Netherlands Enterprise Agency

Geological Desk Study

Hollandse Kust (noord) Wind Farm Zone

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Author: Deltares

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Geological study Hollandse Kust (noord) Wind Farm Zone

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Title
Geological study Hollandse Kust (noord) Wind Farm Zone

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Summary
This report presents the publicly available bathymetric, geophysical and geological data and the relevant literature of the "Hollandse Kust (noord) Wind Farm Zone". Available seismic data are assessed on their suitability for the construction of a geological model. Based on the currently available data, possible constraints on the construction of a wind farm zone have been addressed.

References
Request for proposal: RfP WOZ 2170022 Geological desk study Hollandse Kust (Noord) WFZ, dated 17 January 2017
Deltares' proposal: 11200513-000-BGS-0001-c Quotation for Geological desk study Hollandse Kust (noord), dated 26 January 2017
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		Tommer Vermaas					
		Chris Mesdag					
		Marc Hijma					
		Ger de Lange					
		Marco de Kleine					

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Contents

Managementsamenvatting

De Rijksdienst voor Ondernemend Nederland (RVO) heeft Deltares gevraagd een geologische bureaustudie uit te voeren als voorbereiding op een geofysisch veldonderzoek in het "Windgebied Hollandse Kust (noord)". In deze studie wordt een overzicht gepresenteerd van de beschikbare bathymetrische, seismische en geologische gegevens, en wordt de kwaliteit van deze gegevens beoordeeld. Met behulp van geologische kaarten en doorsneden wordt de geologische architectuur en de geologische eenheden van de ondergrond in dit gebied beschreven. Daarnaast zijn de mogelijke belemmeringen onderzocht in relatie tot de ondergrond voor de ontwikkeling van het windpark. De aanbevelingen voor het ontwerp van een uit te voeren seismisch onderzoek worden gedaan in een losstaand memo.

De morfologie van het studiegebied, gevisualiseerd door gecombineerd data uit 5 bathymetrische campagnes, is gekenmerkt door zandgolven met een NW-ZO oriëntatie. Relevante geologische kenmerken, zoals riviergeulen, kunnen gezien worden in de bestaande data uit single channel en multi-channel seismische campagnes. Toch zijn de resolutie en de kwaliteit van deze data te laag en niet geschikt voor gedetailleerde analyse. Publiek beschikbare boorgegevens uit DINOloket, diepe boringen in de buurt van het studie gebied, geologische kaarten en literatuur werden gebruikt om de geologische eenheden in het gebied te beschrijven en hun geometrie in de eerste 100 m onder de zeebodem. De stratigrafische indeling van Rijsdijk et al. (2005) wordt beschouwd als het meest geschikt voor het studiegebied.

De ondergrond bestaat uit Pleistoceen en Holoceen ondiep marien en fluviatiele afzettingen. Deze bestaan hoofdzakelijk uit zand. Klei en slib komen voor als dunne lagen in de zandrijken eenheden en vormen dikkere lagen (tot enkele meters) binnen geul opvullingen in de Holoceen Naaldwijk Formatie, en de Pleistoceen Brown Bank Member en Eem Formatie. Een Holoceen veenlaag komt lokaal voor (maximaal 0.5 m dik). Dankzij enkele diepe boringen is het mogelijk om de eigenschappen van de diepere eenheden in te schatten (15 m tot 100 m diepte). Deze eenheden bestaan uit Pleistoceen fluviatiele en deltaische zand- en klei afzettingen. In het gehele studiegebied zijn geen grote beperkingen aangetroffen om een windpark te ontwikkelen. Kleinere of onbekende mogelijke beperkingen zijn hieronder beschreven.

- De aanwezigheid van de stijve lagen en stenen, als gevolg van de vroegere bedekking door landijs, kan een negatieve invloed hebben op de heibaarheid van de palen tot de vereiste funderingsdiepte.
- De mobiliteit van zandgolven aan het oppervlak moet worden gekwantificeerd voor het ontwerp van funderingen en kabels.
- Zachte lagen in de ondergrond kunnen invloed hebben op de verticale en laterale draagvermogen. Nieuwe geofysische en geotechnische veld data zijn noodzakelijk om de eigenschappen van de zachte geologische eenheden te bepalen.
- Ondiep gas is waargenomen in de seismische data in het gebied. Dit risico dient zorgvuldig onderzocht te worden en, indien mogelijk, moeten gebieden waar ondiep gas voorkomt worden vermeden.
- Het gebied ligt buiten de bekende natuurlijke aardbevingsgebieden. De gemeten aardbevingen werden veroorzaakt door extractie van gas. Een deterministische

seismische risico analyse wordt aanbevolen voor de gas velden die binnen een bereik van 5 km van het studie gebied liggen.

Executive Summary

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO) has requested Deltares to perform a geological desk study as a preparation to a future geophysical field survey in the “Hollandse Kust (noord) Wind Farm Zone”. In this study we first provide an overview of available bathymetric, seismic and geological data, and an assessment of their quality. Then the geological architecture and the geological units of the area are described, supported by geological maps and cross sections. Finally, we address possible geotechnical constraints on the development of the wind farm. Recommendations for a future geophysical survey are explained in a separate memo.

The morphology of the area, visualized by combining a dataset of 5 bathymetric surveys, is characterised by large-scale bed forms (sand waves) with a west-northwest to east-southeast orientation. Limited data from both single channel and multi-channel seismic surveys show relevant geological features such as channel fills and pockets of shallow gas. However, the quality and the resolution of these data are low and not suitable for detailed evaluation.

Borehole data in the study area provide a first order characterization of the geological subsurface. We used publically available boreholes from the DINOloket database, deep boreholes close to the study area, geological maps and literature to describe the geological formations and their geometry in the upper 100 m below the seafloor. The stratigraphic framework of Rijsdijk et al. (2005) is considered to be the most appropriate for the study area.

The subsurface of the area consists of Pleistocene and Holocene shallow marine and fluvial sediments. These deposits mainly consist of sands. Clay and silt are present as interbeds within the mainly sandy units and as relatively thicker beds (up to few meters thick) in channel fills of the Holocene Naaldwijk Formation, the Pleistocene Brown Bank Member and Eem Formation. A Holocene peat layer is locally present reaching a maximum thickness of 0.5 m. Thanks to the few deep boreholes it is possible to provide a first order characterization of the deeper units (15 m to 100 m). These units consist of Pleistocene fluvial and deltaic sands and clays. In the entire study area, both landward and seaward of the 12 nautical mile line no major constraints to develop a wind farm have been encountered. Smaller or unknown possible constraints are listed below.

- The presence of consolidated layers as glacial till and gravel due to the coverage of land ice may adversely affect driveability of the piles.
- The mobility of sand waves at the surface should be quantified and taken into account for proper piles and cables design.
- Soft soil may affect vertical and lateral bearing capacity. Additional geophysical and geotechnical investigations should quantify the geometry and the properties of the units containing soft soils.
- Presence of shallow gas has been observed in seismics data. This hazard should be carefully investigated. Areas with shallow gas should be avoided if possible.
- The area is outside of known natural earthquake hazard zones but has experienced induced seismicity. It is recommended that a deterministic seismic hazard analysis is performed for the gas fields located within a 5 km radius of the project area to confirm the actual seismic hazard.

1 Introduction

1.1 Background

Rijksdienst voor Ondernemend Nederland requested Deltares to provide an overview of the available geological and seismic data at the site of the new Dutch offshore wind zone 'Hollandse Kust (noord)'. The official request for proposal was received by email dated 17 January 2017 and with reference WOZ 2170022. Deltares submitted a proposal on 26 January 2017 with reference 11200513-000-BGS-0001-c. The project award was received on 7 February 2017 (reference number: WOZ 2170022).

1.2 Objectives

The objective of this study is to provide a geological framework of the "Hollandse Kust (noord) Wind Farm Zone" (HKN), using publicly available literature, data, information and knowledge of the region. The framework includes an overview of the available bathymetric, morphological and geological information. These data will be used as reference for the development of a geological model at a later stage in the development of the wind farm zone. This study also provides information on areas within the wind farm zone that might be less suitable for the construction of offshore wind farms.

1.3 Content of the report

In Chapter 2, the available bathymetrical maps, seismic sections and borehole data within the study area are presented. The geological history based on a literature review is discussed in Chapter 3. In Chapter 4 the quality of the available seismic data is assessed. Chapter 5 presents a stratigraphic framework and characteristics of the geological units in the study area. In Chapter 6, a set of geological maps and cross sections of the study area is presented. Chapter 7 elaborates on the possible constraints of the current available data. An overall conclusion is drawn in Chapter 8. Detailed information and examples of the data can be found in the Appendices.

2 Available data

In this chapter, the available bathymetrical data, borehole data and seismic data are presented. In the study area no cone penetration test (CPT) data are publicly available.

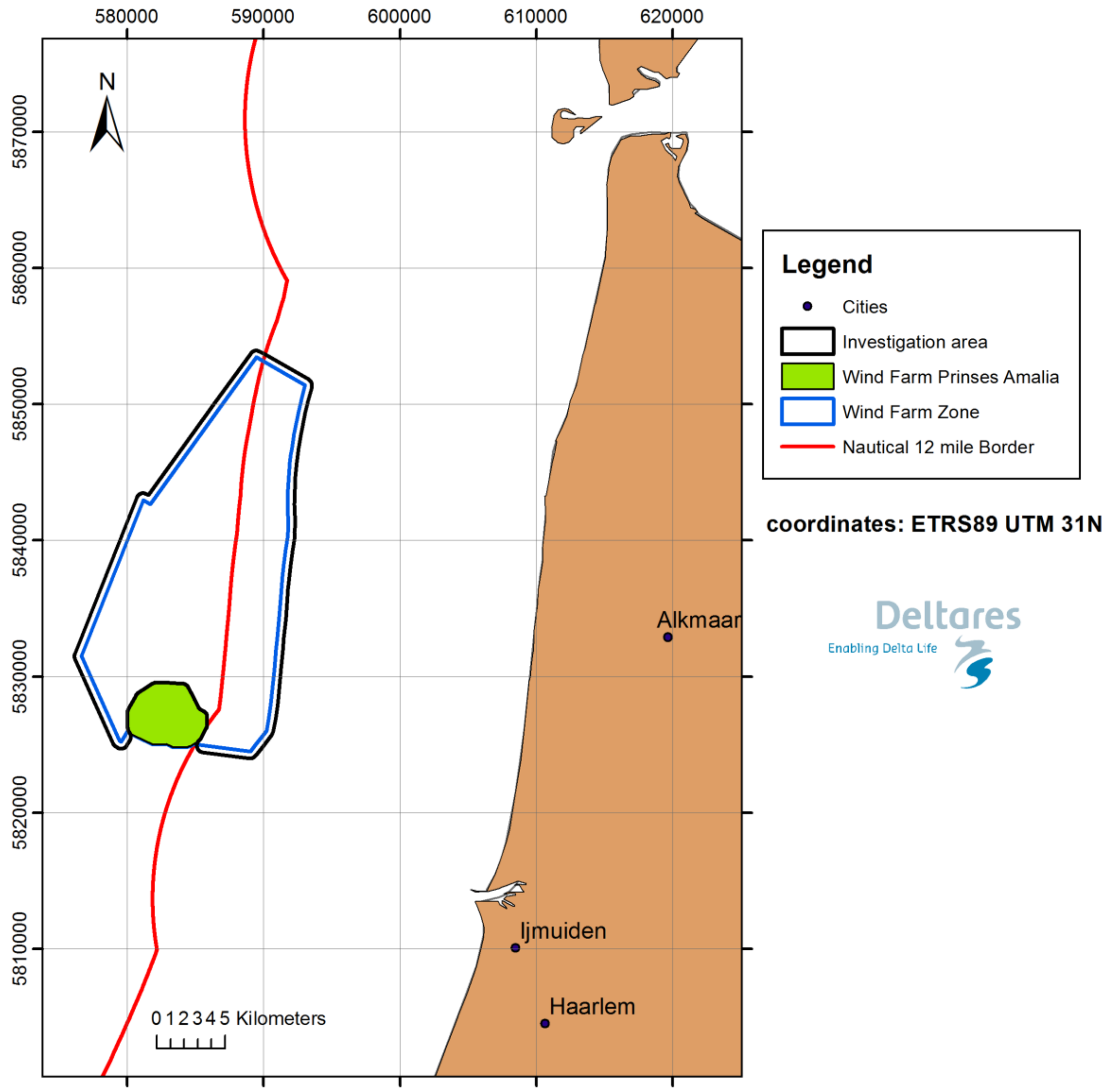

Figure 2.1 Location of the Hollandse Kust Noord WFZ.

2.1 Bathymetrical surveys

Since 1979 a total of 17 bathymetrical surveys were carried out in and around the study area by the Netherlands Hydrographic Office (NLHO, Table 2.1). The location of these surveys is presented in Appendix A. There the surveys are shown in three separate figures for the purpose of visual clarity. The bathymetrical data of the individual surveys is available on www.openearth.eu as a grid with 25 x 25 m resolution, with a documentation of the dataset on:

https://publicwiki.deltares.nl/display/OET/Dataset+documentation+bathymetry+NLHO.

Original data can be obtained from NLHO on:

https://www.defensie.nl/onderwerpen/hydrografie/inhoud/verkoop-zeekaarten-enpublicaties/aanvragen-hydrografische-data.

The interpolation to 25 x 25 m grids has been carried out by Deltares in other studies. The data used for the interpolation are on Level of Visualisation 2 (LOV2), meaning that 1 observation per 3 x 5 meter cell was selected and projected to the centre of the cell. For most multibeam surveys the data coverage is dense enough to result in one data point every 3 x 5 meter. Singlebeam surveys have varying density along the track (3 to 5 meter up to 35 meter) and the distance between the track lines varies (usually between 50 and 1000 meter). Side scan sonar surveys are also available from the NLHO. They are stored on disk but lacks necessary metadata to create a good overview of its availability. The exact coverage is not determined in this study, but it is expected to cover (almost) the entire study area.

For each point in the study area, bathymetry has been measured up to five times (Appendix A). A bathymetric map of the study area was compiled based on the most recent bathymetrical survey for each point (Figure 2.2), providing a full coverage of the study area (Figure 2.3). Besides being used to construct the bathymetric map, the bathymetrical data are can also be used for a morphological description of the area, and for the evaluation of local or regional morphodynamics. The intervals at which the bathymetrical measurements have been carried out provide indications of the sea bed mobility.

Table 2.1 Bathymetrical surveys carried out in and around the study area. Highlighted lines are the surveys that were used in the recent bathymetry map. Column 'source' indicates the used seafloor mapping system (SBES = single beam echo sounder, MBES = multi beam echo sounder). All datasets are available as 25 x 25 m grids on www.openearth.eu original data is available from the NLHO.

Survey ID	**Start date (day-month-year)**	**End date (day-month-year)**	**Area (km2)**	**Source**
15490	01-11-1979	30-11-1979	79	SBES
15491	01-06-1980	30-06-1980	44	SBES
15481	15-09-1984	19-06-1985	118	SBES
374	01-06-1991	30-06-1991	534	SBES
2402	29-03-1996	12-05-1996	80	SBES
2403	29-03-1996	12-05-1996	78	SBES
6164	01-10-2000	20-12-2000	275	SBES
5925	01-01-2001	28-02-2001	334	SBES
5885	01-01-2001	25-04-2001	243	SBES
6455	01-05-2001	30-06-2001	274	SBES
8444	01-01-2002	30-07-2002	1249	SBES
10149	01-08-2002	30-11-2002	1077	SBES
14631	06-02-2009	02-04-2009	182	MBES
14782	10-04-2009	26-05-2009	230	MBES
15406	06-01-2010	06-04-2010	596	MBES
16105	17-02-2011	14-04-2011	115	MBES
16912	13-03-2012	18-06-2012	281	MBES

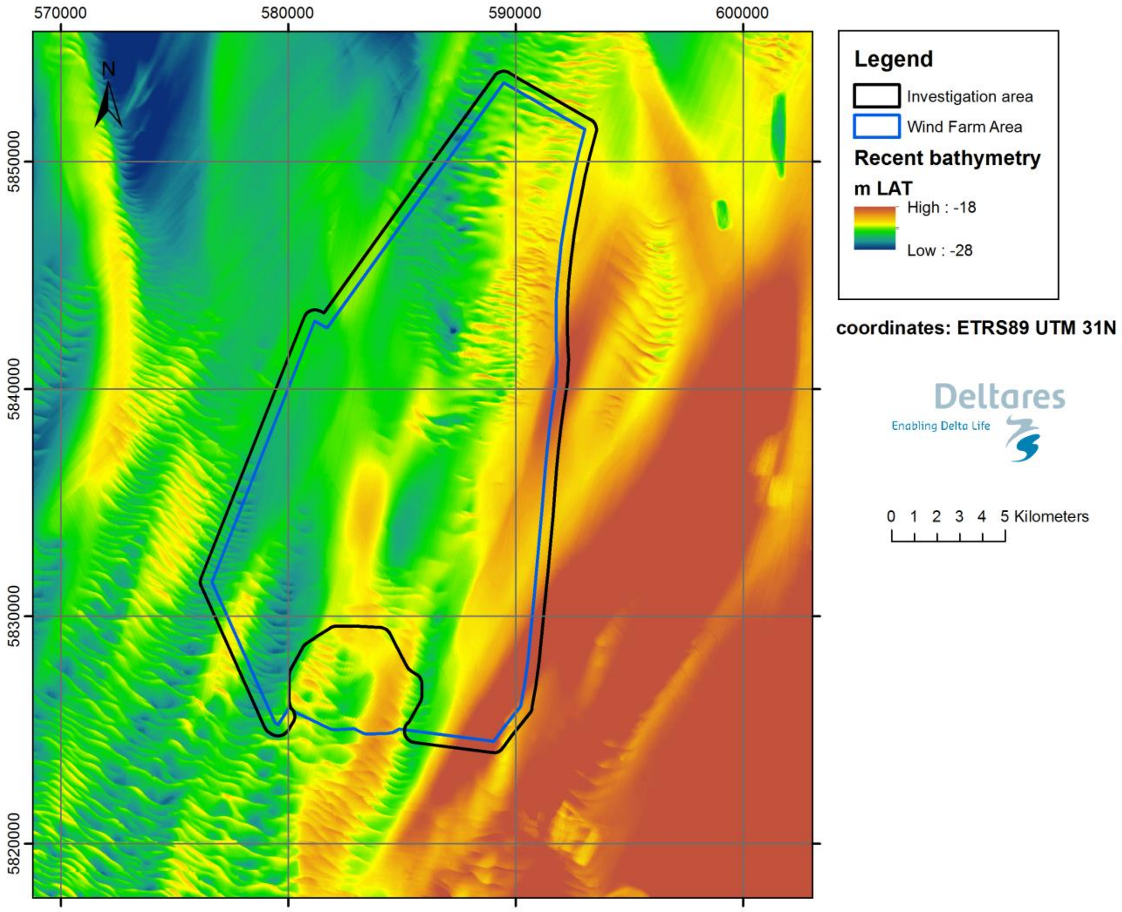

Figure 2.2 Map with date of most recent bathymetrical survey within the study area. The seafloor depth ranges from -18 to -28 m LAT. This range has been chosen in order to clearly visualize the sand ridges and sand waves in the area. For consistency with the other figures in this report, with a depth range between -10 and -30, an alternative version of this figure with depth range -10 to -30 is provided in appendix A.

2.2 Borehole data

2.2.1 Shallow cores from DINOloket

A total of 536 cores and boreholes were extracted from the DINOloket database, 127 of which are located within the wind farm area, and 47 of which within the designated wind farm zone (Figure 2.4). The remaining boreholes outside the study area are presented to provide further context. In addition to the core and borehole descriptions, DINOloket provides 1137 grain size analyses spread over different locations, results of chemical analysis and photos of some of the cores. The data were obtained from DINOloket on February 10th, 2017 (the Geological Survey of The Netherlands | TNO www.dinoloket.nl).

Part of the core and borehole data has been visualised in a cross section covering the whole designated wind farm zone (Figure 2.5**Error! Reference source not found.**). The majority of the cores and boreholes do not exceed a penetration of 5 meters below the sea bed. Some of the available borehole descriptions extend to depth of 12 meters below the sea bed. Resolution of the core and borehole descriptions varies from 1 meter intervals to cm-scale intervals, depending on the purpose for which the cores and borehole has been taken. There may also be inconsistencies in core and borehole descriptions induced by the interpretation of the geologists.

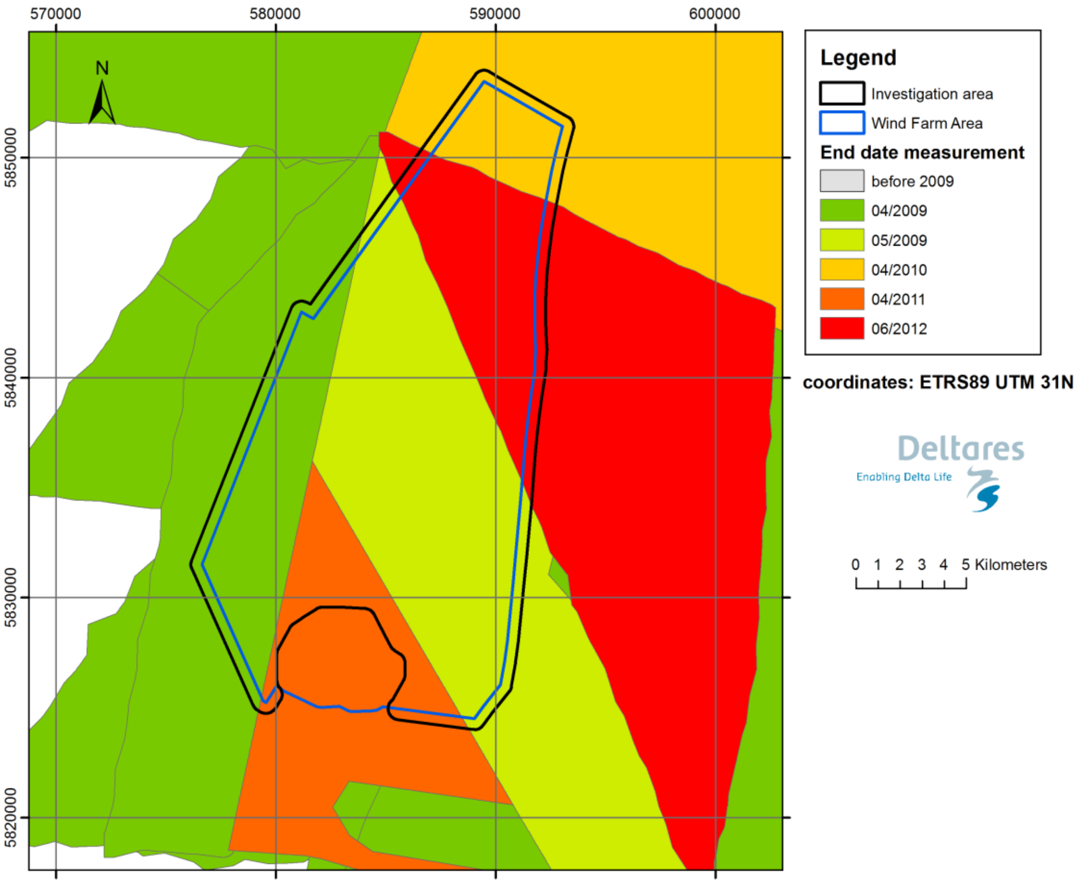

Figure 2.3 Map of the recent bathymetry, the data within the study area is based on five bathymetrical surveys carried out between 2009 and 2012 (see Figure 2.2 and table 2.1).

The cores and the boreholes have been collected during tens of years, due to the sea bed mobility the water depth at the locations can differ from the present depth. The inconsistencies and differences in quality between core and borehole descriptions are inevitable, as they are inherent to their origin from different sources. They should not impose any problems when handling the borehole data with awareness.

The majority of cores and boreholes consist of sand, ranging very fine to very coarse. In some cores and boreholes, particularly in the upper 2-3 m, these sandy deposits are rich in shells. In a small number of cores and boreholes from the DINOloket dataset clay layers of centimetres to decimetres thick are present in the upper 5 meters of the sea bed. These are attributed to the Wormer Member of the Naaldwijk Formation. Three boreholes contain peat, belonging to the Basal Peat (Nieuwkoop Formation). One borehole contains sands with clay interbeds attributed to the Drachten Formation. A few boreholes contain sands and clay interbeds attributed to the Eem Formation. Among these, one borehole log contains a 3 m thick clay layer (Brown Bank Member of the Eem Formation). One borehole log shows two clay layers with a thickness of respectively 3 meter and 2 meters in the upper 10 meters of the fluviatile Yarmouth Roads Formation.

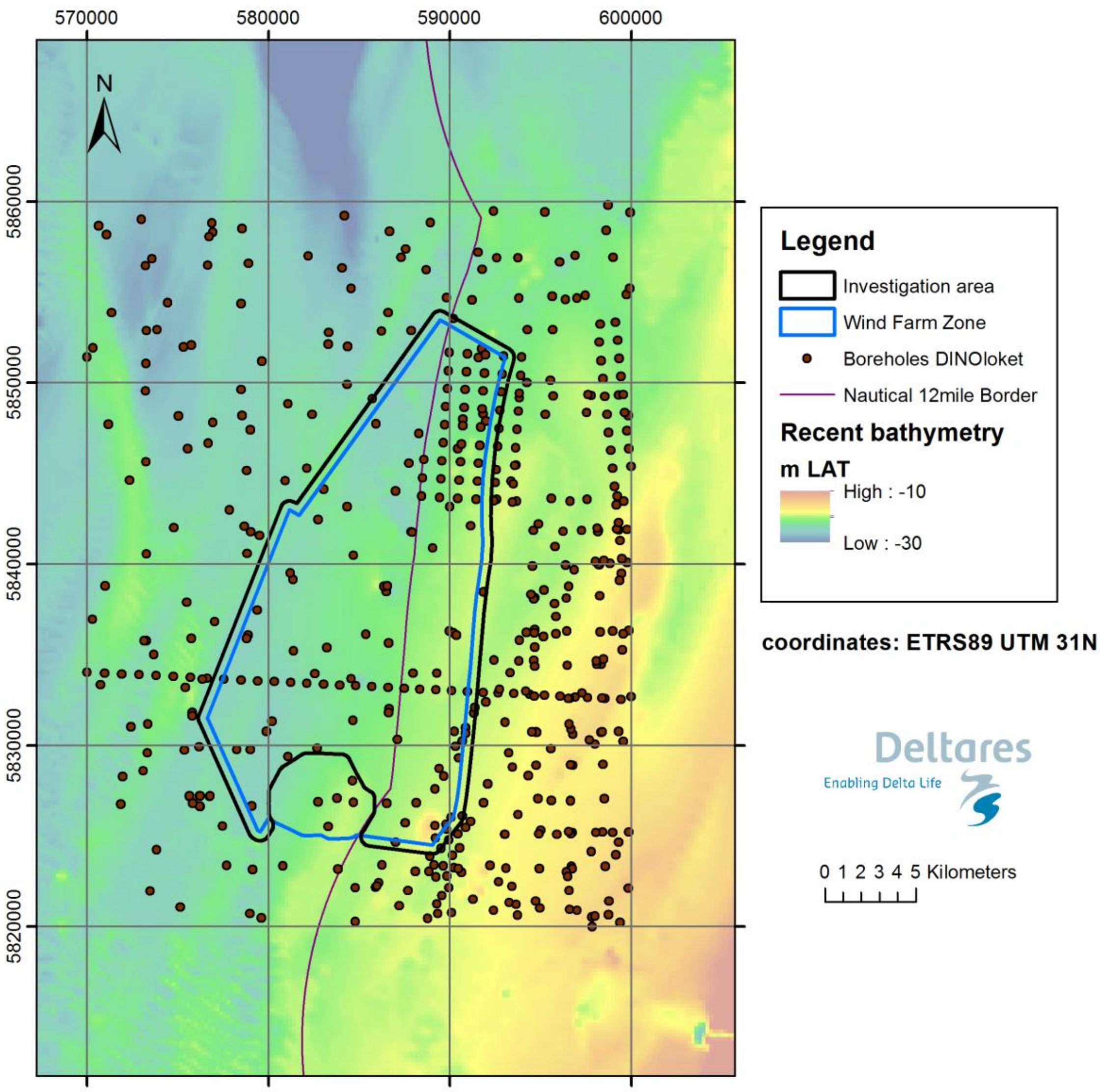

Figure 2.4 Borehole data obtained from DINOloket on 10 February 2017.

