedding is included. Deformation structures, calcium carbonate precipitation as well as bioturbations may occur.
M3 (photo 2)	Mud deposits rich in vegetation remains, whatever their degree in decomposition. One or several humic horizons may be present. Minor intercalations of coarser sediments may be present as well as scattered bioturbations.
M4 (photo 3)	Mud deposits, with variable clay and silt content, composed of stratified and/or unstratified zones. Concentration of calcium carbonate may be important.
M5 (photo 4)	Silt and clay deposits respectively intercalated with clay and silt laminae/layers. Organic matter, whether or not deposited as laminae, may be present as well as bioturbations, deformation structures and some shell remains. Minor fine sand intercalations are observed.
M6a (photo 5)	Mainly massive or vague stratified silt. Secondary components are shells as well as plant remains. Deformation structures may be present.
M6b (photo 6)	Silt deposits characterized by small ripple bedding (ripple cross-stratification, climbing ripples) and/or horizontal to low angle stratification. Part of the lithofacies may have no stratification. The presence of reactivation surfaces is common. Some section of the facies may contain organic matter and/or laminae or small beds of clay and sand. Deformation structures and bioturbations may be observed.
M6c (photo 7)	Silt with intercalations of clay and/or sand. Stratification within the silt deposits is restricted. Deformation structures may be present as well as reactivation surfaces. Secondary components are shells, calcium precipitations as well as plant remains.

Table 2. Facies classification of composite sets.

Code	Description
M-S1 (photo 8)	Alternated complex of contrasting lithologies (ranging from sand to clay) of which the interlayered bedding is not regularly spaced. All components or parts of the alternating complex are internally stratified. Bioturbations and deformations may occur. The existence of shell grit is not uncommon, deposited as laminae or scattered in the facies.
M-S2 (photo 9)	Alternated complex of different lithologies, which have irregular thicknesses and irregular intervals. Shell debris may be present, just as bioturbations, calcium carbonate concentrations and deformations.
M-S3 (photo 10)	Rhythmic even bedded/laminated mud and sand deposits, bioturbations and deformations may occur.
M-S4 (photo 11)	Inclined heterolithic deposits. Thick beds are often internally stratified. Mud deposits may be composed of clasts and lenses.
M-S5 (photo 12)	Complex of silt and fine sand, less common clay. Small ripple bedding (sensu Singh, 1972), low angle cross stratification, horizontal stratification and even massive bedding are characteristic. Successive beds may have similar composition. One grain size class is often prevailing, although within one facies a shift of the dominant grain size class may occur. Very often the stratification is accentuated by the deposition of finer grained particles and/or peat detritus. Reactivation surfaces are common.

Table 3. Facies classification of sand deposits.

Code	Description
S1 (photo 13)	Fine to medium sand complex composed of massive, less stratified zones. Within the stratified parts the horizontal to low angle stratification is prevailing and is sometimes accentuated by very fine shell grit. Reactivations surfaces may be present. Shell remains are common. Deformation structures are ordinary; signs of bioturbations are observed (fauna & flora).
S1a	Analogue characteristics as S1 except that beside the scattered shell remains also concentrations of the shell remains are accumulated in well-developed layers (rather thick layers - >10cm) wherein the presence of siliciclastic gravel is not exceptional, less common are mud clasts.
S2 (photo 13)	Stratified and partly massive fine to medium sand, the medium fraction is less frequently observed. Mud laminae, most often discontinuous and scattered, and/or mud clasts are present. Exceptional, laminae with peat detritus are seen. Mollusc remains may be present in low concentration spread within the facies or accumulated in laminae or small beds. In some parts bioturbations are visible. Reactivation surfaces and/or erosional bedding planes may occur.
S2a	Analogue characteristics as S2 except that beside the scattered shell remains also concentrations of the shell remains are accumulated in well-developed layers (rather thick layers $\geq$ 10cm). If only one layer is present, its presence is not indicated.
S3 (photo 14)	Stratified fine to medium sand although small massive layered parts are not exceptional. The stratification includes cross- stratification, horizontal bedding, small ripple bedding, flasers and to a minor extent wavy bedded intercalations. Peat detritus, shell grit or fine siliciclastic sediments may be accumulated along the foresets or on top of the ripple surface. Deformation structures as well as bioturbations are observed. Shell debris, although not in large quantities, occur also in a random position. Clay pebbles and clay layers are observed occasionally.
S3a (photo 15)	Succession of small depositional units consisting of different types of stratification sometimes in combination with a differentiation in the grain size distribution. Boundary between the units may be erosional and/or depositional.
S4 (photo 16)	This lithofacies is typified by rather vague sedimentary structures also in the mud intercalations, if present. Fine shell debris and/or very small gravel are sometimes observed in a scattered position. Most often de vertical extension of this facies is limited.
S4a	Most sedimentary structures are missing because of intense bioturbations or physical deformations.
S5 (photo 17)	Fine to medium fine sand, mostly stratified at the base - although it may be vague - and evolving upwards into a massive structured facies mainly because of soil forming processes. Patches, mostly vague bounded, of finer and coarser grains may be present as well as flint splinters and parts. The upper section may contain rootlet casts belonging to the Holocene vegetation.

Table 4. Facies classification of gravel deposits.

Code	Description
SH1 (photo 18)	Matrix supported skeletal remain deposits (predominant mollusc remains) consisting of fragments and grit, gravel sized siliciclastic sediments may be included as well as (sedimentary) mud clasts. Sporadically mud is present in the form of thin layers. If stratification is visible, low angle and avalanche front cross-stratification predominate.
SH2 (photo 18)	Facies composed of matrix supported shell remains (fragments and grit) with zones of predominant siliciclastic sediments (sand). Gravel sized siliciclastic sediments may be deposited as well as mud clasts. If stratification is visible, low angle and avalanche front cross-stratification predominate in the shelly deposits.

Tabel 5. Facies classification of small-scale cyclic deposits, organic and heterogeneous deposits.

Code	Description
F1 (photo 19)	One or several small cycles of sedimentation with an upwards decrease in grain size. A cycle consists of a lag deposit (may contain clay balls or lumps, gravel, shell fragments) superimposed by a sand deposit. Different type of stratification may be present.
F2 (photo 20)	One or several small cycles of sedimentation with an upwards decrease in grain size. A cycle may consist of a succession of sand and mud or is dominant sandy with a variation in the grain size distribution. Coarse particles may form a lag. Bounding surfaces are present between the layers. Different type of stratification may be present.
F3	Graded bedding is a special entity. The bedding may grade normally or reverse.
H1 (photo 21)	Heterogenic deposit, may be composed of sand, gravel sized material but also mud. Shell remains may occur as well as deformation structures. Erosive bedding planes are common.
H2 (photo 22)	Succession of layers, stratified and massive, of various compositions (gravel to mud). May include plant and shell remains. Erosive bedding planes are common.
P (photo 23)	Mainly organic matter of vegetable origin, unrelated to the degree of decomposition, with a varying content of siliciclastic sediments.

3. Sequence architecture based on facies analysis and interpretation

3.1. Definition of a subenvironment

As the study area is located in the contact zone between the continent and the sea, relative sea-level changes in the past had a direct impact on the depositional history and consequently on the sequence stratigraphy of the area. Remnants of a complex interaction of different sedimentary environments are present in the shallow subsoil.

In order to characterize the different sedimentary palaeo-environments in the area one needs to identify first of all the preserved palaeo-subenvironments since a specific series of subenvironments stands for one particular environment.

An association of two or more lithofacies forms a particular subenvironment. The identification of a subenvironment is considerably hampered when the sequence is incomplete due to the fact that most commonly one particular lithofacies is not automatically linked to one specific subenvironment as shown in Table 6.

3.2. Definition of the environments

As already mentioned above, once the lithofacies and their associations are defined, the next step in the sedimentological study is the reconstruction of the environment. In Table 7 the defined environments and their relation to the subenvironments is indicated. The term "undifferentiated environment" is used when either specific sedimentary characteristics are lacking or when a depositional unit is the result of a continuous evolution passing through several subenvironments (e.g. a bank emerges above the water level and evolves into a vegetated bank over limited vertical extension. Sedimentary entities composed of mutual lithofacies, like the one in the outer part of a tide-dominated estuary and on the shoreface, are provisionally incorporated into one environment because sufficient and adequate data are generally lacking to make a further differentiation.

3.3. Depositional systems

Every depositional environment is part of the larger entity called depositional system. Depositional systems are the suitable entities to work within the framework of the reconstruction of the sedimentary history of an area. As the study area is located at the coast, both continental and paralic environments developed due to sea-level fluctuations during the Quaternary. The deposition systems identified in the study area are summarized in Table 8.

Table 6. The principle facies associations forming subenvironments present in the study area.

Subenvironment	Lithofacies
Shore-shelf complex, including swales and tidal sand bars/ ridges/banks[2], inlets, marine dominated part of an estuary	SH1,SH2, S1, S2, S3, S4, F1, H1, H2, (F3)
Mud flats	M1, M2, M4, M6 (a & c)
Mixed flats	M-S1, M-S2, M-S3, SH (thin layers)
Sand flats	S2, S3, SH (thin layers)
Salt marsh	M3, M4, M6 (a & b), (P, SH thin layer)
Tidal channel, mixed part of an estuary s.s., lags	S2, S3, S4, M-S1, M-S2, M2, M6b, M6c, H1, H2, F1, F2
Tidal point bars, benches	M-S4, S3, H1, (M-S1)
Undifferentiated tidal environment	All lithofacies present within a tidal environment + S6
Fluvial channel fill, crevasses, fluvial dominated part of an estuary, lags	S3, S4, M6, H1, H2, (F3)
Fluvial lateral accretions	M-S1,M-S2, S3, H1, (F3)
Fluvial bars	F1, F2, S3, M6, H1
Fluvial levees	M-S1, M-S2, S3
Floodplain & abandoned channel	M1, M2, M3, M4, M5, M6, (F3)
Undifferentiated fluvial environment	All lithofacies present within a fluvial environment + S5
Aeolian dunes	S3, P
Wet coversand	S3, S4, S5
Dry coversand	S4, S5
Marsh/swamp	P, M3

Table 7. The link between the subenvironments and the environments.

