Geology of the Dutch coast

The effect of lithological variation on coastal morphodynamics

Deltares

Title
Geology of the Dutch coast

Client	Project	Reference	Pages
Rijkswaterstaat Water, Verkeer en Leefomgeving	1220040-007	1220040-007-ZKS-0003	43

Key words
Geology, erodibility, long-term evolution, coastal zone

Abstract
This report provides an overview of the build-up of the subsurface along the Dutch shorelines. The overview can be used to identify areas where the morphological evolution is partly controlled by the presence of erosion-resistant deposits. The report shows that the build-up is heterogeneous and contains several erosion-resistant deposits that could influence both the short- and long-term evolution of these coastal zones and especially tidal channels. The nature of these resistant deposits is very variable, reflecting the diverse geological development of The Netherlands over the last 65 million years. In the southwestern part of The Netherlands they are mostly Tertiary deposits and Holocene peat-clay sequences that are relatively resistant to erosion. Also in South- and North-Holland Holocene peat-clay sequences have been preserved, but in the Rhine-Meuse river-mouth area Late Pleistocene-early Holocene floodplain deposits form additional resistant layers. In northern North-Holland shallow occurrences of clayey Eemian-Weichselian deposits influence coastal evolution. In the northern part of The Netherlands it are mostly Holocene peat-clay sequences, glacial till and over consolidated sand and clay layers that form the resistant deposits. The areas with resistant deposits at relevant depths and position have been outlined in a map.

The report also zooms in on a few tidal inlets to quick scan the potential role of the subsurface in their evolution. Several tidal inlets have resistant layers directly below the base of the channel or within the flanks of the channel. However, in almost any case the data-density is insufficient to map the resistant layers in necessary detail. This is essential in order to understand and predict the migration patterns of the tidal channels. In addition, hardly any research has gone into quantifying the erodibility of the different deposits. At this point, it is therefore not possible to go beyond general terms in describing the role of the different deposits on coastal zone evolution. To improve this, several recommendations are given that focus on prioritising relevant areas to study, making more use of existing seismic data, gathering of additional data and studying differential erodibility.

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1	Dec. 2015	Marc Hijma		Ad van der Spek		Frank Hoozemans	
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Content

1 Introduction

There is considerable variability in the build-up of the subsurface near the shorelines of The Netherlands. This is explained by the complex geological history that involved numerous sea-level falls and rises, associated shifts between cold and warm periods, differential tectonic subsidence and two glacials in which ice sheets reached The Netherlands. As a consequence it is possible, in both vertical and horizontal directions, that the build-up of the subsurface changes within ten meters from e.g. loose tidal-channel sand to stiff, over consolidated fluvioglacial clay. There is no doubt that the build-up of the subsurface influences the evolution of the Dutch coastal system (e.g. Beets and Van der Spek, 2000; Hijma and Cohen, 2011; Vos et al., 2011). On the long-term it will partly determine e.g. the overall geometry of the shoreline, the position of tidal inlets and the erodibility of the shoreface. For the shorter term knowledge of the subsurface build-up is important to e.g. understand fluctuating lateral-migration rates of tidal channels. This is especially relevant when they are situated close to important infrastructure (dikes, dams) or beaches and could have, by erosion, a negative impact on flood safety.

It is expected that more than half of the build-up of the subsurface in the coastal zone consist of easily erodible sand. The focus of this report therefore lies on the distribution of relatively erosion-resistant deposits that influence both short-term and long-term coastal evolution. South of Texel these deposits mostly consist of clay and peat from back-barrier environments, but in (former) Rhine-Meuse river-mouth areas also of fluvial clay. In addition, southern Zeeland is characterised by the presence of very old erosion-resistant Tertiary deposits. In contrast, the erosion-resistant deposits in the northern Netherlands are mostly related to glacial periods and consist of glacial till and over consolidated sand and clay.

The onshore distribution of these deposits is relatively well known as there exists a substantial body of literature in The Netherlands dealing with the onshore subsurface near the shoreline. Offshore, less data are available and as a consequence the knowledge about the build-up of the subsurface is less detailed. This is often undesirable from a coastal-management perspective as the most dynamic morphological changes occur offshore and especially in the vicinity of active tidal channels. To improve this situation, a first necessary step is to have a general overview of the existing literature, information and the general subsurface build-up along the shoreline. A next step would be to identify offshore areas where both the coastal development is most likely influenced by the presence of erosion-resistant deposits and predicting future evolution is relevant for coastal-zone managers. The third step would be to gather and analyse all existing data for the areas, preferably also in cooperation with third parties, e.g. engineering companies that have additional offshore data. Since the amount of offshore data is limited, in many cases it will be necessary to acquire and analyse additional data to have a detailed enough understanding of the subsurface. The final step would be to translate the improved understanding into coastal management plans.

The goal of this report is to provide the first step by providing a general overview of the offshore subsurface build-up that can be used to identify areas where erosion-resistant deposits occur at relevant depths (Chapter 2). In addition, Chapter 3 zooms in on the subsurface build-up in relevant areas such as tidal inlets. Chapter 3 is not comprehensive, meaning that it does not present a detailed study of tidal-channel behaviour of all large tidal inlets in relation to the subsurface build-up, as this would be a very large study. However, it does provide insight in the current subregional understanding of the subsurface build-up. Chapter 4 presents a small-scale map of areas where the morphological evolution is likely influenced by the presence of erosion-resistant deposits. In order to improve this map with respect to detail and usefulness, it is necessary to gather additional information and knowledge, but also to analyse existing data in more depth. Chapter 5 lists the most important knowledge hiatuses and gives several recommendations to fill them.

2 Overview of the subsurface deposits along the Dutch shoreline

The largest part of the shoreline of The Netherlands lies in the Southern North Sea tectonic basin and experiences tectonic subsidence (Figure 2.1). The southwestern Netherlands lie on the shoulder of this basin and form a transitional zone towards the Weald-Artois anticline. Rates of tectonic subsidence in the southwestern Netherlands are therefore lower than further north (Kooi et al., 1998).

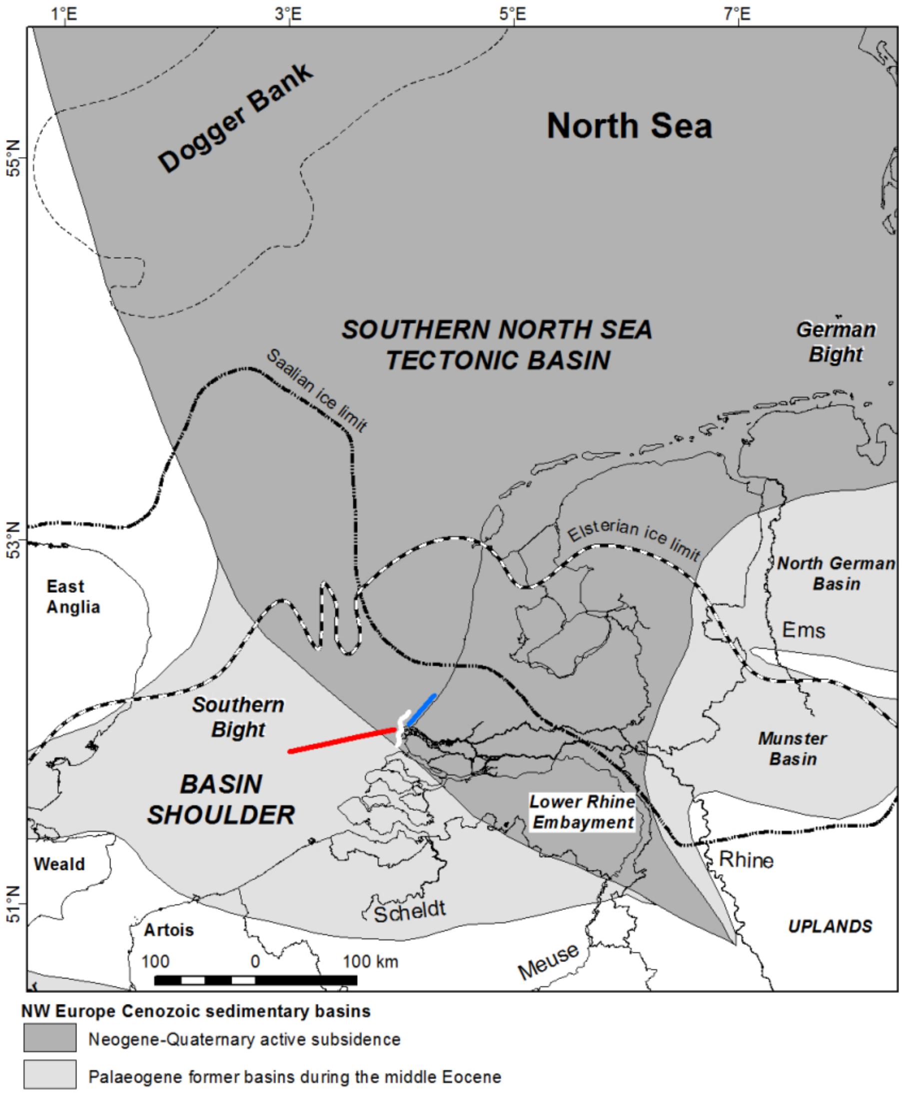


Figure 2.1 The largest part of the coastal zone of The Netherlands lies in the Southern North Sea tectonic basin The southern part, basically the southwestern Delta, lies on the basin shoulder (picture modified from Hijma et al., 2012). The coloured lines indicate the locations of cross-sections shown in this report. Red: Figure 2.3; Blue: Figure 2.9 and White: Figure 2.14.

This tectonic configuration is in place since the Middle-Oligocene, about 30 million years ago (Figure 2.2). The Oligocene is part of the Cenozoic, a geological period that lasted from 65 to 2.6 million years ago. The Cenozoic was previously labelled the Tertiary and as this name is still in use in The Netherlands, this report will use it as well. During the Tertiary sea levels were relatively high, especially in the first half when they were frequently more than 50 m higher than present. In the second half of the Tertiary average sea level became gradually lower (Miller et al., 2005). For most of the Tertiary the Netherlands were part of a (shallow) marine basin. Sea-level fluctuations resulted in changes in water depth and hence changes in depositional environments. During sea-level lowstands the shoreline of the basin ran roughly across the Belgium-German border (Westerhoff et al., 2003).

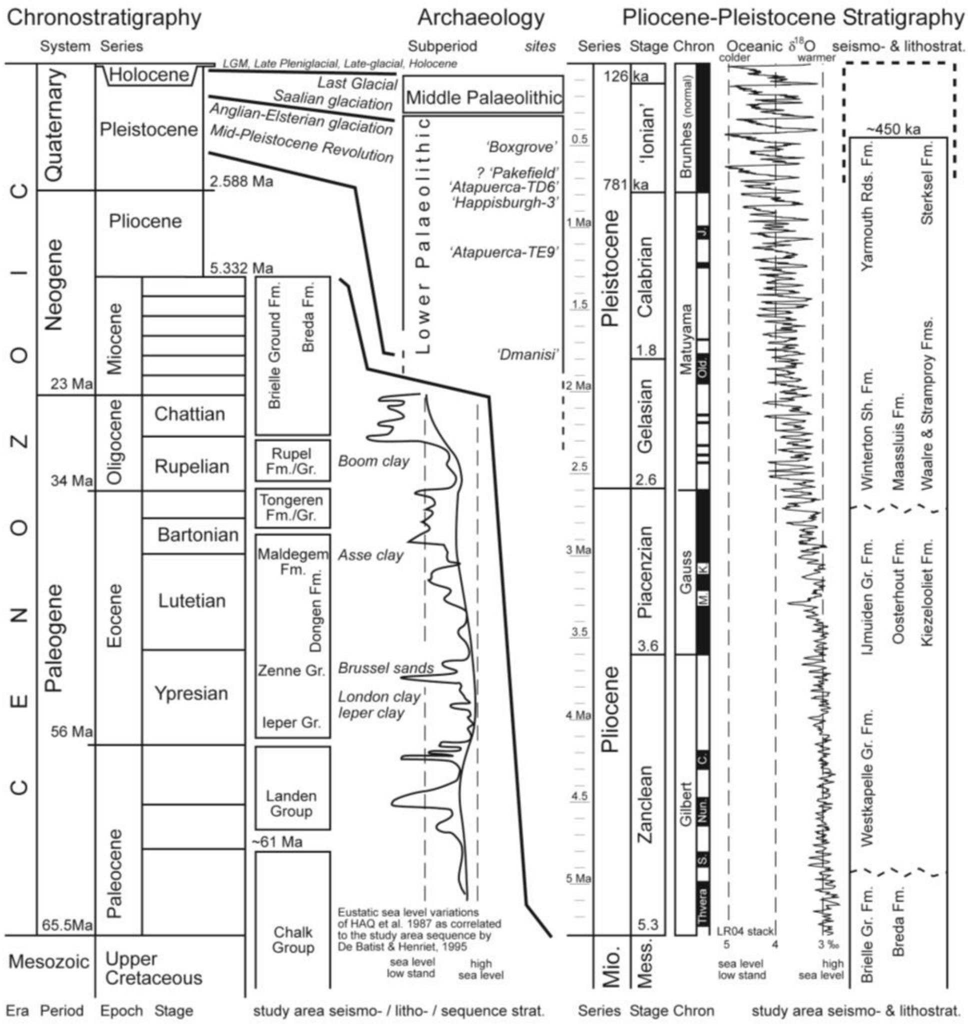


Figure 2.2 Chrono-, seismo- and lithostratigraphy of the last 65 million years. Marine isotope curve LR04 from Lisiecki and Raymo (2005). Seismo- and lithostratigraphic units after Westerhoff et al. (2003) and Rijsdijk et al. (2005). Fluctuations in the marine isotope curve reflect fluctuations in sea level: when oceanic $\delta^{18}O$ levels are low, sea level is relatively high and when $\delta^{18}O$ levels are high, sea level is relatively low.

During the Tertiary thick stacks of (shallow) marine deposits accumulated in the area of The Netherlands. Their lithological composition depends on the depositional environment at the time and ranges from tens of meters of clay to very shell-rich sand. Well-known clay units are the Asse Clay and the Boom clay of the Dongen and Rupel Formations, respectively (Figure

2.3). At the basin shoulder the Tertiary deposits lie relatively shallow, in Zeeuws-Vlaanderen they lay directly at the surface in some places. To the north the Tertiary deposits dip into the Southern North Sea tectonic basin (Figure 2.3). North of Rotterdam, the Tertiary deposits always lie deeper than 150 m below the surface. Their thickness varies from several hundreds of meters in Zeeland to over 1500 m in the Northern Netherlands.

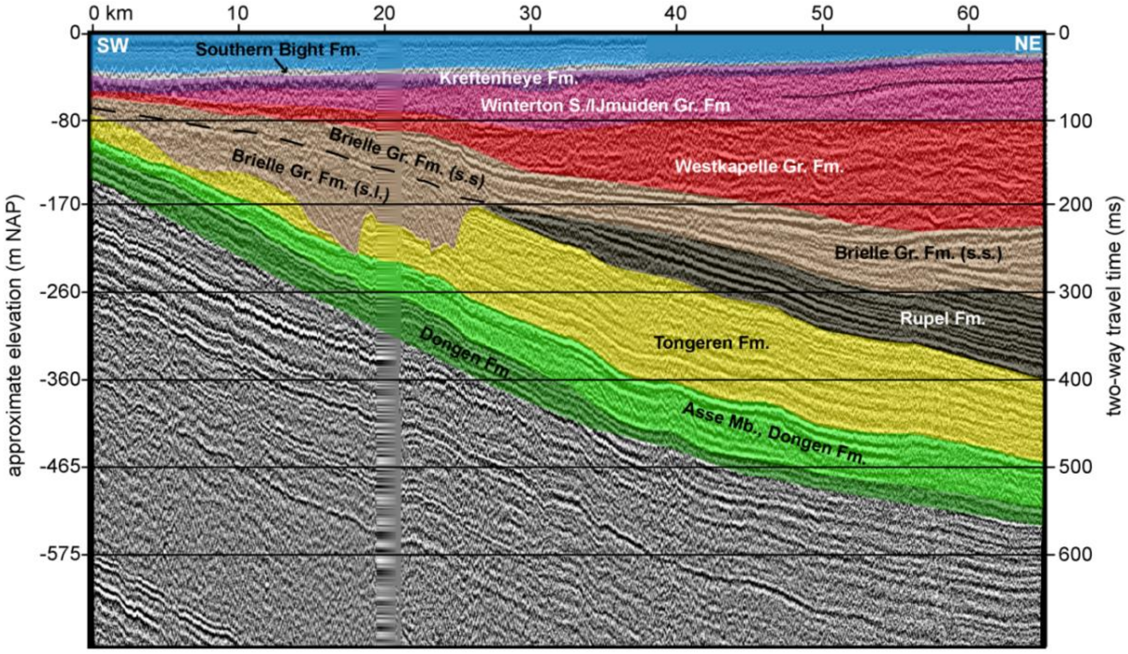


Figure 2.3 Offshore cross-section showing dipping Tertiary deposits. The younger deposits lie increasingly horizontal (after Hijma et al., 2012). See Figure 2.1 for the location. The transition from Tertiary to Quaternary deposits lies within the Winterton Shoal/IJmuiden Ground Formations. Below the Dongen Formation lie undetermined Tertiary deposits.

During the Tertiary the North Sea basin slowly filled in with sediments coming from the Rhine-Meuse system and the large, presently non-existing, Eridanos system that entered the Netherlands in the Drente-Groningen area from the east (see Westerhoff et al., 2003, for palaeogeographical maps). At the end of the Tertiary fluctuations in climate and sea level became more pronounced, marking the start of the Pleistocene around 2.6 million years ago (Figures 2.4-2.5). The Pleistocene is characterised by frequent changes between very cold, terrestrial conditions and warm, deltaic conditions. These changes are also reflected in the Pleistocene deposits that range from glacial till to beach sand. During two glacials, the Elsterian and the Saalian, the Scandinavian ice sheets reached the Netherlands (Figure 2.1). In Zeeland, at the border with Belgium, the Pleistocene deposits are absent or very thin, but northwards, into the Southern North Sea Tectonic basin, their thickness gradually increases to over 400 m.