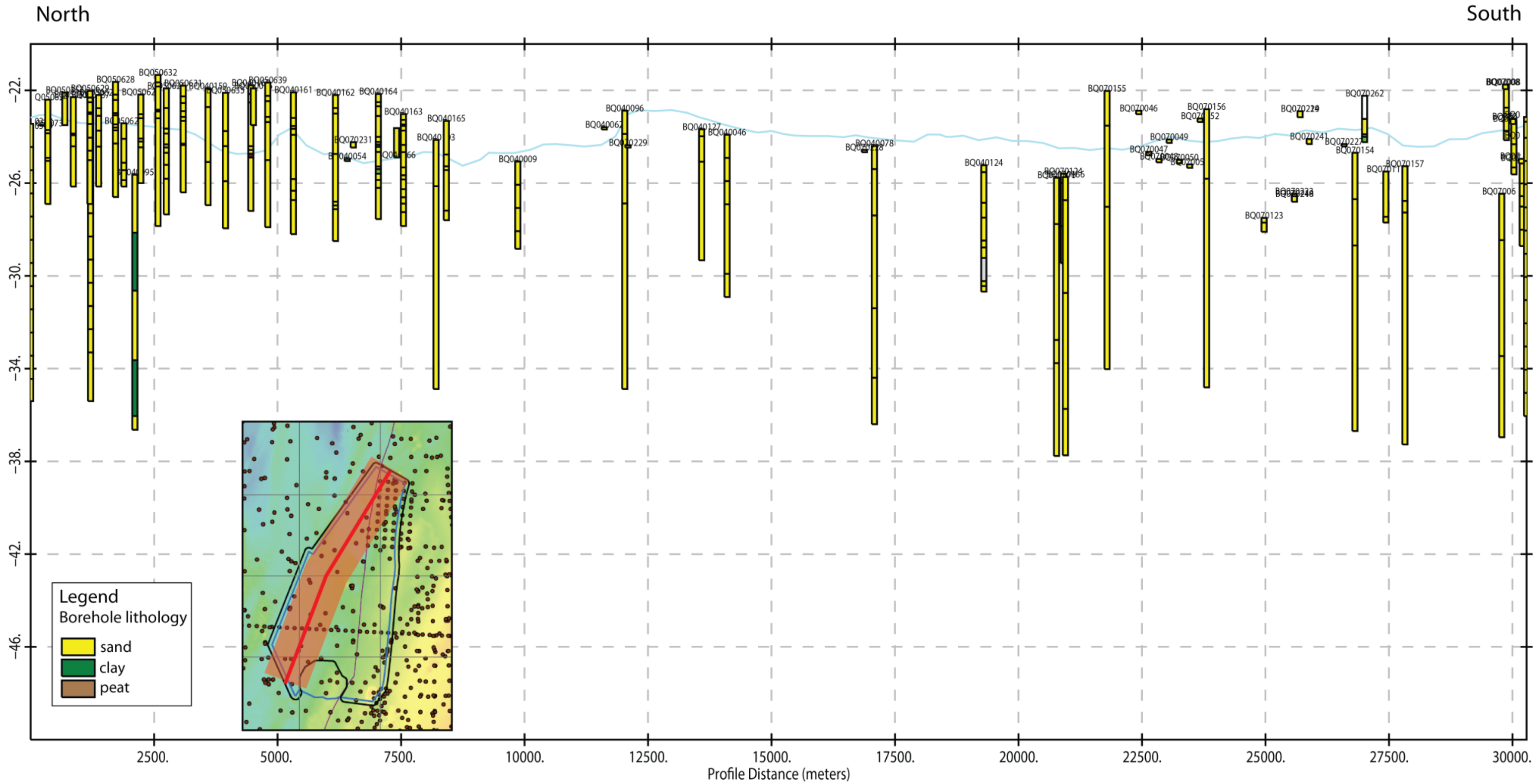

Figure 2.5 North-south cross section through the area outside 12 nautical mile line showing boreholes at and projected (maximum distance 2500 m) on this section and the present seafloor (blue line). Differences in water depth are mainly due to sea bed mobility

2.2.2 Deep boreholes

Within the study area most publically available boreholes from DINOloket do not exceed a penetration of 12 meters, except for one borehole (BQ040138), which reaches a depth of 70 m below the seafloor. In addition, a deep borehole just outside the area of study reaches to a depth of 80 m below the seafloor (BQ040139) and five boreholes onshore reach depths greater than 100 m. Seven boreholes with a penetration of > 70 meters were carried out for BP in the vicinity of the area (Figure 2.6, boreholes A1, A2, B3Q8, B1Q4, B2Q4, D1, and D2). A detailed description and interpretation of these boreholes is enclosed as Appendix B.

These deep boreholes provide only lithological information and no stratigraphic description. In order to better constrain the deep stratigraphic architecture, we analysed five deep boreholes from DINOloket located at the coast and two offshore boreholes (12-41 and 12-42, de Bruijn et al., 2015). In particular, these boreholes were used to constrain the depth of the Yarmouth Roads Formation/top of the Winterton Shoal Formation and to build a deep geological cross section.

The stratigraphic position of the sediments in the deep boreholes, containing fine to coarse sand, silty sand and clay layers, has not been given. Based on the geological maps by TNO (see chapter 6), the shallower clay layers can be considered as part of the Naaldwijk Formation and the deeper layers as part of the Yarmouth Roads Formation (Figure 6.10).

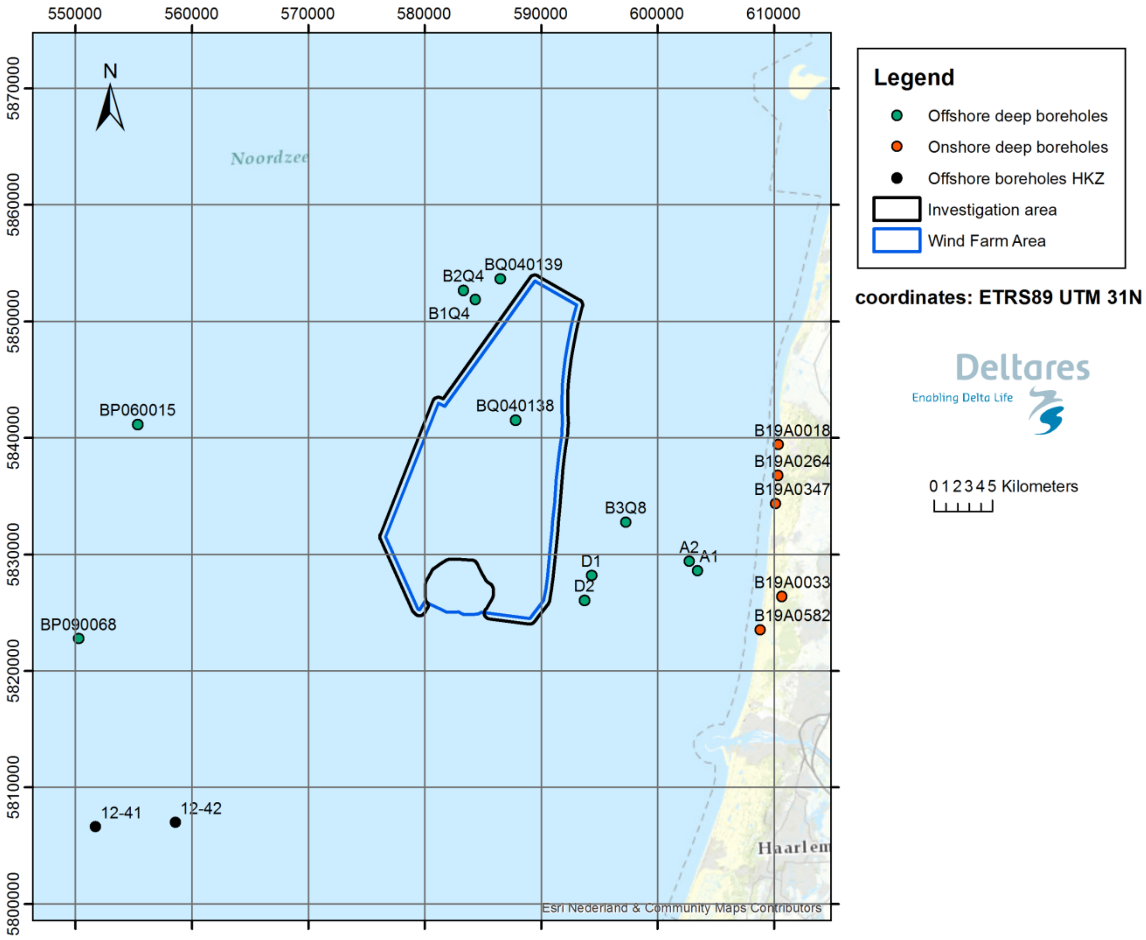

Figure 2.6 Locations of the deep boreholes in the vicinity of the study area.

2.3 Seismic surveys

Seismic surveys have been carried out in and around the study area for several decades. All data shown are digitally available and can be requested at the Geological Survey of the Netherlands | TNO. This paragraph describes the available data, the quality and suitability of these data is assessed in Chapter 4. Large amounts of public seismic data are also available on http://nlog.nl/nl/home/NLOGPortal.html. In the study area mainly analogue seismic data from this source is available. This data was not assessed in this study. In the study area, both single and multichannel surveys have been carried out (Figure 2.7 and Figure 2.8). Details on the seismic survey lines are given in section 2.4, table 2.2, and chapter 4.

Each dataset has the coordinate reference system European Datum 1950. The spacing between single channel survey lines in the study area varies from 1-2 km (in the SE) to 5-6 km. Multichannel surveys spacing is 3 to 5 km. Multi-channel survey lines are N-S, E-W or NW-SE oriented. Coverage is good over the entire study area.

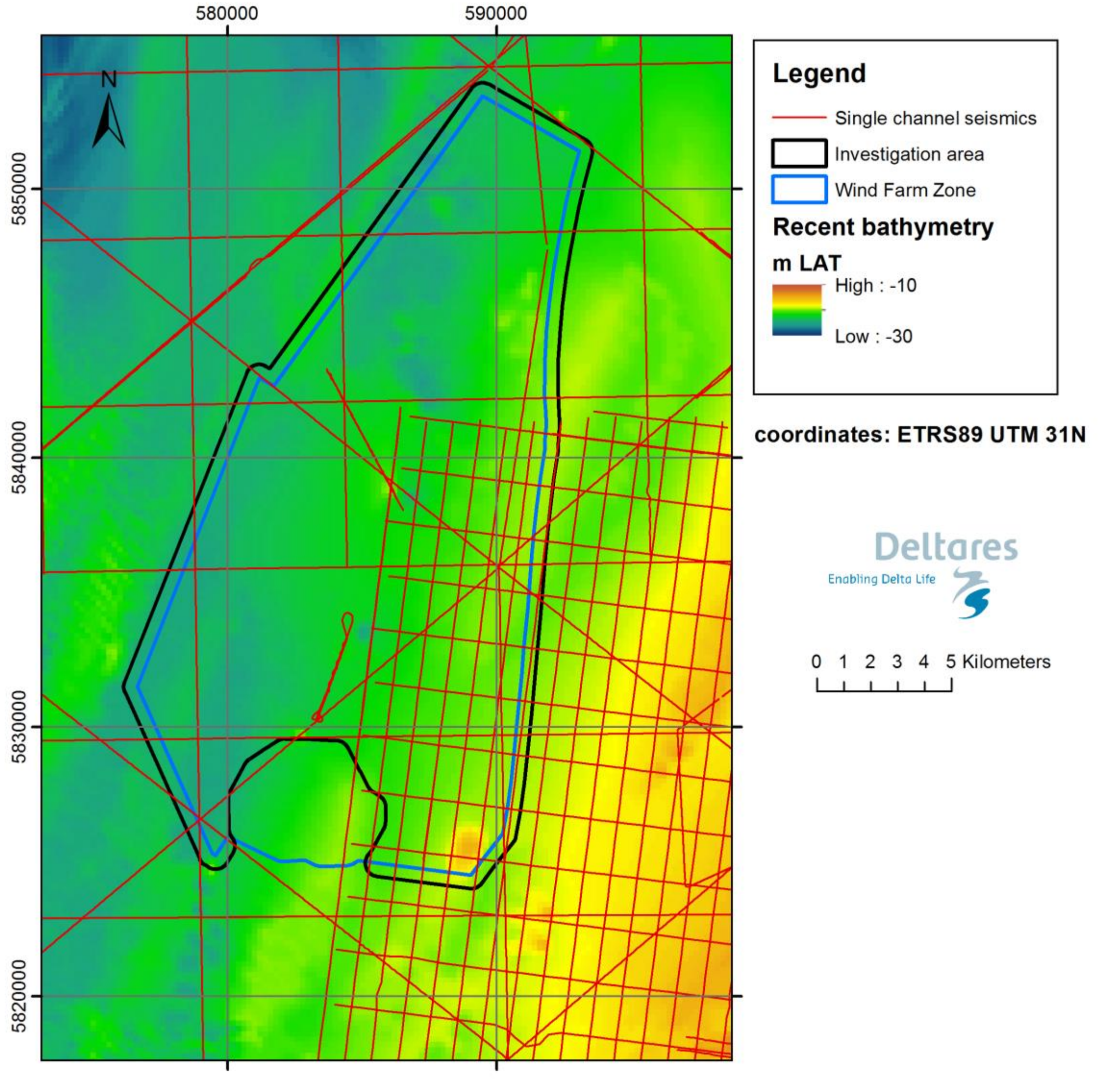

Figure 2.7 Lines of single channel seismic surveys across the study area. See table 2.2 for a description of the used seismic sources types.

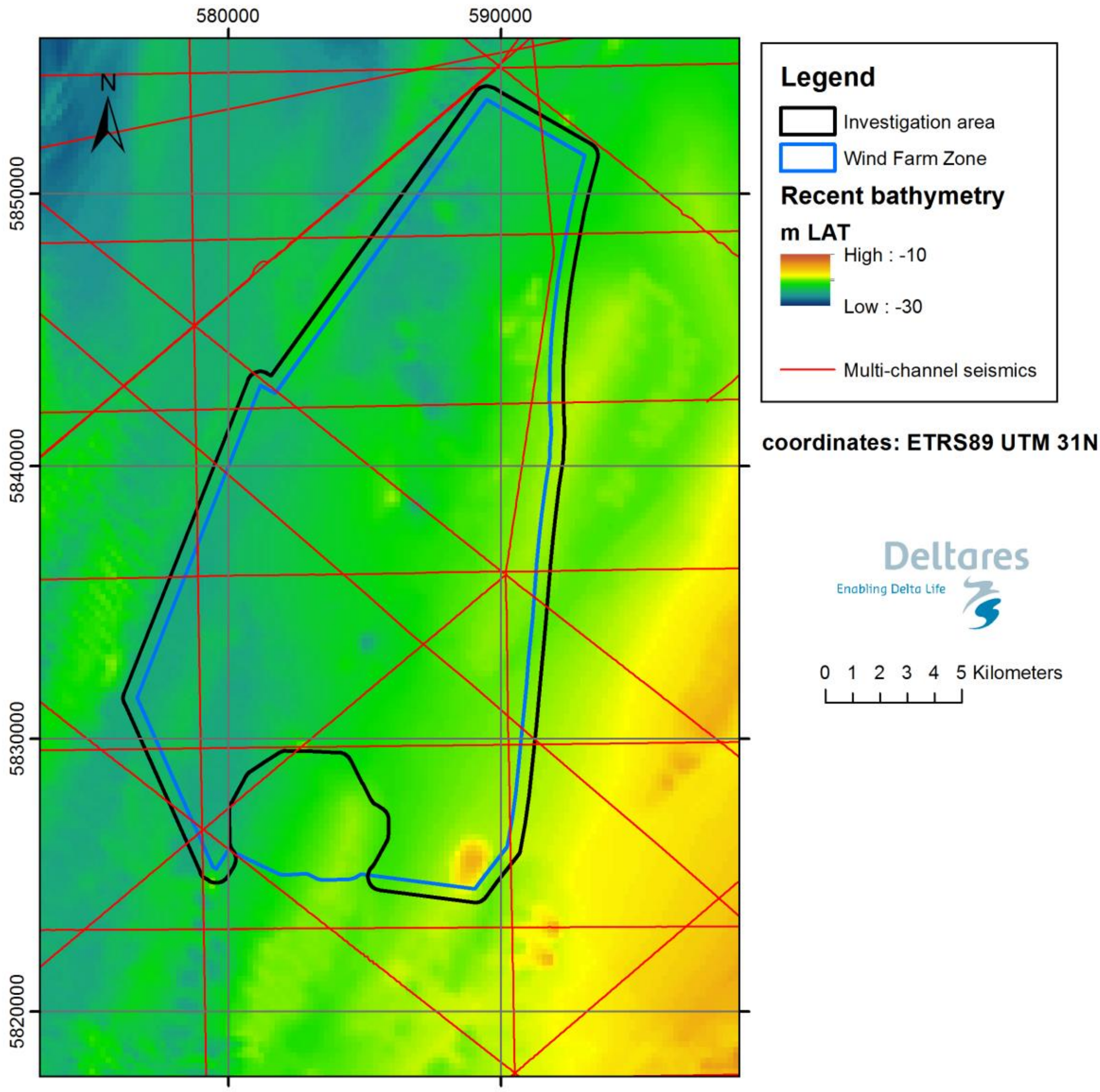

Figure 2.8 Lines of multi-channel seismic surveys across the study area. See table 2.2 for a description of the used seismic sources types.

2.4 Assessment of seismic data

The available seismic data with high vertical resolution collected with an XSTAR-Chirp system (single channel) covers the shallow part of the subsurface, approximately the first 10 to 15 meters (about 5 to 10 meters in sand and to up to 20 meters in unconsolidated clay). The signal produced (500 to 8000 Hz) is suitable to map geological units at shallow depth at high resolution and is only useful for the more heterogeneous units. Water gun and sleeve gun systems (multi-channel) provide lower resolution (meters) but higher penetration depth (hundreds of meters) as more power can be delivered by lower frequency sources (50 to 400 Hz). The data are suitable to analyse the larger scale units. Smaller scale geological units and heterogeneities are not visible in these data.

Prestack data are also available so re-processing of the data could be done to improve the imaging of the geological layers. However, the surveys at the time of acquisition were designed for large-scale geological surveys and not for site surveys for wind farms, so re-processing the lines may not yield the desired improvements. All data is available in time, and can be easily converted to depth. Velocity analyses have been done for all lines as a part of the multi-channel processing. In summary the XSTAR (Chirp) data do not provide enough depth penetration, while the water gun and sleeve gun systems data resolution is too low for the aim of this study.

Table 2.2 Available seismic survey data in and around the study area.

Project	Source	First year	Number of channels	Max. depth Indication (m)	Prestack available	Suitable for depth 0-100m?	Vertical resolution
eeg87	water gun	1987	12	500	Yes	barely	5 m
ijmgr95	chirp (XSTAR)	1995	1	15	-	0-10 m	30 cm
ijmgr95	sleeve gun	1995	12	1500	Yes	hardly any reflectors 50 - 100m	4 m
ijmgr96	chirp (XSTAR)	1996	1	15	-	0-10 m	30 cm
ijmgr96	sleeve gun	1996	12	1000	Yes	hardly any reflectors 50 - 100m	4 m
Eg97	chirp (XSTAR)	1997	1	15	-	0-10 m	30 cm
Eg97	sleeve gun	1997	12	1000	Yes	hardly any reflectors 50 - 100m	4 m
trapese	chirp (XSTAR)	1998	1	15	-	0-10 m	30 cm
Berg01	chirp (XSTAR)	2001	1	15	-	0-10 m	30 cm

3 Literature review

In this chapter we present an overview of the relevant literature and the regional geological evolution with focus on the uppermost 100 m that consist of Pleistocene and Holocene deposits. For this overview we used peer-reviewed articles, previous reports and maps by Deltares or TNO-Geological Survey of The Netherlands (GDN) and core and borehole data from the DINO-database. The cores are usually only a few meters deep, occasionally boreholes reach below 10 m, and hence the level of knowledge and detail progressively diminishes with depth. For the deeper subsurface, here up to 100 m below sea bed, the available offshore geological maps can be used to obtain a general understanding of the regional geological build up. These maps have been constructed using a combination of deep boreholes with seismic data (see also Chapter 2 and 6).

Below the regional geological evolution is described between 1000 and ~500 kilo years before present (kyr), the period before the first ice sheet reached The Netherlands. The influence of glaciations between ~500 and 140 kyr and in the final part focus on the period since 140 kyr is highlighted. A chronostratigraphic correlation panel of the Pleistocene formations in the North Sea is shown in Figure 3.1.

3.1 Geological evolution between 1000-500 kyr (Middle Pleistocene)

Between 1000-500 kyr climate changed repeatedly from cold, glacial conditions to warm, interglacial conditions. During glacial periods sea level was low due to storage of water in ice sheets, while in interglacial periods sea level could reach similar levels as present. On average sea level was ~50 m lower than today (Hijma et al., 2012), meaning that during most of the time the southern North Sea was dry land. In this period the Dover Strait was still closed and England was connected to the continent via a chalk landbridge (Hijma et al., 2012). North of this landbridge the southern North Sea Basin hosted several large river systems such as the Thames, the Rhine, the Meuse and the Eridanos. The Eridanos system originated from the Gulf of Bothnia area and is also known as the Baltic River System. It became inactive around 700 kyr ago due to repeated glaciations in Scandinavia (Cohen et al., 2014).

These river systems deposited significant amounts of sediments in the southern North Sea region. In the study area the fluvial deposits of this time can be found from depths between -25 and -30 m LAT and have their base well below -100 m LAT (Figure 6.10). The upper 60-70 m consist of fine to medium sand with occasionally some clay laminae or reworked peat (Yarmouth Roads Formation). These deposits were deposited by the rivers Rhine and Meuse during variable sea levels: when sea level was high the environment was estuarine/deltaic, while during lower sea levels the environment was deltaic. Below the Yarmouth Roads Formation lies the Winterton Shoal Formation that partly resembles the characteristics of the Yarmouth Roads Formation, but can contain shallow-marine deposits as well. The onshore equivalents of these formations are the Sterksel Formation (Yarmouth Roads Formation), Waalre-Peize Formation (fluvial-deltaic Winterton Shoal Formation) and Maassluis Formation (shallow marine-estuarine Winterton Shoal Formation) (Rijsdijk et al., 2005).

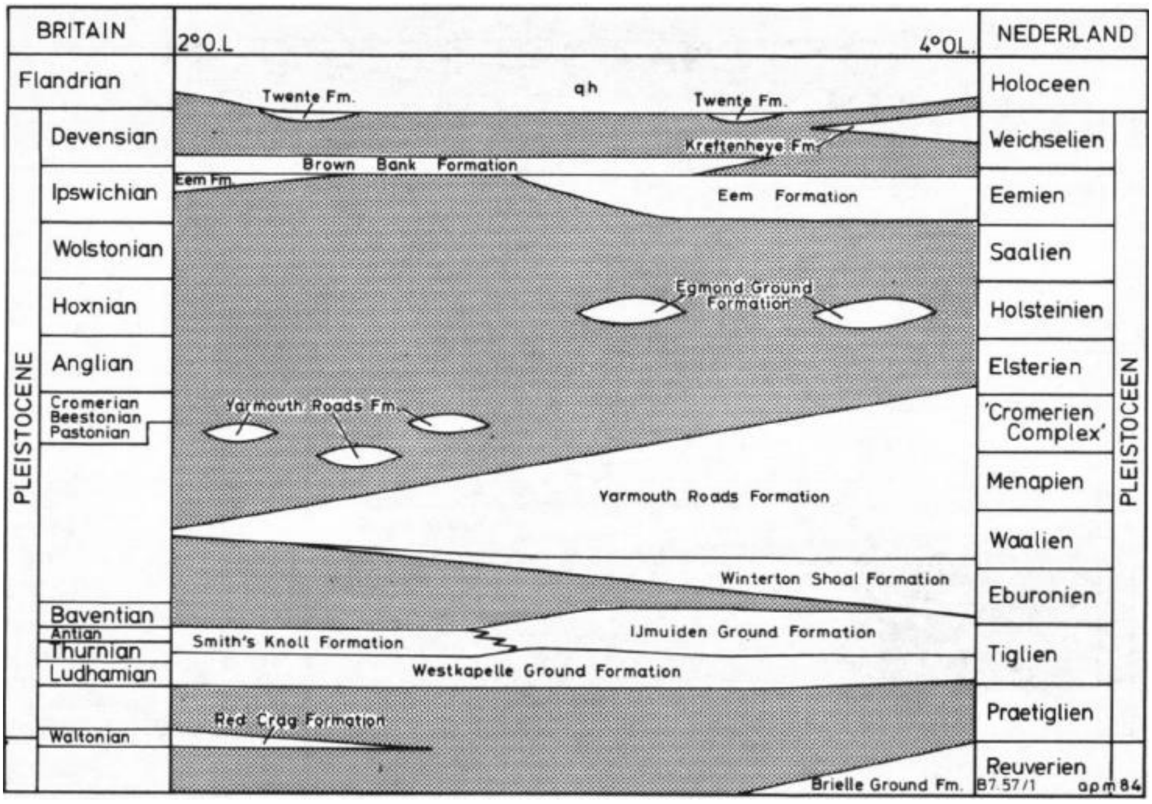

Figure 3.1 Chronostratigraphic correlation of Pleistocene units across the North Sea (from Laban et al., 1994). The Pleistocene starts 2600 kyr ago; the Holocene 11.7 kyr ago.

3.2 Geological evolution between 500-140 kyr (Middle Pleistocene)

This period is characterized by significant landscape change due to extensive glaciations. During at least two glacials, the Elsterian and the Weichselian (Table 3.1), the British and Scandinavion ice sheets coalesced in the North Sea region, hereby blocking the northern drainage path of the Rhine and Meuse river systems (Figure 3.2). Their outflow was forced south, resulting in erosion of the chalk bridge, the creation of the Dover Strait (Laban & Van der Meer, 2013; Hijma et al., 2012) and a connection between the English Channel and the southern North Sea during periods of high sea level.

Table 3.1 Glacial-interglacial phases nomenclature in the North Sea region.

	Netherlands	**Britain**	**Equivalent to MIS**
Glacial	Weichselian	Devensian	4-2
Interglacial	Eemian	Ipswichian	5
Glacial	Saalian	Wolstonian	6
Interglacial	Holsteinian	Hoxnian	9 or 11
Glacial	Elsterian	Anglian	12

During the Elsterian the ice sheet stopped just north of the study area, while during the Saalian the ice sheet reached as far south as Zandvoort and hence covered the study area (Figure 3.2) hereby forming a glacial basin and several ice-pushed ridges. The glacial basin lies directly west of Hollandse Kust (Noord), while the ice-pushed ridges lies directly south.

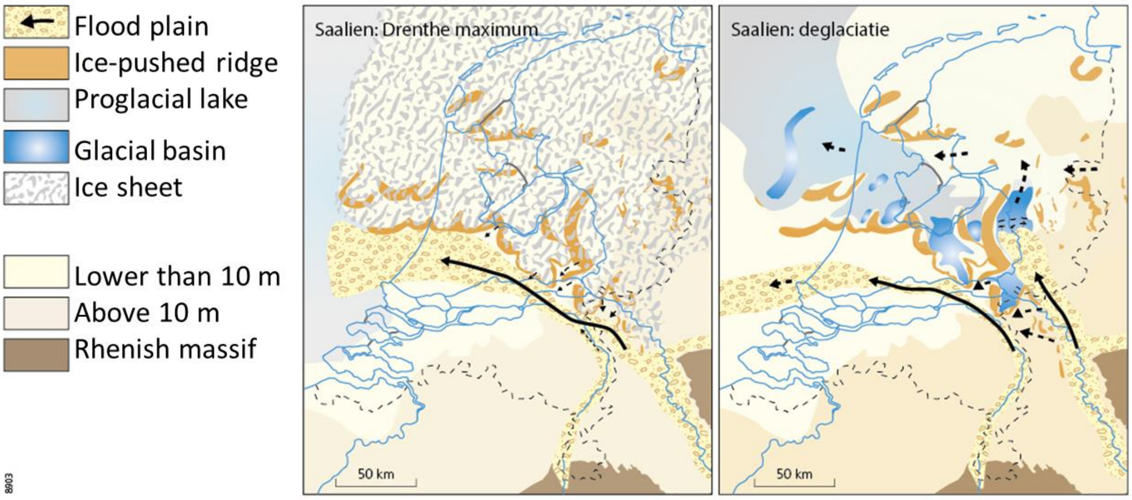

Figure 3.2 Paleogeographical situation during the maximum extent of the Saalian ice sheet (left) and during the following deglaciation (right). Modified from Stouthamer et al., 2015.

Few boreholes in the study area and wider region describe sediment from this period. In the northern part there are indications for preserved patches of terrestrial (Drachten Formation: peat, clay, sand of Saalian age, previously known as the Tea Kettle Hole Formation) or more estuarine and shallow marine sediments (Egmond Ground Formation: clay, sand of Holsteinian age and offshore equivalent of the Urk Formation). The patchiness is the result of erosion during the last 140 kyr. It is possible that locally lacustrine deposits have been preserved. These deposits filled the glacial basins after the ice-sheets retreated and belong to the Uitdam Member of the Drente Formation. There are no indications for the presence of till, but its presence cannot be excluded.

3.3 The last 140 kyr (Middle to Late Pleistocene)

After the Saalian glaciation the Rhine formed an incised valley (Figure 3.3AB) that during the Eemian interglacial was transgressed by the sea (Figure 3.3C). Fluvial sediments that filled the valley have not been described offshore, but the transgressive estuarine and shallow marine sediments of the Eem Formation occur in the study area and wider surroundings. After the peak of the interglacial, sea level dropped and the study area became part of the deltaic plain of the Rhine (Figure 3.3D). If the preserved deltaic sediments consist of significant clay and peat layers they are generally classified as the Brown Bank Member of the Eem Formation. The more sandy sediments are, depending on the either fluvial or tidal characteristics, part of the Kreftenheye or Eem Formation respectively.

Around 80 kry ago (end of interglacial, beginning of the Weichselian) the sea level dropped significantly and the Rhine incised resulting in large-scale erosion of the Eem Formation and Brown Bank Member of the Eem Formation. The southern part of the study area became part of the Rhine valley (Figure 3.3EF) and fluvial sediments of the Kreftenheye Formation were deposited. After the Rhine abandoned the area around 40 kyr and until the start of peat formation during the early Holocene (11.7-8.5 kyr), different types of deposits formed in the study area belonging to the Boxtel Formation (Peters et al., 2015). They consist of sediments deposited by brooks (sand, sandy loam), peat, thaw-lake deposits and wind-blown (eolian) deposits (cover sand). Although the Rhine had left the area, the valley it created was still present and drained by the paleo-Vecht system.

At the start of the Holocene sea level was still below -50 m LAT, but around 8.5 kyr sea level had already reached -20 m LAT (Hijma and Cohen, 2010). This resulted in rising ground-water levels and widespread peat formation, known as the Basal Peat Bed (Nieuwkoop Formation). Continued sea-level rise resulted in drowning of the peat landscape and the formation of initially a back-barrier setting and later a shallow-marine environment. This means that the shoreline migrated across the area at some point, hereby truncating older deposits. Since the area was relatively low-lying in the paleo-Vecht valley, the area drowned rapidly and changed into a large tidal basin (North-Holland Basin).

