DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/63**

Geological desk study Bornholm Windfarm cable transects

Geological seabed screening in relation to possible location of cable transects

Jørn Bo Jensen & Ole Bennike

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

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Client Energinet

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GEUS

Contents

1. Summary

Energinet A/S has requested that GEUS undertakes a geological desk study of the Bornholm cable transect. The study has resulted in a general geological description and establishment of a geological model. The study is based on existing data and is to be used as a background for future interpretations of new seismic data, geotechnical investigations and an archaeological screening.

In this study we used a combination of published work, archive seismic and sediment core as well as CPT data, to assess the general geological development of the south-western Baltic Sea region, including the planned Bornholm OWFs and cable transect from Bornholm to Køge Bugt. Detailed information has been acquired from The Baltic Pipe offshore pipeline transect, which for long stretches runs parallel with the planned cable transects. This means that crucial information comes from seismic profiles and vibrocores, reporting The Baltic Pipe offshore pipeline transect studies.

A geological description has been provided and a geological model presented.

A surface sediment map has been compiled using a combination of Emodnet seabed substrate data from the German and Swedish zones and the latest version (2020) of the Danish 1:100,000 seabed substrate map.

Detailed data are presented in the transect sections A–D among others described on the basis of profile sections A–M, modified from Baltic Pipe investigations (Rambøll 2020). Boomer and sediment echosounder data as well as vibrocore data form the background for the interpretations.

In the south-western part of the Baltic Sea, studies of Late Glacial and early Holocene shore-level changes form the basis for evaluation of the potential to find submerged settlements in the windfarm areas. We consider the early and mid-Mesolithic the most likely.

The detailed studies of the transect A–D provides seabed sediment information that can be used in relation to evaluation of geotechnical challenges to cable deployment as for example in transect A near Bornholm, where Jurassic and Cretaceous bedrock at the seabed as well as glacial boulders may pose problems. However, long stretches may on the other hand be easy to handle due to the existence of sufficient unconsolidated layers.

2. Introduction

GEUS has been asked by Energinet to provide an assessment of the potential cable line transects A to D, from the Bornholm Offshore Windfarms (OWF 1 and 2) to Køge Bugt and Fakse Bugt landfalls. The assessment consists of a presentation of available background data, establishment of a geological model based on existing data and a description of surface-near geological layers along the transect segments A–D. The report addresses possible geological challenges and serve as a background for future interpretations of seismic data and a marine archaeological screening (Figure 2.1).

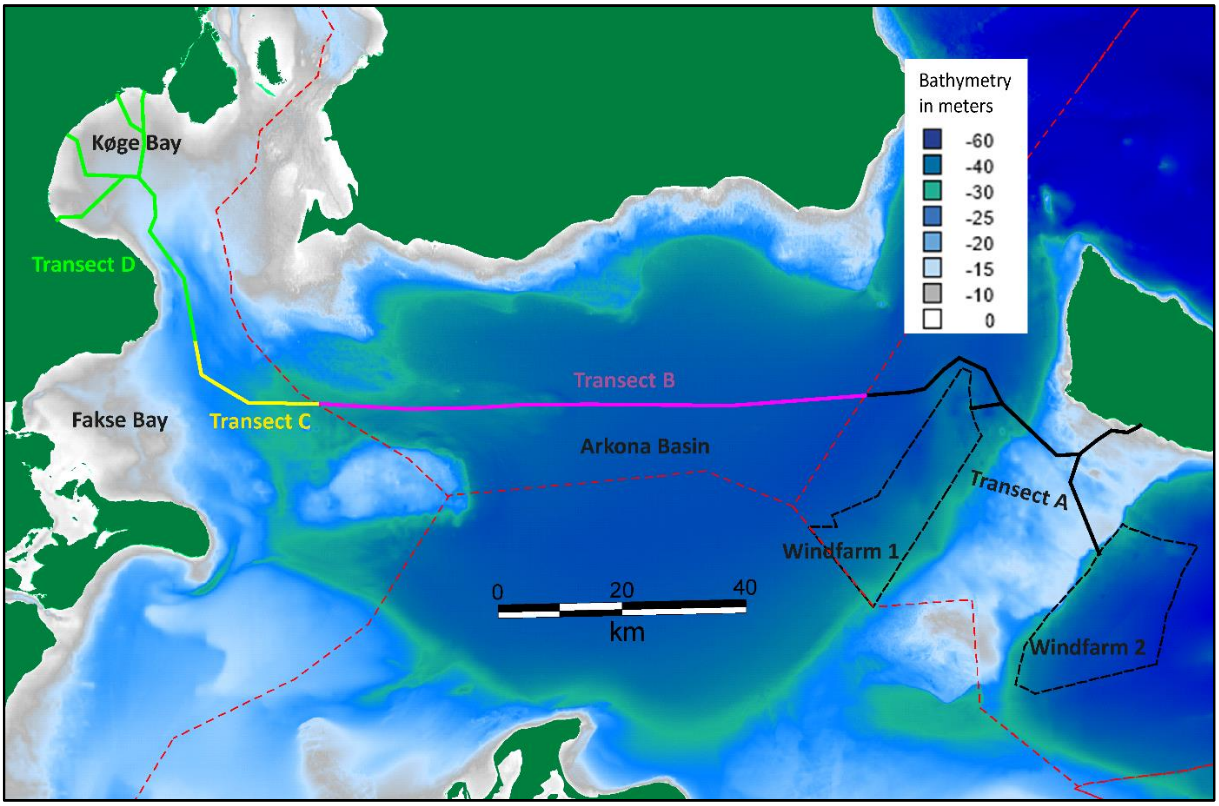


Figure 2.1. Overview map of the south-western Baltic Sea with location of Windfarm 1 and 2 (polygons with black dashed lines) and cable transect segments A to D. The red dashed lines show the border of the Exclusive Economic Zone.

3. Data background

As a basis for the desk study, existing background papers and reports have been used together with primary data from the GEUS Marta database (https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/marin-raastofdatabase-marta/), which is the main supply of shallow seismic data and vibrocore data (Figure 3.1). In addition, data not included in the Marta database have been used. These data comprise Baltic Pipe boomer, pinger and vibrocore data as well as Rønne Banke Windfarm data.

3.1 Background reports

Geophysical and Geotechnical reports for the Rønne Banke OWF (Fugro 2014 a, b, EGS 2014 a, b) provide detailed information on the Bornholm region.

In the report, Geological desk study offshore Bornholm (GEUS 2021) the general geology of the region was presented and existing seismic facies units were described.

Detailed information about The Baltic Pipe offshore pipeline transect is reported by Rambøll (2020). The Baltic Pipe run over long stretches parallel with the planned cable transects, so crucial information comes from seismic transects and vibrocores, reporting The Baltic Pipe offshore pipeline transect studies.

The Arkona Basin geology was the subject of scientific investigations by Lemke (1998). Lemke described the seismic facies and produced combined distribution and thickness maps of Late Glacial clay.

3.2 GEUS archive shallow seismic data and sediment cores

The Marta database includes available offshore shallow seismic data and core data in digital and analogue format (Figure 3.1). An increasing part of the seismic lines can be downloaded as SGY files from the web portal.

As can be seen on (Figure 3.1) a large amount of archive data is available in the transect area, except in the Swedish zone.

However, the existing seismic lines collected by the Baltic Pipe and the Nord Stream projects provide information about the Windfarm 1 and 2 areas as well as long stretches along the planned cable transects, including the Swedish zone (transects B and C). The data types consist of side scan, sediment echosounder and boomer data.

In our study we have included archive data collected by Tom Flodén from Stockholm's University. The data were used for general mapping in the Arkona Basin by Lemke (1998; Figure 3.2).

The existing cores in the Windfarm 1 and 2 areas are all vibrocores with up to 6 m penetration. Most of the vibrocores were collected during the Baltic Pipe project. Core descriptions are available in the Marta database but no samples have been preserved.

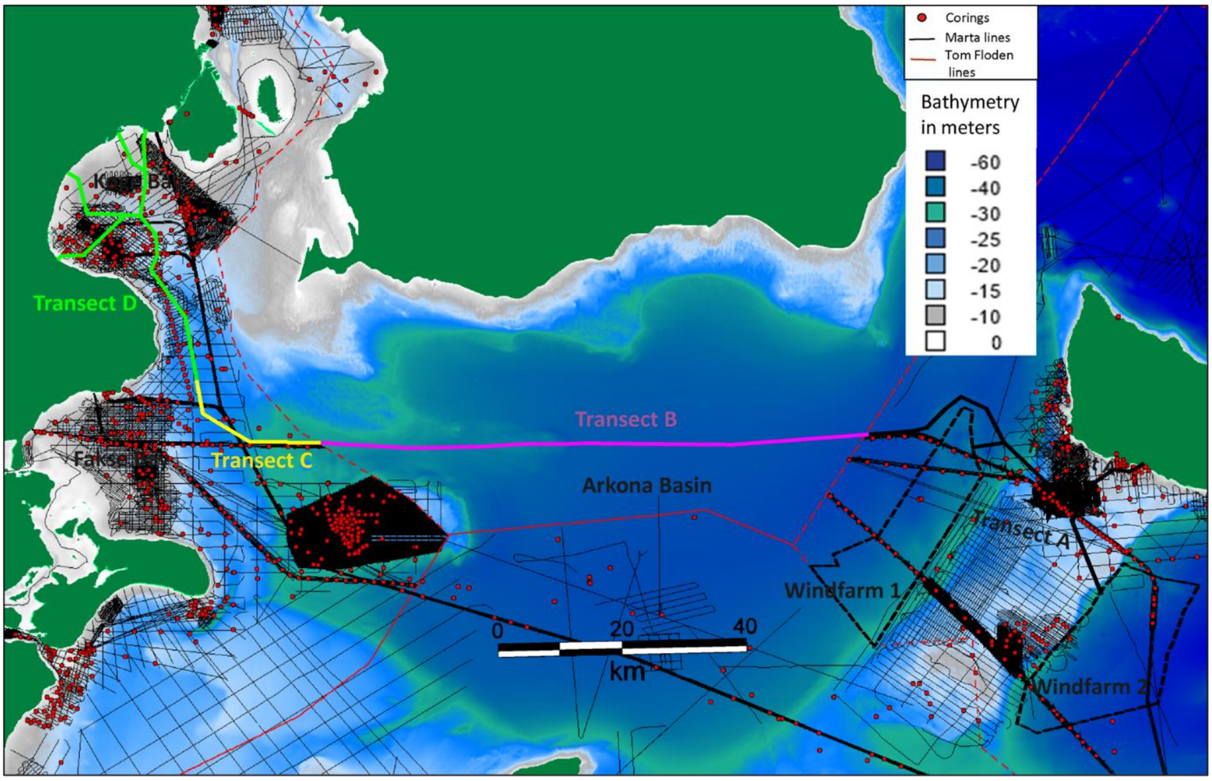


Figure 3.1. Distribution of Marta database seismic grid and core data southwest of Bornholm. The locations of the proposed windfarms are indicated by polygons. The bathymetry is from Emodnet.

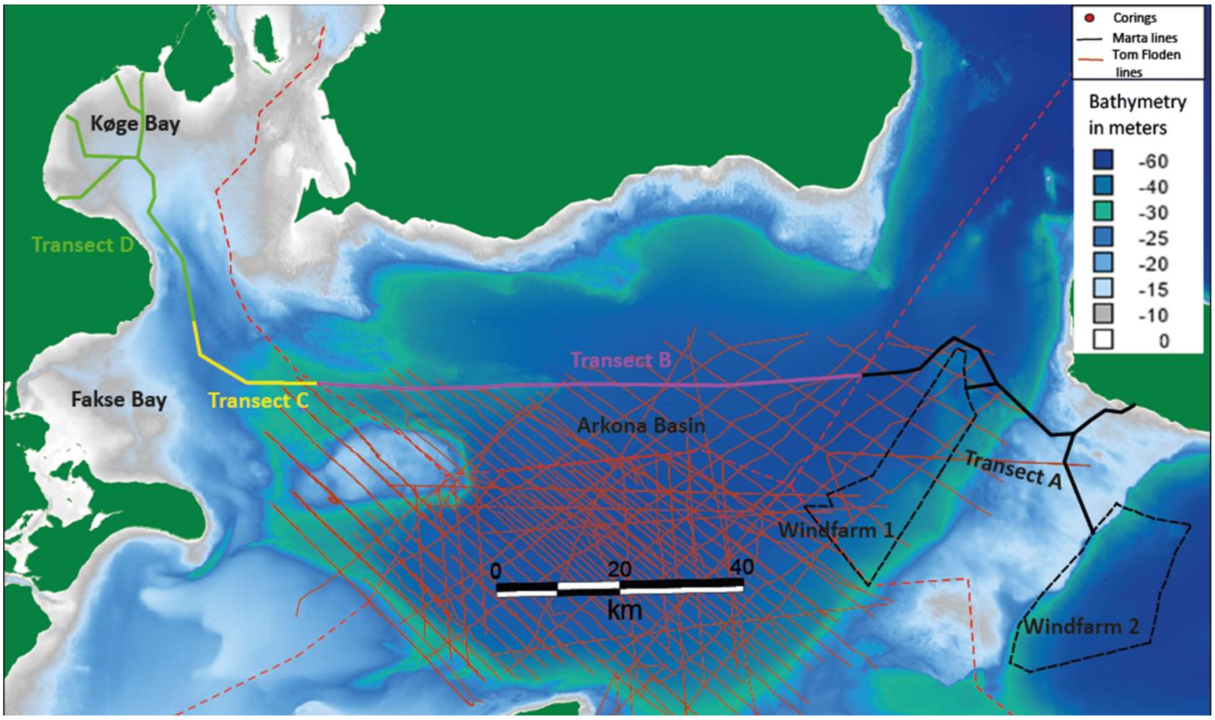


Figure 3.2 Archive seismic data collected by Tom Flodén from Stockholm's University used for general mapping in Arkona Basin by Lemke (1998). The locations of the proposed Windfarms are indicated by polygons. The bathymetry is from Emodnet.

4. Pre-Quaternary geology of the south-western Baltic Sea

Detailed pre-Quaternary descriptions of the Bornholm region were presented in Geological desk study offshore Bornholm (GEUS 2021). The focus of this report is on information related to the possible cable transects.

The south-western Baltic Sea is crossed by the 30–50 km wide WNW–ESE-trending Sorgenfrei–Tornquist Zone that separates the Baltic Shield, the Skagerrak-Kattegat Platform and the East European Precambrian Platform in the northeast from the Danish Basin in the south-west (Figure 4.1). 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 (Liboriussen et al. 1987; Erlström & Sivhed 2001; Mogensen & Korstgård 2003). The old crustal weakness zone was repeatedly reactivated during Triassic, Jurassic and Early Cretaceous times with dextral transtensional movements along the major boundary faults.

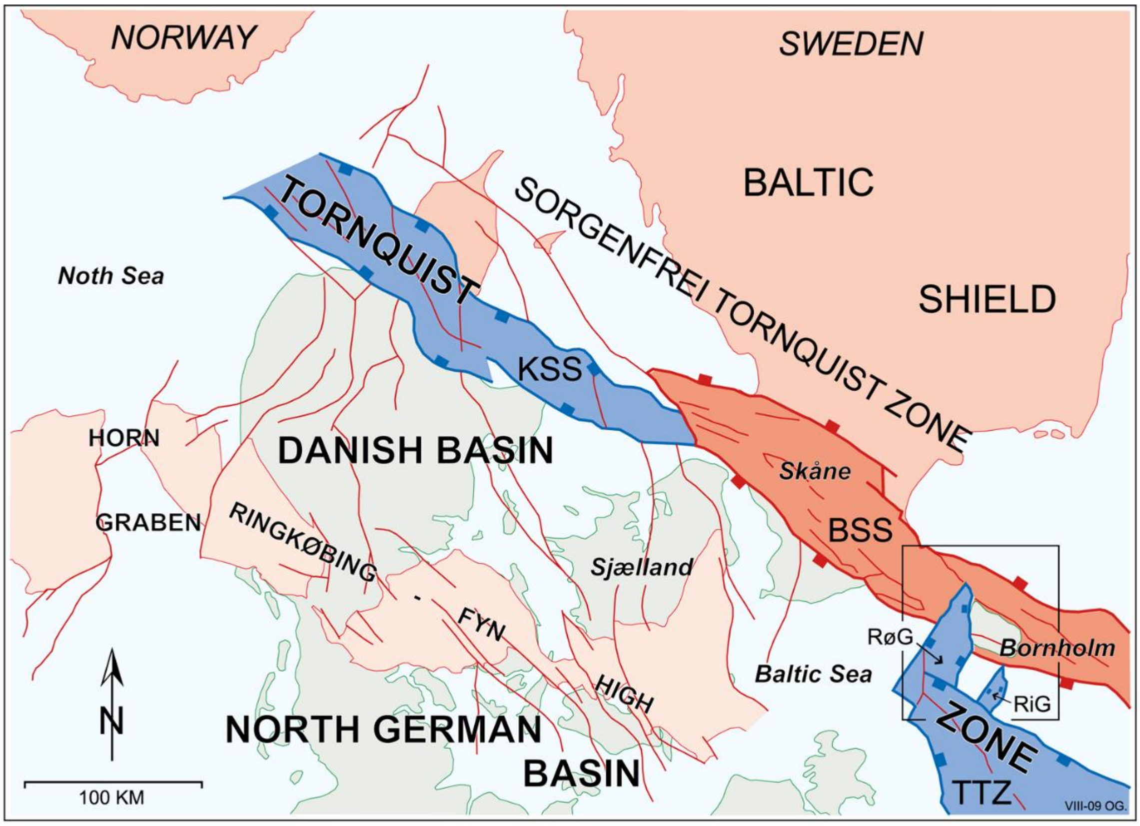


Figure 4.1. Position of the Bornholm area in the Tornquist Zone between the Baltic Shield/East European Platform and the Danish Basin/NW European craton (Graversen 2004, 2009).

The pre-Quaternary surface along the cable transects is presented in Figure 4. 2.. Transect A, near Bornholm show complicated block faulting with bedrock consisting of Jurassic to Danien sediments, whereas the Swedish Zone (transect B), consist of Danien limestone and Fakse – Køge Bugt (Transects C and D) have mixed Upper Cretaceous and Danien chalk and limestone.

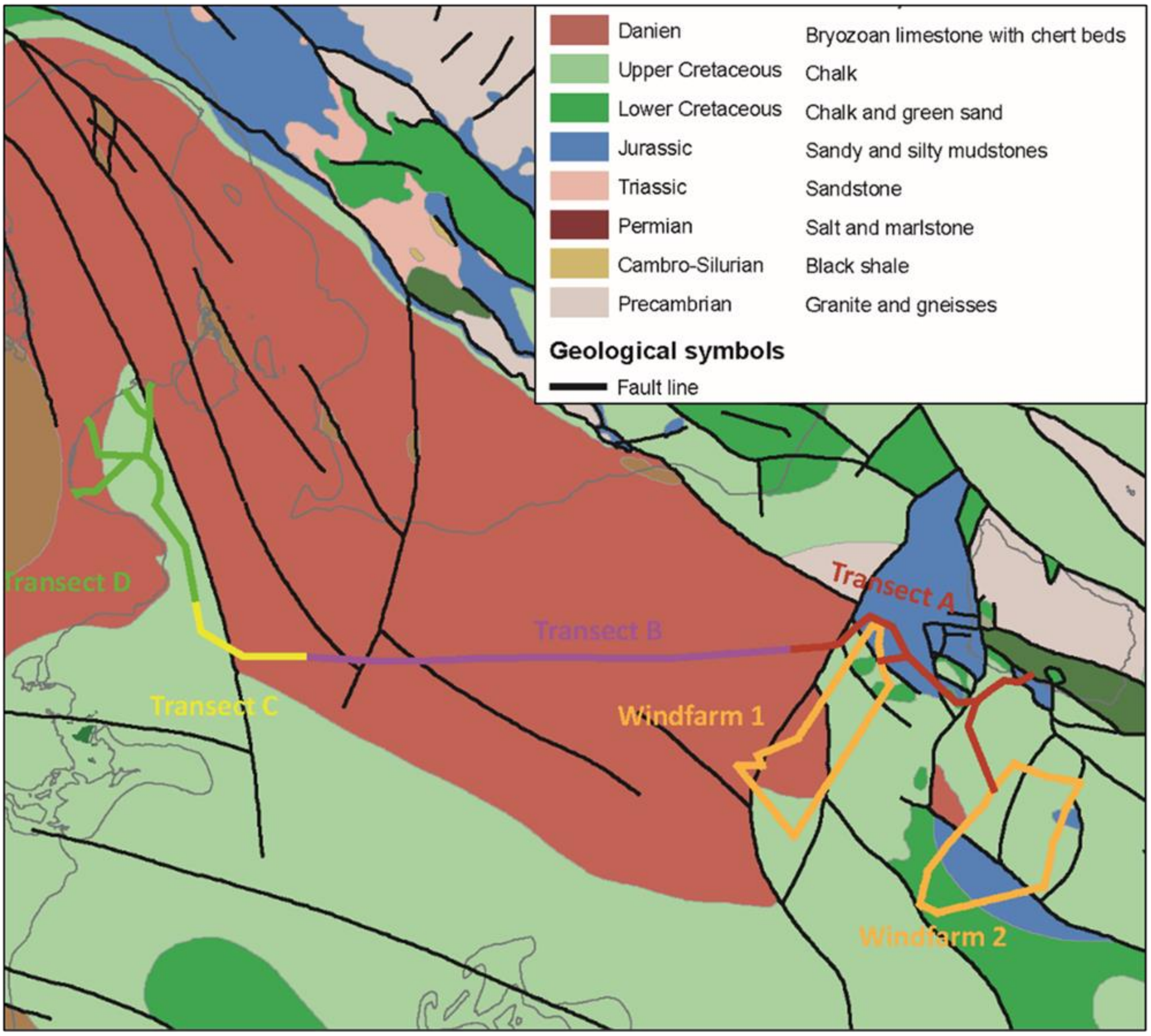


Figure 4.2 Bedrock geology in the cable transect area from Køge Bugt to Bornholm. From Varv (1992). Cable transect A–D is indicated.

The general geological development of the study area has resulted in a characteristic pre-Quaternary morphology (Binzer & Stockmarr (1994) (Figure 4.3).

The combined present bathymetry and pre-Quaternary surface morphology show that only a thin Quaternary unit of a few metres to about 30 m thickness can be expected in the mapped areas. Unfortunately, most of Transect B and C are not mapped in relation to the pre-Quaternary surface morphology. The expectation is however that the northern part of Arkona Basin follows the same pattern, whereas an increasing Quaternary sediment thickness is observed in the southern part of the Arkona Basin (Lemke 1998).

The seabed sediment map in Figure 6.1 shows large areas with exposed pre-Quaternary seabed sediments and sedimentary rocks offshore Bornholm and in the near-shore northern Fakse Bugt area.

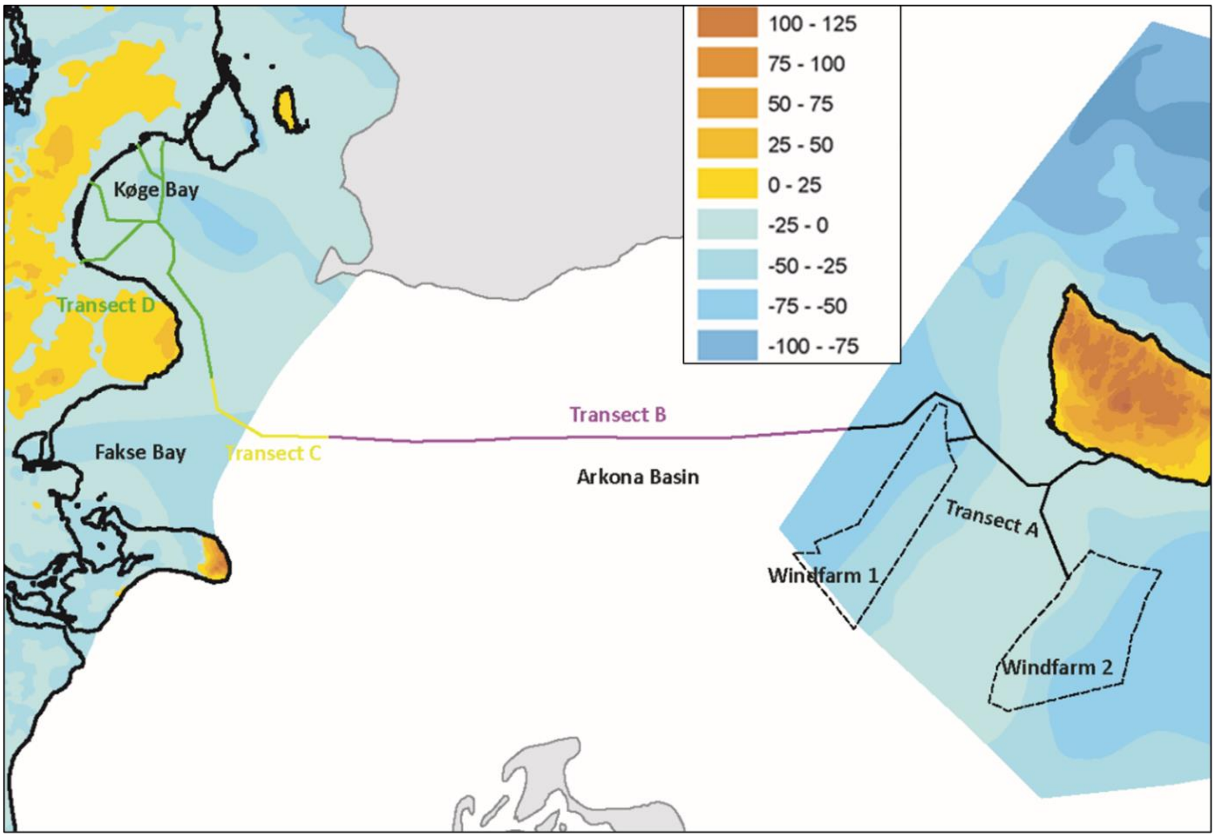


Figure 4.3 Pre-Quaternary morphology (Binzer & Stockmarr (1994). Cable transects A to D are indicated.

5. Quaternary geology of the south-western Baltic Sea

Four Late Saalian to Late Weichselian glacial events, each separated by periods of interglacial or interstadial marine or glaciolacustrine conditions, have been identified in the south-western Baltic region. The thickness of Quaternary sediments in the region can exceed 100 m in the basins (Jensen et al. 2017). The Scandinavian Ice Sheet reached its maximum extent in Denmark about 22,000 years BP followed by stepwise retreat.

The Bornholm region was probably deglaciated shortly after 15,000 years BP. Moraine ridges on Rønne Banke and Adler Grund trending parallel to the former ice margin resemble ridges reported southeast of Møn (Jensen 1993). They may mark short-lived re-advances during the winter, formed during the general retreat of the ice margin. After the deglaciation, a glaciolacustrine environment, the Baltic Ice Lake, was established with ice bergs (Figure 5.1).