About 11,700 years ago the Holocene started, an interglacial period characterized by rapid transgression of the terrestrial landscape in its first half and stabilisation of the shoreline in its second half (see e.g. Vos et al., 2011). The way the transgression shaped the Netherlands into its present form was for a large part dictated by the topography of the Pleistocene landscape and the differential erodibility of the various Pleistocene and Tertiary deposits.

In the following paragraphs an overview is given of the preserved deposits along the shorelines of The Netherlands with focus on the preserved deposits that are relatively erosion-resistant like clay, peat, till or very old and compacted deposits. For the overview, the shoreline is divided into several subregions. For each subregion the preserved Tertiary and

Pleistocene deposits will be described first, followed by an overview of the preserved Holocene deposits. To facilitate the interpretation of this chapter, the deposits that have a relatively low erodibility and hence form the focus of this chapter are listed below. In the chapter the origin and general distribution of the deposits will be given. From southwest to northeast the deposits are:

1) Tertiary clays, especially from the Dongen and Rupel Formations
2) Tertiary sands, more resistant than younger sands due to cementation
3) Holocene clayey tidal deposits (Naaldwijk Formation).
4) Early Pleistocene clays, either from the Maassluis or the Waalre Formations
5) Early Holocene alluvial and lagoonal peat and clay sequences, in front of the present Rhine-Meuse river mouths, but also in the IJmuiden-Eems areas (Echteld-Nieuwkoop and Naaldwijk Formations)
6) The Bergen bed, a Holocene clayey infill of a large tidal-inlet (Naaldwijk Formation, Bergen Bed)
7) Eemian peat and clay sequences (Eem Formation)
8) Thaw-lake deposits from the last glacial (Boxtel Formation)
9) Lagoonal-deltaic deposits from the late Eemian-early Weichsel (Eem Formation)
10) Glacial till (Drente Formation)
11) Overconsolidated sand (Urk, Drachten, Peelo Formations)
12) Overconsolidated clay (Potclay, Peelo Formation)

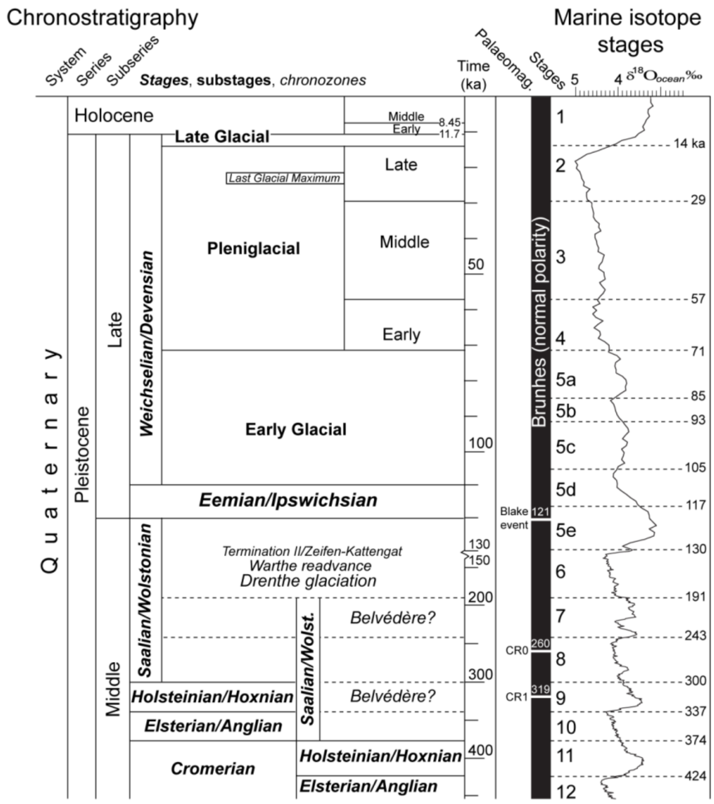


Figure 2.4 Northwest European chronostratigraphical subdivision and correlation with the marine isotope record. Competing scenarios for some regional stage correlations (e.g. Litt, 2007) are also plotted (modified from Busschers et al., 2008). Marine isotope curve LR04 from Lisiecki and Raymo (2005). Fluctuations in the arine isotope curve reflect fluctuations in sea level: when oceanic δ^{18}O levels are low, sea level is relatively high and when δ^{18}O levels are high, sea level is relatively low. Note scale break at 135 ka (picture modified from Hijma et al., 2012).

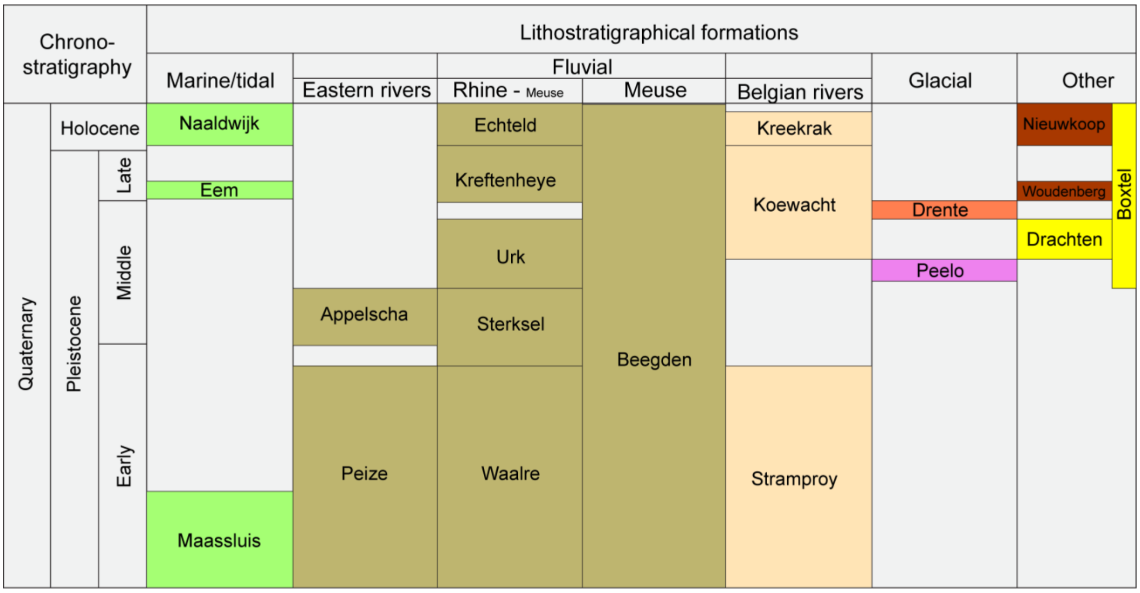


Figure 2.5 The age and depositional setting for the lithostratigraphic formations of the Quaternary (adapted from www.dinoloket.nl and Hijma et al., 2012).

2.1 Tertiary and Pleistocene

2.1.1 Zeeland

At most places along the shoreline of The Netherlands Tertiary deposits lie too deep to influence current coastal evolution. An exception is Zeeland where Tertiary deposits can lie directly below the Holocene deposits or below a thin Pleistocene cover (Figure 2.6). Zeeland is also characterised by a strong gradient in the elevation of the top of the non-eroded pre-Holocene substrate: it drops from near zero in Zeeuws-Vlaanderen to over -20 m NAP near Goeree. At several locations Holocene tidal channels have reworked the older deposits to depths of over -30 m NAP (Figure 2.7).

Until the far north of Walcheren Tertiary deposits can be found directly below Holocene deposits, although in general the Tertiary deposits below Walcheren are buried by Pleistocene sediment. Locally though, Holocene tidal channels have cut into the Tertiary deposits. The formations that generally contain the thickest clay layers, Dongen and Rupel (Figures 2.2, 2.8), lie below Zeeuws-Vlaanderen and the mouth of the Westerschelde (see also Chapter 3).

Southward of Westkapelle, the Tertiary deposits are frequently capped by tidal deposits from the Eemian (Figure 2.4) that in turn often lie below a thin layer of Weichselian aeolian cover sand (see also Figure 2.8). Northward of Westkapelle, until about Goeree, the top of the Pleistocene deposits is formed by either the aforementioned tidal deposits (Eem Formation) or early Pleistocene fluvial-estuarine deposits (Waalre Formation). The Eem Formation contains deposits ranging from tidal-channel deposits to muddy salt-marsh deposits. The deposits from the Waalre Formation formed in similar fluvial-estuarine settings as today, but due to their age and long exposure the deposits are relatively stiff.

An important change in the build-up of the subsurface occurs near Goeree that forms the southern edge of the late Pleistocene Rhine-Meuse valley in which the Kreftenheye Formation has been deposited (Figure 2.8). Below the shoreline of Goeree the top of the Kreftenheye lies relatively deep (-25 to -30 m NAP) and is commonly reworked by tidal channels. The Kreftenheye Formation consists mostly of medium to coarse sand with gravel, but also contains clay and loam layers.

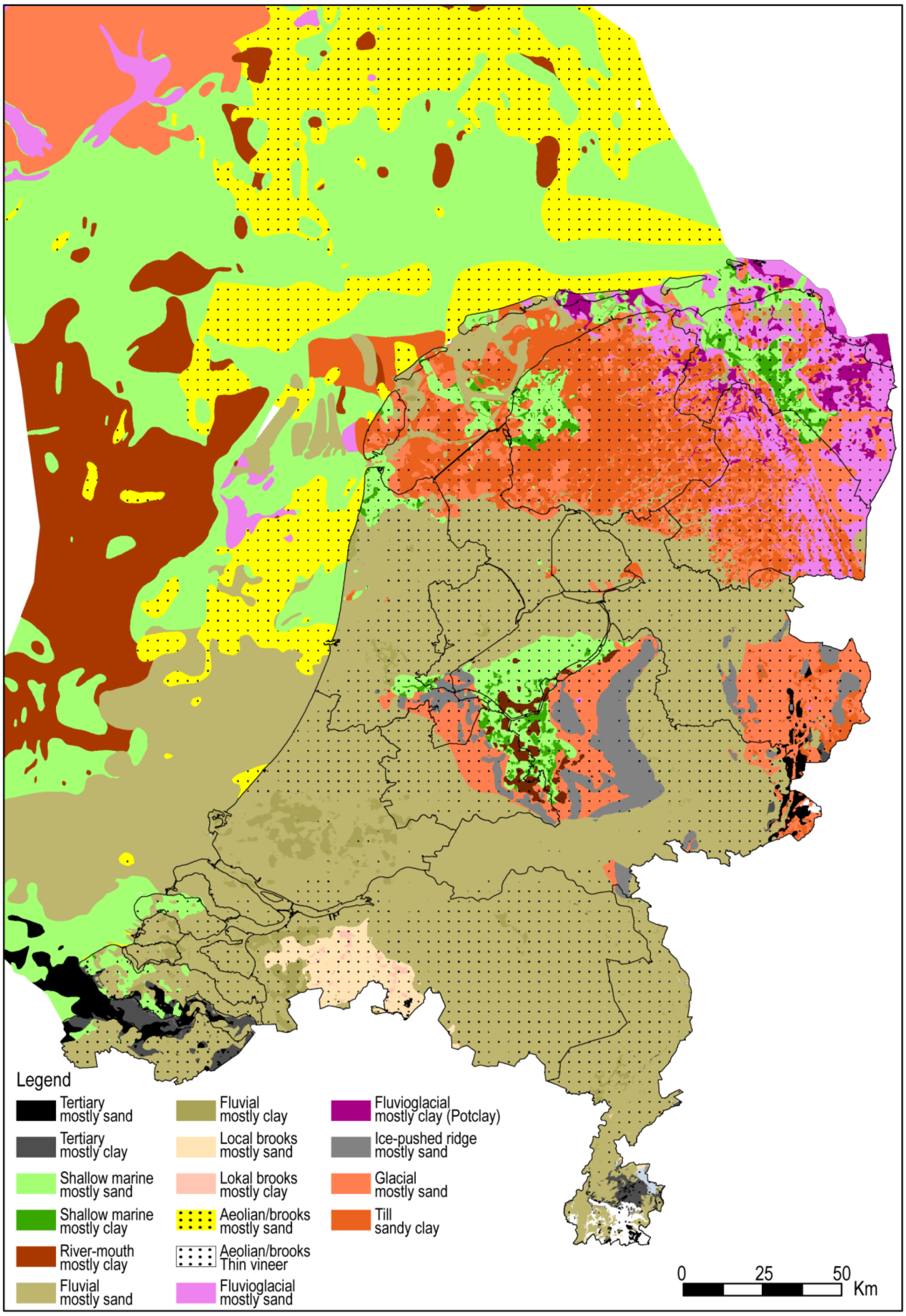


Figure 2.6 Overview of the type of deposits that lie below the base of the Holocene. In Zeeland, South- and North-Holland it are mostly fluvial deposits, with the exception of the Westerschelde area where Tertiary deposits are present and some areas where shallow marine deposits lie below the Holocene deposits. The northern part of the Netherlands has a very complex stratigraphy with fluvial, marine and glacial deposits below the Holocene. For the onshore area data from the Digital Geological Model (DGM) of TNO-Geological Survey of the Netherlands were used (Gunnink et al., 2013), both available via www.dinoloket.nl. The offshore distribution is a compilation of different geological maps.

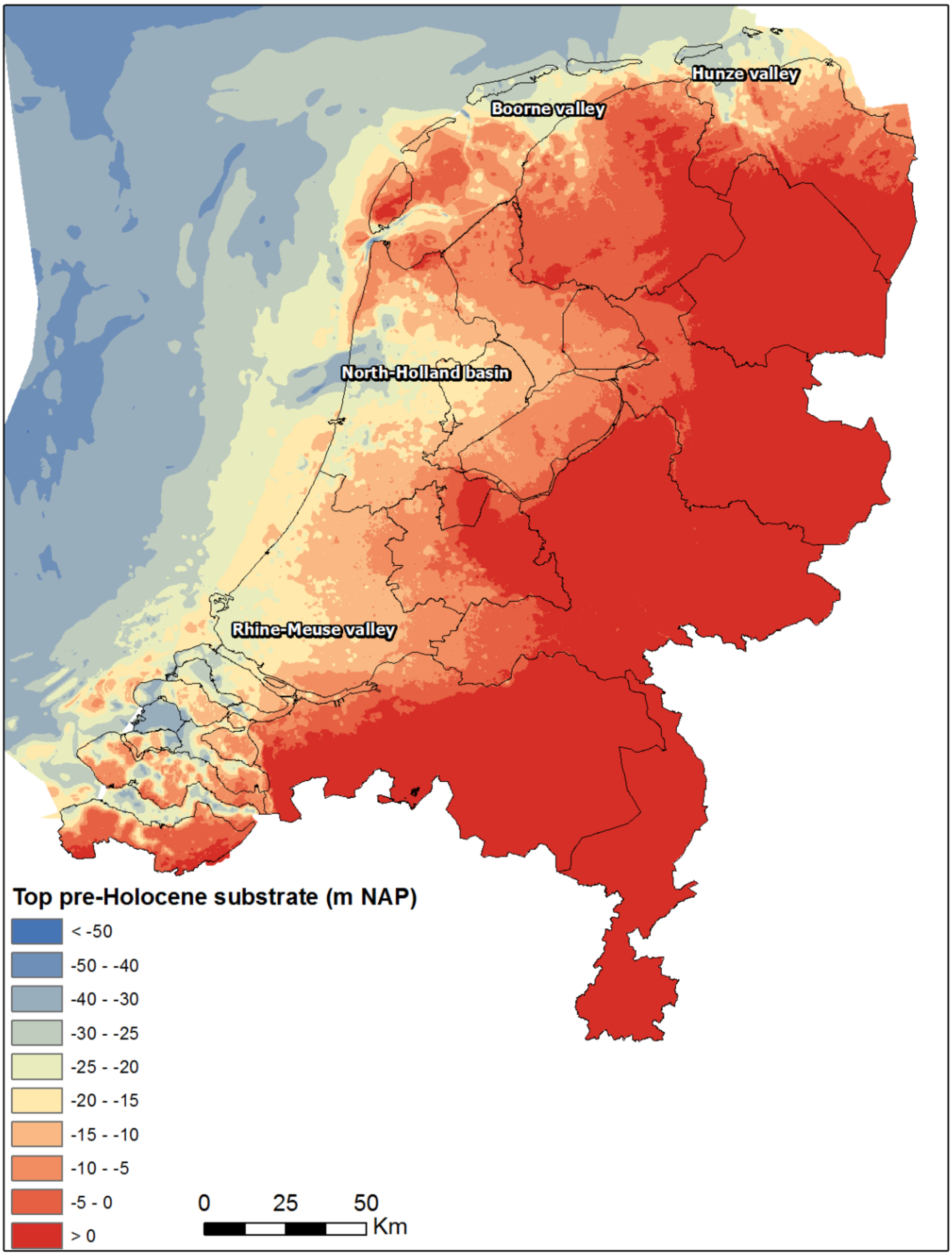


Figure 2.7 Elevation of the present top of the pre-Holocene substrate. Striking features are the extensive erosion by tidal channels in Zeeland, the wide valleys of the current Rhine-Meuse system (South-Holland) and a former Rhine system (North-Holland basin, Bergen tidal basin) and the smaller Boorne and Hunze valleys in the Northern Netherlands. The onshore elevations are based on DGM (www.dinoloket.nl), the offshore on the different geological maps for that area.

2.1.2 South- and North-Holland (until Wieringen)

From Goeree to Bergen, the top of Pleistocene deposits generally consists of the Kreftenheye Formation (Figure 2.8). The youngest Pleistocene Rhine-Meuse system was active in the Late Glacial-early Holocene and cut a valley between Goeree and Scheveningen that was partly filled-in later on. The valley floor is frequently, especially in the Maasvlakte area, capped by a stiff overbank clay (Wijchen Member) that is also found offshore (Figure 2.9) at depths of -17 to over -20 m NAP. The Wijchen Member mostly lies below the early Holocene basal peat. This means that in the offshore zone southwest of the Maasvlakte area, where basal peat is frequently found, the Wijchen Member is also preserved (
Figure 2.13).

