DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2023/34**

Screening of seabed geological conditions for the offshore wind farm areas Kriegers Flak II North and Kriegers Flak II South

Desk study for Energinet

Jørn Bo Jensen, Ole Bennike & Jørgen O. Leth

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

GEUS

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G E U S

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1. Dansk resumé

Energinet har bedt GEUS om at udføre en geologisk screening af Kriegers Flak II Nord og Syd havvind områderne og den mulige kabelkorridor til Rødvig på Sjællands østkyst. Undersøgelsen er tænkt som baggrund for en geologisk og geoteknisk vurdering af områdets potentiale for etablering af en havvindmøllepark. Der opstilles en geologisk udviklingshistorie af området og der gives en oversigt og en beskrivelse af alle de geologiske enheder, der kan forventes i området.

Rapport er primært baseret på en tidligere screeningsrapport om den generelle geologiske udvikling af Kriegers Flak II Nord og Syd havvind områderne (Jensen & Bennike 2022), suppleret med anden tilgængelig geologisk viden om havbunden i kabelkorridoren. Til at vurdere den generelle geologiske udvikling af Østersøen og specifikt den vestlige del er der benyttet en kombination af publicerede artikler og rapporter, samt GEUS-arkiv seismiske data og boringer. Dækningen af eksisterende seismisk data i vindmølleområderne er sporadisk og antallet af geologiske prøvedata er yderst begrænset. Derfor er informationerne fra nærområdet i stor udstrækning anvendt til at beskrive de forventede geologiske forhold.

Den generelle geologiske beskrivelse inkluderer en komplet succession fra den præ-Kvartære tektoniske ramme, den præ-Kvartære overflade, de glaciale aflejringer, smeltevandsaflejringer, aflejringerne fra de senglaciale sø-stadier og de postglaciale aflejringer.

Som en del af studiet er der præsenteret en lokal relativ strandniveaukurve, der dækker de holocæne og senglaciale perioder. Den palæogeografiske udviklingshistorie med fordelingen af land og hav efter den sidste istid er beskrevet med henblik på at øge forståelsen af mulige arkæologiske interesser.

Kortlægningsresultater præsenteres i form af seismiske eksempler og kort over tykkelsen af sedimenter i området. Der præsenteres adskillige konklusioner, som er relevante for fremtidige geotekniske og arkæologiske vurderinger af området. Konklusionerne kan i korthed sammenfattes til:

Prækvartæret i vindmølleområderne består af Maastrichtien/Øvre Kridt skrivekridt eller Danien kalksten. Skrivekridt er karakteriseret ved en varierende hårdhed fra en blød til hård kalksten pga. forskellig grader af forvitring. Danien kalksten er generelt hårdere, men kan variere med lag af mere slamholdig kalksten. Toppen af prækvartæret forventes at ligge mellem 40 og 55 m under havbunden.

De glaciale aflejringer består af moræneaflejringer og smeltevandssedimenter fra den sidste istid, Weichsel. Området kan være præget af aflejringer fra flere isfremstød i forbindelse med isens tilbagesmeltningen med flere genfremstød. De glaciale sedimenter kan forventes at være af heterogen sammensætning og overkonsolideret på grund af tidligere isbelastning og perioder med mellemliggende tørlægning. Sedimenterne består af lerholdige eller sandede moræner med variabelt stenindhold, deformerede glaciofluviale sedimentlag (sand, grus og ler) og stedvist med glacio-tektonisk forstyrrede flager. I den vestlige del af Kriegers Flak II Nord udgør moræneaflejringerne havbunden.

De senglaciale sedimenter i Østersøen præges generelt af ikke-konsoliderede, lerede aflejringer fra stadier af den Baltiske Issø. I vindmølleområderne forventes leret af være overlejret af overvejende sandede sedimenter aflejret i kystnære miljøer med højere geotekniske styrkeparametre. Sandaflejringer forventes findes som et kileformet lag, der bygger ud fra vest mod øst ind i Arkona Basinnet.

De senglaciale aflejringer overlejres af postglacialt, marint sand eller gytjeholdigt finsand. Postglacialt, marint sand er generelt velsorteret med gode geotekniske styrkeforhold, mens det gytjeholdige finsand er et relativt blødt, vandholdigt sediment med varierende indhold af organisk stof og lave geotekniske styrkeforhold.

I Kriegers Flak II Nord består havbunden af moræneaflejringer i den vestlige del og gytjeholdigt sand i den østlige og sydlige del. I Kriegers Flak II Syd området består havbundens sedimenter overvejende af marint sand, i den østlige del dog gytjeholdige finsand.

Den geologiske opbygning af kabelkorridorområdet sydlige del er sammenlignelig med Kriegers Flak II Syd. Den øverste del af havbunden er præget af postglacialt, marint sand, der dog i den sydøstligste del går over i gytjeholdige finsand. Den nordligste del af kabelkorridoren er præget af moræneaflejringer helt op i havbunden. I et område omkring ilandføringsstedet ved Rødvig fremstår Danien kalkstenen direkte på havbunden.

Selvom kystlinjen i postglacialperioden har været dynamisk og fluktuerende vurderes sandsynligheden for at finde druknede landskaber og arkæologiske interessante fund in situ fra tidlig og midt Mesolithikum indenfor Kriegers Flak II og kabelkorridoren at være lille. Det skyldes at områdets eksponering i et højenergi miljø med kraftige bølger og strøm.

2. Summary

Energinet asked GEUS to perform a geological screening of Kriegers Flak II North and South Offshore Windfarm areas (OWF) and the potential cable corridor between the wind farm areas and Rødvig at the east coast of Zealand. This screening report is supposed to present the background information for the geological and geotechnical evaluations prior to the development of new offshore wind farms. The screening report proposes a model for the geological development of the Baltic area, with a specific focus on the wind farms and the cable corridor.

The report is combining a previous screening report presenting the general development of the Baltic Sea and the potential wind farm areas (Jensen & Bennike 2022), with available geological knowledge of the seabed in the cable corridor area.

The evaluation of the general geology of the Baltic Sea was based on a combination of scientific publications, reports and seismic data and core data from GEUS archives. The data coverage, however, is poor in the wind farm areas and, hence, the information from the surrounding areas has been extrapolated to the wind farm areas to describe the expected geological conditions.

This screening report presents a general description of the geological succession from the pre-Quaternary to the post-Glacial deposits exemplified by seismic profiles and thickness maps. The general result is summarized here:

The pre-Quaternary in the wind farm areas consists of Upper Cretaceous chalk and/or Danian limestone. The chalk varies from a soft to a hard limestone dependant on the degree of weathering. The Danian limestone, in general, is hard but can have levels. The expected depth to the top pre-Quaternary is between 40 and 55 m b.s.l.

The glacial deposits consist of moraine and meltwater deposits from the last glaciation, the Weichsel. The area shows evidence of the retreating icefront with several re-advances. The sediments, in general, is heterogeneous and over-consolidated due to ice loads and subaerial exposure, mainly consisting of clayey or sandy tills with a variable content of boulders, and mixed meltwater deposits. Glacio-tectonic influences can be expected.

The late-Glacial deposits in the Baltic Sea characterized by unconsolidated, clayey sediments deposited during the stages of the Baltic Ice Lake. In the southern part of the area the late-Glacial deposits are, however, influenced by wedge-formed, coastal, sandy sediments with fair geotechnical strengths.

The topmost layer of the entire area consists of post-Glacial sandy and/or muddy sandy deposits, except in areas where the till outcrops at the seabed. The muddy fine sand is characterized by a high water content and a various organic content giving rise to low geotechnical strengths.

In the Kriegers Flak II North OWF the till outcrops at the seabed in large areas to the west while the eastern part is dominated by muddy fine sand. In Kriegers Flak II South the seabed sediment consists of sand and muddy sand.

The geological development of the cable corridor is comparable with the Kriegers Flak II South OWF. The seabed sediments, in general, consist of postglacial, marine sand changing to muddy fine sand to the southeast. The northern part of the cable corridor the till I s outcropping at the seabed. In the coastal area close to the landing point near Rødvig, the Danian limestone outcrops at the seabed.

The report presents a local shore level displacement curve covering the late to post-Glacial period. The post-Glacial palaeogeographical history of the Baltic area is presented in a series of maps to better the understanding of the archaeological interests.

Due to the fluctuating and dynamic shoreline history in the southern Baltic Sea Basin, it is possible to find submerged landscapes and archaeological sites from throughout the Holocene. However, the most likely findings are considered to be of early and mid-Mesolithic age. The possibility to find submerged archaeological sites in the Kriegers Flak area are, however, expected to be small, due to the exposure to a long fetch and high energy environment. Any artifacts most likely have been subject to re-deposition and transportation.

3. Introduction

Energinet has asked GEUS to perform a geological desktop screening study of the planned offshore wind farm areas Kriegers Flak II North and Kriegers Flak II South OWFs and the potential cable corridor connecting the wind farm areas to the town, Rødvig, at the east coast of Zealand (Figure 3.1). The results are to be used as background for evaluating the suitability of the subsurface for wind farm siting and for the cable connections. This report is mainly based on the results from a study compiling all available geological information of the Baltic seabed relevant for the development of offshore windfarms (Jensen & Bennike 2022). The work was compiling information from published reports, scientific publications and archive seismic and sediment core data.

The Kriegers Flak II North OWF area is located c. 20 km off the east coast of Zealand and the Island of Møn and the Kriegers Flak II South is located c. 20 km southeast of the island Møn (Figure 3.1). The potential cable corridor is covering the area west of the Kriegers Flak II OWF's bordered by a straight line from Kriegers Flak II South to Rødvig (Figure 3.1).

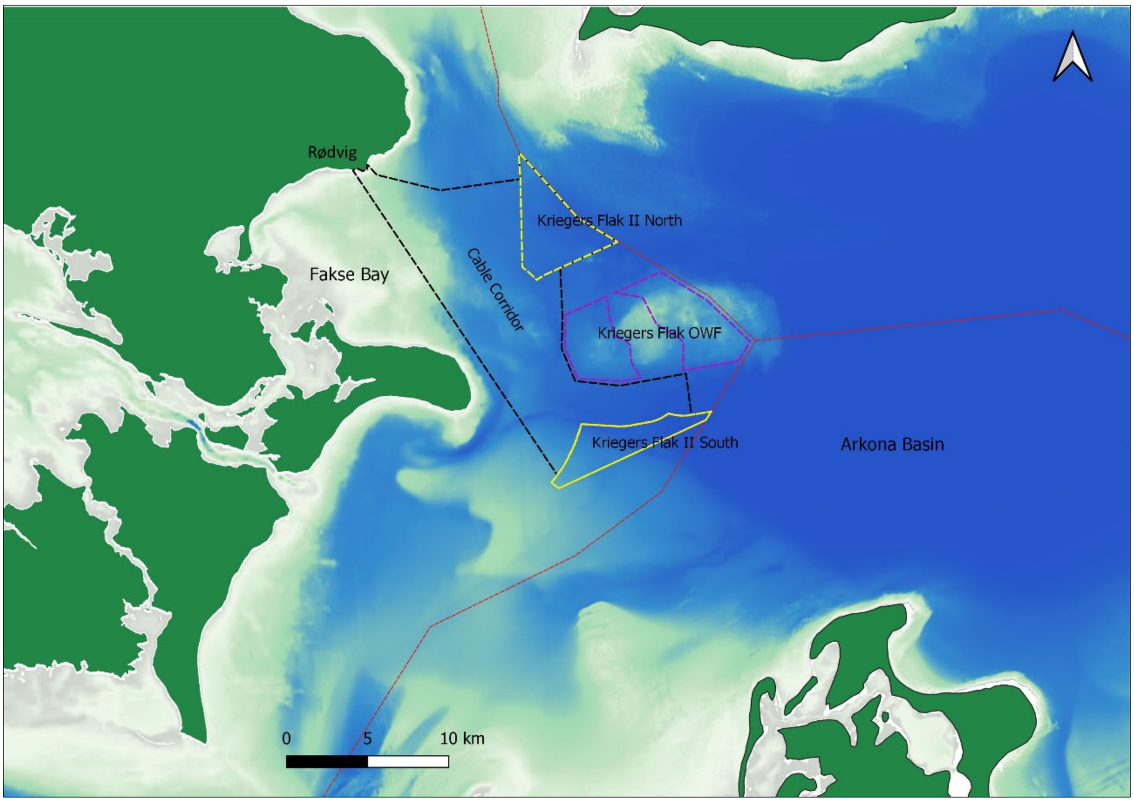


Figure 3.1. Overview map of the southwestern Baltic Sea with location of the existing Kriegers Flak OWF (purple dashes), the cable corridor (black dashes), and the potential wind farm locations Kriegers Flak II North and Kriegers Flak II South (yellow dashes). The EEZ is marked with red dashed lines. The background bathymetry map is from EMODnet Bathymetry (https://www.emodnet-bathymetry.eu).

This report includes a description of the Baltic Sea regional geological development and a conceptual geological model as a background for understanding the geological and geotechnical conditions and archaeological interests in the wind farm areas.

4. Data background

Seismic information and core data together with the screening report compiled for The Danish Energy Agency (Jensen & Bennike 2022) have formed the basis for the present report. Jensen & Bennike (2022) compiled information from published reports, scientific publications, archive seismic data and sediment core data, and combined these with primary data from the GEUS marine raw material database (Marta) (Figure 4.1). In addition, external archive data also were included, such as data collected by Tom Flodén from Stockholm University (airgun and sediment echosounder data) used for general mapping in the Arkona Basin (Lemke, 1998) as well as scientific data collected by The Leibniz Institute for Baltic Sea Research, Warnemünde (IOW) on the R/V Humboldt cruise in 1994 (boomer and airgun data).

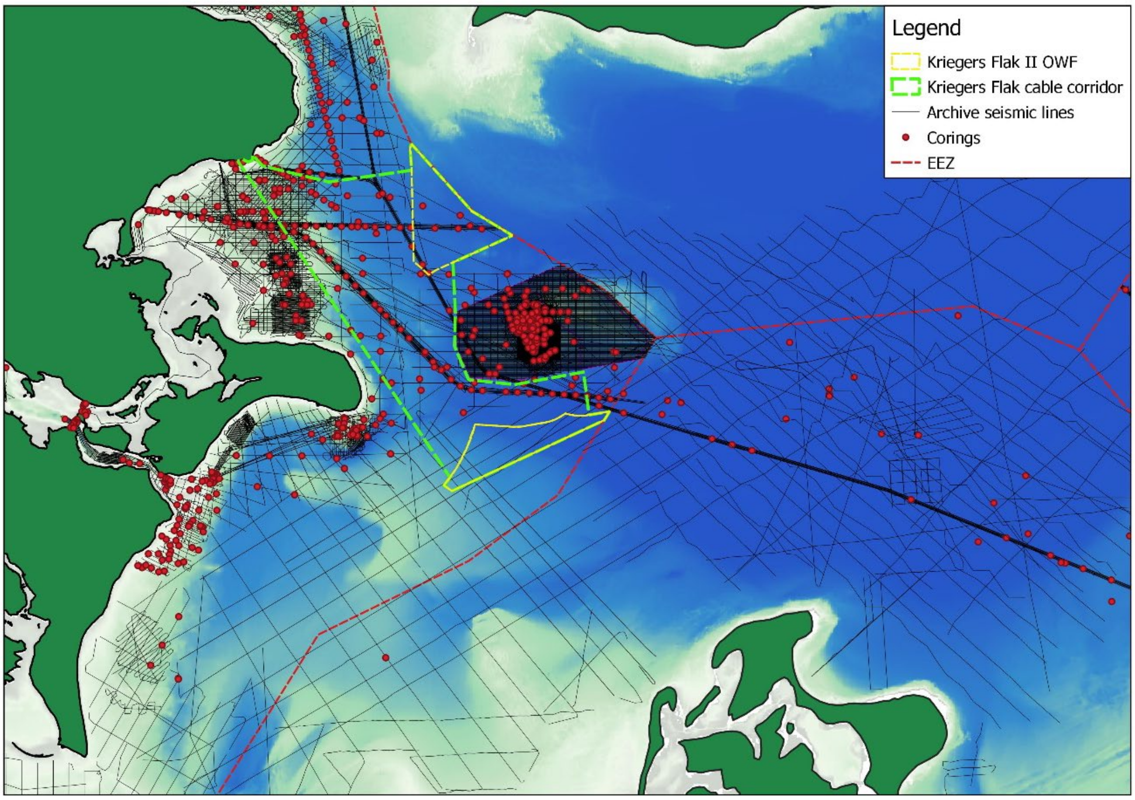


Figure 4.1. Overview of data in the study area and the adjacent area. The Kriegers Flak II North and South are indicated by yellow dashed lines; the cable corridor by light green dashed lines. The EEZ shown by red dashed lines. The background bathymetry map is from Emodnet www.emodnet-bathymetry.eu.

4.1 Background reports

The geological screening report of Kriegers Flak North and South (Jensen & Bennike 2022) builds on a scrutiny of all available geological literature from the Baltic region. By that, it provides an overview of the general geology of the Baltic region and describes the established stratigraphy and the seismic facies units of crucial importance for the Kriegers Flak II area.

Some of the background information that has been emphasized in the screening report is listed here:

Scientific investigations of the Arkona Basin geology (Lemke 1998), providing information on the seismic facies combined with maps of till surface, thickness maps of the Late Glacial clay, and the Holocene.

Scientific investigations describing the seabed geology of the southern margin of the Arkona Basin including the proposed Kriegers Flak II South OWF location (Jensen 1993; Jensen et al. 1997; Jensen et al. 1999).

Essential, detailed information originates from The Baltic Pipe offshore pipeline transect reported by Rambøll (2020). The Baltic Pipe transect crosses the proposed Kriegers Flak II North OWF and the studies provide vital information from the seismic transects and vibrocores.

Reports related to the existing Kriegers Flak OWF include results from the seismic and the geotechnical investigations (Rambøll 2013 and Geo 2013).

Information from marine aggregate mapping of the Faxe Bay (Lomholt et al. 2016) has provided information on the northern part of cable corridor.

4.2 GEUS archive shallow seismic data and sediment cores

The Marta database (Marta) includes available offshore shallow seismic data and core data in digital and analogue format (Figure 4.1). Most of the seismic lines can be downloaded as SGY files from this web portal.

As seen on Figure 4.1 the Marta database contains only sparse information from the proposed Kriegers Flak II North and South OWF areas. In the cable corridor area, the seismic lines in Figure 4.1 represents legacy analogue data except for the Baltic Pipe data and data in the Faxe Bay area (Lomholt et al. 2016).

However, the existing seismic lines collected by the Baltic Pipe project (not in Marta) provides information within, and close to, the potential wind farm areas (Rambøll 2013 and Geo 2013). The acquired data include side scan sonar, sediment echosounder, boomer data and vibrocore data.

The cores shown in Figure 4.1 are all vibrocores of max. 6 m length. Many of these were collected in relation to the Baltic Pipe project and the R/V Humboldt cruise in 1994. Core descriptions are, in general, available from the Marta database. No samples have been preserved.

5. Geological setting

The geological framework presented in the following chapter is applicable for the Baltic Sea in general and the Kriegers Flak II OWF's and the cable route areas specifically.

5.1 The general pre-Quaternary framework

Detailed descriptions of the pre-Quaternary geology of the Bornholm and Arkona Basin region have been presented in geological desk studies offshore Bornholm GEUS (2021a) and Arkona Basin cable transects GEUS (2021b).

The southwestern Baltic Sea is crossed by the 30-50 km wide WNW-ESE-trending Sorgenfrei–Tornquist Zone separating the Baltic Shield, the Skagerrak-Kattegat Platform, and the East European Precambrian Platform in the northeast from the Danish Basin in the southwest (Figure 5.1). The Sorgenfrei–Tornquist Zone has been active during several phases after the Precambrian. The lineament is characterised by complex extensional and strike-slip faulting and structural inversion (Figure 5.2) (Liboriussen et al. 1987; Mogensen & Korstgård 2003; Erlström et al. 1997). The old crustal weakness zone was repeatedly reactivated during Triassic, Jurassic and Early Cretaceous times with dextral trans-tensional movements along the major boundary faults.

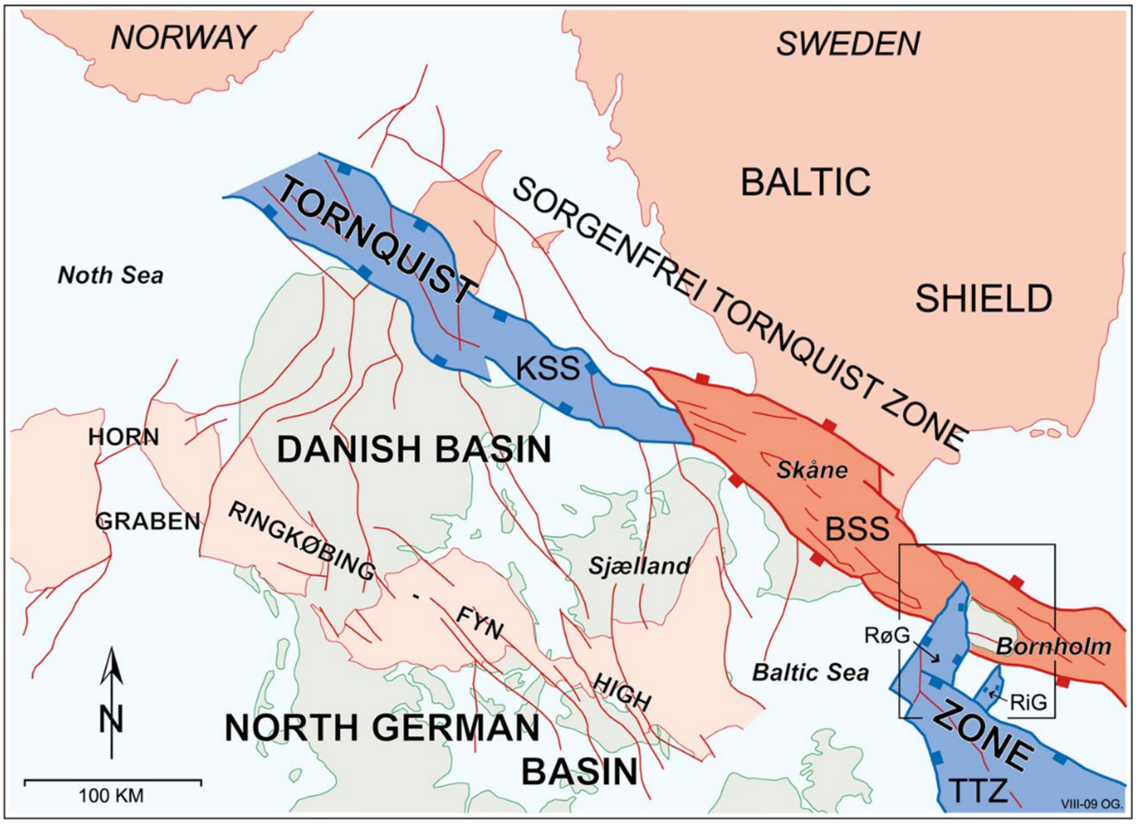


Figure 5.1 Map showing the southwestern Baltic Sea and surrounding tectonic elements.