The back-barrier deposits can consist of brackish lagoonal clay (Velsen Bed of the Naaldwijk Formation) or tidal-channel and tidal-flat deposits (Wormer Member of the Naaldwijk Formation). The tidal-channel deposits occur locally and are often clearly visible in seismic data. Especially in the southern part of the study area the Basal Peat Bed and clay-rich deposits of the Wormer Member of the Naaldwijk Formation seem to have been preserved. The infill of the North-Holland basin also contains the characteristic Bergen Bed of the Naaldwijk Formation. The Bergen Bed consists of (sandy) clay and generally starts below -15 m NAP and can be over 20 m thick. Its mapped offshore extension ends ~4 km east of the study area (Erkens et al., 2014). After the shoreline migrated to the east of the study area, the sandy deposits were shaped into sand banks and sand waves (Van Dijk and Kleinhans, 2010). These deposits are part of the Southern Bight Formation.

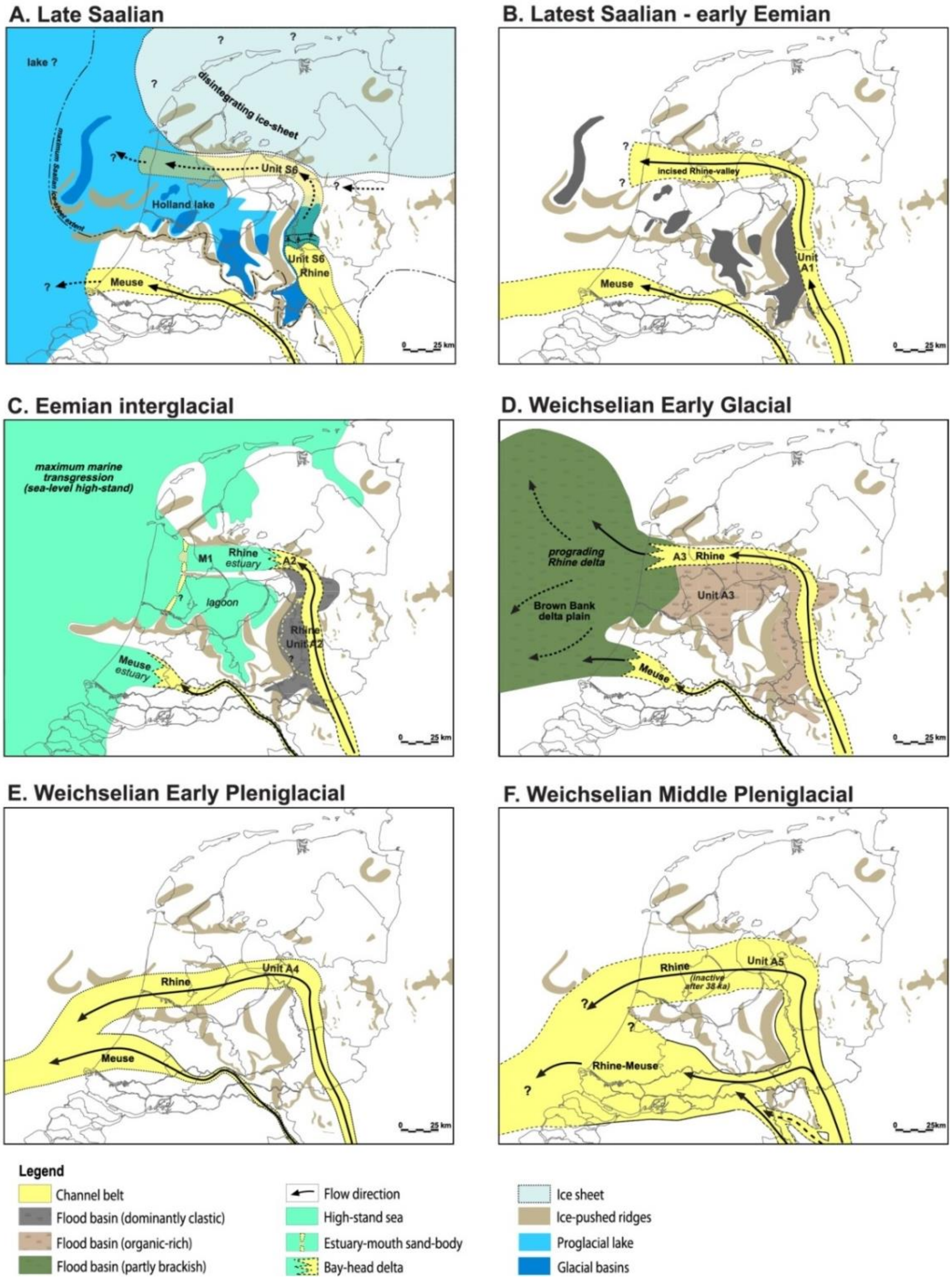

Figure 3.3 Large-scale evolution of fluvial-estuarine systems in The Netherlands between 140-30 kyr. From Peeters et al., 2015.

4 Interpretation of seismic data

Figure 4.1 shows part of the single channel seismic line berg01-5001 (project berg01) (A), and details of the project eg97 (B) and (C). The assumed velocity to estimate depth from time data is 1600 m/s. The location of these lines is shown in figure 4.2. The profile in (A) displays a strong reflector at 2 to 4 m below the seafloor. This may represent a clay or peat layer in the Naaldwijk Formation or the basal peat (Nieuwkoop Formation). The morphology of the reflector suggests the presence of a channelized feature in the central part of the profile. The profile in (B), from the central part of the study area displays faint non-continuous reflectors from 1 to 4 m below the sea floor, indicating an intercalation of sand and clay layers. These deposits may be attributed to the Naaldwijk Formation.

The upper layer is transparent, suggesting the presence of homogenous sand (Bligh Bank Member of the Southern Bight Formation). The profile in (C) shows part of a heterogeneous channelized sediment body in the northern part of the study area, with two strong reflectors at its base. These deposits may be attributed to the Eem Formation.

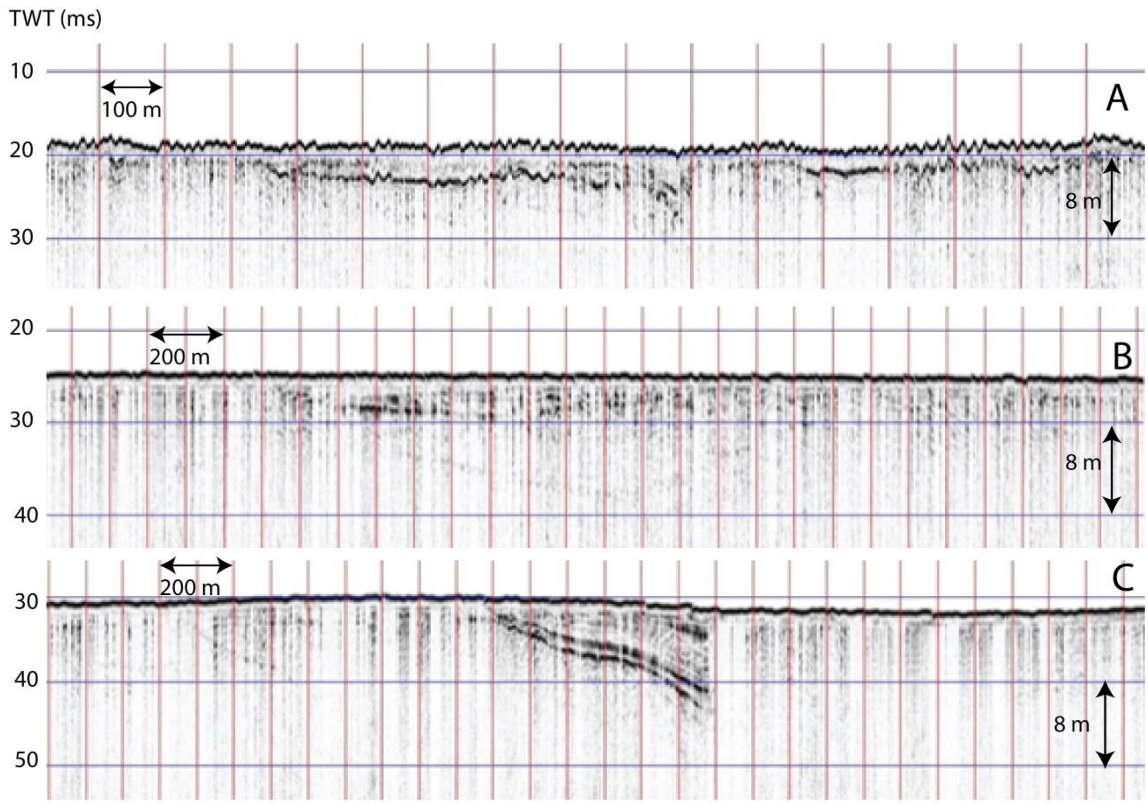

Figure 4.1 Examples of single channel CHIRP geophysical sections in the study area. See table 2.2 for the used seismic source type.

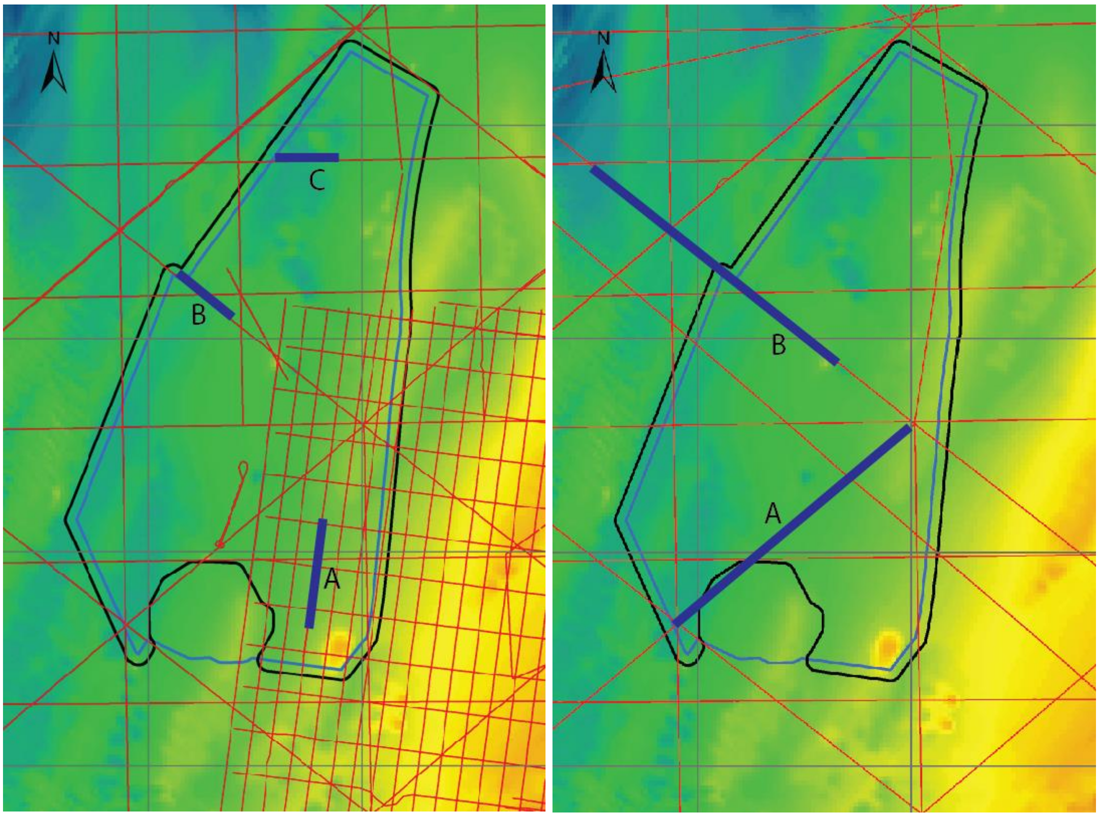

Figure 4.2 Location of the seismic lines visualized in figure 4.1 and 4.3

Figure 4.3 shows three examples of multi-channel seismic records in the study area. The assumed velocity to estimate depth from time data is 1600 m/s. Compared to single channel Xstar seismic records these have a much lower resolution but a much greater penetration depth. Record A (project ijmgr96) shows a strong reflector at around 800 m depth which is affected by numerous faults. These faults can be sometimes traced up to a depth of 300 m. The reflectors at 500-800 m depth show large scale oblique layering, characteristic of deltaic foresets. On the far-right hand side of the record a strong reflection can be seen at 150 m depth indicating possible reflection enhancement by gas.

Profile B (project eg97) shows enhancement of the reflection strength (amplitude) at 150-500 m depth, which is likely caused by trapped gas leaking along faults from gas fields in the subsoil. Profile C is the continuation in the NW direction of profile B outside of the study area. Here a gas chimney is possibly present, together with enhancements at 900 m depth and a small, but very strong one at 300 m depth. Still, if enhanced reflectors only occur at shallow depths and there are no signs of enhancements deeper down, the enhancement could also be induced by a strong lithological change (like sand-hard clay transition) and/or by in situ gas (i.e. organic gas as in peat). Finally, although reflectors in the seismic section may indicate changes in lithology and the presence of certain layers, the thickness of layers cannot (always) be determined, due to the low vertical resolution of the seismic data. This can be the case when only a reflector is visible at the top of a layer, but not at the bottom. This information should be inferred from borehole descriptions.

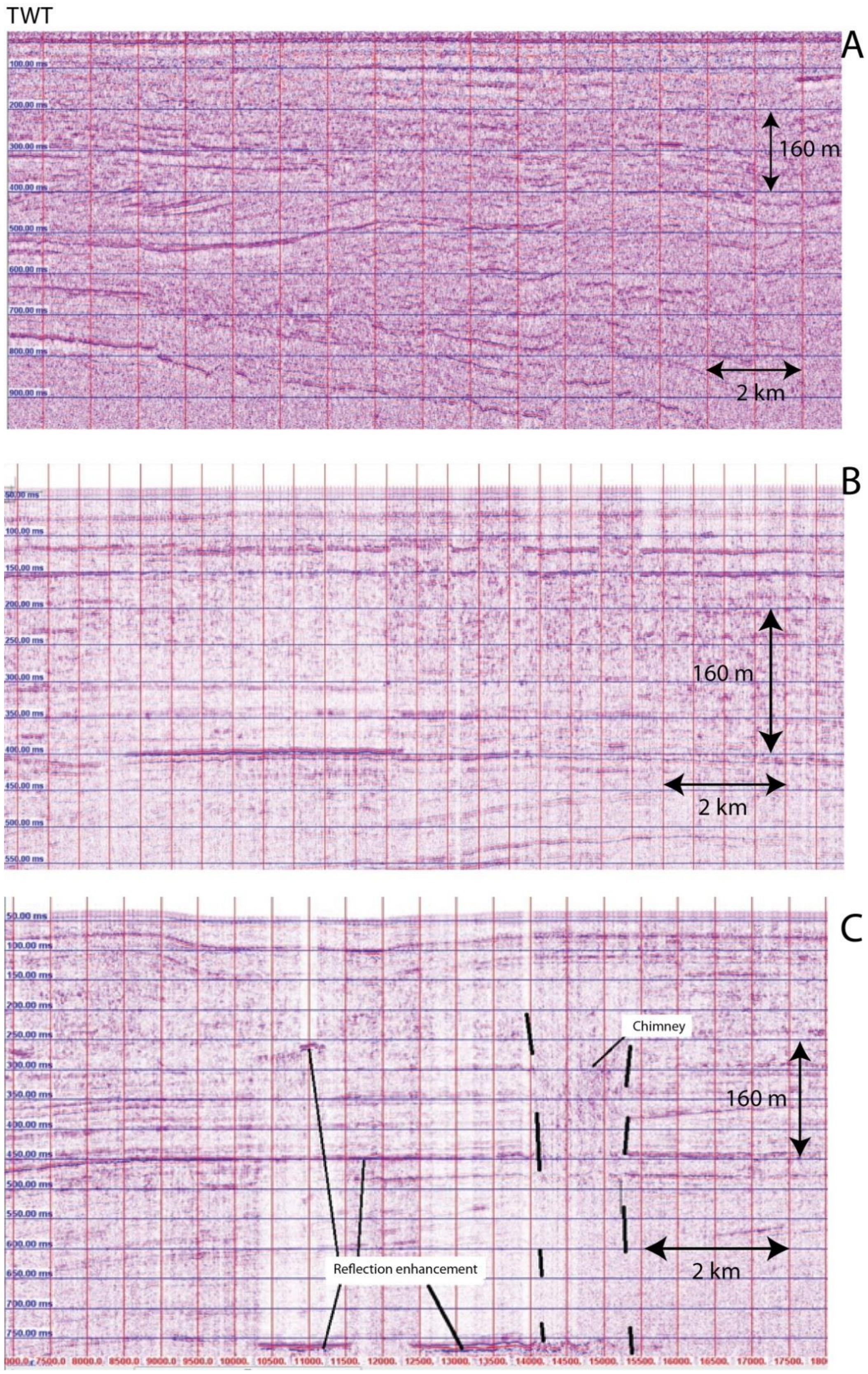

Figure 4.3 Examples of multi-channel geophysical sections in the study area with a chimney of escaping shallow gas. See table 2.2 for the used seismic source type.

5 Stratigraphic framework

5.1 Stratigraphic classification

In the past two decades, various (national) stratigraphic subdivision schemes for the southern North Sea basin and its surrounding have been proposed. These schemes differ for the following reasons:

- Onshore lithostratigraphic systems (usually based on boreholes) are difficult to correlate with offshore seismostratigraphic units (typically based on seismics).
- Political division of the North Sea among British, Belgian, Dutch, German and Danish areas, with geological surveys mapping with different legends and scales. For example this has led to different names for the same formation or to the attribution of the rank of member, formation, or group to the same geological unit.
- The loss of discriminating lithological detail when units are traced from basin margin to basin centre.

As the study area is close to the offshore British-Dutch border, the stratigraphic classification of sedimentary units is influenced both by the Dutch and the British system. Few works have attempted a correlation/classification scheme between the two schemes. Laban et al. 1994 proposed one based on the geological map Flemish Bight (BGS & RGD, 1984), west of the study area. A more comprehensive approach based on regional discontinuities, facies and sedimentary environment correlation and a more precise chronology was proposed by Rijsdijk et al. (2005) (Figure 5.1). In this work the major discontinuities represent regional/global events, such as ice sheet cover and major sea-level fall.

Ebbing et al (2003) and Hijma et al. (2012) provide an extra level of detail on the stratigraphic framework of Rijsdijk et al. (2005) illustrating the general chronology and stratigraphic classification of geological units with focus on the Late Pleistocene to Holocene onshore and near offshore the Netherlands. For the purpose of this study we consider the framework by Rijswijk et al. (2005) to be the most complete and the level of detail to be the most appropriate for the study area. We adopted two exceptions from this framework. For the older Pleistocene formations it is proposed to use the older names Yarmouth Roads Formation and Winterton Shoal Formation. The Yarmouth Roads Formation is considered as the offshore equivalent of Sterksel Formation (and Appelscha Formation in the NE part of the Netherlands). THe Winterton Shoal Formation is considered as the offshore equivalent of the Waalre Formation and Peize Formation. Furthermore, we considered the Drachten as a formation and not as a member of the Boxtel Formation, according to the most recent description in DINOloket. This distinction is based on the temporal and stratigraphic difference. They both consist of fluvial and aeolian sediments deposited in a periglacial environment, but the Drachten formed before the Saalian glacial period and the Boxtel after the Weichselian glacial period.

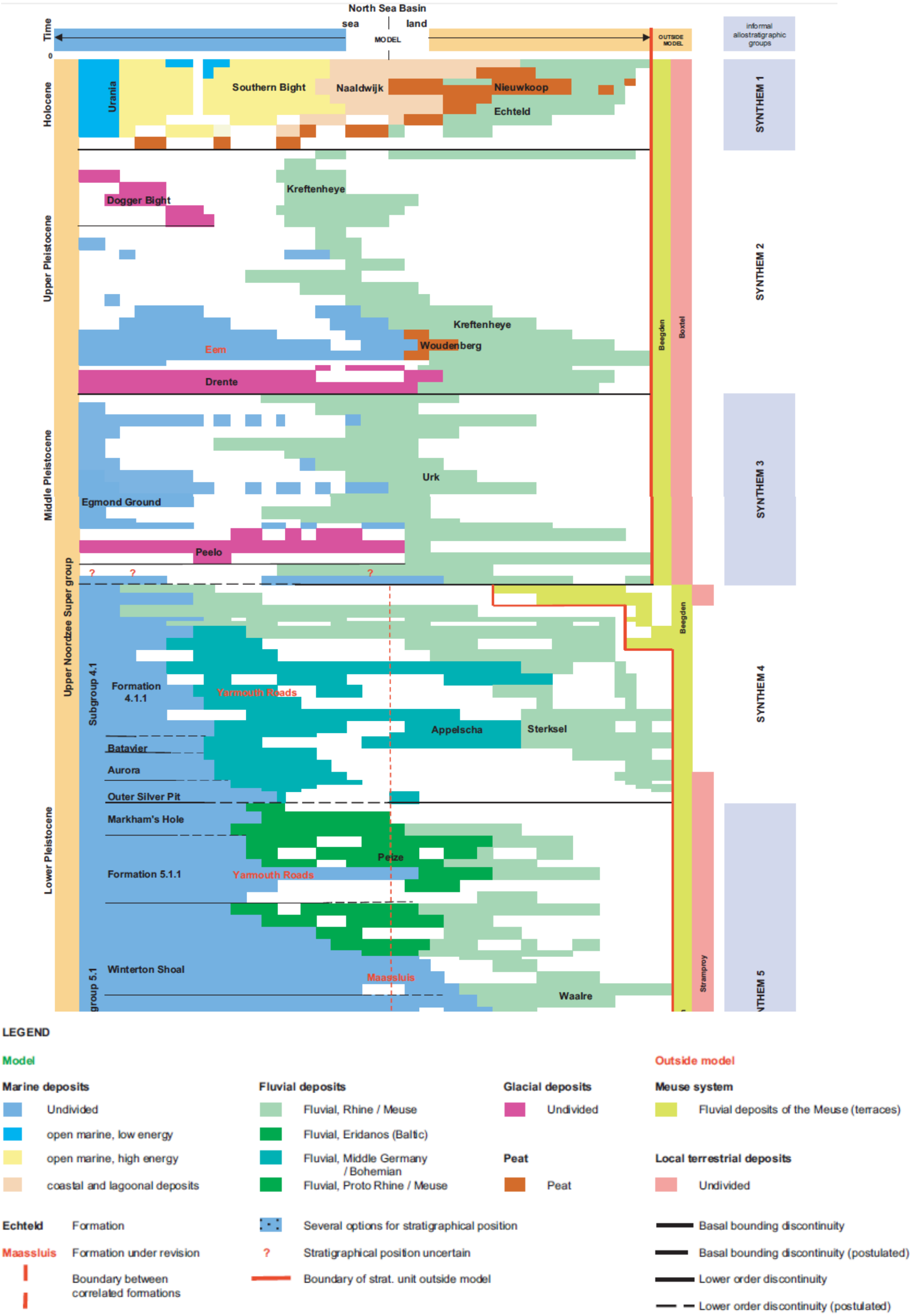

Figure 5.1 Chronostratigraphic/allostratigraphic correlation of Pleistocene units across the North Sea (Rijsdijk et al. 2005).

5.2 Geological units and expected sequence

A general description of the geological units and an overview of the typical geological sequence are given in Table 5.1. Based on the depth, the heterogeneity and lithology, the relevance of each unit for the proposed geophysical survey and turbine foundation design is indicated. Uniform units with sandy lithology are considered less relevant, while clay rich and heterogeneous deposits with a discontinuous occurrence of higher relevance. This description is based on TNO DINO-borehole descriptions and on the geological maps 1:100000 series (BGS and RGD, 1984). The geological units in the sequence are indicated in the schematic geological cross-sections (Figure 6.9 to Figure 6.10, location of sections in Figure 6.11).

The digitized geological maps by TNO were used for constructing the cross-sections and the geological maps. These are based on borehole and seismic data and provide the extent and the thickness of the youngest geological units across the whole study. Still, they have considerable uncertainties related to the low data density in the area. As boreholes are hundreds of meters apart, the depth and thickness of the formation between the boreholes is statistically interpolated and hence it may not portrait the actual geological architecture. This implies that in order to correctly constrain geological properties, a geophysical survey and new boreholes and CPT’s are needed. Furthermore, new boreholes have been drilled after the building of the maps. In order to build the cross-sections we adapted the modelled thicknesses and depth according to the new measured data.

Southern Bight Formation - Bligh Bank Member

The upper sand unit covering the seafloor belongs to the Bligh Bank Member of the Southern Bight Formation and covers the entire study area. It consists of fine to coarse calcareous sand containing shell remains and locally clay layers. In the southern part of the study area, the member reaches a thickness of 5 m, and gravel content is approximately 1 - 5%, locally increasing to 5 - 10%. At the seafloor, active sand waves with a height of 1 to 2 m are present. The upper part of the sand unit that is still active is classified as the Bligh Bank Member. The depositional environment is shallow marine.

Naaldwijk Formation - Wormer Member

The Wormer Member of the Naaldwijk Formation is composed of fine sands and clay. It occurs in isolated channels. The formation consists of coastal and back-barrier clastic sediments.

Velsen Bed and Bergen Bed (part of the Naaldwijk Formation – Wormer Member)

The Velsen Bed consists of humic, silty clay, locally on top of a 0.5 to 1 m thick peat. It occurs in patches, especially in the southern and eastern part of the study area, at depths of 2 to 2.5 m below the seafloor. The Bergen Bed consists of (sandy) clay. It occurs in the area SE of the study area. Isolated patches may be present in the study area as well but have not been observed. The sediments were deposited in a coastal plain environment.

Nieuwkoop Formation – Basal Peat Bed

This peat bed occurs in patches in the southern and eastern part of the study area. When present, its thickness does not exceed 1 m. The depositional environment is fluvial/coastal plain.

Boxtel Formation

This formation consists of very fine to coarse sands, locally with thin layers of fine gravel. This formation occurs throughout most of the area and typically represents the top of the Pleistocene deposits. These sediments were deposited by small fluvial systems in a periglacial environment.

Kreftenheye Formation

The Kreftenheye Formation consists of local calcareous fine to coarse sands containing shells and fine to medium coarse gravel (2 – 16 mm). Gravel content is typically 1-10 %, but locally up to 17 %. Furthermore, wood fragments and hard clay casts are present. This formation occurs only in the southern part of the study area. These sediments were deposited by a braided fluvial system.

Eem formation – Brown Bank Member

The Brown Bank Member of the Eem Formation consists of partly consolidated silty clays and fine sands. It occurs in the central and northern part of the study area in rather isolated patches, 2 to 6 m thick. These sediments were deposited in a lagoon-delta plain environment.

Eem Formation

The Eem Formation consists of fine to medium coarse sands, silt and silty sand (1-15 %), containing shells (5 %) and locally gravel (1 to 5 %). It occurs in the southernmost and northernmost parts of the study area. These sediments were deposited in coastal environment.

Drente Formation – Uitdam Member

This formation consists of fine to coarse sand (poorly sorted) and clay. It possibly occurs in the northernmost part of the study area. These sediments form the sedimentary fill of glacio-lacustrine basins.

Drachten Formation

This formation consists of fine to coarse sands and occurs in disconnected bodies in the study area. These deposits were deposited by fluvial and aeolian processes in a periglacial environment.

Egmond Ground formation

This formation comprises shelly fine sands and locally peat, and occurs in isolated patches. The sedimentary environment is fluvio-deltaic.

Yarmouth Roads Formation

The Yarmouth Roads consists of fine sands and locally silty clay. The upper boundary lies at about -25 to -30 m LAT. These sediments were deposited by large fluvial systems.

Winterton Shoal Formation

This formation consists of fine to medium sand with local clay intercalations. The top of this formation has been recognized offshore in two deep boreholes west of the Hollandse Kust Zuid WFZ and onshore, east of the Hollandse Kust Noord WFZ (Figure 6.10). The sedimentary environment is fluvio-deltaic.

Table 5.1 Characteristics of most important geological units. The median grain size of the sand fraction is based on borehole data in the area of study

Stratigraphic Unit	Thickness	Age	Relevance	Lithology	Median grain size sand (μm)
Southern Bight Formation, Bligh Bank Member	0.5 to10 m , typically 2 to 5 m	Holocene	Low	Medium to poorly sorted, fine to coarse sand, carbonate and shell-rich, sparse clay and silt laminae, locally with gravel	200-300
Naaldwijk Formation, Wormer Member	0 to 6 m	Holocene	High	Very fine to medium sands, locally clay layers	100-250
Naaldwijk Formation, Wormer Member Bergen Bed and Velsen Bed	0 to 1 m	Holocene	High	clay, locally on top of peat, some shell remains	
Nieuwkoop Formation, Basal Peat Bed	0 to 0.5 m	Holocene	High	Peat	
Boxtel Formation	0 to 10 m, typically 2 to 3 m	Upper Pleistocene	Low	Very fine to coarse sands, locally with thin layers of fine gravel	100-350
Kreftenheye Formation	0 to 10 m, typically 3 to 5 m	Upper Pleistocene	Medium	Fine to coarse, poorly sorted sands, with gravel, shells, wood fragments, clay pebbles.	200-400
Eem Formation, Brown Bank Member	0 to 5 m	Upper Pleistocene	High	Clay, peat, silt and sand	
Eem Formation	0 to 5 m	Upper Pleistocene	Medium	Fine to medium coarse sand, silt and silty sand, with shells and locally gravel and mud.	150-300
Drente Formation, Uitdam Member	unknown	Middle Pleistocene	High	Fine to coarse sand, clay	200-2000
Drachten Formation	unknown	Middle Pleistocene	High	Fine to medium sand with organic material	150-300
Egmond Ground Formation	0 to 2 m	Middle Pleistocene	High	Fine grained sands, clay and peat	
Yarmouth Roads Formation	60 to 70 m	Lower to Middle Pleistocene	Medium	Fine to coarse sand with local clay and silt layers	100-300
Winterton Shoal Formation	30 to 130 m	Lower to Middle Pleistocene	Low	Fine to medium sand with local clay intercalations	150-300

6 Geological maps and cross sections

Maps produced by TNO with a scale of 1:100.000 are available for the youngest formations that are expected in our study area. These maps were used to create isopach maps (unit thickness, Figure 6.1 to Figure 6.6), geological cross sections (Figure 6.9, Figure 6.10 and Figure 6.10), and the Holocene subcrop map (Figure 6.7). As explained in chapter 5, these maps have clear limitations and were improved since new borehole data became available. Specifically, we adapted the depth of interfaces according to the new borehole data.