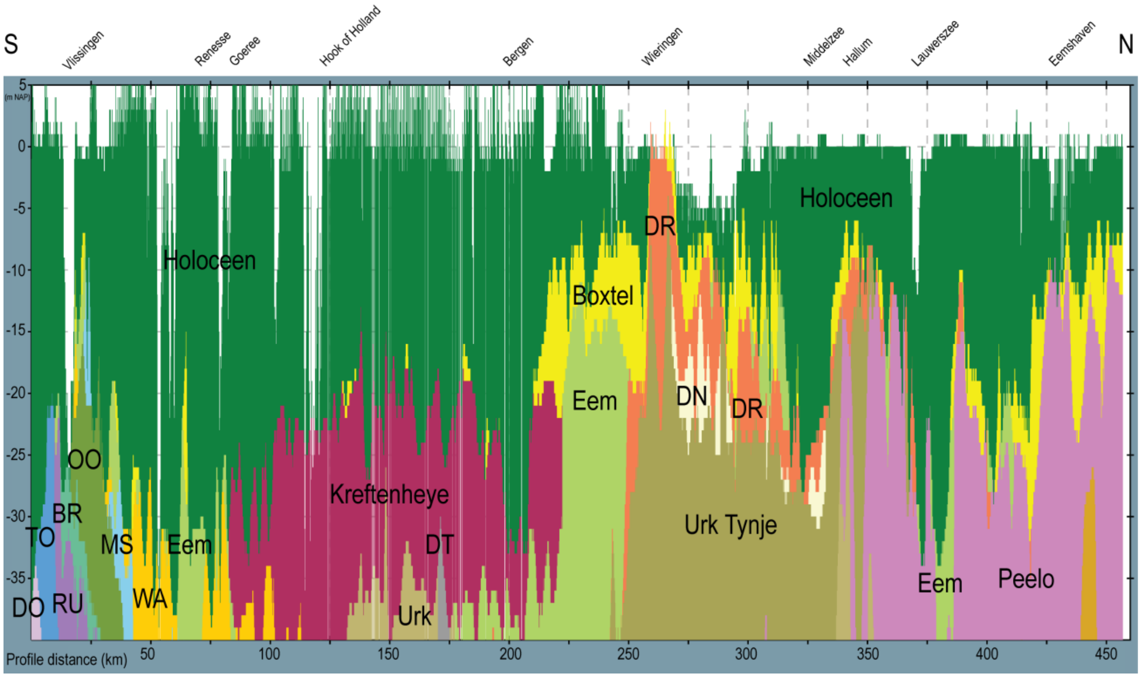


Figure 2.8 Cross-section along the Dutch shoreline from Belgium to Germany (across the Afsluitdijk) showing the position and depth of the geological formations according to DGM. DO=Dongen Formation;TO=Tongeren Formation, RU=Rupel Formation; BR=Breda Formation; OO=Oosterhout Formation; MS=Maassluis Formation; WA=Waalre Formation, DT=Ice-pushed deposits; DN=Drachten Formation and DR=Drente Formation. Based on the GeoTOP-model from TNO-GDN.

North of Scheveningen the Wijchen Member is absent and there the Kreftenheye Formation is capped by aeolian cover sand. At many places the cover sand was eroded during the Holocene transgression. Within the Late Glacial-early Holocene Rhine-Meuse valley no cover sand was deposited within the active flood plain. Instead, smaller but higher patches of blown-up sand, river dunes, formed along dry river banks. Offshore, the smaller aeolian river dunes have survived erosion locally (Figure 2.9). They were also found in The Maasvlakte area during the extension of the Yangtze-harbour (Moree and Sier, 2015).

During the Saalian the maximum extent of the ice sheet along the present shoreline was right at the border of South- and North-Holland (Figure 2.1) and ice-pushed deposits have been inferred at depths of less than -30 m NAP (Figure 2.8). The offshore extent of these ice-pushed deposits and the offshore presence of glacial till are not well known (but see e.g. Laban, 1995; Westerhoff et al., 2003). The till mostly formed as ground moraine and is a mix of clay, loam, gravel and stones. It is relatively resistant to erosion. The ice sheet carved out several deep basins in The Netherlands that in the subsequent Eemian period were rapidly transgressed (Figure 2.10). It is for this reason that north of the ice-pushed deposits Eemian deposits are present, initially at depths below -35 m NAP, but north of Bergen they lie around -10 m NAP. This elevational difference is due to presence of an early Weichselian Rhine-system that via the IJssel basin prograded through the Eemian tidal basin. The Rhine-system partly reworked the Eemian deposits, but also laid down deposits that are assigned to the Kreftenheye Formation, while at the same time tidal deposits of the Eem Formation were formed north of the Rhine-system. North of Bergen the Eemian deposits are generally covered by a relatively thick Boxtel Formation.

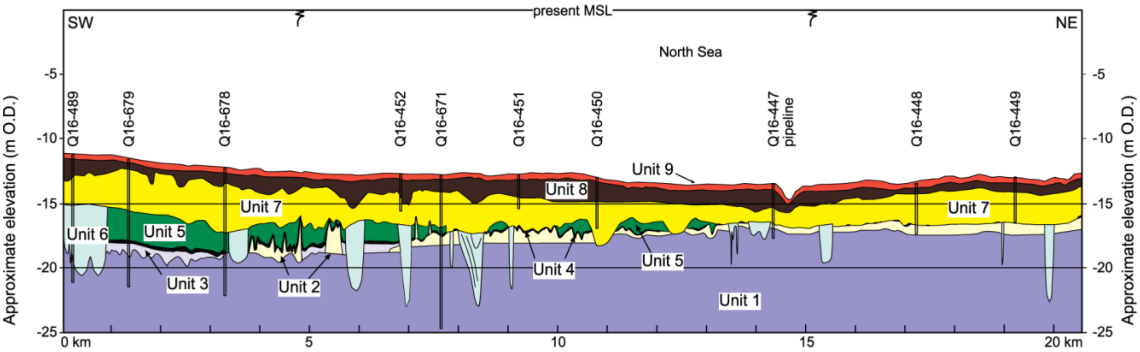


Figure 2.9 Shore-parallel cross-section. Unit 1 is a complex of fluvial channel deposits (Kreftenheye-Echteld Formation), Unit 2 is an aeolian deposit (river dunes and cover sand), Unit 3 is a loamy overbank deposit (Wychen Member), Unit 4 is a basal peat layer, Unit 5 consists predominantly of freshwater clay (Echteld Formation), Unit 6 consists of back-barrier channel fills and Units 7–9 are lower shoreface deposits (Unit 6-9 belong to the Naaldwijk Formation). See Figure 2.1 for location. From Hijma et al. (2010).

2.1.3 Friesland (from Wieringen to Hallum)

North of Wieringen, in Friesland and Groningen, the subsurface configuration is very different compared to South- and North-Holland (see Figure 2.7). It is dominated by deposits that are directly related to periods in which ice sheets reached The Netherlands (RGD, 1977). Another relevant difference is that some of the deposits are over consolidated by the weight of these ice sheets. Over consolidation results in a relatively low erodibility.

The island of Wieringen itself is situated on an ice-pushed ridge with glacial till (Drente Formation) at the surface. Below lie deposits of the Tynje Member of the Urk Formation, fluvial deposits from a pre-Anglian Rhine-Meuse system that consist of medium to coarse sand, but can also contain thick clay layers. From Wieringen to the former Middelzee area the elevation of the glacial till gradually decreases from 0 to -20/-25 m NAP (Fig. 2.7). At many locations the glacial till is covered by the Boxtel Formation. In the Lake IJssel area the Drachten Formation is often present between the till and the Tynje Member. The Drachten Formation has similar characteristics as the Boxtel Formation, but is older and over consolidated.

In the Harlingen area an Eemian tidal basin was present and there the glacial till is covered by tidal deposits. Between Wieringen and the Middelzee area the position of the top of the Pleistocene deposits varies between -5/-15 m NAP, whereas in the Middelzee area the depth of the top drops to below -20 m NAP. The Middelzee formed within the Boorne Valley that has a Pleistocene origin (e.g. Van der Spek, 1994) and was deepened by Holocene tidal channels. East of the Middelzee lies the northern extension of the Frisian-Drentian glacial till plateau that is characterised by a relative shallow occurrence of Pleistocene deposits.

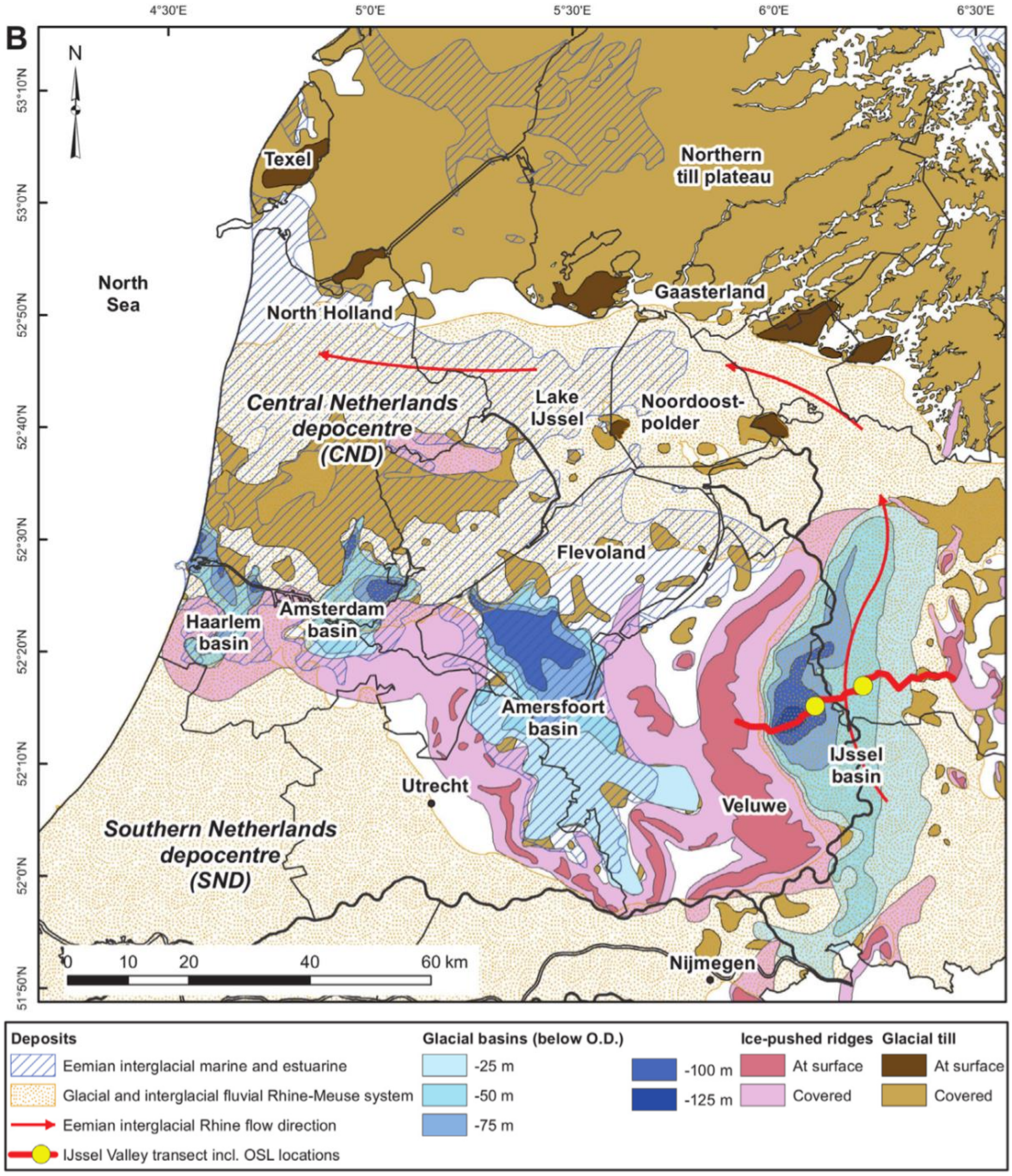


Figure 2.10 Late Pleistocene Rhine and Eemian interglacial marine and estuarine deposits in relation to the inherited (glacio-) topography in The Netherlands (modified from Peeters et al., 2015).

2.1.4 Groningen (from Hallum to Germany)

From Hallum until the German border the Pleistocene deposits are dominated by those of the Peelo Formation (Figure 2.7). These deposits filled in the deep valleys that formed during the Elsterian glacial period. The Peelo Formation is well known for the Potclay it contains. This clay is dark grey to black, over consolidated, very stiff and can be present in layers of over 10 m thick. However, the Peelo Formation is very heterogeneous and over short distances Potclay can abruptly change in thick layers of fine to coarse sand. The Peelo Formation lies relatively shallow in areas between Hallum and the Lauwerszee, in a small area east of the Lauwerszee and south of the Eemshaven. In the Lauwerszee area the top of the Pleistocene lies very deep, occasionally below -30 m NAP. This is due to deepening by Holocene tidal channels of the Pleistocene Hunze-valley. The Pleistocene deposits at the base of the

Hunze-valley are Eemian tidal deposits. These deposits are also present between the Pleistocene high at the eastflank of the Hunze-valley and the Eemhaven area.

Except for the Rottumerplaat-area, no glacial till has been mapped below the shoreline of eastern Groningen (Figure 2.11). Initially the top of the Peelo Formation (Figure 2.7) lies relatively deep, below -20 m NAP, but southward of the Eemshaven it commonly occurs around -10 m NAP, although large variations in elevation occurs due to the presence of Pleistocene brook valleys (Vos et al., 2011) that cut into the top of the Peelo Formation. The Peelo Formation is covered there by the Boxtel Formation that is at its thickest in these brook valleys.

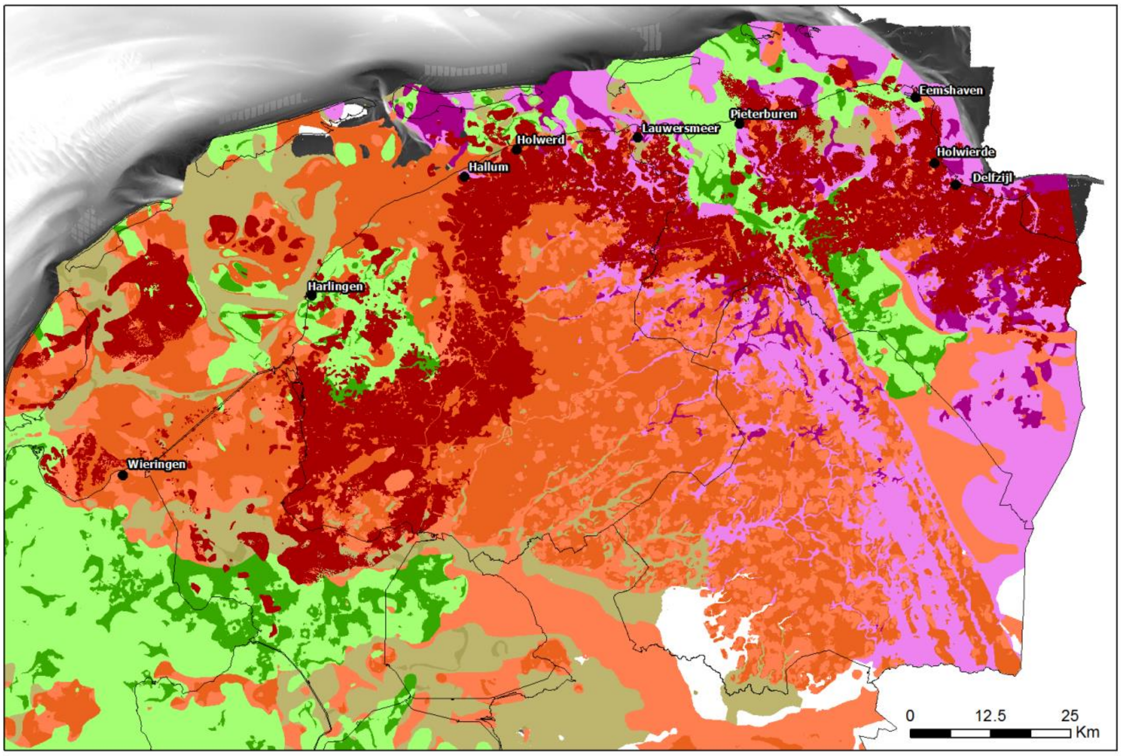


Figure 2.11 Pleistocene formations at the base of the Holocene (according to DGM, excluding the Boxtel Formation; see Figure 2.9 for the legend) and the areas where basal peat is found (according to GeoTOP, brown colours). Bathymetry is shown for reference.

2.1.5 Wadden Isles and Wadden Sea

From Texel to Vlieland the elevation of the top of the Pleistocene gradually lowers from -5 to -20 m NAP. Below the North Sea shorelines of the other isles the top of the Pleistocene frequently lies below -30 m NAP (Figure 2.12). In general, the top of the Pleistocene lies higher at the Wadden Sea side of the isles.

Texel is formed around an ice-pushed ridge and is the only Dutch isle with a Pleistocene nucleus. In the southeastern part of the Texel the Pleistocene deposits lie directly at the surface. The ridge is capped by a thick unit of the Boxtel Formation. Below the Boxtel Formation glacial till is present that is also frequently found below Vlieland and to a lesser extent below Terschelling (Figure 2.13). The deeper subsurface of Texel-Vlieland-Terschelling predominantly consists of the fluvial Urk Formation, although especially below Terschelling Eemian tidal deposits can be found. Below Ameland the Eemian deposits lie on top of the Peelo Formation (Van der Spek, 1994). Where the Holocene basal peat has been preserved, e.g. below the eastern part of Ameland (Van Heteren and Van der Spek, 2003), aeolian cover sand can be expected below the peat. Schiermonnikoog lies above the Hunze-valley that contains thick stacks of Eemian deposits. Below both sides of Schiermonnikoog the Peelo Formation is most likely present (Figure 2.12).