Description of the bedrock geology of the entire Danish area was published by Petersen (1992). Figure 5.2 shows the bedrock in the Kriegers Flak area dominated by Upper and Lower Cretaceous sediments.

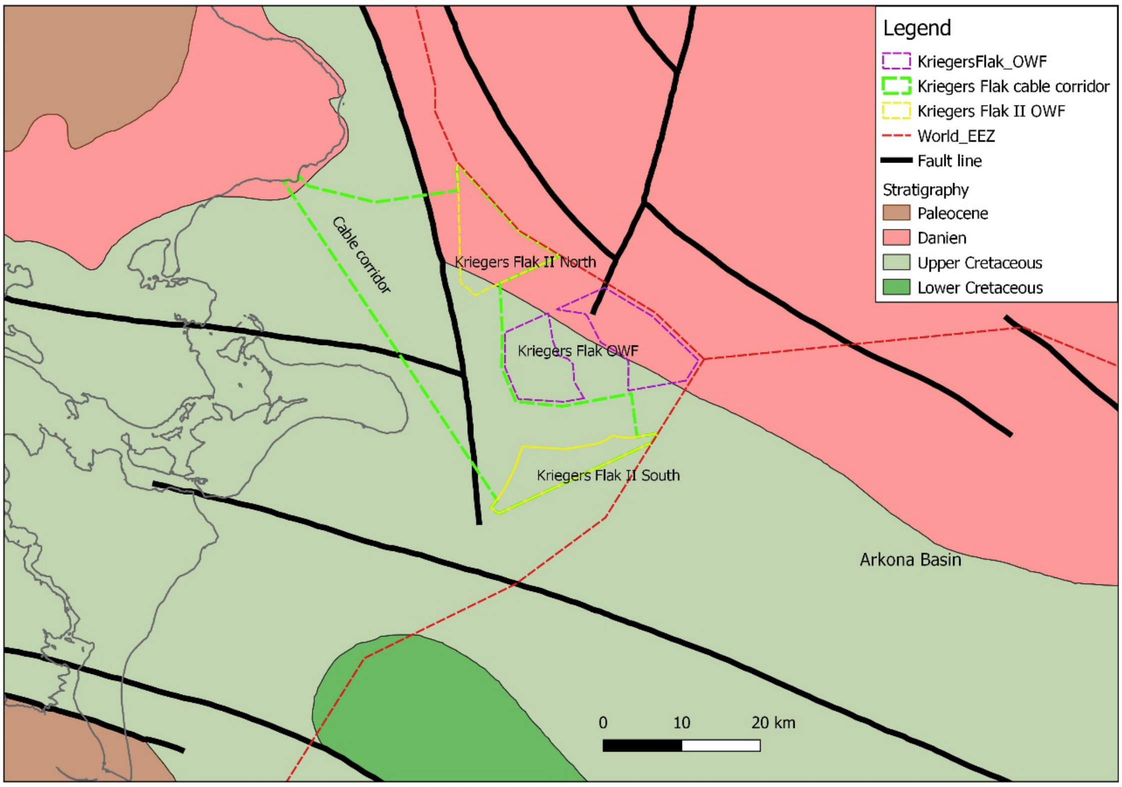


Figure 5.2. Bedrock geology in the Kriegers Flak area. From Pedersen (1992), with location of the existing Kriegers Flak OWF (purple dashed lines), and the potential wind farm locations Kriegers Flak II North and Kriegers Flak II South (yellow dashed lines). The red dashed lines show the EEZ.

5.2 The pre-Quaternary surface

A map of the pre-Quaternary surface topography in the Danish area was published by Binzer & Stockmarr (1994) (Figure 5.3). Unfortunately, the Kriegers Flak II South and North areas are not included in this map. However, it is expected that the northern part of the Arkona Basin follows the pattern to the east and west due to the increasing Quaternary sediment thickness observed in the southern part of the Arkona Basin (Lemke 1998). This anticipation is supported by Anjar et al. (2010) who has studied the borings at the existing Kriegers Flak OWF. The depth to the top of the pre-Quaternary varies between 40 and 55 m b.s.l. (Figure 5.4).

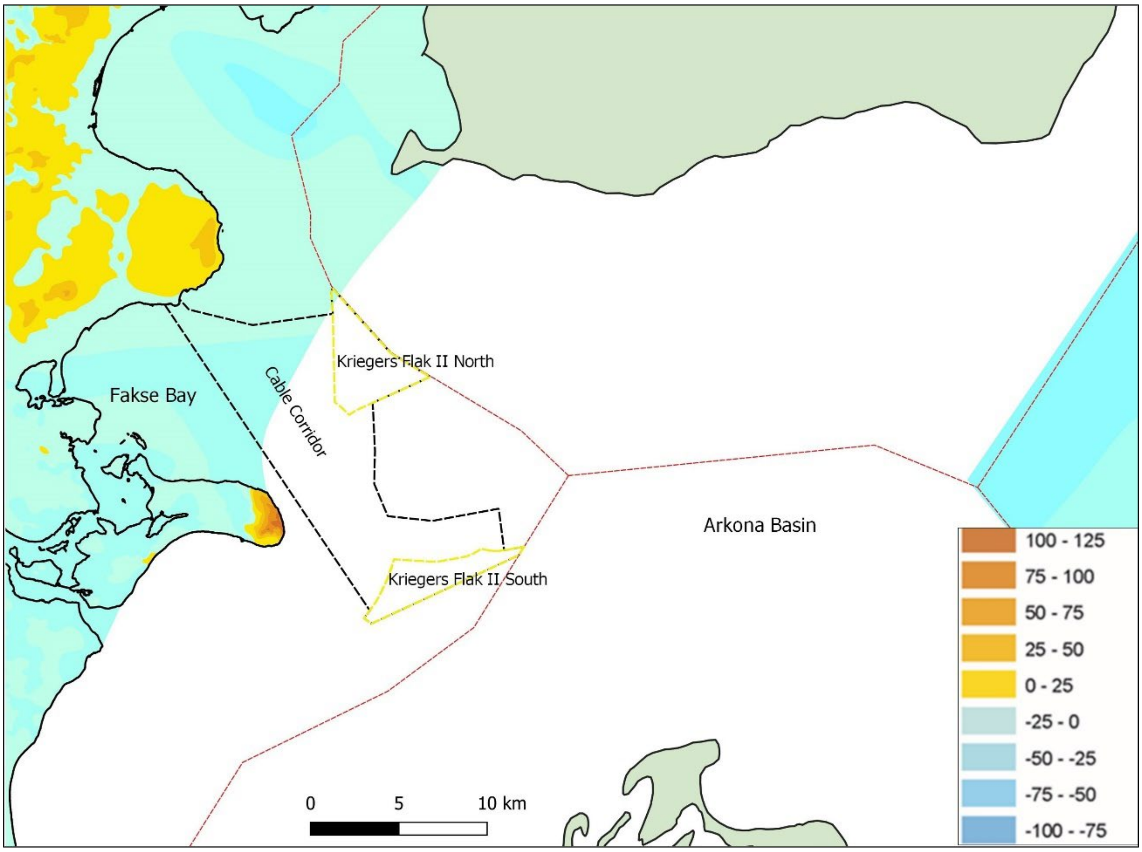


Figure 5.3 Pre-Quaternary surface topography in metres above sea level (Binzer & Stockmarr 1994). Location of Kriegers Flak II North and Kriegers Flak II South and the cable corridor is shown with dashed lines. The red dashed lines show the EEZ.

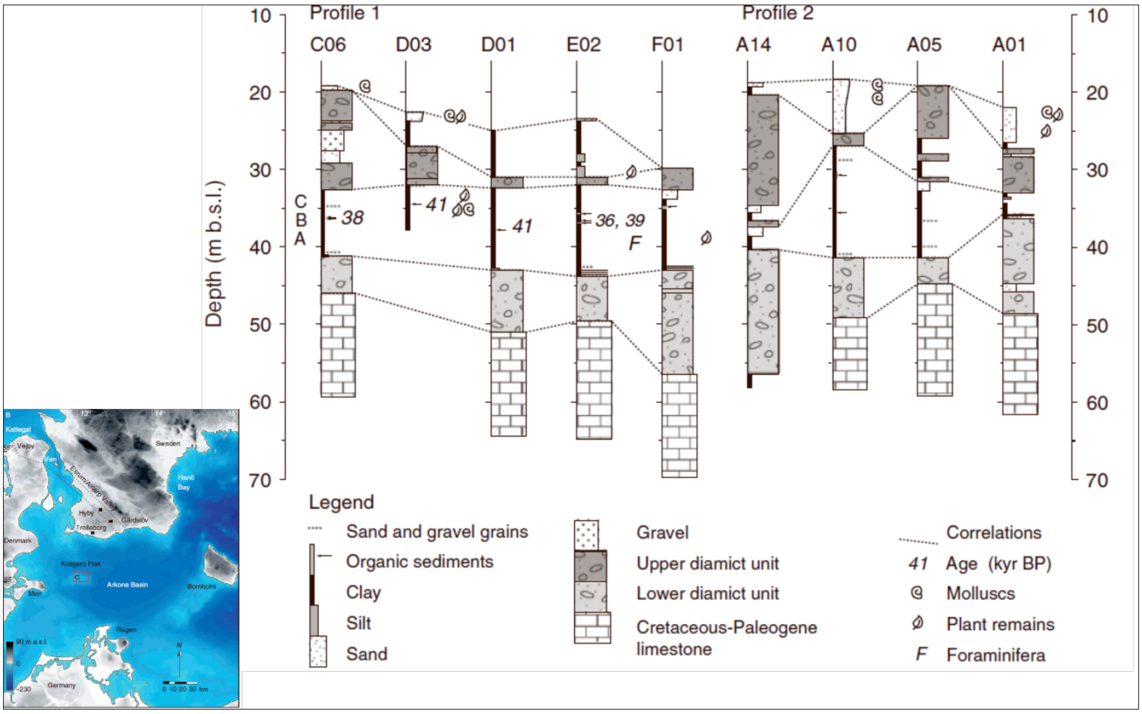


Figure 5.4. Cross-section of the deep cores at Kriegers Flak OWF showing the top of the Pre-Quaternary varying between c. 40 and 55 m b.s.l. From Anjar et al. (2010).

The Baltic Pipe investigations (Rambøll 2020) close to the Kriegers Flak II North OWF also show a thin Quaternary top unit of a few metres above Danien limestone while Kriegers Flak II South OWF show 10 – 30 m Quaternary glacial (till) and Late Glacial sand-clay above Upper Cretaceous chalk.

The seabed sediment map (Figure 7.1) shows large areas with outcropping pre-Quaternary, Danien limestone in the nearshore, northern Faxe Bay area, and in the nearshore area where the cable corridor meets Zealand.

5.3 Glacial deposits and deglaciation

Four glacial events dating from Late Saalian to Late Weichselian, have been identified in the southwestern Baltic region, each separated by periods of interglacial or interstadial marine or glaciolacustrine conditions. The thickness of Quaternary sediments in the region can exceed 100 m in the Arkona Basin (Jensen et al. 2017).

The Scandinavian Ice Sheet reached its maximum extent in Denmark about 22 ka BP followed by a stepwise retreat. The Bornholm region was deglaciated shortly after 15 ka BP. Moraine ridges on Rønne Banke and Adler Grund trending parallel to the former ice margin mark short-lived re-advances during the general retreat of the ice. An interpretation of the general deglaciation pattern is presented in Lange (1984) (figure 5.5).

Figure 5.5 Ice margins and re-advance stages model from Lange (1984).

After the deglaciation, a glaciolacustrine environment with icebergs, the Baltic Ice Lake, was established (Figure 5.6).

Due to well-preserved Quaternary deposits in the Faxe Bay, and in the Arkona- and Bornholm Basins the development of the Late Glacial and Holocene Baltic Sea phases has been intensively studied by Jensen et al. (1997, 1999). The deposits of the Baltic Ice Lake (clay), the Yoldia Sea (clay) and Ancylus Lake (clay), as well as the brackish to marine Littorina Sea (clay and mud) have been described in detail. The Holocene history was also documented by Andrén et al. (2000).

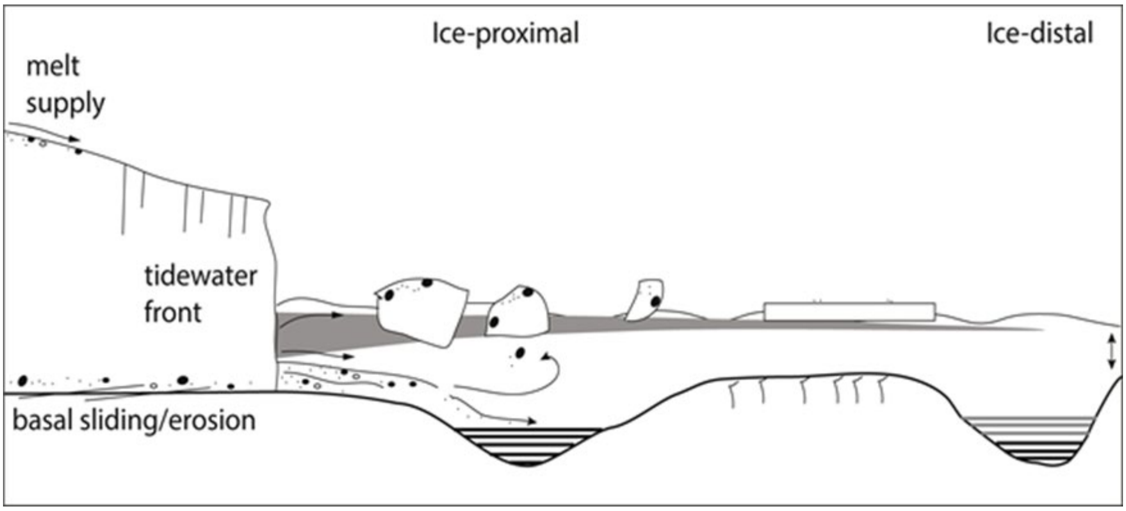


Figure 5.6 Illustration of a glaciolacustrine depositional environment – an analog to The Baltic Ice Lake.

5.4 The Late Glacial and Holocene shore level

The shore level changes after the last deglaciation are different for the two Kriegers Flak II windfarm areas and the cable corridor. In the Kriegers Flak II South area it roughly follows the development of the southwestern Baltic Sea and the Bornholm/Rønne Banke region, while in the Kriegers Flak II North and the cable corridor areas the shore level changes are considered to follow an intermediate development between the northeastern Baltic Sea/Køge Bugt region and the Bornholm/Rønne Banke region.

The main difference between the two regions is that the shore level curve shows a displacement of 6-7 m (Figure 5.7a, b) caused by the higher glacio-isostatic uplift in the Køge Bugt region. Around 6.0 ka BP when the global eustatic sea level rise had surpassed the glacio-isostatic uplift of the region, fossil shorelines and landscapes were submerged. Since then, the sea level has risen only a few metres and the two regions had a similar development.

The shore level in the Bornholm/Rønne Banke region was characterised by highly fluctuating water levels (Figure 5.7a) after the last deglaciation. Transgressions were interrupted by two abrupt forced regressions, the first at c. 12.8 ka BP and the second at c. 11.7 ka BP. Prior to these regressions, the Baltic Ice Lake was dammed by glacier ice in south-central Sweden. In the Rønne Banke region and by that Kriegers Flak II South OWF, the shore level reached a maximum around 20 m b.s.l. during the Baltic Ice Lake stages (Figure 5.7a). After the retreat of the Scandinavian Ice Sheet, the dam was broken twice, and the water level dropped by 20-25 m over a few years.

In the Early Holocene, during the Yoldia Sea Stage (Figure 5.7a), the water level reached a minimum at around 40-45 m b.s.l. From around 10.8 to 10.2 ka BP the water level rose rapidly followed by a short period with relatively stable water level around 9.0 ka BP. Soon the water level continued to rise, and at c. 7.0 ka BP marine waters inundated the region, which mark the beginning of the Littorina Sea Stage.

The deeper part of the Arkona Basin has been continuously submerged after the last deglaciation, but due to the shore level fluctuations, coastal barrier deposits developed in the shallow water areas in the Kriegers Flak II South OWF (Figure 5.6a).

As mentioned, the shore level changes in the Kriegers Flak II North OWF area and the northern part of the cable corridor must be considered as intermediate. Figure 5.7a, b illustrates the different shore level development for the two regions.

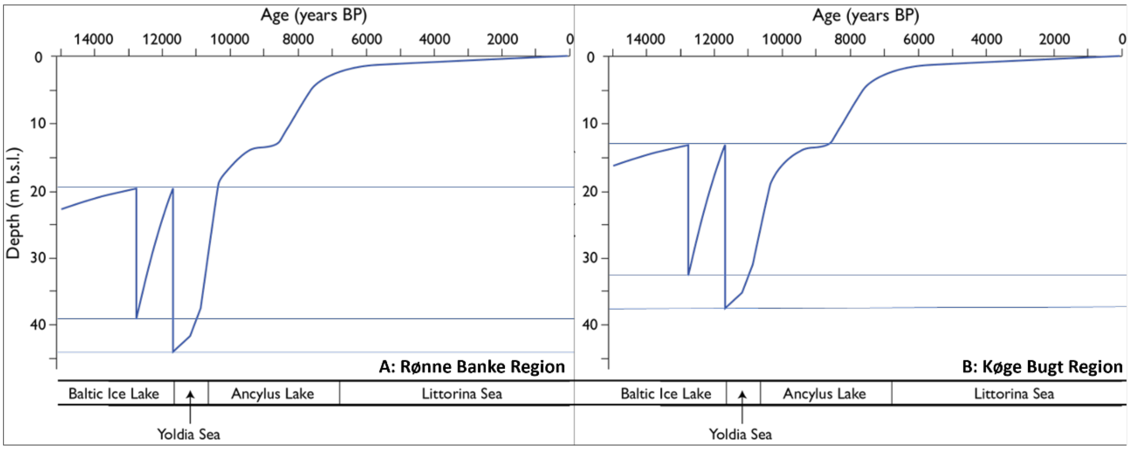


Figure 5.7. A: Shoreline displacement curve for the Rønne Banke region south-west of Bornholm. B: Shoreline displacement curve for the Køge Bugt region. Both curves are based on radiocarbon dating of samples collected from vibrocores. Modified from Jensen & Bennike (2022).

5.5 Baltic Sea palaeogeography

The general deglaciation and Postglacial history of the western Baltic Sea and its relation to the southwestern Kattegat is illustrated in palaeogeographical maps (Figure 5.8 a, b).

About 18.0 ka BP, the deglaciation from the largest glacier extension (Main Stationary Line) in Jutland reached a stage where the ice margin roughly followed the Swedish west coast, the present Zealand northern coastline, extending southward along the western part of the Great Belt and with the distal margin found in the northernmost part of Germany. In this early phase, the deglaciated Kattegat region still was not isostatically adjusted and the relative sea-level was high with sea covering major parts of northern Jutland (Figure 5.8a).

At the next stage, about 16.0 ka BP, the ice margin has retreated to the Øresund region and the western part of Skåne, leaving an ice lobe covering the southern part of Zealand and following the present southern coastline of the Baltic Sea. The ice margin was directly connected to the Kattegat marine basin by a broad meltwater channel, which at this stage was affected by an initial relative sea-level regression. At the same time, local lakes developed along the ice margin, e.g., in the Køge Bugt (Figure 5.8a).

A controversial stage of the deglaciation was reached about 15.0 ka BP, when the ice margin retreat had reached central Skåne. This stage is poorly documented in the present offshore area. However, investigations in Polish waters combined with data from German and Danish waters conclude that the ice margin has been situated west of Bornholm and a large lake - the initial Baltic Ice Lake - started to be dammed in front of the ice sheet. The connection through the Great Belt to the Kattegat became increasingly affected by a regression. Apart from the meltwater streams from the glacier area west of Bornholm, major meltwater discharges were provided by German and Polish rivers. This has been proved by the presence of major Late Glacial delta and beach barrier deposits in Faxe Bay and close to the Kriegers Flak II South OWF (Figure 5.8a).