Subenvironment	Environment
Shore-shelf complex (comprising swales/gullies, tidal sand bars/ridges/banks, inlets and marine dominated part of an estuary)	Shore – shelf system[3]
Salt marsh (supratidal zone)	Tidal
Mud flats Mixed flats (intertidal zone) Sand flats	Tidal
Tidal channels (includes mixed part of estuary s.s.) Lateral and downstream accretion bars (subtidal zone) Lags Creeks	Tidal
Undifferentiated tidal flat subenvironment	Undifferentiated tidal environment
Levees Floodplain & abandoned channel	Fluvial overbank
Channel fill (fluvial dominated part of estuary) Lateral accretion forms Crevasse channel and crevasse splay Bars Lags	Fluvial in channel
Undefined fluvial, sheetflow	Undifferentiated fluvial environment
Aeolian sheet like deposits	Coversands
Swamp, marshes and bogs	Coastal or freshwater peatland

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[1] Tidal sand ridge: tide –dominated shallow marine setting and delta front region of tide-dominated deltas. Tidal sand banks (term used a.o. by Trentesaux et al., 1999): bank in the sea that may exposed by low tide. Tidal sand bar: morphological similar feature as tidal sand ridge but present in estuaries (Dalrymple, 1992)

Table 8. The relationship between environment, depositional system and subenvironment.

Supra-environment	Depositional system	Environment
Paralic system	Shallow marine Coastal plain Estuary/delta	Shore – shelf system including tidal sand bars/ridges/banks and marine dominated and mixed part of an estuary Tidal environment Undifferentiated tidal environment
	Coastal peat bog	Coastal peatland
Continental system	Fluvial system (including fluvial dominated part of an estuary)	In channel environment (containing channel fill, point bar, bar and bench) Overbank environment (including levee, crevasse splay and floodplain, abundant channel) Undifferentiated fluvial environment
	Aeolian system	Dunes Coversands
	Freshwater marsh	Peatland

4. The Pleistocene deposits of the Western Coastal Plain

4.1. Introduction

The introduction of a hierarchic classification also gives insight into the geological evolution of an area thanks to the reconstruction of the sedimentary environments and their vertical succession.

Until now no detailed lithological research was done on the Pleistocene evolution of the western coastal area. Mathys (2009) briefly mentioned the existing theories in her PhD research that concerned the evolution of the eastern part of the Belgian continental shelf. Liu A'Cheng (1990) tried earlier to explain the existing Tertiary morphology in the Belgian and northern French sectors of the continental shelf. According to this author a valley, the so-called Western Valley or IJzer Valley, is located at the French – Belgian border and is incised into the clayey sediments of the Ieper Group. Onshore, the valley has an east-west orientation until Dunkerque where it confluences with the Coastal valley. On the continental shelf it branches off to the northwest. The term "Coastal Valley" was introduced in 1989 by Mostaert *et al.* for a depression that runs parallel with and underneath the present–day coastal plain. Initially the Valley was subdivided into respectively the Western and Eastern Coastal Valley. A marginal platform (Western Marginal Platform), also original defined by Mostaert *et al.* (1989) borders the northern side of the Valley. The abrasion of this platform took place during one or several Middle-Pleistocene transgressions, whereas the Western Valley came into being during a final phase of the Saalian (Liu A'Cheng, 1990). The Saalian age (MIS6) for the Western Valley was confirmed by Mathys (2009).

However, results of palaeo-ecological research do exist for the area of Lo and the surrounding of Vinkem–Izenberge, as well as for the Mannekensvere and Woumen area (Fig. 3). Results of the latter two are discussed later. The first mentioned area is characterized by the presence of the so-called "Cardium layers" described by Tavernier & de Heinzelin (1962). The authors highlighted the presence of shell-rich layers in the area of Vinkem–Lo. However, the elevation of the shell-rich layers ranges between +1.45 and +12.2 m according to their observations. The taphonomic research of the molluscs showed a dominance of *Cardium edule*, now known as *Cerastoderma edule* on all levels followed by the species *Macoma baltica, Hydrobia stagnalis, Theodoxus fluviatilis.* All specimen of *Cerastoderma* are small sized. According to Tavernier & de Heinzelin (1962) the shell rich layers, independent their altitude, are situated in the Middle - Pleistocene. Vanhoorne (2003) observed in the vicinity of Lo within the shell-rich layers a well distinct succession: brackish – marine species at the top, with a dominance of *Cerastoderma glaucum*, freshwater molluscs and ostracoda at the base. All fossil freshwater molluscs still exist in Western Europe except *Pisidium obtusale* ssp. *Lapponicum* that is nowadays restricted to the Polar Regions. All identified foraminifera belong to a marine environment with freshwater input. In some places, as in Lo, peat is observed beneath the shell-rich layers, sometimes preceded by a clay layer. Vanhoorne, who started his palynological investigations in 1952, focussed his research initially on the chronostratigraphic position of the peat (Vanhoorne, 1962). He proposed a Holsteinian age although he did not exclude a Cromerian age. While in his 2003 publication he focussed on the environmental aspect, he also shifted the chronology of the peat to the Cromerian IV and placed the deposition of the superimposed shell layer in the Holsteinian.

4.2. Contour line map of the top of the Tertiary substratum

In the framework of the reconstruction of the Pleistocene evolution of an area, it is essential to construct the contour line map of the top of the Tertiary substratum in the first place. Such a map shows the base of the Quaternary deposits, modulated by processes during the Tertiary and Quaternary.

In the study area, the contour map (Fig. 4) is based on the undisturbed cores that are used to introduce the above-described classification and data of the archives of the Geological Survey of Belgium reaching the top of the Formation of Kortrijk (Eocene).

The Tertiary morphology shows:

1. A SW – NE oriented trench, situated in the most seaward part.
2. An approximately N – S running depression.
3. An area of which the Tertiary substratum rises in southern direction.

Typical for the SW – NE oriented trench is the existence of SW–NE oriented heights separated by rather small depressions. Besides, the morphology of the Tertiary substratum changes in some parts abruptly as a scarp in the vicinity of Koksijde illustrates (Fig. 5). The landward boundary of this entity runs from Adinkerke over the northern part of Veurne and Ramskapelle and further to Mannekensvere and Wilskerke (Middelkerke).

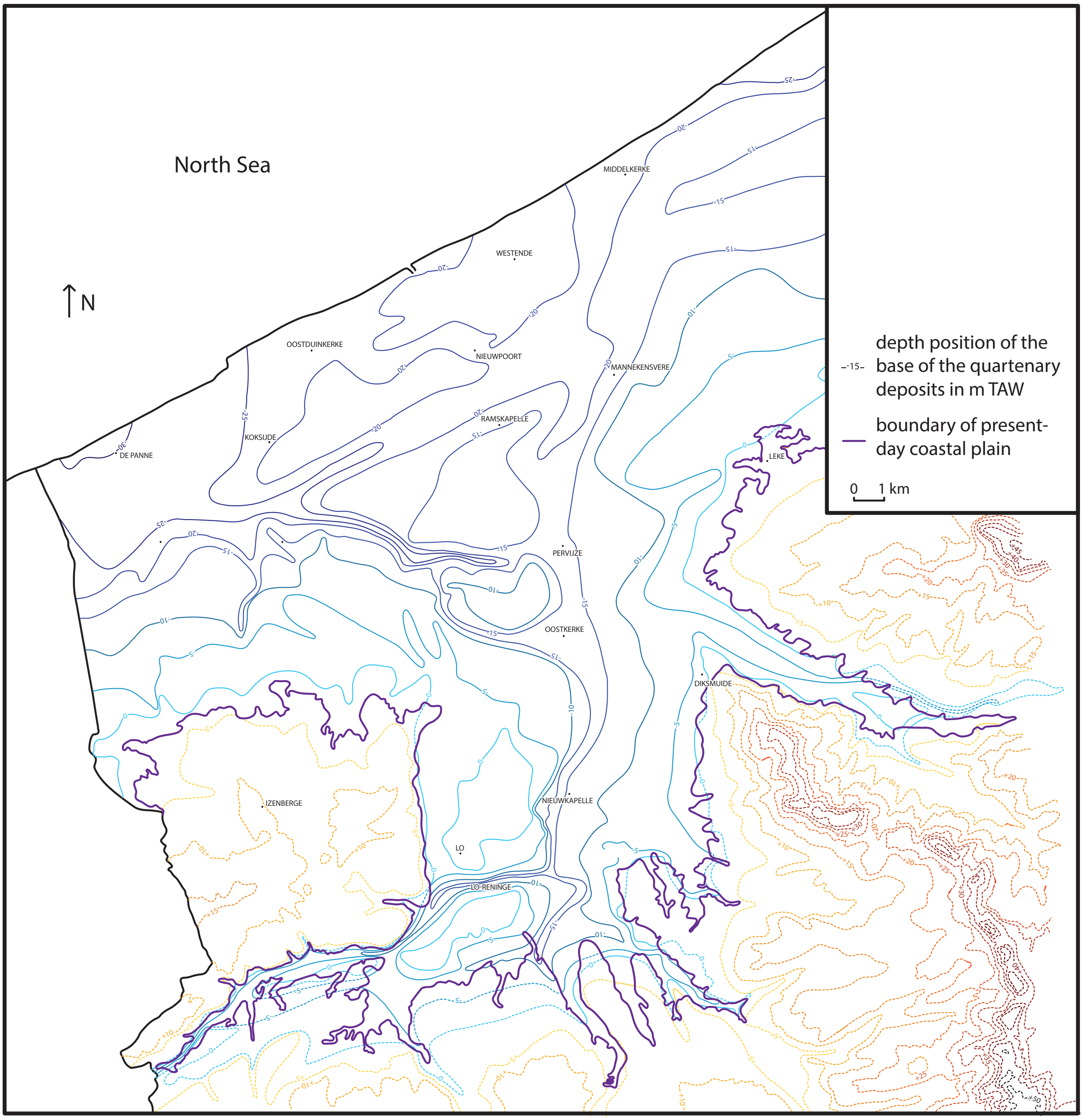

Figure 4. Depth position of the base of the Quaternary deposits.