In the western part of the Wadden Sea it is mostly glacial till that forms the top of the Pleistocene, except where Holocene tidal channels have cut into the underlying fluvial deposits (Figure 2.12). West of Harlingen, and especially in the Schiermonnikoog area, the top of the Pleistocene consists of deposits that belong to the Eem Formation. Eastward of the Terschelling it is mostly the Peelo Formation that lies below the Holocene deposits.

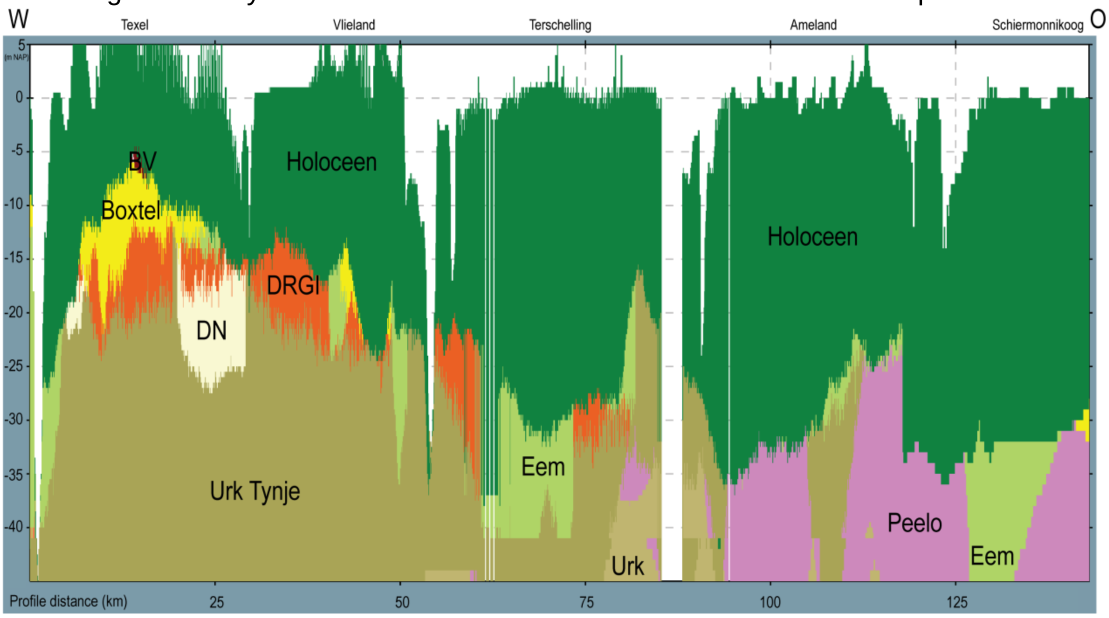


Figure 2.12 Cross-section along the Wadden Isles (North Sea shoreline) showing the position and depth of the geological formations according to DGM. DRGI=Gieten Member of the Drente Formation (glacial till). Based on the GeoTOP-model from TNO-GDN.

2.2 Holocene

The Holocene deposits below the shoreline are dominated by sandy deposits. Offshore, the Holocene transgression resulted in erosion of most of the early-middle Holocene terrestrial deposits and also below the shoreface the Holocene deposits mostly consist of sand. There are, however, several areas that differ from this general build-up and it is on these areas that the overview below will focus.

2.2.1 Zeeland

Below the shorelines of Zeeuws-Vlaanderen relatively thick clay layers occur at different depths, but they are mostly tidal-channel fills of limited lateral extent. Also farther offshore clay layers are present, especially below the Vlakte van de Raan between -15 to -20 m NAP (Van der Spek, 1997; Hijma et al., 2012). Below Walcheren, Noord-Beveland and Schouwen relatively large areas have survived post-Roman erosion by tidal channels (Vos and Van Heeringen, 1997) and in those areas middle-late Holocene Hollandveen is present, commonly between -1.5 to -2.5 m NAP (

Figure 2.13) Below the Hollandveen older tidal-channel deposits can be present, but also thick stacks of early-middle Holocene brackish clay. The offshore extent of the Hollandveen and brackish clays is generally not well known, but north of Schouwen an offshore zone is present where basal peat is frequently found below -25 m NAP (Hijma et al., 2012).

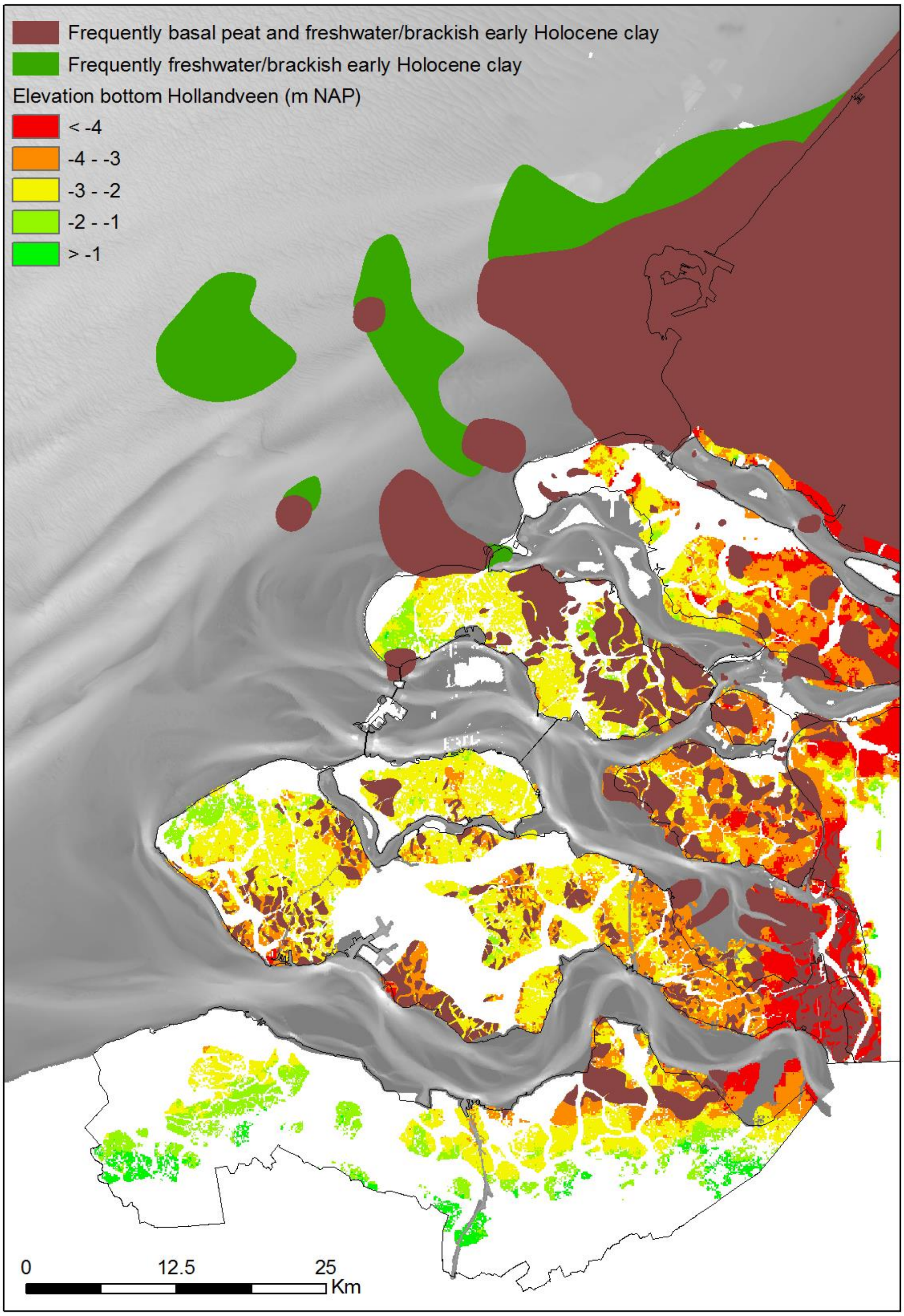


Figure 2.13 Map of the southwestern Netherlands showing the elevation of the bottom of the Hollandveen (based on GeoTOP, the 3D-geological model of shallow subsurface (30-50) of The Netherlands; Stafleu et al., 2013), the areas where basal peat and early Holocene clay frequently are present (based on GeoTOP (onshore) and Hijma et al., 2012 (offshore)) and offshore areas where early Holocene clay is present (Hijma et al., 2012). The bathymetry is shown for reference. Most of the offshore clay and peat bed occur well below -15 m NAP.

2.2.2 South- and North-Holland (until Wieringen)

The Goeree-Hook of Holland area contains meter-thick stacks, also offshore, of early-middle Holocene peat and clays (Figures 2.9, 2.14). The offshore extent has been mapped in considerable detail using seismic data and borehole-information (Van Heteren et al., 2002; Van Heteren, 2007; Hijma et al., 2012). The deposits generally lie below -15 m NAP with maximum depths around -25 m NAP. North of Hook of Holland the preserved deposits become increasingly brackish (Beets et al., 1995), and also increasingly thin as the top of the Pleistocene rises. North of Katwijk until IJmuiden, the base of the Holocene ravinement surface cuts into the Pleistocene (Hijma et al., 2010). Offshore Katwijk lies a lobate-shaped underwater deposit of the Old Rhine delta that consists of sand with clay and shell layers (Figure 2.15, Van Heteren and Van der Spek, 2008).

North of IJmuiden the top of the Pleistocene drops into the North-Holland basin that was transgressed in the early Holocene and turned into a large tidal basin (Figure 2.7). The largest inlet of this basin, the Bergen tidal inlet, closed shortly after 3500 BP (Beets et al., 1996). The North-Holland basin also hosted the Oerij tidal inlet that closed around 2100 BP (Vos, 2015). During the first phase of the transgression, the North-Holland basin formed a relatively shallow basin in which peat formed and brackish clay accumulated. At the southern flank of the North-Holland basin, large stretches of this clay, the Velsen Bed, have been preserved at depths of -16 to -20 m NAP. The Velsen Bed is also found offshore and can be over a meter thick (Erkens et al., 2014), see Figure 2.15.

The infill of the North-Holland basin contains the characteristic Bergen Bed of the Naaldwijk Formation. The Bergen Bed consist of (sandy) clay generally starts below -15 m NAP and can be over 20 m thick (Figure 2.15). Its offshore extension (cross-shore) seems limited to a 2 km wide zone (Erkens et al., 2014). North of the North-Holland basin, the top of the Pleistocene rises rapidly to an elevation above -10 m NAP (Figure 2.7). The Holocene sequence is variable, but contains preserved Hollandveen-brackish clay-Basal Peat sequences that can be over 5 m thick. The offshore extent of such sequences is not well known, but is expected to be limited due to the relatively high elevation at which they occur onshore and hence the vulnerability to shoreface erosion.

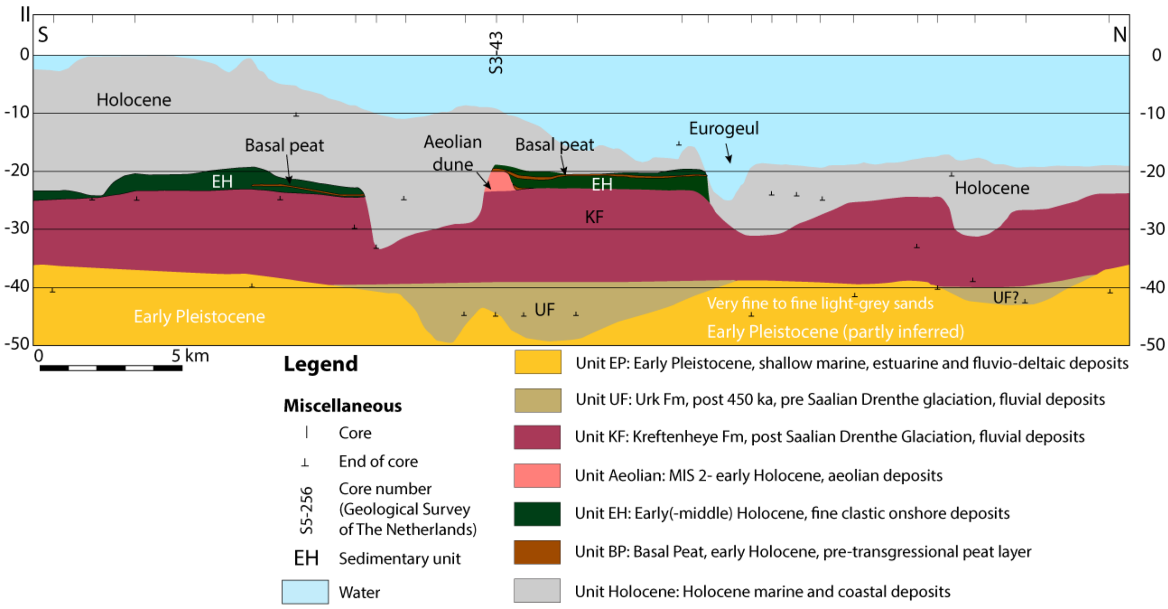


Figure 2.14 Offshore cross-section showing thick stacks of preserved early Holocene deposits (see Figure 2.1 for location, from Hijma et al., 2012).

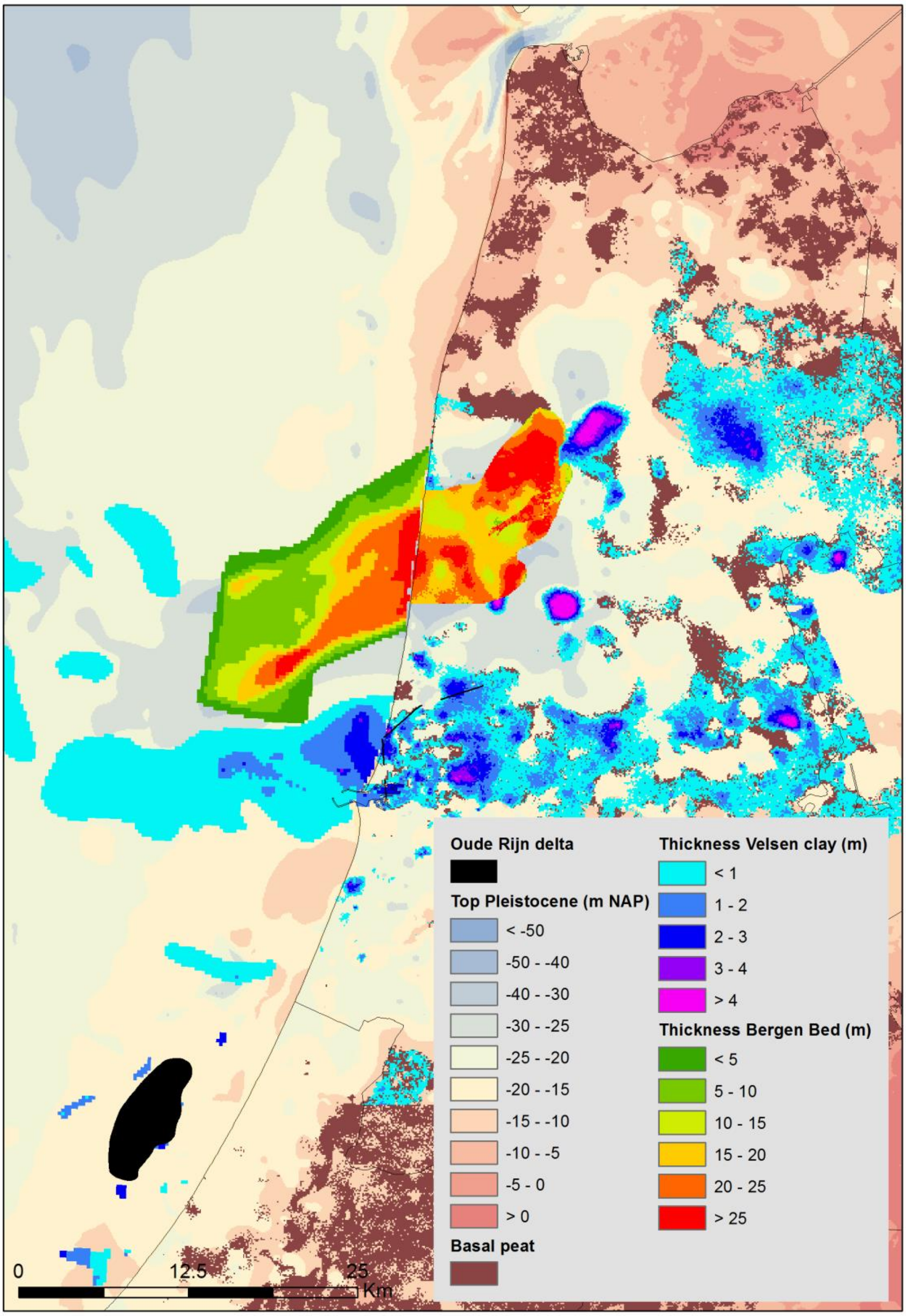


Figure 2.15 Map of North- and South-Holland showing the elevation of the top of the Pleistocene, the Oude Rijn delta (Van Heteren and Van der Spek, 2008) and the extent of the basal peat, the Velsen Bed and the Bergen Bed (based on GeoTOP and offshore seismic surveys, see e.g. Erkens et al., 2014). The base of these deposits lies directly above the Pleistocene.

2.2.3 Friesland (from Wieringen to Hallum)

Along the Afsluitdijk the Holocene sequence generally consists of tidal-channel (fine to medium sand) and tidal-flat deposits (clay, sandy clay, clayey sand). Near both ends of the Afsluitdijk the sequence can be over 5 m thick, while in the centre the Holocene sequence is thinner than 1 m (Figure 2.7). In general the same deposits, tidal-channel and tidal-flat, are found along the Wadden Sea shoreline until Hallum. A unit of clayey tidal-flat deposits is often present directly below the surface and especially between the Afsluitdijk and Harlingen these deposits can be very clayey and over 5 m thick. At places tidal channels have incised deeply, over 20 m deep, especially in the former Middelzee area. Very occasionally the basal peat has escaped erosion (Figure 2.11).