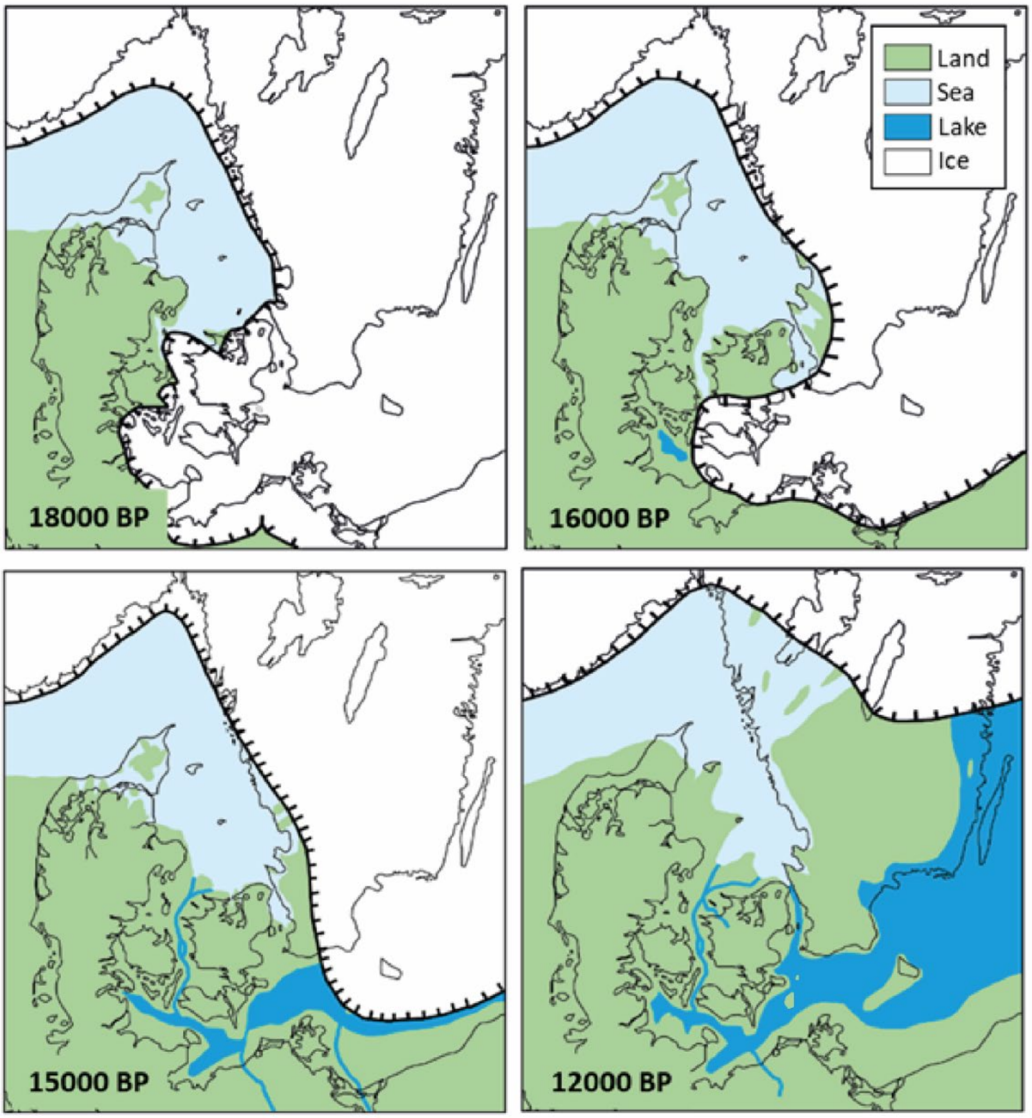


Figure 5.8a. Palaeogeographic maps showing the development of the Danish area from c. 18.0 to c. 12.0 ka BP. Modified from Jensen et al. (2003).

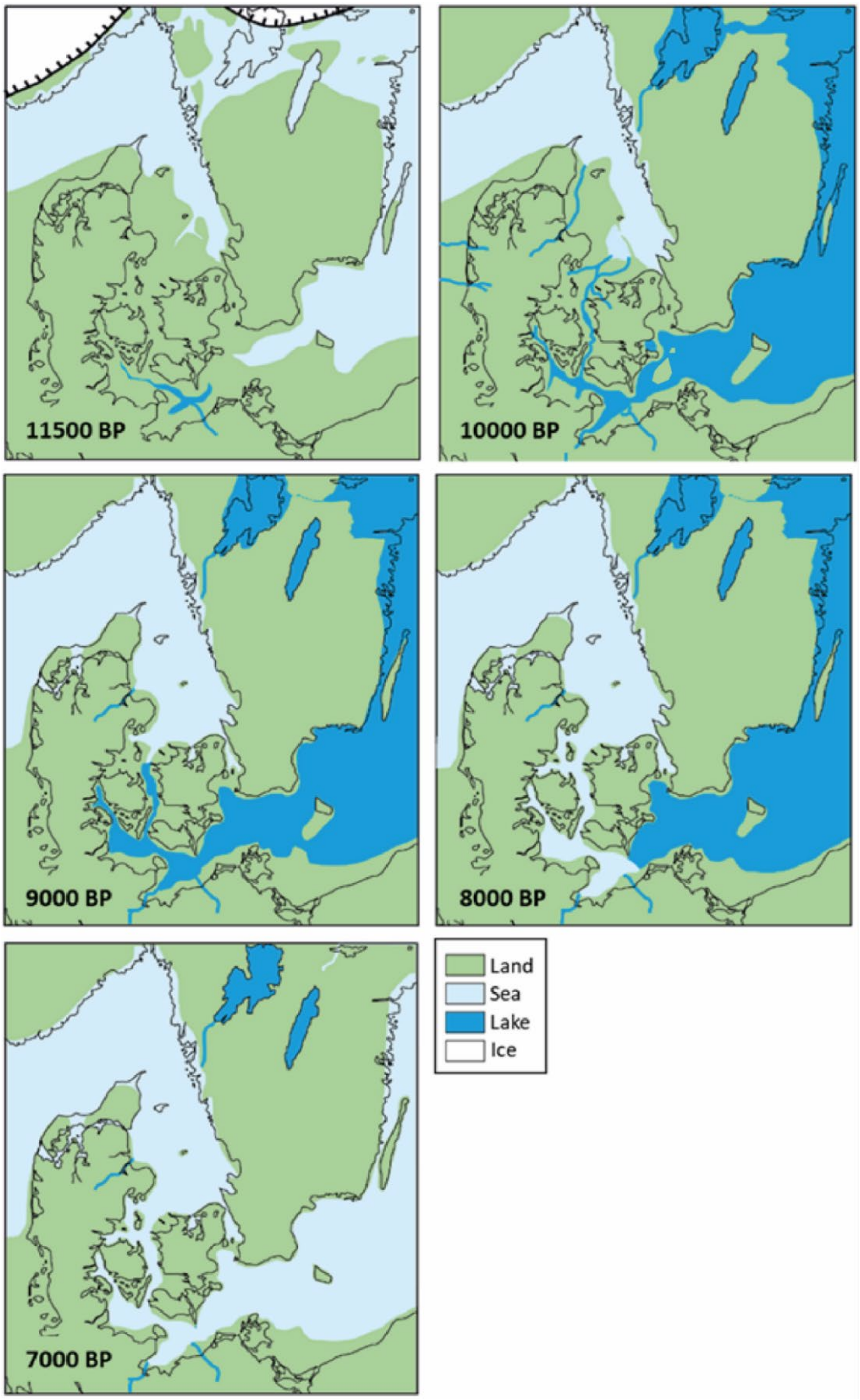


Figure 5.8b. Palaeogeographic maps showing the development of the Danish area from c. 11.5 ka BP to c. 7.0 KA BP. Modified from Jensen et al. (2003).

The initial damming of The Baltic Ice Lake was followed by a regression, before the second and most extensive Baltic Ice Lake damming occurred having its maximum of about 12.0 ka BP. At that time minor channels drained the lake through the Great Belt and Øresund and only a small land bridge in south-central Sweden separated the Baltic Ice Lake from the sea. Under this damming, reactivation and substantial beach barrier deposition continued in Faxe Bay and in the area close to Kriegers Flak II South OWF. Further retreat of the ice front resulted in a catastrophic discharge event in south-central Sweden with the lake water level dropping about 25 m (Figure 5.8a).

About 11.5 ka BP, a strait was established through south-central Sweden, and the Baltic basin was transformed into a marine or brackish basin named the Yoldia Sea. The Postglacial eustatic sea-level rise surpassed the rate of glacio-isostatic rebound in the southern Kattegat and the lowest Postglacial relative sea-level was reached about 35 m b.s.l.

Continuous glacio-isostatic uplift of south-central Sweden closed the connection to the ocean and the last Postglacial Lake phase of the Baltic, called the Ancylus Lake, was established. Due to damming, the lake reached a maximum water level about 10.2 ka BP with only a narrow drainage pathway through the Great Belt into the southern Kattegat (Figure 5.8b).

About 10.0 ka BP, the Ancylus Lake water level dropped about 9 m during a few hundred years. Several studies e.g., in the southern Kattegat, the Great Belt and at the thresholds Gedser Reef – Darss Sill, and in the southwestern Kattegat, however, show evidence of only a few metres drop of the lake level. At the same time deposits from lakes and estuaries have been found in the Great Belt and southwestern Kattegat (Figure 5.8b).

Fully marine environment was reached in the Great Belt 9.1 ka BP marking the beginning of the Littorina transgression. About 8.0 ka BP the transgression reached the Darss Sill – Gedser Reef area leading to fully marine conditions in the western Baltic about 7.0 ka BP (Figure 5.8b).

5.6 Faxe Bay palaeogeography

Even though the Faxe Bay is part of the general Late Glacial and Postglacial development of the Baltic Sea it is of great importance to focus on the palaeogeographical development of the Faxe Bay (Jensen 1992) specifically to understand the seabed geology of the northern part of the cable corridor (Figure 5.3).

Detailed studies of Faxe Bay have been performed in relation to scientific studies by Jensen (1992). The palaeogeographical model presented in Figure 5.9 show the development of the outer part of the bay from the late stages of the Glacial period to the coastal development during the Holocene transgression.

The three interpreted seismic profiles crossing the northern part of the cable corridor that are presented in Chapter 8.3 provide information on the factual seabed geology.

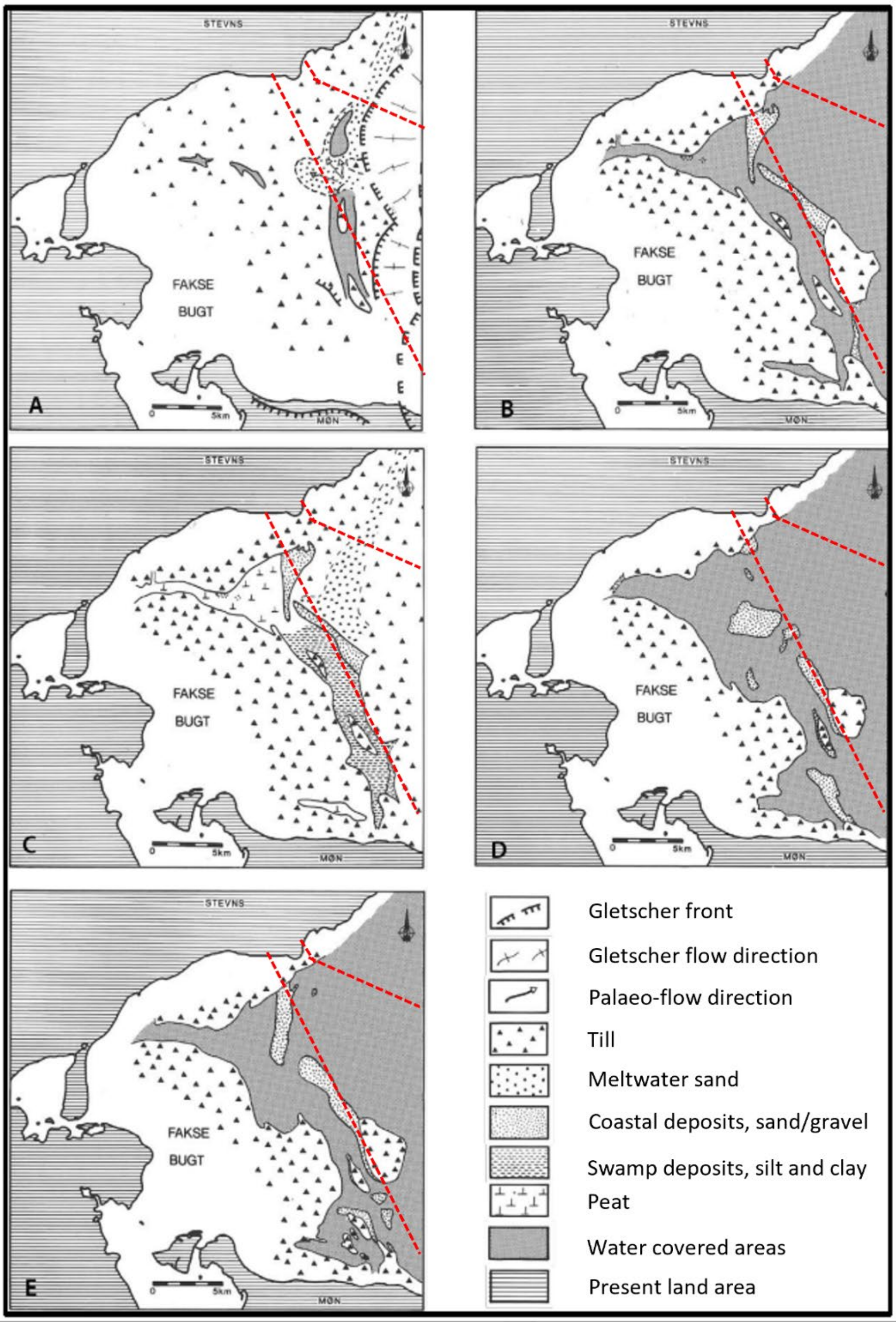


Figure 5.9. Palaeogeographical maps showing the development in Faxe Bay. A: Meltwater deposits in front of the melting glacier; B: Baltic Ice Lake barrier/lagoon system; C: The Continental Period (Fastlandstiden) with swamps in the Faxe Bay; D: Early Holocene marine, coastal deposits; E: Late Holocene marine, coastal deposits. From Jensen (1992). The cable corridor is marked with red hatched lines.

6. Seismostratigraphic and lithological units

A conceptual geological model for the Bornholm Basin was established by Jensen et al. (2017) based on the combination of seismic data and core data. The Arkona Basin stratigraphy is presented in Moros et al. (2002) and Mathys et al. (2005). Results from these and other studies show that the model from the Bornholm Basin is valid for the whole region. Hence the geological model can be used as a valid basis for the Kriegers Flak II area.

Five seismic units were identified (Figure 6.1), separated by unconformities. In the following chapters the Glacial to Holocene units are described based on information from the Bornholm Basin and the Arkona Basin.

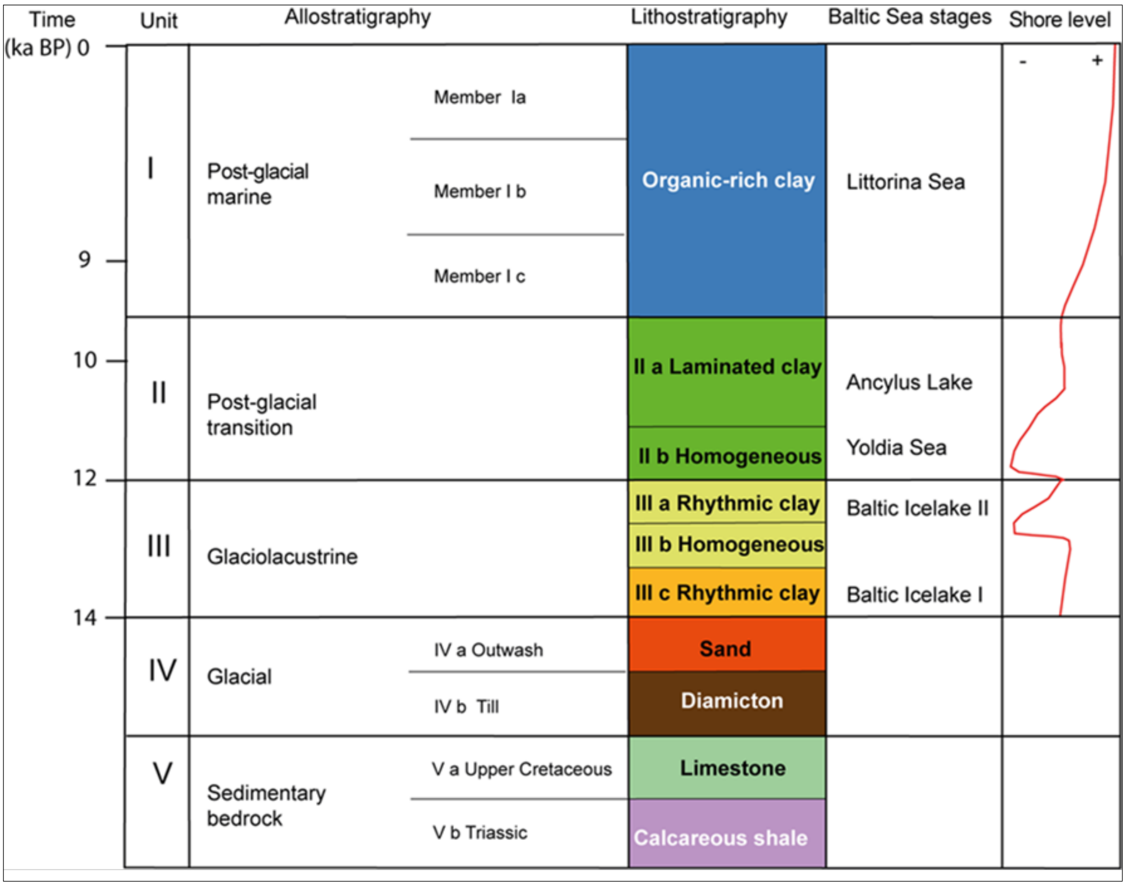


Figure 6.1. Stratigraphical subdivision of the Bornholm Basin (Jensen et al. 2017). The seismic Units I–V are all bounded by unconformities. The shore level curve to the right is the general for the Baltic Sea.

6.1 Unit IV Glacial deposits

The glacial deposits drape the irregular surface of the pre-Quaternary (Unit V). The upper reflector is an irregular unconformity, and the internal seismic configuration is mostly chaotic. The glacial deposits (Unit IV) consist of diamicton and glacial outwash sediments, as documented in the IODP 347 core site M0065 (Andrén 2014, 2015). In general, the distribution of glacial sediment facies is chaotic with alternating sections of clast-rich muddy diamicton and parallel-bedded, medium grained sand with laminated silt and clay interbeds.

6.2 Unit III Late Glacial glaciolacustrine deposits

The depositional environment of the Late Glacial deposits (Unit III) is interpreted as a glacio-lacustrine environment based on studies of diatoms and ostracods. The glacio-lacustrine sediments cover the glacial deposits via an irregular unconformity. In the Bornholm Basin area, a strong upper reflector marks the top of the glaciolacustrine deposits, which, in general, drape the underlying topography with a thickness of 10–20 m. A maximum thickness of more than 50 m is seen in the IODP 347 core M0065 (Andrén 2014, 2015).

Unit III is divided into three subunits:

- IIIc, the lowest unit, corresponds to Baltic Ice Lake sediments deposited in front of the retreating Weichselian glacier and represents an early stable phase of the glaciolacustrine environment. Characterized by very well sorted, greyish brown clay with weak lamination by colour and few silt laminae in mm scale. Large intervals are dominated by massive to contorted appearance. The parallel reflectors and rhythmically layered clay are interpreted as varved glaciolacustrine clay. The fining-upward from silty clay to clay and the decreasing frequency of sand laminations indicate a more and more distal ice front to the basin.

- IIIb, the middle unit, consists of dark grey, homogenous clay. It is a basin-wide intermediate zone consisting of homogeneous clay related to the first Baltic Ice Lake drainage occurring c.12.8 ka BP. This drainage led to a 10 m drop in water level and to the formation of unconformities in the shallow parts of the southwestern Baltic Sea (Jensen et al. 1997; Bennike & Jensen 1998, 2013; Uscinowicz 2006).

- IIIa, the upper unit, consists of greyish brown, silty clay with parallel lamination, coarsening downward to fine-medium grained sand with laminated silt. The lowermost few metres are massive, medium-grained sand layers with few dispersed pebbles and detrital carbonate in all grain sizes up to fine gravel. The indistinct lamination combined with homogeneous, contorted sedimentary structures and clay intraclasts may indicate slumping in an unstable sloping environment with high sedimentation rates.

6.3 Unit II Early Holocene Ancylus and Yoldia

The Early Holocene (Unit II) conformably drapes the glacio-lacustrine sediments in the Bornholm Basin with a rather constant thickness of about 4 m. The seismic characteristic is closely spaced parallel reflectors with upward decreasing amplitude. The upper boundary is a strong reflector. The basin-wide clay drape indicates an accumulation in a deep-water basin with weak bottom currents.

Unit II is sub-divided into two parts: Unit IIb, the lower part, consists of homogeneous, brown clay to greyish clay, gradually changing to grey clay with intervals of black spots and specks upwards; Unit IIa, the upper part, consists of colour-laminated, very fine, dark grey iron sulphide-rich with 2-3 mm thick laminae.

The lower part (IIb) is interpreted to represent Yoldia Sea deposition, and the upper part (IIa) the Ancylus Lake clay deposition.

6.4 Unit I Mid- and Late Holocene marine mud

The IODP 347 core M0065 in the Bornholm Basin describe the Holocene sediments (Unit I) of the Baltic Sea well. The unit is c. 7 m thick and described as well-sorted, dark greenish grey, organic-rich clay with indistinct colour lamination due to moderate bioturbation. The general stratification is overprinted by intervals of black layers with sharp bases.

The boundary from Unit II to Unit I is gradual. The organic-rich clay with bioturbated indistinct lamination and intervals of black layers, indicates oxic conditions during the Mid- and Late Holocene in the Bornholm Basin. The lowermost laminated transition zone may represent an initial anoxic phase.