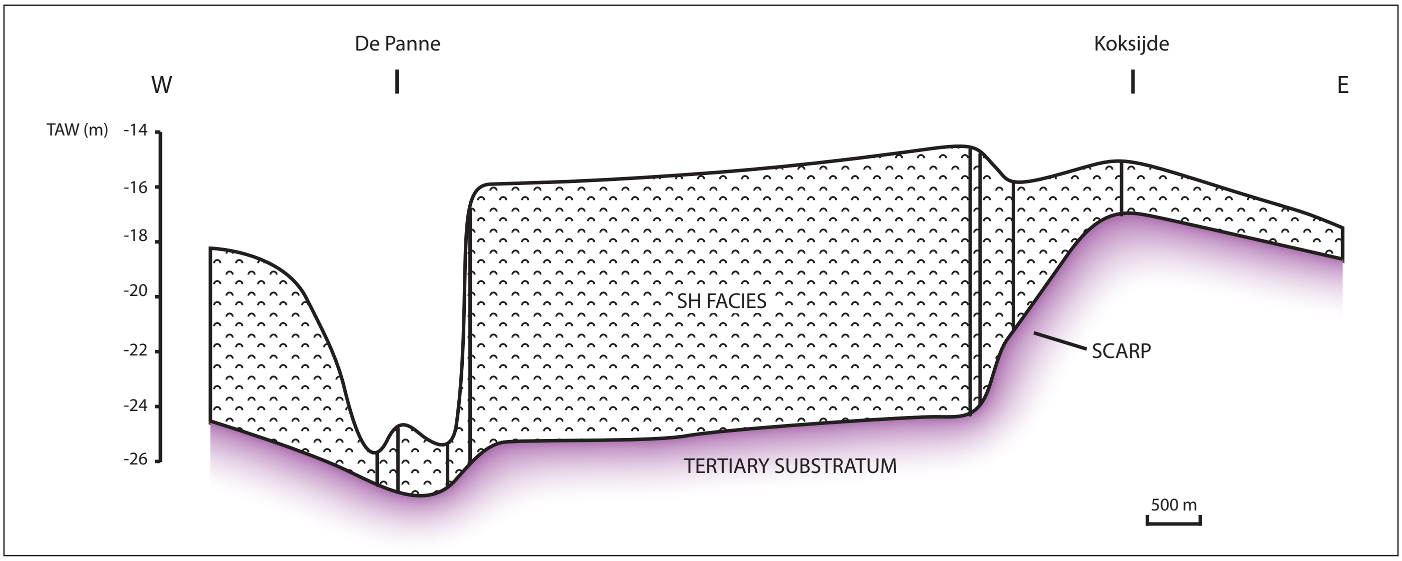

Figure 5. Cross-section showing the scarp present in the Tertiary substratum and the presence of a deep depression in the vicinity of De Panne.

The N – S running depression extents from Mannekensvere via Pervijze to Oostkerke. At Oostkerke it bifurcates. Apart from the southern continuation a new depression follows more or less the present-day Handzame valley (east of Diksmuide). The southern directed branch is once more splitting off at Lo–Reninge, one branch follows essentially the IJzer valley, the others coincide approximately with the valleys of the St. Jansbeek and Kemmelbeek (for location see Fig.2). Although data are limited in the north, more specific between Westende and Middelkerke we expect a continuation of the above-described N-S running depression over there. West of Pervijze and Oostkerke the depression extends to the west and connects with the SW – NE trench.

The so-called Coastal Valley, which according to Mostaert et al. (1989) and Liu A'Cheng (1990) was present all along the Belgian coastal area, was rejected by Matthys (2009) who observed an elevation in the Tertiary substratum between Nieuwpoort and Oostende with an offshore continuation. The onshore part of the contour map of Mathys (2009, p 53) is based on a grit that was drawn in the framework of the development of a Flemish groundwater model by Meyus et al. (2005 *ibid.* Mathys, 2009). The offshore part is based on all existing seismic data. Mathys (2009) suggested that the Flemish Valley, a vast approximately NW – E running depression of Middle – Pleistocene age, and the IJzer Valley are two separated drainage basins. However, the author continued to use the Coastal Valley but the IJzer Valley was no longer part of it (Mathys, 2009, Fig 5.3 on p 55).

4.3. The shore – shelf system and outer part of an estuary

4.3.1. Description and interpretation

a) The SH facies (SH1 & SH2)

These facies are predominantly present in the western onshore fringe of the coastal plain (Fig. 6). The top as well as the base rises in an eastward direction. The SH facies are thickest west of the 5 to 8m high scarp formed in the Tertiary substratum (see 4.2). There, a vertical extension of more than 8m is reached (Fig. 5). On the platform (elevated part east of the scarp) the thickness of the facies diminishes to the east, from ± 4m to ± 2m. Beside a rather widespread general distribution, these facies are extending into 2 local branches; both south of Koksijde (Militair Vliegveld). Peculiar is the fact that at the entry of the branches, more particular along the border, the facies attains a thickness of more than 5m; in the rest of the branches a thickness of only a couple of meters is reached. The SH facies are shoreface deposits. The high flow strength, necessary for the transportation of such a large concentration of shell fragments, was most probably caused by a restricted passage at the height of the Strait of Dover. In the eastern part of the study area SH facies are concentrated near Wilskerke and Rattevalle (Fig. 3). Because of their local presence and their stratigraphic position these SH facies are interpreted as isolated coarse-grained banks within an outer part of an estuary.

b) The S1/S2 facies

The S1/2 facies generally cover the SH facies except in the existing northern branch. The SH/S boundary is wavy, with differences in altitude of a few meters over short distances. The S1/2 facies show a greater extent in comparison with the distribution of the SH facies, both to the south and east. As a consequence the S1/2 facies are present in the subsoil all along the sea border of the present-day coastal plain, except in those places where the pre-existing deposits were eroded by tidal channels in the late Holocene. With the exception of the northern margin of the deep depression described in 4.2, the S1/2 facies are not further observed in the depression. There younger facies are resting either directly on the Tertiary substratum or on the so-called H facies. The H facies, composed of erosional products, is maximum a couple of meters thick.

Figure 7 shows the distribution of the S1 facies. In order to show the existing depth variation of the lower bounding surfaces of the facies, isolines corresponding to the lower bounding surface are added to the distribution map of the SH facies (Fig. 6). Remarkable aspects on this contour line map are 1) a rise of the base (in m TAW) from De Panne in the west to Westende in the east and 2) the existence of an important depression. The depression starts in the vicinity of De Panne, and runs southeast. The down cutting was so important in De Panne that only about 1m of the SH facies is left over (Fig. 5).

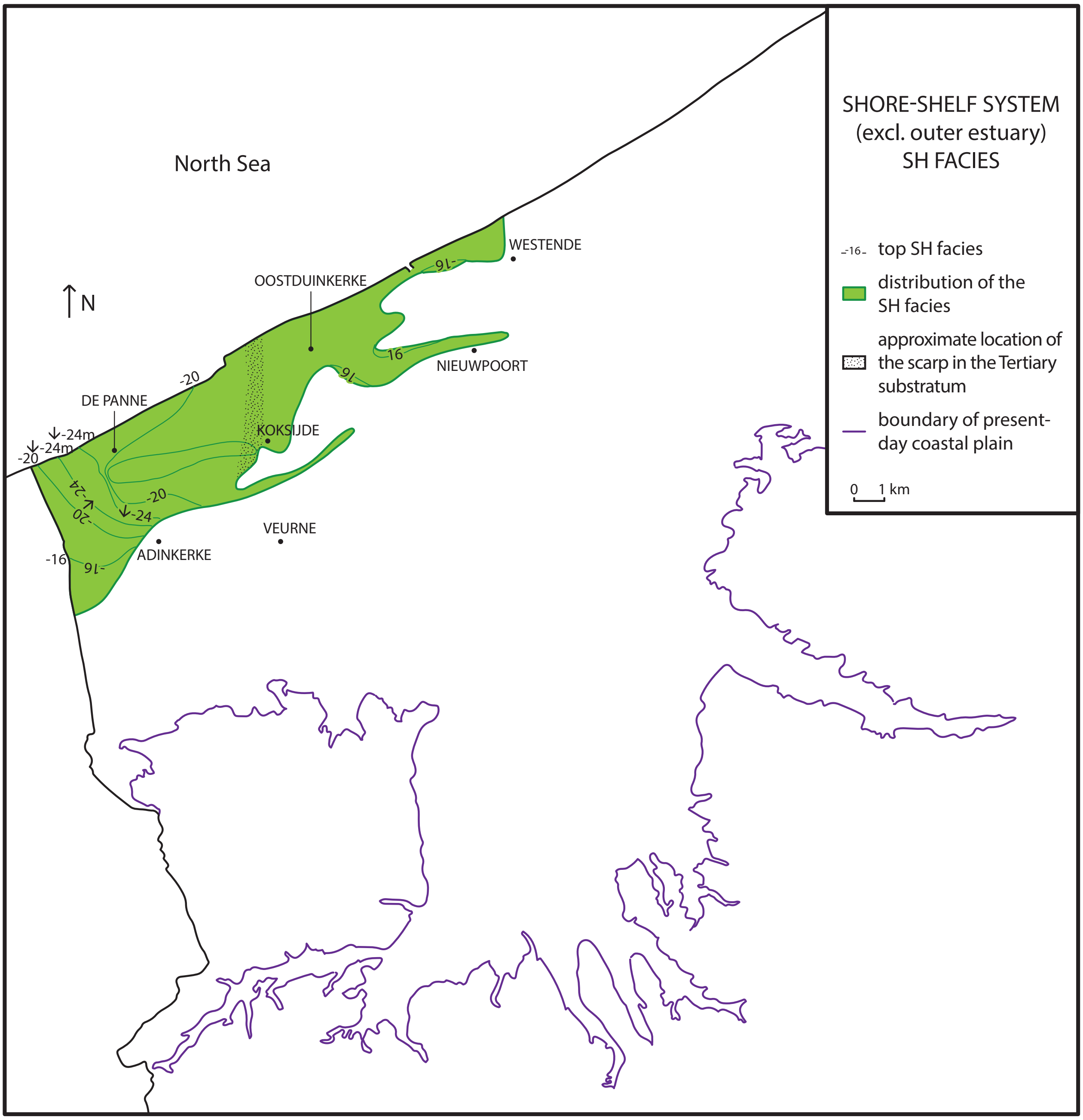

Figure 6. Distribution of the SH facies and depth position of the base of the S1/2 facies.

