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800MW THOR OWF GEOLOGICAL DESK STUDY – GEOLOGICAL MODEL

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1. INTRODUCTION

As part of the Energy Agreement 2018, all political parties stood behind a decision to build three new offshore wind farms in Denmark before 2030. On February 28th, 2019, the parties to the Energy Agreement decided that the first of the three offshore wind farms should be located in the North Sea west of Nissum Fjord, and at a distance of min. 20 km from the shore. The new offshore wind farm (OWF) is named "Thor" after Thorsminde, the nearest village on the shore of Jutland. The offshore wind farm will have a capacity of min. 800 MW and max. 1.000 MW.

Energinet has as part of the Energy Agreement been instructed by the Danish Energy Agency (ENS (Energistyrelsen)) to carry out marine pre-investigations and EIAs for the OWF and the planned export cable routes.

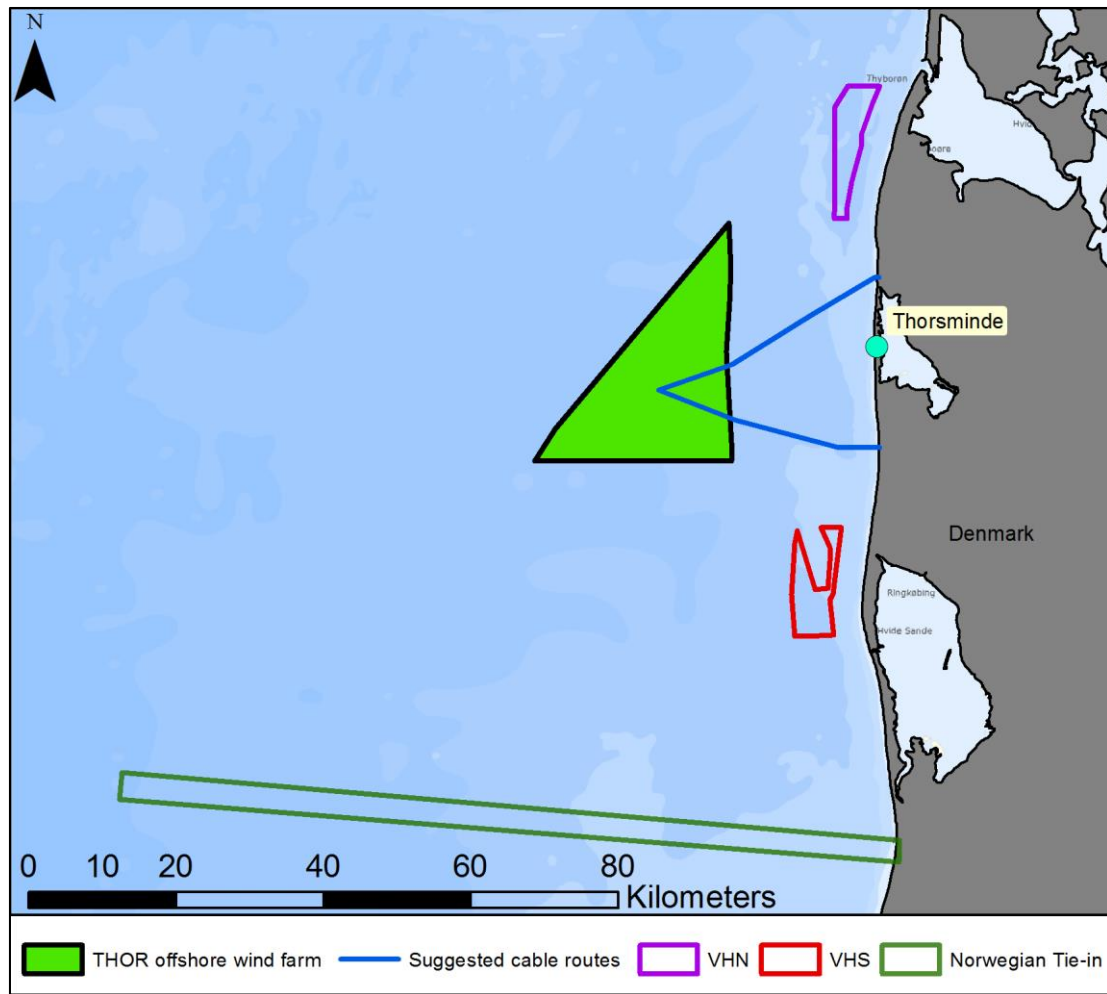


Figure 1-1 Overview of the Thor OWF area related to other offshore projects in the area. Marine projects in the region: OWF Vesterhav Nord (VHN), OWF Vesterhav Syd (VHS) and the planned Baltic Pipe route (Norwegian Tie-In).

Rambøll has as part of the initial stages of these pre-investigations prepared this Geological Desk Study (DTS) to support Energinets planned geoscience-focused surveys (geophysical, geotechnical etc.) of the Thor OWF pre-investigation area and the associated planned export cable routes, and to support the geoarchaeological assessments of the area.

With respect to the latter, Energinet must ensure that the relevant archaeological museum – Strandsmuseum St. George in Thorsminde – carries out archaeological assessments of the marine project area as part of the pre-investigations and as part of the EIA. Regarding the planned geoscience-focused surveys, it is expected that geophysical and geotechnical cable route surveys and site investigations for the Thor OWF will be carried out in 2019-2020.

It has been agreed with Energinet to split the DTS into 2 different reports:

- Report 1: The Geoarchaeological report primarily intended for the marine archaeologists, /1/.
- Report 2: This Geological model report primarily indented for preliminary interpretations of the planned geoscience-focused surveys, particularly the planned seismic surveys.

However, the relevant stakeholders are encouraged to consult both reports, as the Geoarchaeological report contains detailed information about the Late Glacial and Holocene relative sea level history in the area, while the Geological model report contains a conceptual geological model and descriptions of the regional geology, depositional and erosional history and expected sediments in the area.

In Figure 1-1 is presented the location of the net 800 MW Thor OWF pre-investigation area (in short: the OWF area) and the associated potential export cable routes (CR). In the figure are also shown selected relevant marine projects in the region, that are being referred to in the DTS: OWF Vesterhav Nord (VHN), OWF Vesterhav Syd (VHS) and the planned Baltic Pipe route (Norwegian Tie-In).

The Thor OWF project area covers approximately 440 km² with water depths expected to range from ca. 25 m LAT to 35 m LAT (Lowest Astronomical Tide). The OWF area extends from c. 20 km to c. 48 km from shore. The two CRs, which both origin at the same location in the approximate center of the OWF, are approximately 31 and 34 km long of which c. 10 km are within the OWF area.

As can be seen from Figure 1-1 OWF VHN is situated c. 14 km to the NE of the Thor site while VHS is located c. 14 km to the SE. The Norwegian Tie-in part of the planned Baltic Pipe is located c. 51km S of the Thor site. Ramboll carried out a Geoarchaeological DTS for that project in 2017. The HR3 OWF (not shown) is located a further c. 6 km more to the south of the planned Baltic Pipe route.

2. METHODOLOGY – REPORT 2

2.1 Geological DTS relevant for the preliminary seismo-stratigraphic interpretation

A geological DTS is intended to accumulate, synthesize, and present information collected and extracted from existing data sources. It is used to help understand and communicate the physical conditions and associated constraints on project development. The data sources include public data sources and proprietary data from Ramboll and our client's files.

As the primary purpose of this part of the geological DTS is setting up a conceptual geological model primarily indented for preliminary interpretations of the planned geoscience-focused surveys, particularly the planned seismic surveys, this report focuses on:

- Regional geology
- Subsurface geology including examples of existing interpreted seismic sections
- Seafloor and subsurface sediment layering and characteristics

The above elements are synthesized into a conceptual geological model for the sub-surface geology relevant for the expected maximum installation depths including a conceptual geological profile.

The primary purpose of the Geological DTS is to form a geological basis for the planning, optimization, execution and interpretation of the planned geophysical surveys of the site and cable route(s).

3. DATA

The preparation of the Geological DTS has followed these steps:

1. Data collection
2. Report 1: Selection of most relevant shore level displacement curve(s), Integration of shore level displacement curve with existing bathymetry and expected installation depths for the OWF and CRs
3. Report 2: Assessment, interpretation and description of relevant geology in the area. Construction of conceptual geological model and profile for the area

The data sources for both Report 1 and Report 2 include public data sources and proprietary data from Ramboll and Energinet.

3.1 Bathymetry

Several databases contain lists of depths to seabed (bathymetry), and/or bathymetric models, such as for instance the European (EU) funded 'EMODnet Bathymetry'. In this report, EMODnet is applied.

According to the official webpage of EMODnet, /2/, bathymetric survey data and aggregated bathymetry data sets have been collated from public and research organisations. These have been processed, quality assured and used to produce regional Digital Terrain Models (DTM). Thereafter, these have been integrated into the EMODnet DTM (Digital Terrain Model) for European seas.

The EMODnet DTM has a grid size of 1/16 arcminute. Each grid cell has a variety of information, including x,y coordinates and average water depth in metres (LAT), which is applied in this report. For metadata, please refer to the website of EMODnet, /2/. Bathymetry based on EMODnet data is presented as seabed maps and as seabed profiles.

The relevant nautical map, "93-Nordsøen" provided by Energinet, has been consulted as well.