6.5 Late Glacial and Holocene coastal deposits

Contrary to the Bornholm Basin and the Arkona Basin the western margin of the Baltic Sea shows evidence of coastal developments during the highstands of the Baltic Ice Lake and during the transgression of the Littorina Sea. The evidence presented here is from the Faxe Bay (Jensen & Nielsen, 1998) and the Kriegers Flak OWF area (Jensen 2013, 2019). The Faxe Bay is located at the east coast of Zealand, facing the western margin of the Baltic Sea close to the Kriegers Flak II North OWF and especially the cable corridor (Figure 3.1). The Kriegers Flak OWF area is located close to both proposed Kriegers Flak II wind farm areas and studies of the geological development of this area, is, therefore, relevant for the understanding of the potential new windfarm areas.

During the Baltic Ice Lake highstands moraine landscapes along the Faxe Bay were exposed to erosion. Clay and silt were transported into deeper waters, whereas sand, fine gravel and coarse gravel primarily contributed to the formation of beach deposits. In the following time a coastal barrier system developed in the Faxe Bay area, resulting in the damming of a lagoon (Figure 6.2). After a falling water level during the Yoldia Sea period (11.2-10.6 ka BP), parts of the lagoon became dry land.

As the Baltic Ice Lake reached its highest water level at about 11.5 ka BP, the coastline of Faxe Bay was found at a level about 13 metre lower than today. Later, the Ancylus Lake was formed in the Baltic Basin lasting from 10.6-8.4 ka BP, which coincides with the ‘Continental Period’, with a low sea level (Figure 5.7). The following global sea level rise resulted in a renewed inflow of marine waters into the Baltic basin through the Danish Belt Sea forming the Littorina Sea. The deposits of the Faxe Bay show evidence of the Holocene transgression of the Littorina Sea.

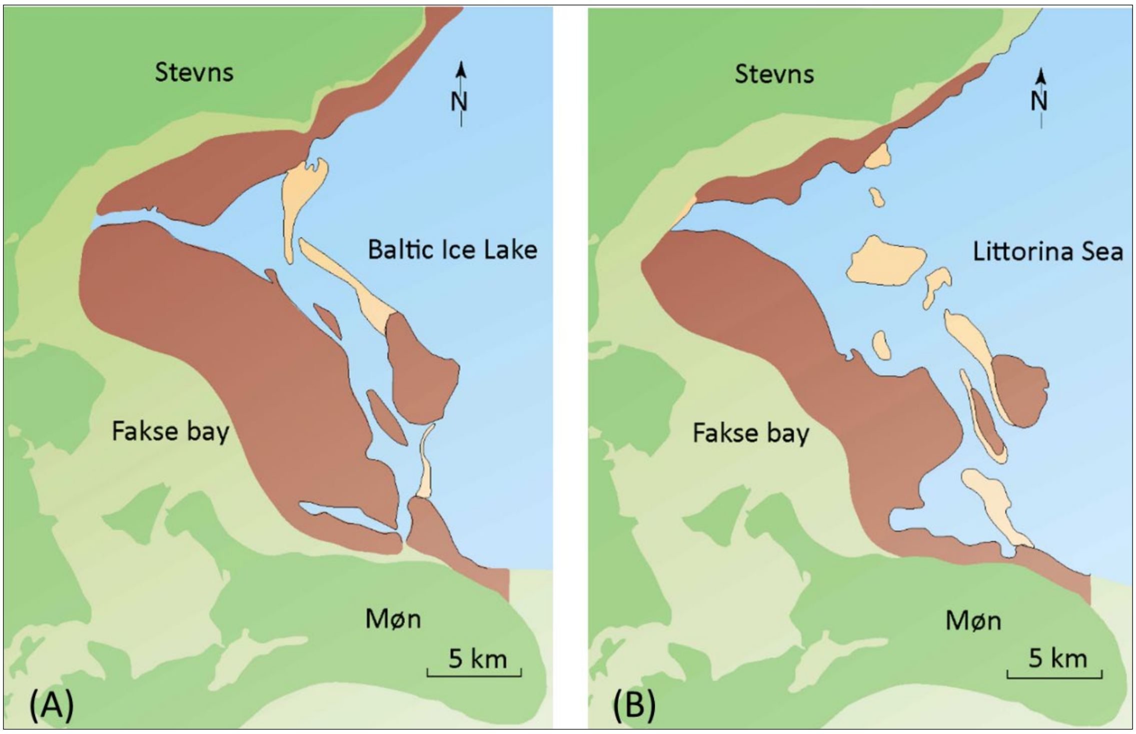


Figure 6.2 Palaeogeographic maps which shows (A) the barrier island and lagoon system during the high-stand of the Baltic Ice Lake and (B) the spit system formed when the sea level of the Littorina Sea was approximately 10 m lower than today. From Jensen & Nielsen (1998).

The Faxe Bay fossil barrier lagoon system is visible in the seabed sediment map (Figure 7.2) in the western and central part of the bay. The Kriegers Flak II North OWF area is in an intermediate till zone, exposed to erosion or bypassing of clay and silt, that was transported into the deeper Arkona Basin and deposited as the Baltic Ice Lake clay.

The Kriegers Flak OWF area has been subject to a coastal development comparable to the Faxe Bay. During the Baltic Ice Lake highstands the Kriegers Flak glacial landscapes was exposed to erosion and sand, fine gravel and coarse gravel contributed to the formation of beach deposits.

As the Baltic Ice Lake reached its highest water level at about 11.5 ka BP, the coastline of Faxe Bay was found at a level about 13 metre lower than today. A renewed period with coastal environment took place during the Holocene transgression of the Littorina Sea depositing coastal, sandy sediments at Kriegers Flak.

A geological model for Kriegers Flak OWF was compiled by Jensen (2013, 2019) describing the progradation of coastal and spit platform deposits, one during the transgressive Baltic Ice Lake and two related to the Littorina transgressions (Figure 6.3). Due to a fetch of more than 100 km to the east, the coastal erosion mainly took place on the east coast of Kriegers Flak followed by coastal progradation on the leeside to the west and southwest. A sub-recent sand cover was deposited subsequently on top of the coastal deposits.

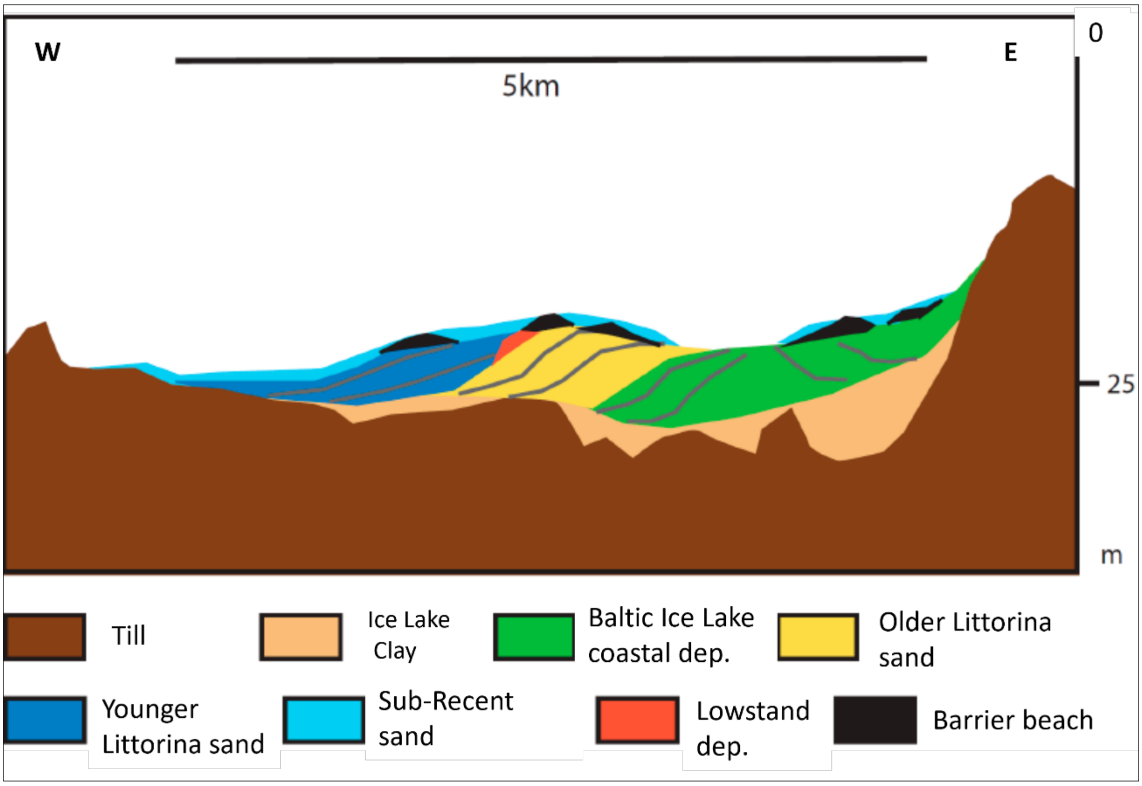


Figure 6.3. A simplified geological model of the Kriegers Flak OWF showing the different stages of coastal, sandy progradation. From Jensen 2019.

6.6 The Arkona Basin development

The Late Glacial and Holocene development of the western Baltic Sea region has been studied by Lemke (1998) based on an open grid of airgun data, sediment echosounder data and 6 m vibrocores. Maps of surface topography and isopach maps from this study provide useful information for the evaluation of the seabed conditions of the nearby Kriegers Flak II OWFs and the cable corridor (figures 6.4 to 6.7).

The stratigraphical sub-division of the Arkona Basin shows the same units as the Bornholm Basin (figure 6.1). Furthermore, the sediments representing the Late Glacial Baltic Ice Lake and the younger sediments have similar characteristics.

The till surface topography map (Figure 6.4) shows a maximum depth to the till surface of 75 m below the present sea-level in the central part of the basin, decreasing to a depth between 40 and 50 m b.s.l. in the Kriegers Flak II South OWF area.

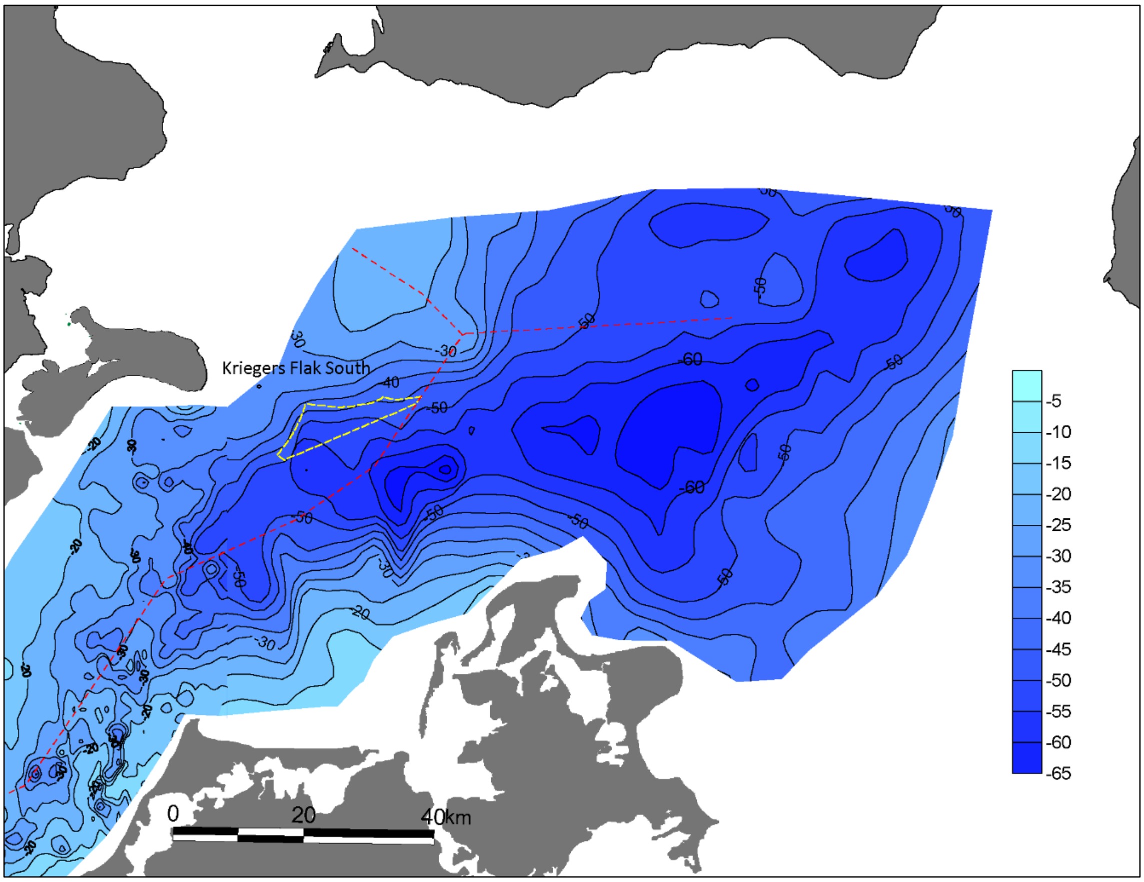


Figure 6.4 Till surface topography mapped by Lemke (1998). Location of Kriegers Flak II South is shown with yellow dashed lines. The red dashed lines show the EEZ.

The till surface is covered by Late Glacial and Holocene clays and mud in the central parts of the Arkona Basin, changing to proximal sandy coastal deposits in the western margin of the basin near Kriegers Flak II South OWF.

The thickness of the Late Glacial clays in the Arkona Basin (Figure 6.5) is up to 12 m in the central and northeastern-most areas, decreasing in the northern area from 10m in the east to 0m in the west, with an average of about 4 m.

Unfortunately, the thickness of proximal sandy coastal deposits in the western margin of the Arkona Basin close to Kriegers Flak II South OWF was not mapped by Lemke (1998) (Figure 6.5), but comparing the till surface topography (Figure 6.4) with the Late Glacial surface topography (Figure 6.6) indicates that a thickness of up to 30 m can be expected.

Mapping of the Holocene mud distribution (Figure 6.7) show a mud unit deposition of up to 10 m in the central part of the Arkona Basin. In the Kriegers Flak II South OWF area the thickness of Holocene mud is estimated to between 0 and 2 m in the easternmost part, while a thin sandy layer is expected in the westernmost part.

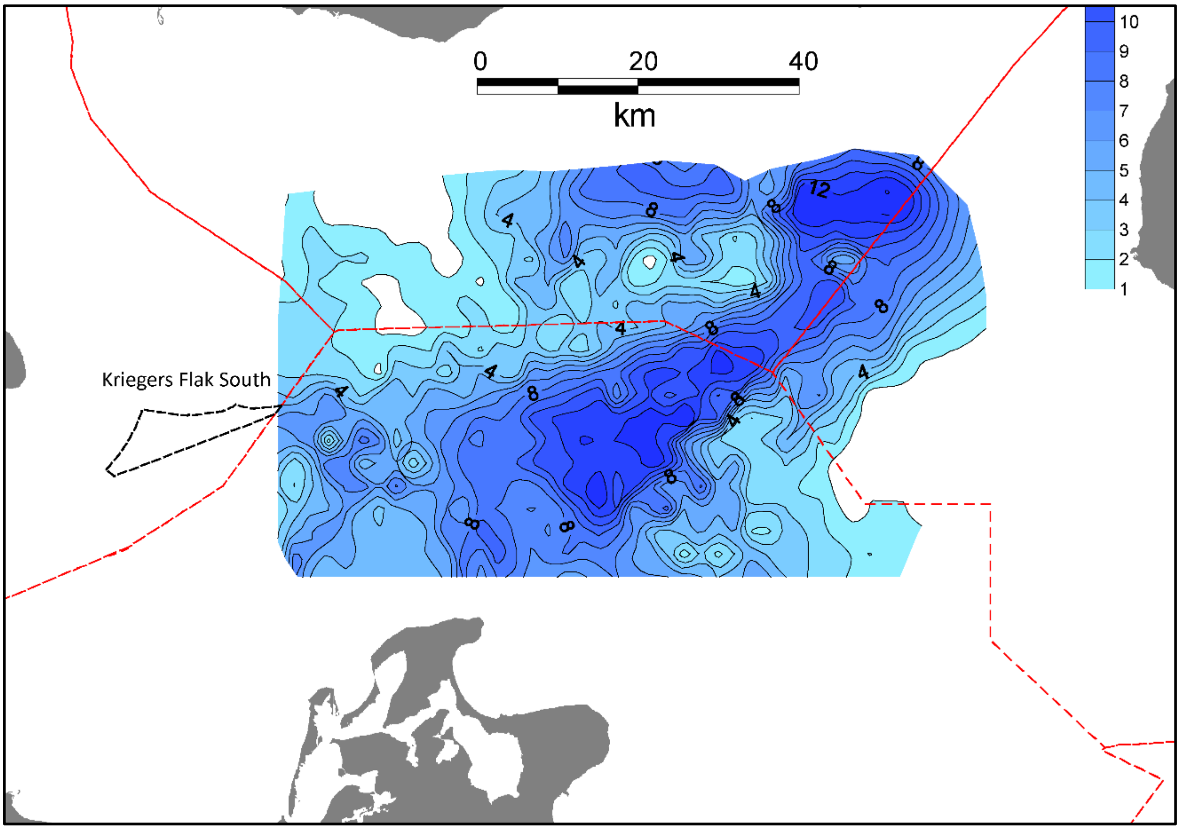


Figure 6.5 Thickness of Late Glacial clays by Lemke (1998). Location of Kriegers Flak II South OWF is shown with black dashed lines. The red dashed lines show the EEZ.

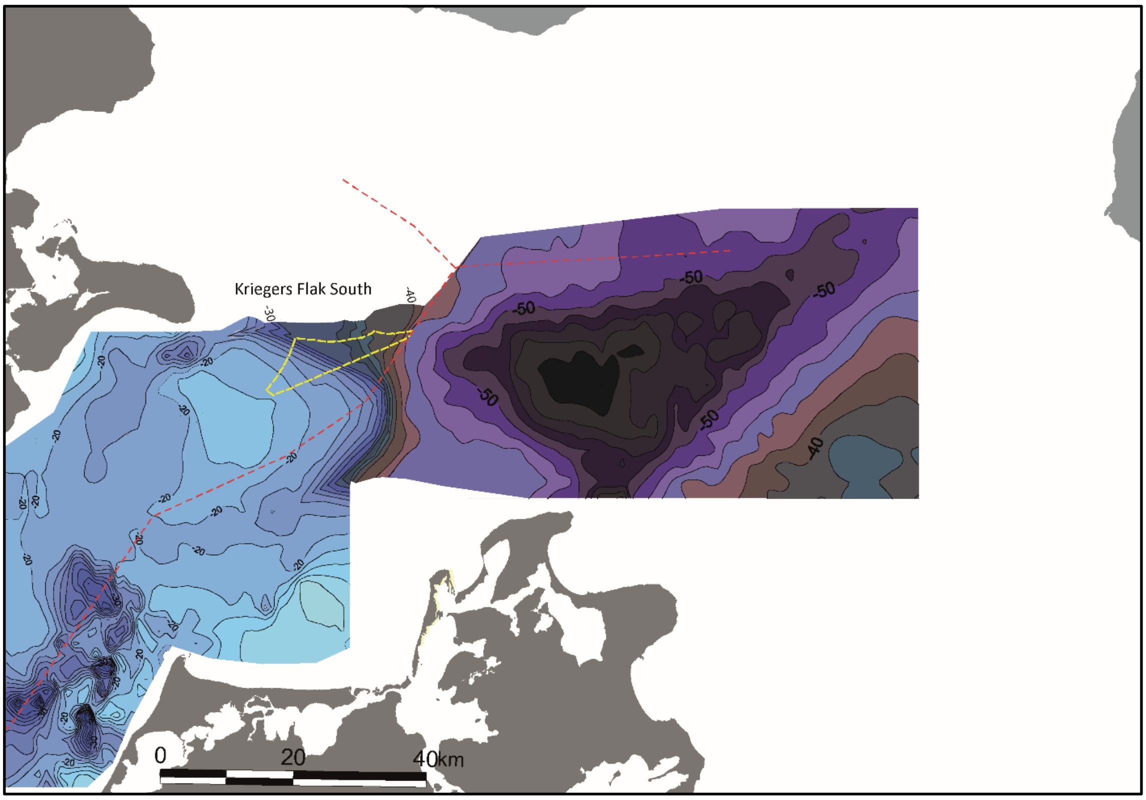


Figure 6.6 Late Glacial surface topography by Lemke (1998). Location of Kriegers Flak II South OWF is shown with yellow dashed lines. The red dashed lines show the EEZ.