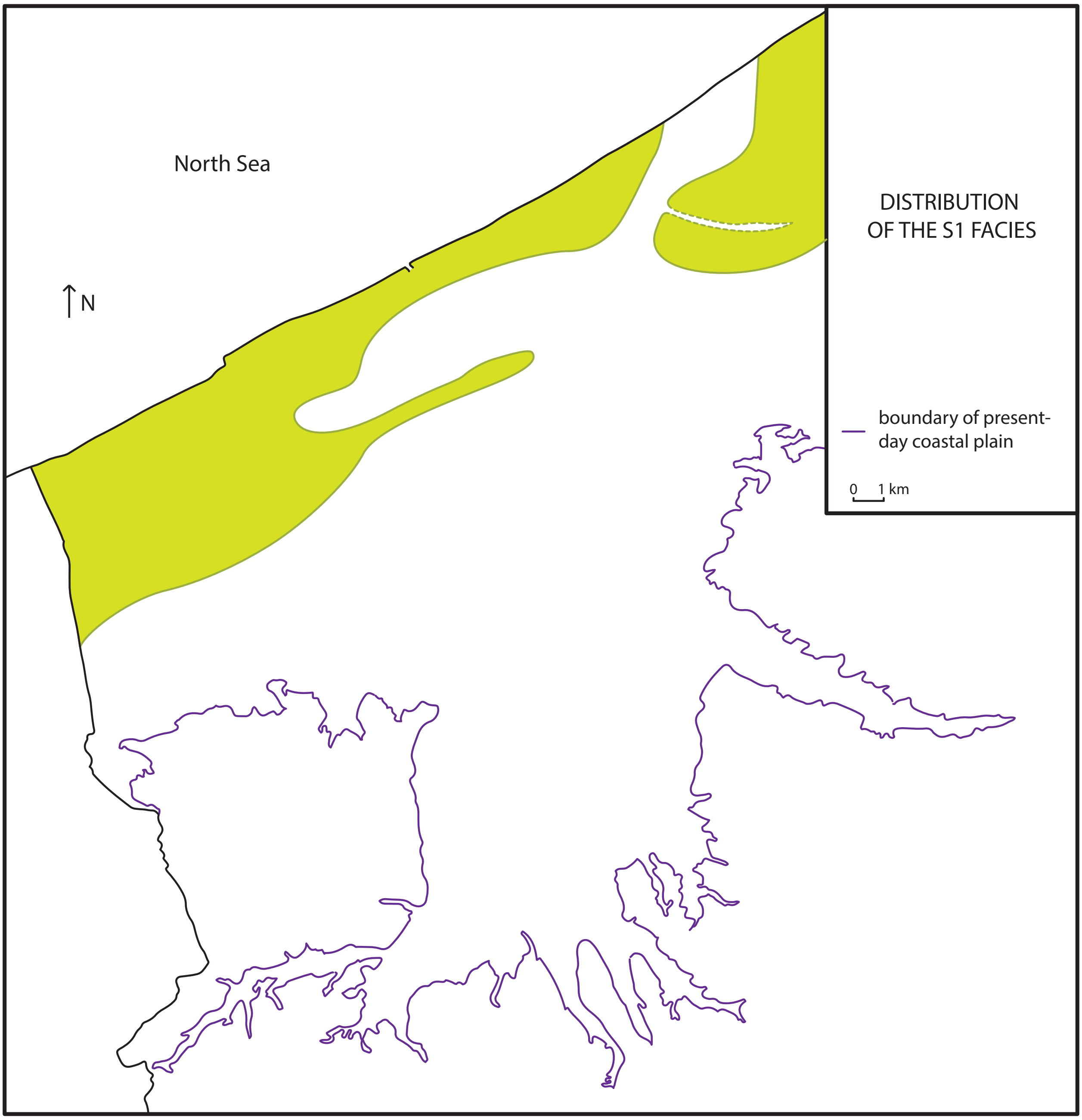

Figure 7. Distribution of the S1 facies.

The S1 facies is restricted in the west with the exception of the area around De Panne where the vertical extension exceeds 16 m. There, the facies is both infilling the depression and extending upward forming an elevation (Fig. 8). Elevations, but less high, are also found in the central and eastern sections. In the eastern part of the present coastal area the distribution of the S1 facies has a tabular form and attains a thickness of maximum *ca.* 6 m; the lower bounding surfaces of this facies is wavy. If both S facies are present in one sequence, facies S2 is most often in an overlying position. In general the accumulation of the S2 facies was taking place in areas where the concentration of suspended sediments was high enough, and where slack water lasted long enough or current velocity was very low so that mud particles could settle and become preserved. The latter is only possible when no or limited reworking takes place after deposition (e.g. Reineck & Singh, 1980; Dalrymple & Choi, 2007). As the S1 facies are accumulated in shallow marine and outer estuarine environments, only the outer part of the existing depression is filled with the S1 facies. The S2 facies appears, dependent on the amount of mud drapes, on tide-dominated shelves, in the outer and middle estuary, in tidal channels and on sand flats. As a consequence the S2 facies is present more inland.

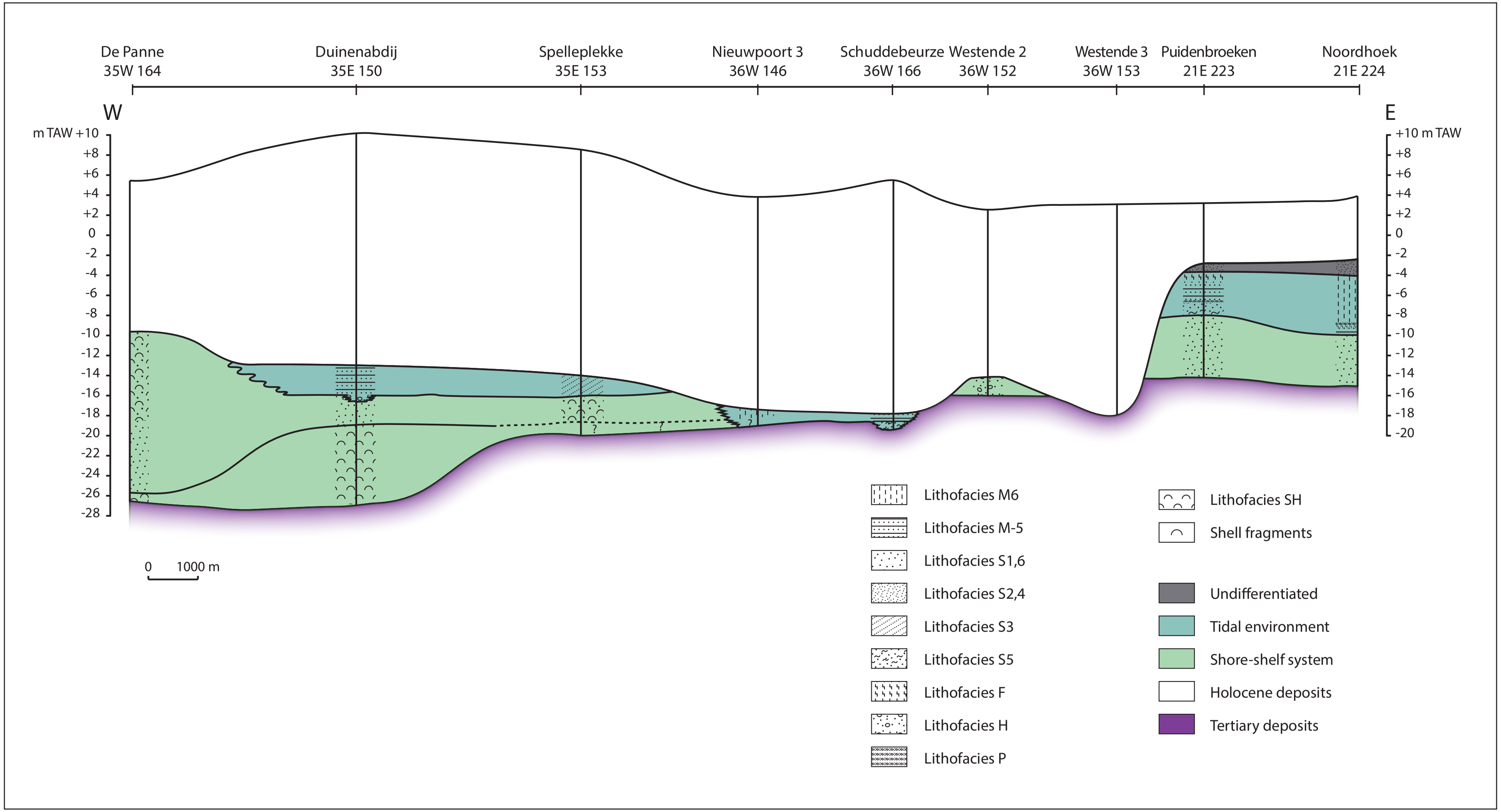

Figure 8. Cross-section approximately parallel to the present coastline showing the distribution of the different facies. Note the important variations within the SH and S1/2 facies in the west. The location of this cross-section is situated on figure 3.

The shell-rich intercalations in both the S1/2 facies stand for temporary higher energy conditions like those present during storm events. Some of the archive data mention the presence of *Corbicula fluminalis* and *Valvata piscinalis var. antiqua* in the S facies. Their presence in Oostende is according to Dollfus (1894) the result of a nearby large river debouching into the sea.

c) Other facies

Likewise in the shore-shelf system the outer part of an estuary as well as ridges and banks are included, not only the above-described facies are observed but also the S3, S4, F1, H1, H2 facies. The cross bedding typifying S3 is in this environment the result of the migration of dunes. Mud drapes, if present, are thin and rather scarce. The depositional history within the sequences shows several reactivations.

4.3.2. Discussion

The distribution of the SH facies points to a source area located in or west of the English Channel. The impact of water coming from the northeastern Atlantic Ocean via the northern part of the North Sea seems to be insignificant. Besides, still today the sediment transport on the continental shelf is dominated by a southwestern supply (Anthony et al., 2010; Héquette & Aernouts, 2010; Reynaud & Dalrymple, 2012), the mud fraction excluded (Zeelmaekers, 2011). The huge amount of shells in the facies SH is most probably related to the presence of a restricted passage at the location of the Strait of Dover through which the current flow coming through the English Channel increased. Such kind of phenomenon is also observed by Keene & Harris (1995) in the Torres Strait in NE Australia. The original cliff present in the top of the Formation of Kortrijk (see section 4.2.) disappeared because of a predominance of aggradational processes. The direct result was an extension of the shallow marine environment to the east. Data from the archives of the Geological Survey of Belgium and recent data (2012) from the Agentschap Geotechniek show that west of Oostende SH facies are absent. The SH facies in the area of Wilskerke and Rattevalle (Fig. 3) does not correspond to the SH remnants of the western part of the study area and is interpreted as isolated coarse-grained banks related to an outer estuary. Initially the invasion of the sea started in the most western part of the study area that became as first a part of the continental shelf.

In a relative time position these shallow marine deposits are placed in the first half of an interglacial (in analogy with the Holocene evolution described by e.g. Van der Molen & Van Dijck, 2000).

As mentioned before, the shallow marine deposits are not restricted to coarse-grained sediments but consists also of the so-called S1/2 facies. Their typical irregular lower bounding surface is most probably the result of transgressive erosion. The finer grained character of the S1/2 facies may be the result of either a different source area or a general decrease in the flow strength at the moment of transportation and deposition. Reduced flow strength may be induced by the creation of larger water depth (Bridge & Demicco, 2008) which may be the direct result of sea-level rise. A widening of the transportation path for example due to the enlargement of the passage of the Pas de Calais/Strait of Dover might be an explanation. Beside the tabular bedded S1 facies some ridges are present in the north, creating landward sheltered places where tidal flats could develop (Fig. 8).