2.2.4 Groningen (from Hallum to Germany)

From Hallum to the Lauwerszee area the thickness of the Holocene sequence initially decreases gradually to less than 5 m, but then increases again to over 10 m (Figure 2.7). This is due to the presence of the Pleistocene Frisian-Drentian glacial till plateau. At many locations a basal peat-brackish clay sequence is present at the base of the Holocene. In the Holwerd-Ternaard area the basal peat can be more than 1 m thick and also offshore the basal peat is frequently present (Van der Spek, 1996), see Figure 2.11. In the Moddergat-Pieterburen area the Holocene sequence can reach a considerable thickness, over 15 m, and contains clay units over 5 m thick, but mostly consists of sandy tidal-channel deposits to depths over -25 m NAP that filled in the Hunze-valley (Figure 2.7). The east flank of this valley is formed by a Pleistocene high that crosses the shoreline northeast of Pieterburen. On top and on the flanks of the high, a basal peat-clay sequence has been preserved around -9 m NAP below tidal-channel deposits. Eastward, up to the Eems estuary, the basis of the Holocene lies relatively deep, between -15/-25 m NAP. The sequence is dominated by sandy tidal-channel deposits that frequently begin directly at the surface. Alternatively the first meters are formed by clayey tidal channel-deposits. At depth, especially below -5 m NAP, 5 to 10 m thick clay units are occasionally present.

South of the Eemshaven, until Holwierde, the Holocene sequence is still well over 10 m thick, but consists increasingly of thick (organic) clay units below -5 m NAP. Sandy tidal-channel deposits do occur, but mostly between 0 to -7 m NAP. South of Holwierde the top of the Pleistocene gradually rises to average elevations of -10 m NAP. Tidal-channel deposits become increasingly rare and the entire Holocene sequence consists of (organic) clay with meter-thick peat layers present between -2 to -5 m NAP. The offshore extent of these peat layers is not well known. In the Delfzijl area both clay and peat layers and sandy tidal-channel deposits are present. Farther eastward, until the Dollard, peat layers are frequent again, tidal-channel deposits are nearly absent and the Holocene sequence mostly consists of clay. Finally, below the shoreline of the Dollard, the Holocene is approximately 5-8 m thick and is formed by 4-5 m of tidal-flat deposits on top of peat.

2.2.5 Wadden Isles and Wadden Sea

Along the North Sea shore the Holocene sequence of the Wadden Isles mostly consist of sand, either tidal-channel or shoreface-beach-dune deposits. The base of the Holocene drops gradually from -5 m NAP below Texel to over -20 m NAP below central Vlieland. Further east, the base of the Holocene fluctuates around -25 m NAP with the exception of the far east of Ameland where the base lies a little above -20 m NAP (Figure 2.13).

The Holocene sequences along the Wadden Sea shorelines are different and can also consist of clay and peat. East of the Hoge Berg of the Texel, the top of the Pleistocene lies very shallow, mostly above -5 m NAP, and is covered by a 0.2-1 m thick peat layer that is capped by clay and a thin layer of sandy deposits. In the De Cocksdorp area the Pleistocene predominantly starts below -10 m NAP and the first 5-10 m of the Holocene consists of sandy clay. Also there basal peat is frequently encountered.

There is very little information about the Holocene sequence along the Wadden Sea side of Vlieland. The information that is available indicates a predominantly sandy sequence with thicker clay units below the eastern side of the isle. The base of the Holocene lies between -15 to -20 m NAP. This in contrast to the Waardgronden, to the southeast of the island, where a thick basal-peat layer is covered by only a thin layer of sandy tidal-flat deposits.

At Terschelling more information is available, all pointing towards a sequence dominated by sand. In the more sheltered polder areas around Midsland-Hoorn clay and peat layers occur in the first few meters (tidal to supratidal-flat deposits). The base of the Holocene lies between -20 to -30 m NAP (RGD, 1977).

The Holocene sequence of Ameland has been studied by Van der Spek (1994). Also here the deposits along the Wadden Sea shoreline consist primarily of sand, labelled cross-bedded sand by Van der Spek, with a base mostly between -20 to -30 m NAP. Below the eastern part the top of the Pleistocene can lie above - 20 m NAP. Offshore in de Wadden Sea the thickness of the cross-bedded sands decreases and basal peat is often present. Also north of Ameland basal peat has been preserved in small patches (Van Heteren and Van der Spek, 2003)

The onshore Holocene sequence of Schiermonnikoog is hardly known. Its position in front of the Hunze-valley explains the near absence of basal peat and strongly suggests that the sequence will consist entirely of tidal-channel deposits. The chance for preserved basal peat is highest below the extreme western and eastern parts of the island. Below the Engelsmanplaat, in between Ameland and Schiermonnikoog, a thick stack of clay with sand layers is present between -12 to -18 m NAP (Sha, 1992).

In the Wadden Sea large patches of basal peat, presumably in many cases covered by lagoonal clay, have been preserved in the Amsteldiep (west of Wieringen), the Waardgronden, the Griend area, north of Holwerd and Pieterburen, to the northwest of the Eemshaven and in the Dollard area (Figure 2.11).

3 The subsurface near tidal channels

Below, the subsurface surrounding some of the major tidal channels are summarized, based on existing literature and additional short analysis. The number of presented tidal channels is not exhaustive as a detailed analysis of the subsurface surrounding of all major tidal channels would require an additional substantial amount of work/time.

3.1 Westerschelde

Near the outlet of the Westerschelde several deep tidal channels are present (Figure 3.1) with the Oostgat in front of Westkapelle and the main navigation channel the Wielingen being the most important.

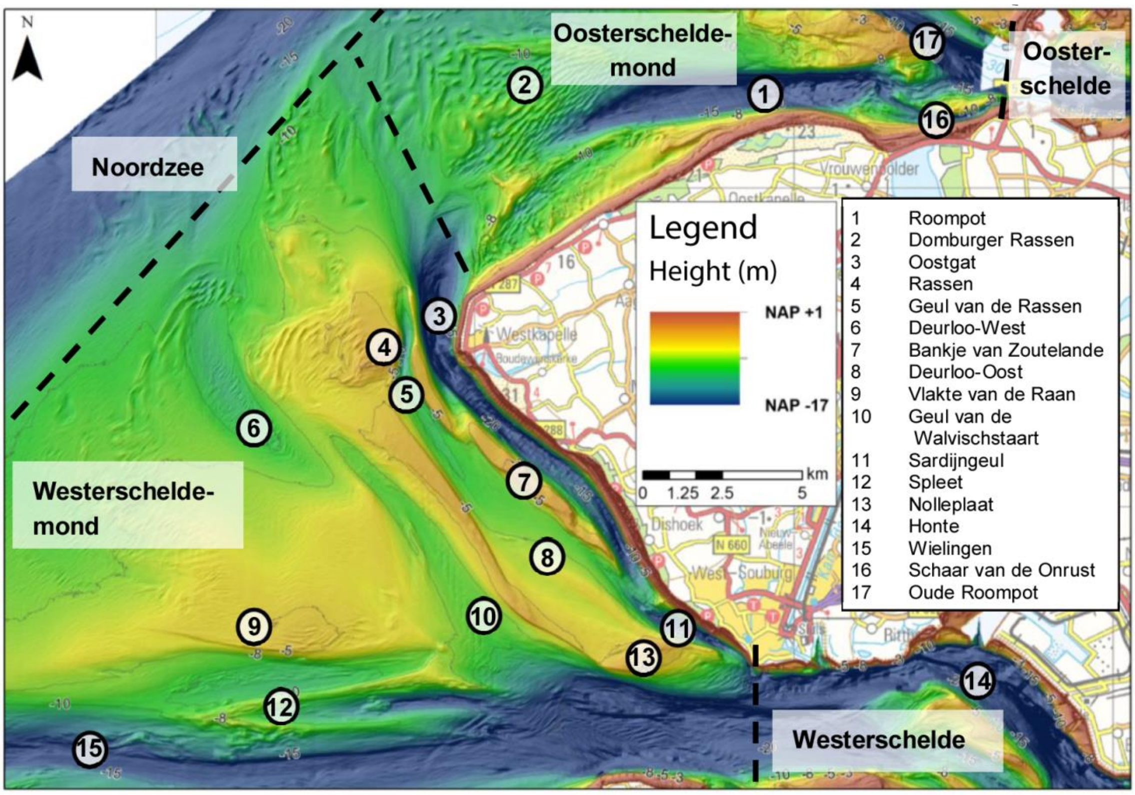
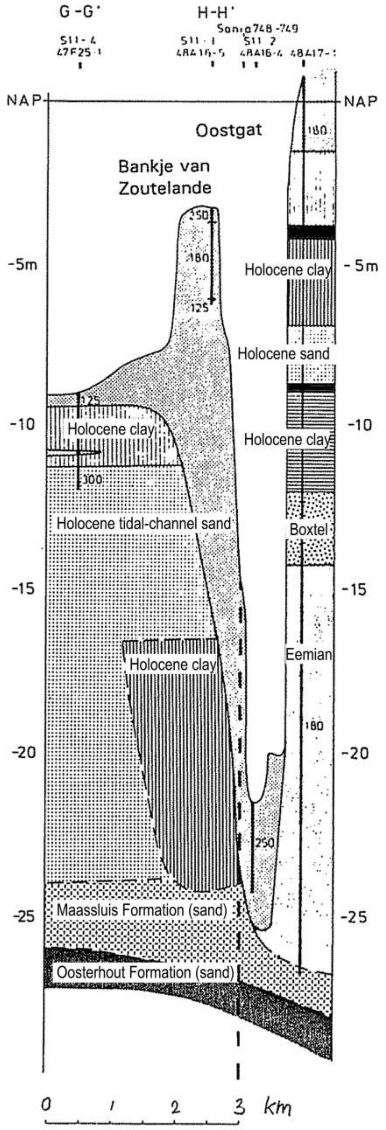


Figure 3.1 Bathymetry and the names of the tidal channels and tidal flats near the Westerschelde mouth, based on measurements from 2010/2011 (after Vermaas and Bruens, 2013).

During the last decades the Oostgat has increased in volume, by expanding both seaward, landward and downward (Vermaas and Bruens, 2013). The floor of the northern part of the Oostgat lies between -30/-35 m NAP, while to the south the elevation increases to -20/-25 NAP. A study by Van der Spek (1997) showed a cross-section across the Oostgat with a base of the Holocene at -25 m NAP (Figure 3.2). The seaward flank of the Oostgat is covered with recent tidal-channel sand, but between –17 to -23 m NAP also thick Holocene clay layers occur locally. On the landward side the sequence consists of mostly clay and peat between -3 to -13 m NAP with Pleistocene sand underneath. Directly below the channel base the Maassluis Formation is present. It is relatively thin, less than five meters thick, with Tertiary sands of the Oosterhout Formation below. The few data that have become available since 1997 agree with this general build-up. It is possible that north of the cross-section in Figure 3.2 the Oostgat has incised into the Oosterhout Formation as the channel in that area is 30 to 35 m deep. Within a few hundred meters landward of the Oostgat several boreholes indicate the presence of meters-thick clay layers at the top of the Oosterhout Formation.



The Wielingen is another important channel in the Westerschelde. It runs west-east and is tens of kilometres long (Figure 3.1). North of Breskens it reaches depths of - 25 m NAP, while more seaward its average depth is around -15 m NAP. North of Breskens the Boom clay of the Rupel Formation starts at -20/-25 m NAP, meaning that the base of the Wielingen is very likely in touch with the Boom clay. Next to the Wielingen channel the Holocene sequence is about 20-25 m thick and consists of Holocene tidal-channel sands and some clayey channel fills. No laterally extensive peat or clay layers are present. Further seaward the base of the Wielingen lies very close to pre-Holocene formations; either the Eem or Tertiary Formations (see also Figure 2.6 and Van der Spek, 1997).

Figure 3.2 The subsurface around the Oostgat south of Westkapelle (after Van der Spek, 1997).

3.2 Haringvliet

The (former) Haringvliet estuary near the Haringvlietsluizen has a very variable depth (Figure 3.3), with seaward of the sluices depths of less than 5 m –LAT, due to recent sedimentation after completion of the dam and sluices, and landward of the sluices scour holes as deep as 30 m –LAT which were formed when the estuary was still open.

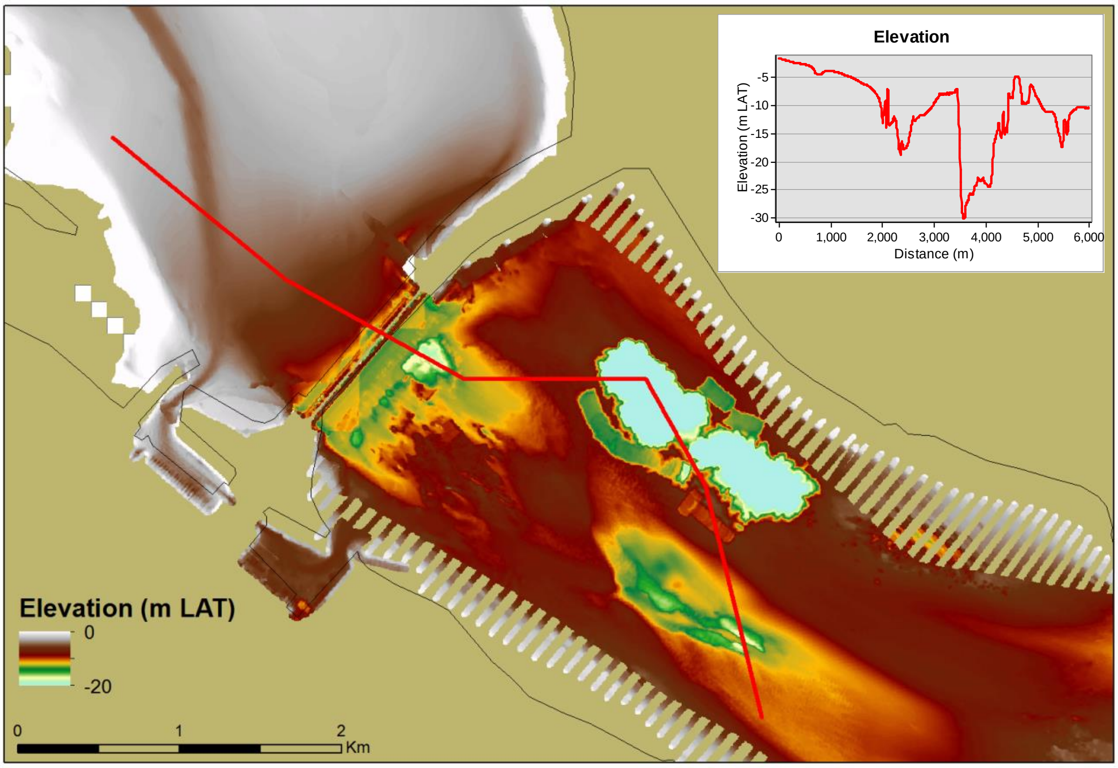


Figure 3.3 Bathymetric map for the Haringvliet estuary near the sluices. The bottom elevation along the red line is given in the profile in the upperright corner (going from west to east). The onshore colour indicates that the top of the Pleistocene sediments is formed by sandy fluvial deposits (see Figure 2.5 for legend). Zero LAT lies about 1 meter lower than 0 NAP.

Boreholes indicate that near the sluices the Holocene sequence along the southern shore is built up of sandy tidal-channel deposits, while along the northern shore peat and clay layers are frequently found between -1 to -5 m NAP, too shallow to influence the behaviour of the Haringvliet channels. Below -5 m NAP Holocene tidal-channel deposits are present. The top of the non-eroded Pleistocene lies just below -20 m NAP and if non-eroded could consist of the stiff Wijchen Member. It is unknown, however, if and how deep the Haringvliet channels have incised into the Pleistocene fluvial sediments of the underlying Kreftenheye Formation. In the scour hole the Kreftenheye is presumably almost completely removed as the elevation for the top of the Waalre Formation lies around -35 m NAP. The top of the Waalre Formation is well known for its stiff clay layers that would prevent further deepening of the scour hole.

3.3 Nieuwe Schulpengat

The Nieuwe Schulpengat is a relatively young tidal channel that formed around 1955 (Elias et al., 2014). It has basically been increasing in size ever since with its southward end slowly rotating towards the west and its northern part moving landward (Elias et al., 2014). It lies in an area with a heterogeneous build-up with glacial till and both Pleistocene and Holocene clay and peat layers (Van der Spek and Van Heteren, 2004). To better understand this build-up and the role it plays in the morphological evolution of the channel, several cores were taken along the landward flank of the channel (Figure 3.4; Van der Spek and Van Heteren, 2004).