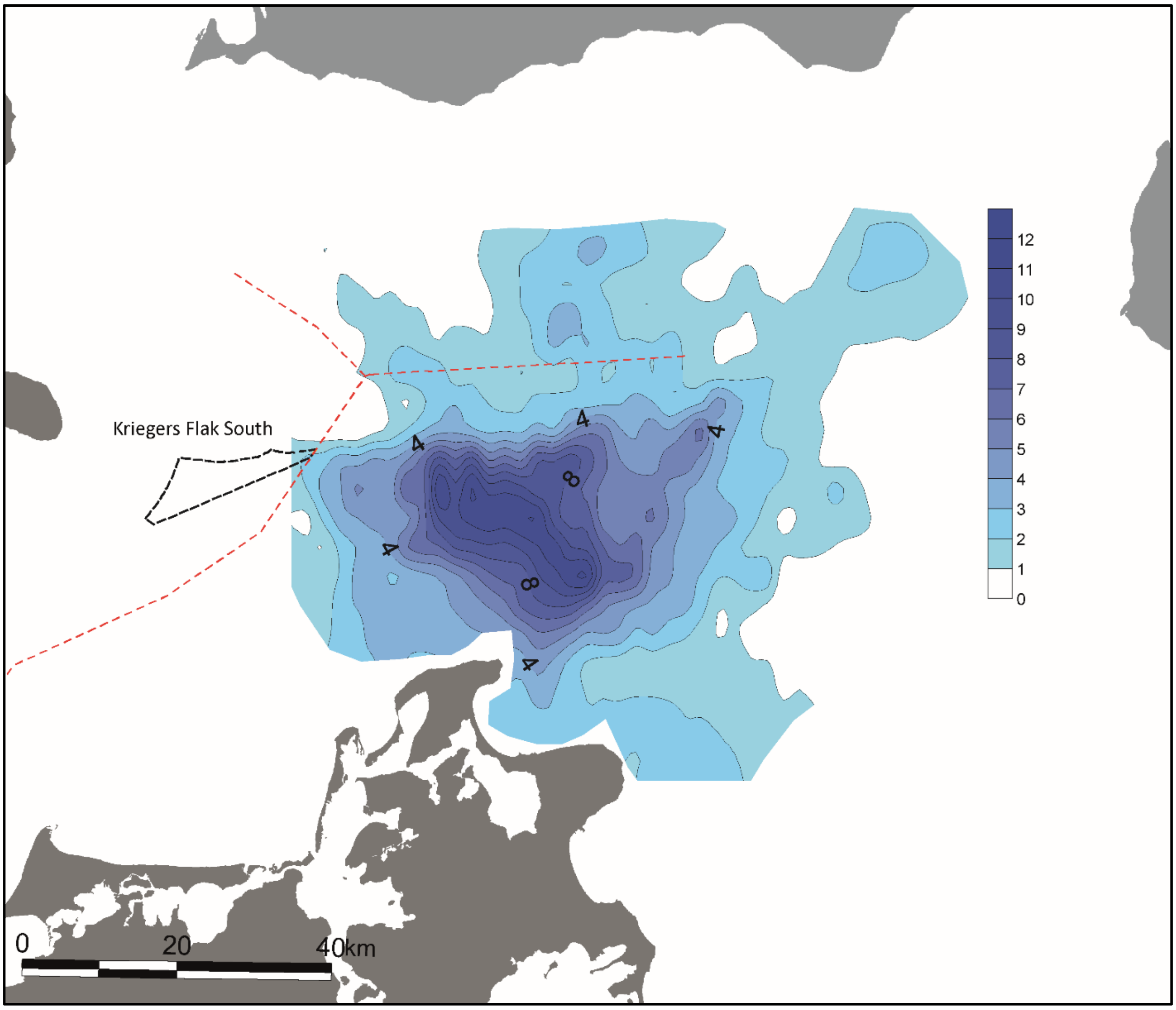


Figure 6.7 Thickness of Holocene mud by Lemke (1998). Location of Kriegers Flak II South OWF is shown with black dashed lines. The red dashed lines show the EEZ.

7. Seabed morphology and seabed sediments

The bathymetric map of the Kriegers Flak II OWF's presented in figure 7.1 originates from EMODnet Bathymetry (https://www.emodnet-bathymetry.eu). The seabed morphology of Kriegers Flak II North is characterised by a rather flat seabed with a gentle southward dip, ranging from 20 to 35 m b.s.l. The Kriegers Flak II South shows a shallow western seabed platform 15–20 m b.s.l. interrupted by a central rather steep eastward slope down to about 30m b.s.l., followed by a gentle eastward dipping seabed from 30 to about 45m b.s.l, in the easternmost part.

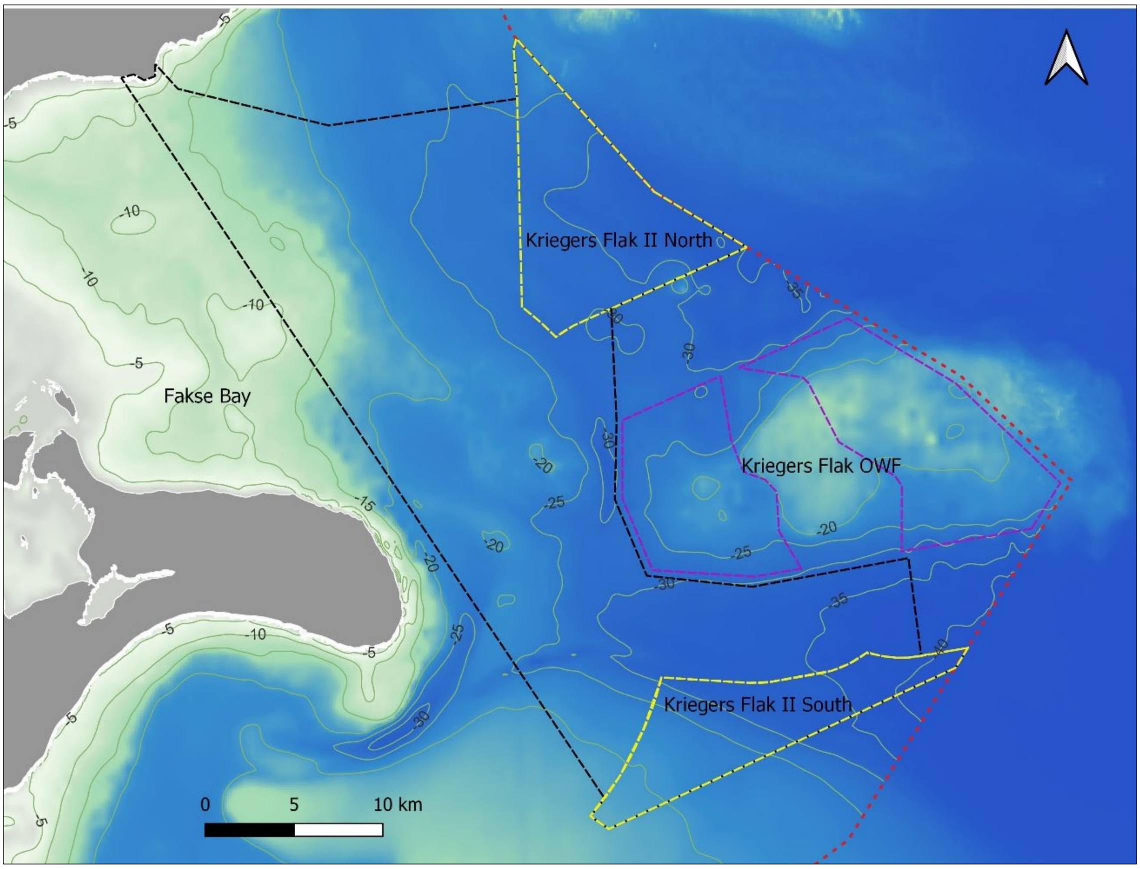


Figure 7.1 Bathymetric map of the Kriegers Flak II North and South areas (yellow dashed lines), and the existing Kriegers Flak OWF (purple dashed lines). EEZ is indicated with red dashed lines.

The seabed sediment map (Figure 7.2) is compiled by combining the EMODnet-Geology seabed substrate map scale 1:1M for the German and the Swedish EEZ (https://www.emodnet-geology.eu/data-products/seabed-substrates), with the Danish seabed sediment map scale 1:100.000 (2020 version) for the Danish EEZ (https://data.geus.dk/geusmap/?mapname=marta). The confidence of the sediment map in the Kriegers Flak II OWFs is low due to a very limited amount of acoustic data and only few seabed samples.

The seabed sediment map (Figure 7.2) shows a northwestern area dominated by till in the shallower part of the Kriegers Flak II North OWF, followed by muddy sand in the deeper southeastern part of the OWF area. In Kriegers Flak II South OWF the shallow western platform and the central eastward slope is dominated by medium-fine sand at the seabed, gradually changing into muddy sand and sandy mud in the easternmost part of the OWF area.

The cable corridor has a complex seabed sediment distribution due to the large areal coverage. The eastern part is generally dominated by muddy sand surrounding the Kriegers Flak OWF. In the southern half the seabed sediments are predominantly sandy, while a large area in the central part consists of glacial till. The northern part is mostly sandy and gravelly except for the coastal area near the landing point at Rødvig, where Danien Limestone is outcropping at the seabed.

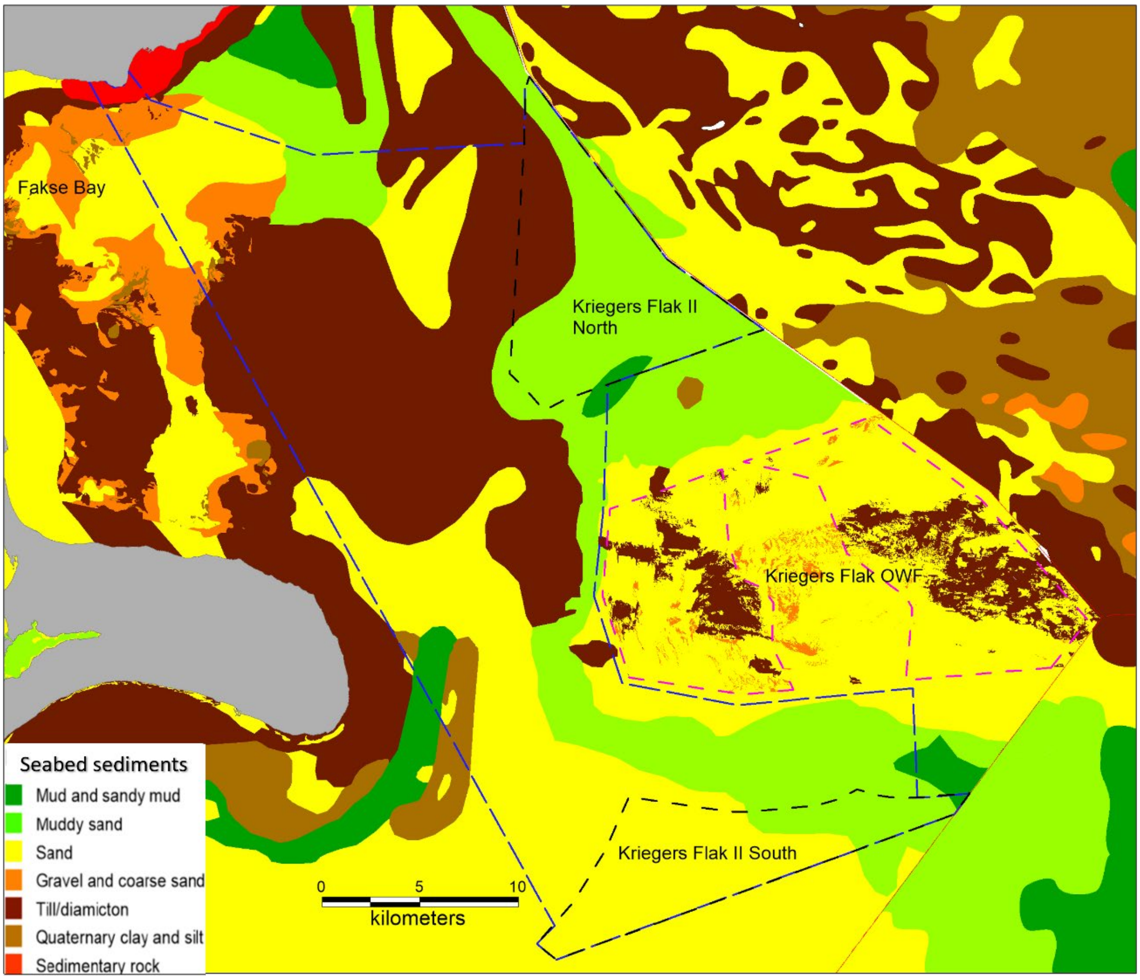


Figure 7.2. Seabed sediment map around the Kriegers Flak II North and South (black dashed lines) and cable corridor (blue dashed lines) areas. The map is based on a combination of the EMODnet 1:1M seabed substrate map and the Danish 1:100.000 (2020 version) seabed sediment map. The existing Kriegers Flak OWF (purple dashed lines) and the EEZ (red dashed lines) are indicated.

8. Detailed studies of Kriegers Flak II North and South OWF

This section presents detailed data seabed geology information modified from previous projects close to the Kriegers Flak II North and South OWF as well as the cable corridor. These projects are:

1) The Baltic Pipe investigations (Rambøll 2020)

2) Investigations related to the Kriegers Flak OWF by Rambøll (2013)

3) Investigations related to the Kriegers Flak OWF by GEO (2013).

8.1 Kriegers Flak II North OWF and the cable corridor

A general indication of the expected seabed geology in the Kriegers Flak II North OWF and the northern part of the cable corridor is given from the Baltic Pipe studies (Rambøll 2020) by combining the seabed sediment map (Figure 7.2) with 3 seismic profiles from the project: Profile E – F (Figure 8.1); Profile G – H (figure 8.2), and Profile N – M (Figure 8.3).

The interpretation of the seismic profiles has been documented from vibrocores with lithological descriptions.

8.1.1 Baltic Pipe profile E – F

This profile having a W-NW to E-SE orientation is crossing the southernmost part of Kriegers Flak II North (Figure 8.1). The profile shows that the deepest easternmost part from 35m b.s.l. to the westernmost part about 25 m b.s.l., has up to 10 m till covered by about 5 m Baltic Ice Lake clay (highest level of Baltic Ice Lake clay about 30 m b.s.l.) and a top unit of 2-4 m Holocene muddy sand.

In the Kriegers Flak II North part of the profile the till unit is thinning to the west on top of Danien limestone. Till with boulders is observed around 25 m b.s.l., with a patchy coverage of a few metres of Holocene sands and muddy sands.

Further to the west this profile continues into the cable corridor. The pre-Quaternary is changing from Danien limestone to Upper Cretaceous chalk with only at thin cover of till and/or Holocene sand. The sandy mud has disappeared. In the western part of the profile the till is outcropping at the seabed. The limestone disappears in favor of a thickening of the till to more than 10 metres.

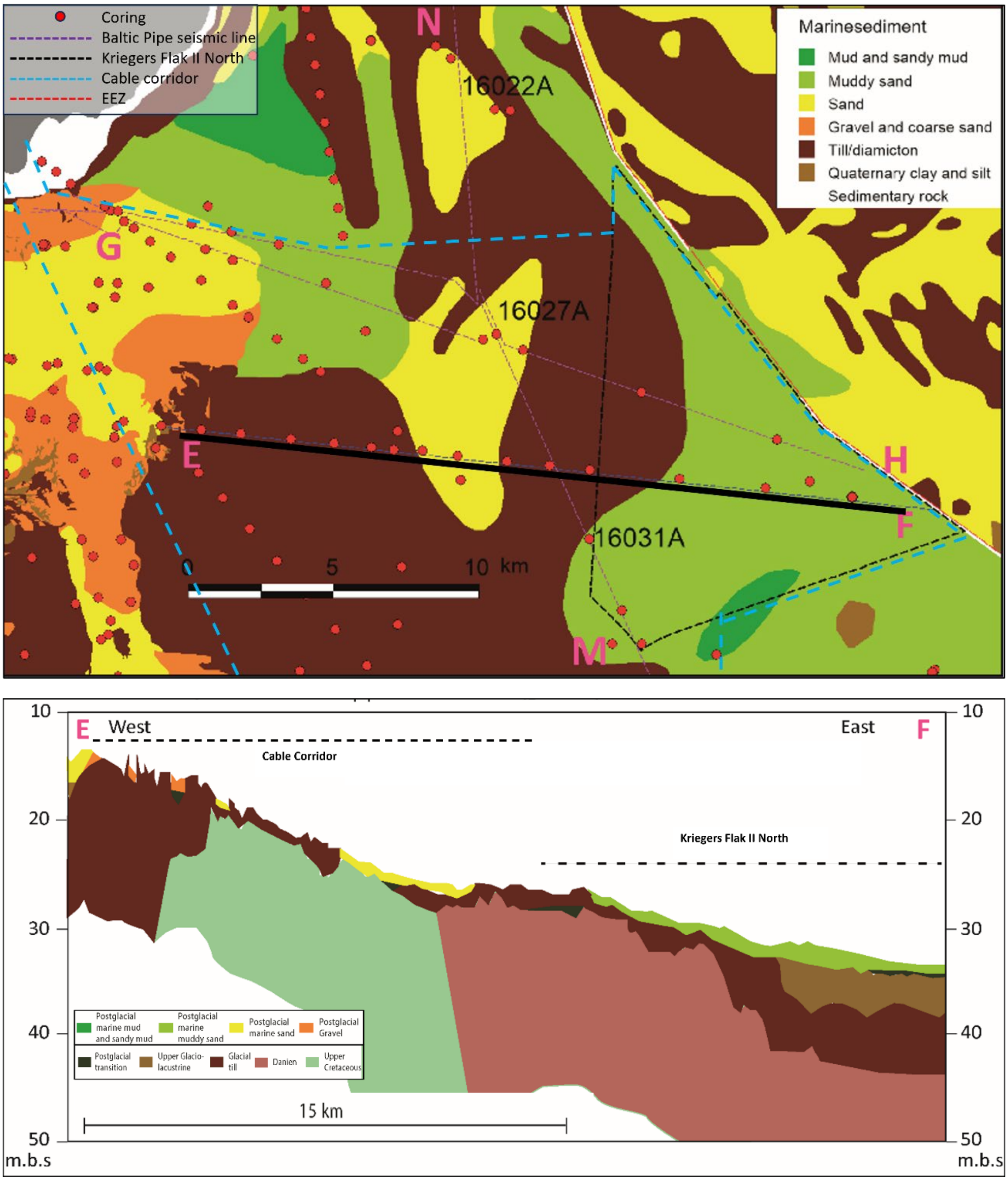


Figure 8.1 Upper figure: Surface sediments in the outer Faxe Bay region with the location of Baltic Pipe profile E - F indicated. Lower figure: Interpretation of Baltic Pipe seismic profile E - F with indication of the Kriegers Flak II North.

8.1.2 Baltic Pipe profile G – H

This NW-SE seismic profile is crossing the central part of Kriegers Flak II North (Figure 8.2) and continues into the northernmost part of the cable corridor. It supports the picture from the profile E – F (Figure 8.1) that the seabed, in general, consist of a few metres of

Holocene sand and muddy sand on top of a few metres of Late Glacial clay and till overlying bedrock of Danian limestone.

In the cable corridor the pre-Quaternary changes from Danian limestone to Upper Cretaceous chalk forming a stable basement over the entire profile. It is overlain by 2-4 m till and 2-4 m of Holocene sand except in a 5 km wide basin filled with muddy sand.

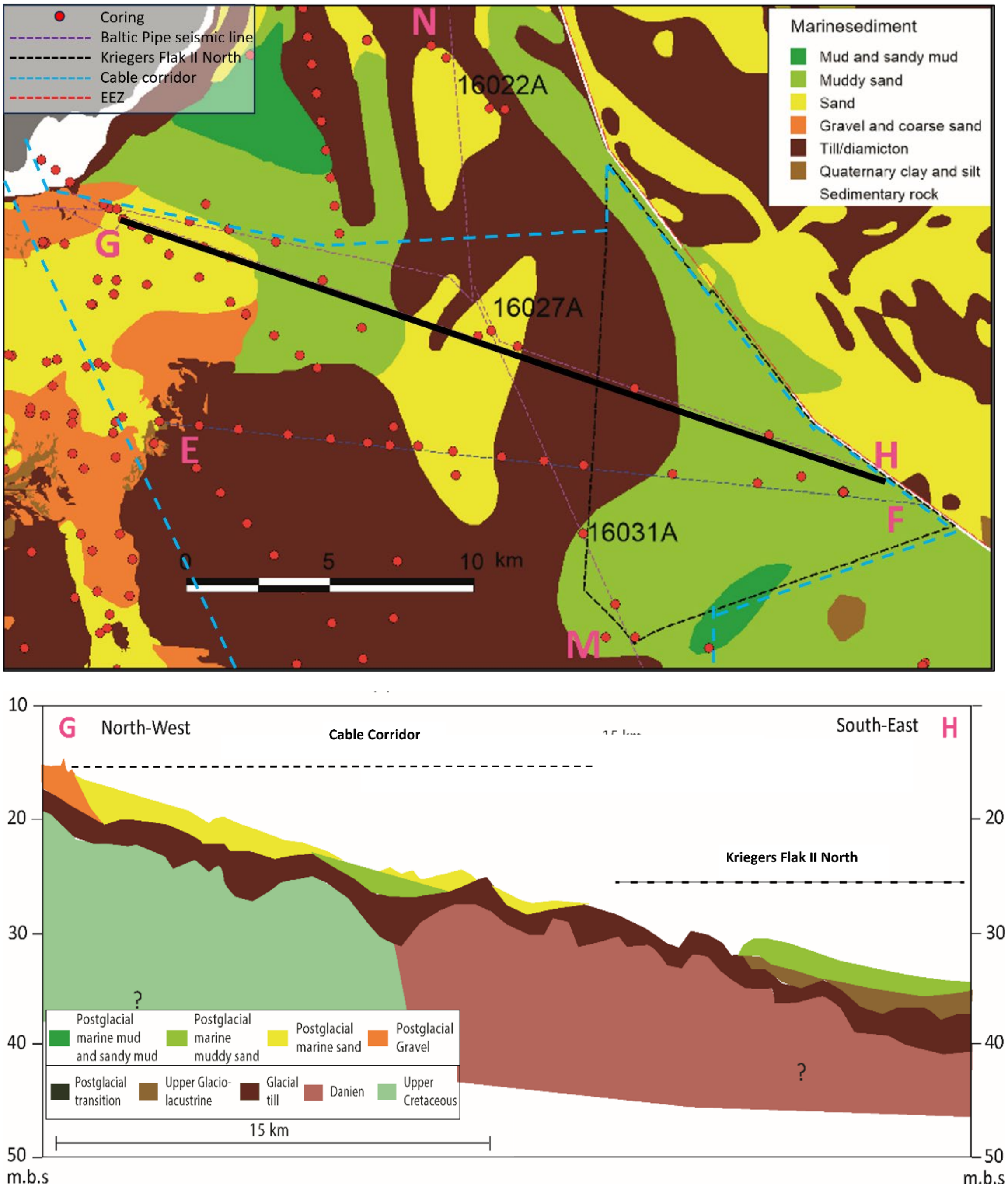


Figure 8.2 Upper figure: Surface sediments in the outer Faxe Bay region. Location of Baltic Pipe seismic profile G – H is indicated. Lower figure: Interpretation of Baltic Pipe seismic profile G – H with indication of Kriegers Flak II North.