3.2 Geological and geophysical data

Data and reports from the following databases have been assessed in order to be able to describe shallow geology along the planned cable routes and OWF area:

- the national well / borehole database 'Jupiter' maintained by GEUS
- the marine raw materials database 'MARTA' maintained by GEUS, including overviews of various marine shallow geology surveys and reports
- the national seabed sediment map developed and maintained by GEUS
- the national "groundwater reports" database developed and maintained by GEUS

In addition to the above, data used for this report include scientific papers and non-proprietary reports, which have been obtained from literature that Ramboll either owns or has obtained via internet search for this project.

In Figure 3-1 is shown an overview of the reported geophysical survey projects and lines in the investigation area. In addition to these, the VHN and VHS pre-investigation reports, including reports /3/ and /4/, have also been consulted (these are not available via Marta).

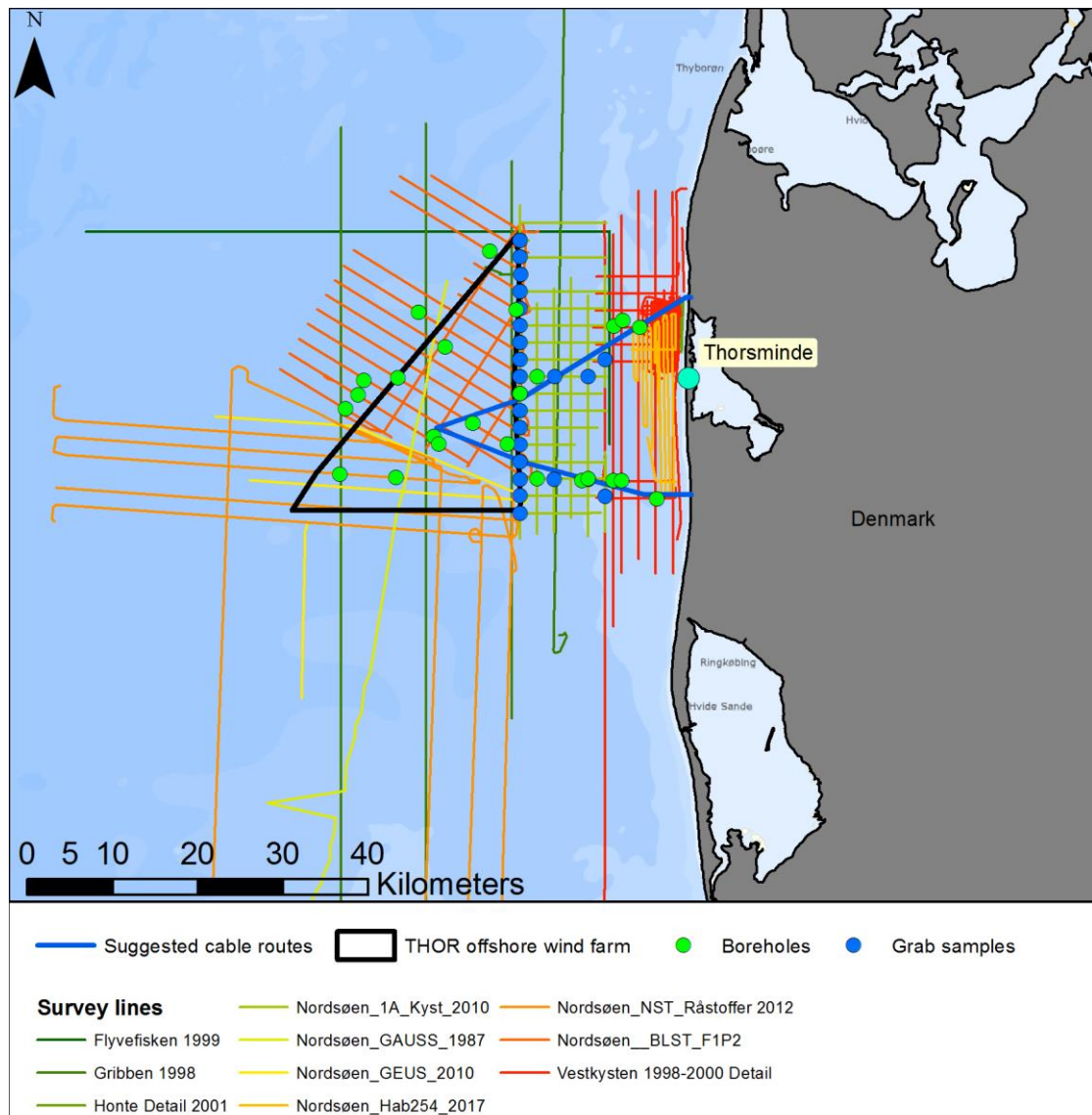


Figure 3-1: Overview of reported shallow seismic/geophysical surveys in the area plus existing boreholes (typically vibrocores and seabed samples) and grab samples, based on the Marta database.

4. REGIONAL GEOLOGY

4.1 Geological setting

This chapter first describes the general geological setting in the Danish part of the North Sea, followed by a description of the pre-Quaternary and Quaternary sedimentary deposits in the project area.

4.1.1 Pre-Quaternary history

In the Danish part of the North Sea Basin, the pre-Quaternary surface varies between sediments from the Upper Cretaceous Chalk towards the northeast, and Paleogene and Neogene sedimentary units towards the central part, Figure 4-1. In the region where Thor OWF is situated the pre-Quaternary sediments are from the Miocene.

In the period from Oligocene in the Paleogene Period to early Pliocene the North Sea Basin was filled with sediments from deltas, which were build out from the Scandinavian Shield.

The transition between Quaternary deposits and older sediments is observed only a few meters below seabed near the Thor OWF. The thickness of the Quaternary sediments in general increases towards west.

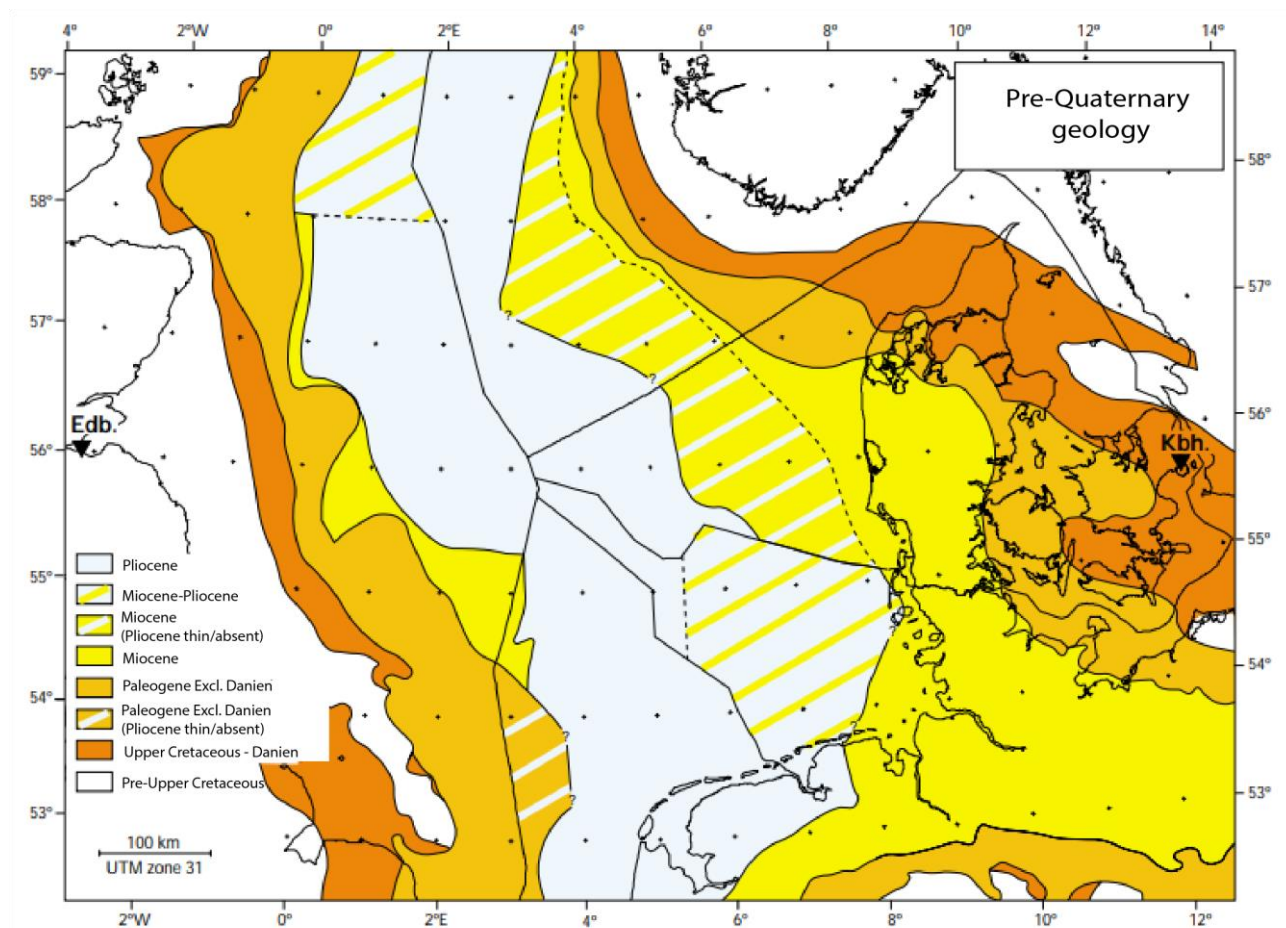


Figure 4-1: Pre-Quaternary geology in the North Sea Basin /5//4/.