Within a relative time position, these deposits are either accumulated during a slow sea level rising stage or during a phase when the relative sea level already began to fall. Whatever the exact position of the relative sea level was, low ridges provided protection from the open sea at the moment of deposition. A similar situation along the eastern Belgian coast during the Eemian is described by Mostaert *et al.* (1989) and is, according to the authors, comparable to the present-day situation along the German Bight.

4.4. The estuarine and tidal flat environments

4.4.1. Description and interpretation

In the study area the tidal environment is linked to both an estuarine and coastal plain environment. Because of the sedimentological similarity in both environments only one definition of the subenvironments is given. In the northern part of the study area two distinct levels are observed at which tidal deposits are present. One starting around a depth of -16m, with most remnants concentrated in the western part, and a second one with its base level around -10m. These latter deposits are largely clustered east of Veurne. Tidal remnants are absent in the north part of the second half of the study area. In the southern part, deposits with a tidal signature are again a component of the sequence.

a) The intertidal zone

The intertidal zone is an important element of a tidal flat. The grain size of the sediments determines the extension of the different intertidal zones and also whether particular zones can come into being. If the sediment source is favourable, the most distal part of the intertidal zone consists of a mud flat, the proximal part of a sand flat. In between the two extreme parts a mixed flat may be present. Because the intertidal zone is very dynamic it is evident that a large diversity of facies is present, both in a lateral and vertical extension.

It is striking that along the coastal fringe the mud flats are missing for the greatest part at the lower level except in the most eastern part. When present the clay fraction prevails. On the contrary, at the upper level in the north mud flat deposits are quite well preserved but show a differentiation in the distribution of the mud fraction along the sequence. Silt is dominant in the uppermost part of the sequence, clay in the lower one. In the southern part of the study area mud flats are only observed in restricted parts. The facies that form the building blocks of the mud flats are M1, M2, M4 and M6, for the latter one more specifically M6a and M6c. Contrary to the SH and S1 facies, mapping of these facies was not feasible.

Both sand flats and mixed flats are surveyed at the two levels in the north. A mixed flat consists of the facies M-S1, M-S2, M-S3 with or without thin layers of the facies SH. The SH facies are thrown on the tidal flat during storms. The sand flat deposits are composed of the S5, S3 and, to a minor extent, S2 facies. Analogue to the mixed flat deposits are the presence of thin SH layers, also the result of storm events. The cross-stratified parts are predominant small ripple bedded and enclose most often discontinuous mud laminae (flasers).

b) The subtidal zone (tidal channels and mixed part of an estuary)

The channel deposits are well preserved. The deposits are, however, only a couple of meters thick and are bounded above and below by deposits belonging to different sedimentary subenvironments. In the west-east running depression situated in the north (see 4.2) on the contrary, the deposits have a large vertical extension since they form the infilling material. Whatever the vertical dimension of the facies, the structure is identical. Within the S category S2, S3, S4 and S5 are distinguished. The alternating units consist of M-S4 and M-S1, and the mud deposits are restricted to M2 whereas the residual deposits comprise both H1 and H2. The sedimentological properties point very often to migrating channels bordered by intertidal and supratidal zones. Subtidal deposits are mostly concentrated in the northern but also, although less, southern part of the study area.

c) The supratidal zone

A deposit is interpreted as being accumulated in a supratidal zone when the sediments show signs of vegetation growth but no peat development. Stratification may be disturbed or even destroyed by the bioturbations of plants. The following facies are characteristic: M3, M4, M6. Very thin layers of SH are observed and are the result of storm events. The vertical extension of the supratidal deposits is normally limited to less than a meter in the northern part. In the south the deposits are thicker. However, the question arises whether the sediments were deposited in a salt marsh or in a floodplain because that particular region was within the evolution part of the landward section of an estuary during a certain phase. Therefore, a study of microfossils is necessary for an unambiguous distinction between salt marsh and floodplain.

4.4.2. Discussion

As mentioned before, in the north two levels of tidal deposits are present in the subsoil. The deepest one lies behind protective ridges that created landwards a coastal plain. The higher situated tidal environments are mostly limited to the east. Great variations on the level of subenvironments are present but the installed subenvironments are not directly related to the effects of shore-related waves and currents. It is very striking that tidal-induced deposits are also observed in the southern part of the study area where two distinct depositional regions exist. The first one is situated at the western edge of the current coastal plain where the Pleistocene deposits are thin and lay around and above 0m TAW. The most landward extended region converges with the present-day valleys of the IJzer, St. Jansbeek and Kemmelbeek. The top of the Tertiary substratum in these depressions is reaching different depths. The depressions of the St. Jans- and Kemmelbeek are deeper scoured than the IJzer depression.

a) Southwest part:

The basal part of the sequence at Lollege (Fig. 3) consists of remains of a flat on which some pioneer vegetation grew. The lowermost sediments of the core ‘t Vosje (Fig. 3) originated in the same environment but as point bar deposits. Preceded by an erosional phase the overlying unit consists of channel deposits characterized by rapid sedimentation. Remains of marine shells are present as grit and small fragments, with a predominance of *Cerastoderma* often concentrated in layers and laminae.

Halfway the two drillings lays the Kellen core (Fig. 3) where the base of the Pleistocene deposits is situated *ca.* 5m lower. SH facies is dominant at the base over a thickness of approximate 2m. Because of its stratigraphic position and the huge amount of shell fragments it seems that this facies is an erosion product of the shallow marine deposits of Middle-Pleistocene age, the so called Formation of Herzeele (Sommé *et al.*, 1978), present in the upstream course of the IJzer river. On the contrary, the sedimentological properties of the overlying deposits point to a tidal environment, an environment that also extends southwards.

b) Southeast part:

The Woumen borehole (Fig. 3) provides important data. In this place the environment evolved from a tidal-induced one into a floodplain/salt marsh and again a tidal flat. The sedimentologically defined environments are confirmed by palaeontological analyses (unpublished report by H.M. Roe, 1999). The research was concentrated on pollen analyses but data concerning diatoms, foraminifera and ostracoda were also incorporated. Within the examined Pleistocene deposits 3 local pollen assemblage biozones were recognized .The lowest lying zone (WO-1,-4.06/-3.8m) has a rather low pollen concentration and shows the dominance of *Corylus* within the arboreal pollen spectrum, followed by *Pinus* and *Quercus*. Poaceae dominates the non-arboreal pollen concentration. The second zone (WO-2, -3.8/-2.83m) is characterized by a low but continual percentage of Chenopodiaceae. *Corylus* is even more dominant in the arboreal pollen spectrum as well as Poaceae in the non-arboreal pollen. Most striking element in the third zone (WO-3, -2.93/-1.32m) is the important rise of Chenopodiaceae. Roe (unpublished report, 1999) concluded that the environment evolved to a fully temperate woodland that since the second pollen zone was situated near the margin of a coastal area. In zone 3 even a salt marsh environment was installed. On bases of the preserved microfauna the basal Pleistocene deposits in the drilling Woumen (-7.88m to -5.41m) belong to marginal marine environments as present in estuaries, intertidal and other shallow water coastal areas.

c) Upper level in the northern part:

The presence of channel deposits in the northeast is rather exceptional. Foraminifera analyses (unpublished report, M. Bates, 2011) of one of these remains were carried out for the Rattevalle core (Fig. 3). The results show clearly an estuarine origin, and more particularly the outer part of an estuary in which high-energetic conditions prevailed with the formation of crags. All counted foraminifera are warm-loving species. Concerning the ostracoda, no freshwater species is present. Upward in the stratigraphic sequence (found in the core Leeuwenhof (Fig. 3) – situated southeast of Rattevalle) typical estuarine species as well as freshwater species are present. In addition, due to the absence of some species (such as the foram *Ammonia*) the author of the report concluded that during the aggradation the climate was cooler than today.

4.5. Fluvial deposits

4.5.1. Description and interpretation

In the framework of this research the fluvial deposits were also considered with regard to the changing sea level during the Quaternary. Although the fluvial environment may be described in varies ways (overview see Miall, 1985; 1996) it is essential to define the architectural elements within the channel and overbank setting. However, while the fluvial subenvironments are morphologically well defined, their classification within a drilling is not always possible as the following examples illustrate. The upper part of a point bar and a natural levee consist of identical facies (Singh, 1972), the same problem arises on the level of a bench and natural levee.

Within the study area the fluvial deposits show important variations both vertical and horizontal. In the southern central sector of the study area the fluvial deposits occupy the whole sequence, but do not form a uniform entity. Where present in the north the fluvial deposits cover the upper most part of the sequence whereas in the south a shift between tidal and fluvial environments, whether or not repeated, is observed. Remains of tidal activity, although weak, are present in the proximal part of the Kemmelbeek valley in the drillings Rattekot and Westbroek (Fig. 3).

On basis of the present-day knowledge regarding the sedimentary characteristics of the fluvial dominated part of the transitional zone of an estuary and the distributary part of a delta, it is decided to incorporate these parts into the fluvial environment as differentiations in cores are hard to define.

a) Fluvial within the channel

The classification of Miall (1996) distinguishes eight architectural elements within a channel. However, in the study area no gravel deposits are observed and neither are gravity-induced sediments. Consequently the type of elements is reduced to channel fills, lateral-accretion macroforms with the incorporation of point bars, benches and counter point bar (the latter two described by e.g. Taylor & Woodyer (1978); Smith (1987), Smith et al. (2011), Sisulak & Dashtgard (2012) and finally downstream-accretion macroforms. The term channel fill stands for the vertical sediment infilling of a channel. The lithofacies S3, S4, S5, M6, H1, H2, and to a minor extent F3, are distinctive for the latter element. The different types of lateral accretion macroforms are characterized by the lithofacies M-S1, M-S2, M-S4, S3, S5, H1 and less common F3. Finally, the downstream accretion forms are built up by the lithofacies F1, F2, S3, M6 and M1. In all architectural elements the silt fraction is common. The small ripplebedded and to a minor extent horizontal laminated simple bedsets are characteristic. Because an upper flow regime that produces horizontal laminated bedding (like in environments with ephemeral stream flow) also appears in the overbank area, the term undifferentiated fluvial is used. The same term is also applied when it is not clear to which element the horizontally laminated sand units belong; whether to laminated sand sheets or to channel fills.