8.1.3 Baltic Pipe profile N – M

This N-S seismic profile is crossing just a corner of the Kriegers Flak II North OWF, but a large stretch of the cable corridor (Figure 8.3). Upper Cretaceous chalk with an uneven surface is close to the seabed along the whole profile covered with only a few metres of till. Locally thin layers <2 m of Late Glacial lacustrine clay, Holocene sandy sediments, and in the south Holocene muddy sand appear with many till outcrops at the seabed due to the thin cover layers.

The pre-Quaternary map in Figure 5.2 indicates that the bedrock in this area is Upper Cretaceous chalk.

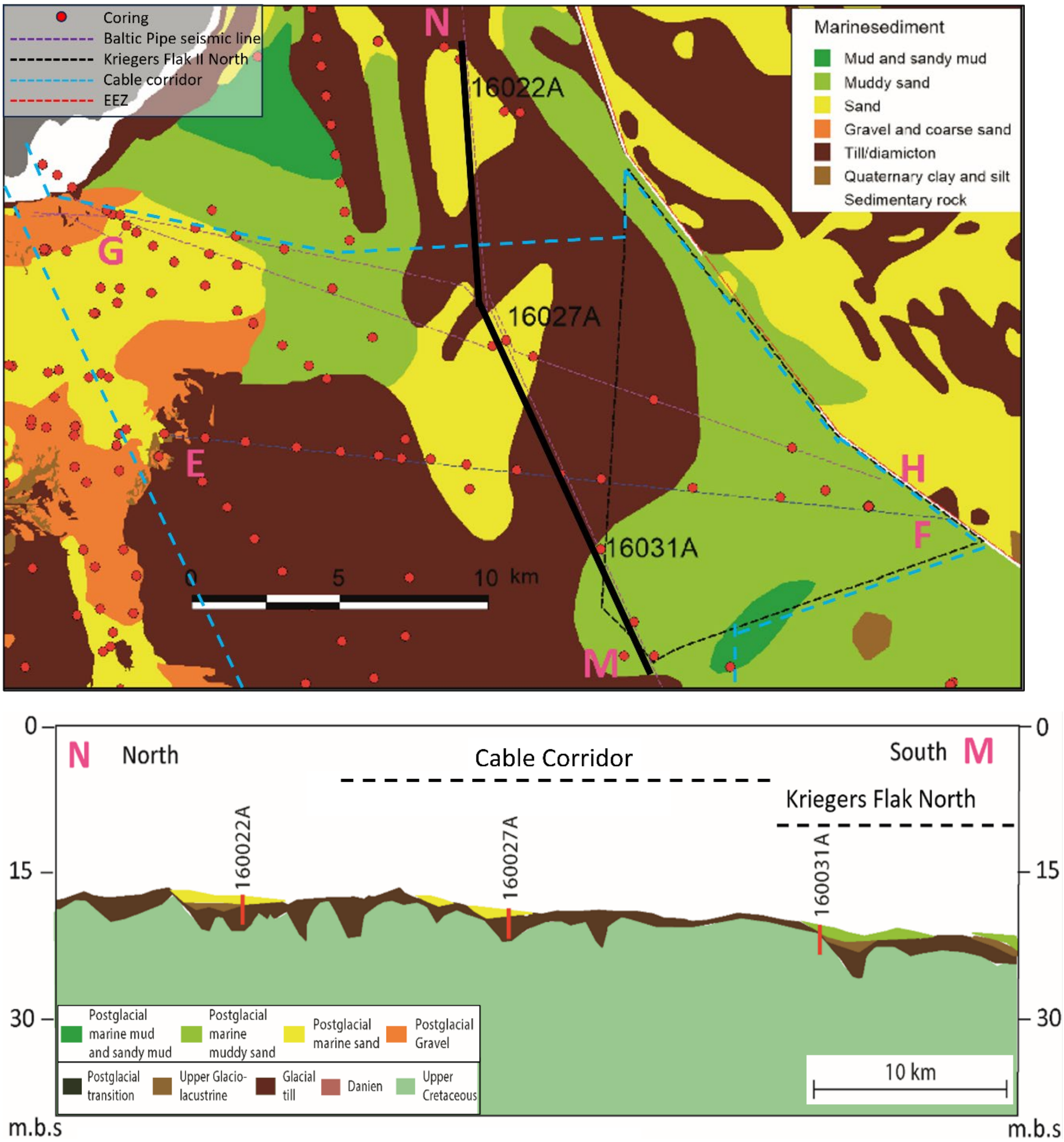


Figure 8.3 Upper figure: Surface sediments in the outer Faxe Bay region. Location of Baltic Pipe profile profile N - M is indicated. Lower figure: Interpretation of Baltic Pipe seismic profile N - M with indication of Kriegers Flak II North.

8.2 Kriegers Flak II South OWF and the cable corridor

Very little existing data are available from Kriegers Flak II South OWF and the surrounding cable corridor. However, the previous chapters describing the general geology of the south-western Baltic Sea and the Arkona Basin have revealed, that the Kriegers Flak II South OWF is located at the margin of the Arkona Basin (Lemke 1998). Thus, the bedrock geology is represented by Upper Cretaceous chalk (Figure 5.2) and the glacial till deposits are dominated by ice margin readvance marginal ridges following the general deglaciation pattern (Figure 5.5).

The till surface topography has a maximum depth of 75m b.s.l. in the central part of the Arkona Basin, shallowing up to about 40m b.s.l. in the Kriegers Flak II South OWF area (Figure 6.4).

In the Kriegers Flak II South OWF area the till surface is expected to be covered by Late Glacial and Holocene clays and mud, like in the central parts of the Arkona Basin, changing to proximal sandy coastal deposits (Jensen et al. 1997) in the shallow western margin of the Arkona Basin.

Unfortunately, the thickness of proximal sandy coastal deposits in the Kriegers Flak II South OWF area has not been mapped in detail by Lemke (1998), but by comparing the till surface topography (Figure 6.4) and Late Glacial surface topography (Figure 6.6) a thickness of up to 30m can be deduced.

The following chapters present interpretations of the seabed geology of Kriegers Flak II South OWF and the surrounding cable corridor, partly from The Baltic Pipe project (Rambøll 2020), and partly from scientific projects Jensen et al. (1997) and Lemke (1998). See Figure 8.4 for locations of the seismic lines and vibrocores.

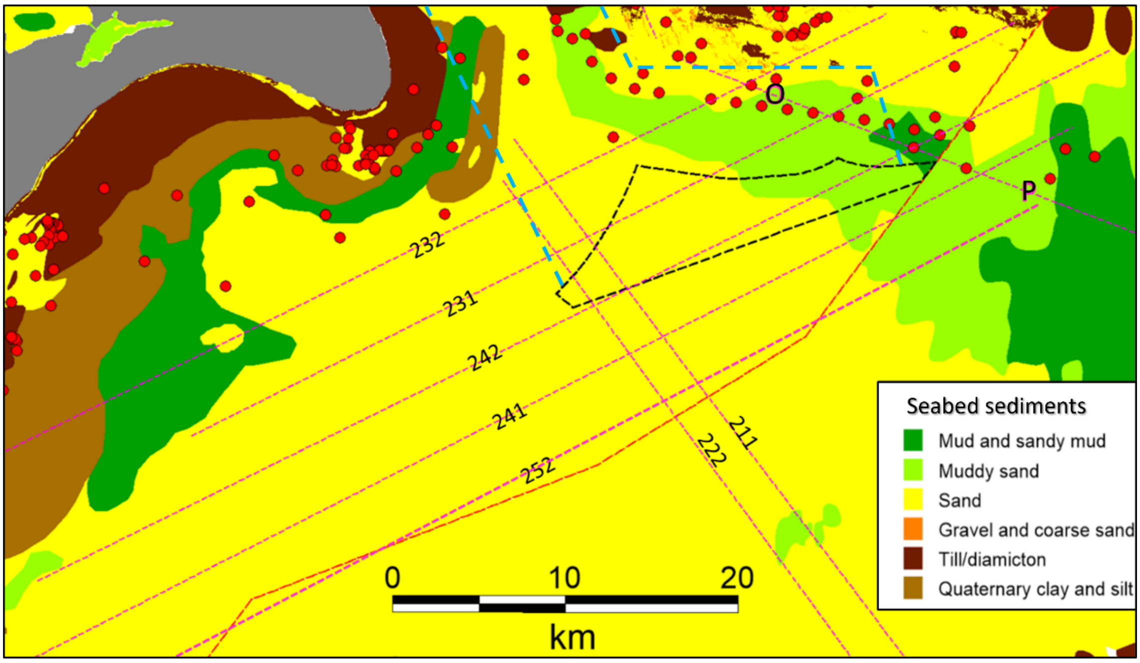


Figure 8.4 The seismic lines described in the text (pink dashed lines) and vibrocores (red dots) on top of the seabed sediment map. Kriegers Flak II South OWF marked with dashed black lines, the cable corridor with blue lines, and the EEZ with red dashed lines.

8.2.1 Baltic Pipe profile O – P

The Baltic Pipe sparker profile O – P crosses the southeastern corner of the cable corridor and passes just east of the Kriegers Flak II South OWF, at the western margin to the Arkona Basin (Figure 8.4). The seismic profile in Figure 8.6, combined with a few vibrocores (Figure 8.5) show the Upper Cretaceous chalk between 50 to 65 m b.s.l.. A till unit covering the chalk is thinning from c. 5 m to 0-2 m thickness to the northwest as the depth to the chalk is decreasing. The till is overlain by the lower and upper Baltic Ice Lake clay units (equivalent to unit III - Figure 6.1) draping the till with a thickness of 15 m in the basin thinning to a few metres to the northwest like the underlying till unit. An early Holocene, freshwater unit of organic clay/silt (unit II) is draping the Ice Lake deposits. The uppermost unit consist of soft, marine, Holocene sandy mud/sand (unit I).

The geological succession along profile O – P is indicative for what can be expected in the cable corridor between Kriegers Flak II South OWF and the existing Kriegers Flak OWF. It is also representing the seabed geology in the eastern part of the Kriegers Flak II South.

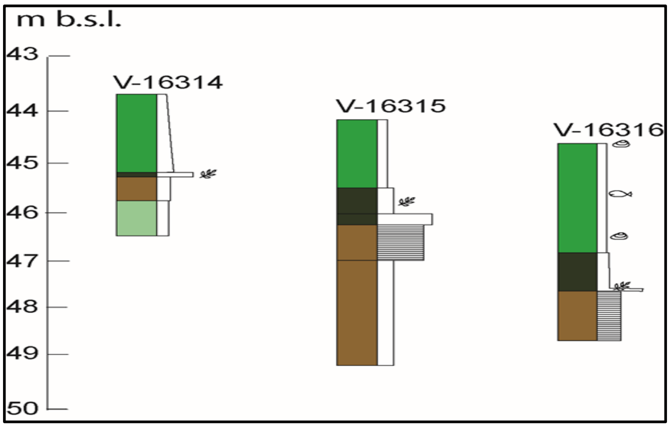


Figure 8.5 Vibrocore logs along Baltic Pipe profile O – P. See Figure 8.6 for legend.

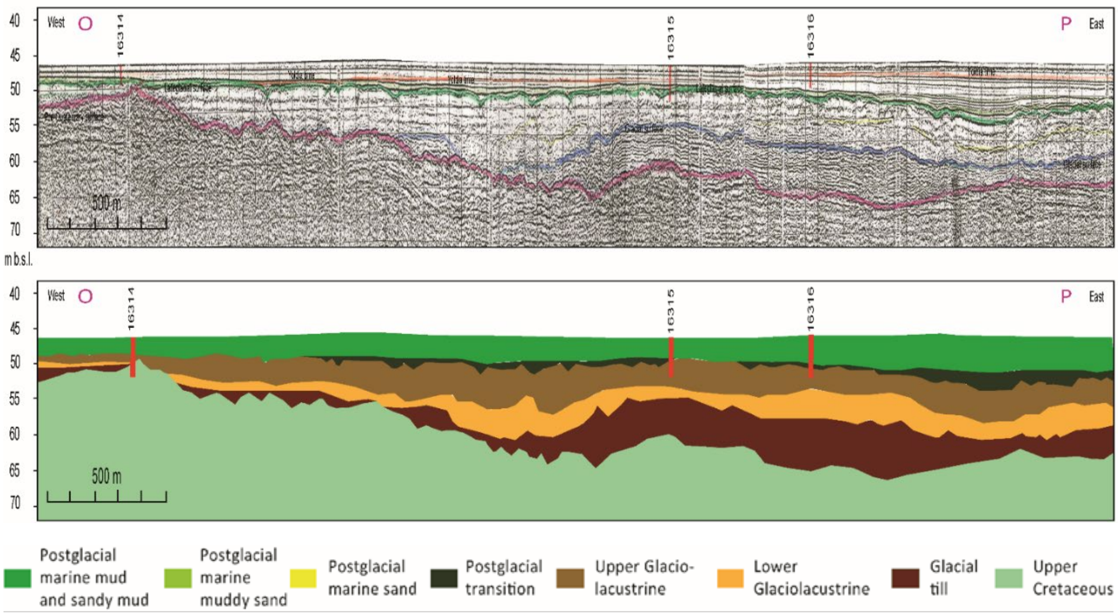


Figure 8.6 Baltic Pipe sparker profile O – P (upper figure) and geological interpretation (lower figure). Vibrocore positions are marked with red lines. For location, see figure 8.4.

8.2.2 Seismic profiles from scientific studies

A series of archive boomer and airgun seismic lines collected for scientific purposes cross the Kriegers Flak II South OWF and the cable corridor area (Figure 8.4). The interpretations are reported in Jensen et al. (1997) and Lemke (1998).

The main conclusion from these studies is that the till surface was covered by an up to 35 m thick wedge of Late Glacial sandy deposits developed as a coastal beach barrier between Møn and Rügen in connection with two Baltic Ice Lake highstands and regressions between 12.8 and 11.7 ka BP (Figure 5.7). The highstands reached a level of about 20 m b.s.l. The sandy deposit prograde from west to east into the Arkona Basin and represent the present eastward sloping seabed.

The interpretations of the seismic profiles crossing the Kriegers Flak II South OWF and the cable corridor are presented in the Figures 8.7 to 8.13.

The till thickness varies from a few meter to more than 15 m, due to the development of ice marginal ridges (Figure 8.8, Figure 8.11 and Figure 8.13).

The Baltic Ice Lake deposits follow the general pattern in the southwestern part of the Baltic Sea, as described in section 6.2, but the lower and upper glaciolacustrine deposits change facies from clay in the Arkona basin (Figure 8.5 and Figure 8.10) to fine-medium sand coastal sediments, at the western margin of the Arkona Basin (Figure 8.12).

According to vibrocores the top of the wedge consists of fine-medium sand developing into clay at the foot of the wedge. The maximum thickness of the wedge is up to 35 m (Figure 8.12) south of the Kriegers Flak II South OWF. The internal reflection pattern supports sandy costal deposits above basin clay.

Inside the Kriegers Flak II South OWF the Late Glacial deposits mainly consist of the upper prograding sandy costal deposits (Figure 8.8, Figure 8.9, Figure 8.13 and Figure 8.14).

Early Holocene, freshwater, fine-grained, organic-rich sediments (equivalent to unit II figure 6.1) are found in the Arkona basin (Figure 9.9) and inside the OWF at the foot of the prograding unit (Figure 8.8, and Figure 8.9) as well as in depressions west of the OWF (Figure 8.7 and Figure 8.12).

The final Holocene transgression eroded the sediments and re-deposited sand and muddy sand on top of the Late Glacial coastal deposits.

Inside the Kriegers Flak II South OWF about 1 m of Holocene sand has been deposited on top of Late Glacial sand while up to 5 m west of the OWF (Figure 8.13 and Figure 8.14).

Recent to sub-recent muddy sand and sandy mud has been deposited in the western part of the Arkona Basin and in the shallow waters close to Møn (Figure 8.8, Figure 8.9 and Figure 8.12).

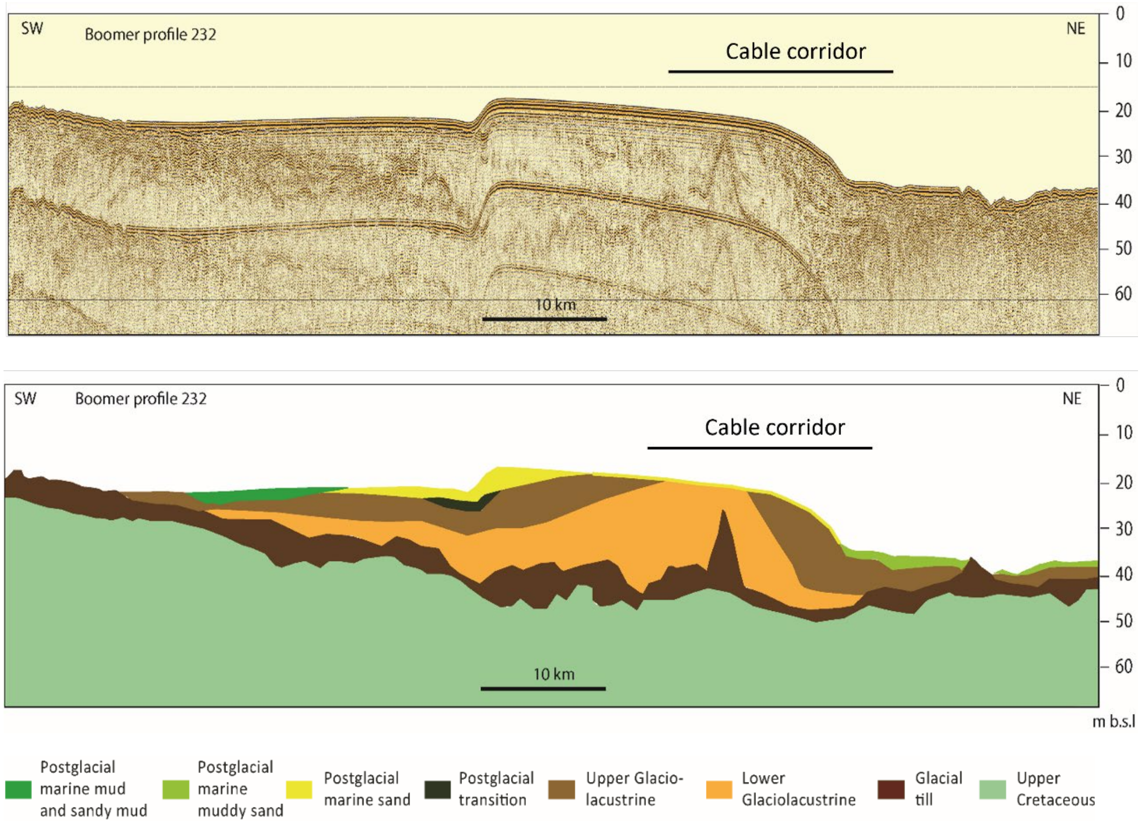


Figure 8.7 Boomer profile 232 and geological interpretation. For location, see Figure 8.4.

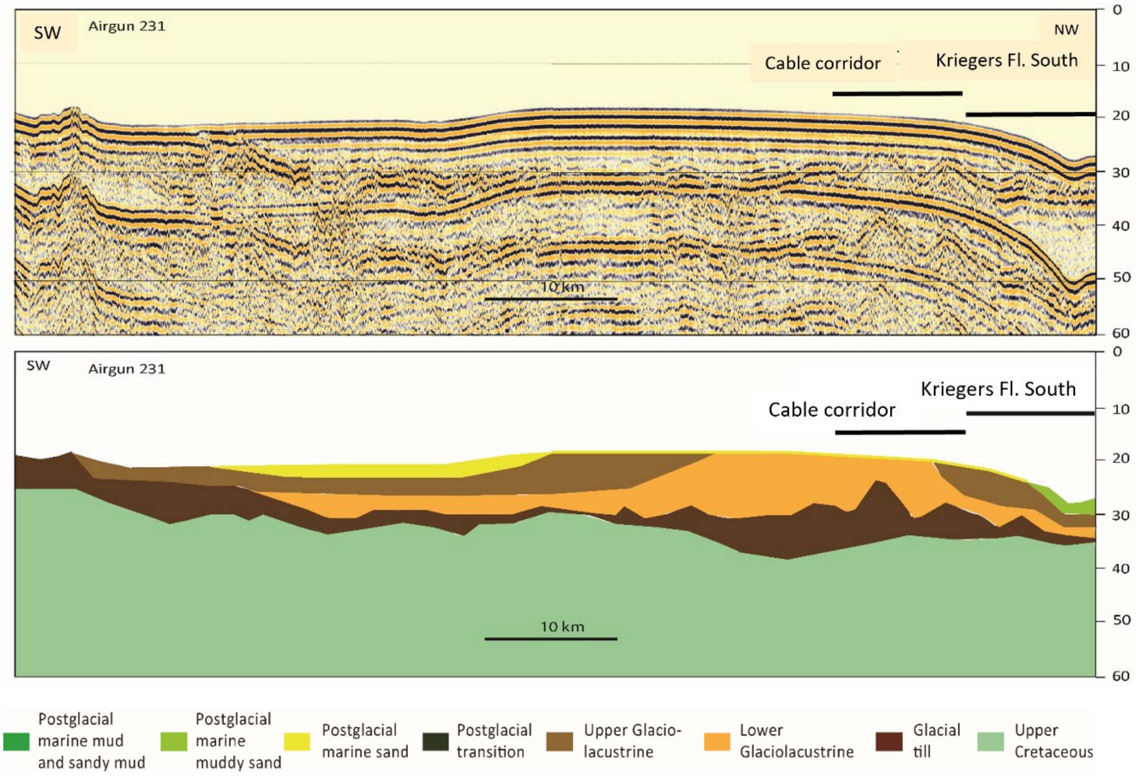


Figure 8.8 Airgun profile 231 and geological interpretation. For location, see Figure 8.4.