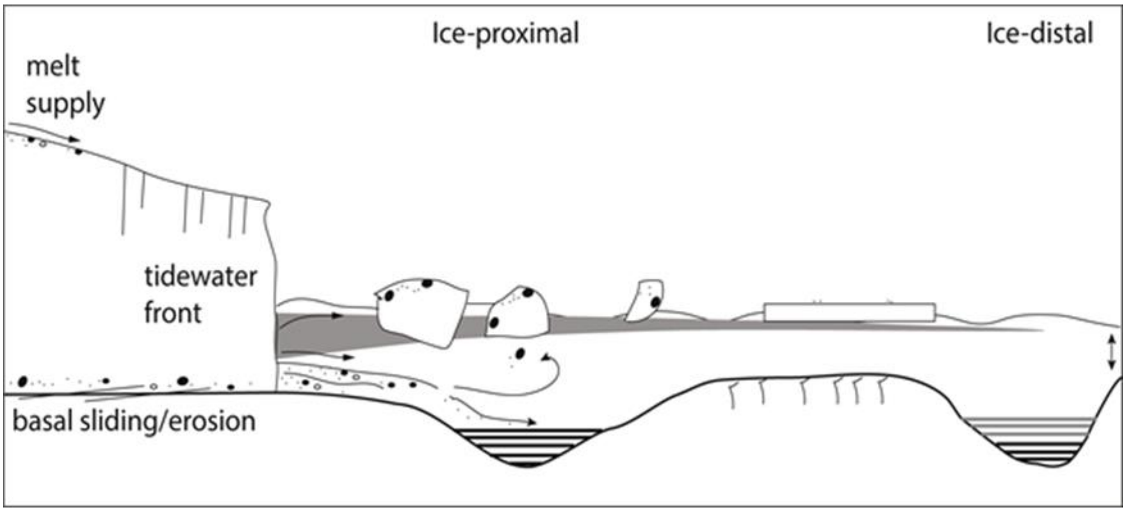


Figure 5.1. Illustration of a glaciolacustrine depositional environment.

The Quaternary sedimentation in the Køge Bugt, Fakse Bugt, Arkona Basin and Bornholm Basin, has been intensively studied in relation to the development of the Late- and Postglacial Baltic Sea phases (Jensen et al. 1997, 1999), because of the well-preserved Baltic Ice Lake clay and the Yoldia Sea and Ancylus Lake clay, as well as the brackish to marine Littorina Sea clay and mud deposits. The Holocene history was documented by Andrén et al. (2000).

5.1 Palaeogeography of the deglaciation of Denmark

The knowledge about the general deglaciation and Postglacial history of the south-western Kattegat and the western Baltic can be presented in a series of palaeogeographical maps

Figure 5.2 a and b.

- About 18,000 years ago, the deglaciation from the largest glacier extension (Main Stationary line) in Jutland had reached a stage where the ice margin roughly followed the Swedish west coast, the present Sealand 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, and the sea covered major parts of northern Jutland.

- At the next stage, about 16,000 years ago, the ice margin had retreated to the Øresund region and the western part of Skåne leaving an ice lobe that covered the southern part of Sealand and followed the present southern coastline of the Baltic Sea. The ice margin was directly connected by a broad meltwater channel to the Kattegat marine basin, which at this stage was affected by an initial relative sea-level regression, whereas local lakes were under development along the ice margin in the south-westernmost Baltic Sea as example in Køge Bugt.

- A controversial stage of the deglaciation was reached about 15,000 years ago, as the ice marginal retreat had reached central Skåne. For this stage only limited information has so far been available about the present offshore area, but investigations in Polish waters combined with data from German and Danish waters show that the ice margin must have been situated west of Bornholm and a large lake must have been dammed in front of the ice sheet with connection through the Great Belt to the Kattegat, which at that time was increasingly affected by a regression. Apart from meltwater flow from the glacier area west of Bornholm, major meltwater contributions were provided by German and Polish rivers as proved by the existence of major Late Glacial delta deposits.

- After the initial damming of The Baltic Ice Lake two phases of damming occurred followed by major drainage events. The last and most extensive damming was at its maximum about 12,000 years ago, when minor channels drained the lake through the Great Belt and Øresund and only a small land bridge separated the Baltic Ice Lake from the sea in south-central Sweden. Further retreat resulted in a catastrophic drainage event in south-central Sweden and the lake level dropped by about 25 m.

- About 11,500 years ago a strait was established through south-central Sweden and the Baltic Basin was transformed into a marine basin called the Yoldia Sea. This name comes from an arctic bivalve species named Portlandia (Yoldia) arctica, which is found in sediments deposited during this time. 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 below present sea-level.

- Continuous glacio-isostatic uplift of south-central Sweden closed the connection to the ocean and the last lake phase of the Postglacial Baltic was established, called the Ancylus Lake. The stage is named after a fresh-water gastropod, Ancylus fluviatilis, which lives in rivers and in the coastal zone of large lakes. Due to damming, the lake reached a maximum level about 10,200 years ago with only a narrow drainage pathway through the Great Belt into the southern Kattegat. Initial transgression resulted here in the formation of a rather large lagoon – estuary basin, partly blocked by transgressive coastal barriers. Remains of this system are preserved on the sea floor (Bennike et al. 2000; Bendixen et al. 2017).

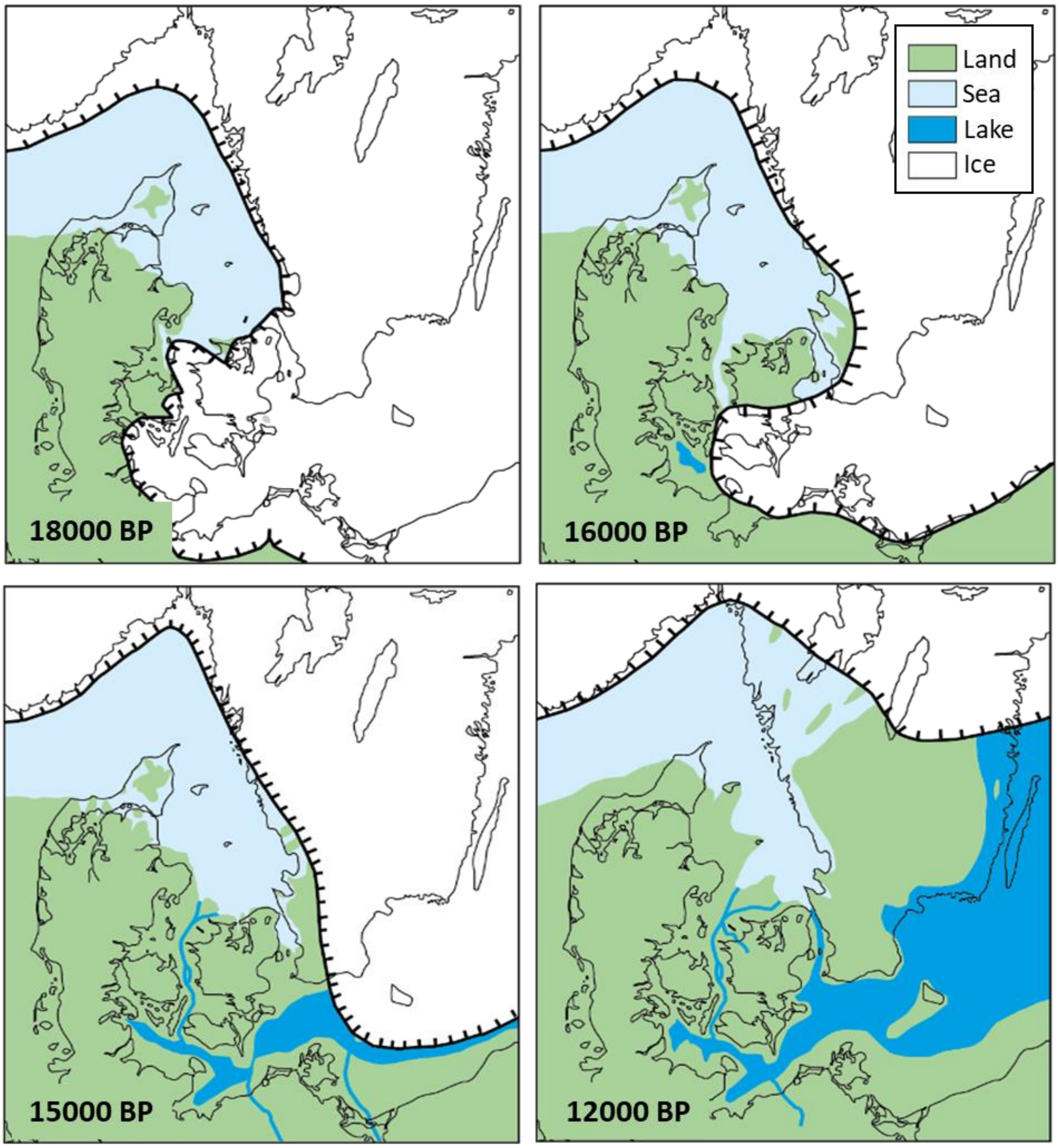
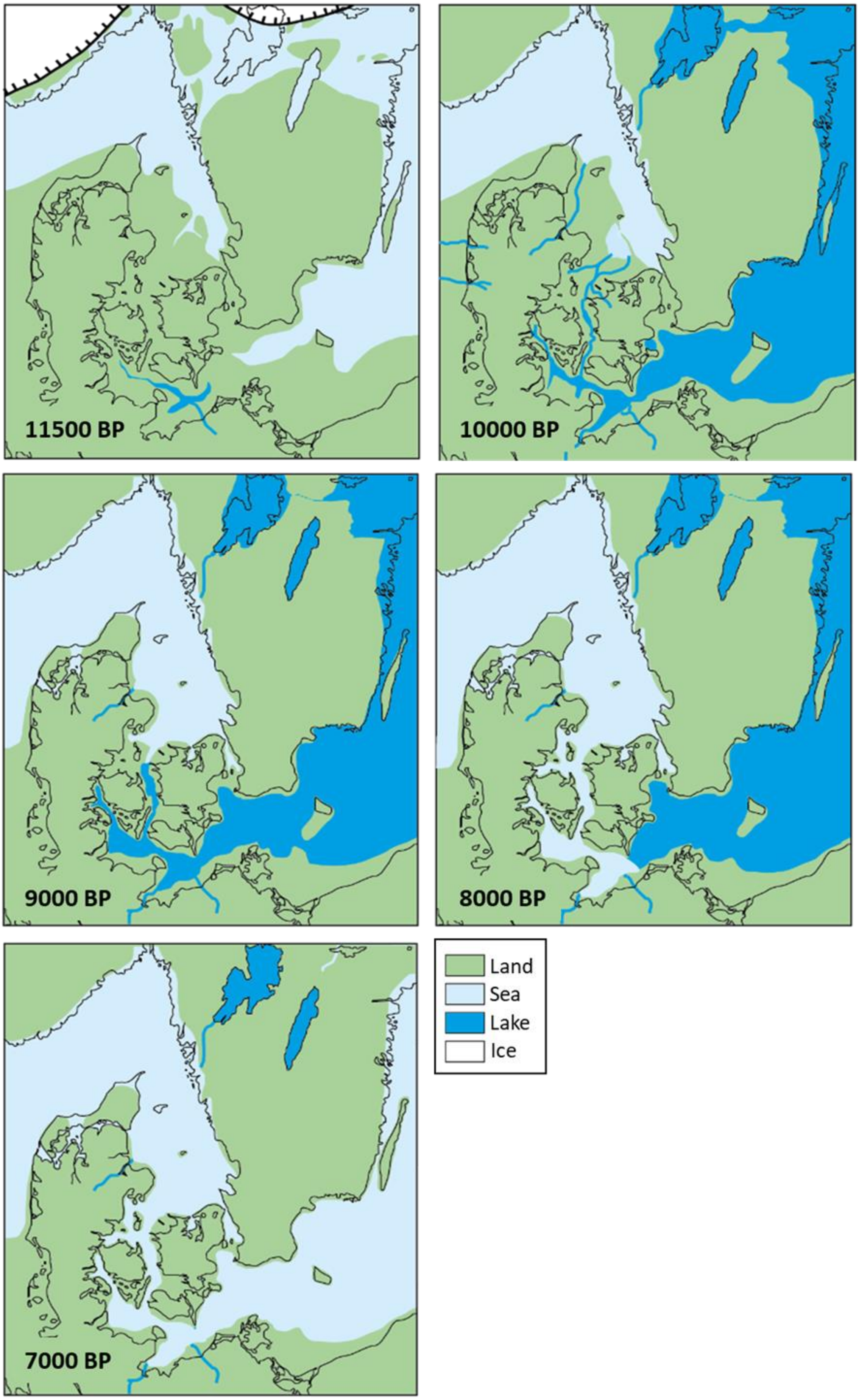


Figure 5.2. Palaeogeographical maps showing the development of the Danish area from ca. 18,000 to ca. 7000 years before present (BP). Modified from Jensen et al. (2003). The figure continues on the next page.



11500 BP
10000 BP
9000 BP
8000 BP
7000 BP
Land
Sea
Lake
Ice

- About 10,000 years ago the Ancylus Lake level dropped, maybe by about 9 m within a few hundred years. The traditional opinion has been that the drainage was through the Great Belt. However, investigations in the southern Kattegat, the Great Belt as well as at the thresholds Gedser Reef – Darss Sill, south-east of Langeland and in the south-western Kattegat show that only a small lake level fall in the order of a few metres can be provided by this drainage route. Moreover, for the time of drainage calm lake and estuarine sedimentation is recorded in the Great Belt and in the south-western Kattegat.
- The calm lake sedimentation was followed by a gradual transgression and a change into brackish water conditions about 9400 years ago and a fully marine environment was reached in the Great Belt 9100 years ago marking the beginning of the Littorina transgression.
- About 8000 years BP the transgression had reached the Darss Sill – Gedser Reef area.
- And about 7000 years BP also the western part of the Baltic proper was marine.

5.2 The geological model in the Bornholm region

The Quaternary geological model for the region builds on a network of seismic data from the Marta database as well as scientific data collected over the last few decades, mainly in connection with the EU BONUS project: Baltic Gas. A seismic stratigraphy was developed, and core positions were selected and followed by an Integrated Ocean Drilling Program (IODP 347).

At Expedition 347 in October 2013, cores were recovered at Site M0065 (Figure 5.4, Figure 5.5, Figure 5.6 and Figure 5.7) in the Bornholm Basin, with an average site recovery of 99%. The water depth at the coring site was 84.3 m, with a tidal range of <10 cm. A total depth of 73.9 m b.s.f. was reached, at that depth bedrock was encountered. Piston coring was used to recover the clay lithologies before switching to a combination of open holing and hammer sampling to maximize recovery in the sandier lithologies. No samples were recovered from the lower part and only the upper 49.2 m could be described.

The obtained sediment sequence was divided into three lithostratigraphical units (Andrén et al. 2015). Description of lithology and downhole core logging was performed with physical parametres illustrated in Figure 5.7.

A combined geological model based on seismic data and core data was established by Jensen et al. (2017). Results from the rest of the south-western Baltic Sea show that the model is valid for the whole of the cable transect region.

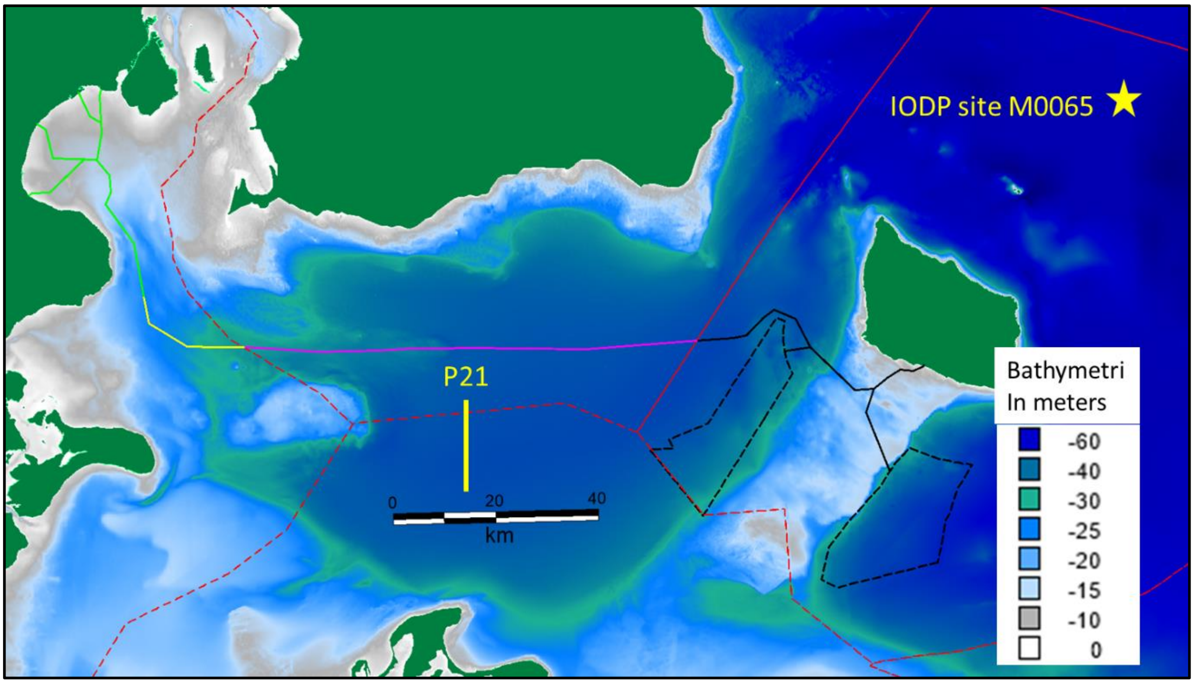


Figure 5.3. Map of the south-western Baltic Sea with location of IODP sire M0065 (yellow star) in relation to the Windfarm 1 and 2 (polygons shown with black dashed lines) and cable lines. P21 shows the location of seismic line from Mathys et al. (2005). Red dashed lines: EEZ border.

Six seismic units were described all separated by unconformities (Figure 5.4).

The Crystalline basement and Sedimentary bedrock Unit V as well as the Glacial Unit IV were mainly identified on deeper seismic airgun data, whereas details of the Late- and Post-glacial softer deposits are best seen on the sediment echo-sounder profiles (Figure 5.5).

The bedrock distribution follows the deeper structures shown in Figure 4.1 and Figure 4.2 and the glacial deposits follows the regional glaciations.

The Late- and Postglacial Units III–I were deposited in basins with a changing shore level, well known in the south-western Baltic Sea (Figure 5.4) (Andrén 2000 and Uscinowicz 2006) and a close match can be expected between shore-level lowstands and allostratigraphical unconformities.

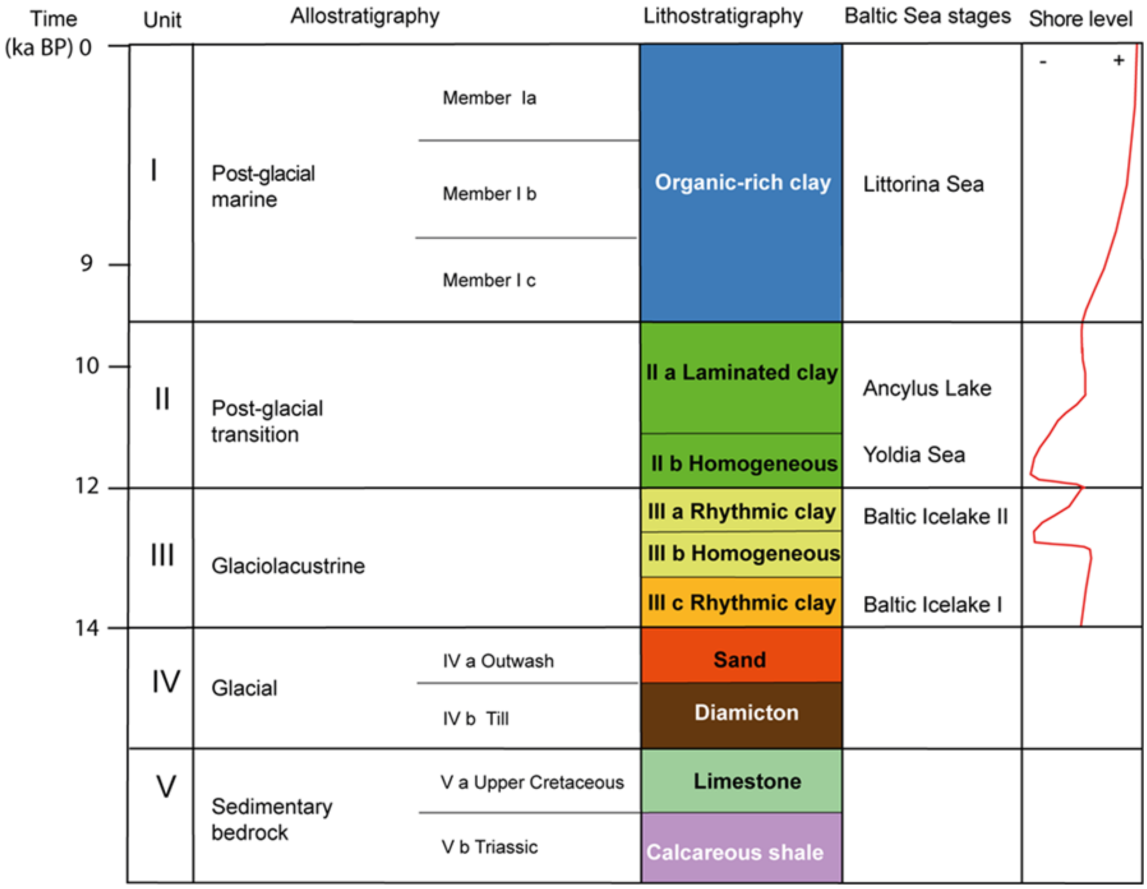


Figure 5.4. Stratigraphical subdivision of the Bornholm Basin (Jensen et al. 2017). The seismic Units I–VI represent allostratigraphical formations, some of which are divided into members, all bounded by unconformities. Mappable lithostratigraphical formations (informal) are identified within the allostratigraphical framework and Baltic Sea stages as well as the general Baltic Sea shore-level changes are correlated with the established allostratigraphy.

5.2.1 Unit IV Glacial deposits

The glacial deposits drape the pre-Quaternary irregular surface. Unit IV is usually 10–20 m thick, but in the Christiansø Ridge zone, crystalline basement rocks are sometimes found at the seabed, whereas the unit is more than 50 m thick in the strike-slip fault basins. The upper reflector is an irregular unconformity, and the internal configuration is mostly chaotic except in some of the strike-slip fault basins, where internal unconformities exist. The glacial deposits consist of diamicton and glacial outwash sediments, as documented in the IODP 347 sites (Figure 5.5) and Andrén (2014).

The distribution of glacial sediment facies is in general chaotic with alternating sections of clast-rich muddy diamicton and bedded, medium grained sand with cm to dm-scale laminated silt and clay interbeds as seen in IODP site 66. However, IODP site 65 is in a strike-slip fault basin, where there is a clear subdivision into a lower diamicton member (IVb) and an upper outwash member (IIIa), separated by an unconformity.

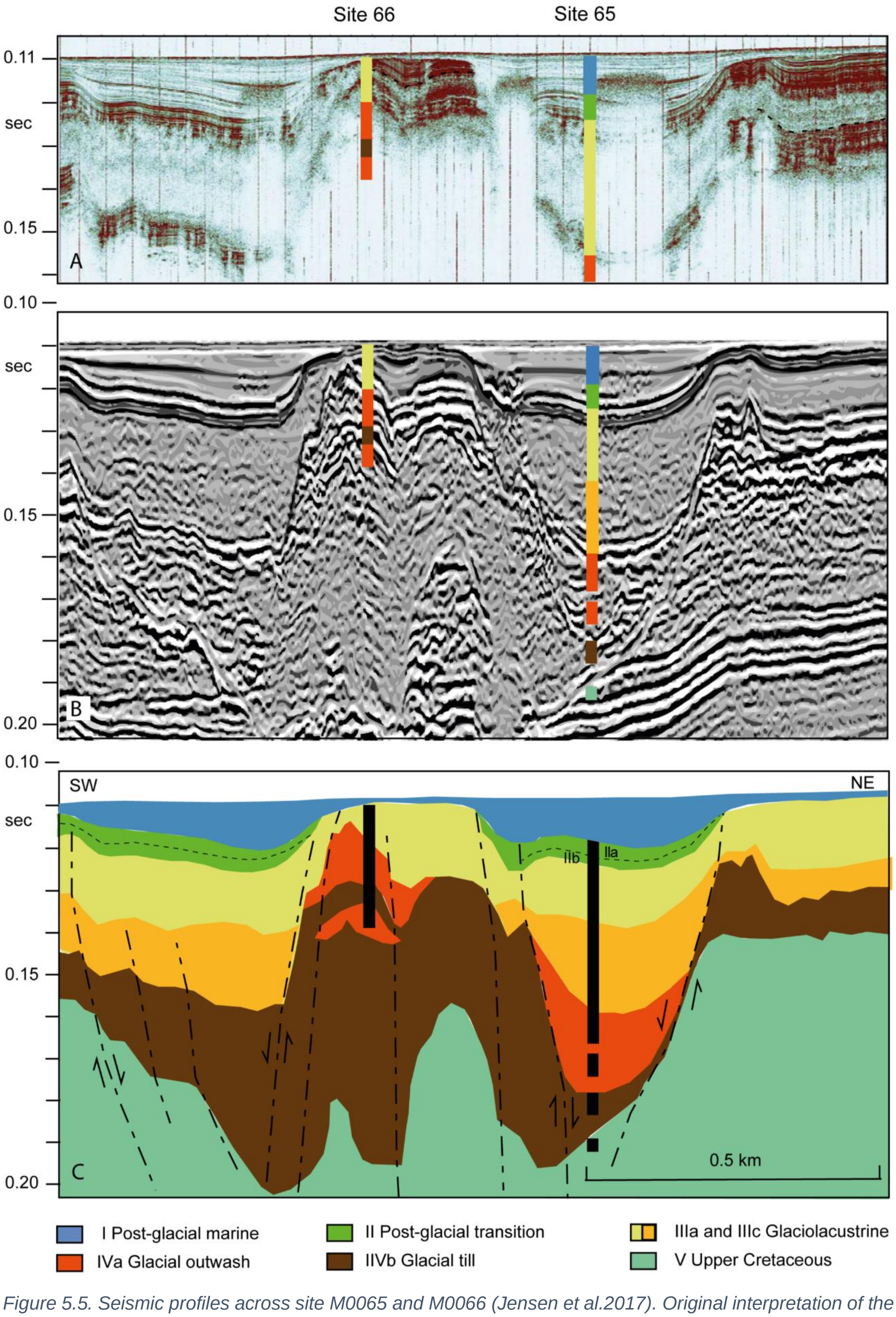


Figure 5.5. Seismic profiles across site M0065 and M0066 (Jensen et al.2017). Original interpretation of the seismic transect: Airgun (A) and Atlas parasound (B) data (Andrén 2014), as well as sediment documentation for sites 65 and 66. The interpretation (C) follows the classification in seismic units described in Figure 5.4. The location of the IODP sites is shown in Figure 5.3.

5.2.2 Unit III Late Glacial glaciolacustrine deposits

The glaciolacustrine sediments cover the irregular unconformity of the glacial deposits in the Bornholm Basin, except in the topographically high Christiansø Ridge area, where Unit IV is truncated or absent, indicating erosion. In the basin areas, 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. An increased thickness of more than 50 m is found in the minor strike slip fault basins (Figure 5.5). The internal reflection configuration also varies through the basin.

Unit III is sub-divided into three subunits:

- IIIc is the lowest unit characterized by greyish brown clay with weak lamination by colour and few silt laminae in mm scale. Large intervals are dominated by massive to contorted appearance; numerous interspersed, grey clay/silt intraclasts of mm to cm scale, very well sorted.
  Unit IIIc corresponds to Baltic Ice Lake deposited in front of the retreating Weichselian glacier and represents an early stable phase of the glaciolacustrine environment. The parallel reflectors and rhythmically layered clay, seen all over the Bornholm Basin, are interpreted as varved glaciolacustrine clay. The upward decrease in grain size from silty clay to clay and the decreasing frequency of sand laminations indicate that the ice margin became more and more distal to the Bornholm Basin.

- IIIb unit consists of dark grey, homogenous clay. It is a basin-wide intermediate zone consisting of homogeneous clay that can be related to the first Baltic Ice Lake drainage that occurred in the late Allerød (Figure 5.6). This drainage led to a 10–20 m drop in water level and to the formation of unconformities in the shallow parts of the south-western Baltic Sea (Jensen et al. 1997; Bennike & Jensen 1998, 2013; Uscinowicz 2006). The relatively deep Bornholm Basin was covered by water even after this drainage event and the unconformity seen in shallow areas is replaced by a basin correlative conformity. However, the water level drop in the Bornholm Basin is reflected in changes in internal reflector configurations and in a lithological shift to homogeneous clay.