b) Fluvial overbank

In contrast to the great attention channel deposits have received in sedimentological studies, research on overbank deposits is rather limited. Very often, even Miall until 1985, considered the overbank deposits as one element. Now, the overbank deposits are subdivided into floodplain fines- natural levee-, abandoned channel-, crevasse channel- and crevasse-splay deposits (o.a. Singh, 1972; Reineck & Singh, 1980; Farrell, 1987; Smith et al., 1989; Brierley at al., 1997; Berendsen & Stouthamer, 2001). Although these deposits have a distinct geomorphological constitution, the sedimentological characteristics are not unique. As a consequence the interpretation of these elements in cores, even in the undisturbed ones, may be problematic when only one element is present. Some examples: within the overbank deposits a distinction between floodplain fines and abandoned channel deposits may be difficult to make in a core; in an estuary the sedimentological distinction between a floodplain *s.s.* and a tidally influenced one, or even an inland located salt marsh is very hard to define on basis of a macroscopic survey on cores. Besides, the subenvironments may shift along the longitudinal profile on a small time scale (per season) and on a longer time scale (per climate variation). To reduce possible misinterpretation as much as possible, the infilling material of abandoned channels are incorporated into the overbank deposits. Besides, in rivers with a fine-grained sediment load (fine sand to silt) it is very difficult to make a distinction between crevasse-channel deposits and channel-fill deposits on basis of only sedimentological properties. Because all fluvial sediments in the study area have a fine-grained character, crevasse-channel deposits are incorporated into the channel fill deposits. Nevertheless floodplains and abandoned channels have the following specific facies: M1, M2, M3, M4, M5, M6 and less common F3. Levees are typified by the facies M-S1, M-S2, S3 and S5.

c) Coastal or freshwater peat land

The development of freshwater marshes and peat bogs was constrained to the northeast and to the surroundings of Woumen. During the peat accumulation siliciclastic sediment input, with the grain size fraction varying from clay to sand, remained important. The peat may be completely decomposed or may contain some macro remains like seeds as observed in the Oostende Vliegveld core (Fig. 3).

4.5.2. Discussion

Fluvial deposits prevail in the central part of the study area. However, important differentiations with regard to their stratigraphic position and constitution are observed.

Mud deposits, present as a uniform entity or alternating with sandy sediments are predominant. In the sequence the pure silt deposits often take an intermittent position. The sedimentary structures show that the silt deposits originated both in running water and in nearly standing water. Their omnipresence within the environment points to a silt dominant fluvial system during a certain timeframe. The transition from a mixed load to a silt dominant river is either the result of adjustments in the drainage basin (like the modification in the importance of a distinct channel within the river system) and/or a change in the hydrodynamic of a river system. However, next a complete different river system can into being. Indeed, in those areas where erosional activities were limited after deposition sandy fluvial sediments are preserved. In some cores like e.g. Kruisabele, Schaap and Cayenne (Fig. 3) the fluvial deposits are the only Pleistocene deposits within the Quaternary sequence.

5. Conclusion

Since the lithological up building of the Quaternary deposits is very complicated due to the complex relationship between the successive climate changes, base-level changes, sedimentation and erosion processes, a method is needed to organize the Quaternary deposits on a fast and easy way in order to get a clear and unambiguous stratigraphy.

To obtain this goal, the introduction of a lithofacies classification is required in the first place. The classification is based on widespread depositional characteristics in which local, place restricted, features are excluded. Consequently this method is applicable in similar depositional environments whatever their location. It forms the basic tool to understand on the one hand the erosional/depositional mechanisms that modelled the area and on the other hand the origin and evolution of different environments. Consequently, the obtained information has not only a pure scientific value but may be utilized as basic instrument in applied fields like engineering, modelling and archaeology. Furthermore, these elements are useful to predict in the near future, among other things, the effects of climate changes on the modifications of the natural environment.

An obvious application of the classification is definitely the construction of cross-sections, which form a basic instrument in the reconstruction of the depositional history of an area. Besides, once the data is introduced in a digital database, the application of the lithofacies classification is almost unlimited; 3D representations, thematic maps and so on can simply be created without further investigation.

The detailed investigation of the cores gave a complete new insight of the sedimentary depositional evolution of the Western Coastal Plain during the Pleistocene. It is clear that the evolution of the study area is much more complex and that the up building of the area took most probably a longer period than ever thought. The introduction of a new litho- and chronostratigraphy in the western coastal area is indispensable in the future.

In the northwestern part of the Western Coastal Plain shallow marine deposits, with their source area most probably located in or west of the English Channel, predominate the geological record whereas in the eastern part a much more complex sequence is preserved. This situation is related to the presence of an approximated south – north running depression, known as the IJzer Valley. The deepening of the south–north depression is, given its geometry and position, of fluvial origin and originated most probably during several glacial periods. The south–north running palaeo-depression has in the south a bird's foot pattern, extending to the present day valleys of the IJzer, St. Jansbeek and Kemmelbeek. The palaeo-depression is therefore not only shaped by the IJzer, as previously thought, but also by streams coming from the southeast. Tidal deposits are preserved on different altimetric levels, especially in the south, implementing different formation periods. But studies (see e.g. Bates *et al.*, 2003) have indicated that the use of altitude above present-day sea level as an absolute time indicator is unreliable and absolute chronological data are however required. The central part of the palaeo-valley is for its greatest part filled with fluvial sediments. Moreover, within the fluvial record, deposits belonging to different river styles and to various places along the longitudinal profiles are observed.

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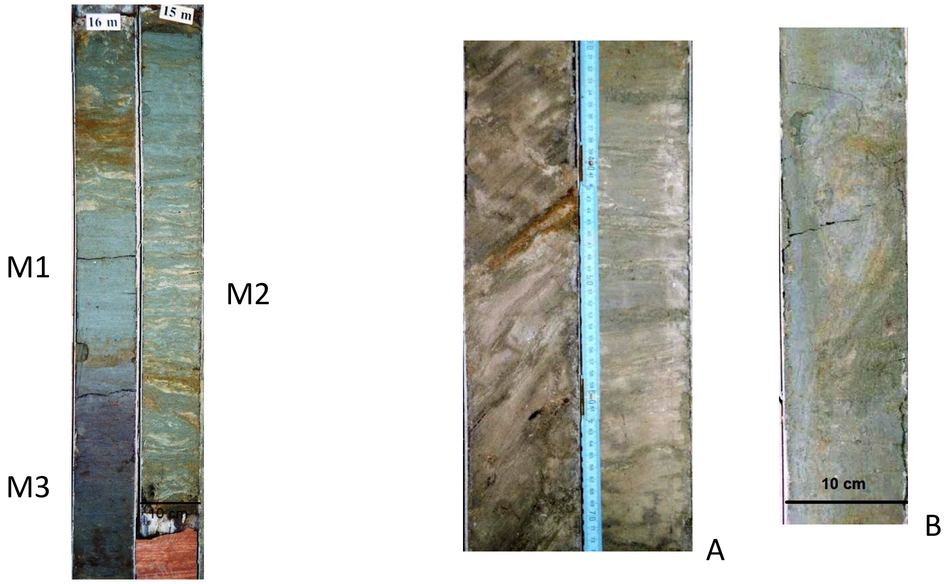
Photographs of the defined lithofacies

M2 facies

A series of M lithofacies are successively deposited, starting with M3 and evolving into M1 and M2.

A: the deposition of the M2 facies starts with a steep slope, as the accumulation continues the depositional surface becomes approximately flat.

B: the sandy intercalations are deformed.

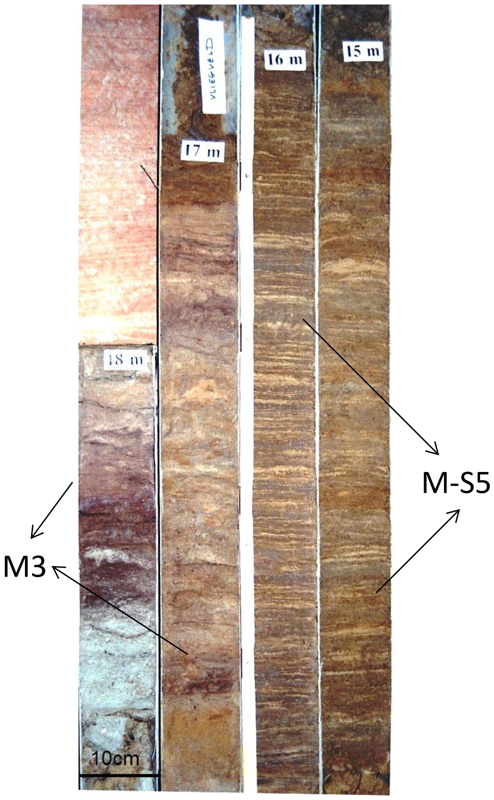


Photoplate 1.

M3 facies

The main characteristic of the M3 facies is the organic enrichment. In this core a succession of humic horizons is observed.

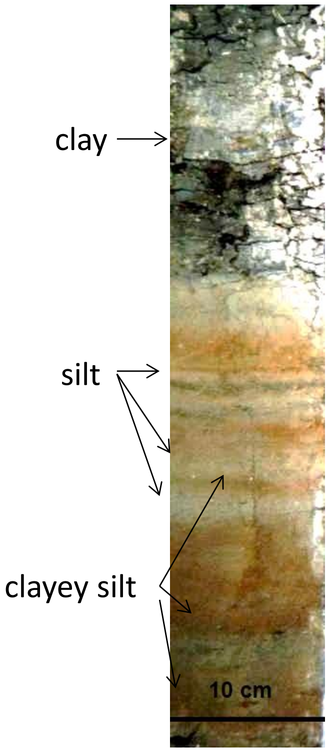
The silty laminae/beds of the M-S5 lithofacies are also rich in organic material.



Photoplate 2.

M4 facies

A complex of mud deposits with variable clay and silt content. No stratification is present, the oxidation pattern is misleading.



Photoplate 3.

M5 facies

The typical alternation of silt and clay laminae.

Physical and biological processes deformed the sedimentary structures formed during deposition.

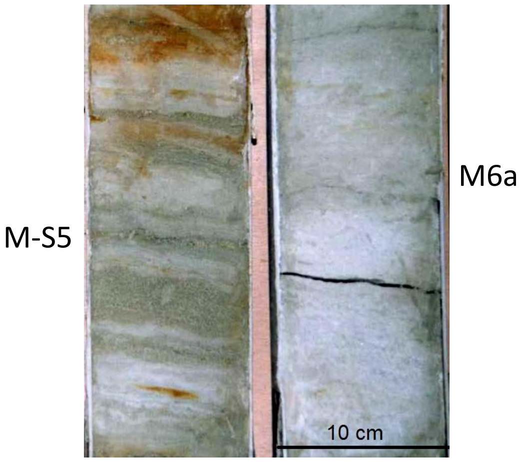
Photoplate 4.