The presence of several salt diapir structures and associated faults indicates tectonic movements and local uplift in the area north of Thor OWF. The salt tectonism has been active since the Cretaceous and is still on-going. Figure 4-2, which shows the level of the Top Chalk [m], indirectly shows the presence of salt structures in the area north of the Thor OWF. The salt diapirs are found sporadic in the area, and together with the faults they show a general NNW-SSE orientation. The presence of salt diapir structures and associated faults, does not affect the properties of the sediments found around Thor OWF.

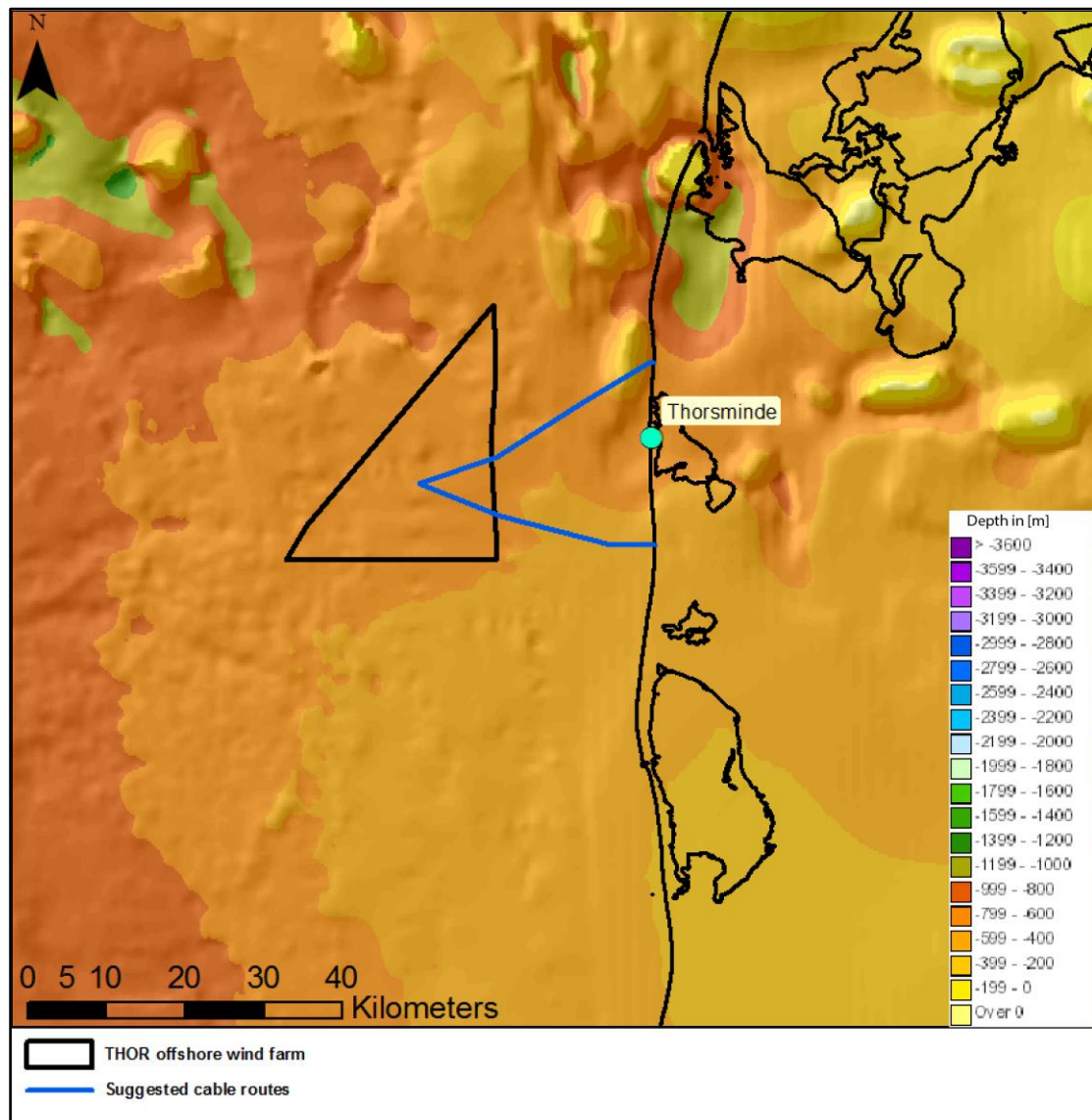


Figure 4-2: Top chalk depth structure map, depth in meters /6/.The map shows indirectly the presence of salt structures in the area north of Thor OWF. Yellow colour indicate higher areas where salt movements has created local uplifts.

Figure 4-3 shows a relatively thin layer of Quaternary sediments above the pre-Quaternary units. It is expected that the pre-Quaternary structures have had a significant influence on the sedimentary history of the Quaternary, and the present seabed shows evidence of buried pre-Quaternary valleys.

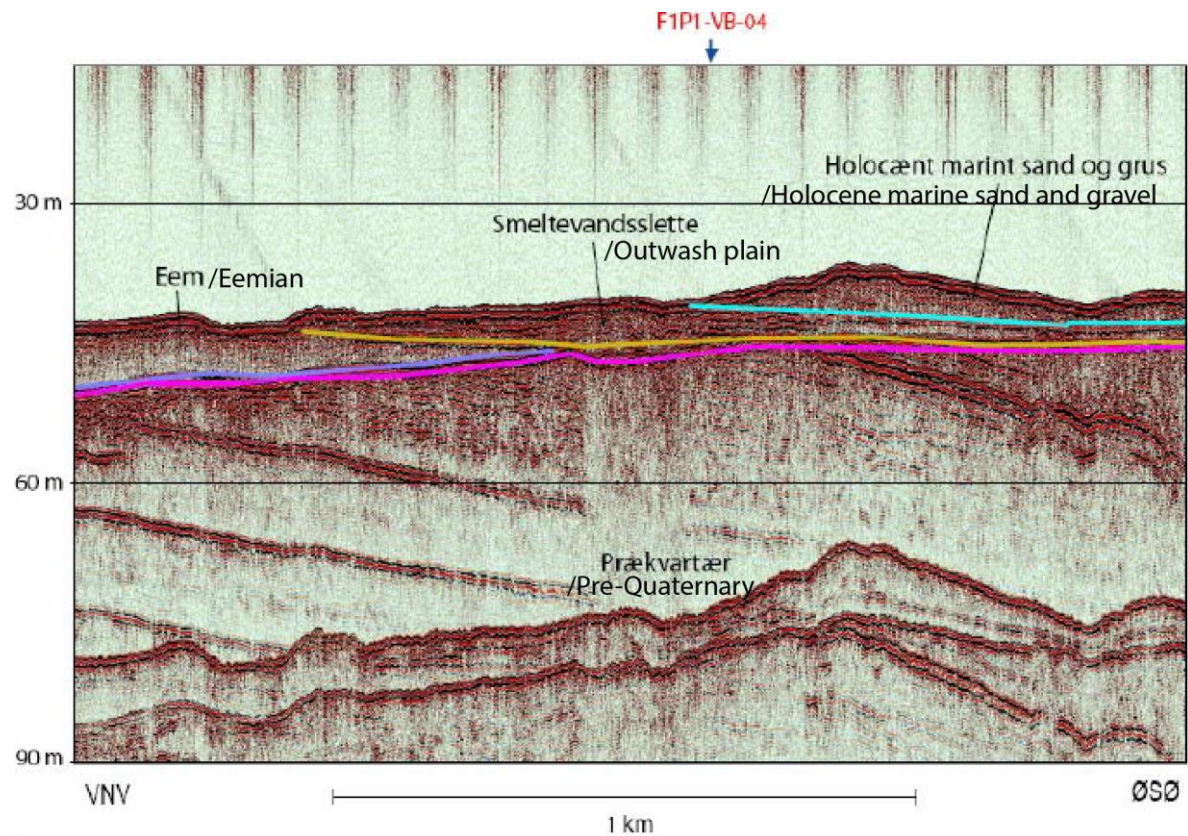


Figure 4-3: Seismic profile F1P1_83A shows a relatively thin quaternary unit above the pre-Quaternary layers, /7/. The profile is located near the last glacial maximum (LGM), north of the Thor OWF. Light blue line indicates the base of the Holocene marine sand and gravel. Orange line marks the base of the Weischelian meltwater sediments. Lilac line shows the base of the Eemian deposits and pink line shows the base of the Quaternary sediments, the Pre-Quaternary surface, see Figure 4-6 for location of the seismic profile.

Buried paleo-valleys, are a characteristic of the pre-Quaternary surface in the area around the Thor OWF as well as for large parts of the North Sea. Figure 4-4 shows a net of buried Quaternary valleys which are cut deep into the pre-Quaternary sediments.