- IIIa is the upper unit, it consists of greyish brown, silty clay with horizontal lamination, downwards coarsening to fine- to medium-grained sand with laminated silt; the lowermost few metres are massive, medium-grained sand with few dispersed pebbles, detrital carbonate in all grain sizes up to fine gravel. The indistinct lamination in subunit IIIa, combined with homogeneous and contorted sedimentary structures as well as clay intraclasts may indicate slumping in an unstable sloping environment with high sedimentation rates. This could be due to piano key neotectonics (Eyles & McCabe 1989) that led to reactivation of minor, along-basin, strike-slip faults.

The sediments in unit III are barren of diatoms, foraminifers or ostracods and the depositional environment is interpreted as a glacio-lacustrine environment. The sandy sediments in the lowermost part of the retrieved succession represent a proximal glacio-lacustrine environment.

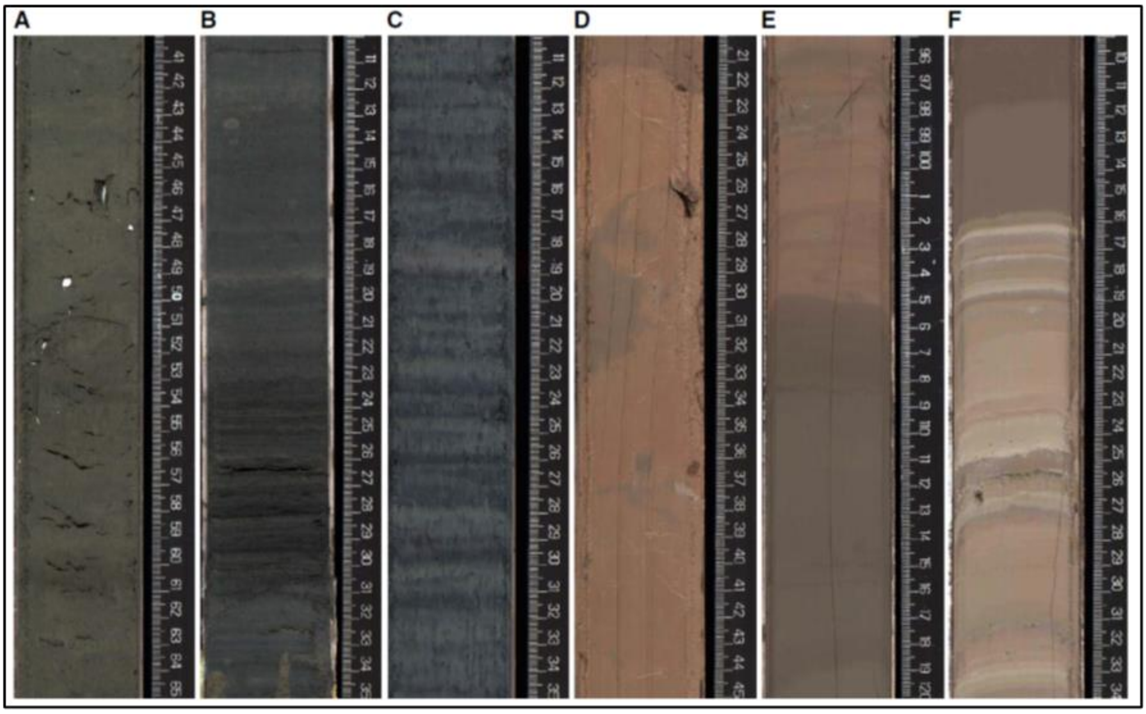


*Figure 5.6. Examples of lithostratigraphic units, Hole M0065A. A. Unit I. B. Unit I. C. Unit II. D. Subunit III*c. *E. Subunit IIIb. F. Subunit III*a.

5.2.3 Unit II Early Postglacial transition clay

Unit II conformably drapes the glaciolacustrine sediments in the Bornholm Basin with a rather constant thickness of about 4 m. The seismic characteristics of Unit II are closely spaced parallel reflectors with an upward decreasing amplitude. A strong reflector is seen at the upper boundary. In the minor strike-slip fault basins, local thickening of the unit, on-lapping and erosional truncation is observed. This is probably due to synsedimentary down-faulting of the basins and relative uplift of the margin (Figure 5.5).

At IODP site 65, which is in one of the minor strike-slip fault basins, Unit II is 4 m thick and consists of grey to dark grey clay. In the lowermost part (subunit IIb) homogeneous brown clay is observed, gradually upwards changing to grey clay with intervals of black spots and specks. The uppermost part of the clay (formation IIa) is laminated by colour with very fine dark grey iron sulphide-rich, 2–3 mm thick lamina. The density of laminae decreases downwards. The basin-wide clay drape indicates accumulation of Unit II in a deep-water basin with only weak bottom currents. Previous studies in the Bornholm Basin (Kögler & Larsen 1979; Andrén et al. 2000b) documented the same lithological sequence; it has been interpreted to represent deposition in the Yoldia Sea (the lowermost homogeneous part) whereas the Ancylus Lake clay (AY) is represented by the uppermost laminated part. Sulphide migration downwards from the upper organic-rich sediments is a likely explanation for the diagenetic iron sulphide enhanced laminations.

5.2.4 Unit I Mid- and late Postglacial marine mud

In the central Bornholm Basin, northeast of the Christiansø Ridge, the basin infill of the youngest Unit I have an asymmetrical external wedge shape and the sediment echo-sounder data show complex internal reflection patterns (Figure 5.5). Frequent low amplitude, concave and internal on-lap parallel reflectors dominate the major synsedimentary down-faulting zone. In the minor strike-slip fault basins, we established three allostratigraphical members (Ic, Ib and Ia; Figure 5.4). These members show asymmetrical bundled on-lap infill of the basins and the bundles are bounded by reflectors representing internal unconformities and correlative conformities.

The complex reflection pattern indicates that late Postglacial down-faulting resulted in episodic, synsedimentary deposition in the strike-slip basins and that sub-recent to recent sedimentation is still asymmetrical with sedimentation in the southern central basin and erosion at the north-eastern margin of the basin. Transport of sediments from the Arkona Basin west of Bornholm into the Bornholm Basin and along the southern basin margin is a likely process to have provided sediment deposited as a wedge-shaped contourite.

In IODP 65, Unit I is ~7 m thick (Figure 5.5). The unit consists of 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. Scattered shell fragments are found down to the lowermost transition zone to Unit II, where about 10 cm of non-bioturbated clay with prominent mm-thick laminae is found. Organic debris is common (possibly algal or plant debris) and large centric diatoms are found. Some silt and sand are also present. The boundary to Unit I is gradual. The organic-rich clay, with bioturbated indistinct lamination and intervals of black layers, indicates more oxic conditions during the mid- and late Holocene in the Bornholm Basin than in the central Gotland Basin. The lowermost laminated transition zone may represent an initial anoxic phase, similar to the anoxic phases reported in the Gotland Deep (e.g., Zillén et al. 2008).

5.2.5 Physical properties

This section summarizes some of the preliminary physical property results from Site M0065. Gamma density was measured at 2 cm intervals (Figure 5.7). Gamma density increases progressively from the core top to the base of lithostratigraphic Subunit IIIb. Gamma density exhibits a shift to higher values in Subunit IIIc and remains generally high (~2 g/cm^3) throughout lithostratigraphic Subunit IIIc.

P-wave velocity was also measured at 2 cm intervals (Figure 5.7). P-wave velocity exhibits low and relatively constant values (~1000 m/s) from the core top to ~18 m b.s.f. Values are higher and highly variable in the middle interval of lithostratigraphic Subunit IIIa (~18–32 m b.s.f.). The lower interval of lithostratigraphic Subunit IIIa, Subunit IIIb, and the upper interval of Subunit IIIc are all characterized by generally more constant values (~1500 m/s). From ~39 m b.s.f. to the bottom of Hole M0065, P-wave velocity values are overall higher (>1600 m/s) than the upper section. However, there is a slight decreasing trend from ~39 to ~43 m b.s.f., where P-wave velocity increases again to the bottom of the hole to a high of ~1800 m/s.

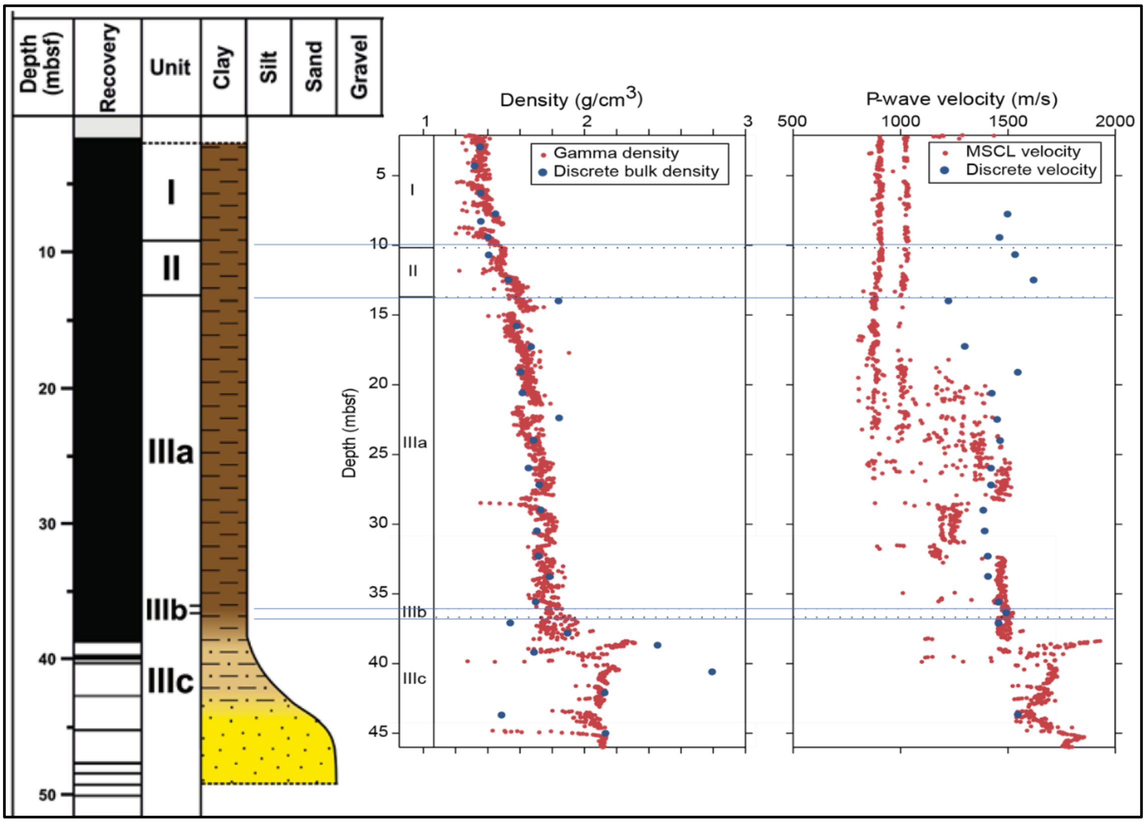


Figure 5.7. IODP Site M0065 core lithology, density and P-wave velocity.

5.3 The Arkona Basin geological background information

The Arkona Basin region is mainly situated in the German and Swedish EEZ, and only limited information is available in the GEUS archives.

From the Baltic Pipe and the Nord Stream projects we use information about Windfarm 1 and 2 as well as longer stretches along the planned cable transects including the Sweedish zone (transects B and C). The data types consist of side scan, sediment echosounder and boomer data are reported in Rambøll (2020).

From the Arkona Basin we have in addition included archive seismic data collected by Tom Flodén from Stockholm's University. These data were used for general mapping of the Arkona Basin by Lemke (1998) (Figure 3.2) and scientific papers (Moros et al. 2002, Mathys et al. 2005).

5.3.1 Arkona Basin stratigraphy

The Arkona Basin sediment stratigraphy is presented in Moros et al. (2002) and Mathys et al. (2005). Comparing Figure 5.8 and Figure 5.10 with the stratigraphical subdivision of the Bornholm Basin (Jensen et al. 2017), the same units are observed representing the Baltic Ice Lake and younger sediments with similar characteristics.

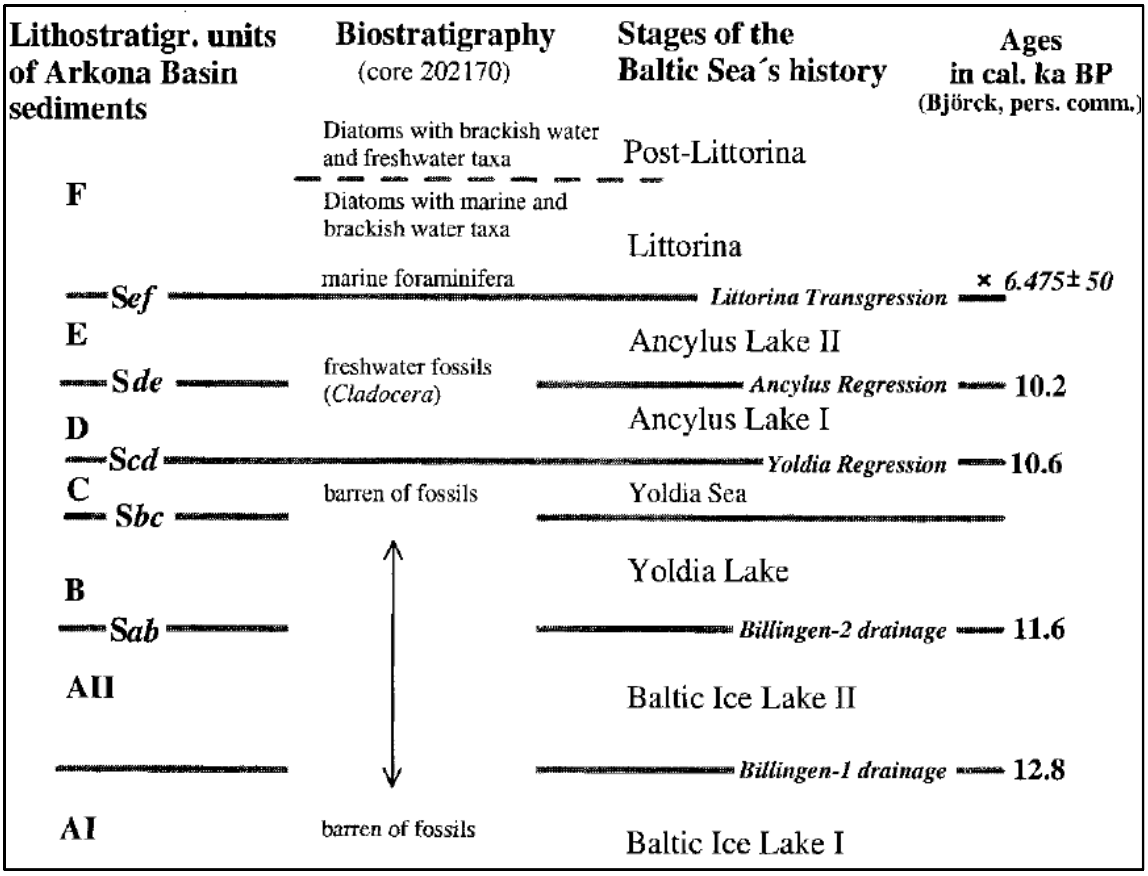


Figure 5.8 Link between the lithostratigraphic units, the sandy layers, biostratigraphic information observed in Arkona Basin sediments and the known stages of the Baltic Sea's history

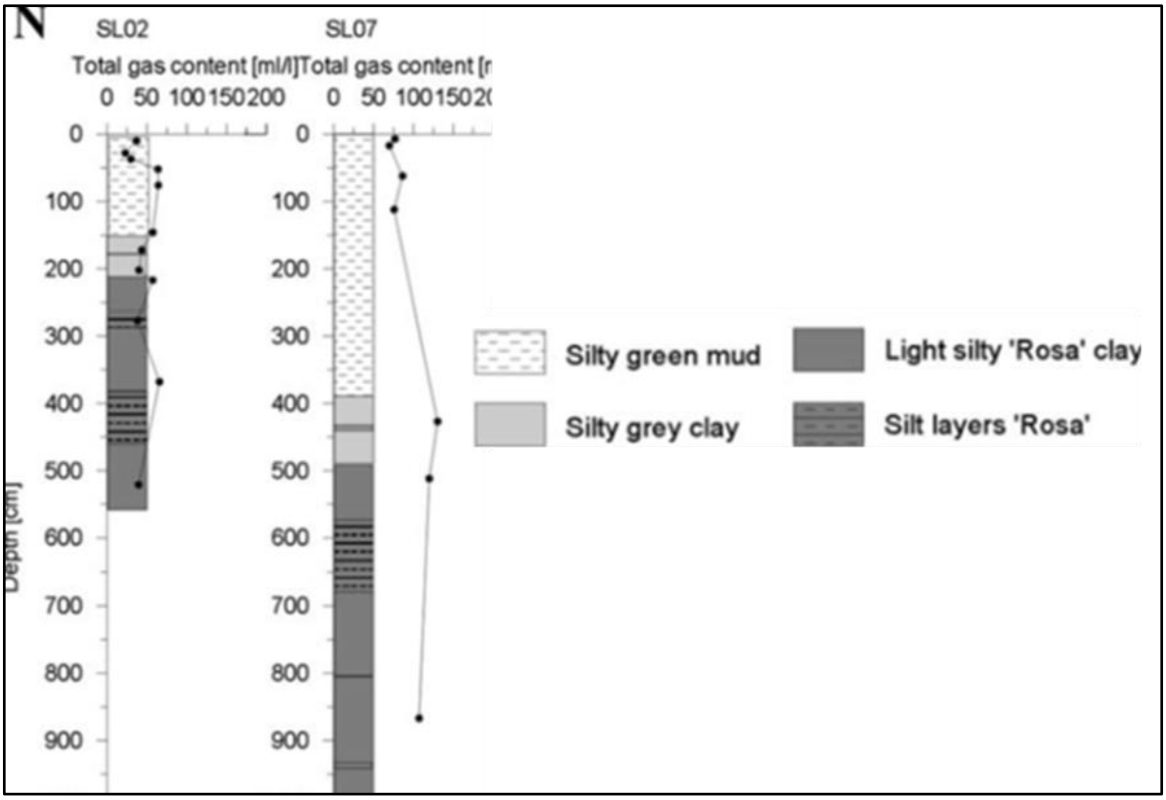


Figure 5.9 Lithological logs from profile P21 (Figure 5.10).

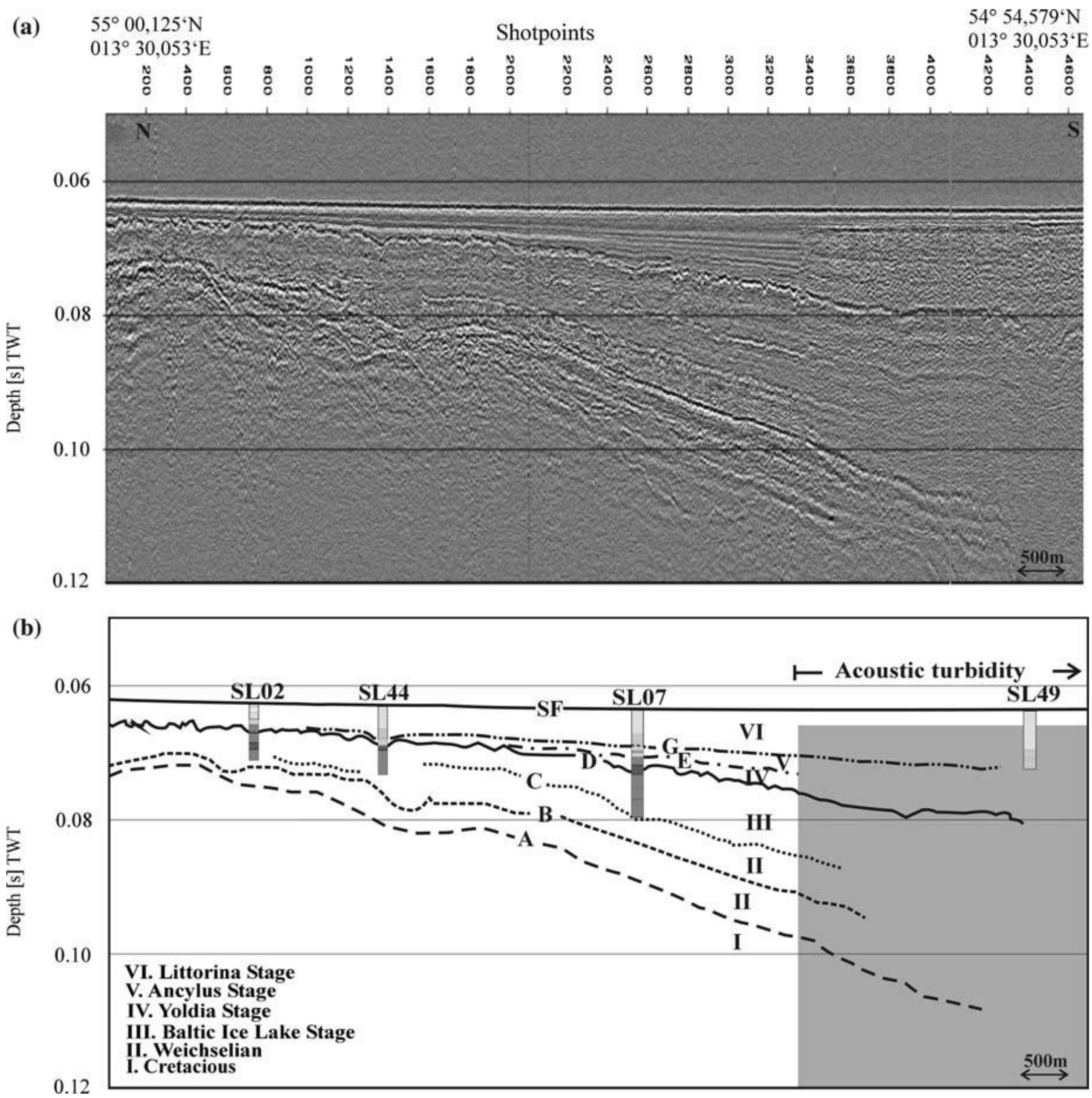


Figure 5.10 (a) Original seismic profile 21 with indication of an acoustic turbidity zone; (b) Seismostratigraphic interpretation of profile 21, SF = seafloor from Mathys et al. (2005). For location see Figure 5.3.

5.3.2 Arkona Basin sediments

The well-established stratigraphy for Arkona Basin was used by Lemke (1998) in a substantial monograph about the Late- and Postglacial development of the western Baltic Sea region. The study is based on airgun data acquired by Tom Flodén (Figure 3.2), supplemented by sediment echosounder data and 6 m vibrocores.

The till surface in the basin is the oldest unit exposed at the seabed, with a patchy appearance in the marginal north-western part of the basin (Figure 6.1). The till surface morphology has a maximum depth of 75 m below present seabed (b.s.l.) in the central part of the basin. Along the cable transect in the northern part of the basin the depth to the till surface is up to 55 m.

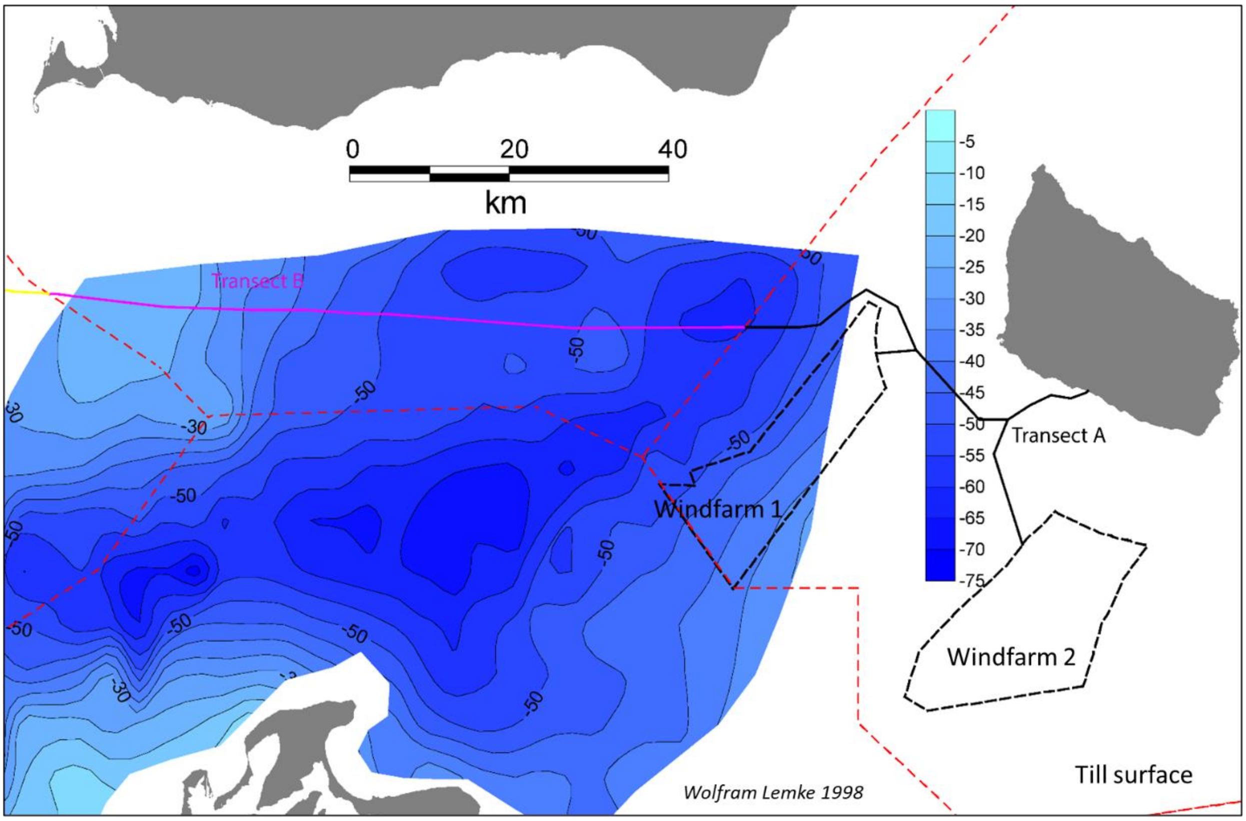


Figure 5.11 Till surface morphology mapped by Lemke (1998). The locations of Windfarm 1 and 2 (black dashed lines) and cable transects are indicated. The red dashed lines show the EEZ.

The till is overlain by Late Glacial and Holocene clay and mud in the central parts of the Arkona Basin.

Mapping of the combined thickness of the Late Glacial clay shows (Figure 5.12) a thickness of up to 12 m in the central and northernmost areas, whereas the cable transect area has thickness from 10 m in the east to 0 m in the west, with an average of about 4 m.

Mapping of the Holocene mud distribution show that an up to 10 m thick mud unit is found in the central part of the Arkona Basin. In the cable transect area the Holocene mud is up to 2 m thick.