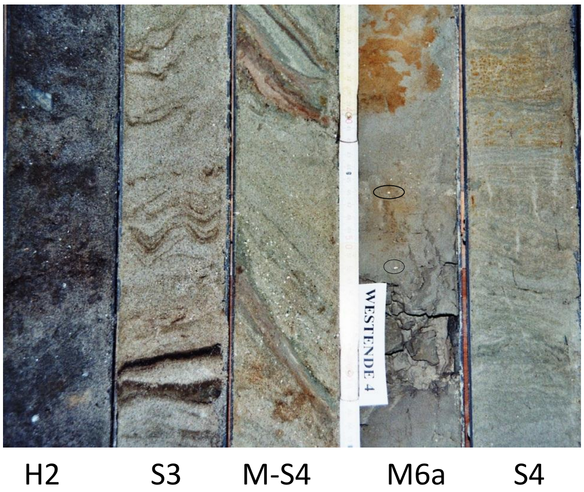
M6a facies

Before a massive silt facies (M6a) accumulated a M-S5 facies was deposited. In the latter facies beds are also not stratified.

Some shell fragments are observed in the massive structured M6a lithofacies (see circles).

Note the root imprints in S4 and the very steep slope on which the sediments of facies M-S4 are deposited.

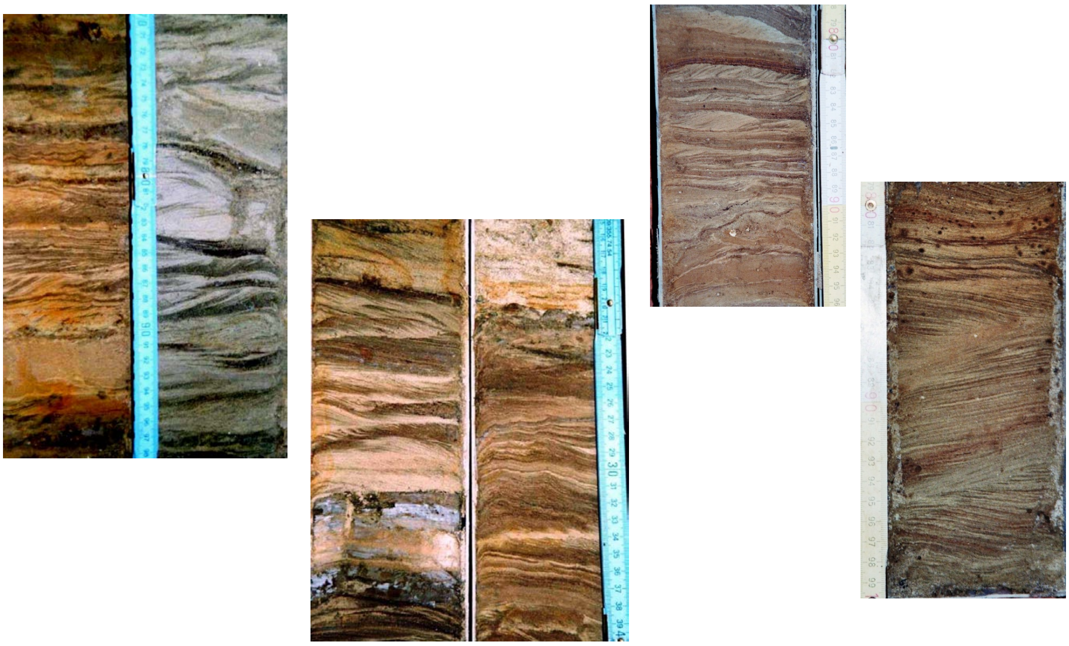




Photoplate 5.

M6b facies

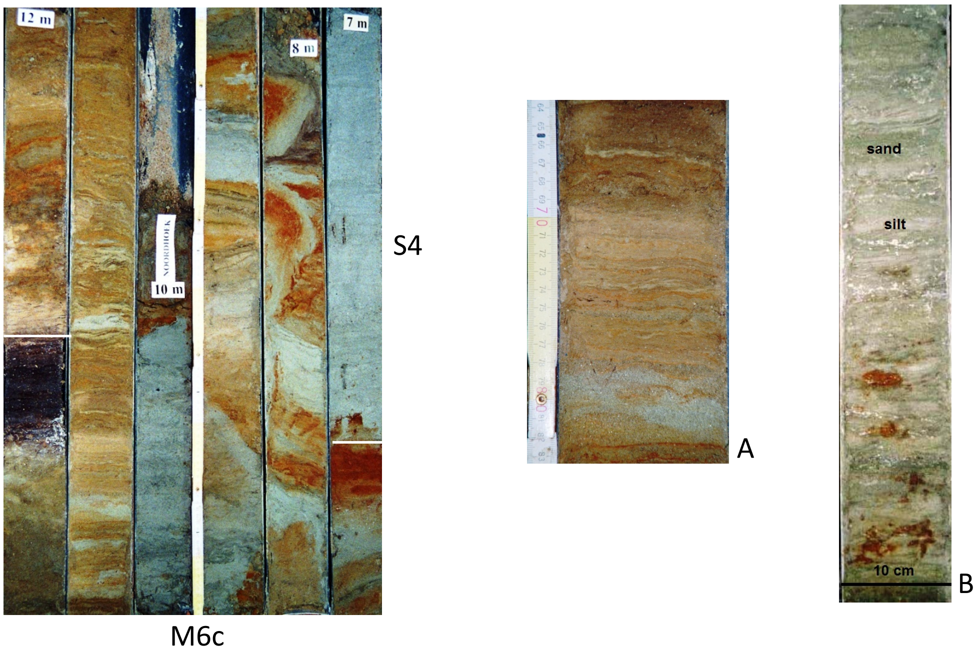
Different types of stratification within the silt deposits. Note the dominance of small-ripple bedding and (sub)horizontal lamination. Deformation structures are quite frequently present.



Photoplate 6.

M6c facies

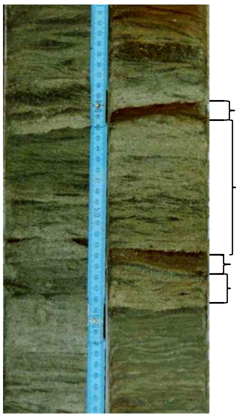
The bounding surfaces (upper/lower) of a layer/lamina are often wavy (A). Deformation structures are present in different dimensions. Note the calcium carbonate precipitations in the deposits (B).



Photoplate 7.

M-S1 facies

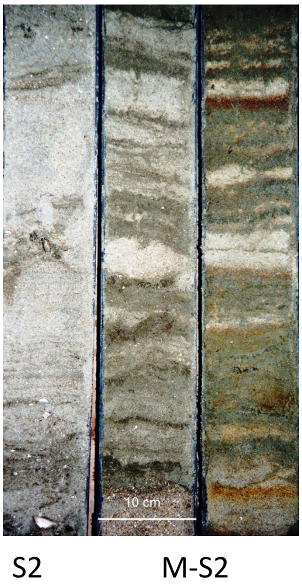
Within this lithofacies the dimension of the individual sand/mud beds is irregular.



Photoplate 8.

M-S2 facies

Typical is the absence of sedimentary structures in the units of the composite sets (see also A). The lower bounding surface of facies M-S2 is wavy. Note the small bioturbations.



Load cast structures are abundant.

Photoplate 9.

M-S3 facies

Within this succession a series of lithofacies is present. The most lower-lying sediments (lower left corner) consists of a M-S3 facies with the typical rhythmic bedding. The top of this facies is scoured.

The lithofacies M-S1, also composed of multiple lithologies, shows the typical irregular spaced bedding.

Photoplate 10.

M-S4 facies

S3 facies proceeds the M-S4 facies. Characteristic is the small ripple bedding with herringbone cross-stratification.

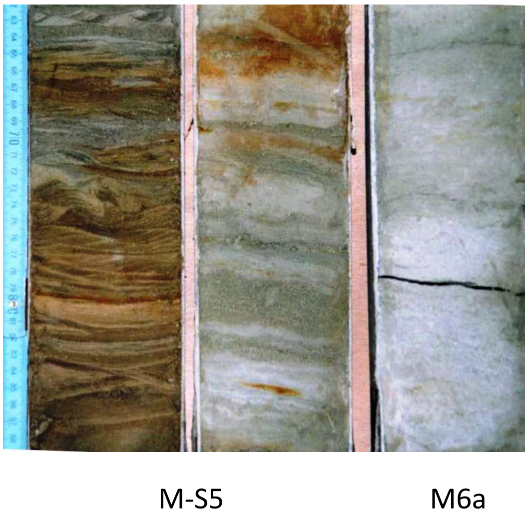
Within the M-S4 facies the angle of deposition declines upwards.

Photoplate 11.

M-S5 facies

The sedimentary structures within the sets of the M-S5 lithofacies change continuously, especially in the silt deposits.

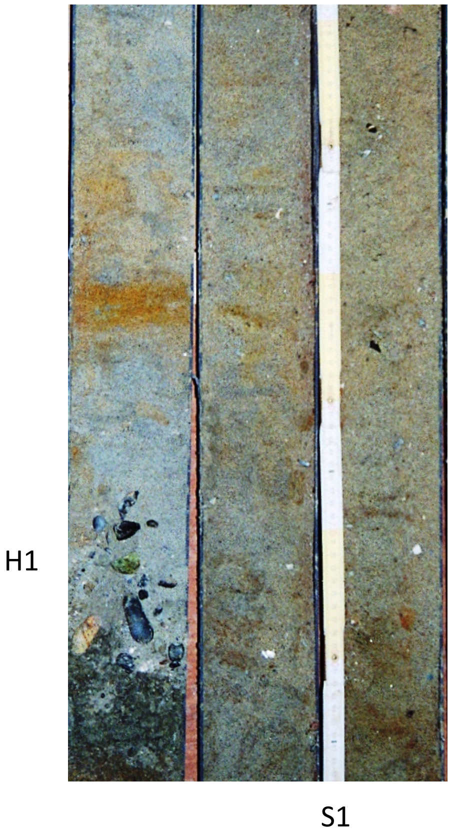
Note the ripple cross-bedding in the upper left corner.



Photoplate 12.