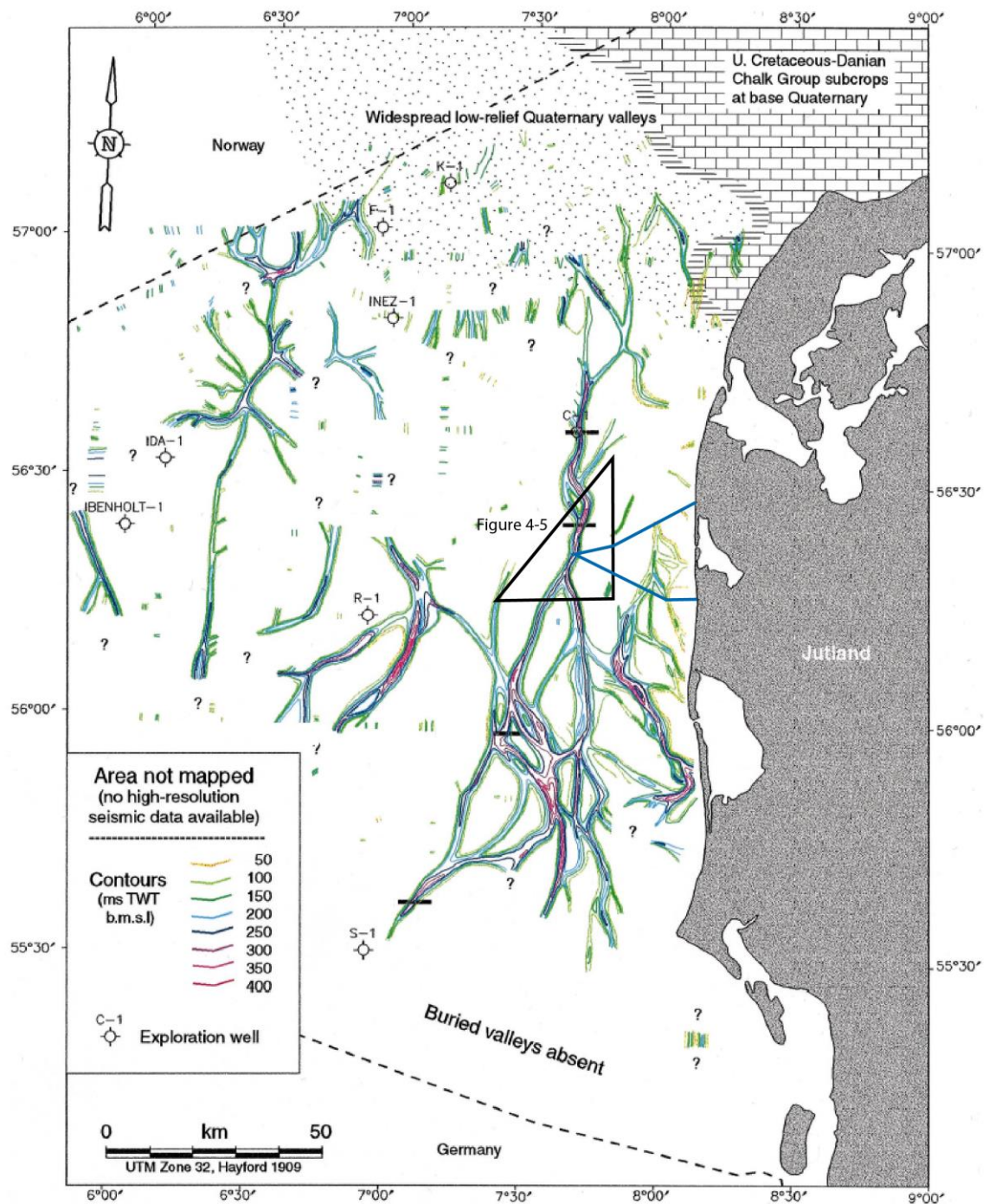


Figure 4-4: Buried Quaternary valleys in the eastern part of the North Sea, modified from /8/
Approximately location of Thor OWF is shown with a black line, CR's is shown with blue lines.

Such valleys or larger channels are related to the glaciations and weak zones in the Pre-Quaternary sediments. The channels are reused by the ice sheets moving and later on filled with glacial, interglacial and lateglacial sediments. The thickest Quaternary deposits in the area are registered in the paleo-valleys in the pre-Quaternary surface and are often, but not always, related to depressions in the present-day bottom relief. Thor OWF is situated in the area west of Nissum Fjord, Figure 4-4, where several deep buried valleys are mapped. In the central part of the Thor OWF investigation area at least one large N-S oriented valley is located.

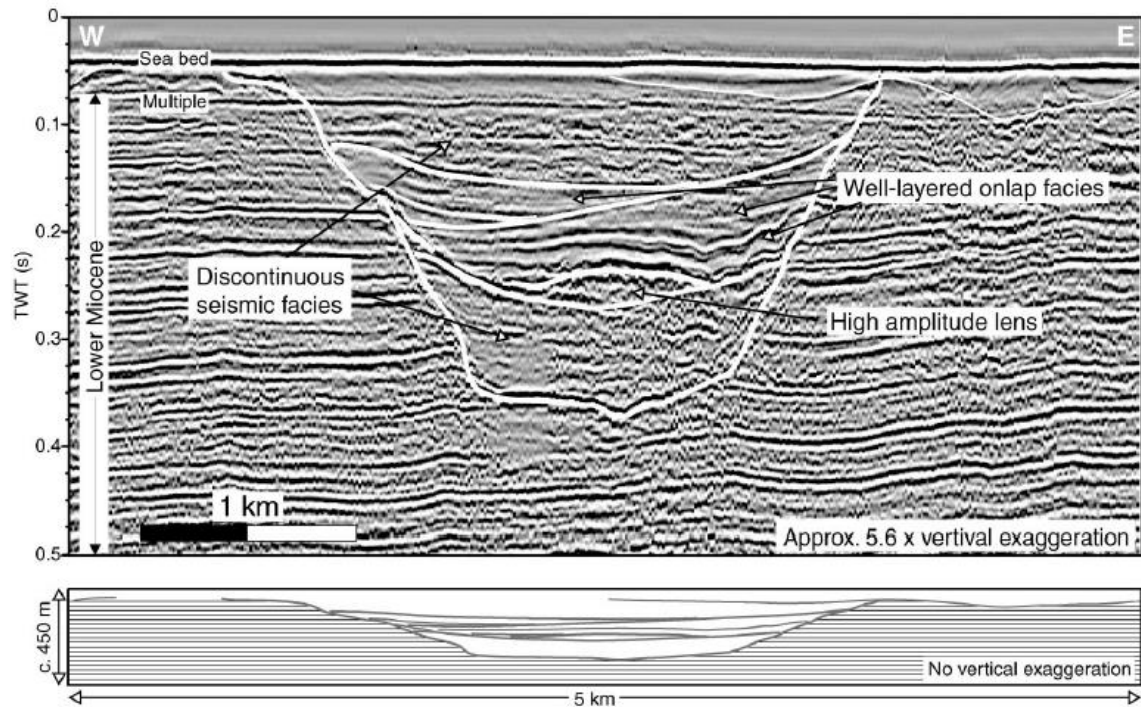


Figure 4-5: Interpreted high resolution seismic profile across a buried Quaternary valley, showing a typical infill sequence, for location see Figure 4-4, /8/.

Figure 4-5 show a interpreted high resolution multichannel seismic profil across a buried Quaternary valley, showing a typical infill sequence consisting of a lower, seismically disrupted/chaotic unit, followed by a seismically well-layered unit displaying onlap fill, for location see Figure 4-4, /8/.

4.1.2 Quaternary history

During the Quaternary period the western part of Jutland and nearby offshore areas was covered by ice streams a number of times during the Elsterian as well as the Saalian glaciation. Remnants from the old glacial landscape from the Saalian glaciation, are found as large moraine plateaus ("Bakkeøer") on the outwash plain west of the Last Glacial Maximum (LGM) of the last ice age, the Weischelian, Figure 4-6. The ice streams and their meltwater with associated debris eroded the pre-Quaternary surface and deposited glacial till and glaciogenic (deglaciation and meltwater) sediments. The glaciers also caused glaciotectonic deformation of older glacial/glaciogenic deposits and the pre-Quaternary deposits.