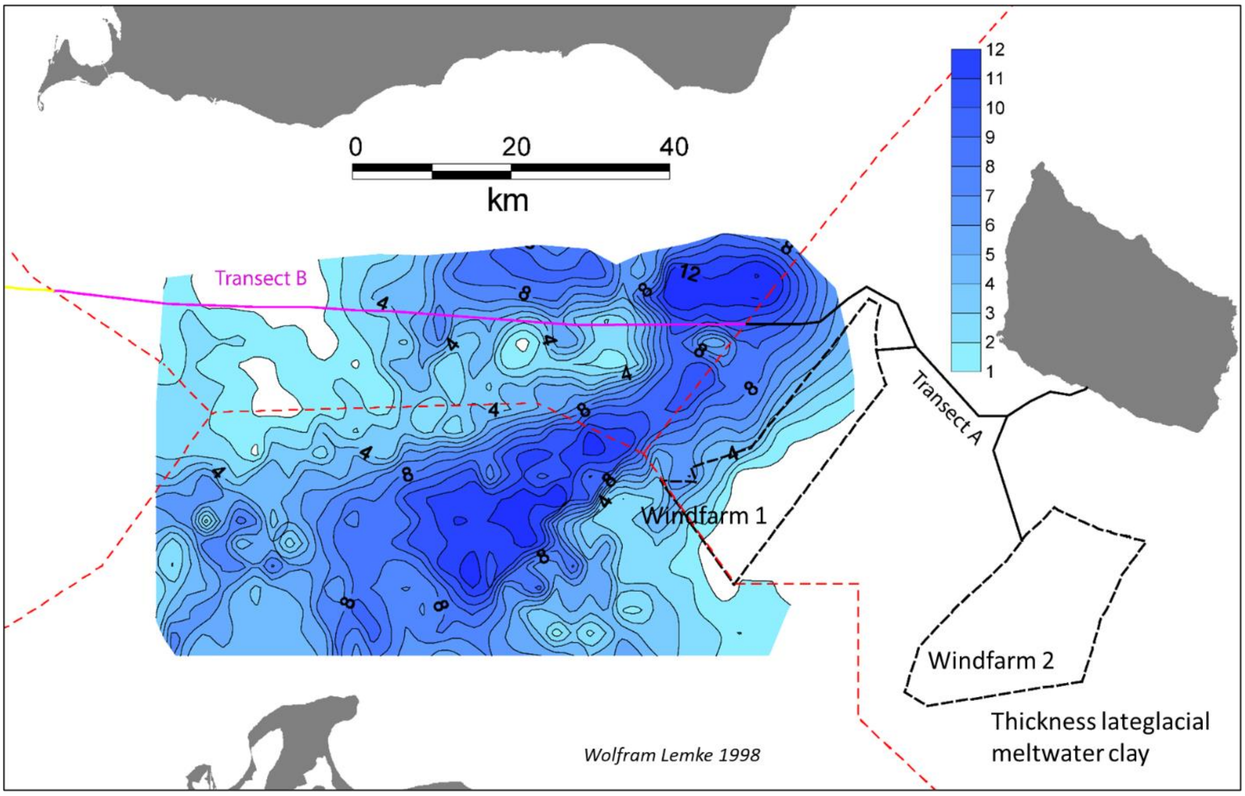


Figure 5.12 Thickness of Late Glacial clay mapped by Lemke (1998). The locations of Windfarm 1 and 2 (black dashed lines) and cable transects are indicated. The red dashed lines show the EEZ.

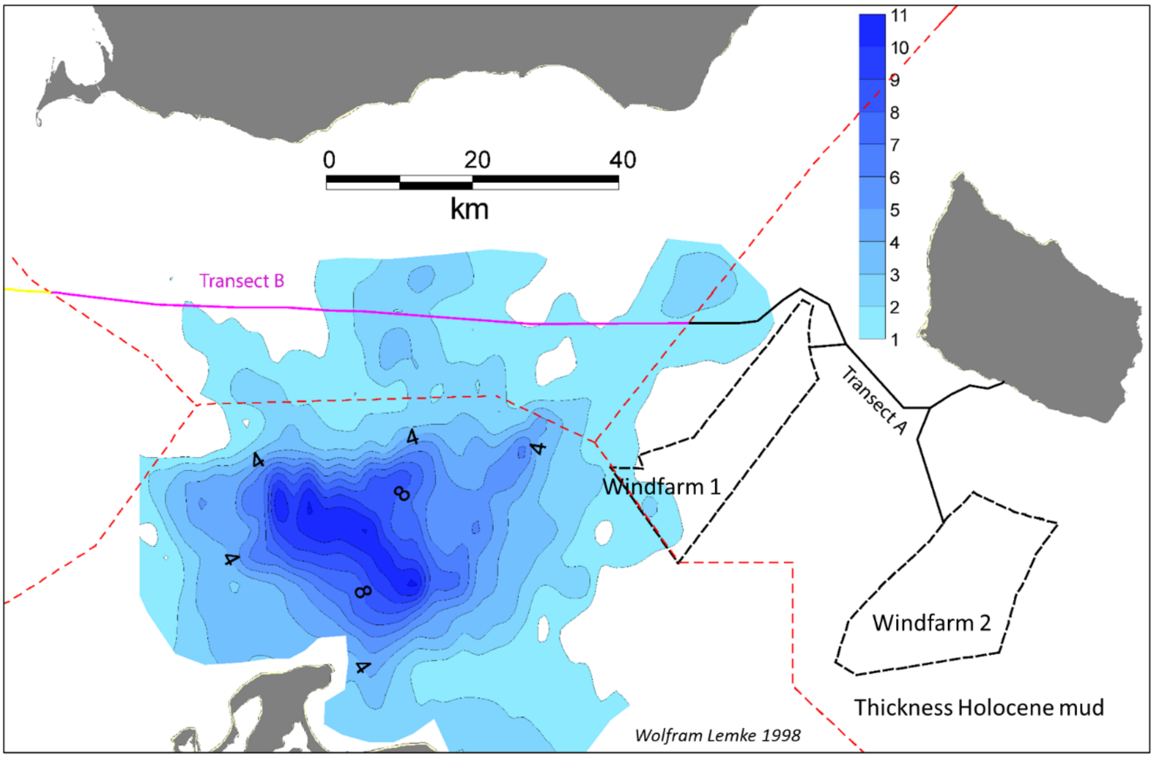


Figure 5.13 Thickness of Holocene mud mapped by Lemke (1998). The locations of Windfarm 1 and 2 (black dashed lines) and cable transects are indicated. The red dashed lines show the EEZ.

5.4 Fakse Bugt geological background information

In the Fakse Bugt, the seabed shows evidence of both the rise of the Baltic Ice Lake and the transgression of the Littorina Sea. As the Baltic Ice Lake reached its highest level, the coastline of Fakse Bugt was found at a level of about 13 metres lower than today. Moraine cliffs along the glacial lake were exposed to erosion. Clay and silt were transported into deeper waters, whereas sand, fine gravel and coarse gravel contributed to the formation of beach deposits. In the following time a coastal barrier system developed, which resulted in the damming of a local lake. After lowering of the water level during the Yoldia Sea stage, parts of the area became dry land.

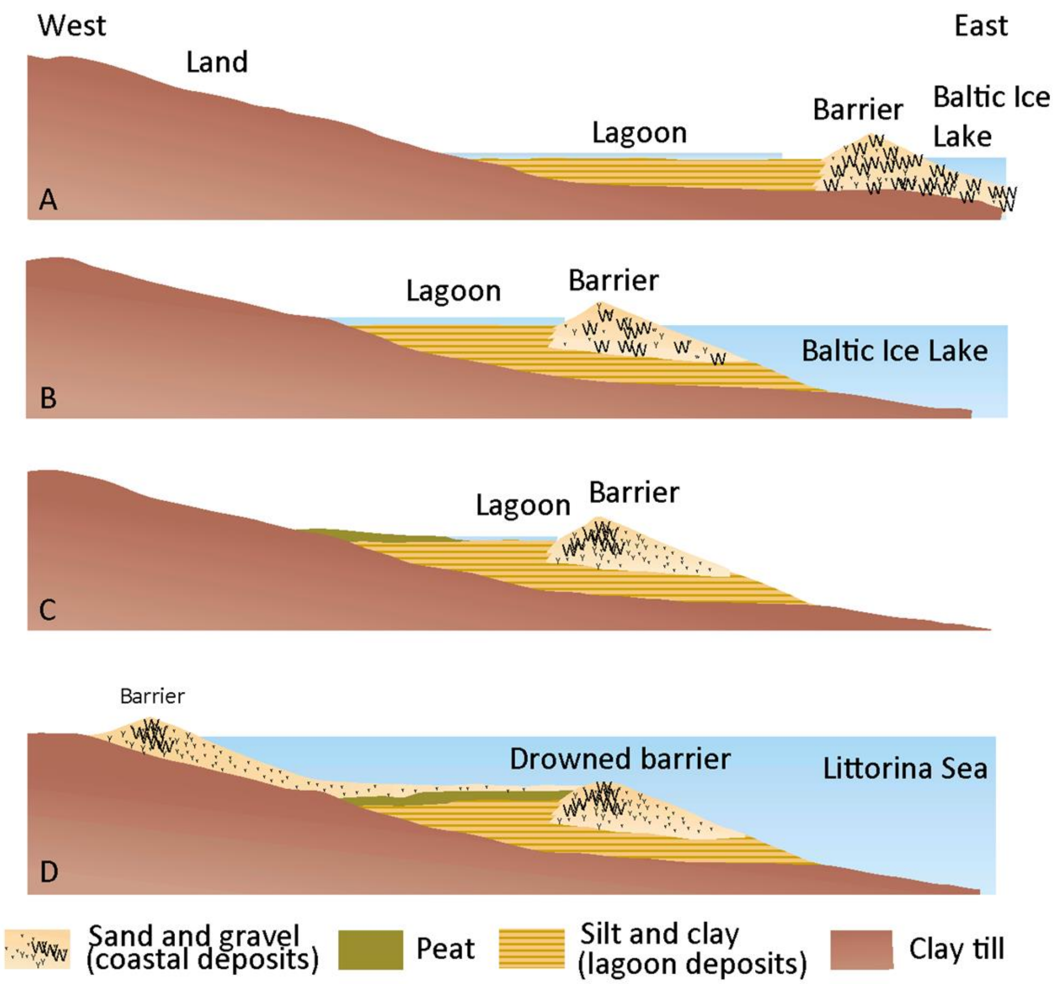


Figure 5.14 Presentation of the geological development of Fakse Bugt from Jensen and Nielsen (1998). A: Barrier – lagoon system which was formed by the Baltic Ice Lake around 13,000 years BP. B: The persisting rise of the lake level resulted in a westward migration of the barrier – lagoon system. The water level reached its maximum about 11,700 years BP at a level 13 m below present sea level. C: With the drainage of the ice lake the Fakse Bugt became dry land shortly after 11,700 years BP. D: The transgression of the Littorina Sea caused a drowning of the former coast lines and a new spit system formed about 6500 years BP

A lake was formed again in the Baltic basin: the Ancylus Lake, which lasted from 10,600 to 8400 years BP and which coincides with the so-called Continental Period, when sea level was still low. The following rise of the global sea level resulted in a renewed inflow of marine waters in the Baltic Basin, this time through the Danish Belt Sea, and the Littorina Sea Stage began. In Fakse Bugt the seabed shows evidence of both the rise of the Baltic Ice Lake and the transgression of the Littorina Sea. As the Baltic Ice Lake reached its highest level shortly before 11,700 years BP, the coastline of Fakse Bugt was found at a level about 13 meter lower than today. The moraine cliffs along the glacial lake were exposed to erosion. Clay and silt were transported into deeper waters, whereas sand, fine gravel and coarse gravel preferably contributed to the formation of beach deposits. In the following time a coastal barrier system developed, which resulted in the damming of a local lake (Figure 5.14 and Figure 5.15 A). After lowering of the water level during the Yoldia Sea period (11,700–10,600 years BP), parts of the area became dry land. As the Littorina Sea (Stone Age Sea) had reached the older coastal formations from the Baltic Ice Lake period, the coastal processes were reactivated and continued to further develop the old barrier system. Later this system was inundated. Leeward of the elevated moraine cliffs a system of spits developed, which also were gradually inundated (Figure 5.14 and Figure 5.15 B). Today this fascinating puzzle of drowned coastlines and lagoon sediments still exist on the seafloor.

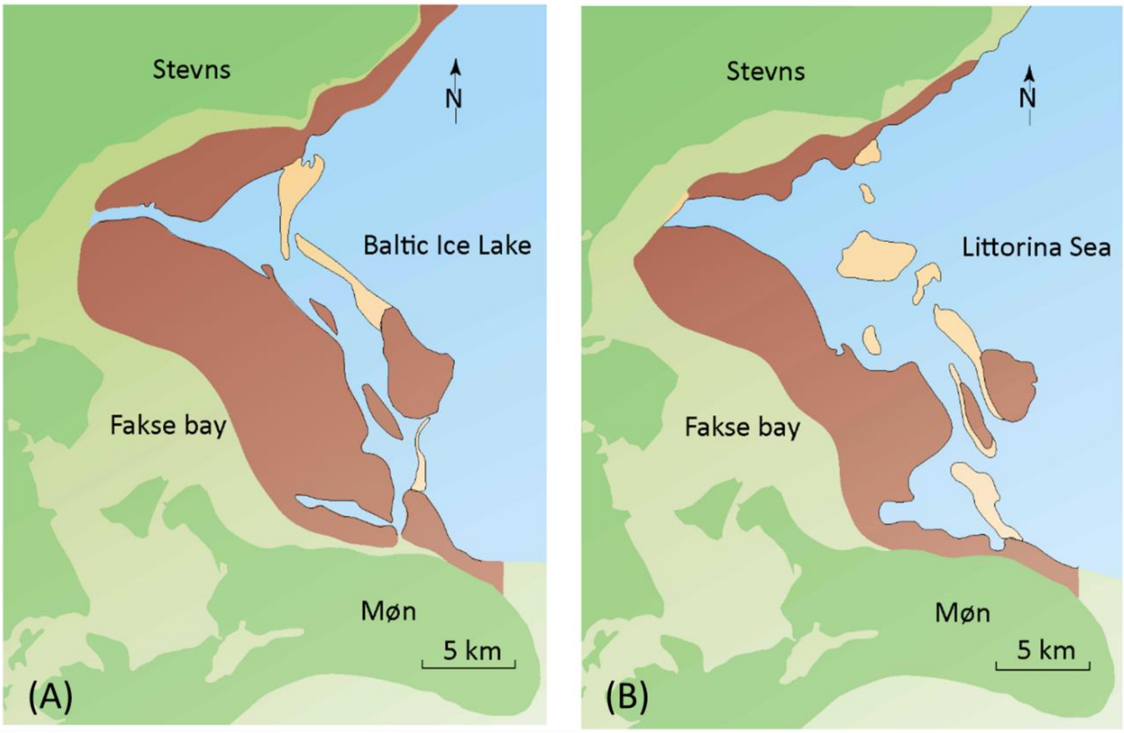


Figure 5.15 Palaeogeographic maps from Jensen and Nielsen (1998), which shows (A) the barrier island and lagoon system during the high stand of the Baltic Ice Lake and (B) The spits system formed when the sea level of the Littorina Sea was approximately 10 m lower than at present time.

The Fakse Bugt fossil barrier lagoon system is preserved at the seabed (Figure 6.1) in the western and central part of the bay, whereas the planned cable transect C and D is in an intermediate till zone, exposed to erosion or bypass of clay and silt, that was transported into the deeper Arkona Basin and deposited as the Baltic Ice Lake Clay.

5.5 Køge Bugt geological background information

Køge Bugt is in the southern part of Øresund, with near-surface bedrock consisting of Danien and Cretaceous limestone and chalk, covered by a thin Weichselian till unit with meltwater incised channels (Figure 5.16). In connection with the final deglaciation of Køge Bugt about 16,000 years BP (Figure 5.16) the ice margin had retreated to the Øresund region and the western part of Skåne. The ice lobe covered the southern part of Sealand and followed the present southern coastline of the Baltic Sea. The ice margin was directly connected by a broad meltwater channel to the Kattegat marine basin, with Køge Bugt as a proximal fresh-water dominated basin, with sedimentation of coarse-grained sand in the lower part of the Late Glacial sediments, fining up to silt and clay in the uppermost metres.

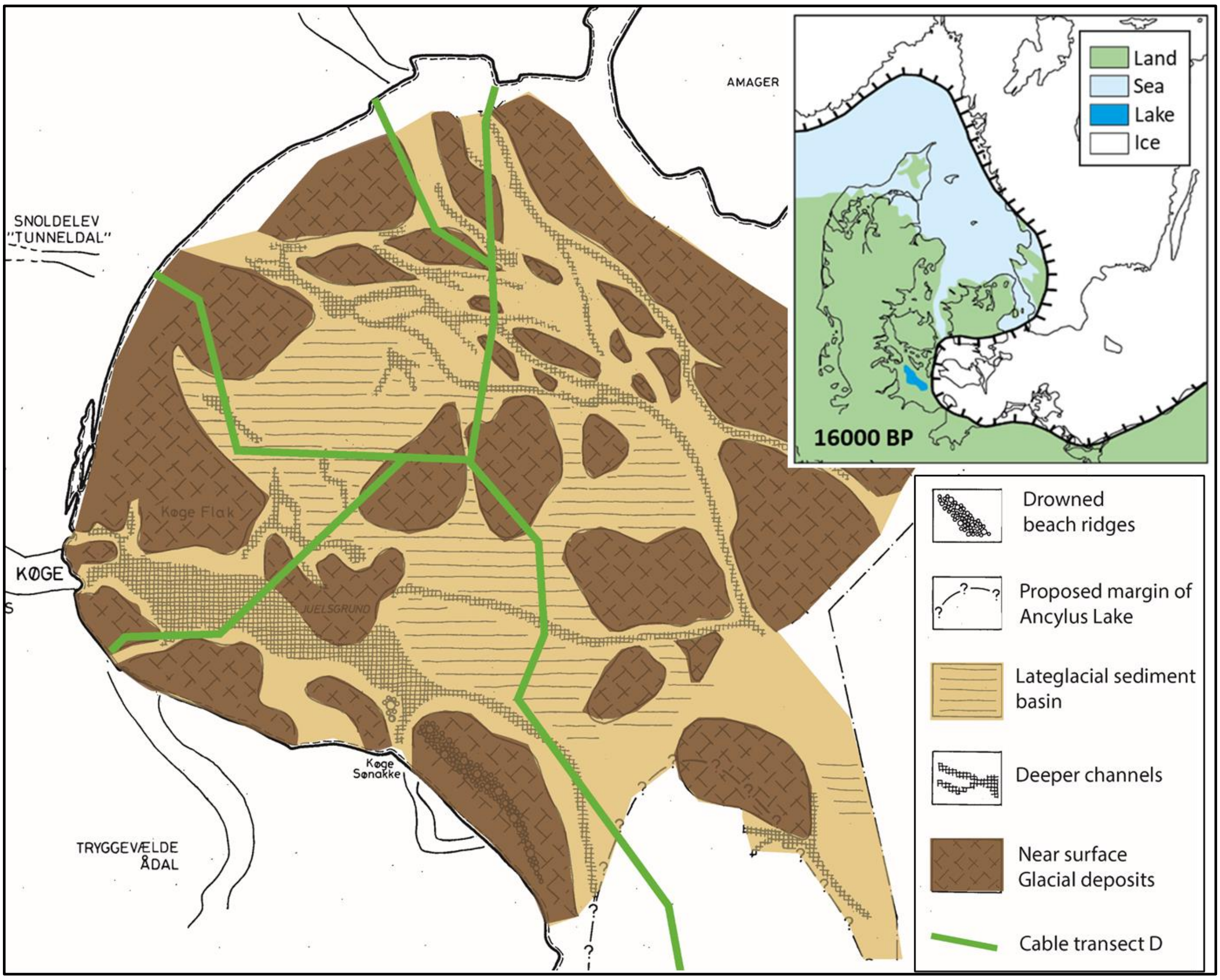


Figure 5.16 Køge Bugt general distribution of near-surface glacial deposits (till) and Late Glacial sediment basins (Skov og Naturstyrelsen 1987). The inset map shows a palaeogeographical reconstruction at 16,000 years BP. The locations of Cable transect D and the EEZ border are shown.

Køge Bugt has a patchy glacial surface, with incised valleys and basins, infilled by Late Glacial and Postglacial sediments that were mapped by Skov- og Naturstyrelsen (1987). The general map shows that the planned cable transect D will pass a patchwork of till and Late Glacial and Postglacial sediments.

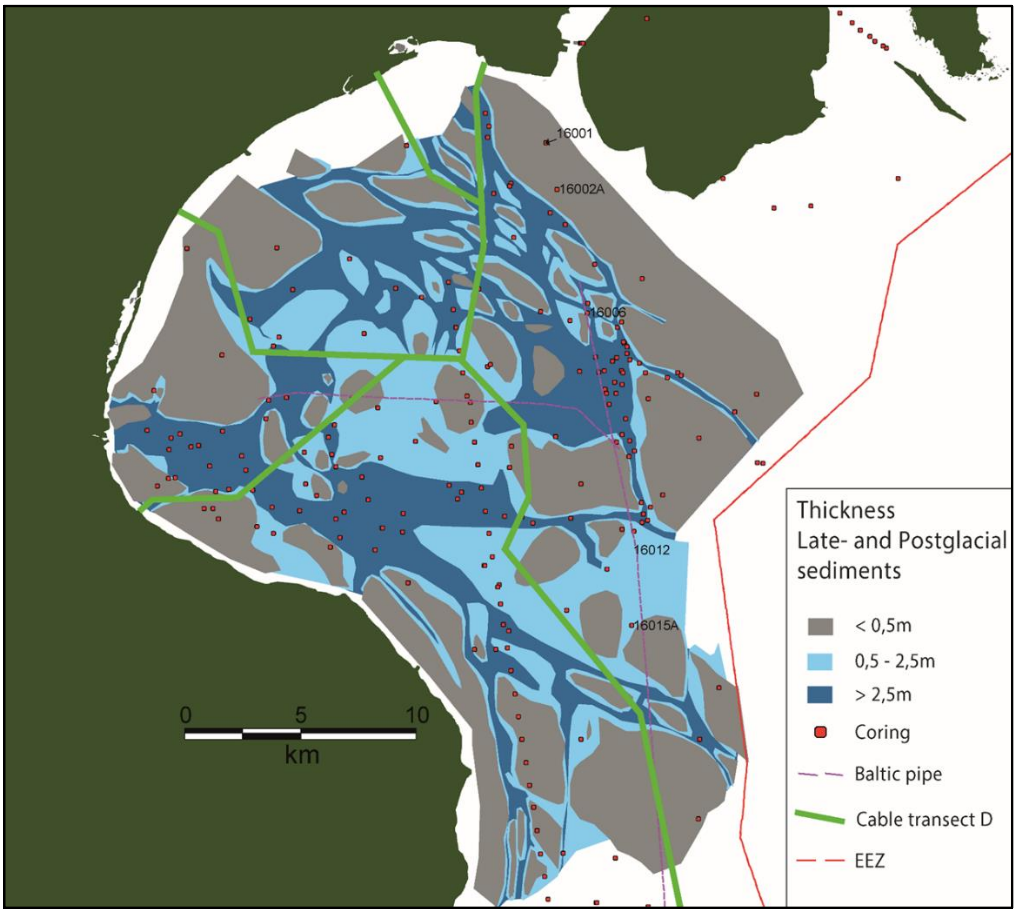


Figure 5.17 Thickness distribution of Late- and Postglacial sediments in Køge Bugt (Skov og Naturstyrelsen 1987). The locations of Cable transect D, Baltic Pipe transect and the EEZ border are shown.

6. South-western Baltic Sea surface sediments

A surface sediment map has been compiled using a combination of Emodnet seabed substrate 1:1M (https://www.emodnet-geology.eu/data-products/seabed-substrates) from the German and Swedish zones and the latest version (2020) of the Danish 1:100,000 seabed substrate map.

The planned cable transect will follow a complex line from Mesozoic Lower Jurassic sand and clay to Upper Cretaceous limestone at the seabed close to Bornholm, followed by glacial and Late Glacial clay on the margins of Rønne Banke.

In the Arkona Basin Swedish zone, the upper seabed consists of a thin layer of Holocene mud and Baltic Ice Lake clay, turning into patchy till and Baltic Ice Lake clay in the westernmost Swedish zone north of Kriegers Flak.

In the Danish outer Fakse Bugt and off Stevns, Upper Cretaceous chalk is covered by few a metres of till and thin patchy meter-scale layers of Postglacial freshwater and marine clay, sand, and mud.

In Køge Bugt, Upper Cretaceous chalk and Danien limestone is covered by few metres till with incised channels, infilled by Late Glacial sand to silt and clay. Finally patchy thin layers of Holocene meter scale layers of Postglacial freshwater and marine clay, sand, and mud.

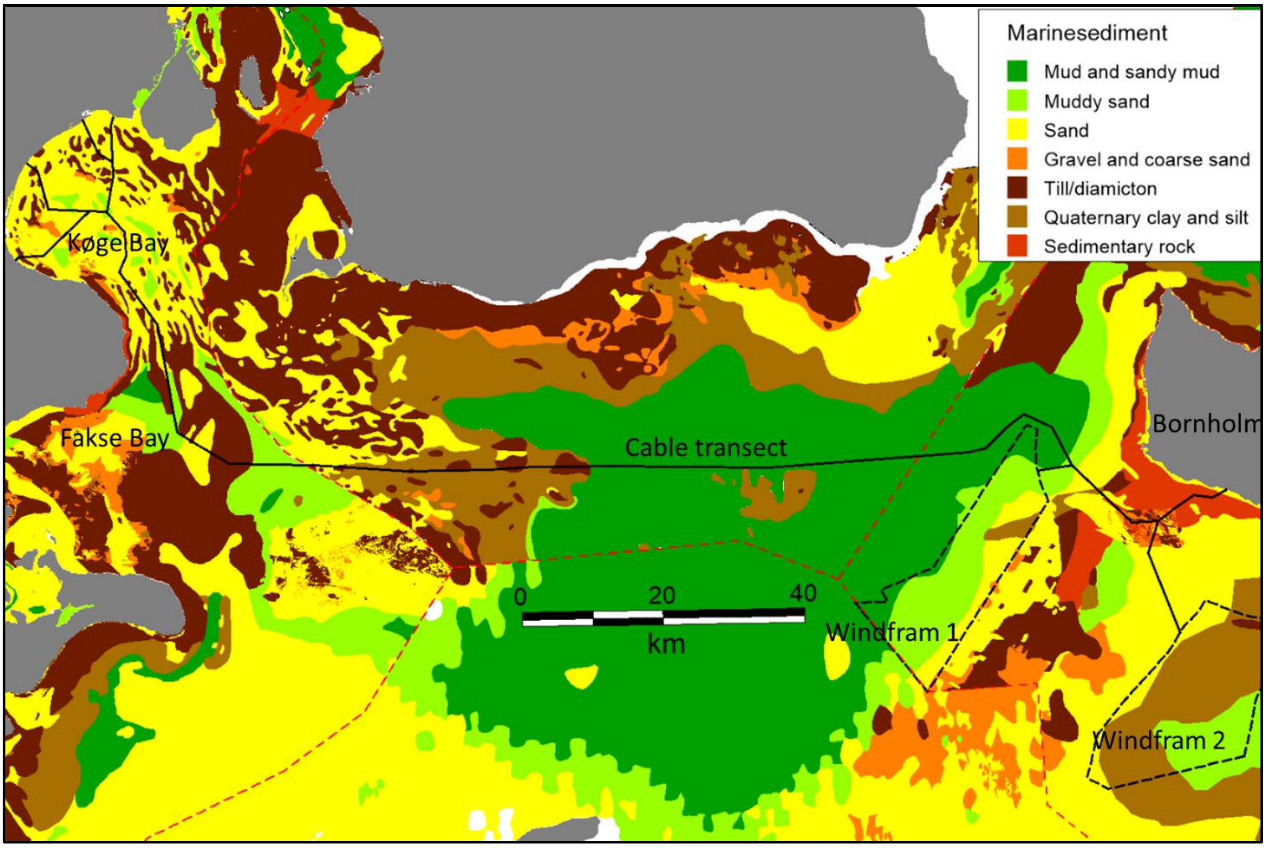


Figure 6.1 Seabed substrate map from the cable transect area based on a combination of Emodnet 1:1 M and Danish 1:100,000 2020 version.