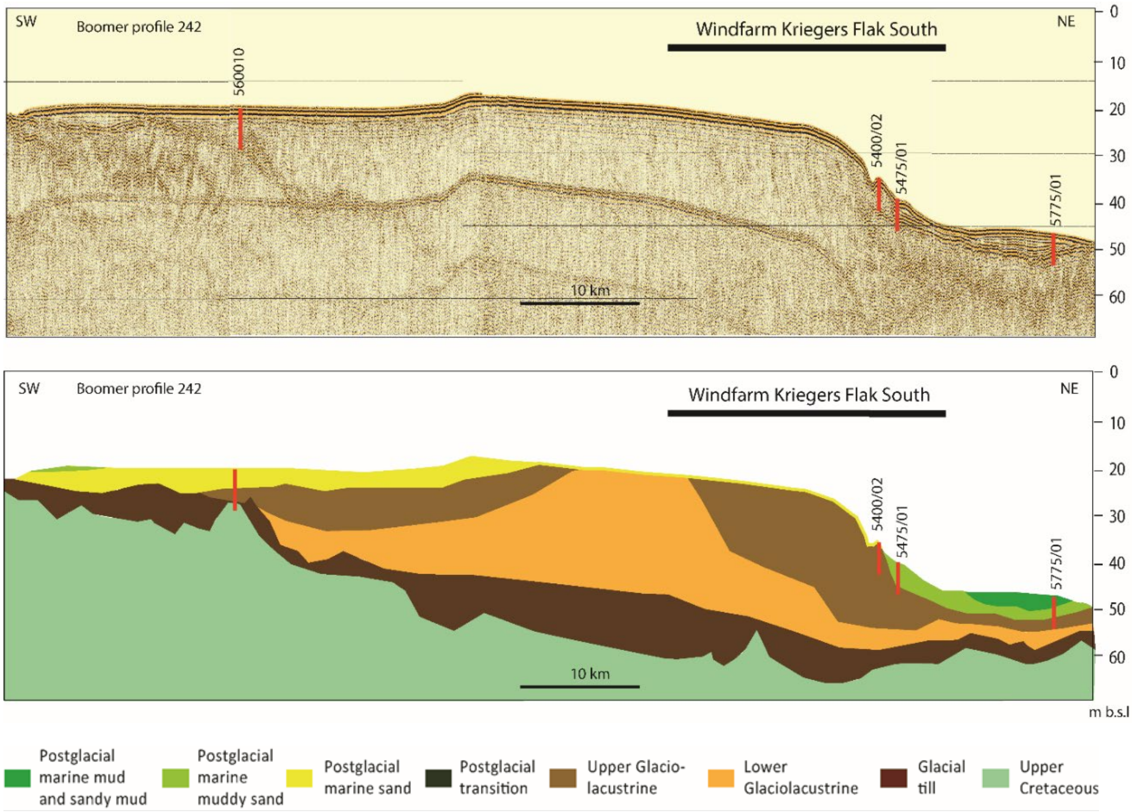


Figure 8.9 Boomer profile 242 and geological interpretation. For location, see Figure 8.4.

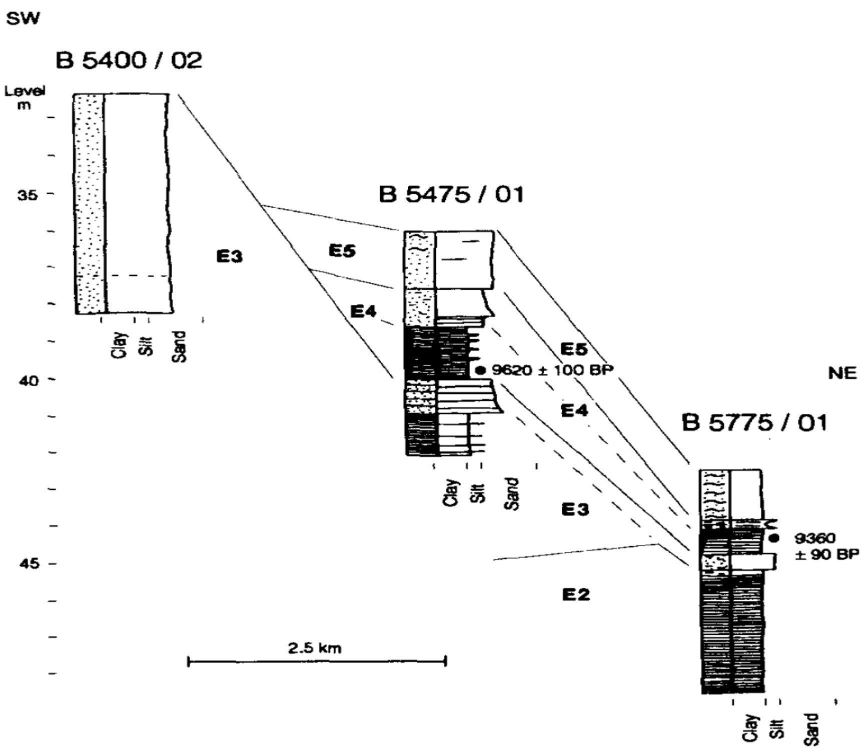


Figure 8.10 Vibrocore logs along Boomer profile 242, from Jensen et al. (1997).

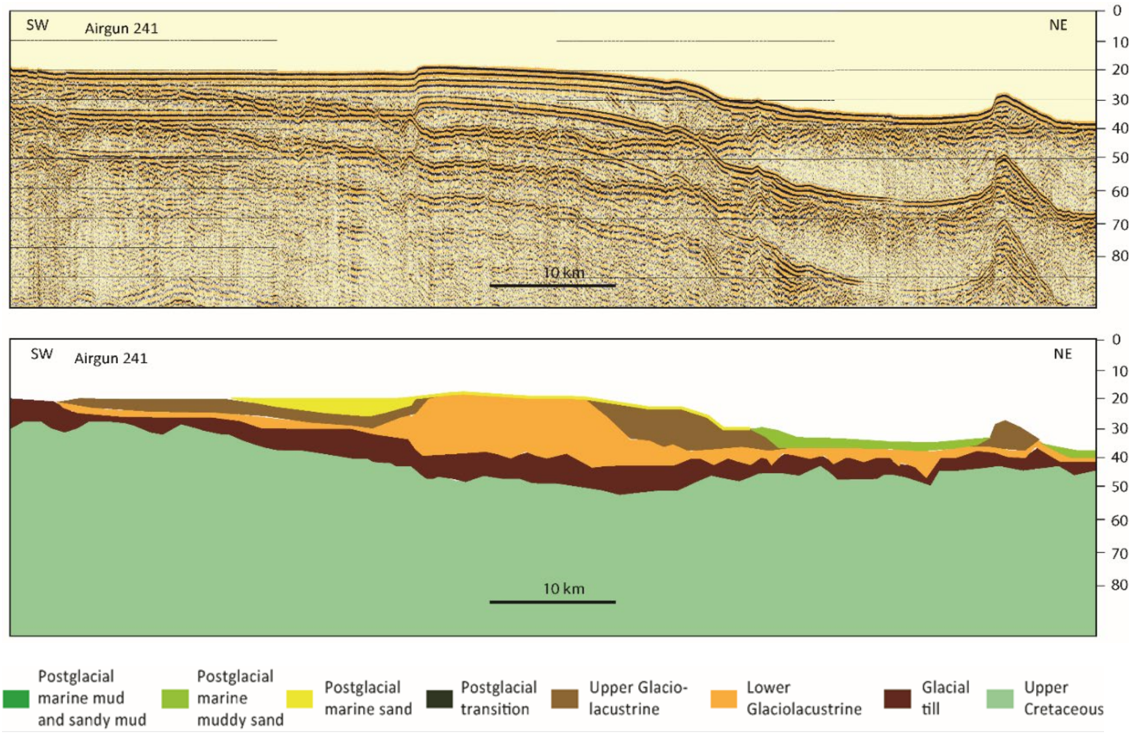


Figure 8.11 Airgun profile 241 and geological interpretation. For location, see Figure 8.4.

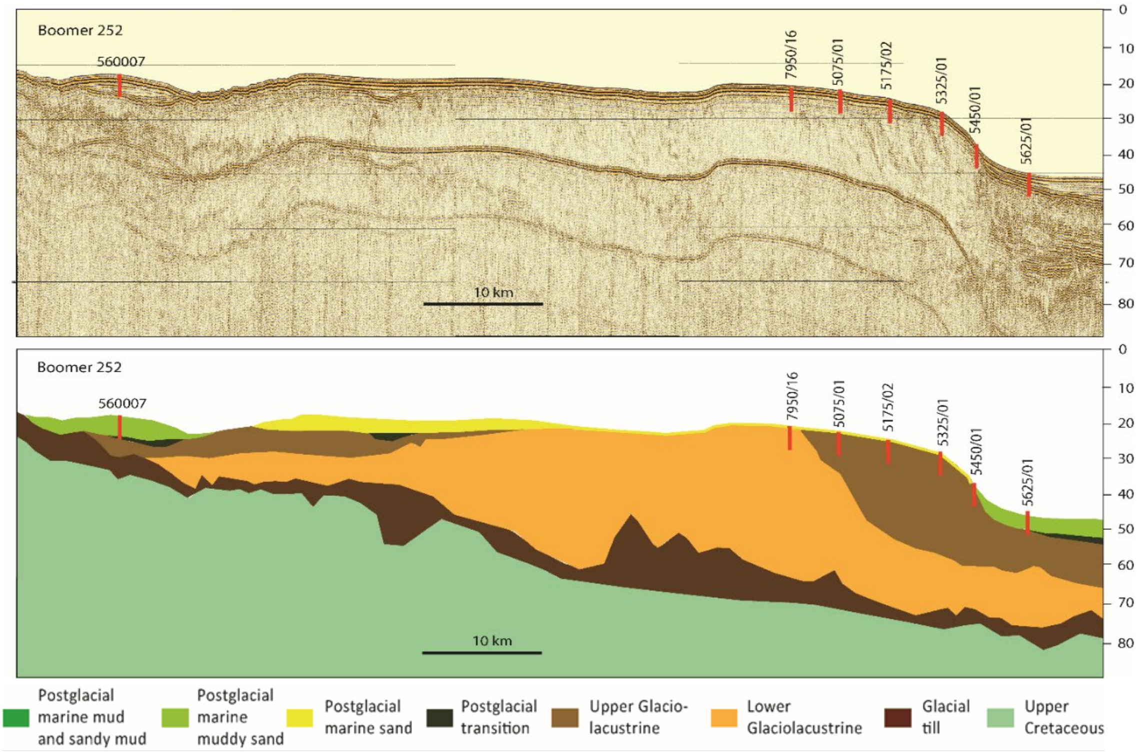


Figure 8.12 Boomer profile 252 and geological interpretation. For location, see Figure 8.4.

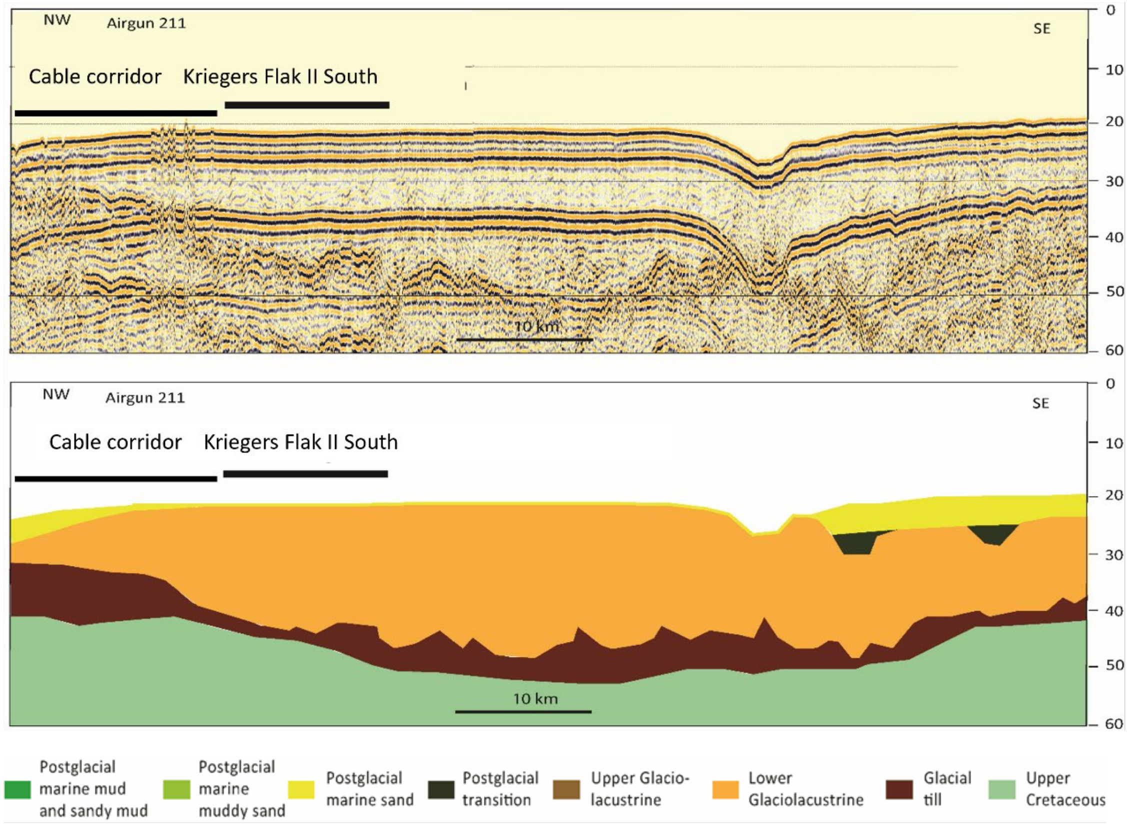


Figure 8.13 Airgun profile 211 and geological interpretation. For location, see Figure 8.4.

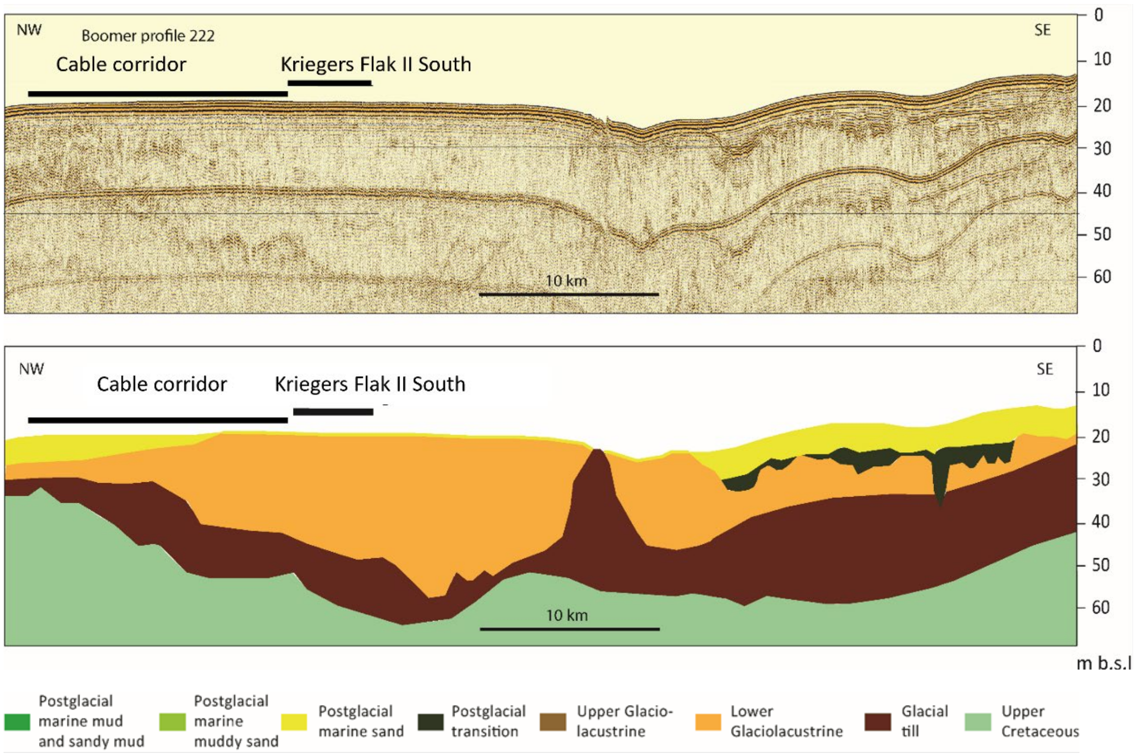


Figure 8.14 Boomer profile 222 and geological interpretation. For location, see Figure 8.4.

8.3 Faxe Bay development and the cable corridor

The development of the outer part of the Faxe Bay is essential for understanding the seabed geology of the northern part of the cable corridor. In addition to the general palaeogeographical model of the Faxe Bay presented in Figure 5.9. results from an aggregate mapping program (Lomholt et al. 2016) provide detailed information on the northern part of the cable corridor (Figure 8.15). The seabed geology varies considerably over a short distance, which appears clearly from the three interpreted seismic profiles presented in Figure 8.16.

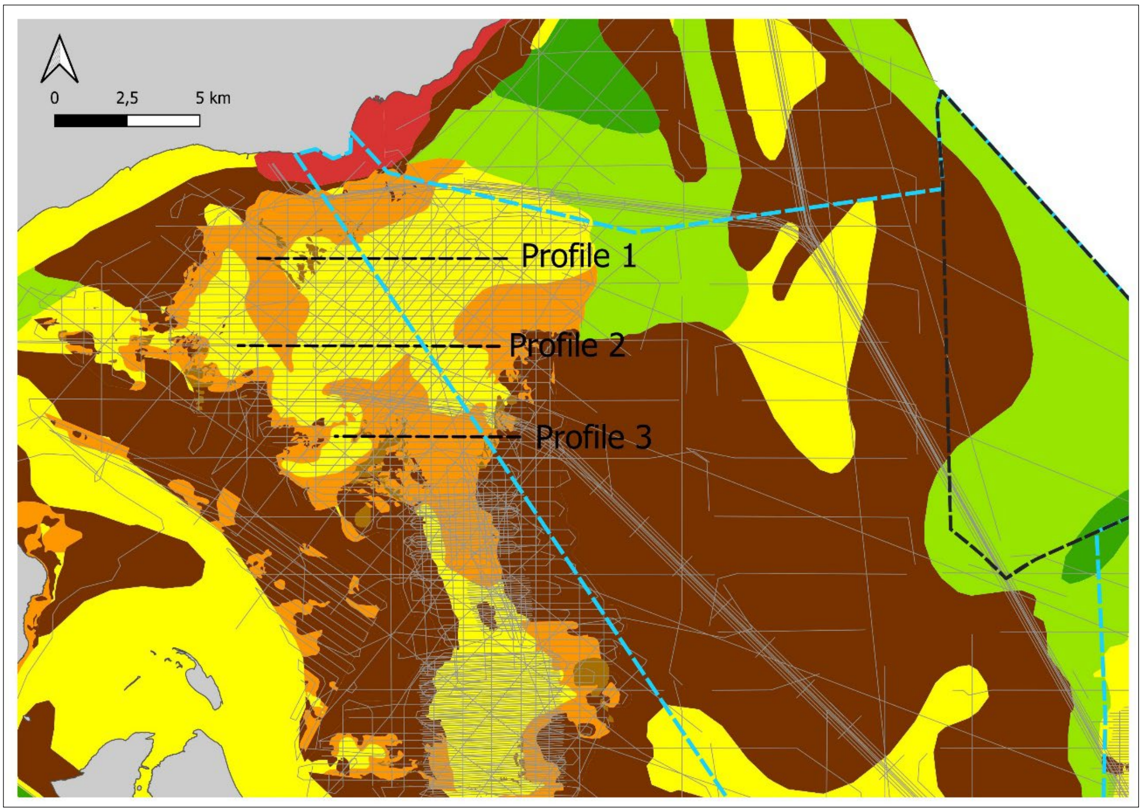


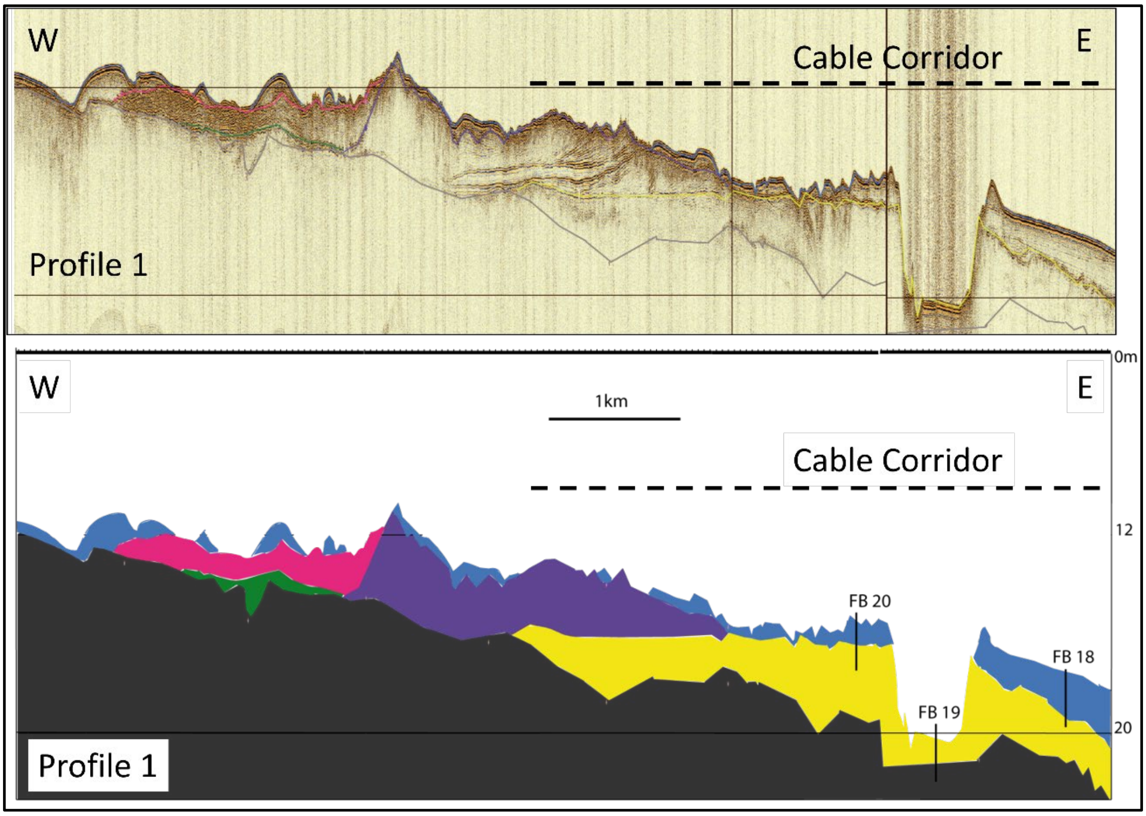
Figure 8.15 Map showing the location of three seismic profiles (black hatched lines) illustrating the stratigraphy in the Faxe Bay and the northern part of the cable corridor (blue hatches lines).