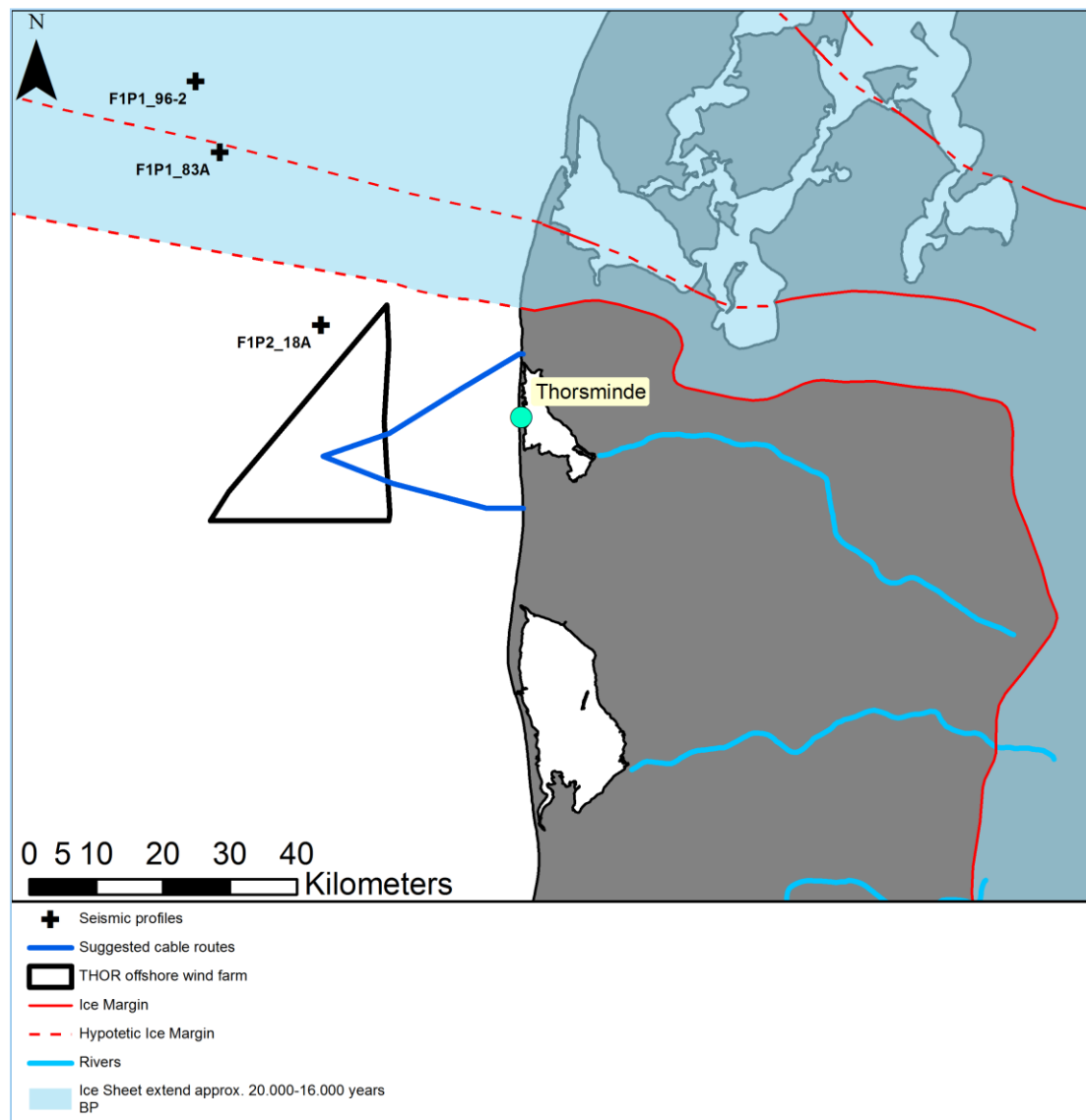


Figure 4-6: Maximum extent of the Fennoscandian ice sheet during the Late Weichselian, crosses marks the approximately location of the seismic profiles shown on Figure 4-3, Figure 4-9 and Figure 4-10, /7/ and /9/.

The Saalian glaciation was followed by a warm period, the Eemian interglacial. The climate was warmer and more humid than today, and coastal areas in Denmark was flooded by the Eemian Sea. The sea level rose and flooded the low-land areas and deposited clay-rich sediments with high organic content.

During the last ice age, the Weichselian, only the eastern and northern part of Denmark was covered by the Fennoscandian ice sheet. See Figure 4-6, which shows the maximum extension during the last ice age. The Thor OWF area was ice-free and covered by proglacial river plains and/or Saalian moraine plateaus. In the proglacial river plains glaciofluvial sand and gravel was deposited. However, it cannot be ruled out that the northernmost part of the OWF area was covered by the Weichselian Fennoscandian ice sheet as the maximum extent of the ice sheet is uncertain in present offshore areas. Impacts from the Weichselian ice sheet is represented by glaciotectionic disturbances in the glaciofluvial sediments near the glacier margin. Glacial deformations are offshore observed in proximal glacial sediments near the maximum extend of ice sheets in the Weichselian glaciation and in Weichselian meltwater sediments deposited between the old moraine plateaus ("Bakkeøer") from the Saalian glaciation.

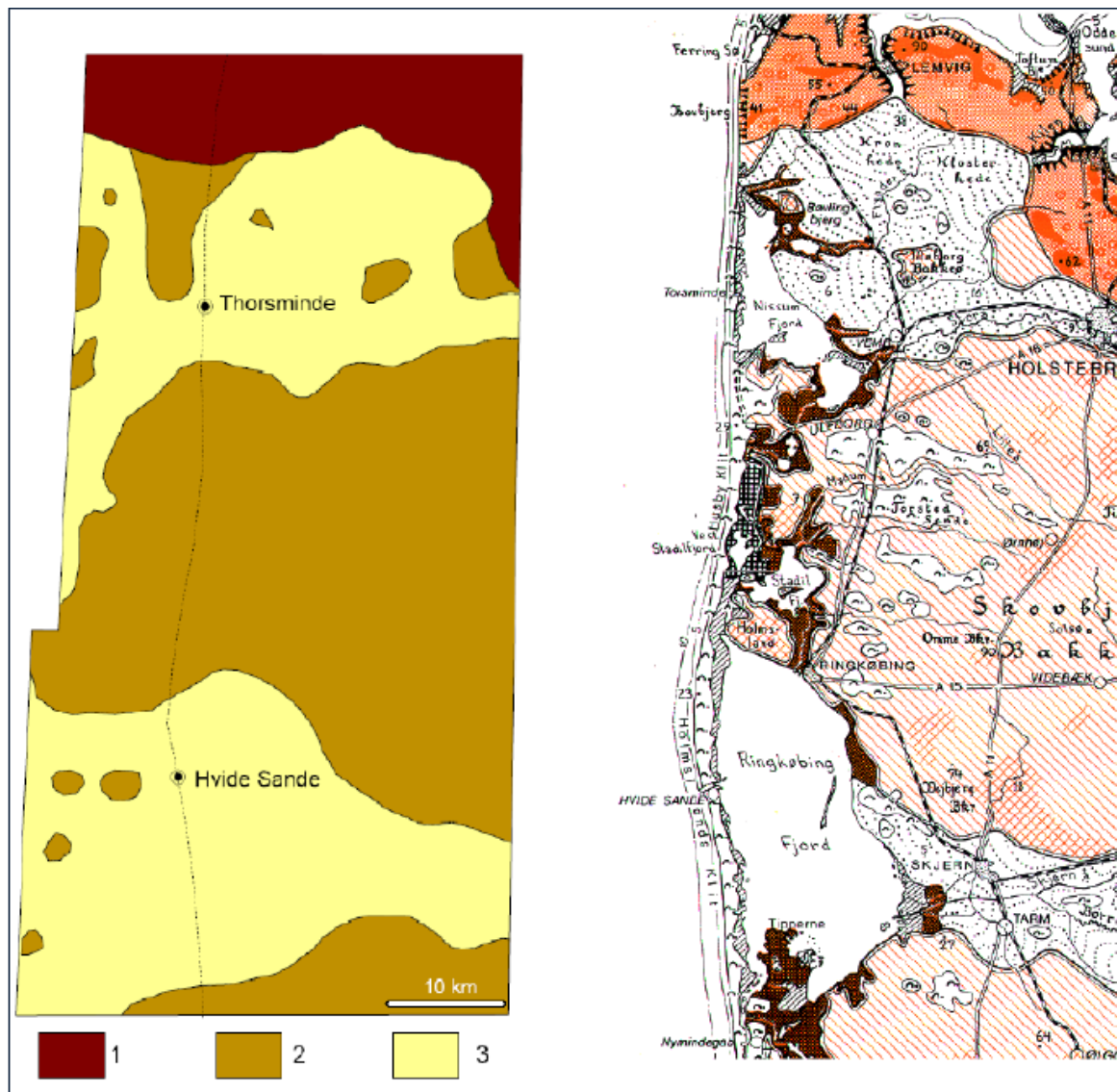


Figure 4-7: The coastal zone near Thor OVF. Right: Classical onshore geomorphological map Left: Surface geological map which cover an area 20 kms offshore from the present Danish coastline. Legend: 1: Weischelian moraine landscape, 2: Old moraine landscape from Saale glaciation ("Bakkeøer"), 3: Weischelian outwash plain. Thor OVF is situated c. 20km – 48km west of Thorsminde /7/.

Figure 4-7 shows in the area east of Thor OVF a glacial depression zone south of the Last Glacial Maximum (LGM), which includes Nissum Fjord.

The peak of the Weischelian glaciation occurred approximately 18,000 years BP. Deglaciation of the Danish area began approximately 16,000 years BP. The geological history of the Danish area during and after deglaciation was controlled by the interplay between deglaciation, uplift of the Earth's crust due to the reduced load from the melting ice sheet and rise in global sea level due to the release of water from the ice sheets.