Additional maps produced by TNO at the scale 1:100.000 provide information on the southern part of the study area (sheet Ijmuidengronden). These include grain size information, among which a map of mud and silt content of the sediment at a depth of 1 and 2 meters beneath the sediment surface and the depth of the Pleistocene sands. Maps within this series are presented in Appendix C. Based on these maps and on the analysed borehole information from DINOloket we can indicate that:

- The Bligh Bank Member of the Southern Bight Formation is present in the entire study area with thickness variable from 0.5 to 10 m, typically 1 to 5 m thick.
- The Naaldwijk Formation (Wormer Member and Velsen Bed) and the Nieuwkoop Formation (Basal peat) occur as isolated bodies between 20 and 25 below LAT.
- The Boxtel Formation is present across the whole study area except for in the southwest. Its thickness is typically 2 to 3 m.
- The Kreftenheye Formation occurs only in the southern part of the study area and is typically 3 to 5 m thick.
- The Eem Formation occurs in the southernmost part of the study area as a continuous body. Even though the Brown Bank Member is not present in the area based on the geological maps, seismic and borehole data indicate its occurrence in disconnected bodies in the central and northern part of the study area.
- Based on borehole data, the Drente Formation (possibly), the Drachten Formation and the Egmond Ground Formation occur locally as disconnected bodies at depths ranging from 25 to 30 m below LAT.
- Glacial till and moraine deposits containing blocks and boulders (Drente Formation – Gieten Member) have not been observed but might be present in the area.
- The Yarmouth Roads Formation occurs throughout the whole area with a thickness ranging from 60 to 70 m.
- The Winterton Shoal formation lies below the Yarmouth Roads formation at inferred depth of 90-100 m below LAT (70 m below the seafloor). Based on borehole data of the area the position of the top of this formation is very uncertain. It might be possible to distinguish this formation from the Yarmouth Roads Formation in seismics based on the occurrence (Winterton Shoal) or not (Yarmouth Roads) of deltaic clinoforms.

To indicate the depth of the base of the Yarmouth Roads Formation, depths from available deep boreholes are shown in Figure 6.12 and Figure 6.13. The offshore boreholes are presented in paragraph 2.2. The onshore boreholes from www.dinoloket.nl are included in

Appendix D. In the onshore boreholes, the base of the Yarmouth Roads Formation is determined as the top of the Waalre Formaton and Peize Formation.

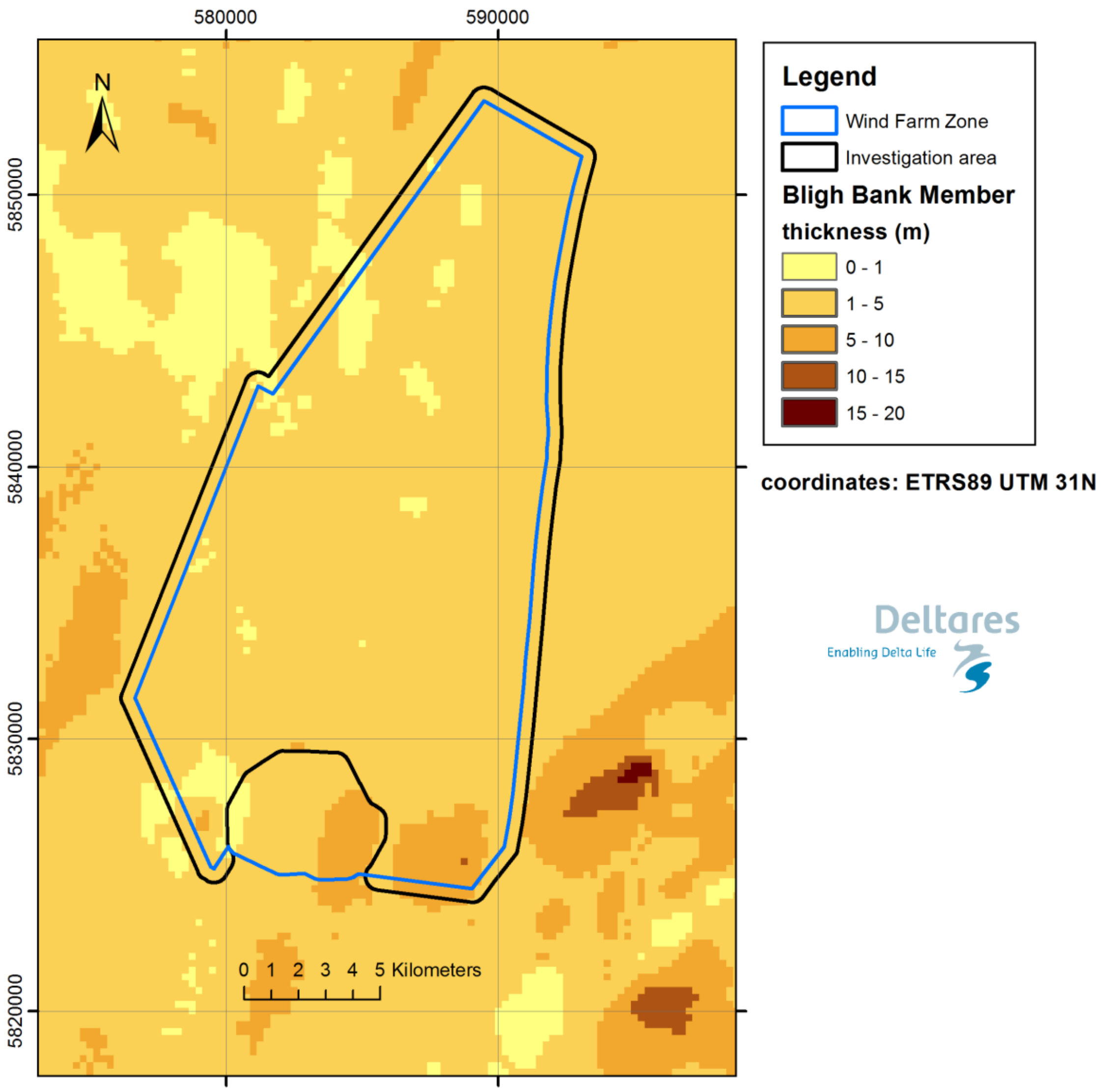

Figure 6.1 Extent and thickness of the Bligh Bank Member of the Southern Bight Formation.

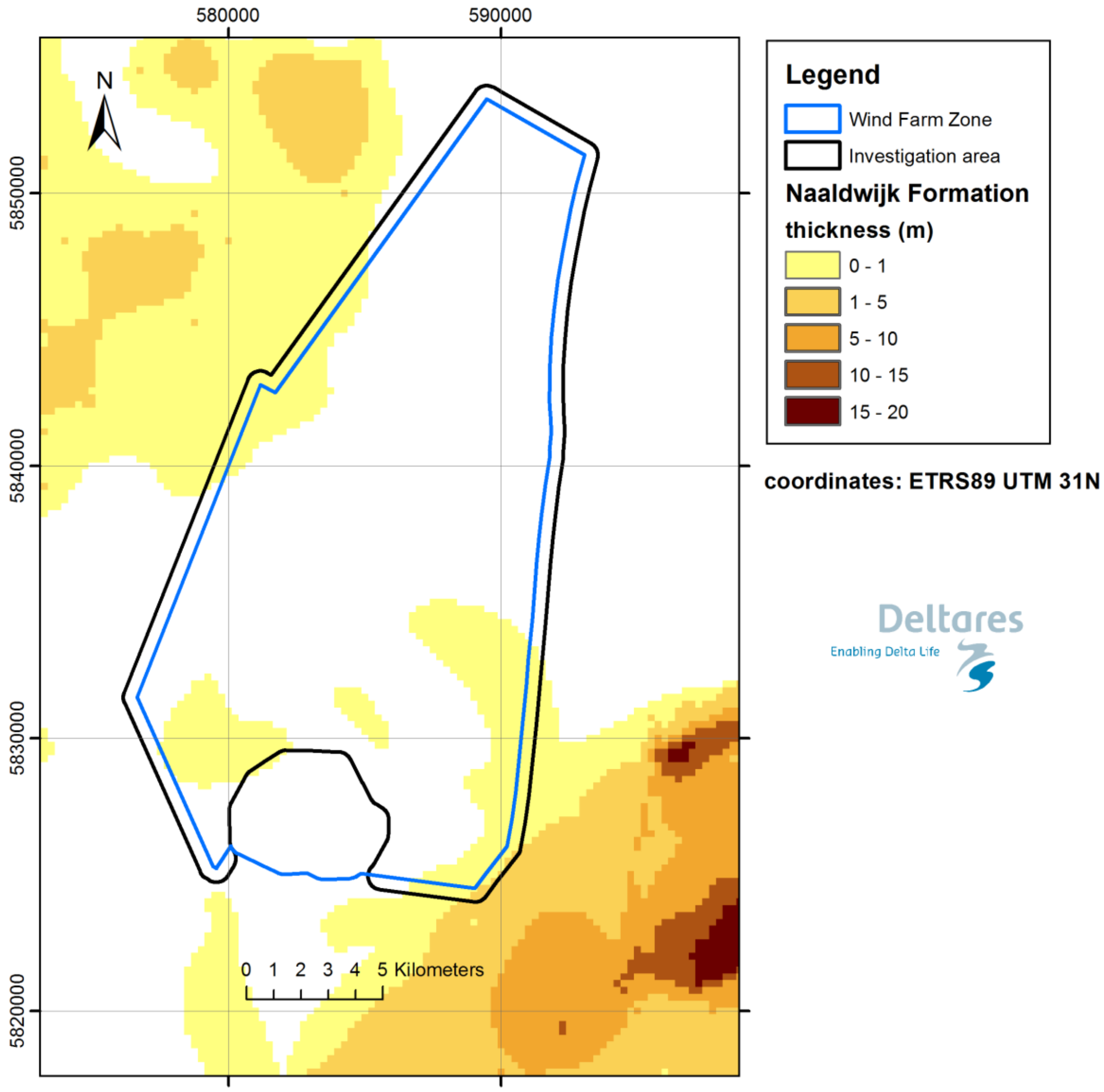

Figure 6.2 Extent and thickness of the Naaldwijk Formation.

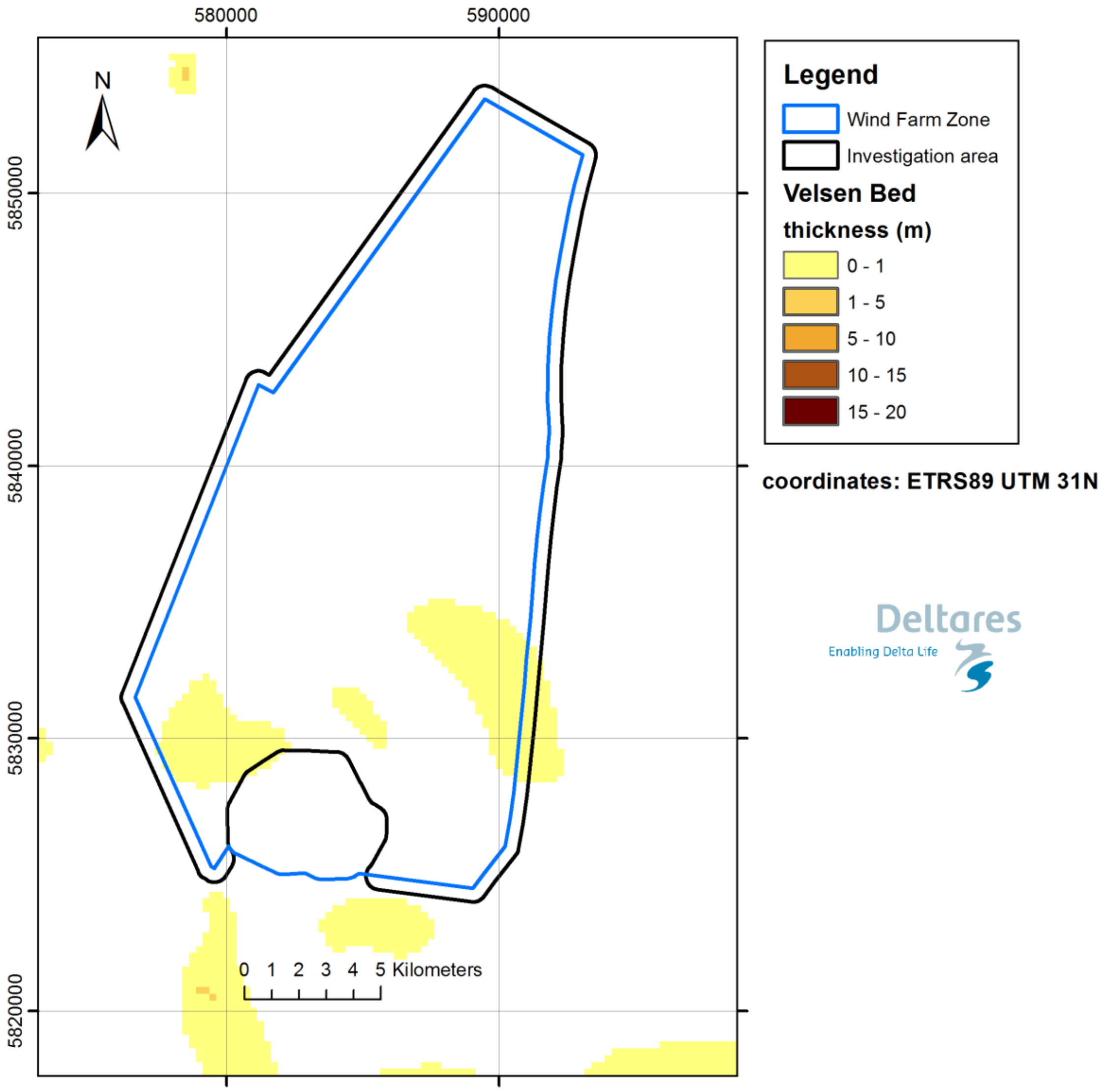

Figure 6.3 Extent and thickness of the Velsen Bed of the Naaldwijk Formation.

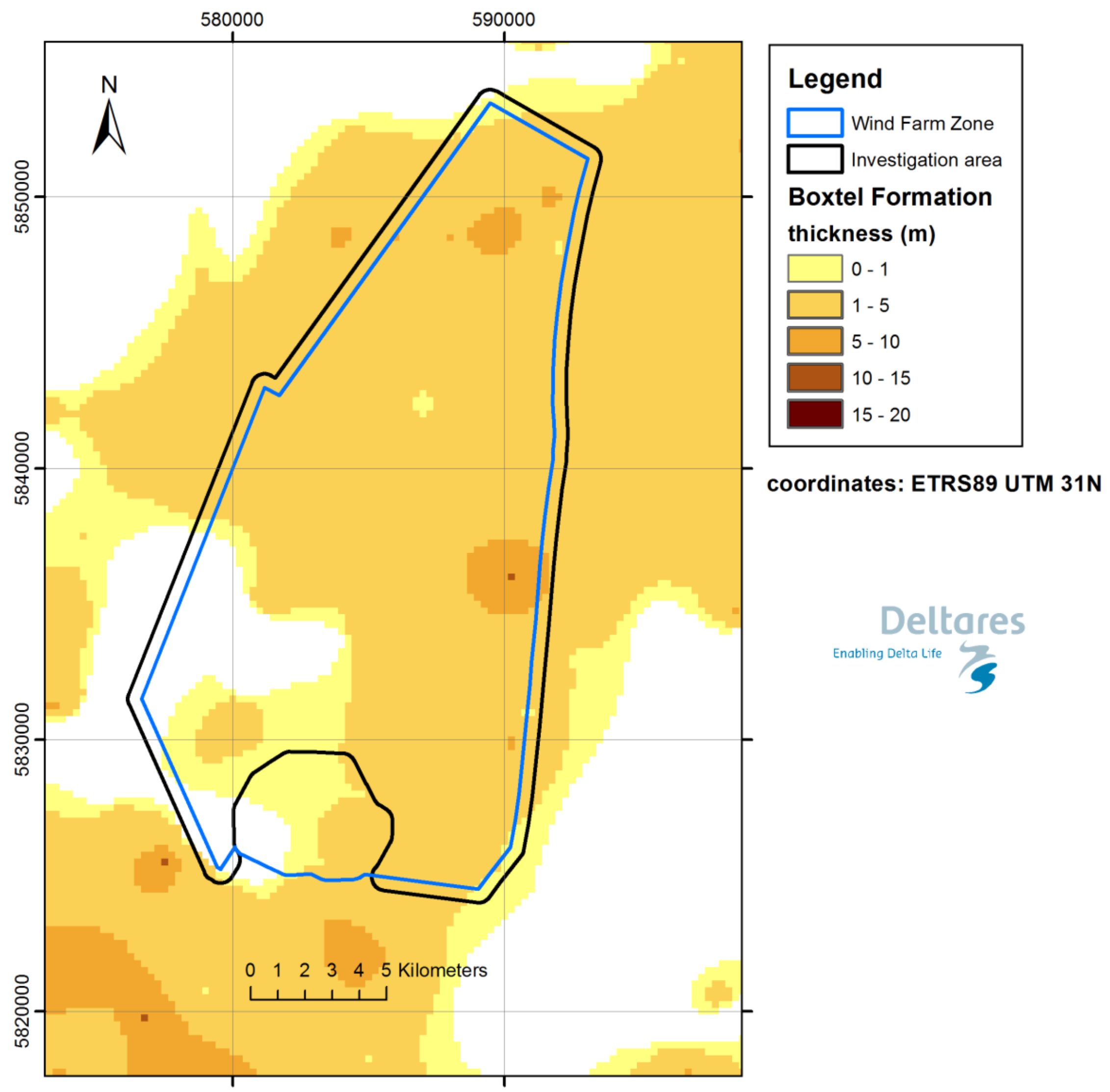

Figure 6.4 Extent and thickness of the Boxtel Formation.

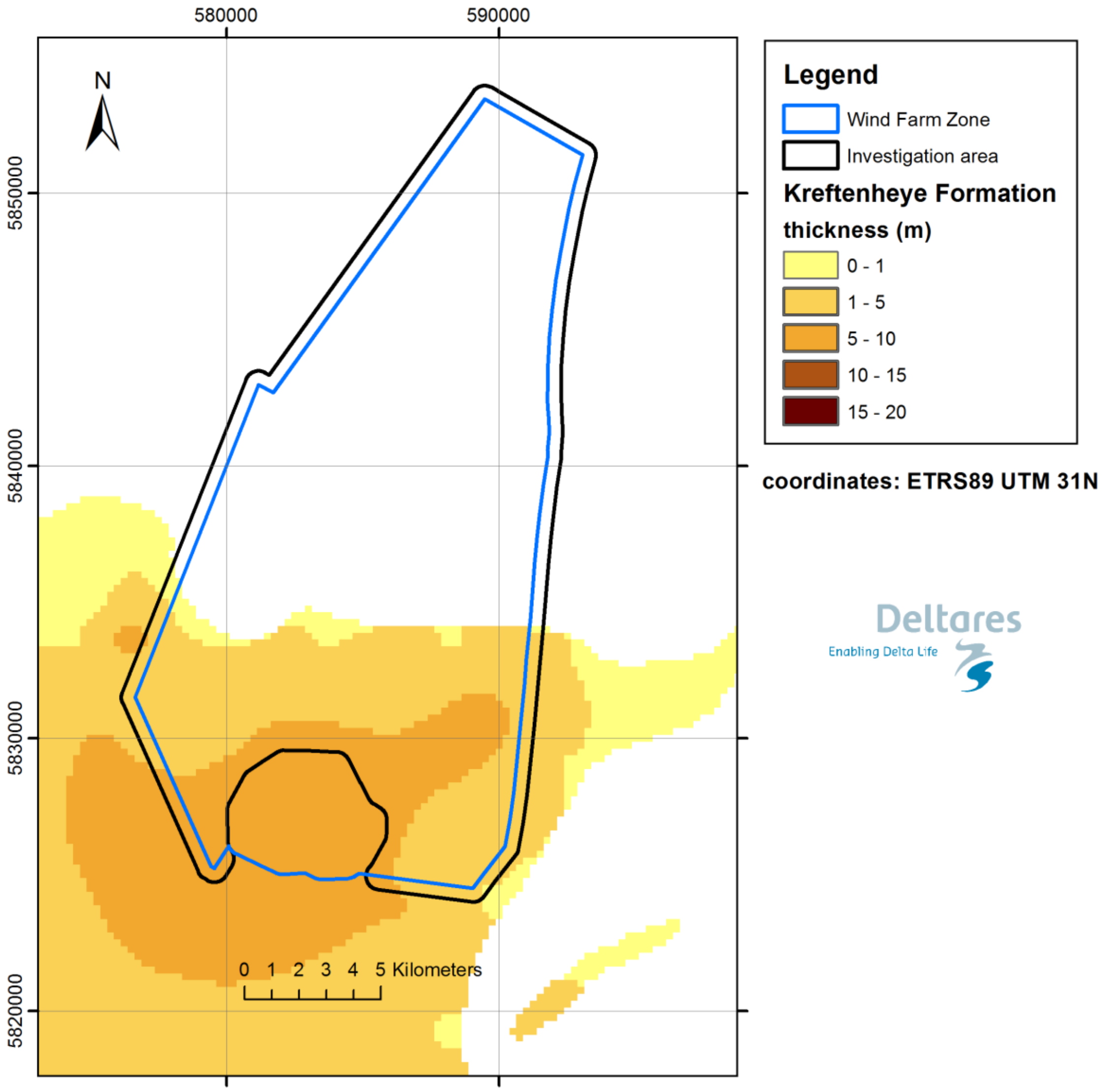

Figure 6.5 Extent and thickness of the Kreftenheye Formation.

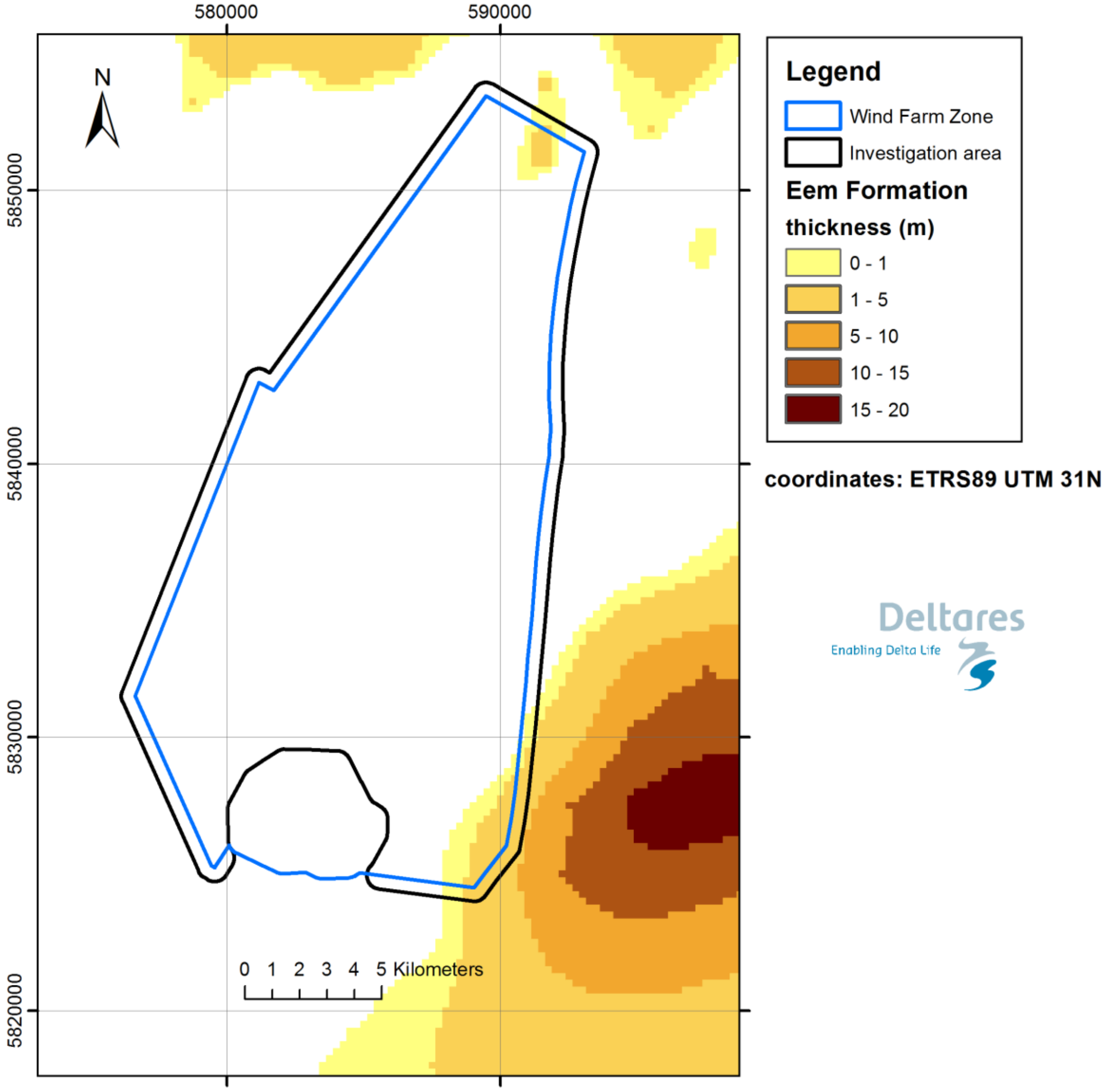

Figure 6.6 Extent and thickness of the Eem Formation.

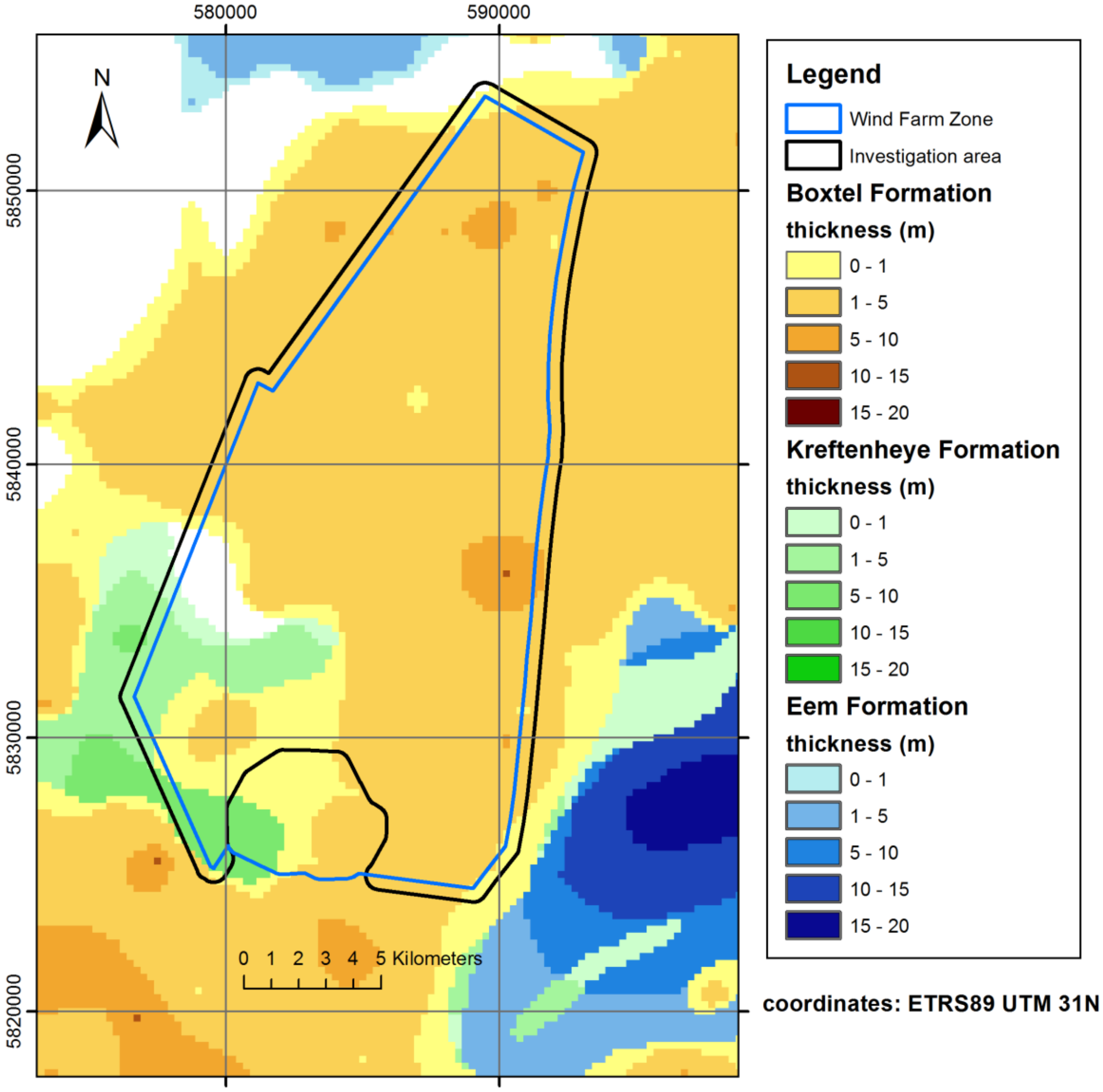

Figure 6.7 Holocene subcrop map showing the extent and the thickness of the Pleistocene formations below the Holocene deposits. Note that a small part of the wind farm area is not covered by any of the listed formations. In absence of borehole evidence the uppermost Pleistocene unit occurring in that area is the Yarmouth Roads Formation (not present in the TNO maps).