7. Dynamic Late Glacial and Holocene shoreline history

After the last deglaciation, the south-western Baltic Sea region was characterised by highly fluctuating water levels (Figure 7.1). Transgressions were interrupted by two abrupt forced regressions, the first at ca. 12800 years BP and the second at ca. 11700 years BP. Prior to these regressions, the Baltic Ice Lake was dammed by glacier ice in south-central Sweden. In the Rønne Banke region, the water level reached a maximum around 20 m below sea level during the Baltic Ice Lake stages. Following retreat of the Scandinavian Ice Sheet, the dam was broken twice, and the water level dropped by 20-25 metres over a few years. During the Early Holocene, during the Yoldia Sea Stage, water level reached a minimum at around 40–45 m below sea level. During this period there was a land bridge from Bornholm to the continent, which allowed red deer, aurochs and hunters to invade Bornholm. A horn-core of an aurochs found on the sea floor south-west of Bornholm dates to this period. From around 10800 to 10200 years BP water increased rapidly, and pine forests in the region were submerged. The rapid increase was followed by a short period with relatively stable water level at around 9000 years BP. Water level soon continued to rise, and at ca. 7000 years BP marine waters inundated the region, which mark the beginning of the Littorina Sea Stage. During the past 6000 years, the water level has increased a few metres only. The global eustatic sea level rise has surpassed the glacio-isostatic uplift of the region, and fossil shorelines and landscapes are submerged.

In the Køge Bugt region, the water level reached a maximum around 13 m below sea level during the Baltic Ice Lake stages (Figure 7.2). The difference between the Rønne Banke region and the Køge Bugt region is caused by higher glacio-isostatic uplift in the Køge Bugt region than in the Rønne Banke region. According to the presented curve, the water level reached a minimum between 35 and 40 m below sea level. During this period, all of Køge Bugt was dry land.

The deeper parts of the Arkona Basin have been continuously submerged after the last deglaciation, but shallow water areas in the region would have been dry land for long periods after the last deglaciation of the region.

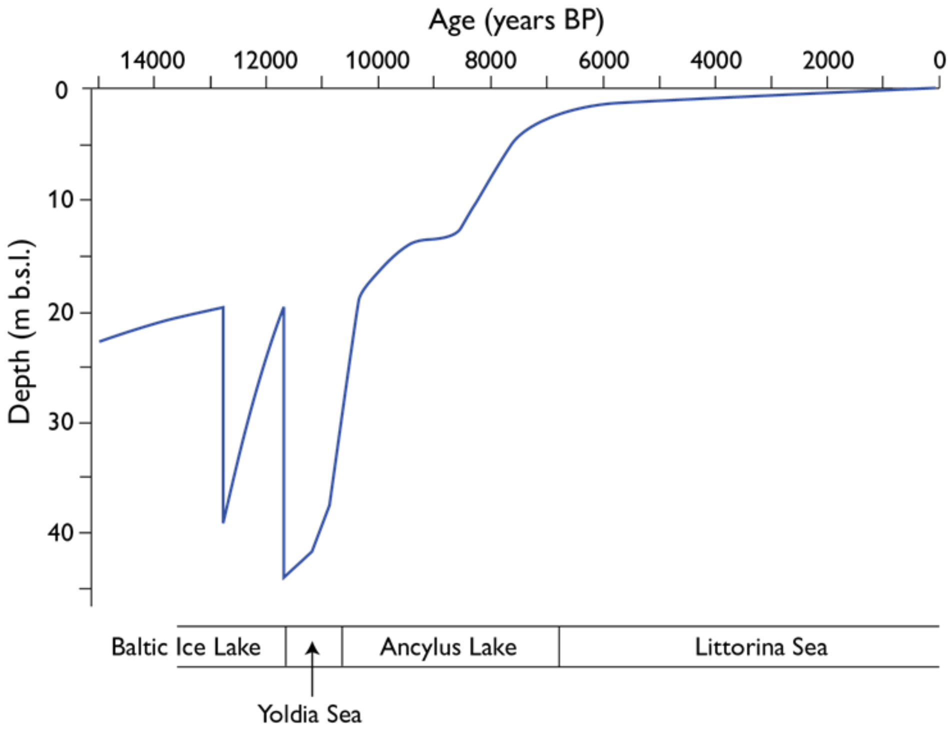


Figure 7.1. Shoreline displacement curve for the Rønne Banke region south-west of Bornholm. The curve is based on radiocarbon dating of samples collected from vibrocores (Table xx).

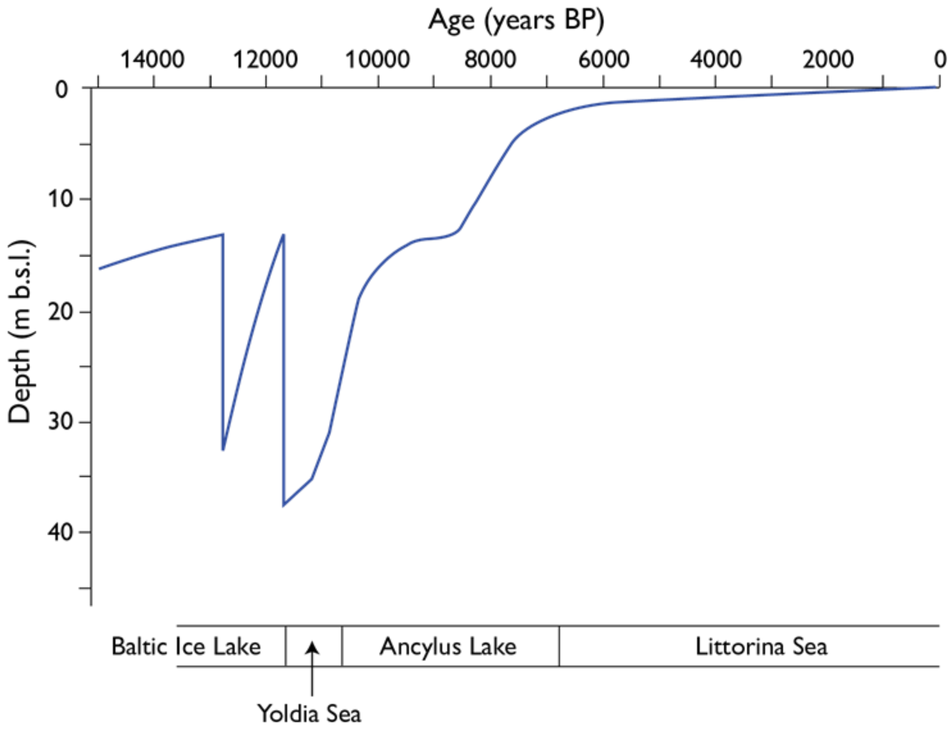


Figure 7.2 Shoreline displacement curve for the Køge Bugt region. The curve is based on radiocarbon dating of samples collected from vibrocores (Table xx).

Selected radiocarbon ages from the cable route region

Core/ site	N. lat. °	E. long. °	Laboratory number	Material	Deprh (m)	Age (^{14}C years BP) [1]	Cal. age (years BP) [2]
Marine							
7250/26	54.821	12.523	AAR-2647	Mytilus edulis	26.3	7090±90	7530
282080	54.845	13.925	KIA-26266	Mytilus edulis	46.5	6675±35	7141
Lake deposits							
548021-1	55.64	12.292	Ua-57758	Salix polaris	15.81	12863±47	15373
200540	54.725	12.766	AAR-2637	B. nana, S. herbacea	27.7	12700±110	15132
520002	55.145	12.398	AAR-1313	Salix polaris	18.7	12440±150	14605
212860	54.248	14.74	AAR-4058	Salix sp.	21.0	12400±90	14530
258000	54.750	13.765	KIA-21680	Cladium	45.2	10980±55	12896
Køge Havn			Beta-488168	Terr plant	9.04	10480±40	12536
257910	54.786	14.59	AAR-8837	Phragmites	29.9	10120±90	11695
222810	54.457	15.156	KIA-9342	Scirpus, Pinus	35.9	9930±45	11337
222820	54.483	15.172	KIA-9343	Pinus, Betula Albae	36.1	9740±55	11177
526015-1	54.949	15.362	Ua-57754	Betula Albae	44.6	9581±59	10934
526030-4	55.135	14.641	Ua-57755	Lycopus, Ranunculus	35.3	9593±51	10938
222810	54.457	15.156	KIA-9341	Menyanthes, Phragmites	34.5	9365±50	10583
548021-1	55.64	12.292	AAR-29111	Cladium mariscus	12.92	9361±35	10577
5775/01	54.913	13.05	AAR-1923	Cladium	44.3	9360±90	10574
BP09 ext 11	54.946	14.744	Beta-560826	Populus	23.0	9240±30	10407
526189	54.806	14.5	Ua-4863	P. sylvestris, Betula	24.4	9230±85	10404
Køge Sønakke			K-5099	Homo sapiens	8.0	8250±85	9227
Køge Nordhavn	55.469	12.228	K-4779	Wood peat	7.5	8090±90	9007
RAM-05-09	54.942	14.754	Beta-560827	Cladium, Scirpus	19.6	8070±30	9002
258010	54.920	13.151	KIA-21682	Phragmites	46.3	7880±50	8522
Køge Havn			AAR-24741	Corylus, fish weir	8.7	7450±32	8267

[1] Radiocarbon ages are reported in conventional radiocarbon years BP (before present = 1950; Stuiver & Polach (1977)).
[2] Calibration to calendar years BP (median probability) is according to the INTCAL20 and MARINE20 data (Reimer *et al.* 2020).

Tabel 1. Selected radiocarbon ages from the cable route region.

8. Details from the cable transect areas A–D

In the following chapters detailed data will be presented from the transect sections A–D among others described on basis of profile sections A–M, modified from the Baltic Pipe investigations (Rambøll 2020). Boomer and sediment echosounder data as well as vibrocores are the survey background for the interpretations.

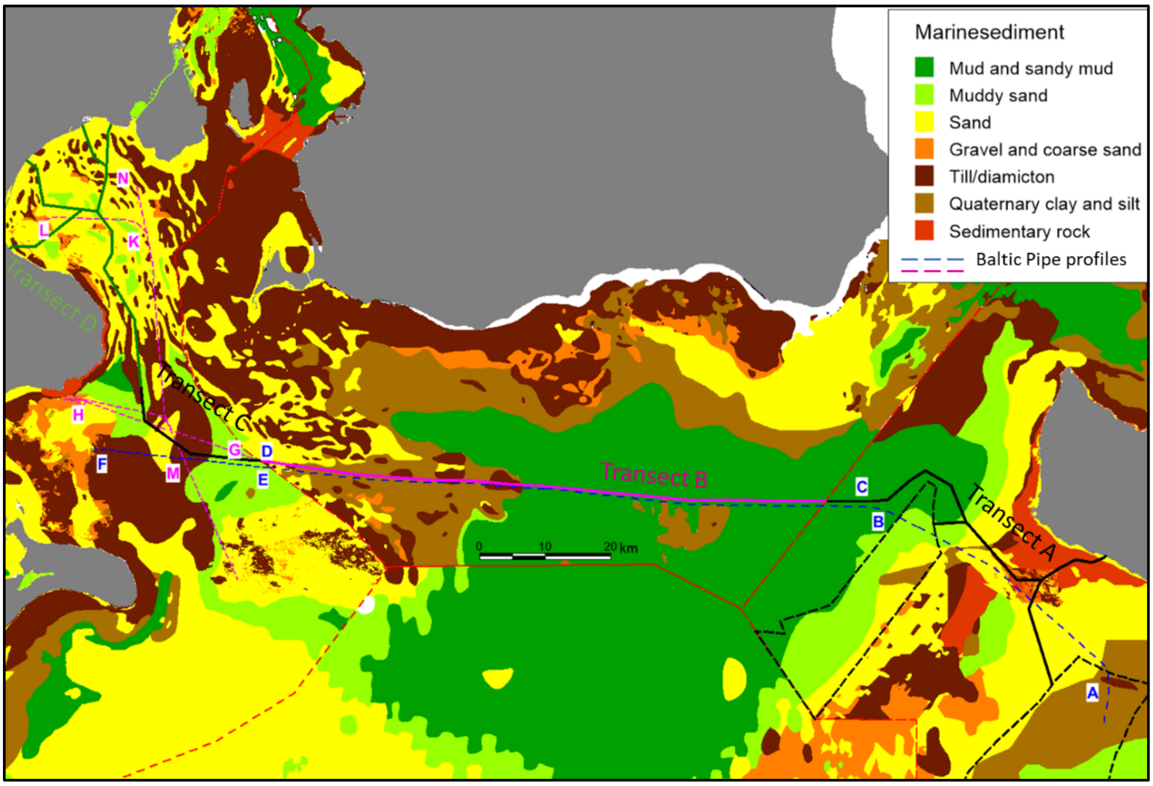


Figure 8.1 Seabed substrate map from the cable transect area base on a combination of Emodnet 1:1M and Danish 1:100,000 2020 version. Transects A–D is indicated as well as profile sections A–M. For details see Appendix B.

8.1 Near Bornholm transect A

The transect A near Bornholm connects Windfarm 1 and 2 with the Bornholm Island and in addition a long westward transect to Køge Bugt. This chapter describes the local geology in the transect A region.

8.1.1 Transect A bathymetry near Bornholm

To the southwest of Bornholm, a shallow water area with Adler Grund and Rønne Banke separates the Arkona and Bornholm Basins (Figure 8.2). The Water depths on Rønne Banke is about 20 m (Rønne Banke windfarm area), and on Adler Grund the shallowest area is about 10 m deep. The maximum water depth in the Bornholm Basin is 92 m and the average depth in the Arkona Basin is 48 m. In the Windfarm 1 area the water depth increases towards the northwest, from ca. 35 to ca. 45 m and in the Windfarm 2 area the water depth increases towards the southeast, from ca. 30 m to ca. 50 m. Transect A combines the windfarms and continues westward into the Arkona Basin.

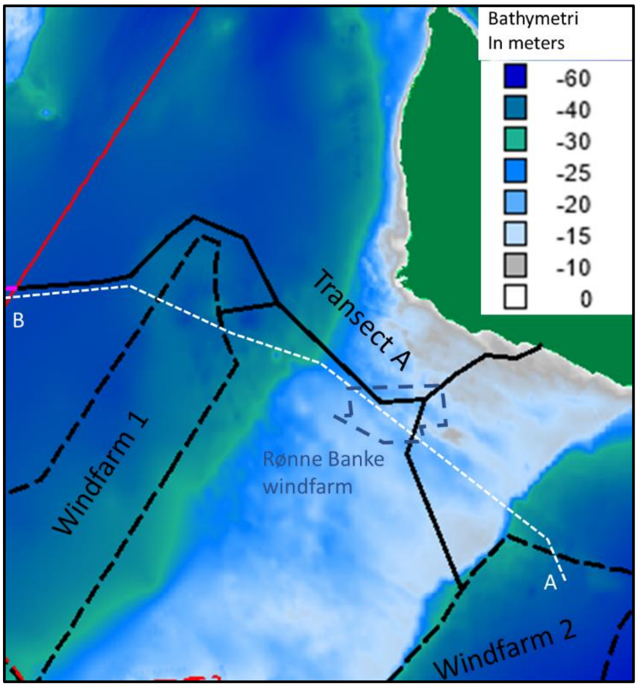


Figure 8.2 Bathymetry in the transect A area. Location of Baltic Pipe profile section A–B is indicated as well as locations of Wíndfarm areas 1, 2 and Rønne Banke.

8.1.2 Transect A seabed sediments near Bornholm

The distribution of seabed sediments reflects to some degree the bathymetry of the region. Fine-grained mud has accumulated in the central parts of the basins, whereas areas with till and bedrock in the shallow parts indicate non-deposition or erosion. In the Windfarm 1 area sand is found in the shallowest areas whereas muddy sand dominates. Small areas mapped as mud and clay and silt are also found. The Windfarm 2 area is dominated by clay and silt, muddy sand, and sand.

According to vibrocore data, clayey till is found at the seabed or close to the seabed in some parts of the Windfarm 1 area and Late Glacial clay deposited in the Baltic Ice Lake is found in the north. Vibrocore data from the Windfarm 2 area indicate marine sand and silt in the south and Late Glacial glaciolacustrine clay in the northeast (Figure 8.3).

Detailed studies in the Rønne Banke windfarm area (GEUS 2021) revealed thin patchy Quaternary till, sand and gravel (about 50% coverage) on Cretaceous Bavneodde Greensand.

Baltic Pipe profile A–B (Figure 8.3) crosses Rønne Banke (through Rønne Banke windfarm area) close to transect A. The profile documents that transect A from north to south passes through few metres mud and sandy mud top layers, under layered by up to 10 m of glaciolacustrine clay/silt, until the seabed reaches about 45 m b.s.l. at the northern margin of

Rønne Banke. The northern Rønne Banke flank from about 45 to about 25 m b.s.l. is characterised by 2–5 m of Holocene sand interrupted by a narrow band of stony till about 40 m b.s.l. (Figure 8.3).

The shallow north-western areas of Baltic Pipe profile A–B, is dominated by 2–5 m of Holocene sand near the Rønne Banke windfarm area, where Cretaceous sand occurs close to the seabed.

East of Rønne Banke windfarm, patchy sand and stony till, in the eastward direction, changes to fine to medium grained Holocene sand, with an increasing thickness up to about 10 m at the eastern steep margin of Rønne Banke, with the shallowest seabed level of about 10 m b.s.l.

East of Rønne Banke at water depths above 30 m, few metres (2–5 m) of fine-grained Holocene sand and glaciolacustrine clay/silt covers till deposits and Upper Cretaceous bedrock.

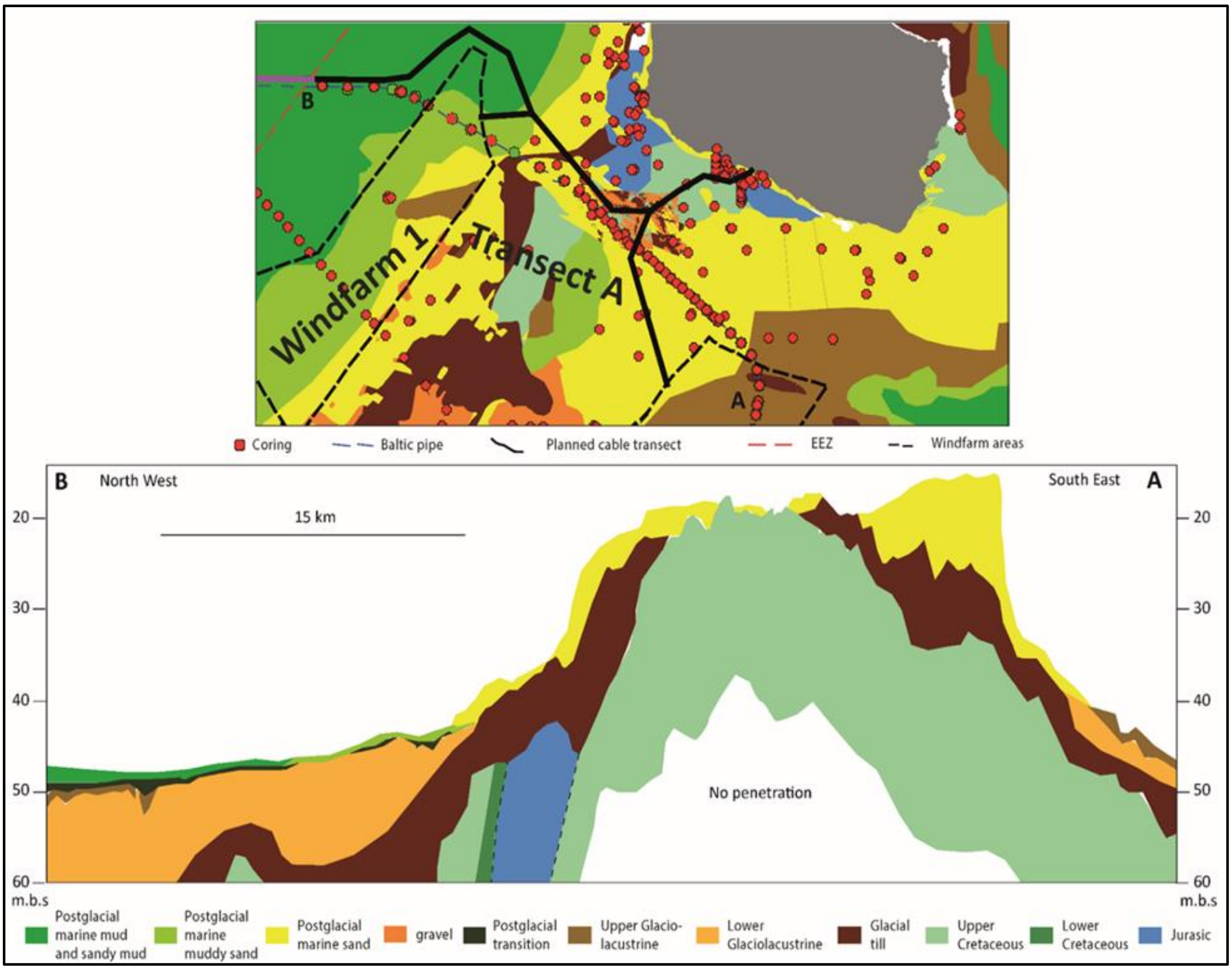


Figure 8.3 Upper figure: Surface sediments in the transect A region. Location of profile section A–B is indicated as well as locations of Wíndfarm 1 and 2 and vibrocore positions. Lower figure: Baltic Pipe profile A–B interpreted sediment profile. For details see Appendix C.

8.1.3 Transect A near Bornholm, near-coastal seabed sediments

Close to Bornholm Transect A enters the Rønne Banke windfarm area and continues to the landfall in Sose Bugt (Figure 8.4).

Seismic lines show a combination of near-surface pre-Quaternary deposits topped by scattered glacial boulders and a patchy cover of Quaternary glacial, Late Glacial and Holocene sediments.

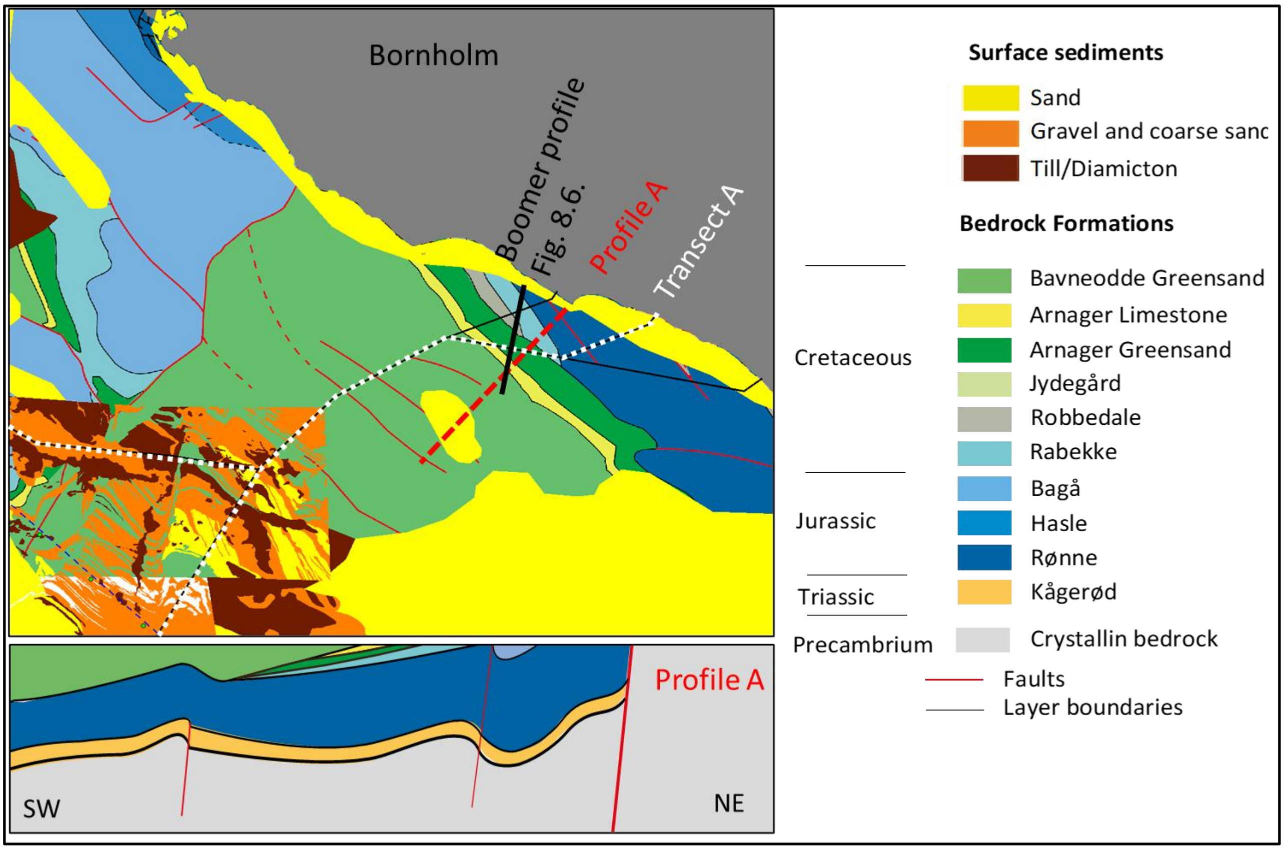


Figure 8.4 Near Bornholm surface sediments from Rønne Banke windfarm area, to Sose Bugt landfall, with pre-Quaternary seabed sediments barely covered by Quaternary sediments. Location of Boomer profile

Detailed information from the Rønne Banke windfarm is reported in a geophysical survey carried out in 2013 by EGS (International) Limited and reported in their report “Danish Windfarm Site Surveys, Site 6, Rønne Banke” (Energinet 2014 (a) and (b)).

Geotechnical investigations were carried out by Fugro Sea core Limited (FSCL) and reported in their report “PRELIMINARY GEOTECHNICAL INVESTIGATIONS 2014_RØNNE BANKE FACTUAL REPORT ON GROUND INVESTIGATION” (Energinet 2014 (c) and (d)).

The surface sediments from Rønne Banke windfarm to the Sose Bugt landfall is described in scientific papers by Hamann (1987), Jensen and Hamann (1989), Graversen (2004) and Graversen (2009).

8.1.4 Sose Bugt landfall to Rønne Banke windfarm sediment distribution

The seabed from the Sose Bugt landfall to Rønne Banke windfarm is in general exposing pre-Quaternary strata at the seabed surface (Figure 8.4).

8.1.4.1 Rønne Formation

The oldest Mesozoic deposits exposed at the sea floor in the Sose Bugt area belong to the Rønne Formation (Figure 8.4). The characteristic seismic facies consists of a pattern of many closely spaced weak reflectors in a generally massive appearing reflection pattern containing a few distinct reflectors (Figure 8.5). Sampling and diving investigations reveal that the seismic picture can be related to the lithological development. The area with closely spaced weak reflectors and the massive reflector pattern is identified as cross-bedded and massive sand deposits. Where locally cemented, they form marked topographical features on the sea floor. The strong reflectors are believed to represent clay ironstone beds, massive beds of clay, and heterolithic units.

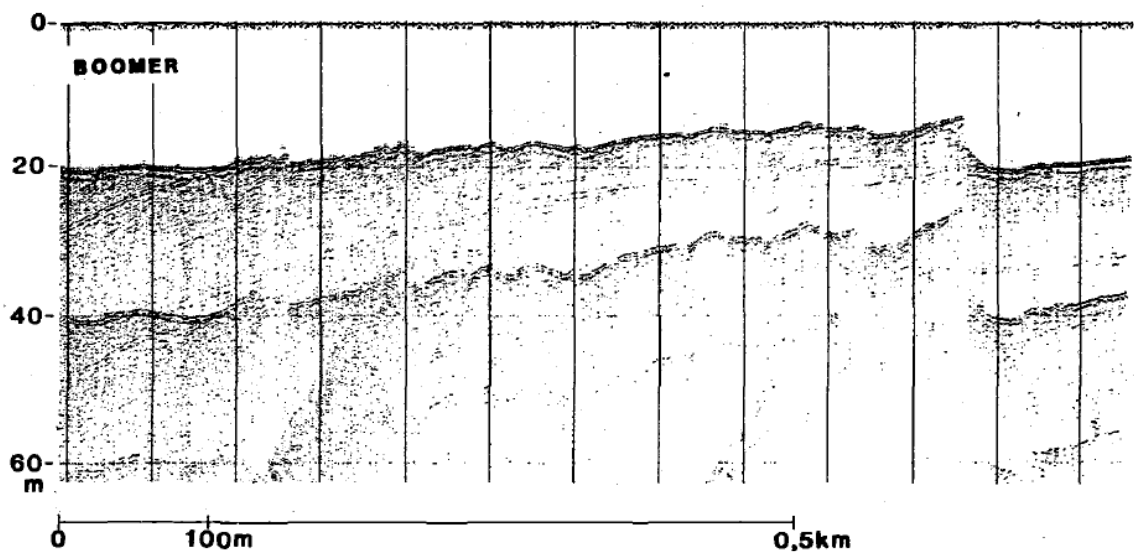


Figure 8.5 Seismic reflection pattern (Boomer) of the Rønne Formation.