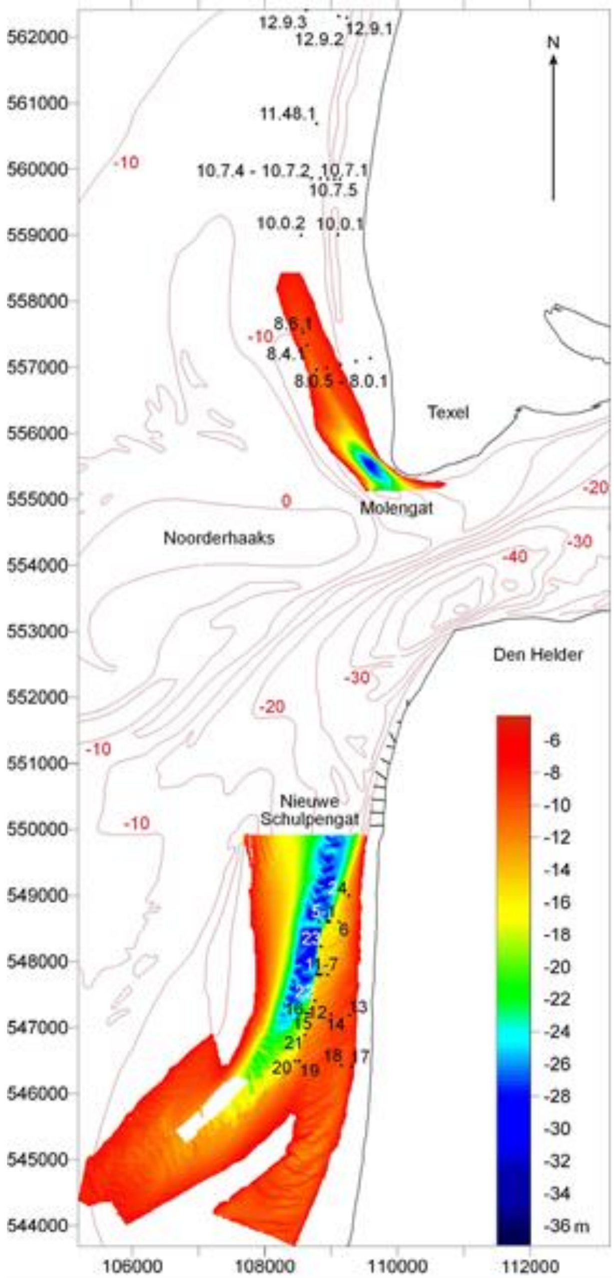


Figure 3.4 The bathymetry of the Nieuwe Schulpengat and the locations of mentioned boreholes in Van der Spek and Van Heteren (2004).

The deepest parts of the channel lie around -25 m NAP. On the landward side a plateau is present just above -15 m NAP (Figure 3.5). In the northern part of the Nieuwe Schulpengat, cores 2 to 5 indicate the presence of stiff clay from the Brown Bank Member of the Eem Formation below -19 m NAP (Figure 3.6). The clay layers are over 5 m thick and lie on top of marine sand. To the south the base of the channels has cut into fine sand, deposited by small rivers (Boxtel Formation). Below the plateau, and hence within the landward flank of the channel, thick, resistant clay and peat layers have been found between -12 to -16 m NAP. They were interpreted as thaw-lake deposits from the last glacial. Van der Spek and Van Heteren (2004) concluded that the Pleistocene build-up will result in relatively low lateral-migration rates, but that it will not prevent lateral migration. In addition they point out that the erodibility of the resistant layers is not well known and that the lateral continuation of the resistant layers is not mapped, but will have a significant influence on migration rates. In recent years the rate of landward migration of the eastern flank of the channel is higher in comparison to the 1997-2000 period. This will be studied in more detailed after the analysis of the geophysical data that was gathered in December 2015.

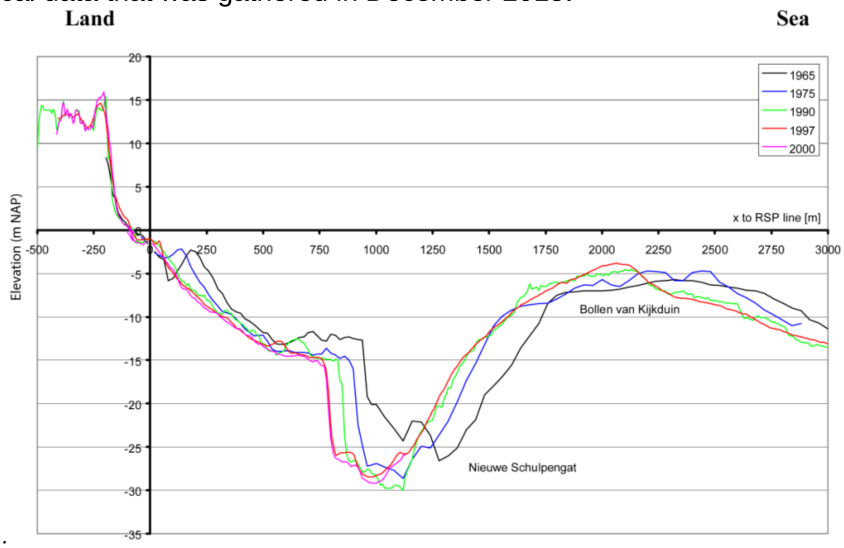


Figure 3.5 Bathymetric cross-section across the Schulpengat (left is landward; right is seaward). From Elias and Cleveringa (2003). The subsurface deposits below and alongside the channel will be known in more detail after the geophysical research of December 2015.

3.4 Vlie tidal inlet

Between Vlieland and Terschelling lies the Vlie tidal inlet. Its major channel is called Vliestroom with the Meepsystem branching of towards the east (Figure 3.7). Figure 2.113 indicates that the tidal channels have cut into Pleistocene fluvial deposits, while in between the channels, e.g. in the Richel and Griend areas, also basal peat and glacial till is present. The number of useful boreholes in the area is very limited; most of the boreholes were done within the Vliestroom and show Holocene tidal-channel sand. The deepest part of the Vliestroom, the tidal inlet, lies below - 40 m NAP, but its average depth is around -20 m NAP. The Meepsystem is shallower, in the order of -10 to -15 m NAP, but depths still reach -20 m NAP.

It was noted that the position of the tidal channels had not changed significantly over the last 2,000 years (Laban et al., 2000). To see whether this could be attributed to the presence of stiff Pleistocene and Holocene layers a geological study was started (De Leeuw, 2007) using seismic data and vibrocore information (Figure 3.7). This study shows that, apart from several patches of basal peat, glacial till forms the only deposit that could potentially influence lateral migration rates as the other present deposits consist of sand. Till occurs frequently, starting at depths of -20 m NAP in the north and at -16 to -18 m NAP in the south. The glacial till appears to be several metres thick. The till is covered by sandy deposits from the Boxtel Formation that is occasionally covered with basal peat.

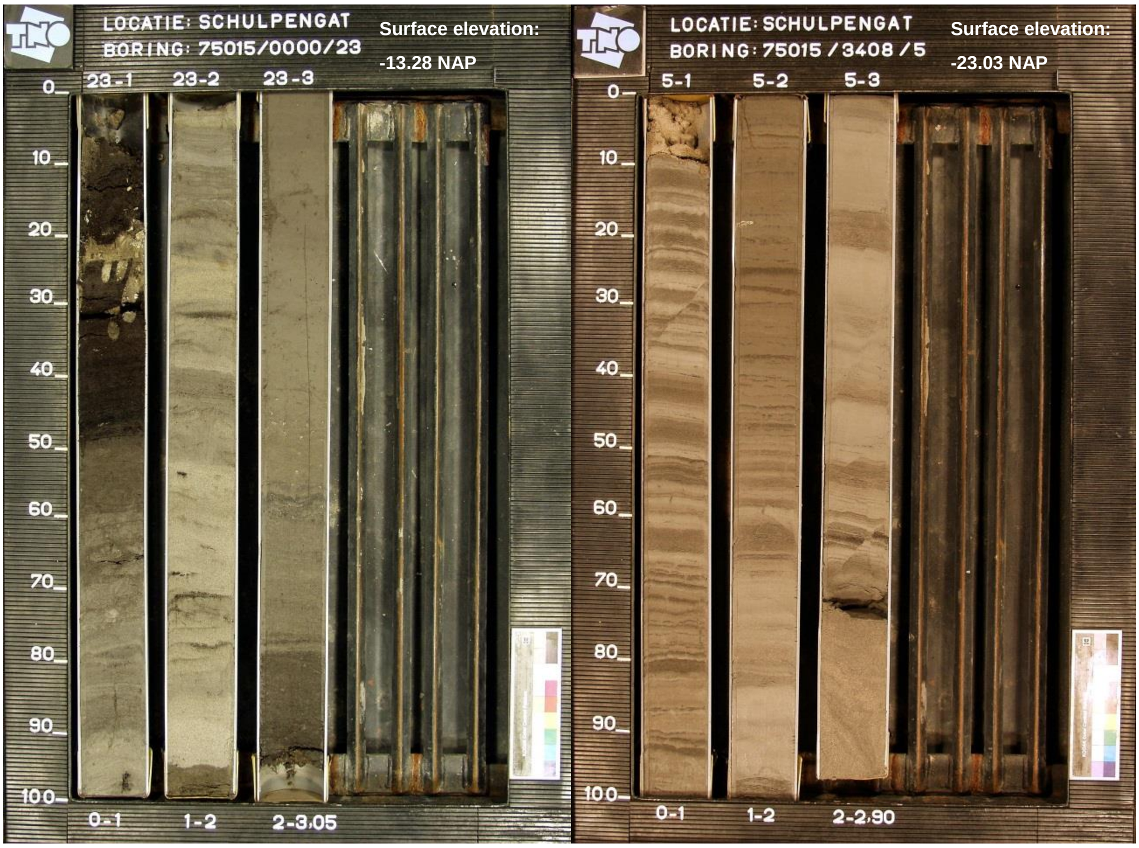


Figure 3.6 Two cores from the Nieuwe Schulpengat. Left: Core 23. The upper 0.5 m consists of a Pleistocene peat layer. The sand-filled "fingers" within the peat are filled-in burrows from the boring clam Barnea candida (Dutch: boormossel). Below the peat fluvial silt and sand layers are present until 1.95 m, with clayey thaw-lake deposits below. They were deposited during the last glacial (Weichselian). Right: Core 5. Between 0.1 and 2.7 m stiff, layered clay from the Eemian is present, with sandy Eemian deposits below.

De Leeuw concludes that the glacial till lies too deep to have an impact on lateral migration rates: the flanks of the channels mainly consist of the sandy Boxtel Formation. Within the Vliestroom the glacial till lies directly below the base of the channel and hence most likely prevents the Vliestroom from deepening. The presence of basal peat and early Holocene clay layers doesn't seem to have had any influence. Still, also De Leeuw suggests that the position of the channels has not changed significantly over the last millennia. Since no resistant layers have been found next to the channels, the reason for the static position has to be linked to hydraulic processes.

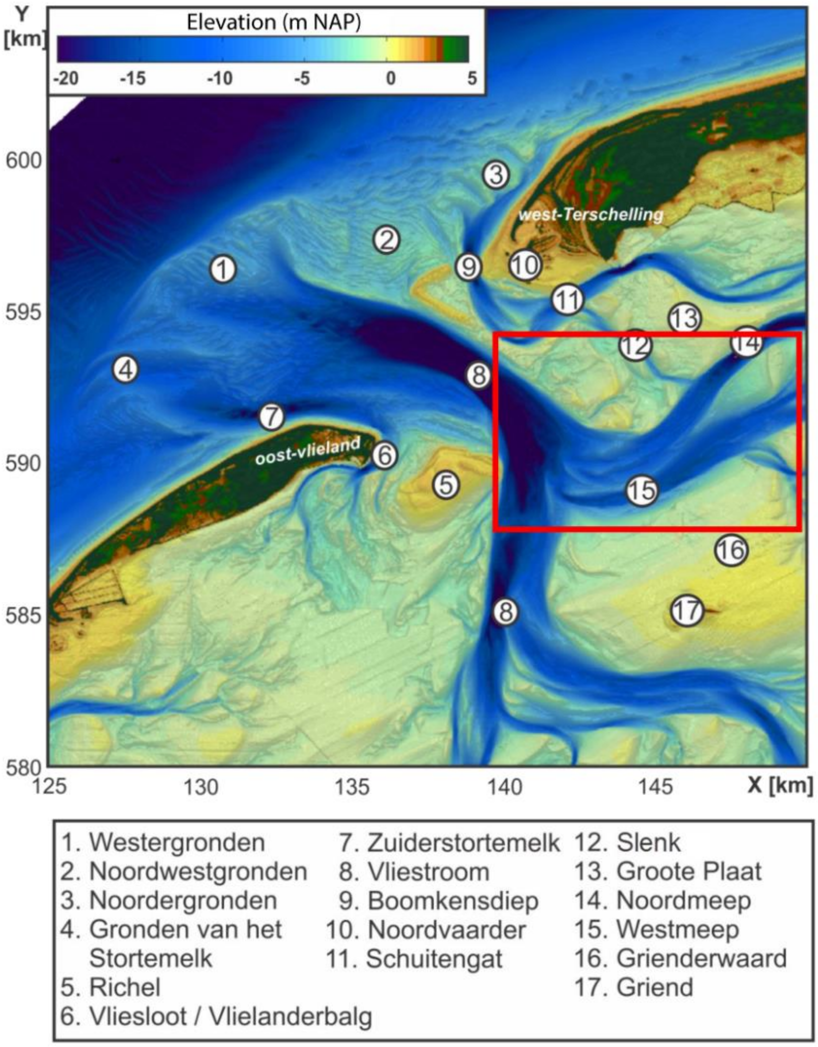


Figure 3.7 Overview of the major channels and flats in the Vlie tidal inlet with the bathymetry of 2010/2011 (Elias et al., 2015). The red box outlines the study area of De Leeuw (2007).

3.5 Ameland tidal inlet

The Ameland tidal inlet lies in between Terschelling and Ameland. Its main channel is the Borndiep that south of Ameland splits eastward into the Molengat and the Dantziggat (Figure 3.8.). Figure 2.11 indicates that several Pleistocene formations can be present below the Holocene, including resistant layers from the Peelo, Drente and Eem Formations. Depths in the Borndiep reach -15 to -30 m NAP, while the Dantziggat locally has maximum depths close to -20 m NAP, but has average depths of -12 to -14 m NAP. The Molengat is relatively shallow with -6 to -8 m NAP. Over the last 80 years relatively large morphological changes have occurred in the Boschplaat-Boschgat area, while the more eastern part of the inlet system was far less dynamic. The Borndiep is slowly moving eastward, hereby eroding the western tip of Ameland (Elias, 2013). The channel position is fixed with stone revetments.

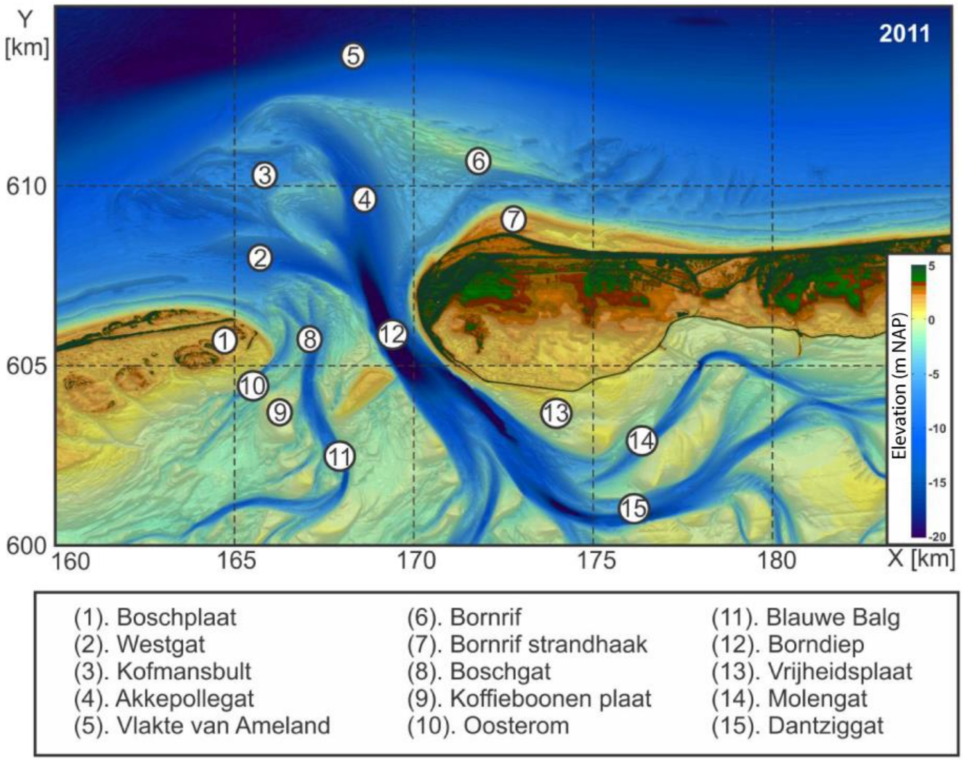


Figure 3.8 Overview of the major channels and flats in the Ameland tidal inlet with the bathymetry of 2011 (Elias, 2013).

The build-up of the area, especially south of Ameland, was studied by Van der Spek (1994). His work and an additional analysis of available boreholes clearly show the presence of Potclay from off –23 to -25 m NAP in the Borndiep area, so just below the base of the channel. Sometimes the Potclay is covered with sand and clay from the Eem Formation. The eastern flank of the Borndiep seems to entirely consist of Holocene cross-bedded sand, thus posing comparatively little resistance to erosion. Also in the western Dantziggat-Molengat area the top of the Pleistocene is commonly formed by Potclay that occurs mostly just above -20 m NAP. The Potclay is occasionally covered by a thin layer of glacial till. South of the Dantziggat the Pleistocene rises to an elevation of -10 m NAP with over 5 m thick glacial till covering the Peelo Formation. The eastern part of the Dantziggat-Molengat area is different with relative high elevations for the top of the Pleistocene, -10 to -15 m NAP, and a very complex mixture of Peelo, Boxtel, Drente and Eem Formations. Here, the base of the Holocene frequently is formed by a basal peat-organic clay sequence.

Both the Borndiep, the Dantziggat and the Molengat have Potclay very close to the base of their channels, so the channels will not get deeper easily. The flanks of the Borndiep seem to contain no significant clay or peat layers that could slow down lateral migration rates. The same applies to the western parts of the Dantziggat-Molengat channels. This is due to their position within the area of the former Boorne-valley, so during large parts of the Holocene tidal channels will have been present. The eastern parts, on the other hand, most likely experience more lateral resistance due to the presence of relatively shallow patches of basal peat. However, below the basal peat it is mostly Pleistocene sand that is present instead of Potclay. But as the extent of the different units (till, Potclay, basal peat) is not well known, the influence of the build-up of the subsurface on migration patterns cannot be determined more specifically. This would require a detailed comparison of the migration patterns of the Dantziggat-Molengat channels with newly acquired subsurface information.