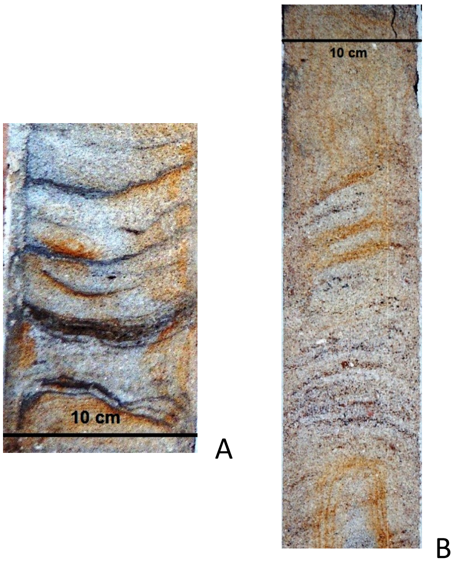
S1 and S2 facies

Overview of facies S1, note the lack of stratification. Some shell fragments are scattered within the sediments. At the contact with the tertiary substratum a lag is present (facies H1).



Facies S1 is characterized by deformation structures. Beside laminae few mud clasts are present in facies S2.

Details of the laminae composition in facies S2: the laminae in A are clastic, in B they consist of shell grid.

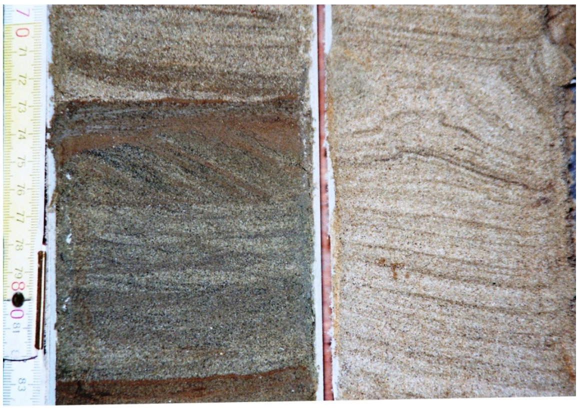


Photoplate 13.

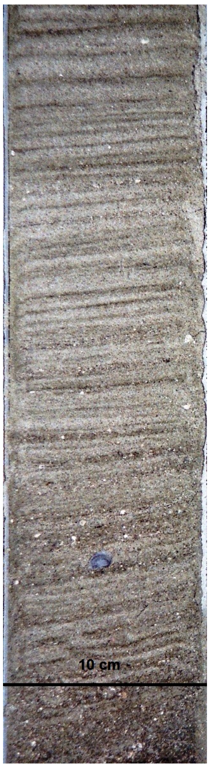
S3 facies

Overview of different types of small-ripple bedding.

Detail of small-ripple bedding with inclined foreset laminae (on the left side). Note the deformation structures on the right side.



Ripple morphology is preserved.



Slightly oblique to horizontal even stratification. Notice the scattered shell remains.

Although most of the stratification is destroyed, herringbone cross-stratification is present on several levels.

Photoplate 14.

S3a facies

Succession of small depositional units consisting of different types of stratification. Their lower bounding surfaces are both erosional and depositional.

Photoplate 15.

S4 facies

The typical vague stratification.

Different types of deformation structures. The wedges have most probably a biological origin (dwellings of crustacea).

Photoplate 16.

S5 facies

The typical vague stratification present in the basal part of the facies.

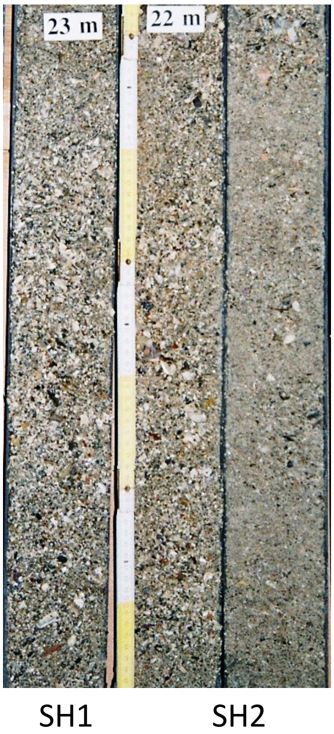
Soil development within the S5 lithofacies. The peat (right bottom) is the Holocene basal peat.

Note the dark-coloured clayey lamellae.

Photoplate 17.

SH1 & SH2 facies

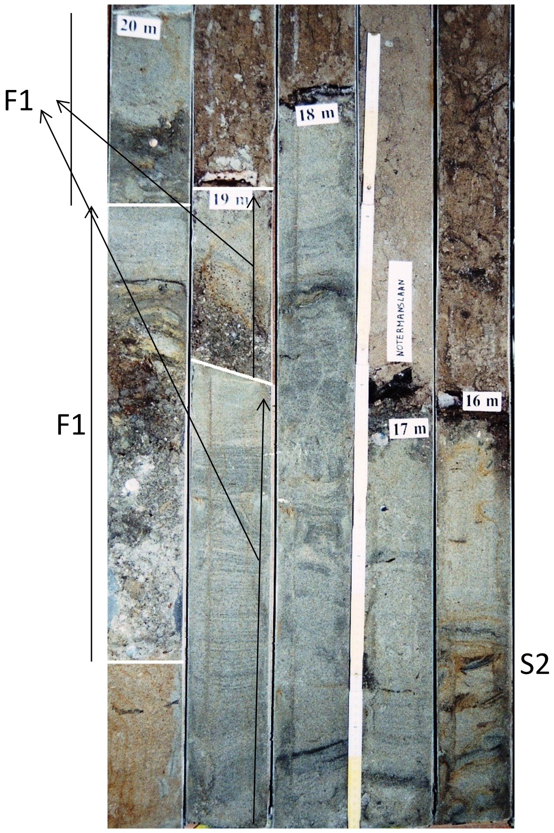
The concentration of the shell remains diminishes upwards in favor of sand deposition.



Photoplate 18.

F1 facies

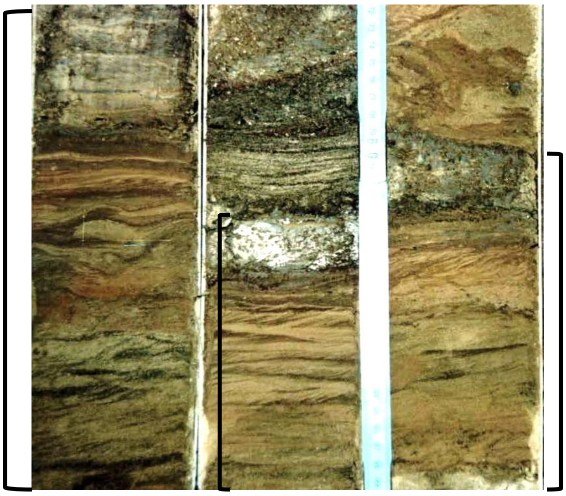
A succession of three F1 facies is present. The basal part of a cycle is composed of gravel-sized components, predominantly composed of clayey clasts. The bedding of the upper layers is successively diffuse, massive and slightly oblique to horizontally layered.



Photoplate 19.

F2 facies

On this picture three cycles are present. The vertical extension of a cycle is variable.



Photoplate 20.

H1 facies

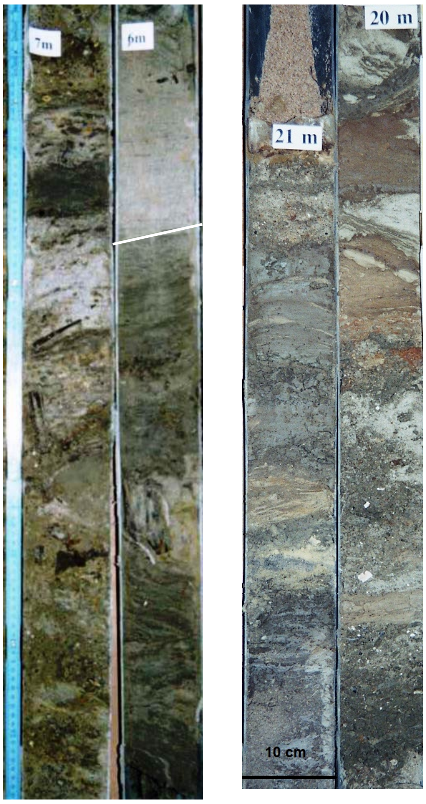
The coarsest fraction of the lag consists mainly of clayey clasts, and shell fragments as gravel components are limited. The matrix is composed of sand.

Photoplate 21.

H2 facies

A H2 facies is a heterogeneous entity consisting of different components reflecting changing hydrodynamic conditions.

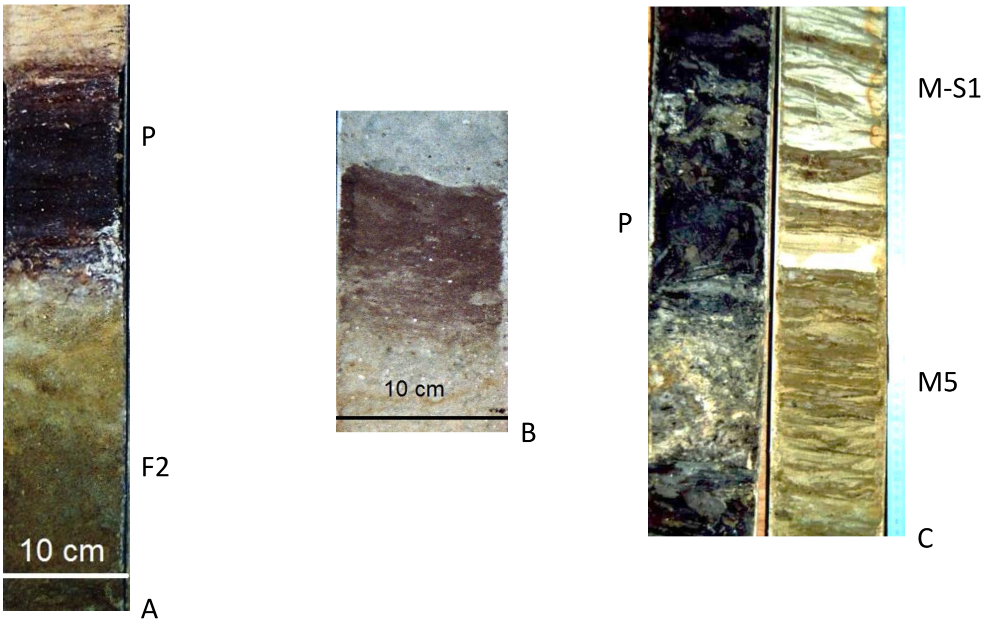
Both wood fragments and clay pebbles form the coarsest clasts.



Photoplate 22.

P facies

The degree of decomposition of the organic matter within the P facies as well as the content of siliciclastic sediments is variable . Both A and B are composed of amorphous organic matter but the amount of siliciclastic sediment is much higher in B. The peat in C contains wood fragments.



Photoplate 23.

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