8.1.4.2 Rabekke Formation

The Rabekke Formation is the oldest unit of the Lower Cretaceous, the unit has a reflection pattern very similar to that in the upper Bagå Formation although the Rabekke Formation has local, closely spaced weak reflectors in a generally diffuse reflection pattern (Figure 8.6). Equivalent deposits on land have been described as a separate member Homandshald Member (Gravesen et al. 1982), which has been interpreted as a fluviatile deposit.

8.1.4.3 Robbedale Formation

The Robbedale and Jydegård Formations form extensive coastal segments in Arnager Bugt and Sose Bugt (Gravesen et al. 1982), the seismic reflection pattern shows closely spaced weak reflectors interrupted by a few more pronounced reflectors (Figure 8.6). Sedimentological studies by Noe-Nygaard & Surlyk (1988) interpreted interlayered quartz sand and clay beds as marine near-coastal deposits.

8.1.4.4 Arnager Greensand Formation

A powerful reflector is seen at the base of the Arnager Greensand Formation (Figure 8.6), the reflector is correlated with a major conglomerate bed. This bed is a well consolidated phosphorite conglomerate that forms ridges on the sea floor, and on the seismic sections, it appears as a well-defined dipping layer, which sometimes produces a seismic diffraction pattern. The presence of this phosphorite conglomerate indicates that there is a hiatus in the succession. In addition to the powerful base reflector there are a few strong reflectors in the lower part of the formation, whereas the remaining part shows a rather diffuse reflection pattern. From submarine sampling it appears that the lithological features which give rise to these strong reflectors, in addition to the phosphorite conglomerate, are zones of cemented glauconite bearing quartz sandstone with phosphorite nodules. The Arnager Greensand Formation has been interpreted to represent coastal marine deposits.

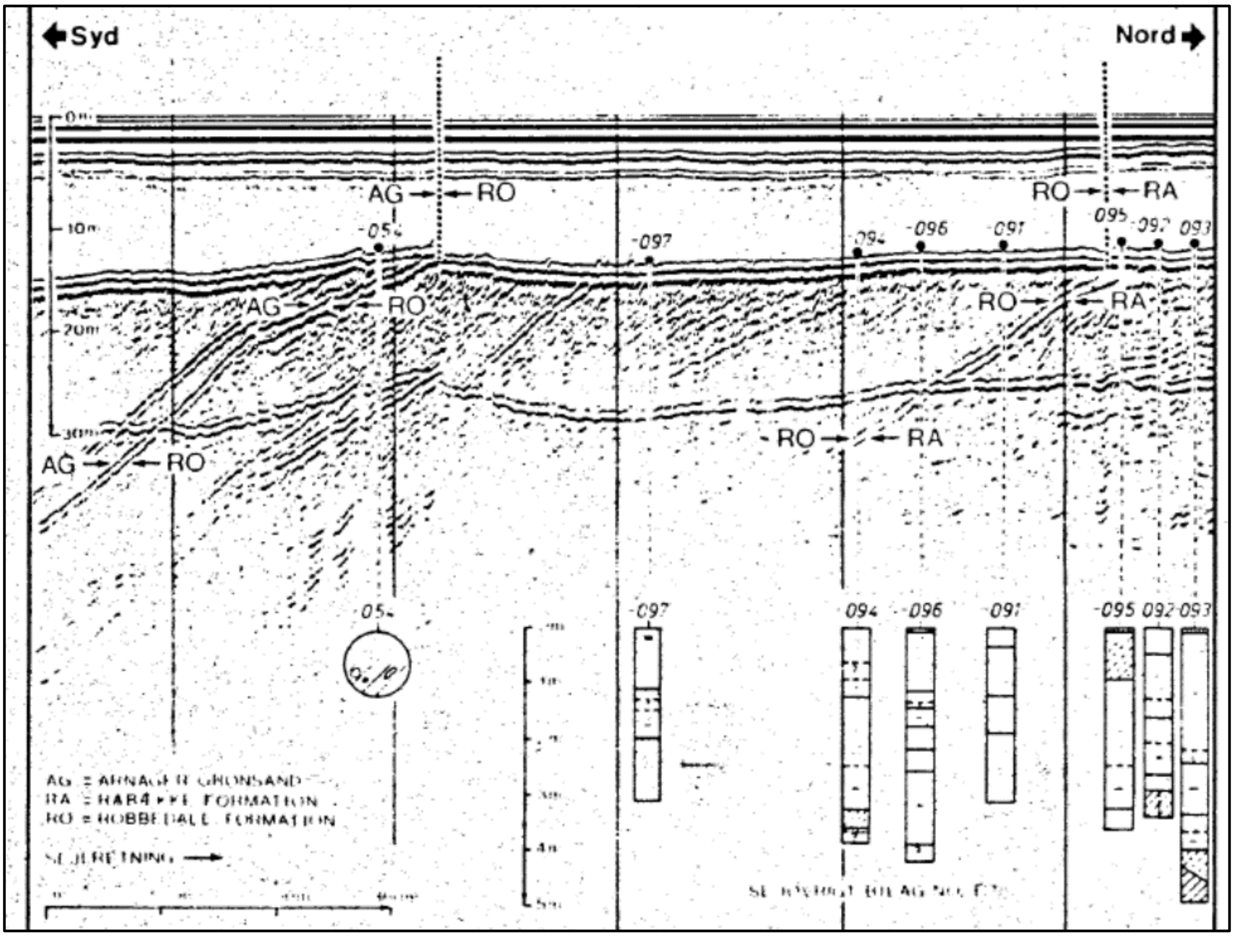


Figure 8.6 Boomer profile south-north crossing of Arnager Bugt. For location see Figure 8.4

8.1.4.5 Arnager Limestone Formation

The Arnager Limestone Formation belongs to the Marine Cretaceous Group (Figure 8.4). The presence of siliceous limestone in this formation results in a readily recognizable seismic reflection pattern; it consists of a series of closely spaced, strong reflectors, which together form a "plateau"-like feature in the sea floor (Figure 8.7. The lithology of the Arnager Limestone has been studied in detail along the coastal profile in Arnager Bugt (Noe-Nygaard & Surlyk, 1985). This study showed that the unit consists of a hard, siliceous limestone (55-65% carbonate) with a sparse macrofauna. The basal part contains a thin conglomerate, whereas the rest of the formation consists of an overlapping reef complex, formed by siliceous sponges that served as traps for fine grained sedimentary particles (Noe- Nygaard & Surlyk,1985). The Arnager Limestone, which has a thickness of 10-20 m, has a concordant upper boundary with the Bavnodde Greensand Formation.

8.1.4.6 Bavneodde Grensand Formation

The Bavnodde Greensand Formation is the youngest Mesozoic formation exposed in the Bornholm region. The seismic reflection pattern is similar to that produced by the Arnager Greensand Formation, with a generally diffuse pattern interrupted by a few strong reflectors (Figure 8.7). The lithology represented by the strong reflectors consists of cemented glauconitic quartz sandstone (and occasional conglomerates) which form ridges on the sea floor; unconsolidated glauconitic sand gives rise to the weak reflectors. Brusch (1984) has interpreted the formation as representing shallow water shelf sediments, deposited in water depth of 40-120 m.

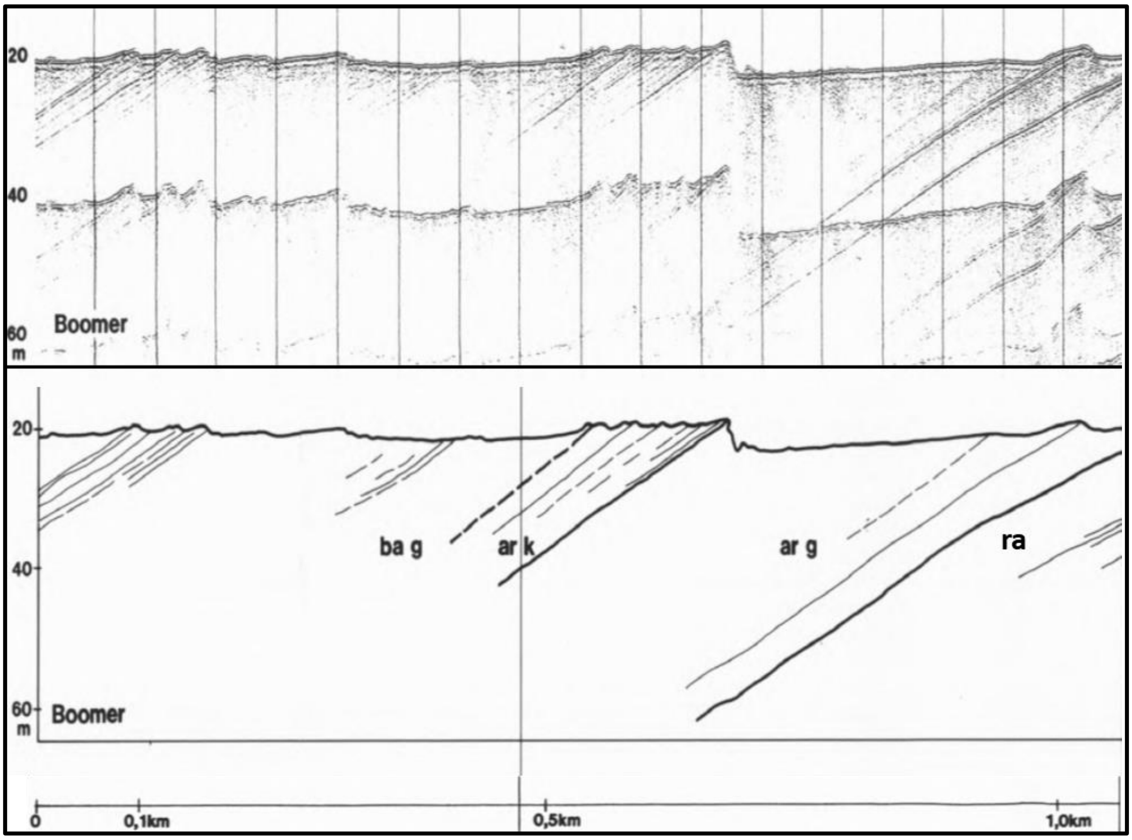


Figure 8.7 Boomer profile from the Rønne Graben illustrating the seismic reflection patterns of Rabekke Formation (ra), Arnager Greensand (ar g), Arnager Limestone (ar k) and Bagneodde Greensand (ba g).

8.1.5 Rønne Banke windfarm sediment distribution

The Rønne Banke windfarm area includes parts of the Rønne Fault, which appears at the seabed and is orientated north northeast to south-southwest across the survey area separating the Rønne Graben to the west, and the Arnager Block to the east (Figure 8.8).

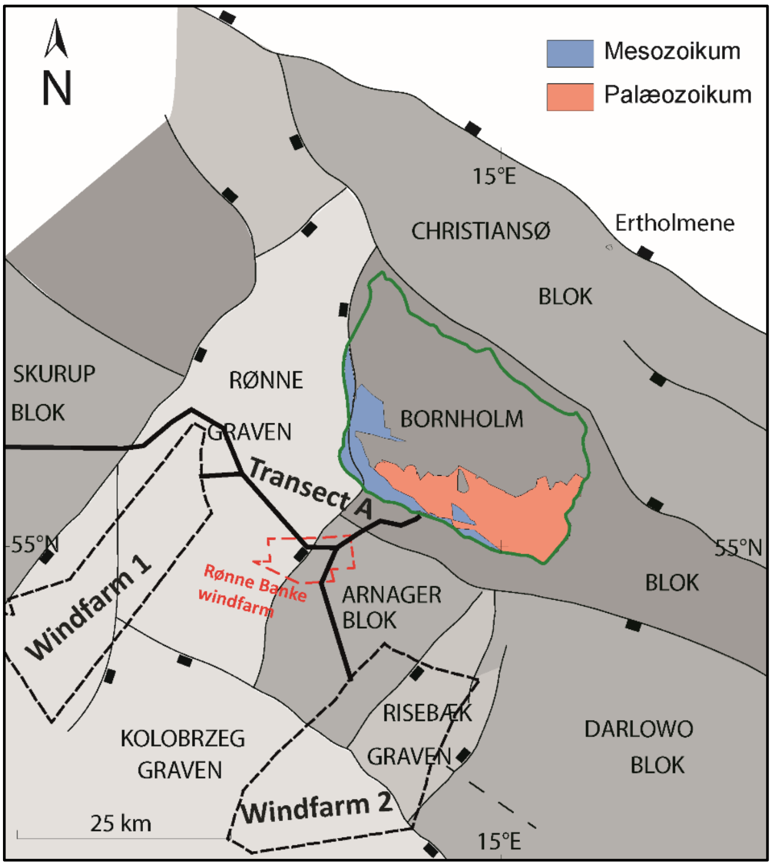


Figure 8.8 Major fault blocks of the Bornholm region. The fault pattern is based on Vejbæk & Britze (1994) and Vejbæk (1997). Location of Transect A, Windfarm 1 and 2 as well as Rønnen Banke windfarm is indicated.

The block faulting complex described in Chapter 4 explains the reason for older sediments occurring west of the Rønne Fault than to the east (Figure 8.9).

The structural history has resulted in severe folding of the sediments on both sides of the fault. The sediments occurring at and within 50 m of the seabed on the west side (Rønne Graben) consist predominantly of Early Jurassic to Late Cretaceous sand and sandstone (variably consolidated) with occasional limestone and shale also with a possibility of clay and coal within 50 m of the seabed (Figure 8.10). On the eastern side of the Rønne Fault the sediments consist of interbedded, cemented sandstone and unconsolidated sand. Outcrops of these sedimentary units occur at the seabed over much of the survey area predominantly to the east of the fault where thick beds of sandstone form ridges at the seabed with troughs of sediment infill between where unconsolidated sand have been eroded (Figure 8.11). The rock outcrop to the west of the fault has a different character with smaller patches of more continuous exposure at the seabed displaying more uniform bedding planes. These patches are expected to consist predominantly of cemented sandstone with minor hard limestone.

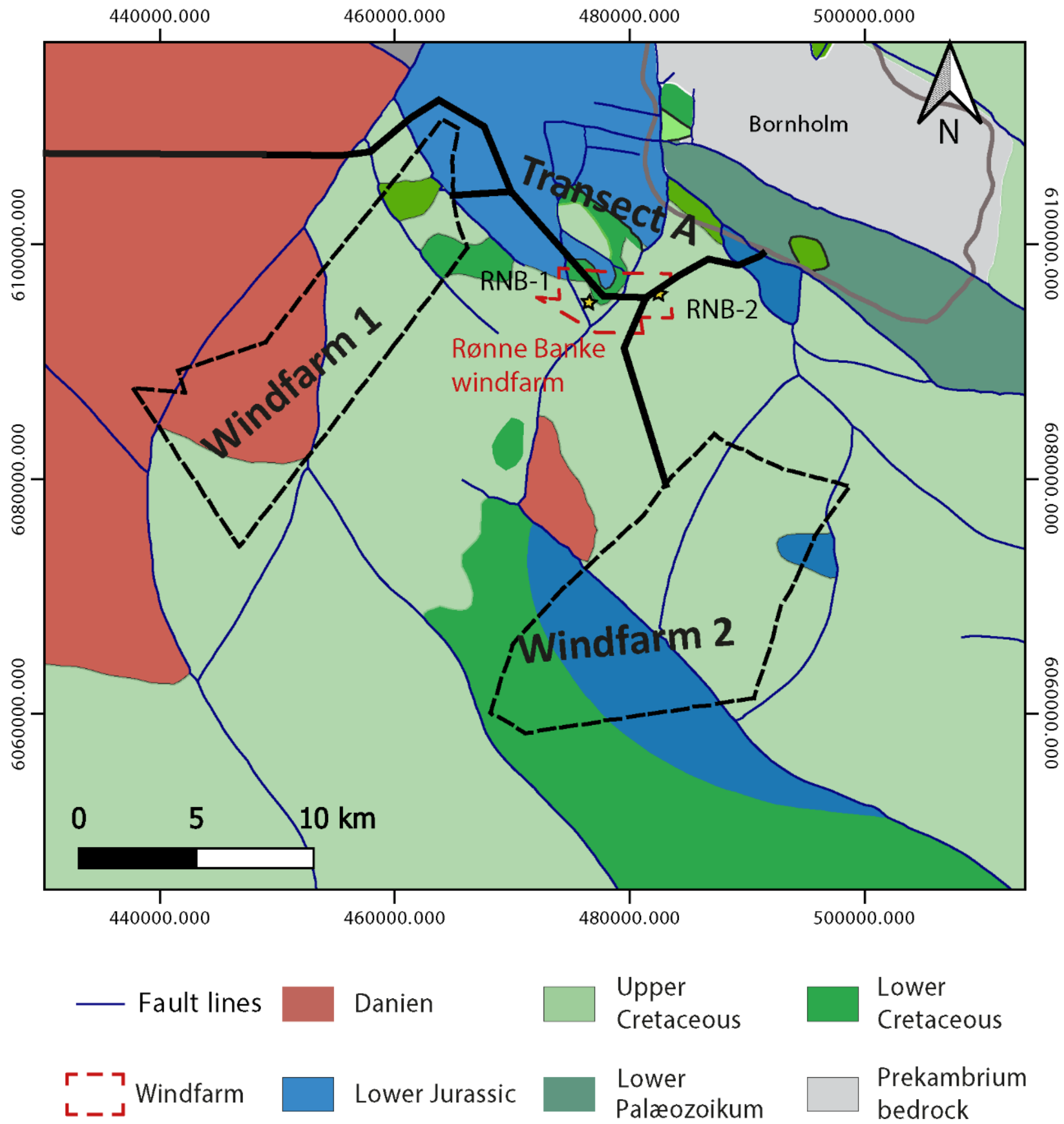


Figure 8.9 Major faults and pre-Quaternary stratigraphic units southwest of Bornholm. The locations of Transect A, Windfarm 1 and 2 as well as the Rønne Banke windfarm are indicated.

Variable thickness of a glacial unit occurs at the seabed over most of the survey area, where rock is not present at the seabed. This glacial unit infills an erosion surface in the bedrock and elsewhere forms a shallow veneer between outcrops (Figure 8.14). The glacial unit is expected to consist of sand, gravel and till in variable concentrations and reaches a maximum thickness of 43 m in an extended channel orientated east–west across the northern half of the survey area (Figure 8.14). More localised eroded depressions infilled with glacial sediments occur on the southern and eastern margins of the survey area (Figure 8.10). A thin layer of post-glacial sand occurs at the seabed in the west of the survey area overlying the glacial sediments. The unit reaches a maximum thickness of 4 m near the western margin of the area and pinches out towards the north and east (Figure 8.13).

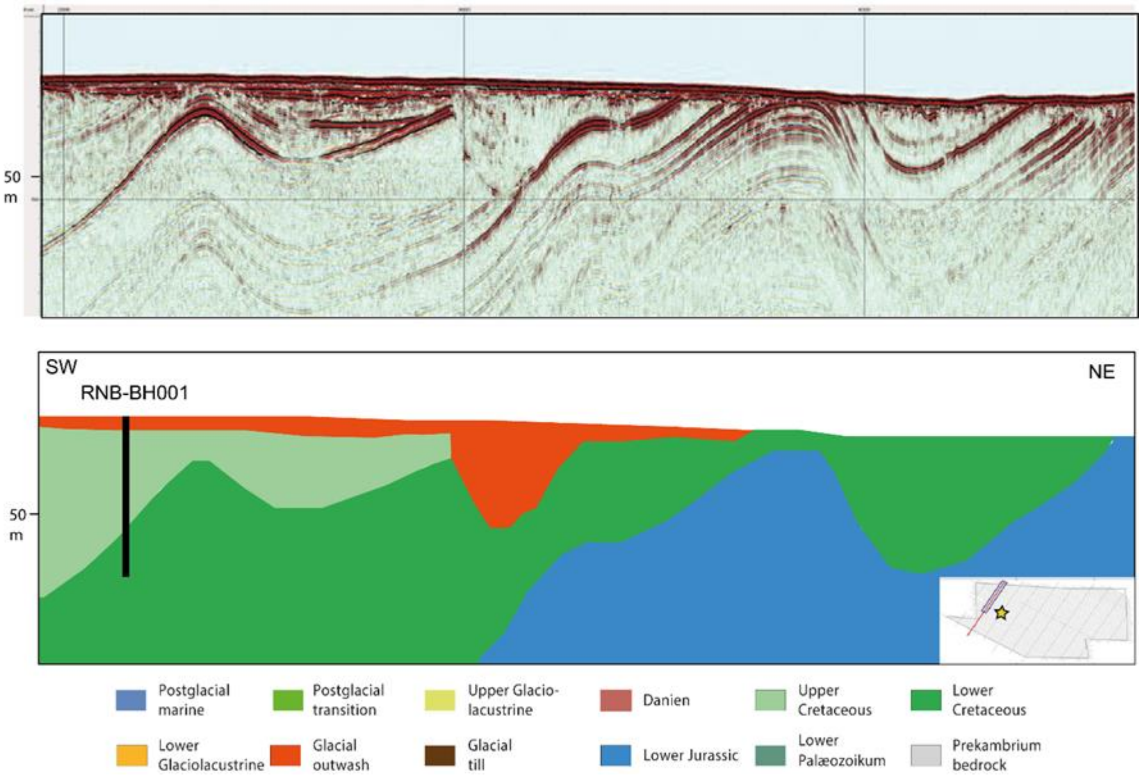


Figure 8.10 High resolution Sparker multi-channel profile XL_010 and below geological interpretation. The location is indicated on the inset map in lower right corner.

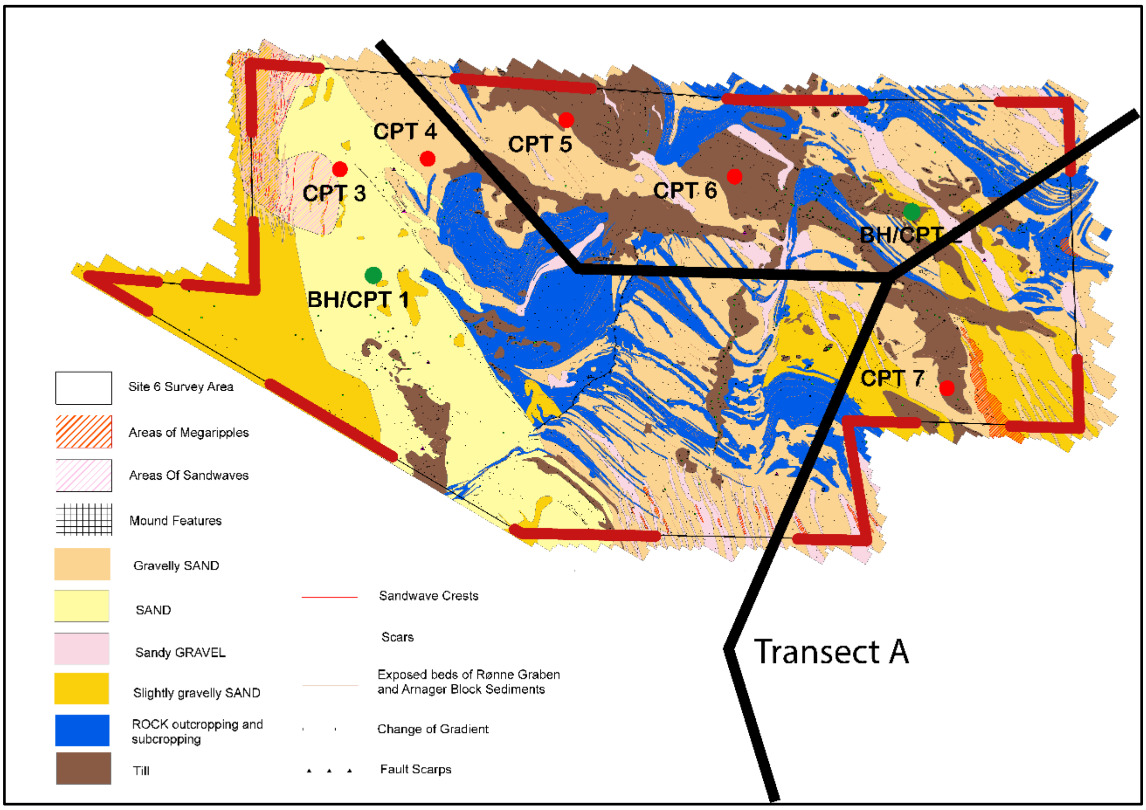


Figure 8.11 Seabed sediment map Rønne Banke Site 6. Surface sediment types and features are indicated as well as the locations of Transect A and boreholes (BH 1 and BH 2) and CPT's (CPT 1 to CPT 7)

8.1.6 Rønne Banke windfarm sediment types and composition

The coring and CPT results revealed several sediment types that improve the understanding of the layers (detailed results in Energinet 2014 (c) and (d)). The combination of lithology geotechnical parametres and stratigraphy (Figure 8.12) provides the possibility of correlation to Windfarm 1 and 2.

		Interpreted Unit	Lithology	Stratigraphy	
	Glacial Sediments (GS)	Quaternary	marine sands outwash sand and gravel Till	Holocene Late glacial (Weichselian)	
Rønne	Arnager Block (AB)	Bavnodde Greensand Formation	Interbedded cemented and unconsolidated Glauconitic SANDS	Upper Cretaceous	Rønne
Fault	Rønne Graben (RG)	Bavnodde Greensand Formation	Interbedded cemented and unconsolidated Glauconitic SANDS	Upper Cretaceous	Fault
		Arnager Limestone Formation	Hard siliceous LIMESTONE (55-65% carbonate)	Upper Cretaceous	
		Arnager Greensand Formation	Basal CONGLOMERATE overlain by interbedded cemented and unconsolidated Glauconitic SANDS	Lower Cretaceous	
		Rabaeke Formation	Upper: SHALE interbedded with SAND Lower: Iron cemented SANDSTONE	Lower Cretaceous	
		Bagå Formation	Upper: Variably cemented SANDS Lower: Interbedded SAND, CLAY and COAL	Early to Middle Jurassic	

Figure 8.12 Stratigraphic diagram of Rønne Banke windfarm on both sites of the Rønne Fault.

8.1.6.1 Holocene marine deposits

The thickness of Holocene marine deposits has been mapped in the south-western part of Site 6 on the basis of the seismic survey (Figure 8.13) and the geotechnical studies that encountered sand, clay and possible organic clay in RNB-CPT003, RNB-CPT004, RNB-CPT005, RNB-CPT006 to a maximum depth of 4 m below seabed (RNB-CPT003). From very loose to very dense occasionally silt, gravelly sand, to medium to extremely high strength sandy clay.