4 Map of erosion-resistant layers in the coastal zone

This chapter presents a map that can be used as a first-order approximation of areas with erosion-resistance layers occurring at relevant depths. The map is divided into three submaps for the southern, central and northern parts of the Dutch coastal zone. The southern zone corresponds to the area where Tertiary and Early Pleistocene deposits lie relatively shallow, in the central zone the erosion-resistant deposits mostly have a Holocene age, while in the northern zone there has been a lot of influence of past glaciations on the formation and distribution of erosion-resistant layers.

Two criteria were used to draw this map: 1) for areas outside the present influence of tidal channels, the resistant deposits have to lie above -15 m NAP and 2) around tidal-channel systems the resistant deposits have to occur within ~250 m of the edge of the channel and within the entire depth range of the tidal channel, so possibly well below -15 m NAP. The -15 m NAP criterion has been chosen, because recent research seems to indicate that for most parts of the Dutch coast there is very little morphological change below this depth (Vermaas et al., 2015). The 250 m criterion was chosen rather arbitrary: the distance had to be within reach of tidal-channel migration in more or less the next decades, but small enough to execute this first-order approximation map within this project. In some areas, with no tidal channels, Holocene clay layers have considerable thicknesses and spatial extent, but occur just below -15 m NAP. Because they occur just below the -15 m NAP criterion, these areas are also displayed on the map. Each area is characterized by a short description. The areas with tidal channels, and hence where erosion-resistant deposits were mapped along the entire depth range of the channel, have names in *italic* on the maps. Chapter 5 gives several recommendations to improve the map in the coming years.

4.1 Southern coastal zone

Important features for this zone are the shallow presence of older and therefore relatively resistant Tertiary and Early Pleistocene deposits. In addition to this, some plateaux near the mouths of the Western and Eastern Scheldt seem related to the shallow presence of Holocene clay. Below, some of the characteristics of the different areas in Figure 4.1 are given.

1. Western Scheldt and Wielingen/Oostgat tidal channels (see also §3.1)
   Apart from some isolated packages of Holocene clay and peat, the most relevant resistant deposits are formed by Tertiary and Pleistocene deposits. This applies especially to the western half of the Western Scheldt where the 'Boom'-clay of the Rupel Formation is often present right below -20 m NAP. To the east, it is mostly clay from the Waalre or Oosterhout Formations that form resistant layers, also below -20 m NAP. The resistant layers lie predominantly below the base of the channels, meaning that only the depth of the channel is directly influenced and not the rate of lateral migration. It is possible that because channel-deepening is hindered, the channel adjusts by becoming wider (Van der Spek, 1997).

2. Vlakte van de Raan
   The Vlakte of de Raan is a wide plateau in front of the Western Scheldt with an average depth of around -7 m NAP. The available boreholes are mostly situated near the eastern edge of the plateau. Several of them indicate the presence of meter-thick sequences of clay starting very close to the surface. In addition, Tertiary deposits start relatively shallow, around -20 m NAP.

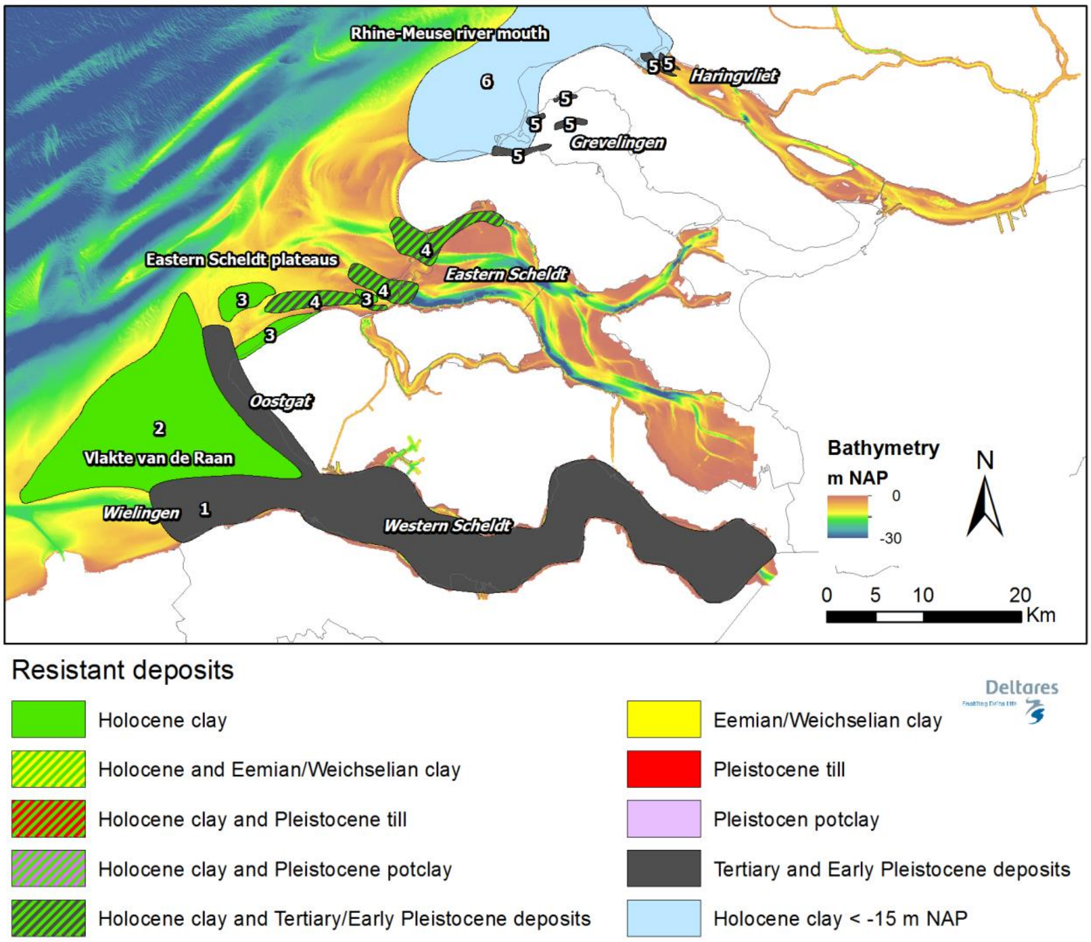


Figure 4.1 Map of the southern coastal zone of The Netherlands with areas indicated where resistant deposits are very likely to have an influence on the morphological evolution. Because of the high degree of uncertainty about the offshore distribution of deposits, the borders of the areas should be considered 'soft'.

3. Eastern Scheldt plateaus
Along the NW-shoreline of Walcheren thick sequence of Holocene clay and peat are present below 0 m NAP until depths of about -7 m NAP. The seaward extension of these deposits is unclear, but most likely they influence nearshore morphodynamics to some extent. At several places clay layers used to crop out at the beach (Van Alphen and Damoiseaux, 1987), but this was before the large-scale nourishment program started.
The largest of the two plateaus was also identified by Van Alphen and Damoiseaux (1987) and linked to the presence of resistant layers near the bed surface. There is little subsurface information about the build-up of these two plateaus.

4. Eastern Scheldt tidal channels
The base of these tidal channels reaches below -30 m NAP at places, hereby reaching Early Pleistocene deposits of the Waalre Formation and the Maassluis Formation. Although they are old and therefore in general relatively more resistant than Holocene deposits, the nature of the deposits is not well known. The few cores available seem to indicate that these Early Pleistocene deposits are predominantly sand and hence there influence could be limited.

The former islands Noord-Beveland and Schouwen have, on a regional scale, thick sequences of Holocene clay and peat layers between -1 and -15 m NAP. Undoubtedly, they had or still have an influence on lateral migration patterns of tidal channels in the Eastern Scheldt. It is important to realise that, especially in this area, morphodynamics are also dependent on the presence of loosely packed and very erodible sand. At locations where this sand is present along channels, flats or flood-defence systems, the chance of flow sliding in submerged slopes is relatively high.

5. Grevelingen and Haringvliet tidal channels (see also §3.2)
   The base of these tidal channels reaches below -30 m NAP at places, hereby reaching Early Pleistocene deposits (Waalre Formation). The available boreholes indicate a thick clay unit at the top of the Waalre Formation. At shallower depths, around -20/-25 m NAP clay layers from the Eem Formation (Grevelingen) and the Kreftenheye Formation (Haringvliet) might influence channel behaviour.

4.2 Central coastal zone

This zone is characterised by the presence of thick Holocene clay and peat layers. They occur mostly below -15 m NAP, but because of their large spatial extent they are shown on the map as well. At this point it is not clear if they still influence the coastal evolution of this part of the Dutch coast. Below, some of the characteristics of the different areas in Figure 4.2 are given.

6. Rhine-Meuse river mouth
   The extent of the late Pleistocene-early Holocene clay and peat layers is relatively well known from seismic and borehole analysis. In almost any case these layers occur below -15 m NAP or deeper. They are most likely not directly influencing current coastal morphodynamics, but certainly have done so in the past. It could well be that this past influence is still reflected in shoreface characteristics like slope and average grain size. In any case, north of this zone the slope of the area between the beach and the -15 m NAP line increases from about 0.2-0.25% to 0.3-0.4%.

7. IJmuiden
   This area is characterized by the widespread occurrence of clay and peat layers between -16 to -20 m NAP. The influence of these resistant deposits, the Velsen Bed, on the current coastal development is most likely limited. But since the IJmuiden navigation channel and the scour hole near the end of the harbour moles cut into these deposits and the deposits have a large spatial extent, they are worth mentioning. Compared to the areas directly north and south of IJmuiden the slope of the shoreface above -15 m NAP is relatively flat, this might be linked to the presence of the shoreface-connected ridges.

8. Bergen
   In this area Holocene clay layers of the Bergen Bed are present across a large area, but again they start just below -15 m NAP. Their thickness can be substantial, in some places more than 10 m.

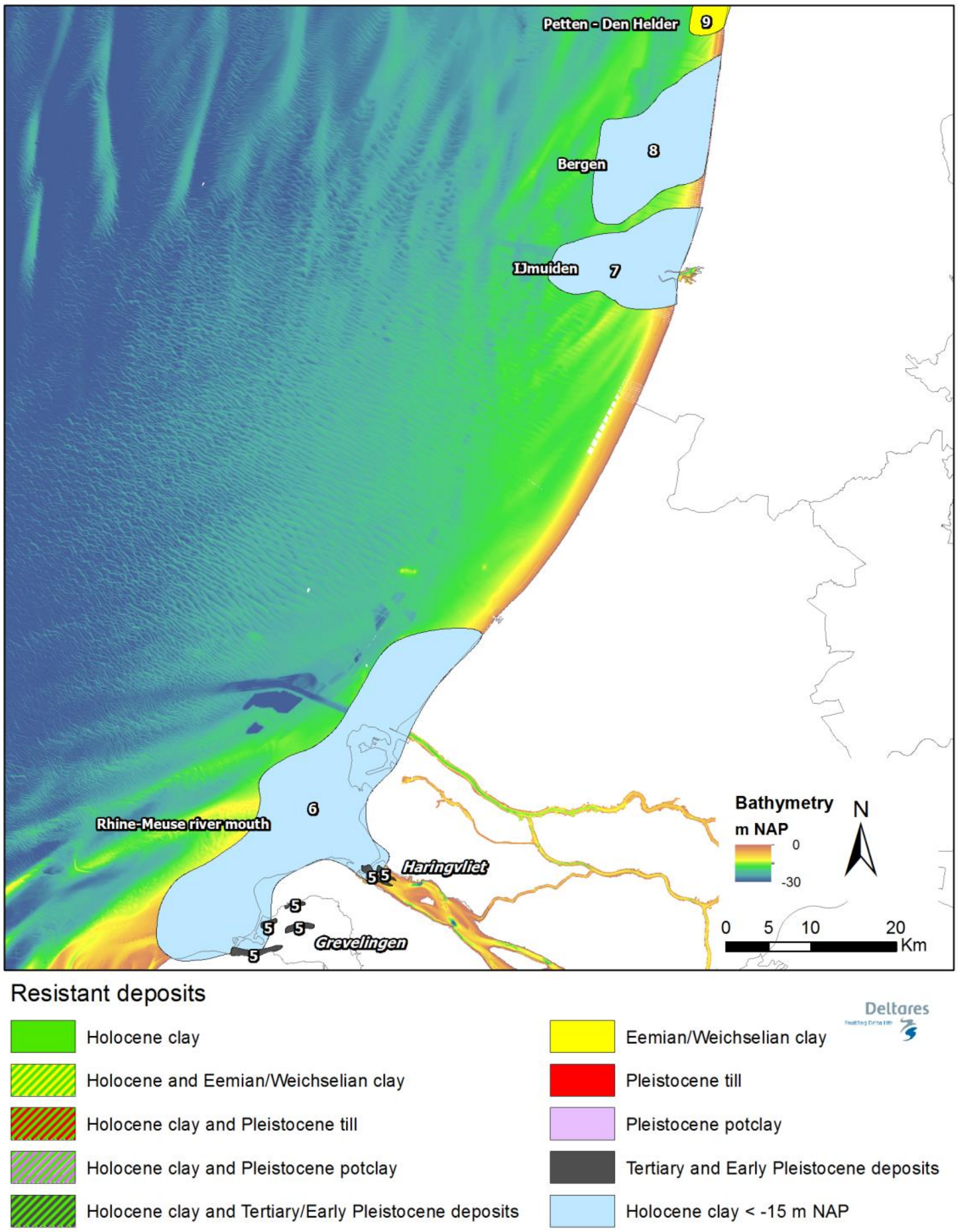


Figure 4.2 Map of the central coastal zone of The Netherlands with areas indicated where resistant deposits are very likely to have an influence on the morphological evolution. Because of the high degree of uncertainty about the offshore distribution of deposits, the borders of the areas should be considered 'soft'.

4.3 Northern coastal zone

Important features for northern zone are the presence of glacial till and Potclay. Furthermore, in the Eems area thick Holocene-clay layers are present. Below, some of the characteristics of the different areas in Figure 4.3 are given. There are no indications for widespread occurrence of resistant layers above -15 m NAP in between the North Sea beaches of the Wadden Isles and the -15 m NAP contour line.

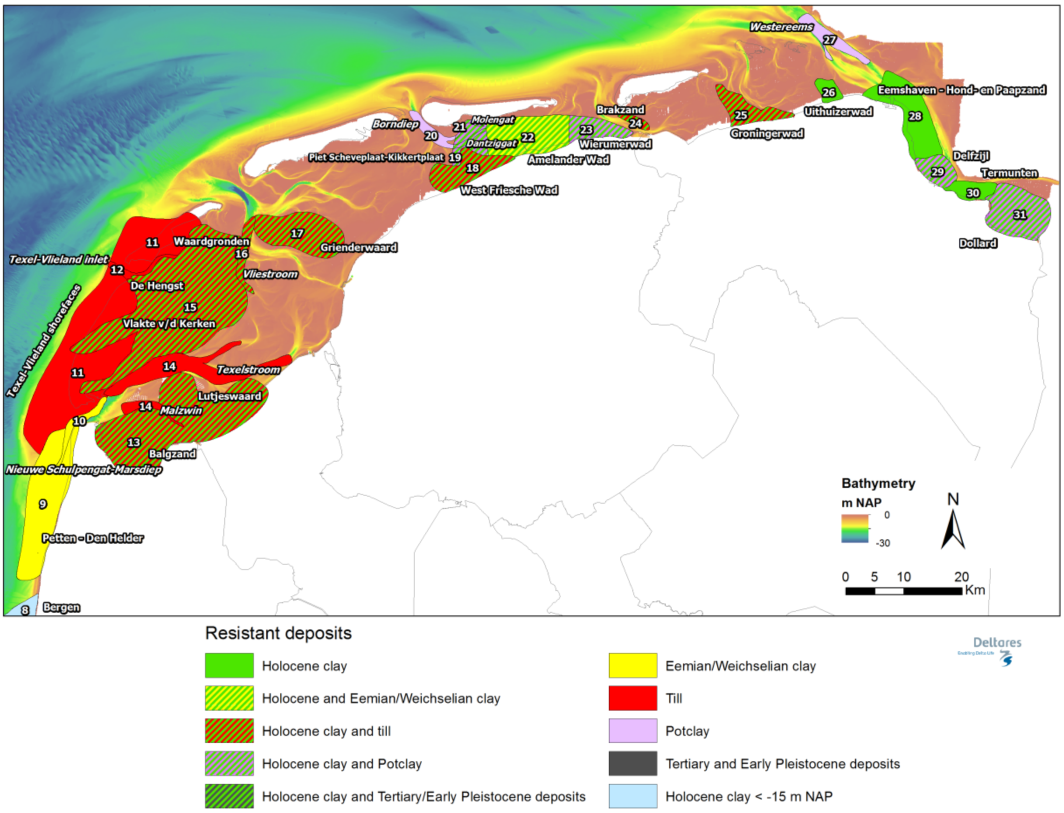


Figure 4.3 Map of the northern coastal zone of The Netherlands with areas indicated where resistant deposits are very likely to have an influence on the morphological evolution. Because of the high degree of uncertainty about the offshore distribution of deposits, the borders of the areas should be considered 'soft'.

9. Petten-Den Helder
   The area is characterized by a relatively high occurrence of Pleistocene deposits, at some places above -10 m NAP. The Pleistocene deposits are very heterogeneous and contain clay and peat layers from predominantly Weichselian age. In some places also Eemian clay is present. Also the Holocene sequence contains numerous clay layers.

10. Nieuwe Schulpengat-Marsdiep (see also §3.3)
    The same sequences as for the Petten-Den Helder area can be expected. However, the Nieuwe Schulpengat-Marsdiep channels reach deeper than -25 m NAP and cut into Eemian deposits that contain clay layers up to 5 m thick (Van der Spek and Van Heteren, 2004)

11. Texel and Vlieland shorefaces
    Glacial till is present above -15 m NAP along both the North Sea and Wadden Sea sides of Texel and Vlieland.