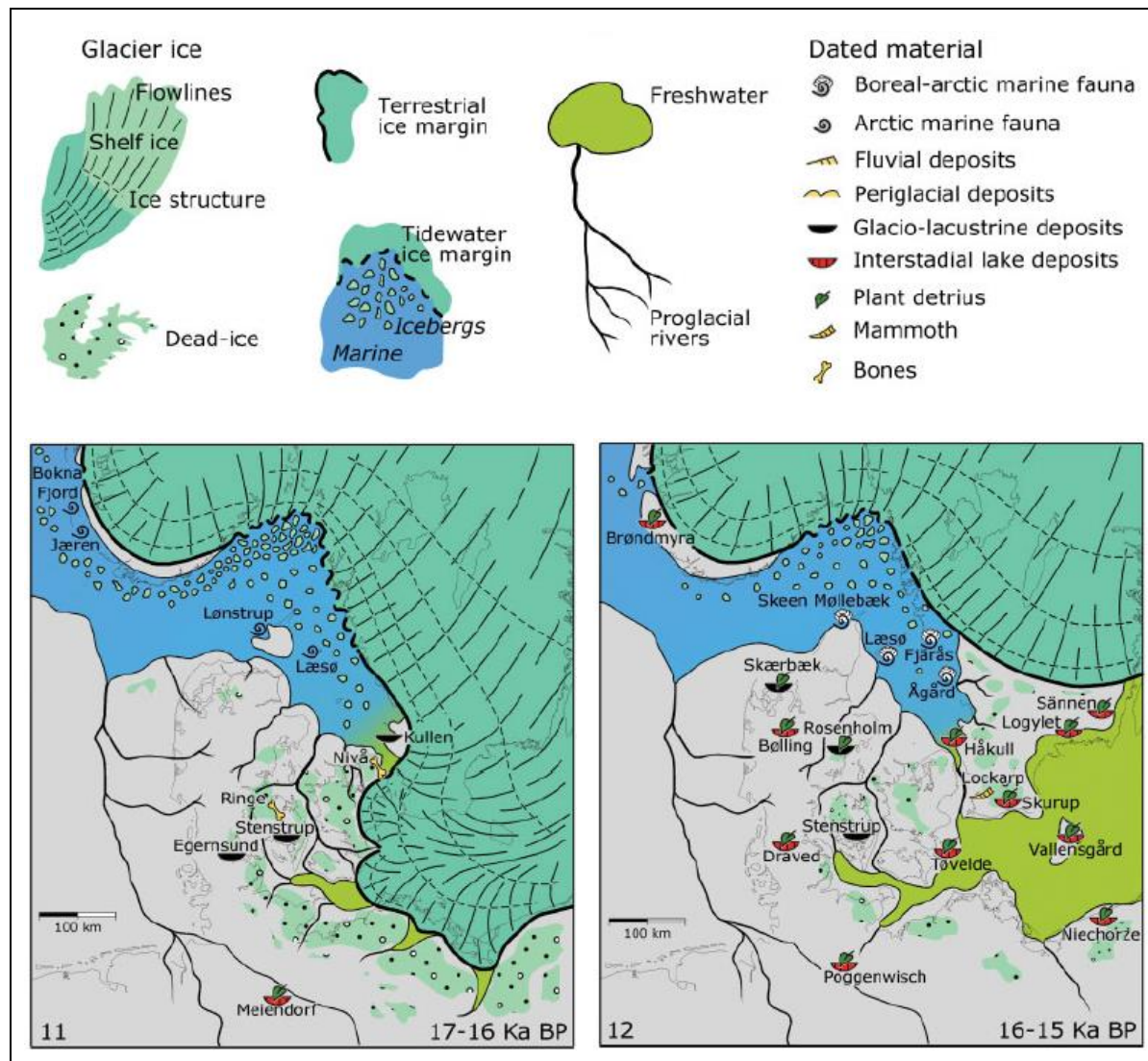


Figure 4-8: Palaeogeographic maps showing the configuration of land (grey), ice (blueish-green), sea (blue) and lake (green) at two different times during deglaciation, /10/.

During the decline of the glaciers, increased melting of the ice sheets released large volumes of water causing global sea level to rise and deglaciated areas were covered by a flooding, the younger Yoldia Sea, Figure 4-8. The left map shows the situation 17-16,000 years BP where the Yoldia Sea covered most of the present Kattegat and Skagerrak, with higher shorelines than the present-day shorelines in the north, and lower shorelines than the present-day shorelines in the south. The present Denmark, a large part of the North Sea Basin and the Thor investigation area was land at that time. The right map shows the situation 16-15,000 years BP where the glaciers further declined, and a large lake covered most of the present Baltic Sea area.

From 11,000 to 6,000 years BP a continued global transgression effected the area, and the North Sea Basin was slowly inundated and the area around the Thor OWF changed from being a land area to a marine area, where the old glacial landscape was eroded and transformed to first an archipelago with former hills forming islands in the open sea. The whole area was covered by sea around 7,000 years BP. The flooded sediments were now exposed to erosion and with time covered by marine sand. Relative sea level changes during the Lateglacial and Holocene are detailed reported in Report 1, /1/.

4.2 Lithologies

4.2.1 Pre-Quaternary sediments

The Pre-Quaternary sediments comprise different geological lithologies from the Miocene, primarily consisting of sand and clay. The Miocene deposits are covering the underlying Chalk deposits.

In areas north of the Thor OWF the chalk units are lifted to near the seabed by salt diapirism.

4.2.2 Glacial sediments

Quaternary sediments cover the floor of the North Sea Basin almost completely. The sedimentary cover comprises glacial deposits from the Saalian and older glaciation, marine deposits from the Eemian interglacial period, lateglacial meltwater deposits from the last ice age, the Weischelian. The thickest Quaternary deposits are registered in paleo-valleys in the pre-Quaternary surface. Figure 4-9 shows a deep buried valley (green reflector) filled with Quaternary deposits. Outside the buried valleys the thickness of the Quaternary sediments does not exceed 10-20 meter.

The oldest Pleistocene sequence in the area consists of glacial sediments of Elsterian and Saalian age. The deposits are dominated by glacial till, interglacial clay deposits from the Eemian interglacial and meltwater sediments from the last ice age, the Weischelian, Figure 4-9 shows the old Saalian glacial landscape above the pre-Quaternary sediments.

Most of the tills are deposited below glaciers, and the sediment is consequently normally pre-consolidated and hard, with high strength due to the pressure from the overlying ice. The tills consist of poorly sorted mixtures of grain sizes ranging from clay to boulders. When tills crop out in the sea floor or are covered by only a thin veneer of marine sediments, boulders and stones are often spread over the sea floor.

Prior to marine inundation during the following Eemian interglacial, small channels were eroded into the Saalian meltwater plain and freshwater sediments sand, mud and peat were deposited, the blue reflector on Figure 4-9 shows the small Eemian channels eroded into the older Saalian landscape. Once the area was inundated, marine mud and clay was deposited, the thickness of the Eemian deposits varies from 5-10 meters.

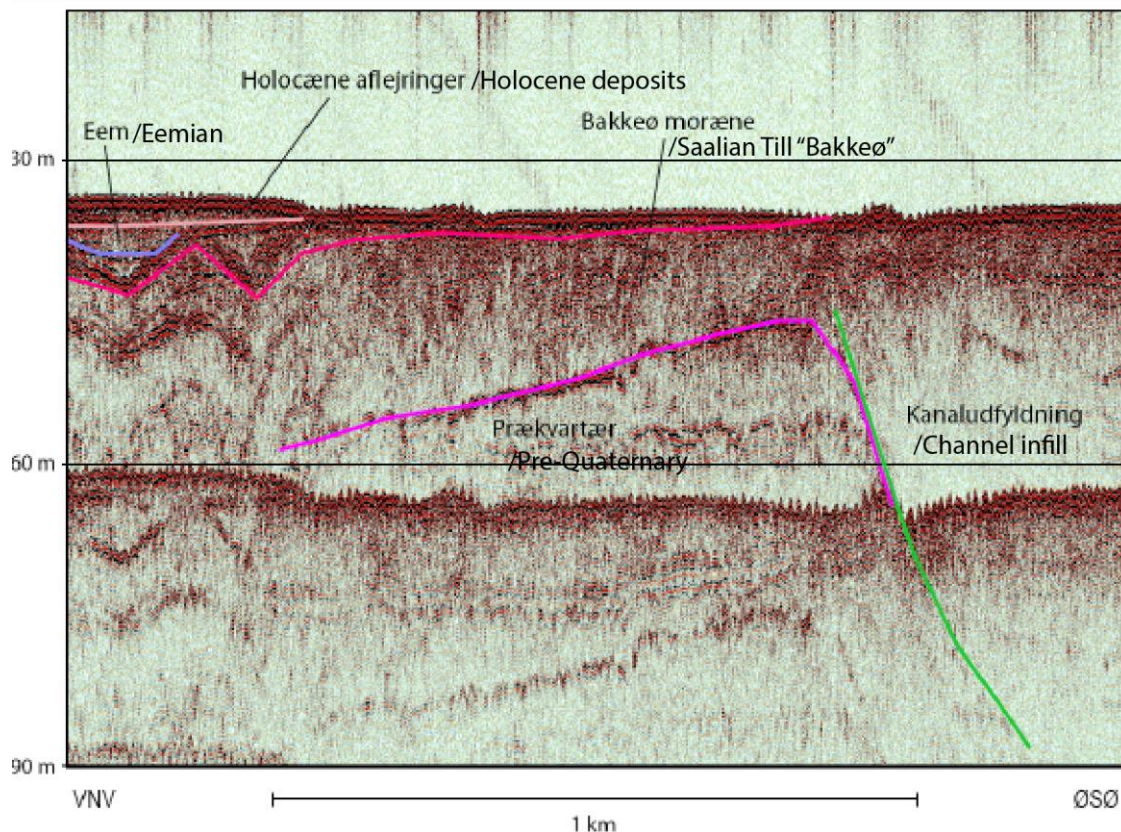


Figure 4-9: Seismic profile F1P2_18A shows Saalian glacial till above pre-Quaternary sediments. The profile is located south of the Weischelian ice sheets maximum extend, /7/. Light red line indicates the base of the Holocene deposits. Red line marks the base of the Saalian glacial sediments. Lilac line shows the base of the Eemian deposits. Pink line shows the base of the Quaternary sediments, the Pre-Quaternary surface. The green line marks the buried valleys, cut into the Pre-Quaternary deposits, see Figure 4-6 for location of the seismic profile.

In addition to the older tills from the Saalian glaciation and marine sediments from the Eemian interglacial period, sorted glacial deposits are also found, Figure 4-10. The sorted deposits mainly

comprise sand/gravels deposited by meltwater in increasing distance from the melting ice-front, leaning to typical fining upwards successions.