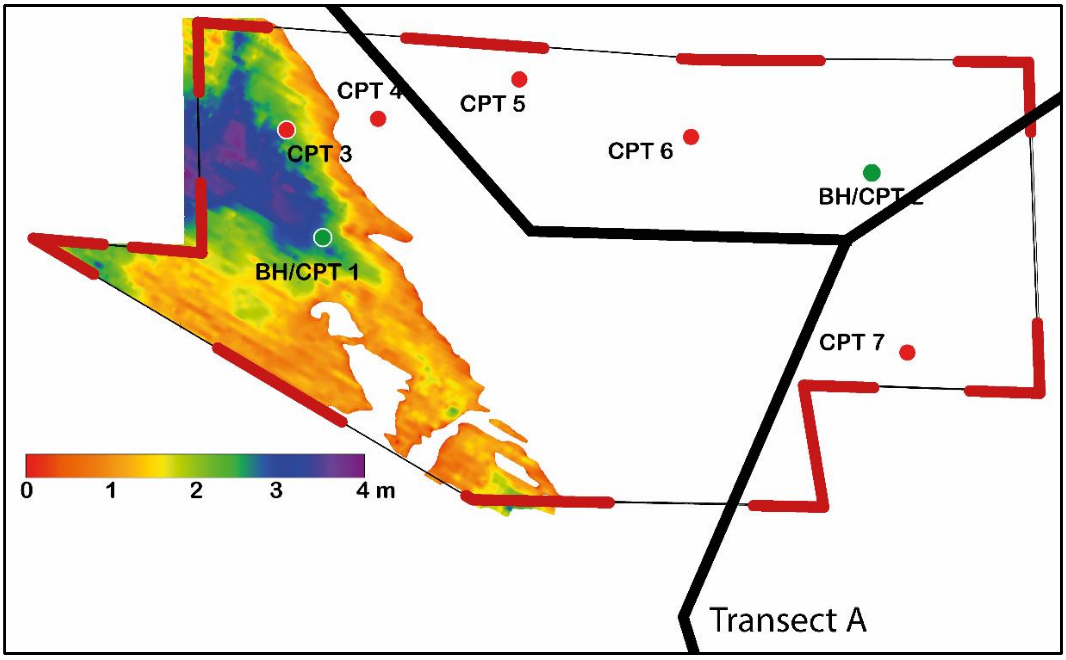


Figure 8.13 Thickness of Holocene marine deposits mapped from chirp seismic data. Locations of Transect A, Boreholes and CPT's are indicated

8.1.6.2 Late Glacial outwash deposits

The tickness of glacial to Late Glacial meltwater sand and till has been mapped (Figure 8.14) based on the seismic data and the geotechnical studies. The map shows meltwater sand deposits in RNB-BH001, RNB-BH002 and RNB-CPT001 to a maximum depth of 6 m below seabed. The fine- and medium-grained sand and gravel contains a variable content of clay and the gravel consist of granite, flint, sandstone and siltstone.

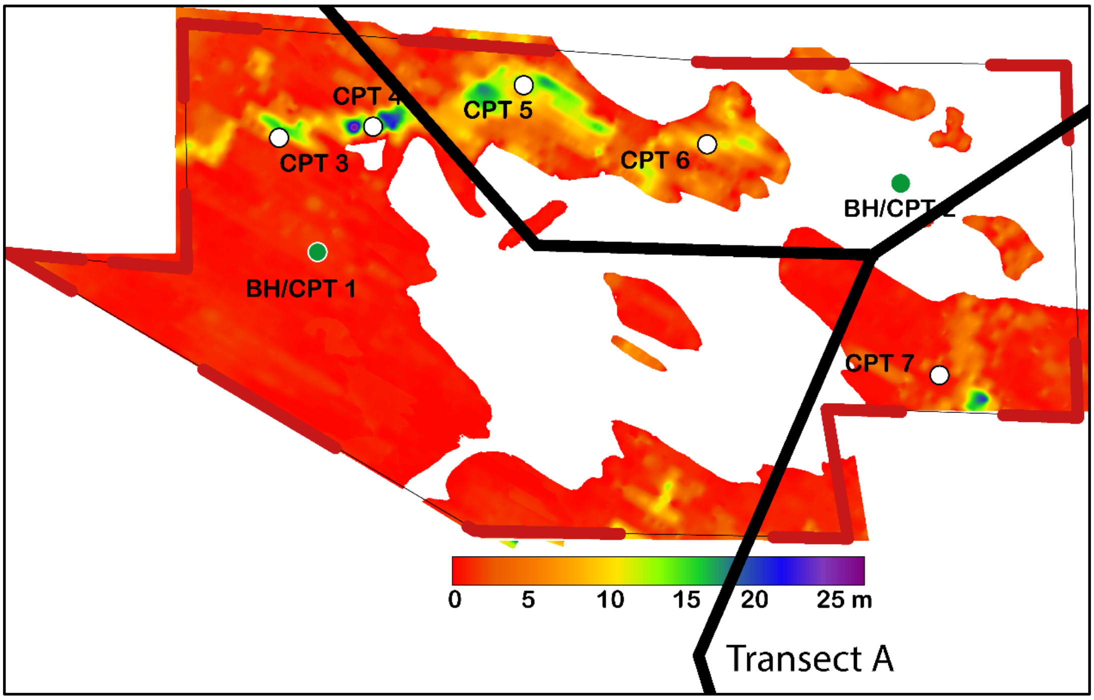


Figure 8.14 Combined thickness of glacial meltwater sand and till. Locations of Transect A, Boreholes and CPT's are indicated.

8.1.6.3 Arnager Block weathered mudstone (possibly till)

Arnager Block Weathered Mudstones is observed in positions RNB-CPT006 and RNB-CPT007 with a maximum thickness of 10 m (RNB-CPT006). Based on interpretation of cone penetration tests it is anticipated that the mudstone generally comprises high to extremely high strength clay with mudstone clasts occasionally with interbeds of sand or weathered sandstone.

Combining the information from the seismic- and geotechnical studies leads to the conclusion that the interpreted mudstone must be clay till (Figure 8.11 and Figure 8.15).

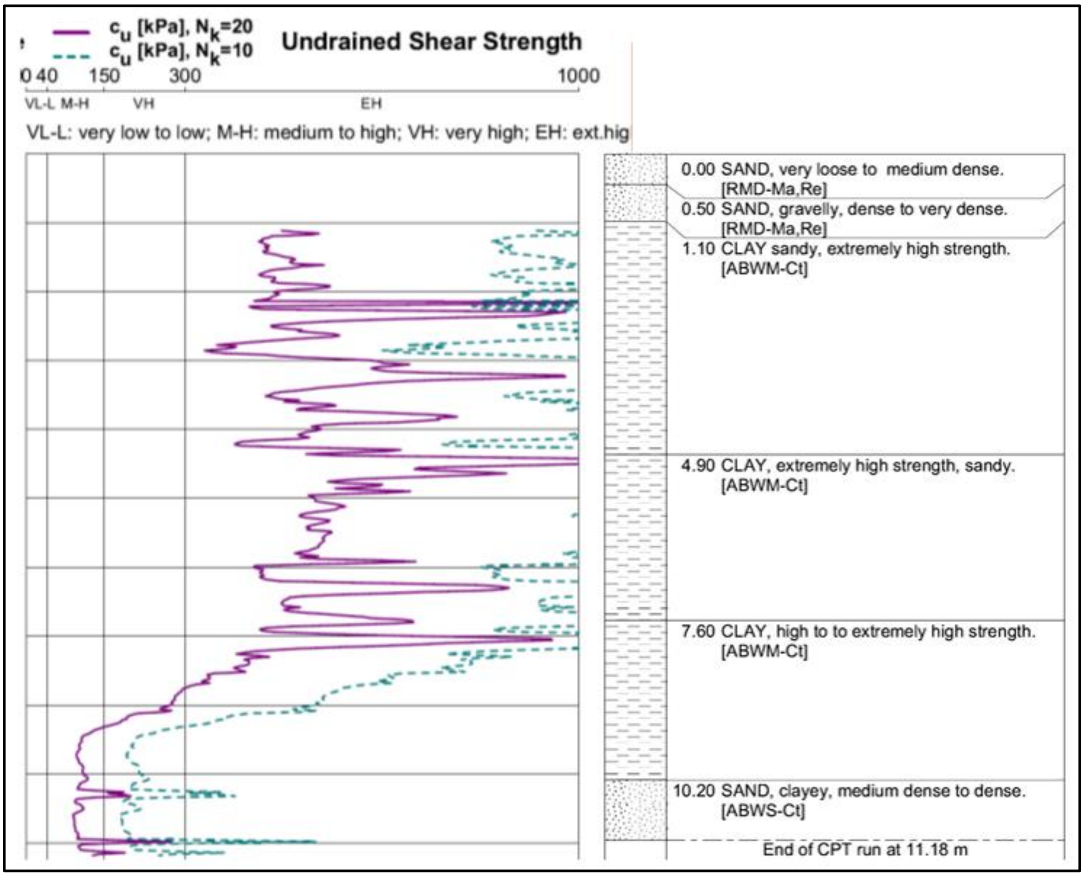


Figure 8.15 Undrained shear strength of RNB-CPT006 showing extremely high strength clay (till) to 10 m and medium high to high in the Bavneodde Greensand below (ref. Energinet 2014 (d)).

8.1.6.4 Arnager Block Sand/Weathered Sandstone (Bavneodde Greensand Formation)

The lithology represented by the strong reflectors consists of cemented glauconitic quartz sandstone (and occasional conglomerates), which form ridges on the sea floor; unconsolidated glauconitic sand gives rise to the weak reflectors. Sandstone was encountered in positions RNB-BH/CPT002, RNB-CPT6a and RNB-CPT7a, b. and recorded to the bottom of RNB-BH002a 50 m below seabed. Interpreted to be Upper Cretaceous Bavneodde Greensand Formation.

Medium high to high undrained shear strength is observed (Figure 8.15).

8.1.6.5 Rønne Graben Weathered Siltstone (Bavneodde Greensand Formation)
Siltstone was encountered at positions RNB-BH/CPT001, RNB-CPT003a, RNB-CPT004a and RNB-CPT005 with a maximum depth of 39 m below seabed at RNB-BH001.The siltstone is extremely weak to weak and the cone penetration test data indicate extremely high to high strength clay. The siltstone is interpreted as Upper Cretaceous Bavneodde Greensand Formation deposits.

8.1.6.6 Rønne Graben Limestone (Arnager Limestone Formation)
Limestone was encountered in RNB-BH001 35 m below seabed, with a thickness of about 2 m and described as a weak brecciated limestone, considered to be the Arnager Limestone Formation (Figure 8.12).

8.1.6.7 Rønne Graben Weathered Mudstone (Arnager Greensand Formation)
Mudstone is observed into locations RNB-CPT003a and RNB-CPT004a with a maximum penetrated depth 24 m below seabed (RNB-CPT003a). The cone test data indicates medium to very high strength sandy and silty clay. Stratigraphically the unit is referred to be Lower Cretaceous Arnager Greensand Formation (Figure 8.12).

8.1.6.8 Rønne Graben Weathered Sandstone (Arnager Greensand Formation)
Sandstone was encountered at position RNB-BH001. The deposits comprised fine, well sorted, silty, dark greenish grey cemented sand. The unit is interpreted as Arnager Greensand Formation interbedded cemented and unconsolidated glauconitic sand (Figure 8.12).

8.2 Swedish sector transect B

Transect B in the Swedish part of Arkona Basin connects the Bornholm region in the east with the outer Fakse Bugt in the west. This chapter describes the local geology in the transect B region.

8.2.1 Transect B bathymetry Swedish sector

The easternmost deepest part of Transect B is at the border to Denmark with water depths of about 48 m (Figure 8.16). Transect B crosses the north-central part of the Arkona Basin and the deeper parts of the basin continues about 50 km westward to the margin of the basin, where it shallows up to about 38–35 m passing north of Kriegers Flak, until it reaches the border to Denmark.

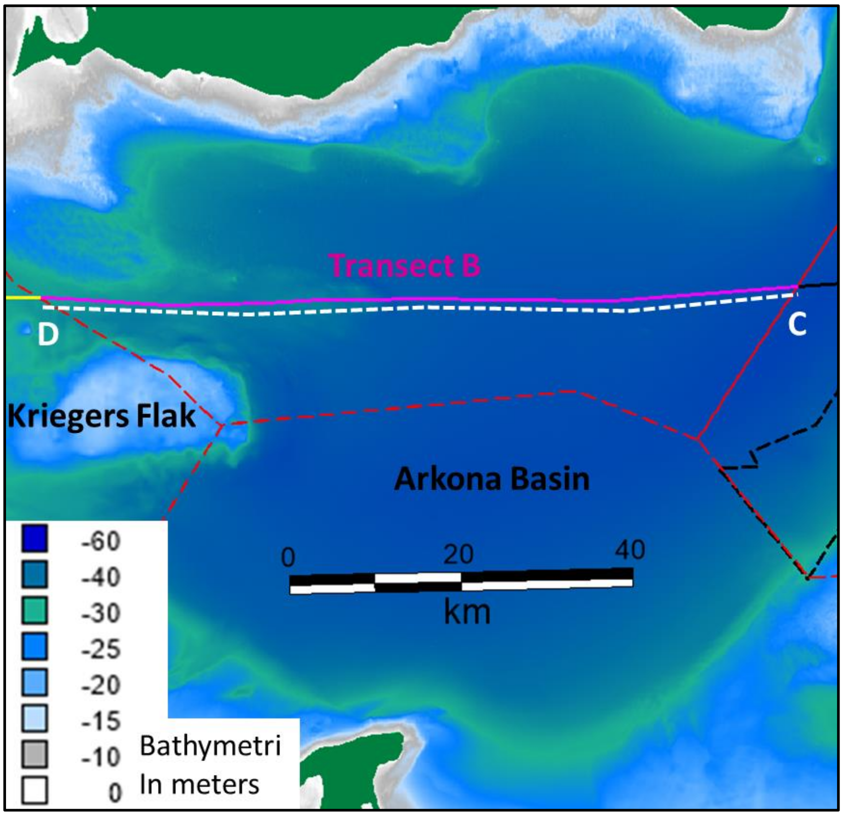


Figure 8.16 Bathymetry in the transect B area. The location of Baltic Pipe profile section C –D is indicated with a dashed white line.

8.2.2 Transect B seabed sediments Swedish sector

The Arkona Basin was mapped in general by Lemke (1998) as described in chapter 5.3.2. The planned cable transect B is located close to the parallel Baltic Pipe transect (Rambøll 2020; Figure 8.17 Profile C–D).

In the eastern deep part of transect B, Danien bedrock is covered by patchy and thin till deposits, followed by more than 10 m of Baltic Ice Lake clay (divided into two units) and a topmost layer of about 5 m of Holocene freshwater and marine gyttja to mud/sandy mud.

The Holocene mud disappears at the western margin of the basin and the Late Glacial clay thins to be missing or only a few metres thick (Figure 8.17). Till with boulders is exposed at the seabed in larger areas and the till thickness varies from a few metres to more than 10 m due to a very uneven bedrock surface consisting of Danien limestone.

Close to the western Danish border a few metres thick top unit is deposited, consisting of Holocene marine fine sand and muddy sand.

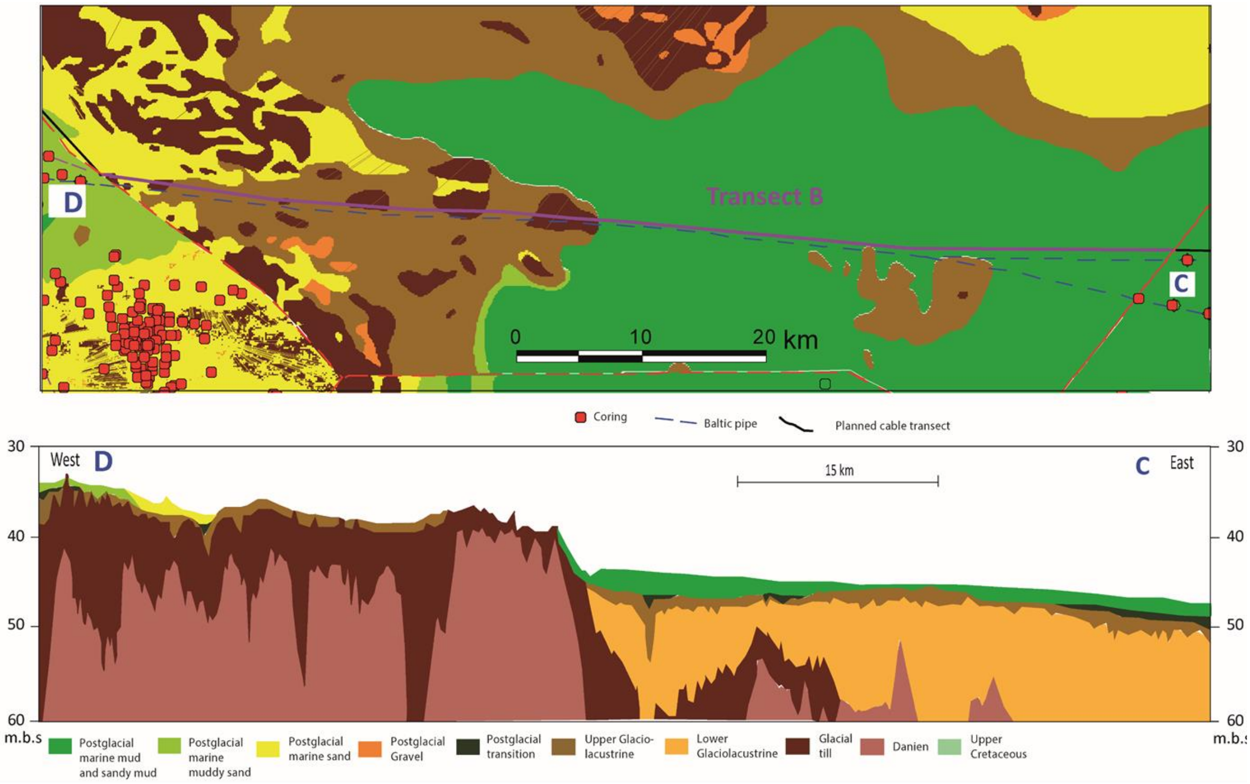


Figure 8.17 Upper figure: Surface sediments in the transect B Arkona Basin region. Location of Baltic Pipe profile section C–D is indicated. Lower figure: Baltic Pipe profile C– D interpreted sediment profile. For details see Appendix D.

8.3 Outer Fakse Bugt transect C

The transect C in the outer part of Fakse Bugt connects the Arkona region in the east with the Køge Bugt in the northwest. This chapter describes the local geology in the transect C region.

8.3.1 Transect C bathymetry outer Fakse Bugt

The easternmost deepest part of Transect C is at the border to Swedish waters at water depths of about 35 m (Figure 8.18). Transect C crosses the outer parts of Fakse Bugt in a northern direction towards Køge Bugt, reaching about 20 m off Stevns.

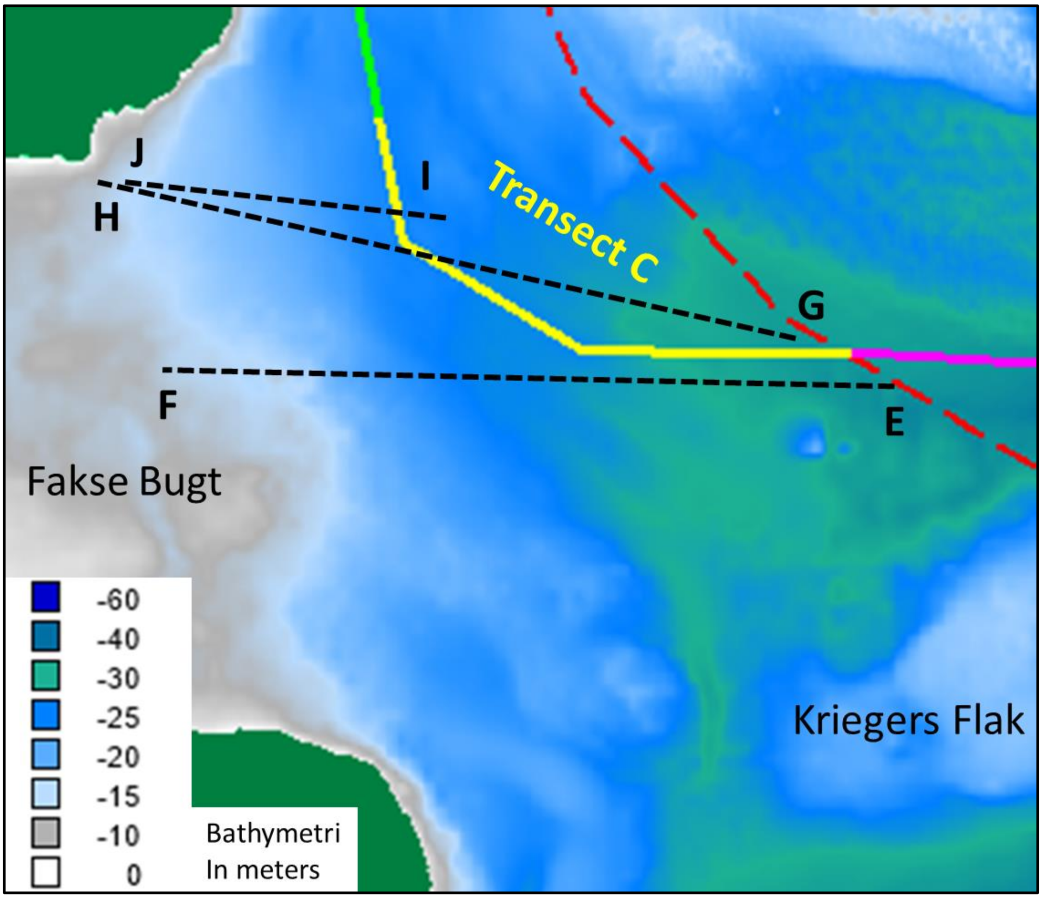


Figure 8.18 Bathymetry in the transect C area. The locations of Baltic Pipe profiles sections E–F, G–H and I–J are indicated.

8.3.2 Transect C seabed sediments outer Fakse Bugt

A combination of the sediment distribution map in the area together with three profiles from the Baltic Pipe studies profiles E–F, G–H and I–J (Figure 8.19, Figure 8.20 and Figure 8.21) gives a general indication of the expected seabed sediments in transect C.

Profile E–F shows that the deepest parts of transect C from 35 m b.s.l. to 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 inner part, the till unit thins to be a few metres thick on top of Upper Cretaceous chalk. Till with boulders is observed around 25 m b.s.l., with patchy cover of few metres of Holocene sand and muddy sand.

Profiles G–H and I–J confirms the general picture described and documents that transect C in general follows a path with a top unit of few metres Holocene sand and muddy sand on top of till.

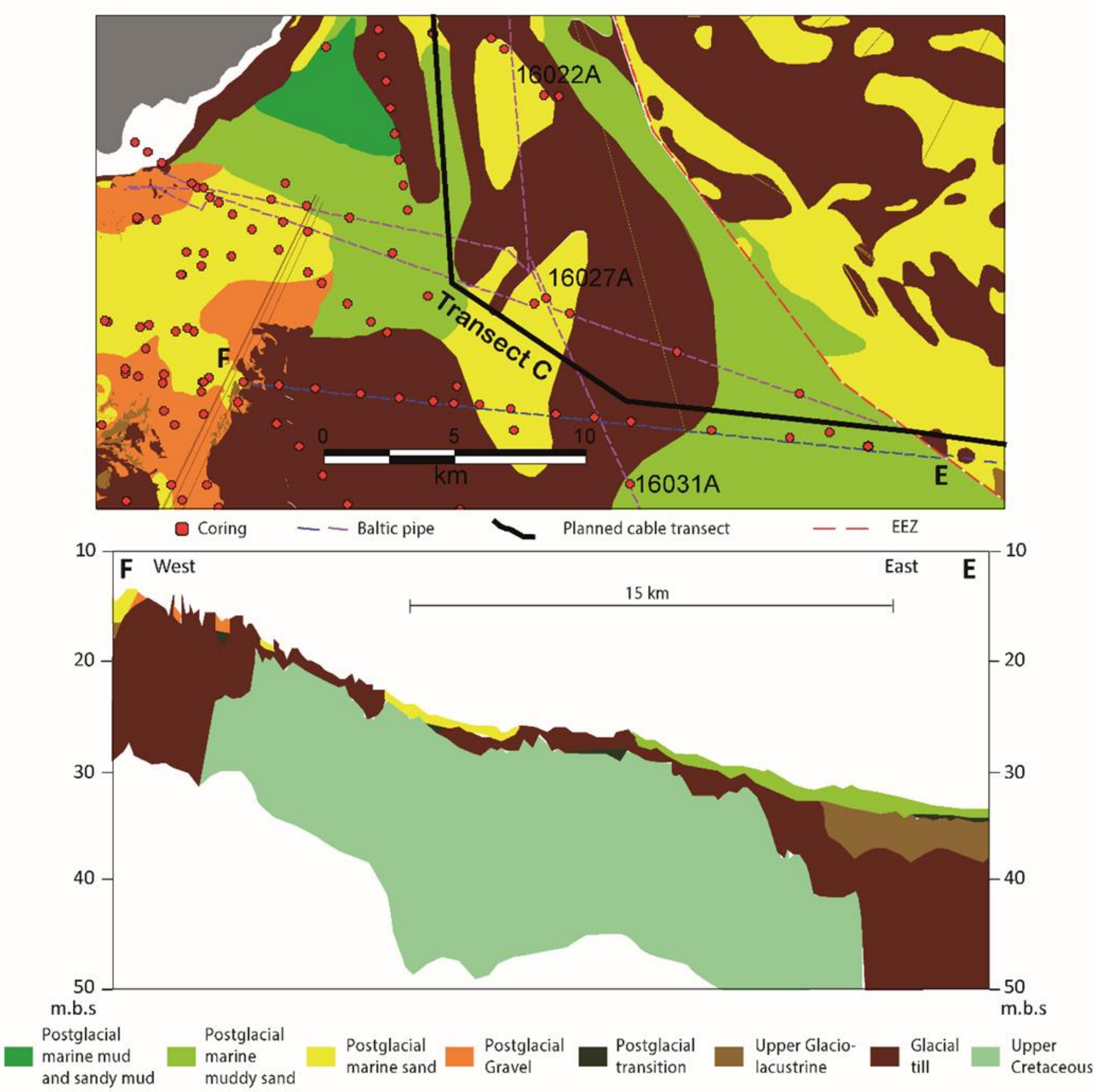


Figure 8.19 Upper figure: Surface sediments in the transect C outer Fakse Bugt region. Location of Baltic Pipe profile section E–F is indicated. Lower figure: Baltic Pipe profile E–F interpreted sediment profile. For details see Appendix E.