12. Texel-Vlieland tidal-inlet channels
    These channels reach below -10 m NAP at many places, a depth that corresponds more or less with the expected top of the glacial till.

13. Balgzand-Lutjeswaard
    This area is extensive intertidal flat with elevations around mean sea level. Especially below the Lutjeswaard the glacial till starts shallow, locally around -5 m NAP. Below the Balgzand the glacial till is occasionally absent. At many places, but predominantly below the Balgzand, Holocene basal peat and clay layers are present as well.

14. Malzwin-Texelstroom tidal channels
    These channels reach well below -15 m NAP at many places, hereby cutting into glacial till. Occasionally they reach into the underlying Urk Formation that can contain thick clay layers.

15. Vlakte van de Kerken-De Hengst-Waardgronden
    At many places glacial till starts around -10 m NAP, but sometimes it reaches as high as -7 m NAP. In addition, extensive peat and clay layers are present at the base of the Holocene, especially between -1 and -7 m NAP.

16. Southern end Vliestroom (see also §3.4)
    This part of the Vliestroom tidal channel is about 15 m deep, with glacial till present along its flanks. The deepest parts reach below -20 m NAP, hereby locally cutting into clay layers of both the Eem and Urk Formations. The Holocene sequence forms the upper 5 m and contains thick peat layers.

17. Grienderwaard
    The elevation of the Grienderwaard lies around mean sea level. The Holocene sequence is 6-7 m thick and the lower half consists of widespread clay and peat layers. The underlying Pleistocene deposits mostly consist of sand until -18/-20 m NAP.

18. West Friesche Wad
    This area is characterized by the occurrence of glacial till below -10 m NAP. The till is expected to be absent at places and then sandy Weichselian deposits most likely form the top of the Pleistocene. The Holocene sequence is up to 10 m thick and seems to consist of irregular patches of sand and clay. In the eastern part Potclay is present below the till.

19. Piet Scheveplaat-Kikkertplaat
    In this area the top of the Pleistocene is frequently formed by Potclay, although occasionally the Potclay is covered by till or Weichselian sand. The Pleistocene mostly starts somewhere between -12/-16 m NAP. The Holocene sequence contains clay and peat layers at the base.

20. Borndiep (see also §3.5)
    The base of this tidal channel reaches -15 to -30 m NAP, hereby locally cutting into Potclay that starts around -23 to -25 m NAP (Van der Spek, 1994). Sometimes the Potclay is covered with sand and clay from the Eem Formation. The flanks of the Borndiep seem to contain no significant clay or peat layers.

21. Molengat-Dantziggat (see also §3.5)
    The tidal channels are smaller and shallower than the Borndiep, with the deepest parts reaching -15 m NAP, hereby most likely touching the Potclay. The eastern parts of these channels lie in an area where the Pleistocene starts around -10/-15 m NAP and consists of a complex mixture of the Peelo, Boxtel, Drente and Eem Formations. The base of the Holocene is frequently formed by a basal peat-organic clay sequence.

22. Amelander Wad
    The geology of the Amelander Wad is complex with a wide range of Pleistocene formations in the subsurface with the Weichselian Boxtel Formation, starting around -10/-13 m NAP, most frequently forming the upper one. The Boxtel Formation contains a few clay layers, but below its base (around -14/-16 m NAP), the top of the Eem Formation contains meter-thick clay layers. Also throughout the Holocene sequence thick clay layers occur across large areas, locally underlain by basal peat.

23. Wierumerwad
    Below the Wierumerwad the top of the Potclay rises from -20 m in the west to -12 m NAP in the eastern part. At places the Potclay is capped by till or Weichselian deposits. Throughout the Holocene sequence thick clay layers occur across large areas.

24. Brakzand
    The subsurface build-up is similar to the Wierumerwad, although the Holocene sequence is less clayey. At places the Potclay is covered by sandy sediments from the Urk Formation.

25. Groningerwad
    There is very little information available for this area. Boreholes directly onshore show till and Potclay within -15 m NAP. Also the build-up of the Holocene sequence is basically unknown, but could contain thick clay layers.

26. Uithuizerwad
    Between -12/-13 m and -15/20 m NAP thick Holocene clay and peat sequences are present.

27. Westereems
    There is not a lot of information about this area, but it is expected that Potclay is outcropping in parts of the channel that reach below -20 m NAP. Farther offshore, Potclay has been found outcropping at the base of an extension of the Westereems channel.

28. Eemshaven-Hond en Paapzand
    Between -1 m and -15 m NAP thick Holocene clay and peat sequences are present. This applies especially to the area south of the Eemshaven

29. Delfzijl
    This area is characterised by a very shallow, at many places above -10 m NAP, presence of Potclay. The Potclay is frequently capped by Weichselian sand. The Holocene sequence contains thick and widespread clay and peat layers

30. Termunten
    In this area the Potclay lies deeper, mostly below -15 m NAP, and is covered by Weichselian sand that starts between -7/-11 m NAP. The Holocene sequence almost entirely consists of clay with numerous peat layers.

31. Dollard
    In the Dollard area the top of the Potclay rises again, starting mostly around -9/-12 m NAP. It is expected that at most places the Potclay is covered by Weichselian sand. As for most areas along the Eems, also here the Holocene sequence is made up of thick clay and peat layers.

5 Recommendations

Chapter 2 has illustrated, on a regional scale, the variable build-up of the subsurface below the shoreface, the shoreline and the Wadden Sea. Chapter 3 has demonstrated that in almost any case, especially offshore, the distribution, the thickness and the facies of the different formations is only known to a limited extent. But it are these subregional characteristics of the deposits that influence long-term developments of tidal channels and the shoreline. In addition, the resistance of the different deposits against erosion is only known in a relative sense. It is, e.g., clear that Potclay is less erodible than Holocene clay, but at this point this cannot be quantified with tests. Insight into the erodibility will be necessary though to predict future long-term developments. This means that there are two main knowledge hiatuses: 1) there is insufficient information on the subregional build-up of the subsurface and 2) there is insufficient information on the erodibility of the different formations.

The above indicates that at this point any map portraying to what extent the morphological evolution of certain coastal area is influenced by the presence of erosion-resistant layers is subject to considerable uncertainty. To improve this and to fill the mentioned knowledge hiatuses several recommendations are given below.

5.1 Subregional build-up

Offshore information about the build-up of the subsurface is limited compared to onshore information. An offshore advantage is the relative abundance of geophysical data (Erkens et al., 2014) as they can be used to study the lateral extent of resistant layers. An area for which many data exist is the Nieuwe Schulpengat area where in 2004 several cores were executed and a proper understanding of the presence of resistant layers was gained. Still, Van der Spek and Van Heteren (2004) recommended acquiring seismic data to check the lateral continuity of these layers. Late 2015 these data have been gathered. This will make the Nieuwe Schulpengat the best studied tidal channel in The Netherlands, in terms of the local geology, and a showcase for how a combination of seismic data and cores can be used to understand and predict migration patterns of a tidal channel. To further improve our understanding of the subregional build-up of the subsurface and the role it plays in the (long-term) development of the coastal zone it is recommended to:

1) To compare the large-scale development of the coastal zone during the last 50 years (e.g. shoreface, inlets) with the subsurface deposits. For many areas the large-scale development has already been studied and published in reports (e.g. Beheerbibliotheken). These large-scale developments could be categorised in classes, perhaps using average migration rates for different areas. These classes could be plotted against the subsurface build-up in those areas to analyse the relationship between the classes and the subsurface. This will hopefully provide a first indication of the erodibility of the different deposits and hence their influence on coastal evolution.
2) Make a priority list of subregions/tidal inlets that should be studied. Prioritisation will most likely be based on a combination of coastal-zone management issues and our current understanding of the subsurface build-up. It is wise to study areas that at least have the potential for erosion-resistant layers being present.
3) Make more use of existing seismic data. A relative wealth of seismic data are available at Deltares/TNO (Erkens et al., 2014). Several seismic lines are only available on paper or have not been analysed in detail. After step 2, the available seismic data for the areas on the priority-list should be quick-scanned.

4) For the most relevant areas a plan for gathering additional information should be made. This plan should be tailor-made, based on the amount of existing information and coastal-zone management issues.
5) During the subsequent analysis, newly acquired knowledge about differential erodibility should be used (see next section). In order to predict future development of the areas it will be necessary to make use of both the constructed geological model and hydro/morphodynamical models.

5.2 Quantifying differential erodibility

There are hardly any measurements available to quantify the resistance of the deposits in a relevant way. This is complicated by the fact that erosion can occur in several ways, namely biologically (biochemically, bioturbation) or physically due to erosion by flowing, sediment containing, water or erosion by breaking waves. In addition, the exact nature of the resistant deposits, e.g. the number of clay layers or the sand content, plays a role.

In The Netherlands few publications have looked into the specific material characteristics of the different deposits in relation to its erodibility. Recently, a PhD-thesis appeared on the influence of biota on transport processes (De Lucas Pardo, 2014). Van der Spek and Van Heteren (2004) present results of torvane and pocket penetrometer tests on sediments taken within or near the Nieuwe Schulpengat. These tests were done on drained sediments and have no absolute value: they are only indicative for the relative strength of the sediments. Van der Spek and Van Heteren (2004) also did a short literature review on erodibility of the sediment they encountered in the Nieuwe Schulpengat boreholes. For sandy deposits they refer to Mitchener and Torfs (1996). That paper shows that sand with an admixture with clay/silt of 30% will have a critical shear stress that is 10 times larger than for pure sand. Kamphuis (1990) describes the erodibility of glacial till and stiff clays in laboratory and field experiments. The erosion rate depended on the amount of sediment in the water: deposits that remained intact under high flow velocities started to erode after sand was added to the flowing water. The erodibility of peat is not well known, apart from field observations that compacted peat is hard to erode: along the banks of the Eastern Scheldt peat layers were sticking out 1.5 m into the channel, because over- and underlying clay layers were eroding more rapidly.

The above shows that there is little quantitative information on the erodibility of the different resistant layers. To improve this it is necessary to do a proper literature review into this matter, including literature that has become available since the report of Van der Spek and Van Heteren in 2004. It is also wise to include knowledge and tests from engineering companies in this literature review. This review should also include a discussion on the minimal thickness resistant deposits should have to significantly influence erosion patterns and also how much it matters if the resistant deposits occur near the base of the channel or halfway the channel wall. In addition, it is recommended to perform erodibility tests using e.g. jet index tests in the field or the sea carousel for the offshore areas (Amos et al., 1992). Determining a useful method to test the underwater erodibility of the resistant layers should also be part of the literature review. Apart from direct measurements, the results from the recommended first step in Chapter 5.1 will provide very valuable long-term data of the erodibility of the different deposits.

6 Conclusions

This report provides an overview of the build-up of the subsurface along the Dutch shorelines. It shows that the build-up is heterogeneous and contains several erosion-resistant deposits that could influence both the short- and long-term evolution of the coastal zones and its tidal channels. The nature of these resistant deposits is very variable, reflecting the diverse geological development of The Netherlands over the last 65 million years. In the southwestern part of The Netherlands they are mostly Tertiary deposits and Holocene peat-clay sequences that are relatively resistant to erosion. Also in South- and North-Holland Holocene peat-clay sequences have been preserved, but in the Rhine-Meuse river-mouth area Late Pleistocene-early Holocene floodplain deposits form additional resistant layers. In northern North-Holland shallow occurrences of clayey Eemian-Weichselian deposits influence coastal evolution. In the northern part of The Netherlands it are mostly Holocene peat-clay sequences, glacial till and over consolidated sand and clay layers that form the resistant deposits. The areas with resistant deposits at relevant depths and position have been outlined in a map.

The report also zooms in on a few tidal inlets to quick-scan the potential role of the subsurface in their evolution. Several tidal inlets have resistant layers directly below the base of the channel or within the flanks of the channel. However, in almost any case the data-density is insufficient to map the resistant layers in detail. It is essential, however, to have detailed insight in the distribution of deposits in order to understand and predict the migration patterns of the tidal channels. In addition, hardly any research has gone into quantifying the erodibility of the different deposits. At this point, it is therefore not possible to go beyond general terms in describing the role of the different deposits on coastal-zone evolution. To improve this, several recommendations are given that focus on prioritising relevant areas to study, making more use of existing seismic data, gathering of additional data and studying differential erodibility.

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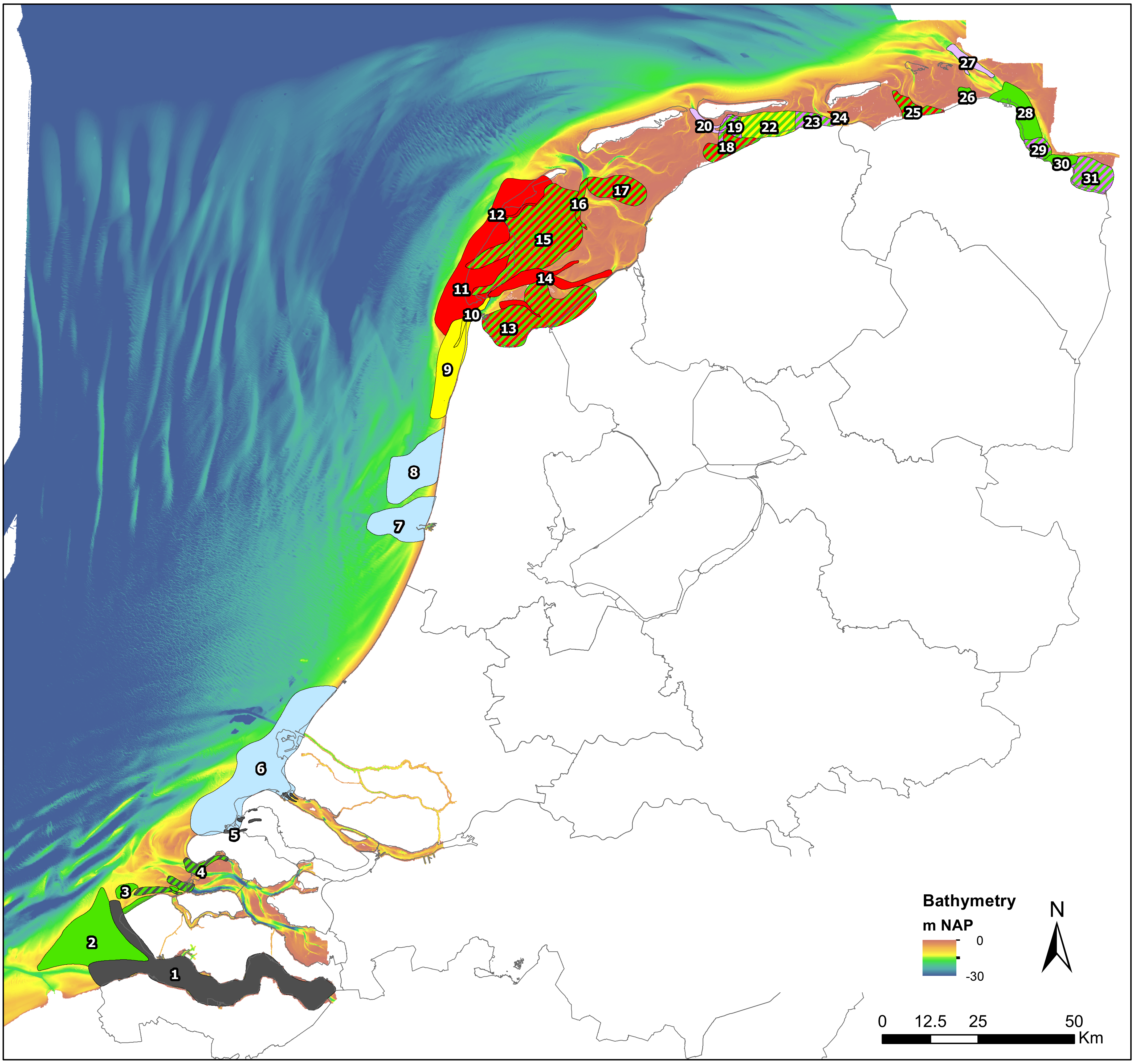
A Map of erosion-resistant layers in the coastal zone

Appendix A: Map of erosion-resistant layers in the coastal zone



*1. Western Scheldt-Wielingen-Oostgat tidal channels**
2. Vlakte van de Raan
3. Eastern Scheldt plateaus
4. Eastern Scheldt tidal channels
5. Grevelingen and Haringvliet channels
6. Rhine-Meuse river mouth
7. IJmuiden
8. Bergen
9. Petten-Den Helder
10. Nieuwe Schulpengat-Marsdiep
11. Texel-Vlieland shorefaces
12. Texel-Vlieland tidal-inlet channels
13. Balgzand-Lutjeswaard
14. Malwzin-Texelstroom tidal channels
15. Vlakte v/d Kerken-De Hengst-Waardgronden
16. Vliestroom (southern end)
17. Grienderwaard
18. West Friesche Wad
19. Piet Scheveplaat-Kikkertplaat
20. Borndiep
21. Molengat-Dantziggat
22. Amelander Wad
23. Wierumerwad
24. Brakzand
25. Groiningerwad
26. Uithuizerwad
27. Westereems
28. Eemshaven-Hond- en Paapzand
29. Delfzijl
30. Termunten
31. Dollard

Resistant deposits

- Holocene clay
- Holocene and Eemian/Weichselian clay
- Holocene clay and Pleistocene till
- Holocene clay and Pleistocene potclay
- Holocene clay and Tertiary/Early Pleistocene deposits
- Eemian/Weichselian clay
- Pleistocee till
- Pleistocene potclay
- Tertiary and Early Pleistocene deposits
- Holocene clay < -15 m NAP

Deltares
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** Names in italic refer to areas with tidal channels. In those areas erosion-resistant deposits are shown along the entire depth range of the channel, so also below -15 m NAP. In all other areas the erosion-resistant deposits on the map occur around or above -15 m NAP.*