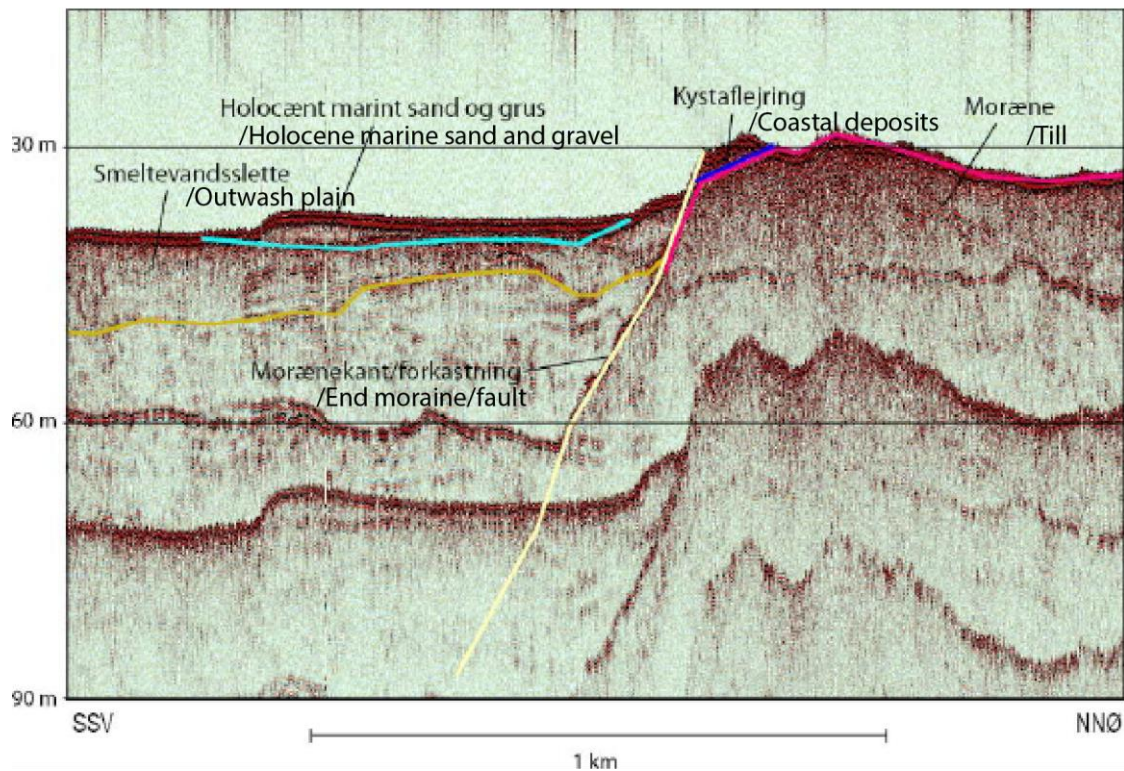


Figure 4-10: Seismic profile F1P1_96-2 shows the meltwater plain deposits south of the main stationary line of the Weischelian glaciation LGM /7/. Light yellow line shows an end moraine/fault. Light blue line indicates the base of the Holocene marine sand and gravel. Orange line marks the base of the Weischelian meltwater sediments. Blue line marks base of coastal sediments, and red line marks the base of glacial sediments deposited during the last ice age, see Figure 4-6 for location of the seismic profile.

4.2.3 Lateglacial and Holocene sediments

The Lateglacial and Holocene deposits are mainly sand and gravelly sand deposited by the Jutland coastal current. The sandy sediment is deposited in open sea with influence of strong currents at the seabed, and giant sand waves are located on water depths between 30 and 20 meters.

In shallow and sheltered areas, the Holocene (Littorina Sea to present) marine sediments consist typically of clay and mud with a high organic content and high-water content. However, recent marine sand and gravel deposits are typical sediments of the coastal zones, and therefore the dominant sediment type around the Thor OWF.

5. GEOLOGICAL MODEL AND STRATIGRAPHY AT AND NEAR THOR OWF

This chapter describes which geological conditions to expect for the wind farm area and the CR's.

5.1 Site specific geological setting including pre-Quaternary geology

The Thor OWF is situated in the North Sea Basin west of Nisum Fjord, and at minimum distance of 20 km from the shore. Thor OWF is situated south of the Weischelian maximum glacier extend (LGM) in an area with a relatively thin Quaternary sediment cover, and pre-Quaternary sediments consisting of Miocene and Cretaceous deposits.

5.2 Seafloor morphology (bathymetry)

In Figure 5-1 **Error! Reference source not found.** is shown the general bathymetry off the coast of Jutland based on EMODnet along with the OWF area and in principle also the two planned CRs, /2/.

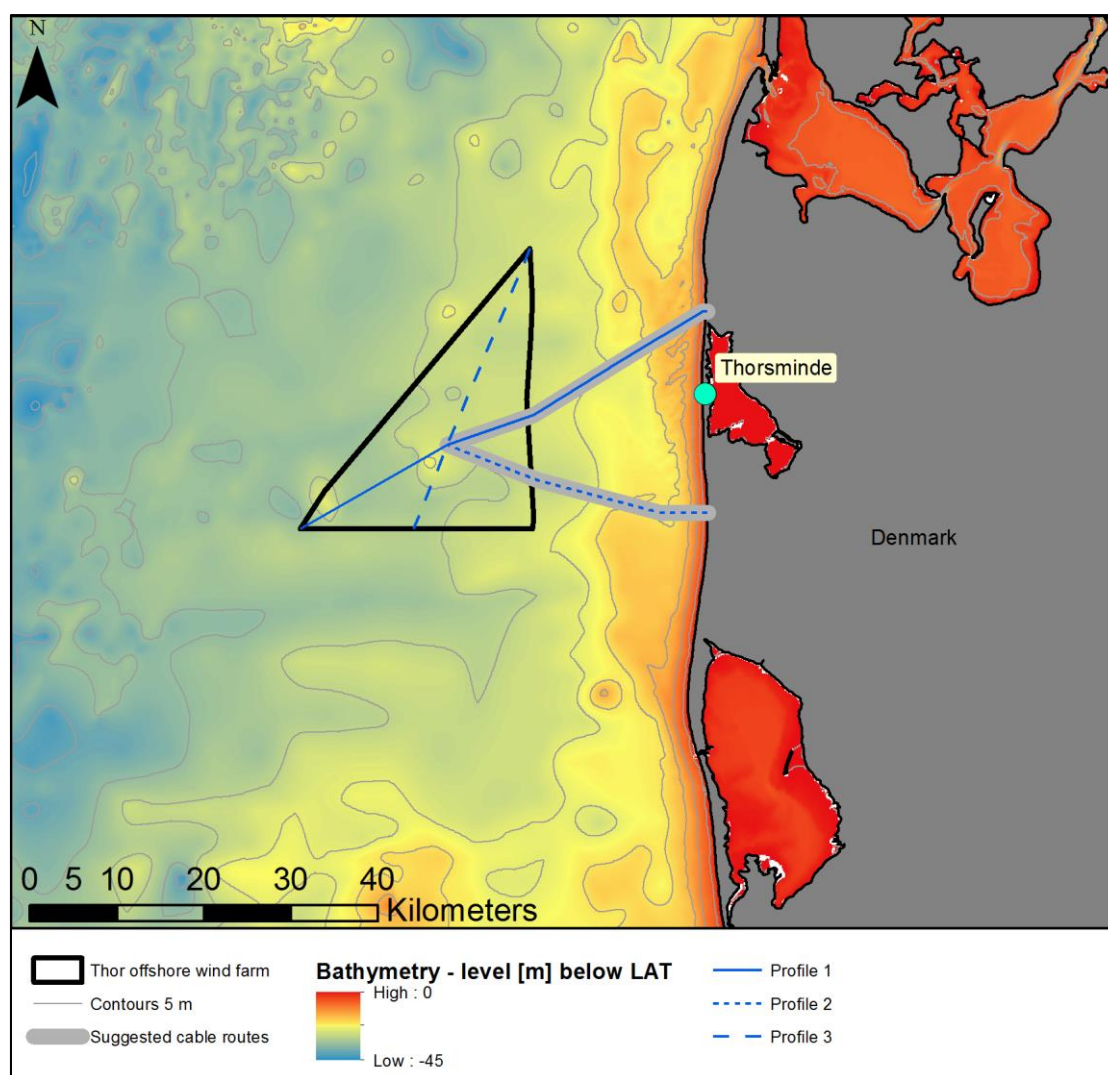


Figure 5-1: Overview Thor OWF and connected cable routes with the general bathymetry based on EMODnet, /2/.

In the Thor OWF area the water depth is relatively shallow and ranges from c. -24 m to c. -34 m LAT with a mean water depth of -29,9 m and with the greatest depths in the southwestern part of the OWF. The seabed is seen from the coast gently sloping towards the southwest and is interpreted as a flooded outwash fan formed by meltwater from the Weischelian glaciers /7/.

5.3 Seabed sediments

Distribution of the seabed soil types around Thor OWF and CR 's is shown on Figure 5-2.