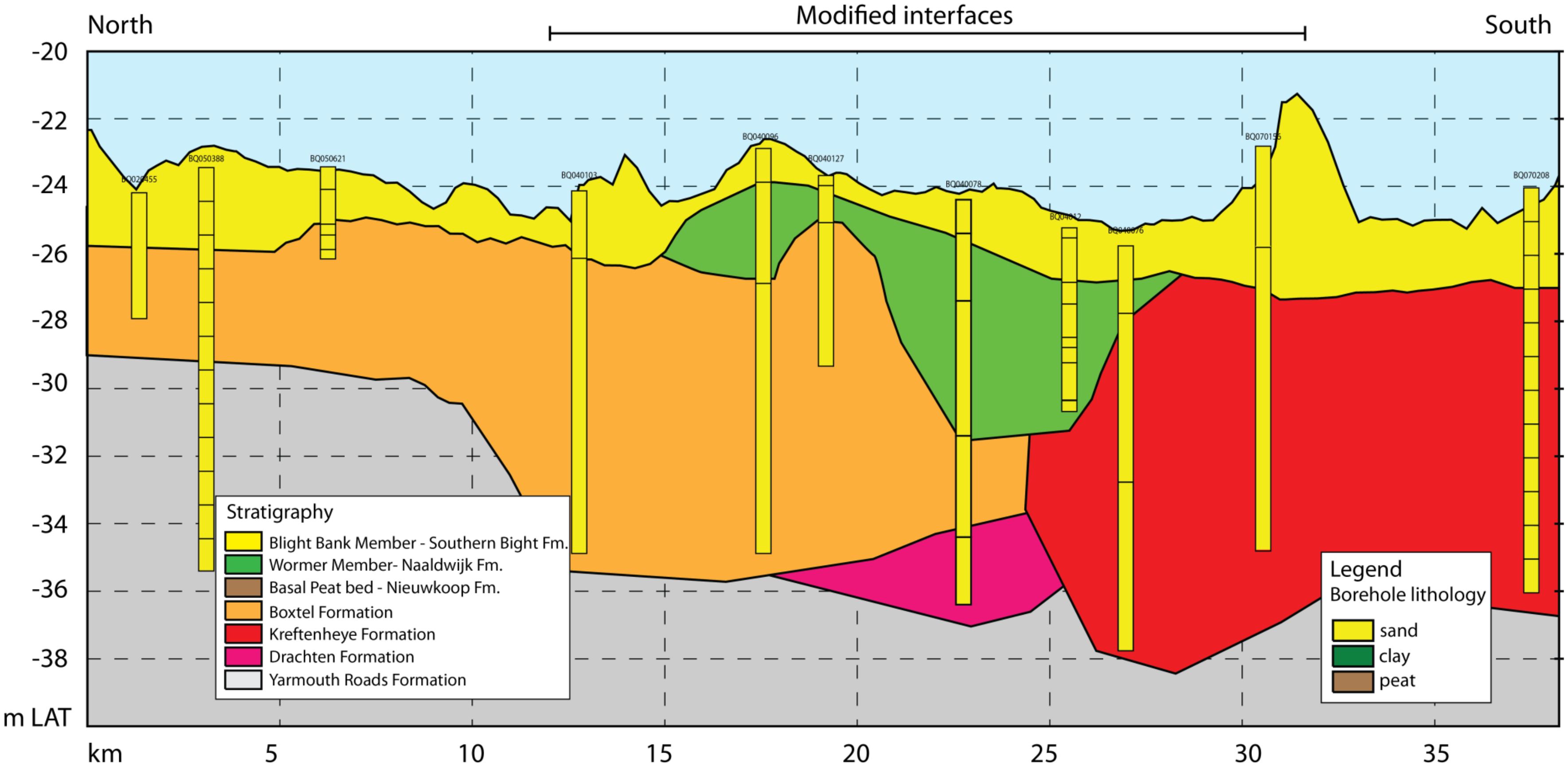

Figure 6.8 Schematic geological cross section 1 (eastern part of the study area). This cross section is largely based on TNO maps 1:100.000. As boreholes can be up to kilometers apart, the interpolation between the boreholes is very uncertain. The maximum distance used to project boreholes onto the profile is 250 m. In the central part of the profiles the boreholes description did not match the interfaces from the 1:100.000 geological maps. We modified the interfaces according to the boreholes. Compared to the maps, the most important modifications are: the base of the Boxtel Formation and of the Kreftenheye Formation is 3 m deeper, the Naaldwijk Formation is present in few boreholes below the Southern Bight Formation, and the Drachten Formation is present in described in the lowest part of one borehole.

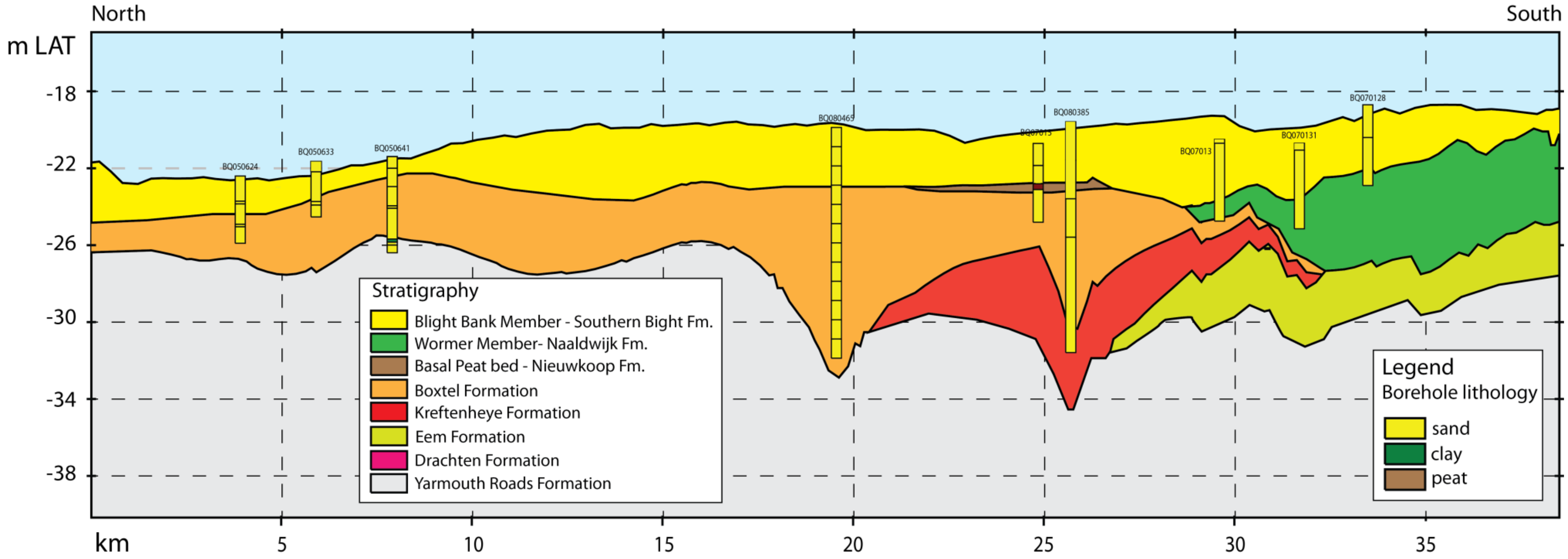

Figure 6.9 Schematic geological cross section 2 (western part of the study area). This cross section is largely based on TNO maps 1:100.000. As boreholes can be up to km apart, the interpolation between the boreholes is very uncertain. The maximum distance used to project boreholes onto the profile is 250 m.

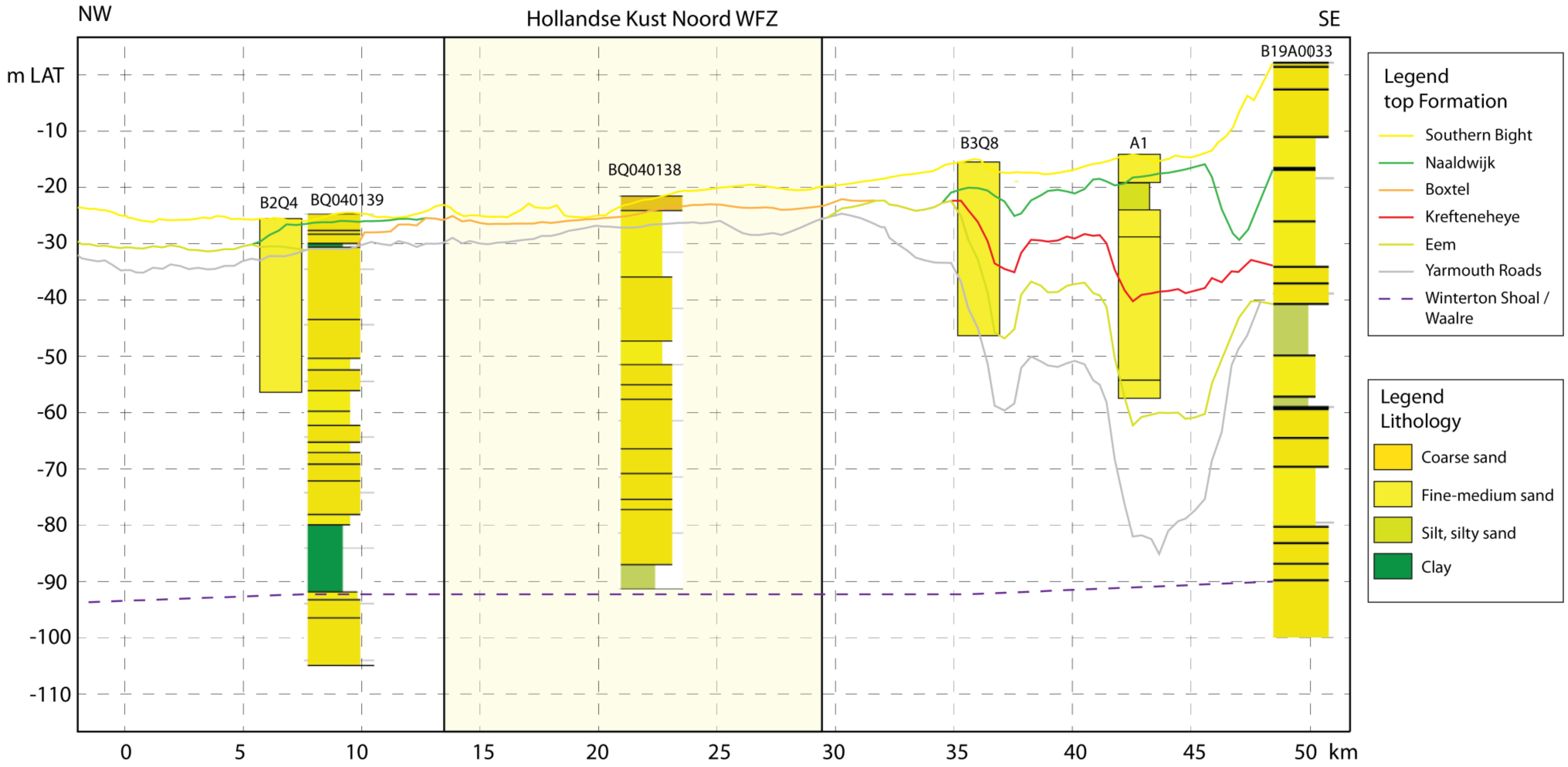

Figure 6.10 Schematic geological cross section 3. Deep boreholes A1, B3Q8, and B2Q4 were digitized based on their description. The maximum distance used to project boreholes onto the profile is 250 m. This cross section is largely based on TNO maps 1:100.000. The top of the Winterton Shoal Formation was correlated as the top of the Waalre Formation in the onshore borehole B19A0033.

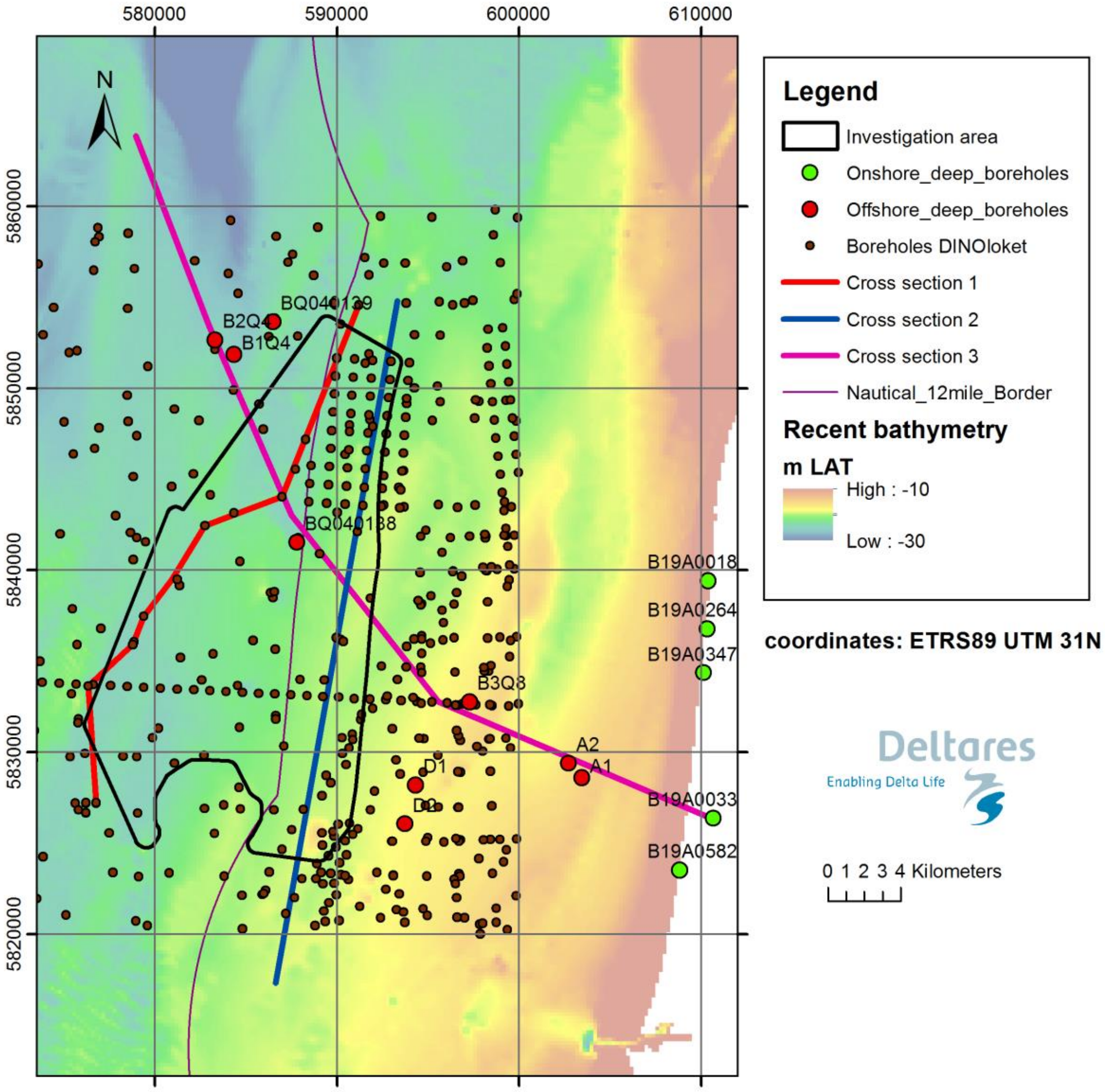

Figure 6.11 Location of the geological cross sections.

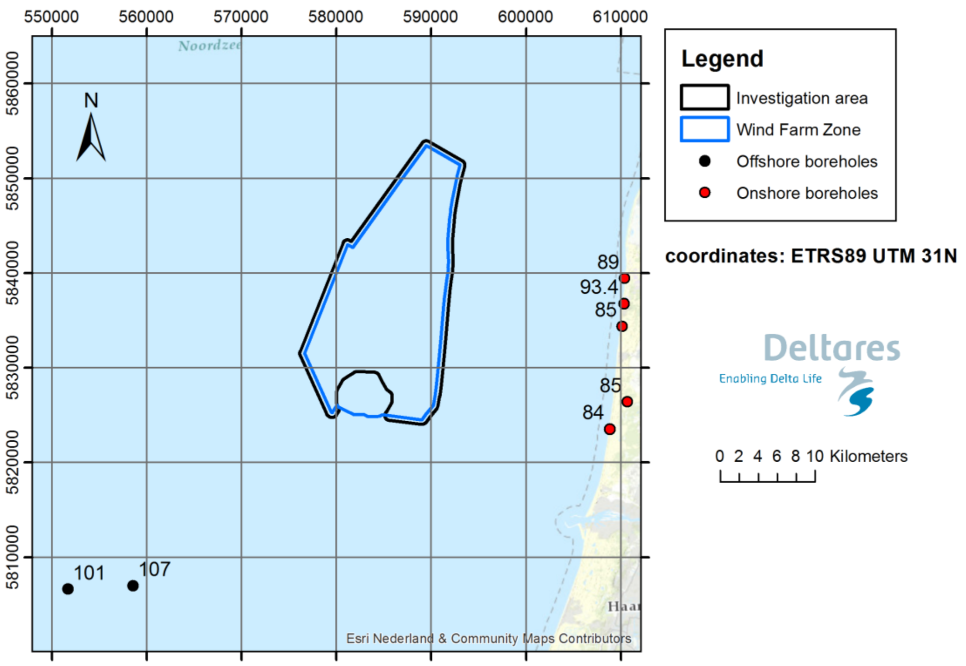

Figure 6.12 Depth (m) of the base of the Yarmouth Roads Formation, relative to LAT. The top of the Winterton Shoal Formation/base of the Yarmouth Roads Formaton was correlated as the top of the Waalre Formation in the onshore boreholes. The sources of the depth information in this map are Fugro interpretation for the offshore boreholes (de Bruijn et al., 2015) and DINOloket for the onshore boreholes.

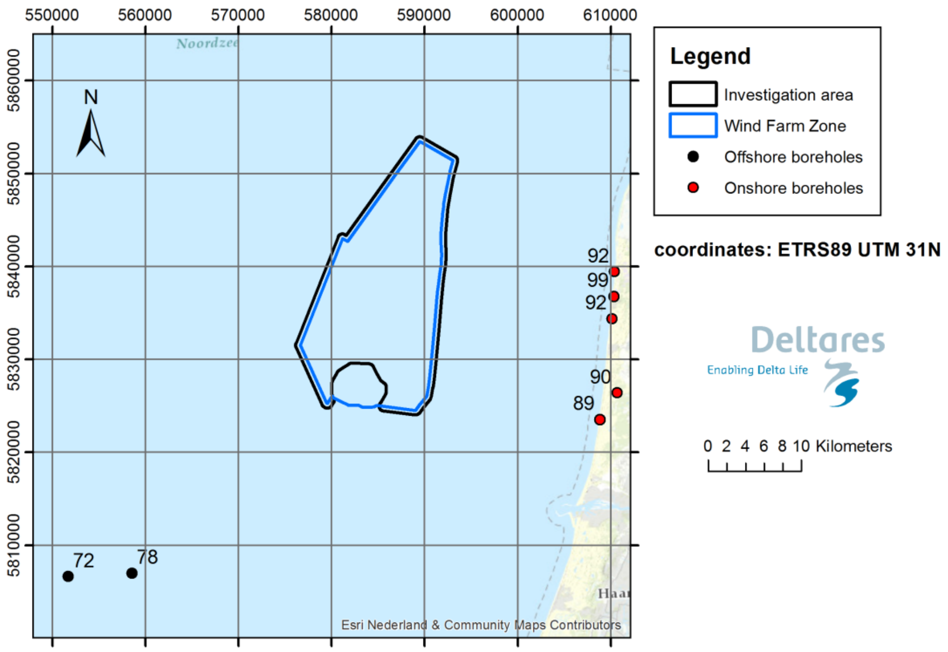

Figure 6.13 Depth (m) of the base of the Yarmouth Roads Formation, relative to bed level. The top of the Winterton Shoal Formation/base of the Yarmouth Roads Formaton was correlated as the top of the Waalre Formation in the onshore boreholes. The sources of the depth information in this map are Fugro interpretation for the offshore boreholes (de Bruijn et al., 2015) and DINOloket for the onshore boreholes.

7 Possible constraints

7.1 Introduction

In this chapter, considerations are given concerning aspects for the design of foundations and structures at or near the seafloor in the study area.

7.2 Morphological characteristics

In the area different types of morphological features are present. The shallow area in the southeast is formed by southwest-northeast oriented shoreface-connected ridges (Van de Meene, 1994). These features are very large sand ridges oriented oblique to the coast. They are 2-30 km long and up to 10 m high. West of the shoreface-connected ridges the area is characterized by north-south oriented sand ridges. The distance between these ridges is 4.5-5 km. The difference in height between the sand ridges and surrounding lows is approximately 5 m.

In different parts of the area, sand waves are superimposed on the sand ridges. Sand waves are dynamic bed forms with wavelengths of the order of 100-1000 m and amplitudes between trough and crest in the order of several meters (Van Dijk and Kleinhans, 2005). The sand waves present in this area have varying dimensions and are quite irregular. The typical height of the sand waves is 1-2 m (trough-crest) with the largest sand waves not exceeding 2.5 m. Wavelengths vary widely from approximately 280 to 650 m (trough to trough).

Each of the morphological features in the area has its typical migration rate. The largest, the shoreface-connected ridges, are relatively stable and move with 0 – 1 m/year. Also the north-south oriented ridges are stable, with similar migration rates. Sand waves have a migration rate in the order of 1-10 m/year. Van der Meulen et al. (2004) reported a migration rate of over 20 m/year near the island of Texel, with typical migration rates decreasing southwards to a stationary (0 – 3 m/year) field near the entrance of the Rotterdam Harbour. Observed migration rates in the Prinses Amalia Wind Park, in the southern part of the study area, were recently assessed to be in the order of 4 m/year by Deltares.

Sand waves can have a significant influence on the future cable burial depth and need to be taken into account when defining the locations of the cables. As the sand waves migrate, a cable located near the sand wave crest may experience significant seabed lowering, which may make the cable vulnerable to anchors or other threats. On the other hand, if a sand wave crest passes the cable that was formerly in a sand wave trough it may experience a significant increase in the burial depth, which locally may cause temperature increases around the cable. Depending of the specifications of the cable and environmental requirements, this may be a problem.

Cables crossing a sand wave field, which spatially migrate with different speeds, may experience a local stress build-up due to an uneven strain. When combined with e.g. thermal stresses this may become critical. It is well known that cables exposed on the seafloor may experience local scour, which in some cases may be sufficient to undermine the cable, causing a free span. When combined with sand wave migration the risk of free spanning increases. A free span of a cable may, besides a local stress build up, also experience vortex induced vibrations.

Also the pile fixation levels are dependent on the sand wave dynamics (Figure 7.1 and Figure 7.2). If a foundation is installed on a sand wave crest it may experience a significant lowering, which combined with scour may cause insufficient geotechnical bearing capacity due to reduced support from the surrounding soil. One way to prevent this is installation of scour protection systems, Still, if the scour protection is not sufficiently flexible and able to adjust to the seabed variations it may become unstable and in worst case fail to protect the foundation. Therefore locations with large predicted seabed lowering are best avoided.

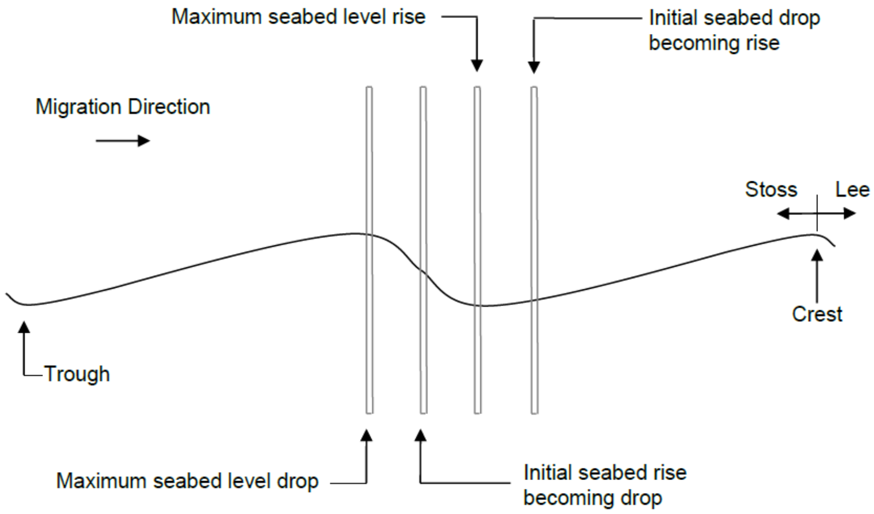

Figure 7.1 Schematic overview of effect of migrating sand waves on pile fixation level

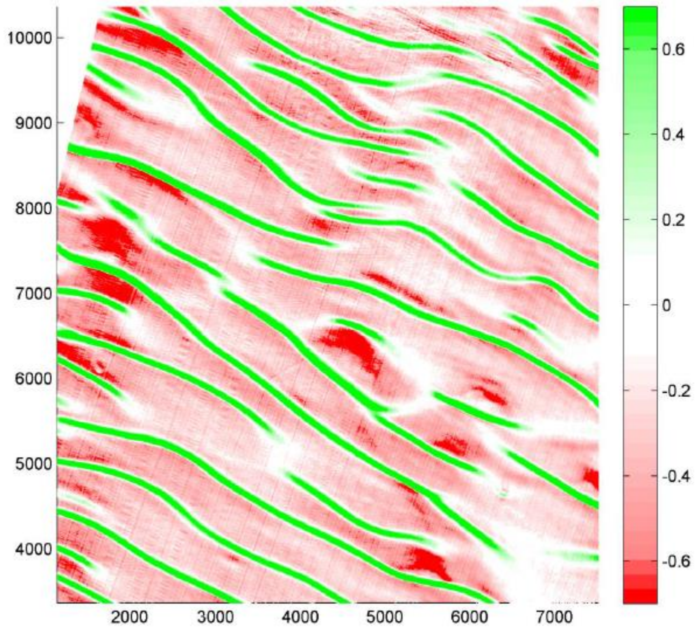

Figure 7.2 Example of seabed level changes in sand wave field offshore the Holland coast during the lifetime of a typical wind farm. Due to the steeper lee sides small areas are governed by a relatively large rise of the seabed (green colours). The stoss sides are characterized by a more gentle drop (red colours).

7.3 Geotechnical characteristics and design recommendations

Given the relatively shallow water depths, the geology of the area, and experience with neighbouring windfarms, open ended pipe piled foundations can be considered suitable, either in the form of monopiles or as piled steel jackets. Conclusions are also valid for penetration depths of skirts. However, the absence of continuous thick clay layers at or near the surface makes the application of suction supported foundation types not likely. The actual bearing capacity requirements and the available soil strengths and seabed morphodynamic characteristics determine the dimensioning of the foundations.

A summary of geotechnical information gathered during the mapping of the North Sea is shown in Table 7.1 (Adopted from the Quaternary Geology Map of the neighbouring Flemish Bight area, BGS and RGD, 1984 based on Fugro, 2003a-c). Note that the values are not from the Hollandse Kust (Noord) and may well differ from the actual values.

Table 7.1 Summary of geotechnical parameters of formations encountered in the HKN area, adopted from Quaternary Geology map Flemish Bight (BGS and RGD, 1984). Note that the values are not from the Hollandse Kust Noord area and may well differ from the actual values.

Unit	lithology	undrained shear strength	plasticity Index	moisture content	bulk density	effective friction angle	porosity	cone resistance
		kN/m^2	%	%	kg/m^3		%	MN/m^2
Southern Bight	shelly medium sand			29	1920	35	41	8-20
Naaldwijk	sand and mud				1800-1900	32	38	1-3
Velsen	mud and fine sand	60- 67	13	32	1910		42	1-3
Boxtel	fine sand			23-24	1880-1950	35-37	39-45	
Kreftenheye	mud							2
Kreftenheye	gravelly sand				1940	32		20-68
Eem	shelly medium sand			15-29	1840-2110	30-43	32-47	17-61
Yarmouth Roads	(gravelly) sand			20-28	1900-2000		35-42	30-49
Yarmouth Roads	mud-sand intercalation	148- 249		31	1900			13-38
Yarmouth Roads	partly consolidated mud	110-500	9-49	20-35	1800-1900		42	4-38

Cone penetration tests within the Hollandse Kust (Noord) Wind Farm Area are not available in the database of DINOloket. The Amalia wind farm at the Southern end of the area was investigated in 2003 (Fugro, 2003a-c). In the Amalia survey area the succession was encountered with the exception of the Eem Formation and the muddy sediments of the Yarmouth Roads Formation. The geomechanical properties fall within the range of Table 7.1. The Basal Peat Member of the Naaldwijk Formation was encountered with low cone resistance (1-3 MPa). Other layers of Table 5.1 not represented in Table 7.1 are the Drente, Drachten and Egmond Ground Formations. It is expected that the geomechanical properties are similar to the ranges presented for corresponding sediments of the Kreftenheye, Eem and Yarmouth Roads Formations. Geomechanical parameters of the Winterton Shoal Formation are not available.