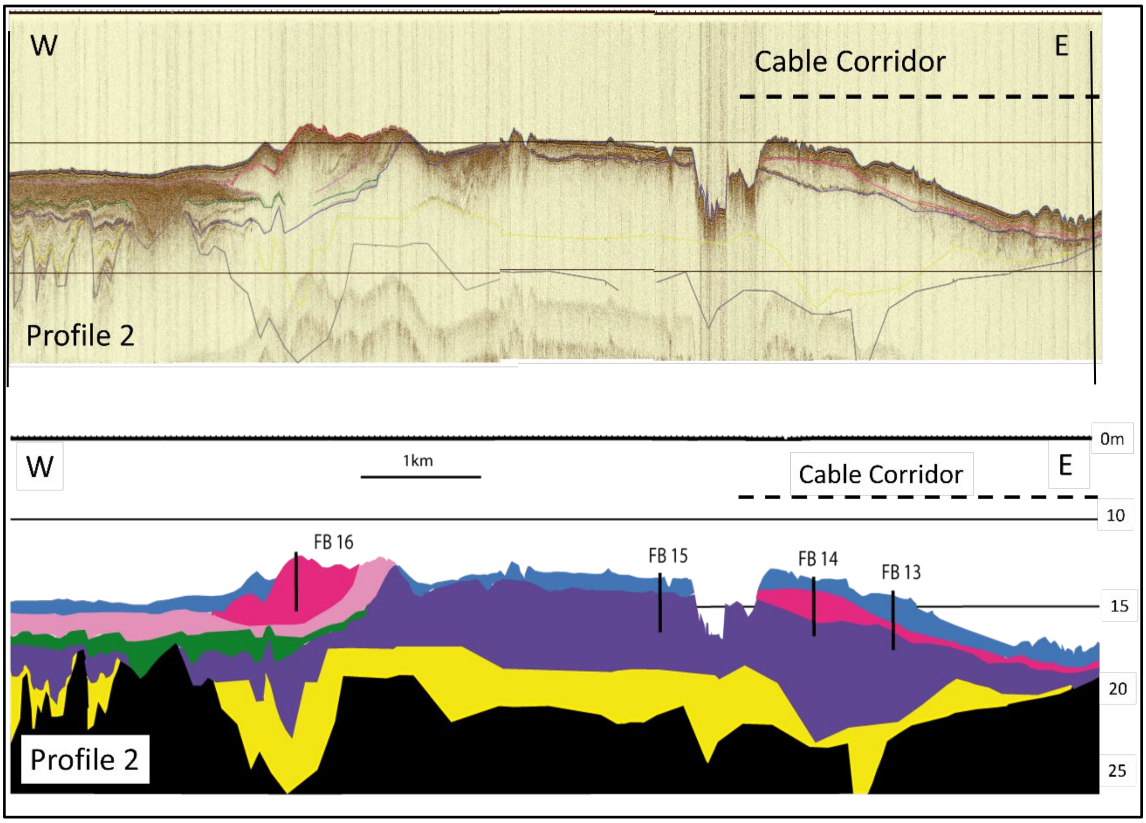
In Profile 1 the seabed is dominated by a relatively thick unit of Late Glacial sandy-gravelly, meltwater deposits on top of the basal till. At the western border a wedge of up to 4 m of silty fine sandy deposits from the Baltic Ice Lake is overlaying the meltwater deposits.

In Profile 2 the meltwater unit is thinning while the fine sandy deposits from The Baltic Ice Lake is thickening up to 4-8 m.

In Profile 3 up to 8m of sandy-gravelly meltwater deposits are infilling the underlying till surface topography. Two other units of importance are the unconsolidated flow till unit in the eastern part, and the Early Holocene non-marine, organic-rich deposit. The upper Early Holocene unit of marine sand and gravel is related to the coastal development phases (Figure 5.9).

All the profiles are covered by a few metres of Late Holocene marine sand.


W
E
Cable Corridor
Profile 1
W
E
1km
Cable Corridor
0m
12
20
FB 20
FB 18
FB 19
Profile 1


W
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Cable Corridor
Profile 2
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Cable Corridor
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10
15
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FB 16
FB 15
FB 14
FB 13
Profile 2

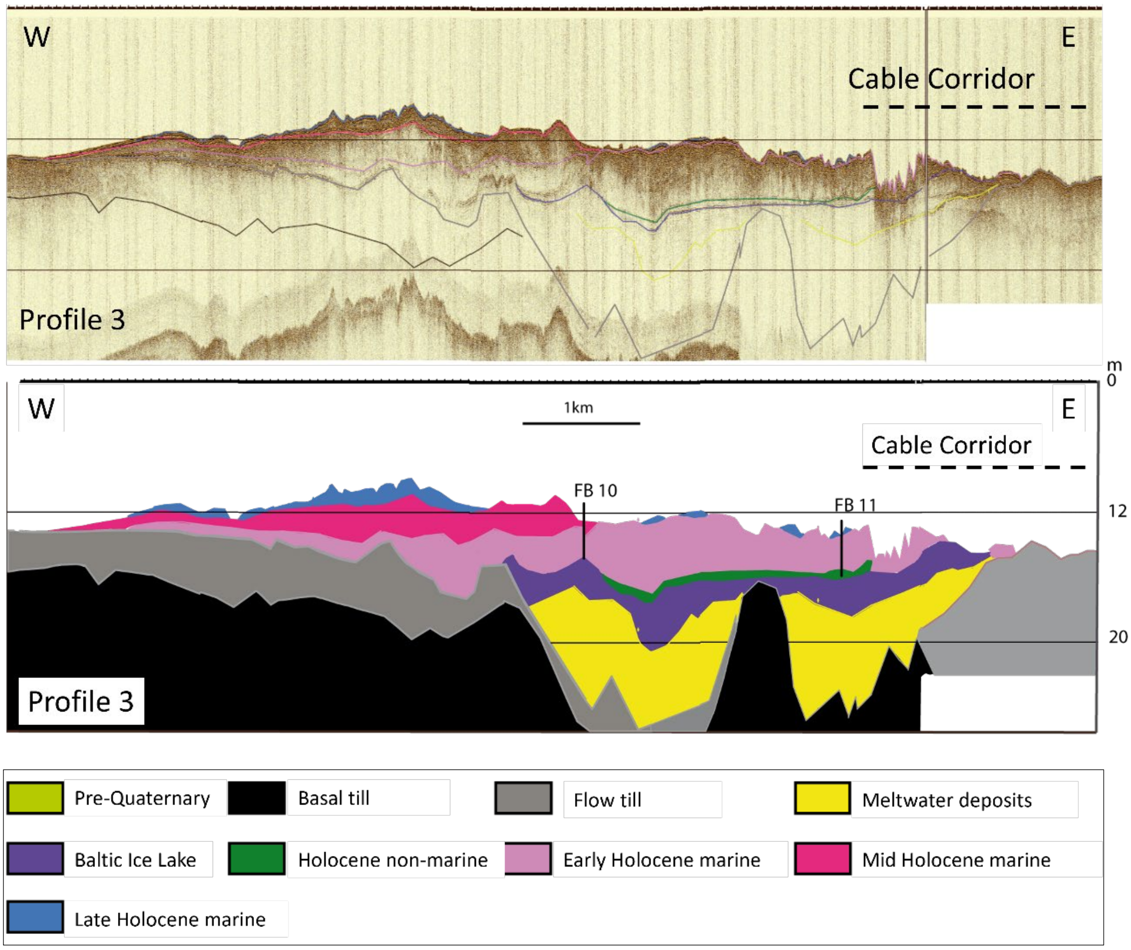

Figure 8.16. Interpreted seismic profiles from the outer part of Faxe Bay. The crossing of the cable corridor is marked with the hatched lines. Redrawn from Lomholt et al. 2016.

9. Evaluation of the geotechnical conditions

The revealed geological development and characteristics of the sediments in the Baltic Sea provide important information for the evaluation of the geotechnical conditions of the Kriegers Flak II North and South OWF wind farms and the cable corridor. Some of the geological characteristics of the mapped units and their possible influence on the geotechnical conditions are discussed below with reference to Velenturf et al. (2021) (Tabel 9.1):

Chalk bedrock:
The chalk bedrock is characterized by varying degrees of weathering, leading to significant variation in properties ranging from those typical for stiff soil to soft rock.

High-lying over-consolidated glacial sediments:
The old glacial deposits may represent over-consolidated and strong sediments, which, in general, can provide a difficulty during construction e.g., for driving piles. They may also comprise more specific hard, potentially heterogeneous, coarse lag deposits (gravel to boulders) that can be difficult to penetrate and may lead to refusal of foundation infrastructure or damage of equipment. Near the seabed, a hard, heterogeneous surface can make it more difficult to predict scour behavior.

Meltwater clay:
Clay deposited in lakes in front of the retreating glacier has not been over-consolidated and may be very soft, with similar challenges as younger soft sediments.

Soft, silty, marine clays and gyttja:
Soft sediments can imply a risk for low geotechnical strength and be a challenge for the foundation design. At the seabed, soft sediments can potentially be unable to bear large loads from e.g., a jack-up rig during construction.

Marine dynamic sand deposits:
Marine dynamic sand deposits may imply migrating erosional and depositional bedforms that can change the seabed topography over the operational lifetime of an OWF site in terms of scouring or burial of e.g., piles or cables.

Peat layers:
Peat layers are very soft, highly compressible, and have a low geotechnical strength. They also have a very low thermal conductivity which might be a challenge for the cable corridor.

Kriegers Flak II North OWF is a rather flat area, located in the outer Faxe Bay at water depths between 20 and 35 m. The area is dominated by Danian limestone covered by a few metres of till, with boulders and a few metres, patchy coverage of Holocene sand and muddy sand.

The seabed geology indicates that the Quaternary sediment succession will be well suited for foundation, while the Danian limestone, if weathered, may be potentially problematic.

Kriegers Flak II South OWF has a sloping seabed from 45 to 20 m b.s.l. and the Upper Cretaceous chalk and the glacial till is covered by an up to 35 m thick wedge of Late Glacial proximal coastal sands prograding southeastward into the Arkona Basin over the basin clay. The seabed slope must be considered, while the wedge sand, in general, is considered well suited for foundation. The easternmost slope foot, however, consists of more than 10 m soft Late Glacial clay and Holocene muddy sand to sandy mud, not well suited for foundation. Below the sand wedge complex a few metres of till is followed by Upper Cretaceous chalk. The till is well suited for foundation while the Cretaceous chalk, if weathered, may be problematic.

For the cable corridor it is difficult to give general geotechnical considerations while the potential corridor covers a very large area. However, the southern part of the cable corridor surrounds the Kriegers Flak II South OWF, and by that, the seabed conditions are comparable to the OWF. This even applies further to the northeast where the cable corridor still is at the edge of the Arkona Basin and is dominated by muddy sand with a relatively high content of water. Further to the north, the cable corridor is covering the outer Faxe Bay where the area is dominated by Danian limestone covered by a few metres of till like the Kriegers Flak II North OWF.

Table 9.1: Sediment types versus geotechnical conditions and challenges. After Velenturf et al. (2021).

Sediment type	**Critical geotechnical conditions/challenges**	**Foundation suitability**
Marine sand	None	Well suited
Marine clay/soft mud	Low geotechnical strength	Not well suited if thick
Peat	High compressibility, low geotechnical strength	Not well suited
Meltwater clay	Low geotechnical strength if not over-consolidated	Not well suited if thick
Moraine clay/till	Over-consolidated and potentially heterogeneous. Can contain coarse lag deposits, boulder stones and dislocated slabs of older sediments	Potentially problematic
Chalk bedrock	Provides a hard substrate for emplacement of seabed infrastructure (e.g., drilled piles). However, may be weathered with lower strengths at the interface with Quaternary sediments	Potentially problematic

10. Archaeological interests

The palaeogeography of the Baltic Sea after the last deglaciation is not only important for establishing the geological model and the subsequent planning of detailed geotechnical investigations, but also of great importance for the screening of marine archaeological interests.

The initial period after the deglaciation was characterized by a highstand phase in the southwestern Baltic Sea (Figure 5.7). The region was deglaciated 16.0-15.0 ka BP and major parts of the Kriegers Flak II North and South OWF were covered by the glaciolacustrine Baltic Ice Lake. This period corresponds to the archaeological Hamburg culture or Hamburgian (15.5-13.1 ka BP) characterized by a Late Upper Palaeolithic culture of reindeer hunters.

The highstand period was followed by an abrupt regression and development of an erosional unconformity at around 12.8 ka BP. During this lowstand period the water level was about 40 m b.s.l. with reed plants growing in the shallow parts of the Arkona Basin. Major parts of the Kriegers Flak region would have been dry land during this lowstand. However, the lowstand period was short-lived and followed by a rapid transgression. A second lowstand period is dated to c. 11.7 ka BP, corresponding to the early part of the Maglemose Culture, and this time the water level was c. 40-45 m b.s.l. and Bornholm was a peninsula connected to mainland Europe (Figure 10.1). Again, the OWFs would have been exposed, but this second lowstand period also was short-lived and soon followed by a new fairly rapid transgression.

The shallow parts of the Kriegers Flak II North and South OWFs have been dry land for long periods during the Late Glacial and Early Holocene. Submerged archaeological sites from the Maglemose, Kongemose and Ertebølle Cultures are known from Mecklenburg Bay off northern Germany (Schmölcke et al. 2006; Hartz et al. 2011; Lübke et al. 2011) and from Køge Bugt and near the island Amager in the Øresund. Submerged fishing constructions made of hazel rods and dated to 9.0-8.4 ka BP have been reported from Hanö Bugt off Skåne (Hansson et al. 2018).

Due to the fluctuating and dynamic shoreline history in the southern Baltic Sea basin, it is possible to find submerged landscapes and archaeological sites from throughout the Holocene. However, the most likely findings are considered to be of early and mid-Mesolithic age.

The possibility to find submerged archaeological sites in the Kriegers Flak area is expected to be small, due to the exposure to a long fetch and high energy environment. Any artifacts most likely have been subject to re-deposition and transportation. Better opportunities for findings are expected along the east coasts of Møn and Zealand facing the Baltic Sea and protected from the dominating westerly winds.

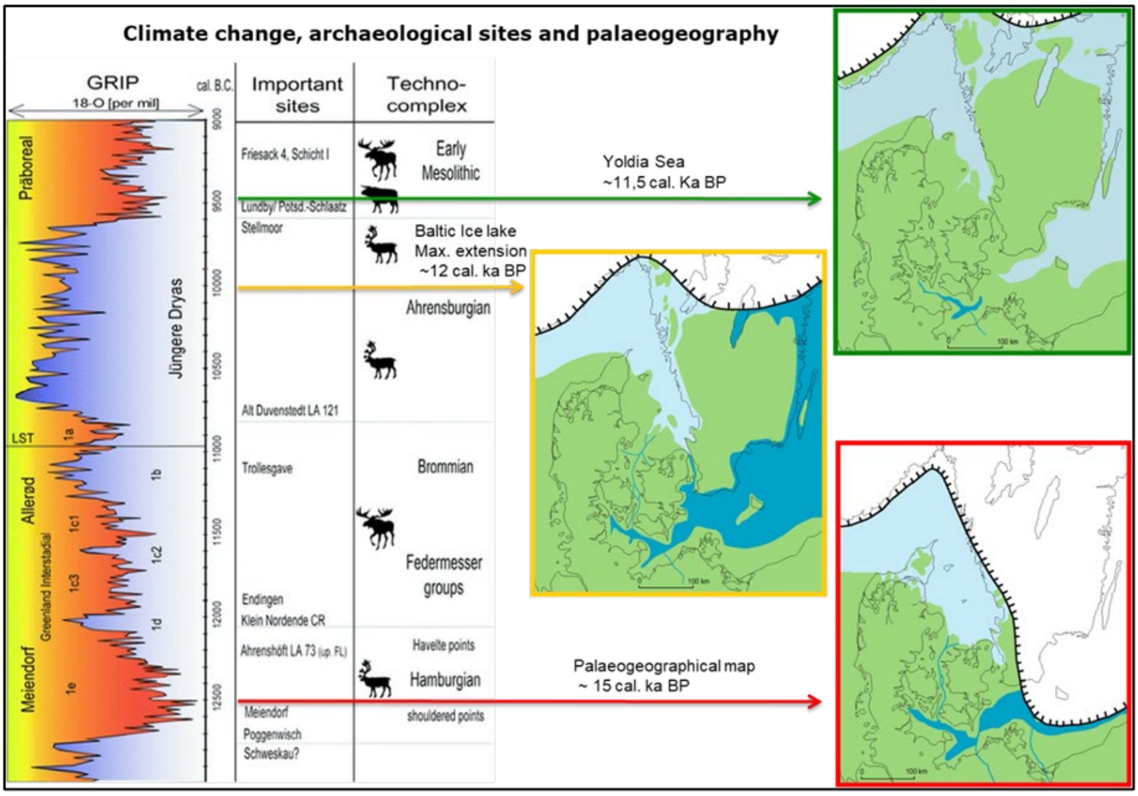

Figure 10.1 General palaeogeographical map of the Late Glacial and Holocene in the Danish area with related archaeological cultures. From Jensen et al. (2003).

11. Conclusions

A conceptual geological model for the Kriegers Flak II North and South OWFs and the adjacent cable corridor area in the southwestern Baltic Sea area has been presented. The model is based on published work of the southwestern Baltic Sea region. Detailed information has been acquired from the GEUS Marta database, Faxe Bay mapping, The Baltic Pipe offshore pipeline transect and from several scientific studies. The interpretation of the seismic transects verified by vibrocores have been vital for the understanding of the complex geology of area. The results of the mapping are presented as seismic examples.

The seabed sediment distribution has been compiled by combining the Danish 1:100.000 seabed sediment map with the EMODnet 1:1M seabed substrate map for the German and Swedish zones.

Information from the existing Kriegers Flak OWF has been presented including a geological model based on detailed seismic studies (Rambøll 2013) and boreholes (GEO 2013). The Kriegers Flak OWF is composed of a rather complex sequence of glacial deposits, as well as Late Glacial and Postglacial deposits, overlying the Upper Cretaceous chalk.

A relative shore-level curve for the period Late Glacial to Holocene is presented for the area. The shore level changes and its relevance for the archaeological screening has been described.

The geological screening leads to several conclusions relevant for the future geotechnical and archaeological evaluation.

Kriegers Flak II North OWF

- The depth to the top of the Pre-Quaternary varies between 40 and 55 m b.s.l. The pre-Quaternary deposits consist of Upper Cretaceous chalk and Danian Limestone.
- Based on a very limited amount of data the succession of geological units indicates that the area is rather uniform in its geological setting.
- The seabed is fairly flat with water depths varying between 20 and 35 m. The subsurface is dominated by Danian limestone covered by a few metres of till with boulders overlain by of few metres cover of Late Glacial fine sand and Holocene sand and muddy sand.
- The geological setting and water depths above 20 m indicates no archaeological interest.

Kriegers Flak II South OWF

- The depth to the top of the pre-Quaternary varies between 40 and 55 m b.s.l. The pre-Quaternary deposits consist of Upper Cretaceous chalk.
- Upper Cretaceous chalk and glacial till are covered by an up to 35 m thick wedge of Late Glacial deposits of proximal coastal sands prograding south-eastwards into the basin over the basin clay.

- The prograding units represent the present eastward dipping seabed slope into the Arkona Basin.

- At the easternmost slope foot, more than 10 m of Late Glacial clay and Holocene muddy sand to sandy mud, covers till and Upper Cretaceous chalk.

- Submerged archaeological sites is unlikely due to water depths above 15–20 m and lack of Postglacial deposits.

<u>The cable corridor</u>

- The seabed conditions of the southern part of the cable corridor are comparable to Kriegers Flak II South OWF.

- To the northeast of Kriegers Flak II South OWF the seabed sediments are dominated by muddy sand with a relatively high content of water.

- To the north, the cable corridor is covering the outer Faxe Bay where the seabed is dominated by Danian limestone covered by a few metres of till comparable to the Kriegers Flak II North OWF.

- Close to landing point at Rødvig, the Upper Cretaceous chalk outcrops at the seabed.

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