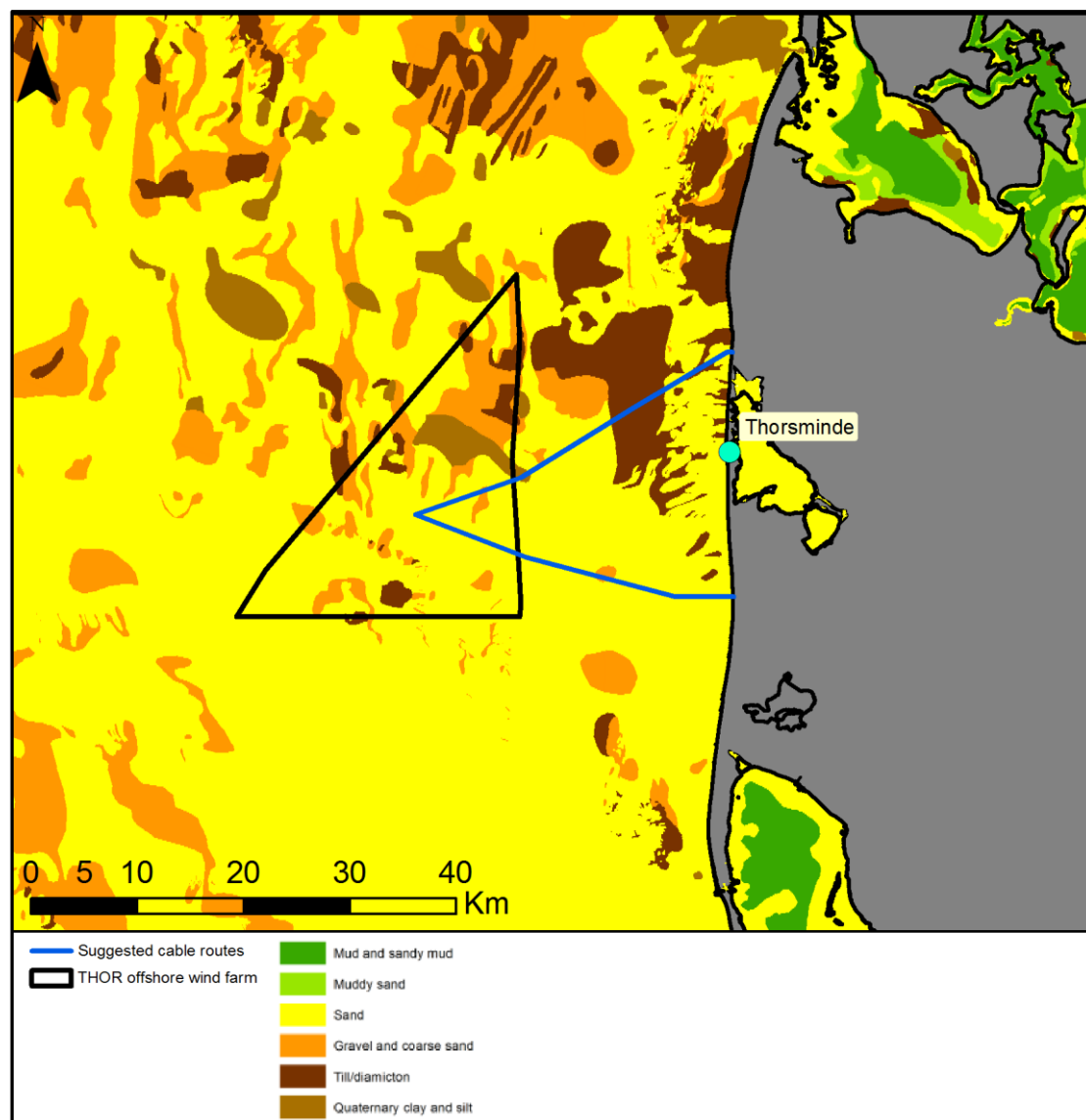


Figure 5-2: Distributions of seabed soil types around Thor OWF, /11/ .

According to the GEUS seabed sediment map the seabed is dominated by sediments such as postglacial, lateglacial and glacial sandy to gravelly sediments (yellow-orange). In the northern part of the Thor OWF area and locally in the central southern part and along the northern cable route till mounds of old glacial till (Saalian age) are outcropping the seabed surface (dark brown/brown).

The seabed in the North Sea is exposed to erosion and sediment transportation. The presence of glacial till in the study area, indicates active erosion or transportation.

5.4 Subsurface geology and stratigraphy

Based in the combined results from the earlier investigations in the area, a schematic diagram of the identified sub-seabed geological units, representative for the site is created and shown in Figure 5-3 and Figure 5-4. This geological model is developed from the above described formations and based on the information from /7/.

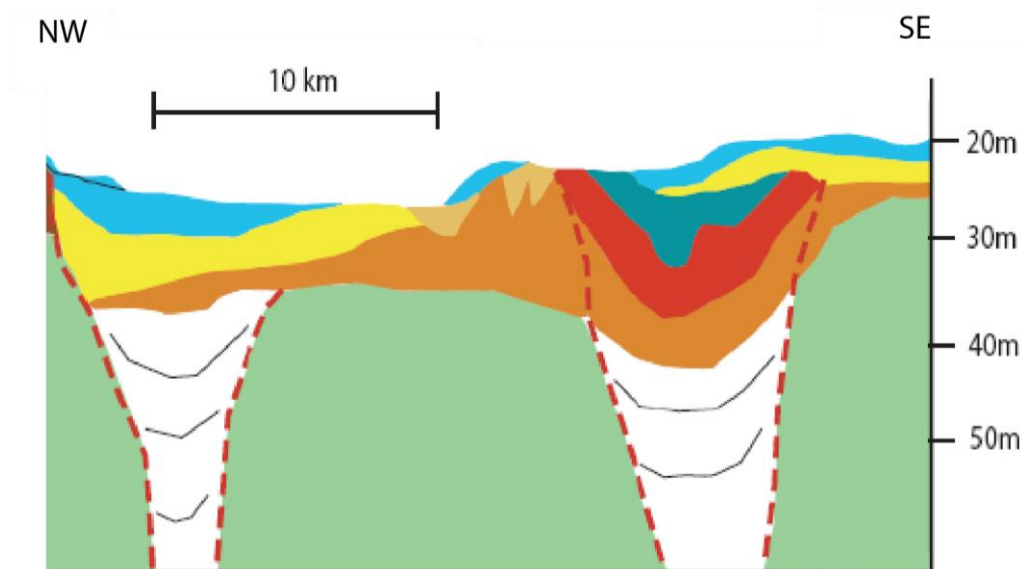


Figure 5-3: Geological conceptual geological model. The colours on conceptual geological model correspond to the stratigraphic model shown on Figure 5-4, modified from /7/.

It can be concluded that the seabed, and the upper geological layers in the area of the Thor OWF exhibits marine postglacial sandy sediments. The seabed surface sediments vary from combinations of fine-coarse sand, with areas of more gravelly composition (Jyske Rev Sand).

Just below the postglacial deposits sandy glaciofluvial (Weischelian) meltwater deposits overlay the older Saalian glacial sediments. The latter are interpreted to truncate deep into the pre-Quaternary sediments in buried valleys in the Thor OWF area. Local deposits of marine Eemian clay are found between the older glacial till deposits and the younger meltwater sediments deposited under the last glacial and deglaciation period.

Figure 5-4 summarises all soil types that are likely to occur inside the wind farm area, from seabed and down to foundation relevant depths, i.e. several tens of meters below seabed, /7/.

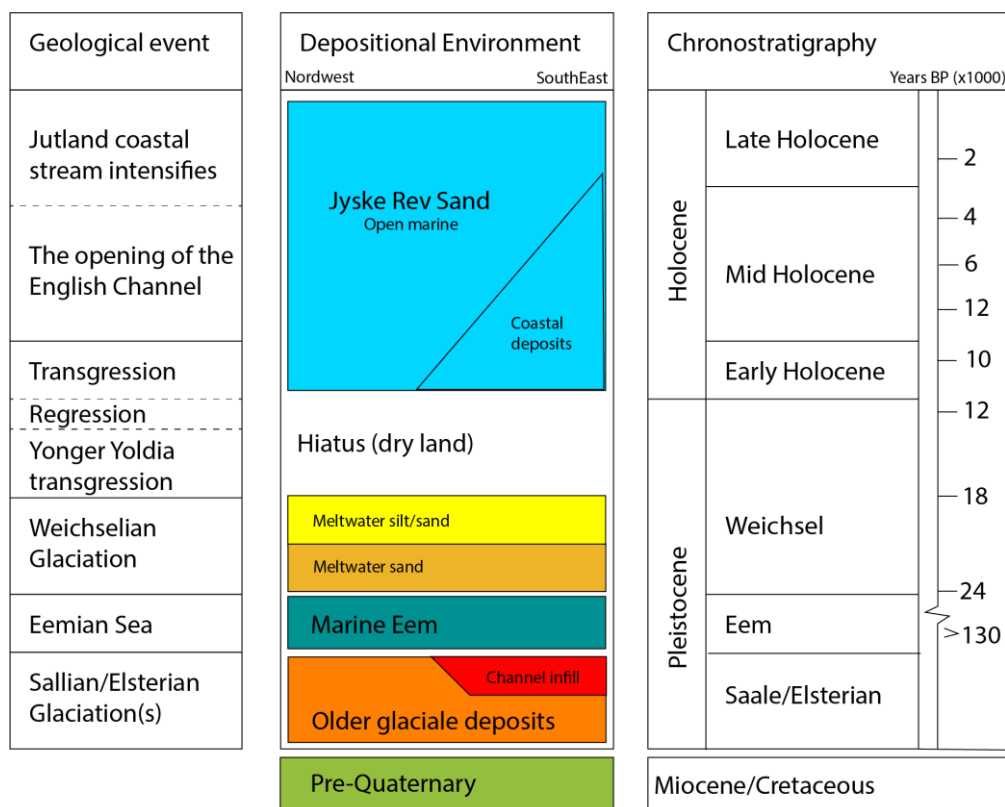


Figure 5-4: Stratigraphic time-scheme, modified from /7/.

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