Vertical bearing capacity

Vertical bearing capacity depends on the characteristics of the geological units penetrated by the piles. The effect of the Bligh Bank Member on vertical bearing capacity depends on the seabed mobility during the design period (large-scale and small-scale morphological processes, such as sand wave migration and scour development, see Section 7.2). Due to sand waves mobility the sand of the Bligh Bank Member may be completely removed or may accumulate to a meters thick layer in a period of several decades. This removal and deposition of sediment load should be taken into account in the determination of the geostatic load in bearing capacity calculations.

Soft soils are likely present in the upper geological units, such as the Wormer Member (including Velsen Bed and Bergen Bed), the Nieuwkoop Formation and the Brown Bank Member of the Eem Formation. They may also be present within channel fills in the Kreftenheye Formation, in the Eem Formation, and in the Yarmouth Roads Formation. The seismic records show that clay layers may be present in channel features down to 15 m below seabed. In the Amalia area discontinuous channel features appear to be scattered over the entire area. These channels are 10 m to 200 m wide and up to 1000 m long.

Below the Bligh Bank Member and Wormer Member, the upper ca. 2-10 m of the soil profile consists of sands of the Boxtel Formation on top of sand of the Kreftenheye Formation. These Pleistocene sands generally have moderate to high cone resistances (see Table 7.1). The deposits of the Eem Formation underlying the Kreftenheye Formation are generally sandy and expected to exhibit a lower cone resistance than the Kreftenheye Formation due to the possible admixture of fines.

The Yarmouth Roads Formation consists of intermittent layers of fine sand and silt-rich clay with variable thickness. The expected high density and higher stiffness of the layers in this formation is attributed to the age of the deposits, which varies from Early to Middle Pleistocene, and to ice sheet loading. The entire study area is expected to have been glacially loaded. The Yarmouth Roads Formation and Winterton Shoal Formation may therefore express very high cone resistances resulting in very dense and silt layers. The deposits are expected to show over-consolidation behaviour.

Lateral bearing capacity

The required lateral bearing capacity is mainly determined by the presence and resistance of the Pleistocene sands of the Kreftenheye, Eem and Yarmouth Roads Formations. Major variations in lateral bearing capacity are expected to be caused by the presence or absence of the Bligh Bank and Wormer Member deposits and by the possible presence of soft clay layers in the upper layers of the profile, possibly up to 15 m below seabed in the Holocene channels. The surficial sediments can have a loose consistency and generate a low lateral bearing capacity. The mobile beds of the Bligh Bank Member are prone to scour, which will progressively adversely affect the lateral bearing capacity after installation unless mitigating measures such as rubble fill are taken.

Pile driveability

From borehole information of the area no indications of cobbles and boulders associated with glacial sediments (Drente Formation – Gieten Member) were encountered. Still, the occurrence of cobbles and boulders cannot be excluded based on the extent of the glacial cover. Very dense silt and sand layers in the top ca. 10 m of the Yarmouth Roads Formation may be present, which may adversely affect driveability to the required foundation depth of the piles. More extensive site investigation (geophysics) to a sufficient depth is required to determine the possible occurrence of boulders and the location of the channel features that may be filled with clay layers.

7.4 Earthquake hazard - Natural, tectonic seismicity

Natural seismicity is mainly restricted to the Southern part of the Netherlands. The project area lies within the tectonic region known as the West Netherlands Basin. This area is considered seismically quiet and no active faults have been recognised in the Neogene and Quaternary sediment column (Worum, 2005). The earthquake hazard was calculated from this historical earthquake catalogue. Figure 7.33 shows the seismic hazard in the Netherlands by tectonic earthquakes with a return period of 475 years, or with a probability of 10% in 50 years as Peak Ground Acceleration (PGA). The hazard due to induced earthquakes by gas extraction is not included in this map.

The historical earthquakes of magnitudes up to M=6 deduced from historical documents was incorporated in the calculation of the seismic hazard map of North Western Europe. This has produced a higher value of Peak Ground Accelleration (PGA), when extrapolated onto the offshore area (Grünthal et al. 1999, Figure 7.4). Figure 7.4 shows that in the area offshore the Dutch coast a PGA with a probability of 10% in 50 years may be expected in the order of 0.2-0.3 m/s^2. The PGA contours were adjusted in 2003 (Jiménez et al, 2003) using up-to-date ground motion prediction equations. This resulted in generally lower PGA values. The given values may therefore be considered as conservative estimates. It should be noted that these values apply to stiff upper ground conditions. When soft layers, like Holocene clays or peats are encountered at foundation locations the amplitudes of seismic waves may be amplified. In that case adjusted PGA values should be derived using procedures described in Eurocode 8 (CEN, 2004-2006)

Induced seismicity and land subsidence

The extraction of natural gas is known to produce induced earthquakes. The area lies in an area of existing oil and gas exploitation (Figure 7.5). There are several records of induced seismicity for these fields in the KNMI database (www.knmi.nl/kennis-en-datacentrum/dossier/aardbevingen), Dost et al., 2012). A seismic hazard study comparable to studies required for onshore and nearshore fields has not been performed. It is recommended that a deterministic seismic hazard analysis is performed for the gas fields that are within a 5 km radius of the project area according to the TNO report (TNO, 2012) to confirm the actual seismic hazard. Furthermore land subsidence related to gas extraction should be evaluated. An analysis of seismic hazard and subsidence was most likely conducted by the oil and gas company prior and during gas extraction. It is recommended to retrieve this information.

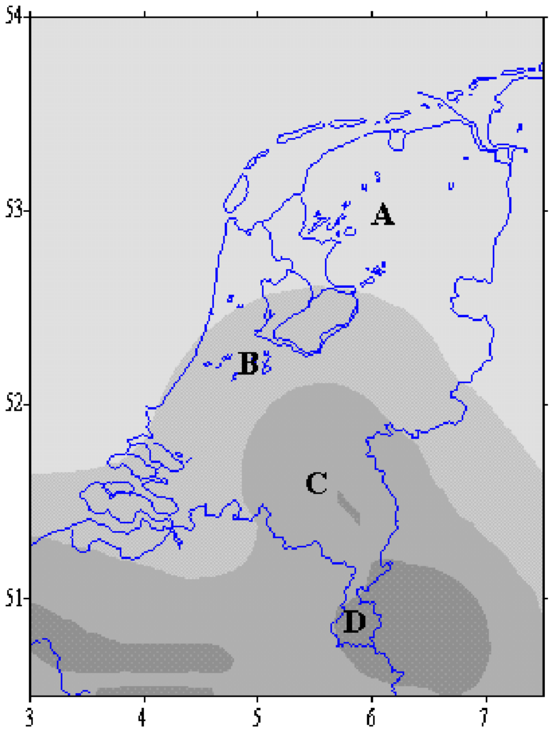

Figure 7.3 Seismic zones in the Netherlands and adjacent North Sea. In this map a zonation is applied based on the expected horizontal Peak Ground Acceleration (PGA). PGA for zones A, B, C and D are 0.1, 0.22, 0.5 and 1 m/s ^{2} respectively. It is assumed that at the ground surface/sea bottom the horizontal component of the movement is the greatest. Source: de Crook, 1996.

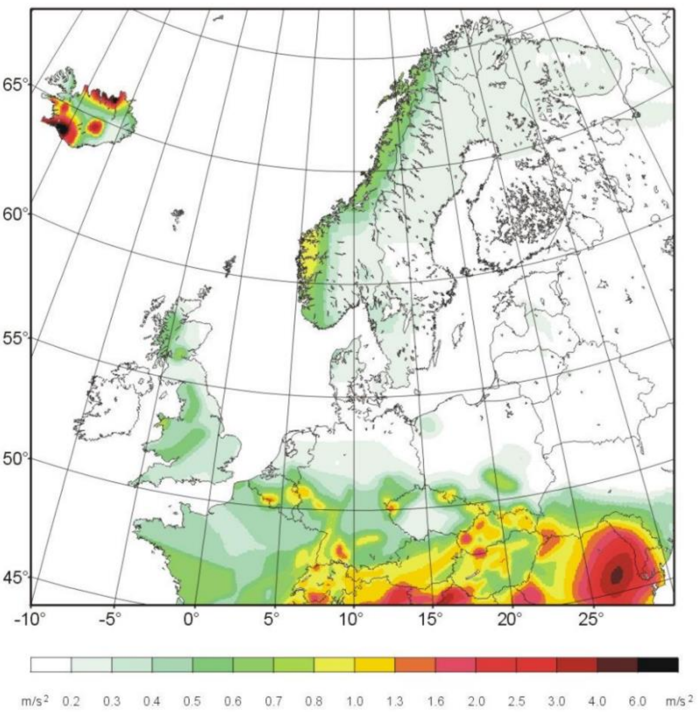

Figure 7.4 Horizontal peak ground acceleration seismic hazard map representing stiff site conditions for an occurrence rate of 10% within 50 years for the GSHAP Region 3 (Grünthal et al, 1999.

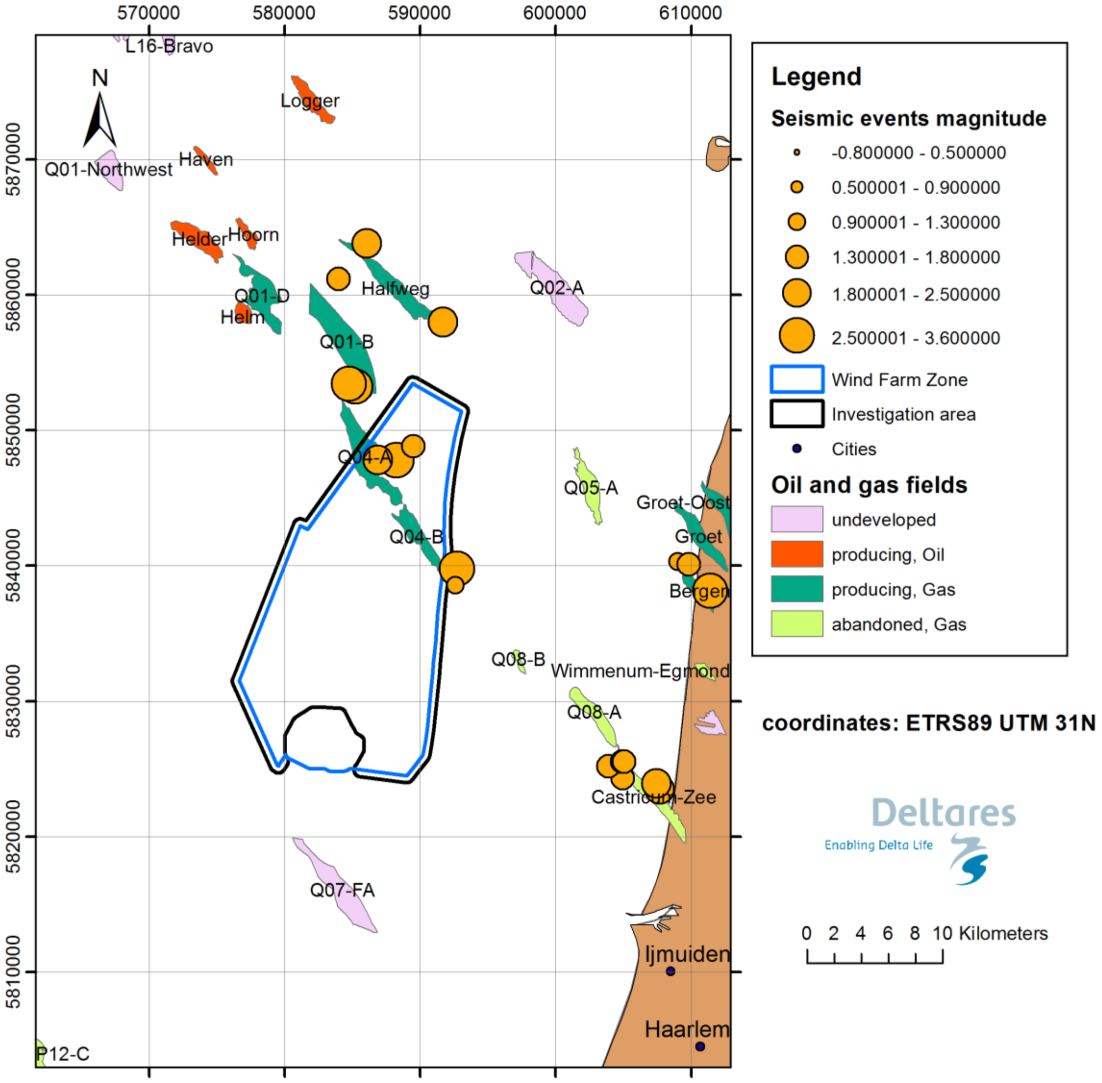

Figure 7.5 Locations of oil and gas fields in the project area and induced earthquakes (source national oil and gas portal www.nlog.nl and KNMI www.knmi.nl/kennis-en-datacentrum/dossier/aardbevingen.

Shallow gas pockets

In seismic sections, blurred zones are locally encountered at different depths in the present sections (see Figure 4.3). This indicates that sediments with shallow gas may be present in the area. The gas is mainly trapped in or under cohesive layers. These are patches and can have dimensions of several tens of metres. The geotechnical effect is a weakening of cohesive layers. Instances have been reported elsewhere and on the adjacent land area that during penetration of clay layers trapped gas escaped to the surface and caught fire. This hazard, which can also compromise buoyancy of vessels, should be carefully investigated on recorded seismic sections. These patches should be avoided if possible.

8 Conclusions

Deltares has performed a geological desk study as a preparation to a future geophysical field survey in the "Hollandse Kust (noord) Wind Farm Zone". This study provides an overview and a quality assessment of available data, a characterization of the geological units based on existing data, a description of possible geotechnical constraints on the development of the wind farm zone and recommendations for the future geophysical survey. The latter is discussed in a memo separately from this report.

Data availability and quality assessment

Based on a selection of the most recent data from high resolution bathymetrical surveys, a map with the recent bathymetry has been created. These data provide a good description of the morphology (sand ridges and sand waves) but are not up to date (older than 2012) and does not provide precise indications on seabed mobility.

Limited data from single channel and multi-channel seismic surveys across the area are available. These show relevant geological features such as channel fills and gas pockets. However, the multi-channel data resolution is too low for more detailed analyses, and single channel data have a too shallow penetration depth (10-15 m).

Several shallow cores and boreholes (<12 m deep, typically <5 m) and one deep borehole (>70 m) are present in the area. In addition, 8 deep boreholes just outside the study area were analysed. The quality of borehole data varies depending on the extent of borehole description, on the vertical resolution, and on the geologist interpretation. The low spatial data density and low penetration depth is not enough for the design of the wind farm but it allows a first order characterization of the geological units and their geometry.

Geological architecture

The subsurface of the area consists of Pleistocene to Holocene shallow marine and fluvial sediments. These deposits mainly consist of sands. Clay and silt are present as interbeds within the mainly sandy units and as relatively thicker beds (up to few meters thick) in channel fills (Naaldwijk Formation, Brown Bank Member – Eem Formation). A peat layer is locally present; reaching a maximum thickness of 0.5 m.

Due to the few deep boreholes it is possible to provide a first order characterization of the deeper units (15 m to 100 m). These units consist of fluvial and deltaic sands and clays. The study area was covered by land ice during the Saalian ice age. As a consequence of loading and glacial processes the deeper layers (below the Eem Formation) are possibly overconsolidated. Furthermore, based on literature data, glacial till and ice pushed ridges may be present in the northern part of the study area.

Geotechnical constraints

In the entire study area no major constraints to develop a wind farm have been encountered. Smaller or unknown possible constraints are listed below.

- The presence of consolidated layers, glacial till and stones due to the coverage of land ice may adversely affect driveability of the piles.

- The mobility of sand waves at the surface should be quantified and taken into account for proper piles and cables design.
- Soft soil may affect vertical and lateral bearing capacity. Further geophysical investigation should quantify the geometry and the properties of the units containing soft soils.
- The presence of shallow gas has been observed in seismic data. This hazard should be carefully investigated. These areas with shallow gas should be avoided if possible.
- The area is outside of known natural earthquake hazard zones but has experienced induced seismicity. It is recommended that a deterministic seismic hazard analysis is performed for the gas fields that are within a 5 km radius of the project area to confirm the actual seismic hazard.

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A Bathymetrical surveys

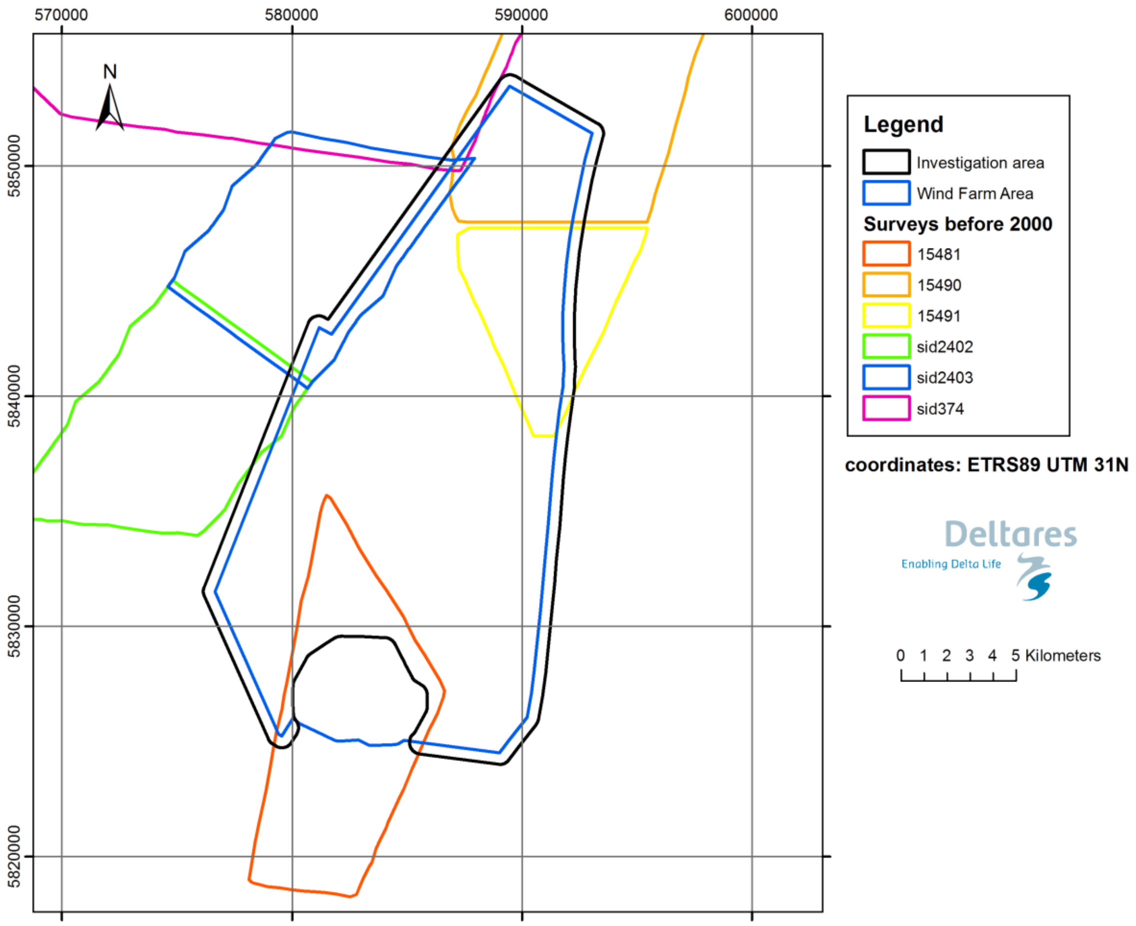


Figure A.A.1 Bathymetrical surveys carried out before 2000.

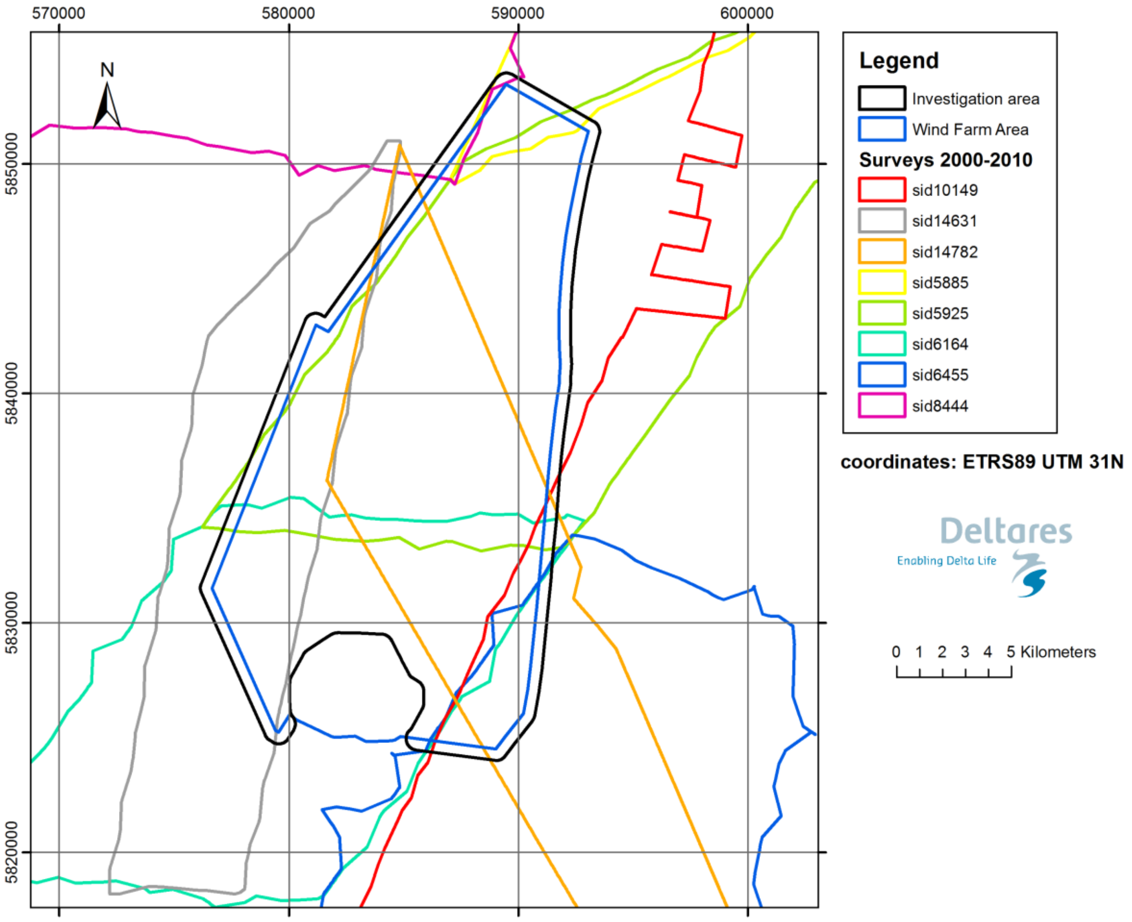


Figure A.A.2 Bathymetrical surveys carried out between 2000 and 2010.

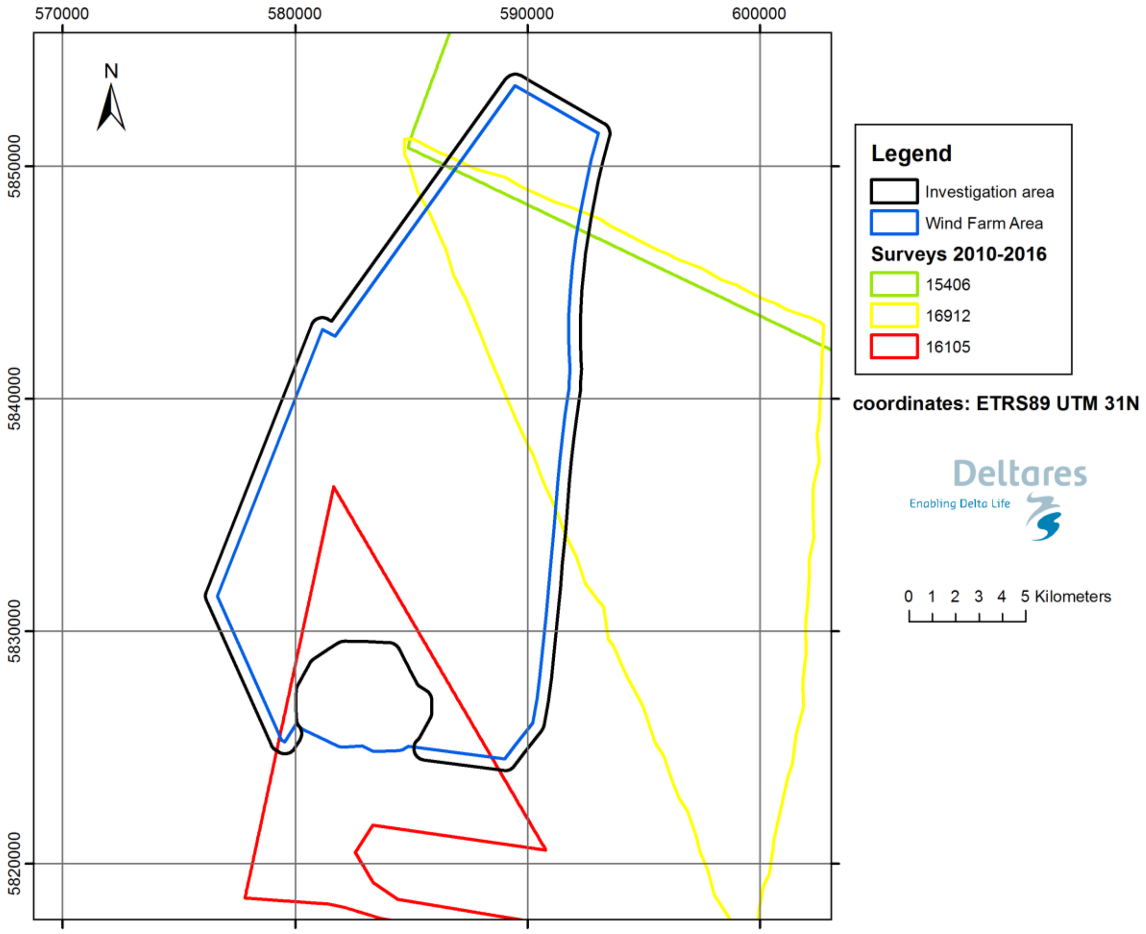


Figure A.A.3 Bathymetrical surveys carried out after 2010.

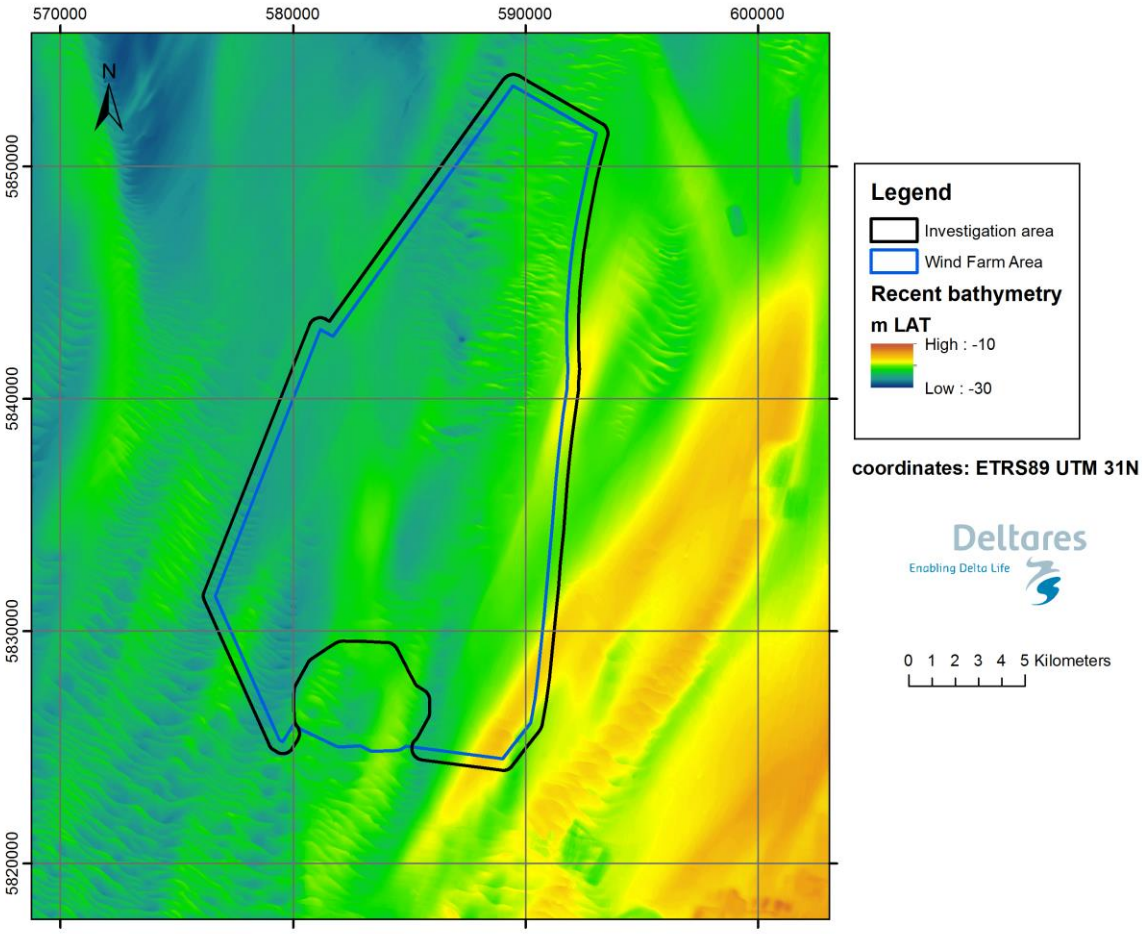


Figure A.A.4 Map with date of most recent bathymetrical survey within the study area. The seafloor depth ranges from -10 to -30 m LAT.

B Deep boreholes offshore

Please see Figure 2.6 for the locaton fo the deep boreholes.

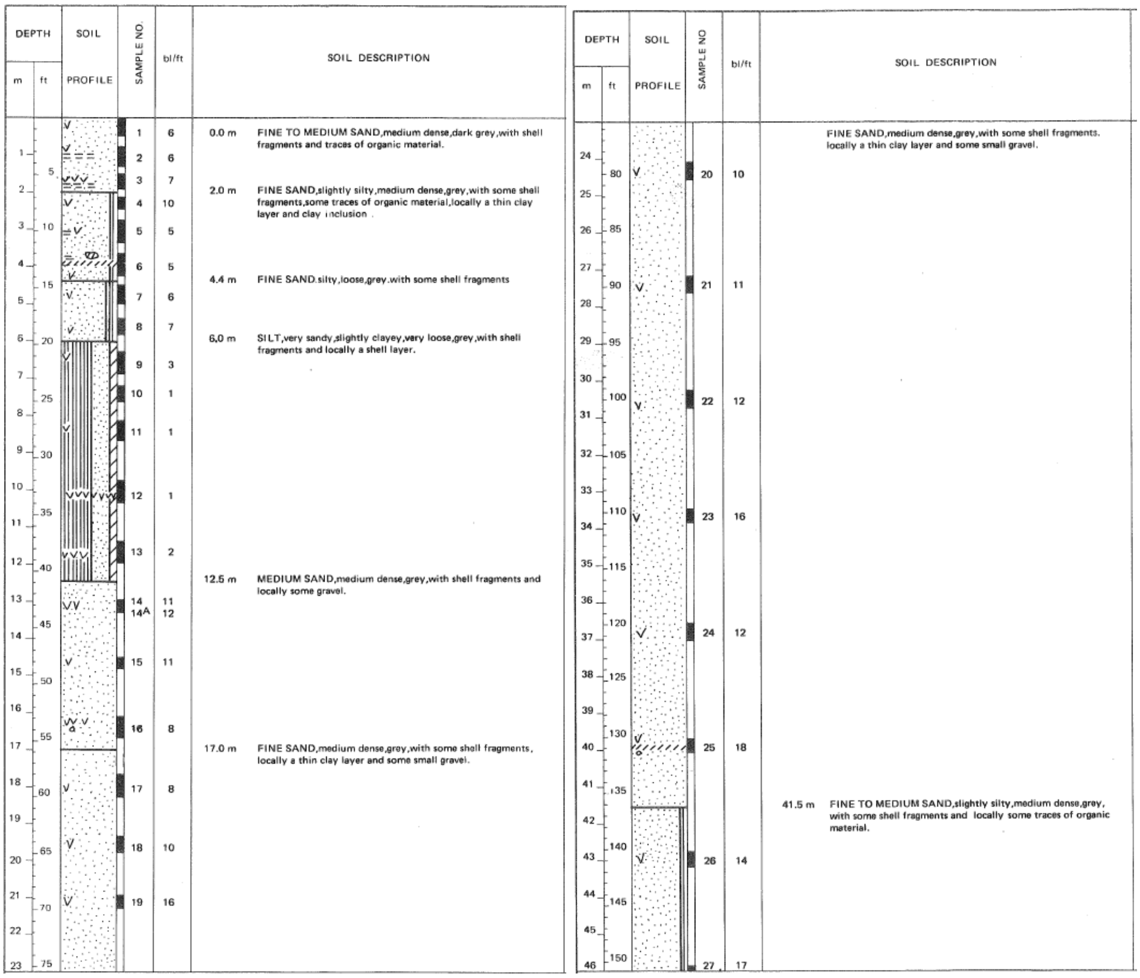


Figure A.B.1 Deep borehole A1.

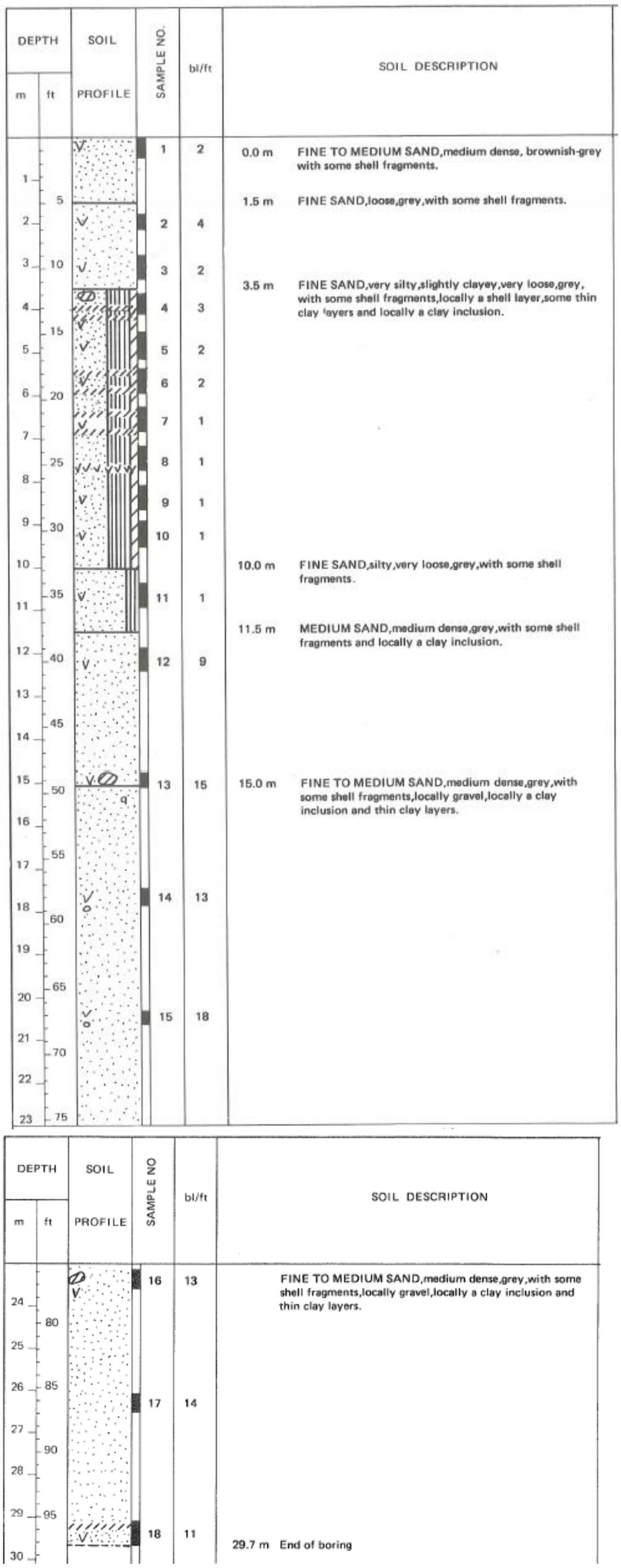


Figure A.B.2 Deep borehole A2.

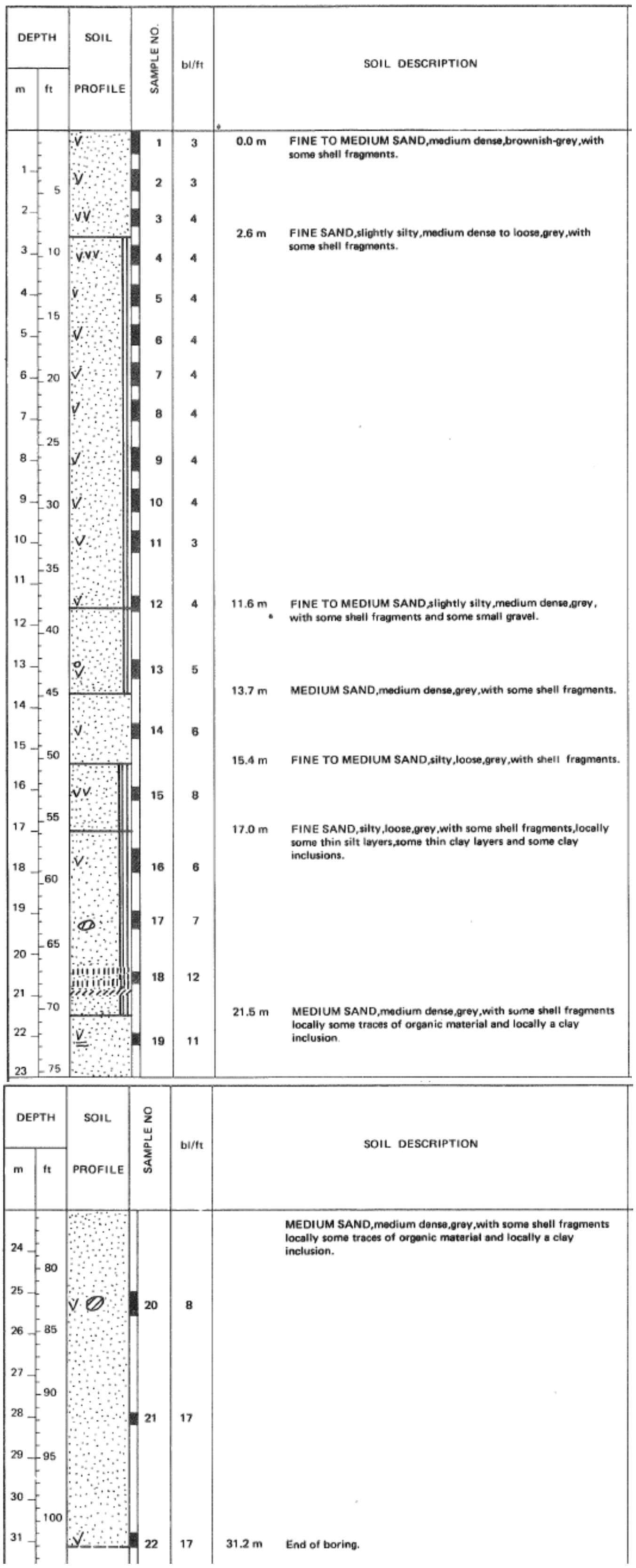


Figure A.B.3 Deep borehole D1.

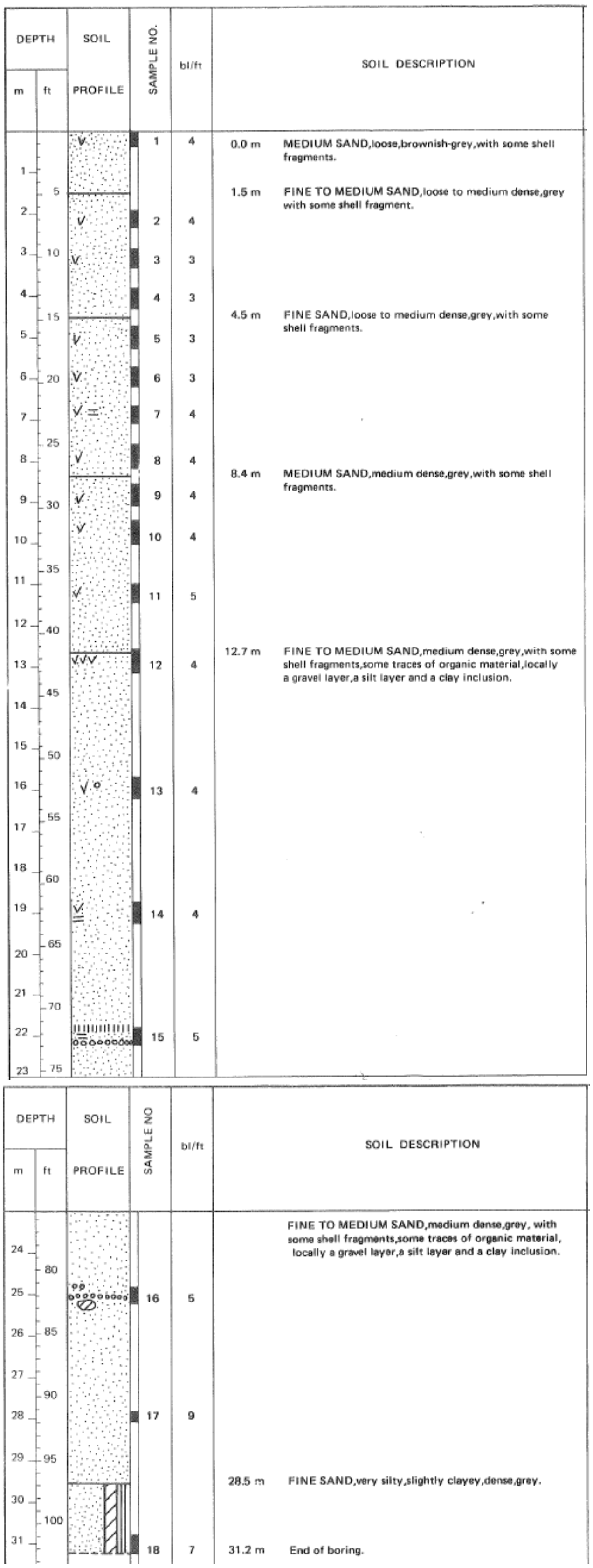


Figure A.B.4 Deep borehole D2.

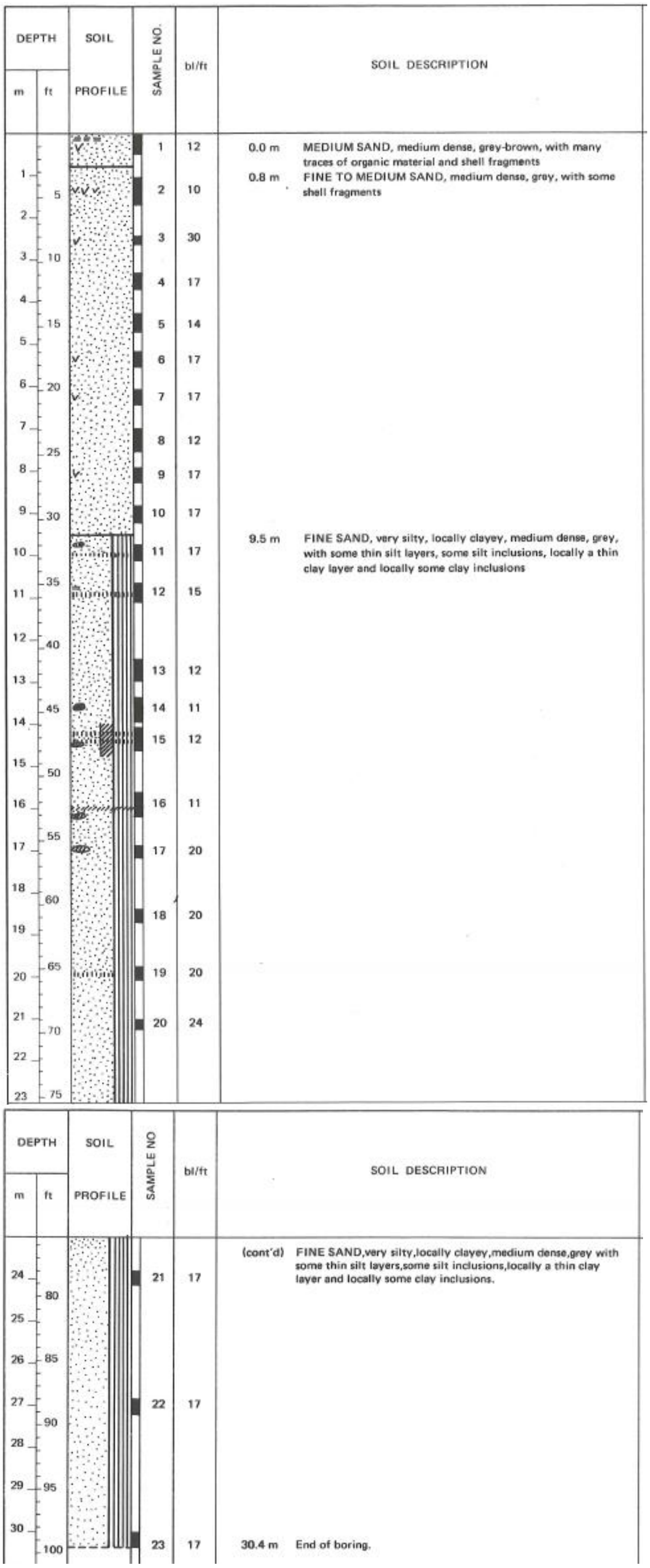


Figure A.B.5 Deep borehole B1Q4.

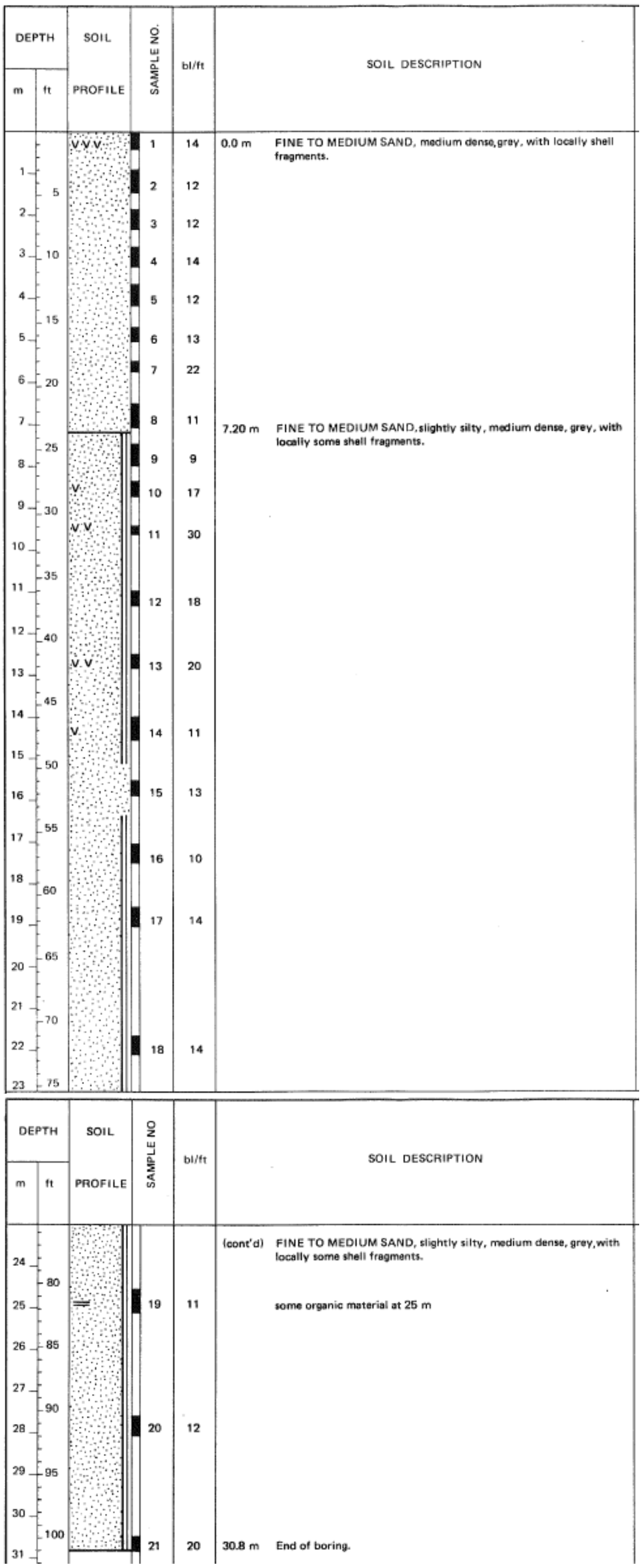


Figure A.B.6 Deep borehole B2Q4.

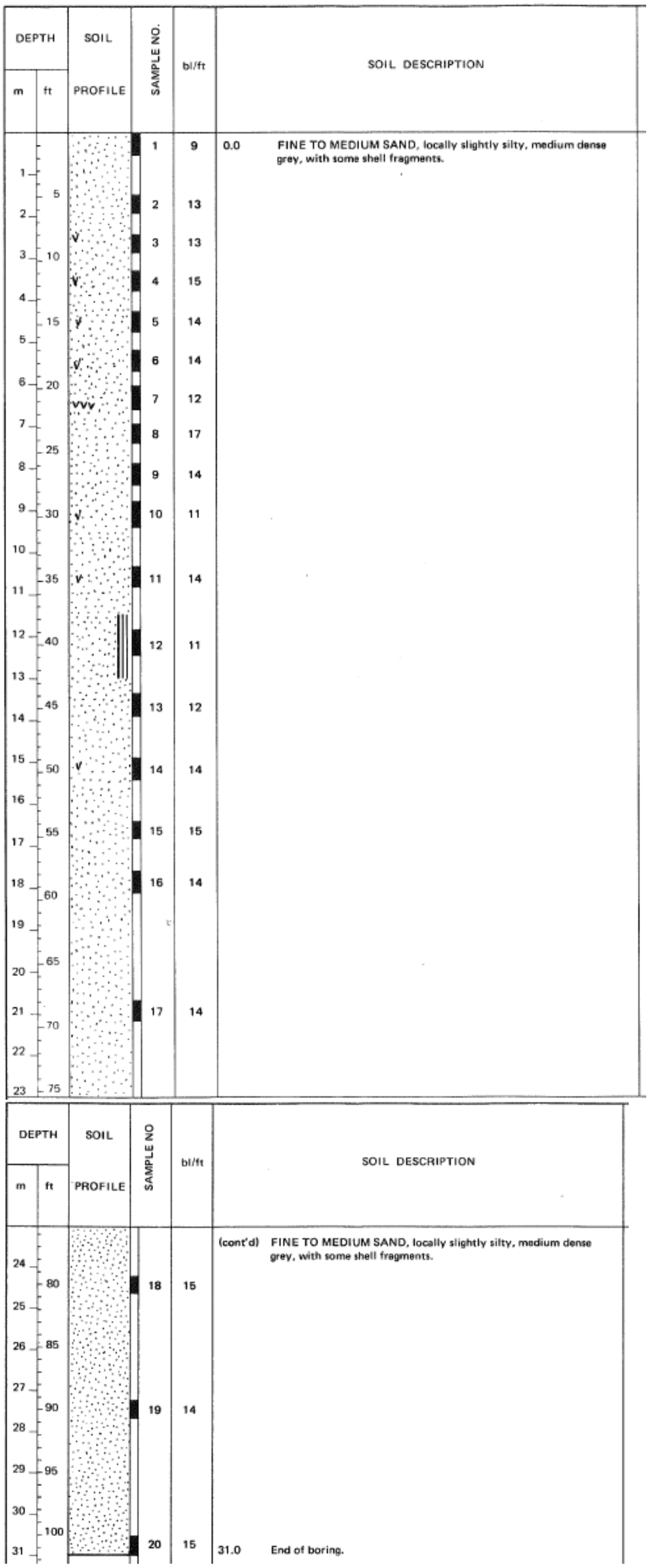
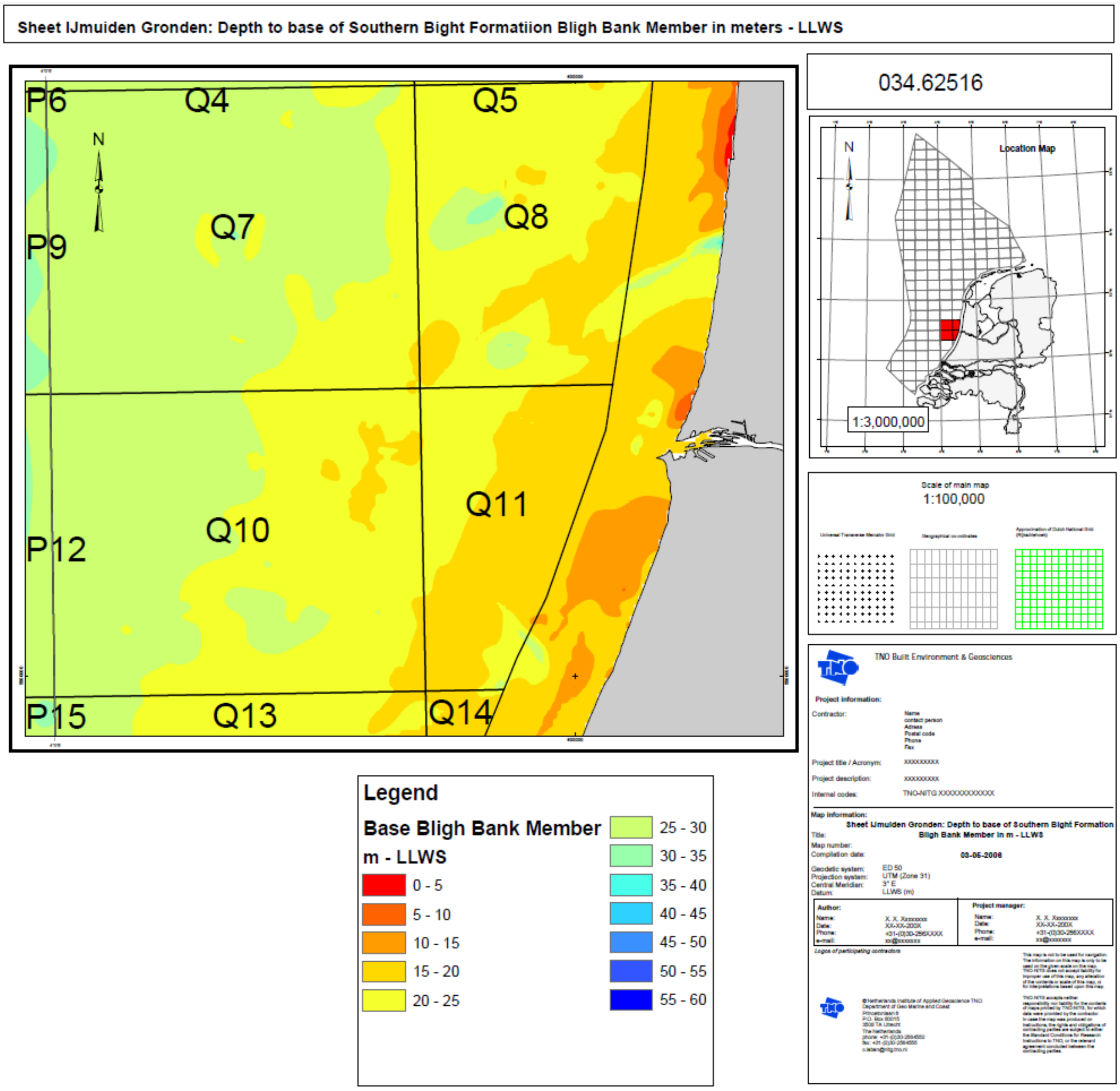
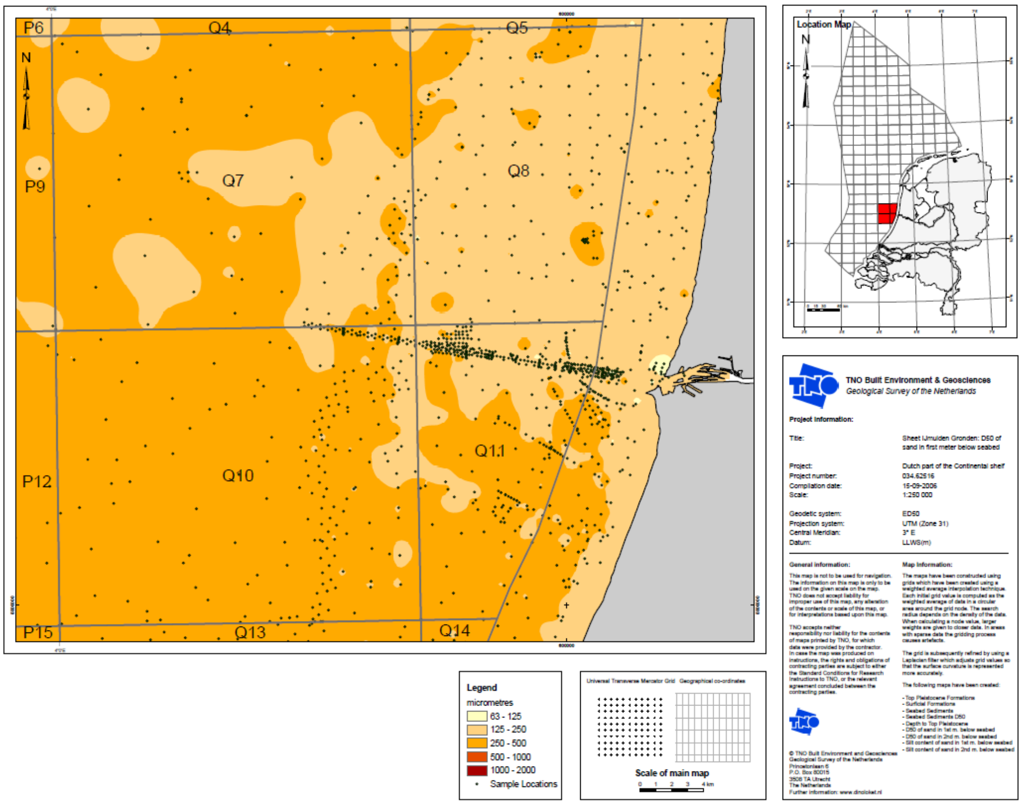


Figure A.B.7 Deep borehole B3Q8.

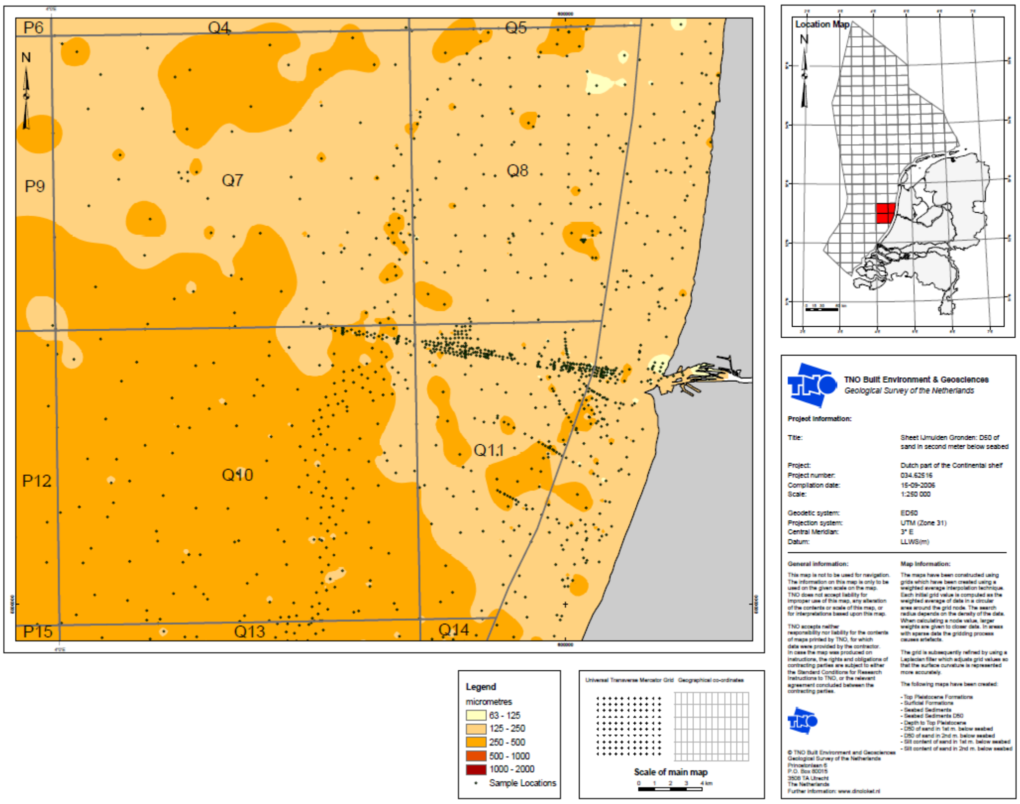
C Seabed sediments maps 1:100.000



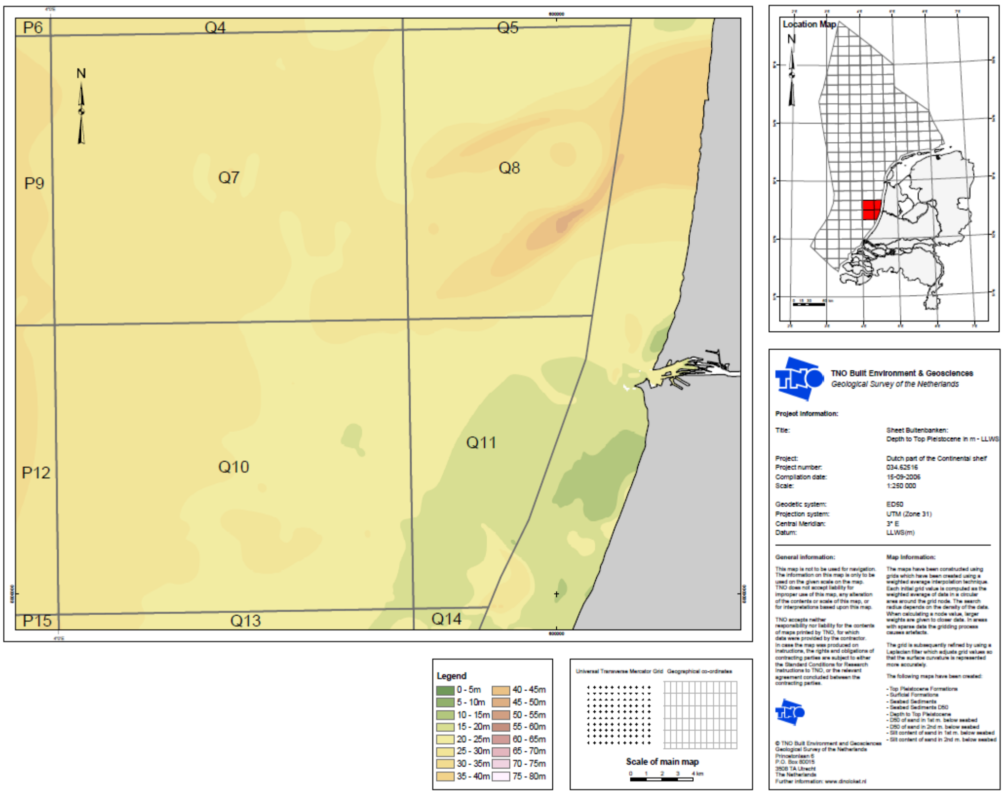
Sheet IJmuiden Gronden: D50 of sand in first meter below seabed



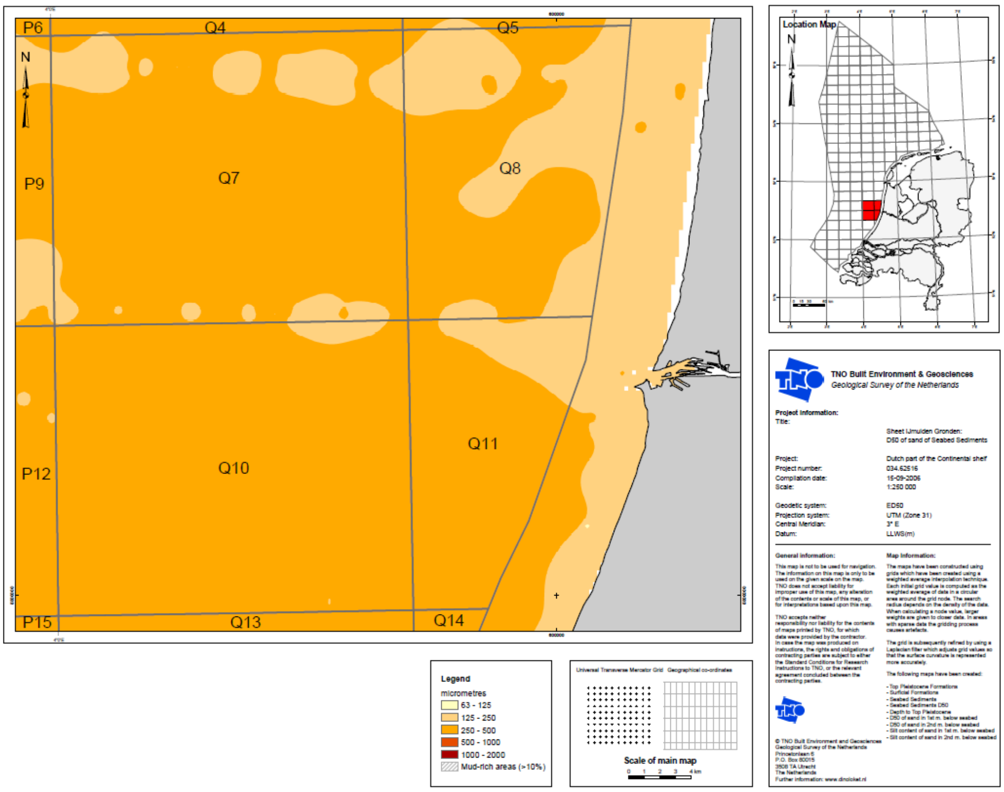
Sheet IJmuiden Gronden: D50 of sand in second meter below seabed



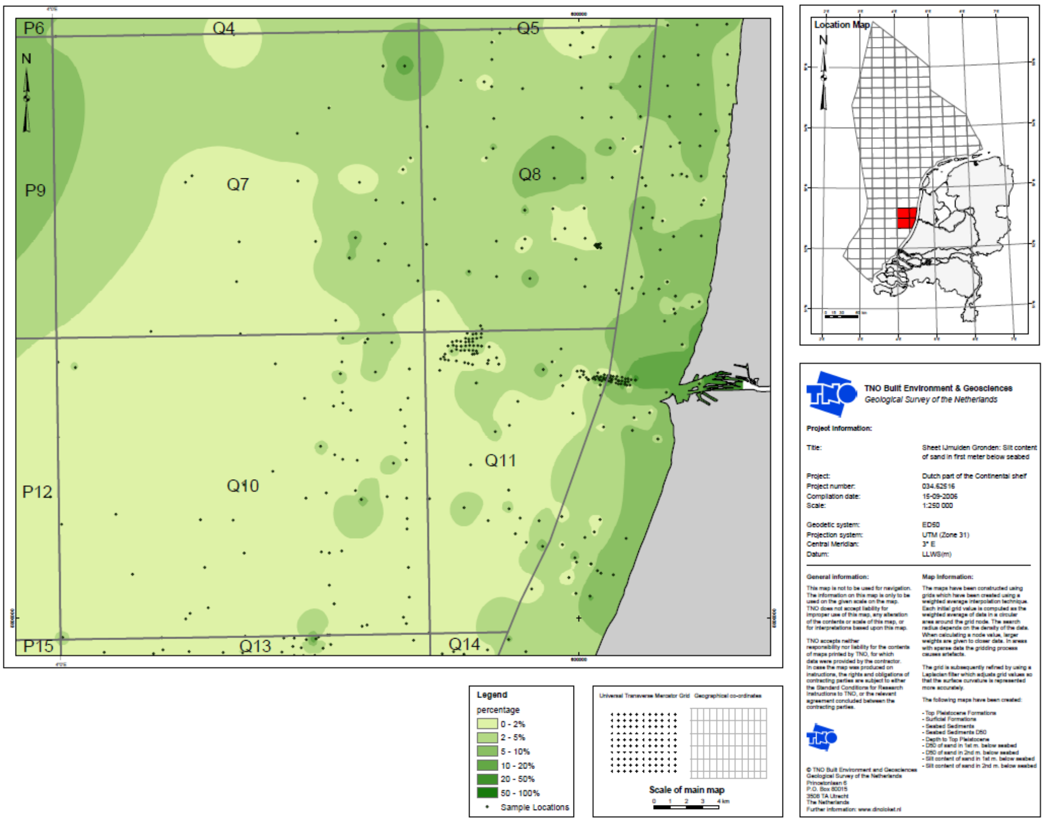
Sheet IJmuiden Gronden: Depth to Top Pleistocene in m - LLWS



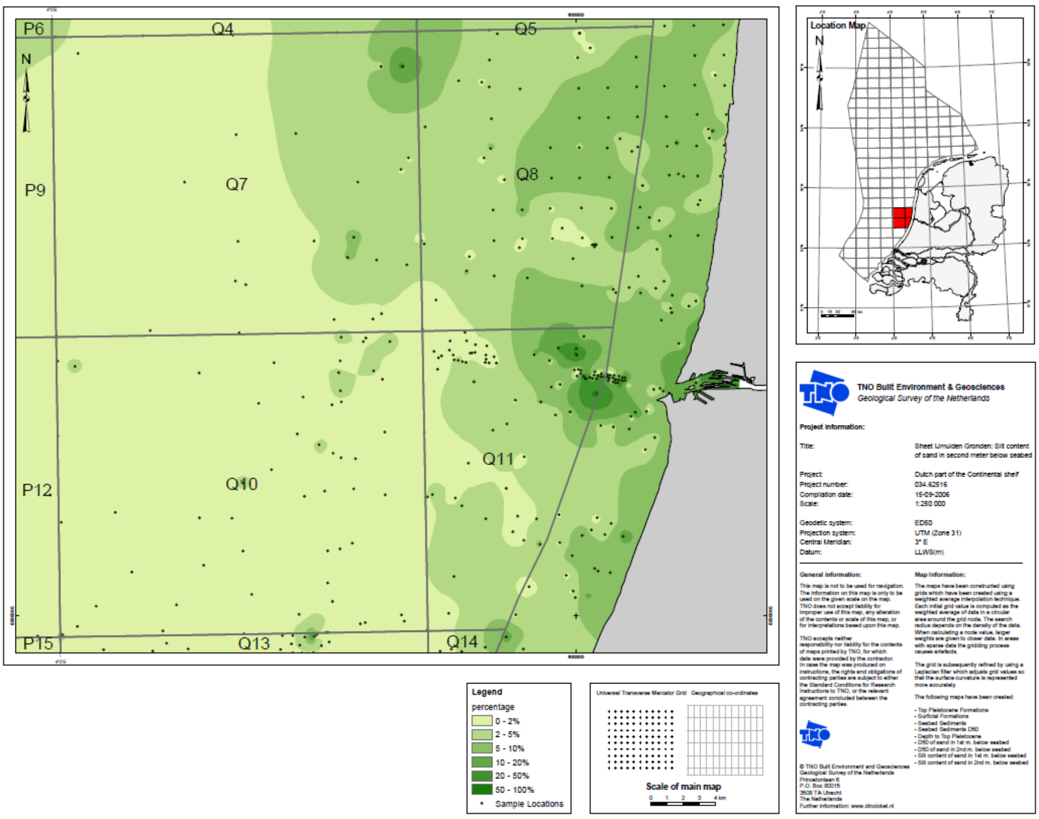
Sheet IJmuiden Gronden: D50 of sand of Seabed Sediments



Sheet IJmuiden Gronden: Silt content of sand in first meter below seabed



Sheet IJmuiden Gronden: Silt content of sand in second meter below seabed

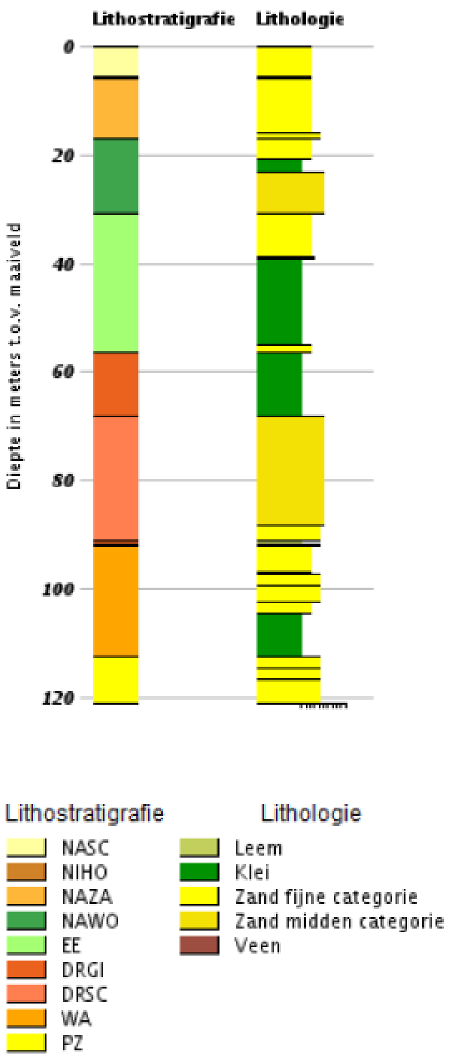


D Deep boreholes onshore

The following boreholes are used in this report. Source is www.dinoloket.nl

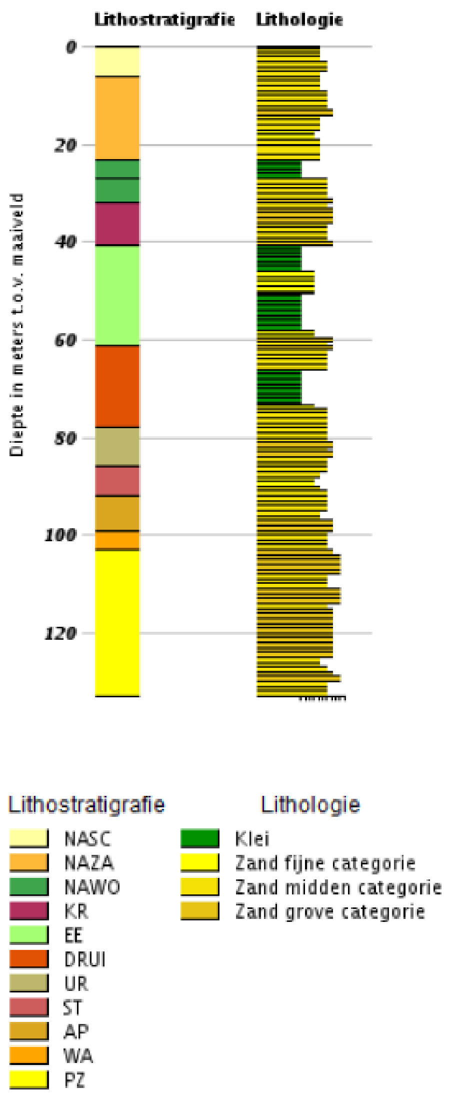
Boormonsterprofiel en interpretatie

Identificatie: B19A0018
Coördinaten: 104030, 523150
Maaiveld: 3,23 m t.o.v. NAP
Dieptetraject t.o.v. Maaiveld: 0,00 m - 121,18 m



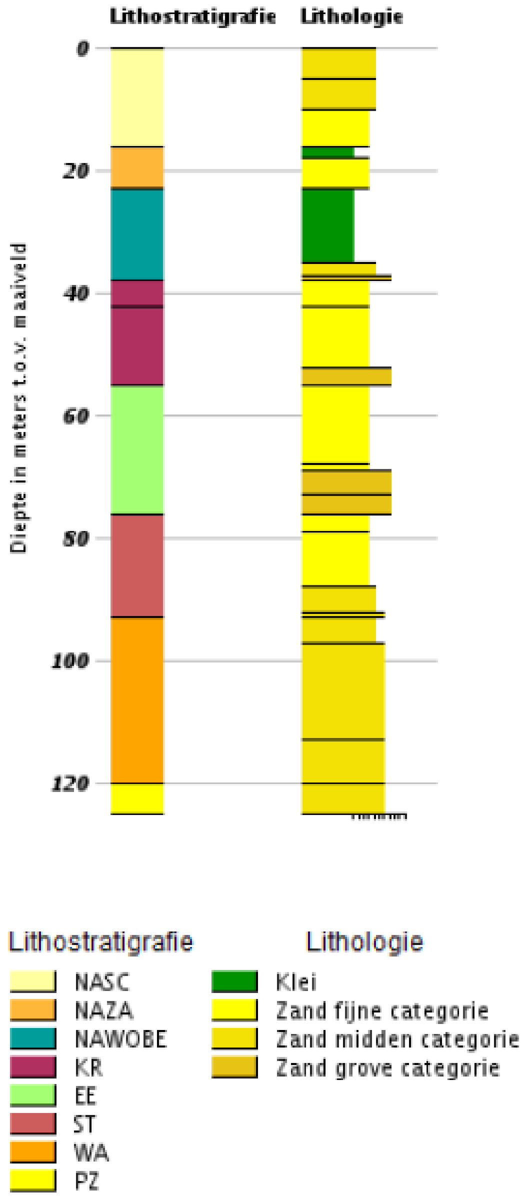
Boormonsterprofiel en interpretatie

Identificatie: B19A0264
Coördinaten: 103910, 520510
Maaiveld: 5,60 m t.o.v. NAP
Dieptetraject t.o.v. Maaiveld: 0,00 m - 133,00 m



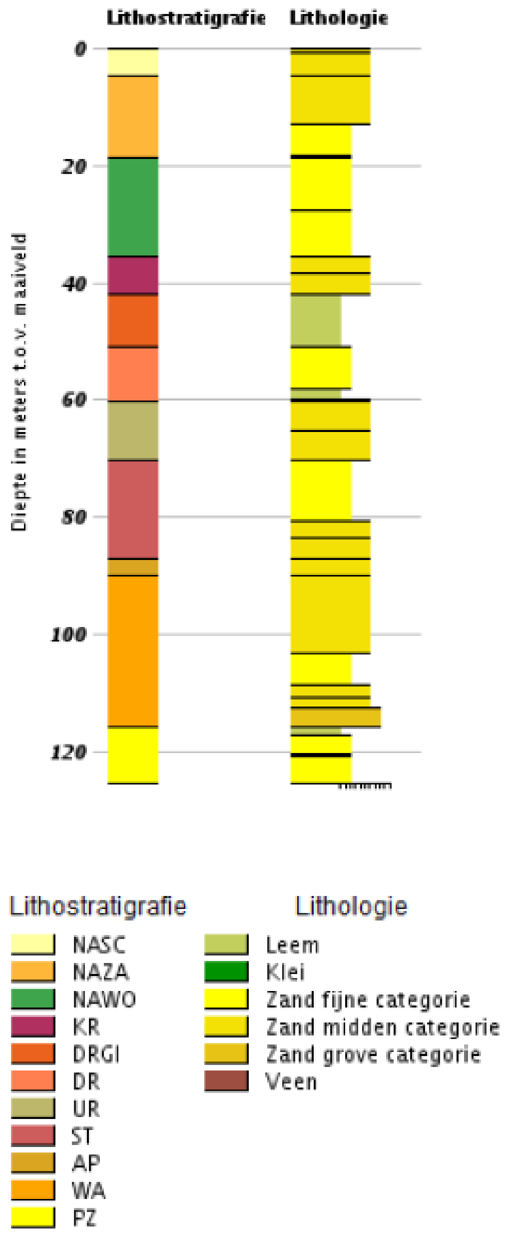
Boormonsterprofiel en interpretatie

Identificatie: B19A0347
Coördinaten: 103625, 518100
Maaiveld: 7,07 m t.o.v. NAP
Dieptetraject t.o.v. Maaiveld: 0,00 m - 125,00 m



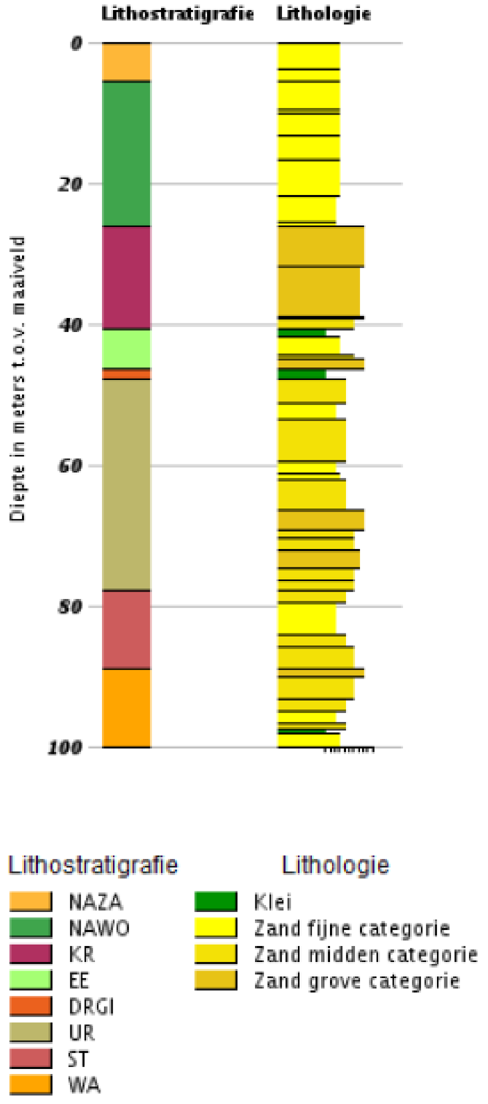
Boormonsterprofiel en interpretatie

Identificatie: B19C0033
Coördinaten: 103890, 510100
Maaiveld: 5,00 m t.o.v. NAP
Dieptetraject t.o.v. Maaiveld: 0,00 m - 125,47 m



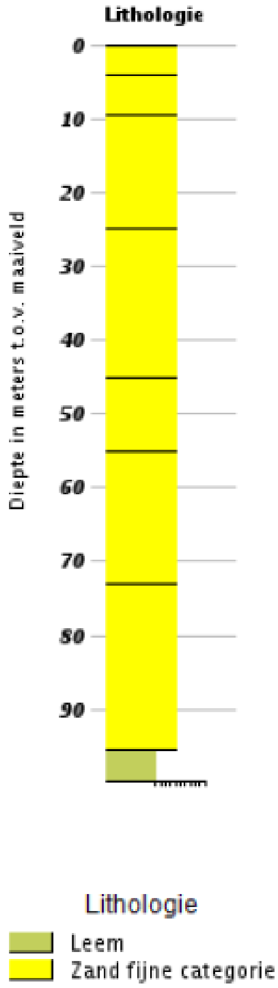
Boormonsterprofiel en interpretatie

Identificatie: B19C0582
Coördinaten: 101947, 507315
Maaiveld: 5,00 m t.o.v. NAP
Dieptetraject t.o.v. Maaiveld: 0,00 m - 100,00 m



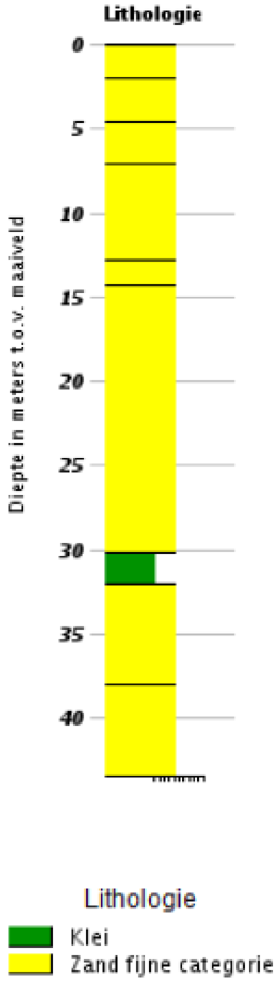
Boormonsterprofiel en interpretatie

Identificatie: BP060015
Coördinaten: 555340, 5841159
Hoogte maaiveld niet bekend.
Dieptetraject t.o.v. Maaiveld: 0,00 m - 99,80 m



Boormonsterprofiel en interpretatie

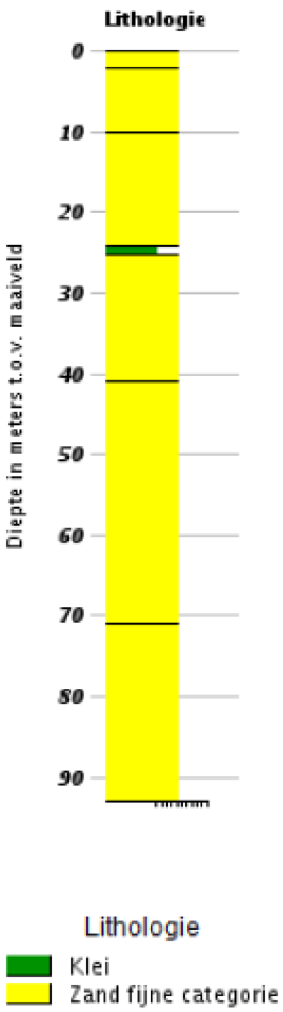
Identificatie: BP090014
Coördinaten: 550664, 5821122
Hoogte maaiveld niet bekend.
Dieptetraject t.o.v. Maaiveld: 0,00 m - 43,46 m



Deltares

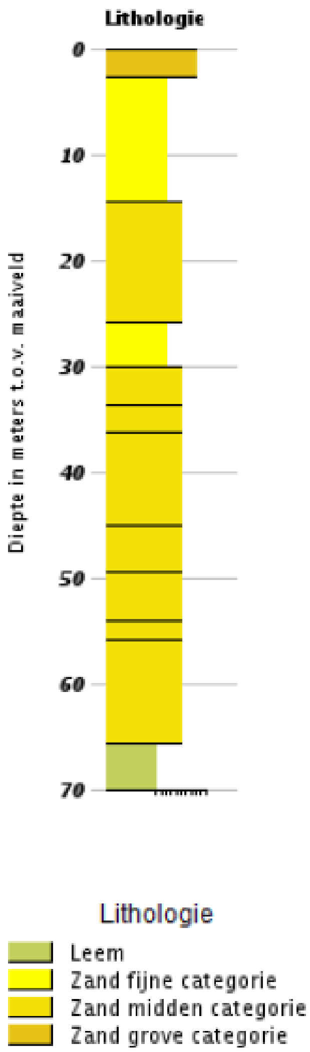
Boormonsterprofiel en interpretatie

Identificatie: BP090068
Coördinaten: 550263, 5822762
Hoogte maaiveld niet bekend.
Dieptetraject t.o.v. Maaiveld: 0,00 m - 93,00 m



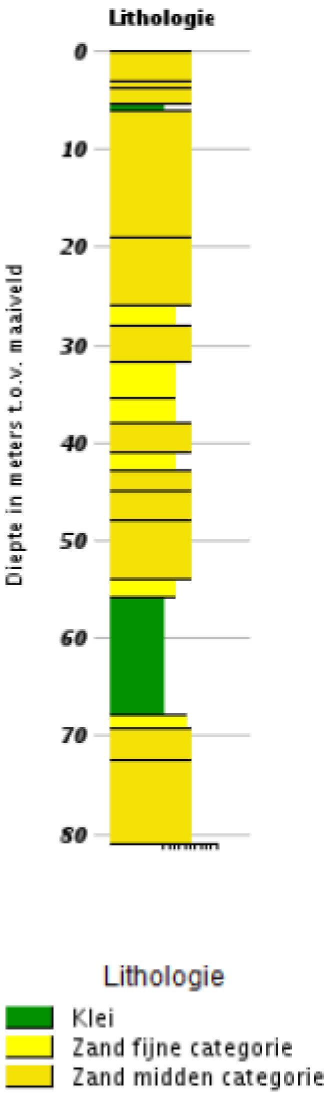
Boormonsterprofiel en interpretatie

Identificatie: BQ040138
Coördinaten: 587817, 5841527
Hoogte maaiveld niet bekend.
Dieptetraject t.o.v. Maaiveld: 0,00 m - 70,10 m



Boormonsterprofiel en interpretatie

Identificatie: BQ040139
Coördinaten: 586496, 5853646
Hoogte maaiveld niet bekend.
Dieptetraject t.o.v. Maaiveld: 0,00 m - 81,00 m



Contacts
Netherlands Enterprise Agency (RVO.nl)
Croeselaan 15 | 3521 BJ | Utrecht
P.O. Box 8242 | 3503 RE | Utrecht
www.rvo.nl / http://english.rvo.nl

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