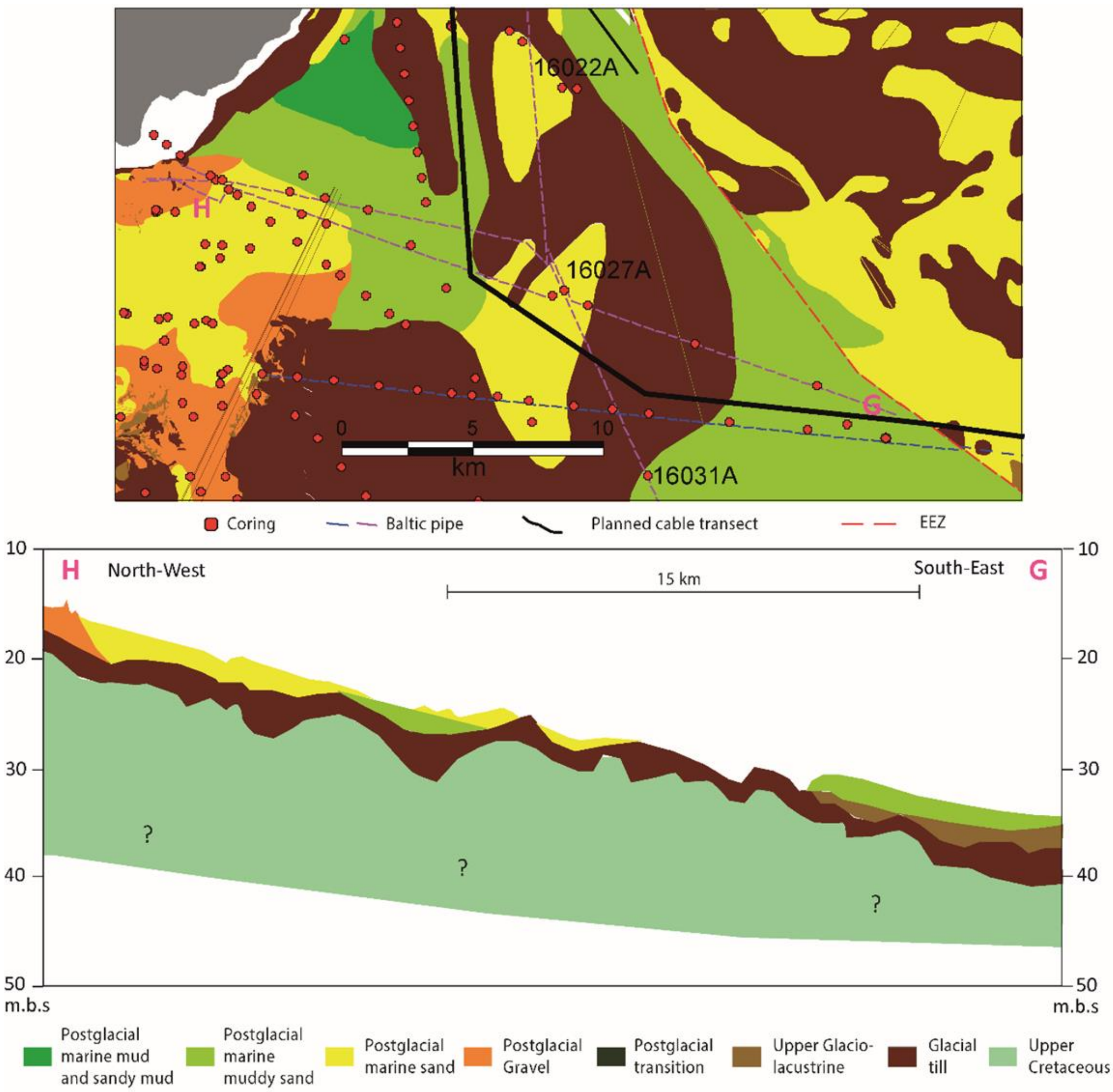


Figure 8.20 Upper figure: Surface sediments in the transect C outer Fakse Bugt region. The location of Baltic Pipe profile section G–H is indicated. Lower figure: Baltic Pipe profile G–H interpreted sediment profile. For details see Appendix F.

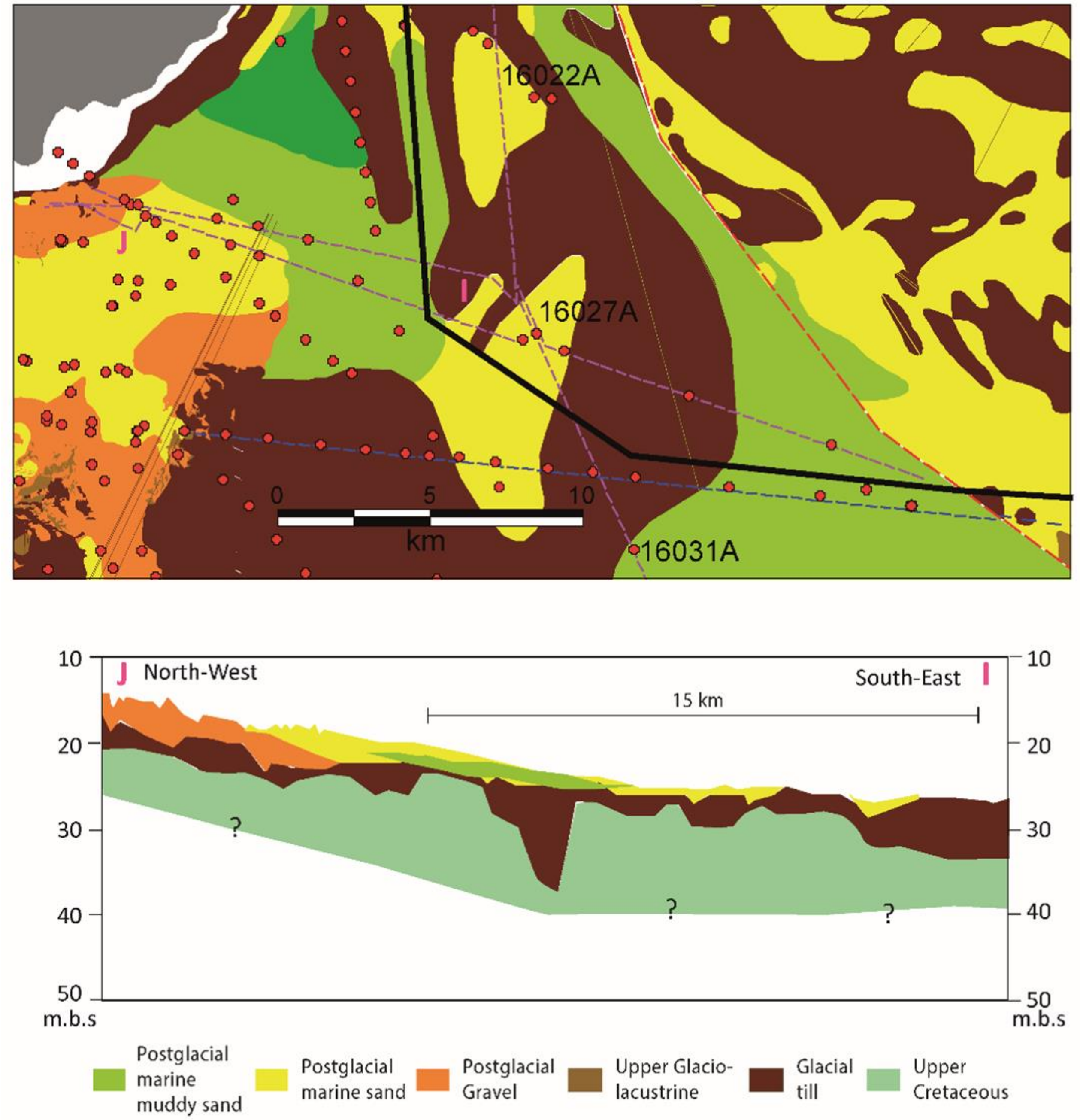


Figure 8.21 Upper figure: Surface sediments in the transect C outer Fakse Bugt region. Location of Baltic Pipe profile section I–J is indicated. Lower figure: Baltic Pipe profile I–J interpreted sediment profile. For details see Appendix G.

8.4 Køge Bugt transect D

Transect D follows a single stringed path from off Stevns to the central part of Køge Bugt, where it divides in to four fingers with landfalls distributed in the bay. This chapter describes the local geology in the transect D Køge Bugt region.

8.4.1 Transect D bathymetry in Køge Bugt

The south-eastern deepest part of Transect D is located off Stevns at water depths of about 20 m (Figure 8.22). Transect D crosses the outer parts of Køge Bugt in a northern direction against the four potential landfalls.

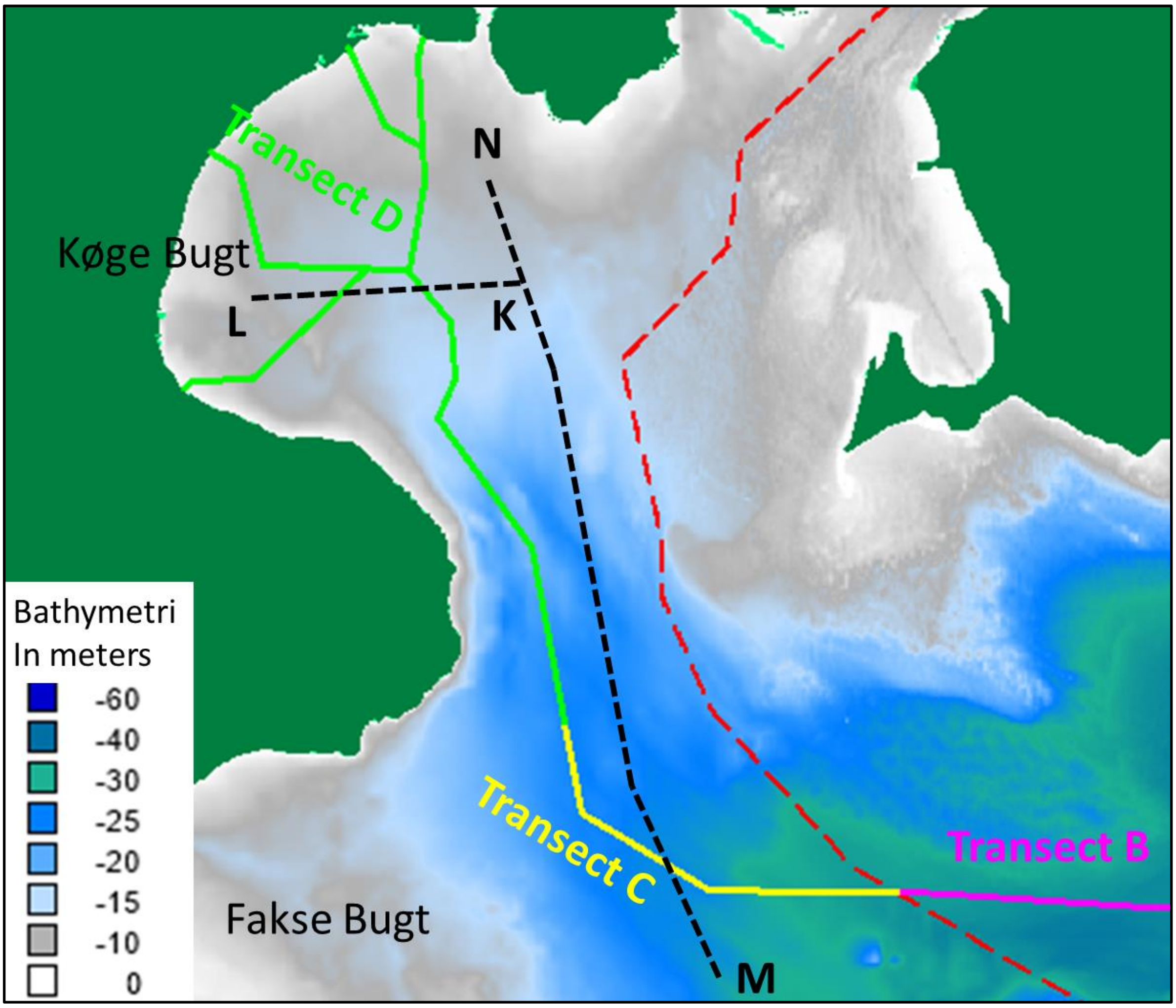


Figure 8.22 Bathymetry in the transect D area. Location of Baltic Pipe profiles sections L–K, and N –M is indicated.

8.4.2 Transect D seabed sediments in Køge Bugt

The Køge Bugt region was mapped already in connection with raw material mapping in 1987 Skov og Naturstyrelsen (1987), as described in chapter 5.5. The mapping shows a general distribution of near-surface glacial deposits (till) and Late Glacial sediment basins in a patchy glacial surface, with incised valleys and basins, infilled by Late Glacial and Postglacial sediments.

The general maps (Figure 5.16 and Figure 5.16Figure 5.17) show that the planned cable transect D will pass a patchwork of till and Late- Postglacial sediments with a thin cover of Holocene sand and muddy sand.

The overall frame of the sediments is however steered by the bedrock features consisting of Upper Cretaceous chalk and Danien limestone (Figure 4.2), separated by a north–south-orientated normal fault.

A combination of the sediment distribution map in the area together with two crossing profiles from the Baltic Pipe studies, profiles K–L (Figure 8.23 and M–N (Figure 8.24), gives a general indication of the expected seabed sediments in transect D.

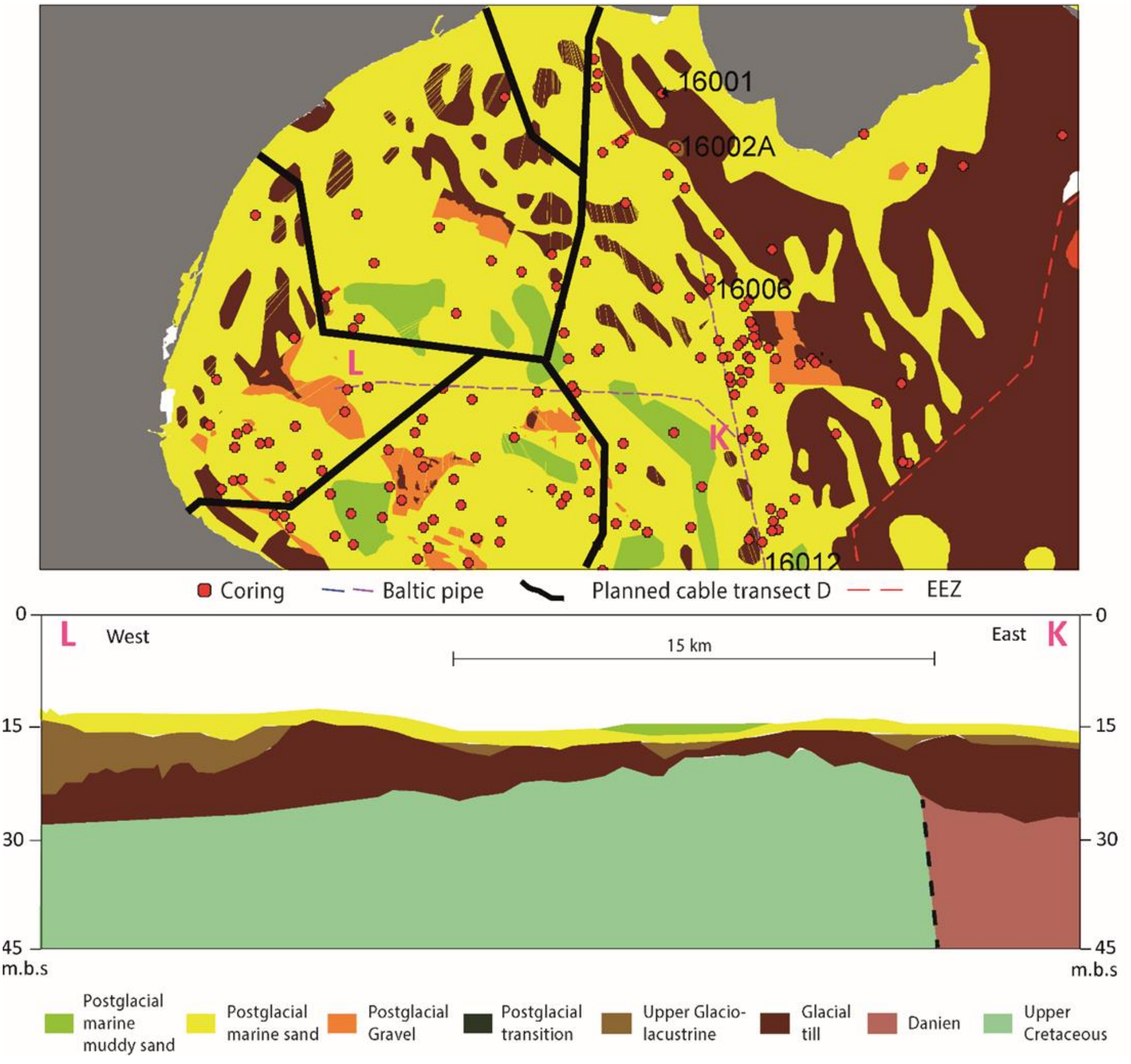


Figure 8.23 Upper figure: Surface sediments in the transect D Køge Bugt region. Location of Baltic Pipe profile section K–L is indicated. Lower figure: Baltic Pipe profile K–L interpreted sediment profile. For details see Appendix H.

Profile K–L shows the sediment distribution in an east–west direction, from the outer to the inner part of Køge Bugt, with a water depth of about 15 m. The north–south-orientated bed-rock fault is illustrated, and it is seen that till covers the bay. The till is from a few metres to more than 10 m thick. As described in chapter 5.5 Late Glacial fine grained basin fill is deposited in the till depressions and incised valleys. A top unit of a few metres of sand and muddy sand covers large parts of the bay, but the seabed sediment map shows patchy appearance of till with boulders.

Profile M–N gives together with the sediment map a south-north sediment distribution, from outer Fakse Bugt to northern Køge Bugt.

In Fakse Bugt and southern Køge Bugt, the general sediment distribution is Upper Cretaceous chalk, with a thin layer of till and boulders, partly covered by Holocene sand and muddy sand.

In Køge Bugt, the bedrock changes to Danien limestone north-west of the fault and increasing Quaternary sediment layers form a wedge-like structure with till thickness increasing to about 10 m in the north and Late Glacial fine-grained basin fill in till depressions. These sediments are overlain by a few metres of Holocene sand and muddy sand. Till ridges with boulders form the seabed in a mosaic pattern.

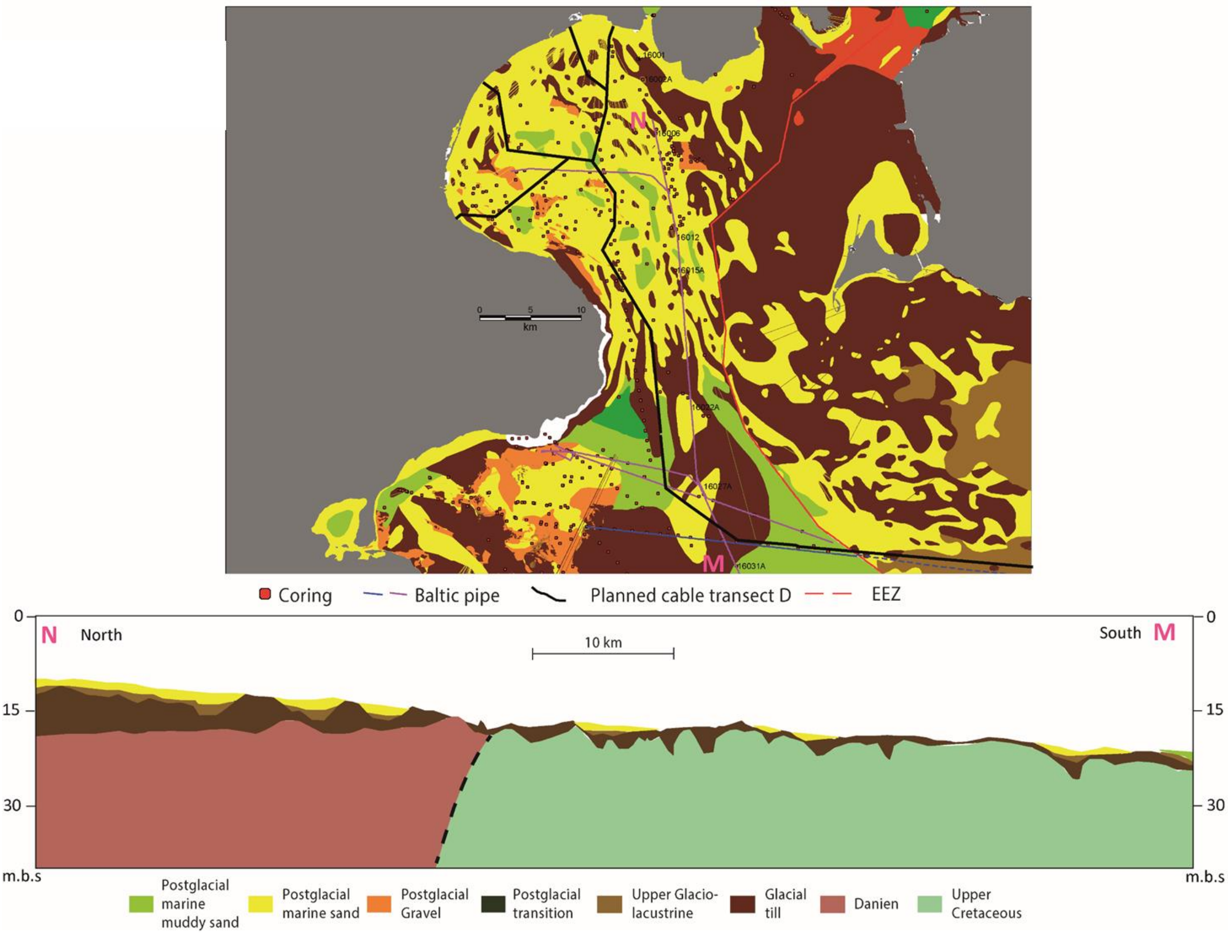


Figure 8.24 Upper figure: Surface sediments in the transect D Køge Bugt region. The location of Baltic Pipe profile section M–N is indicated. Lower figure: Baltic Pipe profile M–N interpreted sediment profile. For details see Appendix I.

A series of vibrocores from south to north along profile M–N documents the lithology.

Outer Fakse Bugt shows a thin layer of till on Upper Cretaceous chalk. The till surface has some minor depression covered by about 1 m sand or muddy sand.

Outer Køge Bugt vibrocores documents the Danien limestone in south and till with varying thickness of Holocene organic-, clay/silt- and sandy- sediments.

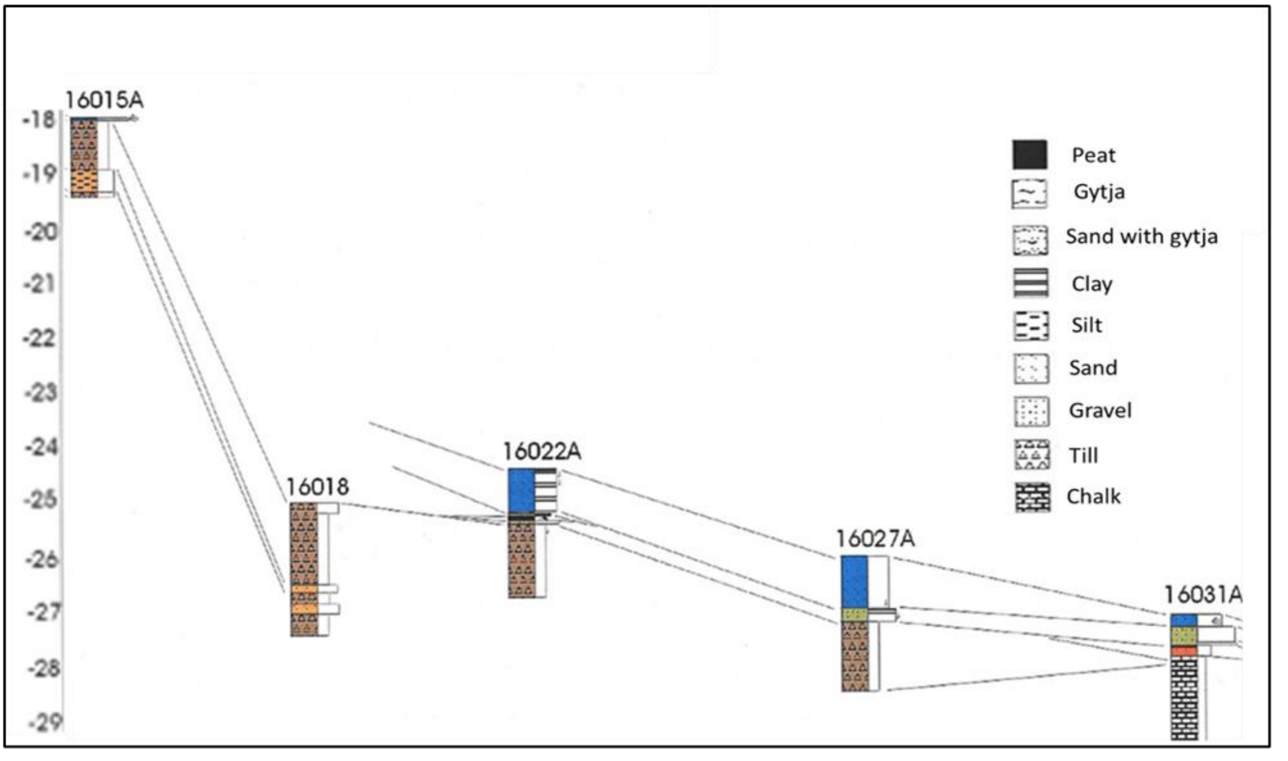


Figure 8.25 Vibrocore verification of surface-near sediments along profile M–N in Fakse Bugt (Figure 8.24 and Appendix I)

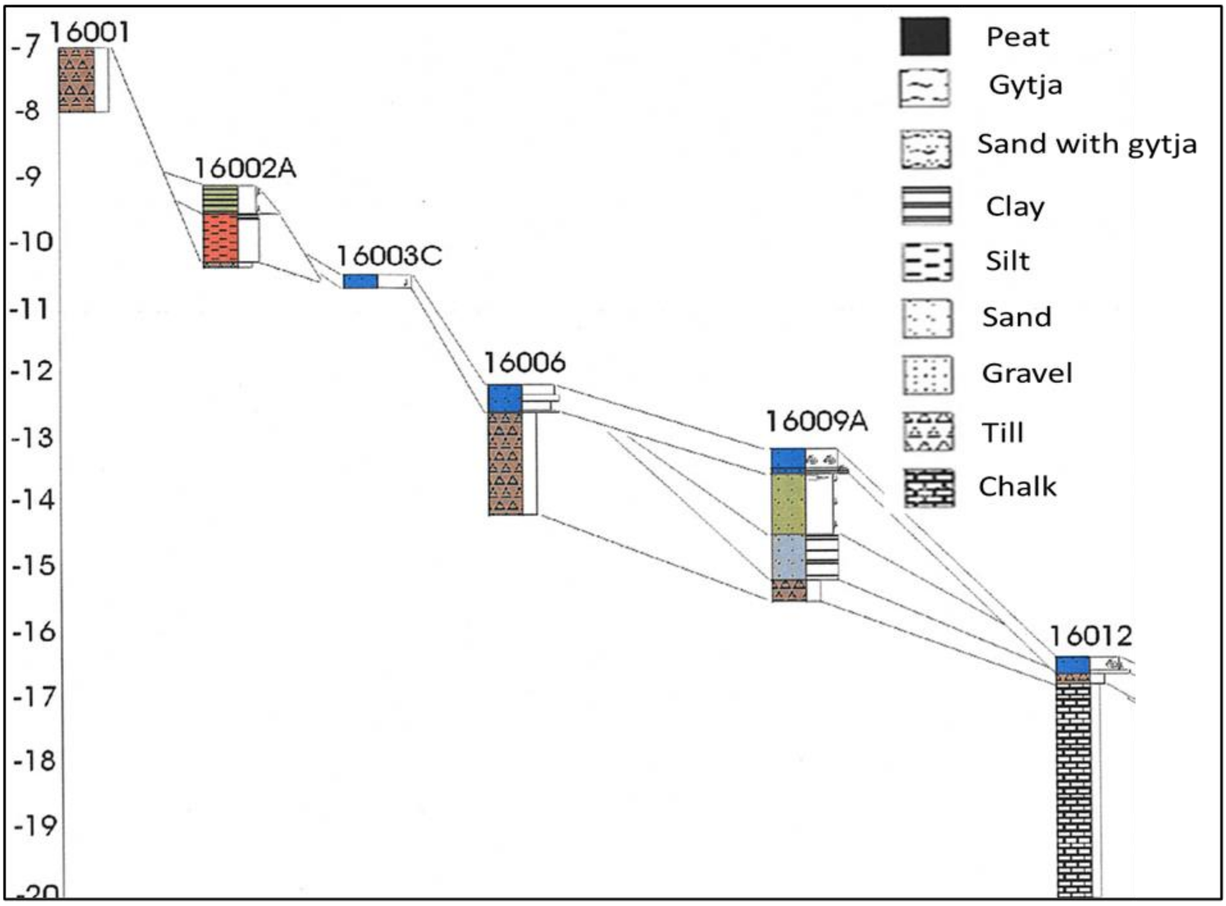


Figure 8.26 Vibrocore verification of surface-near sediments along profile M–N in Køge Bugt (Figure 8.24 and Appendix I).

9. Archaeological interests

In addition to geotechnical interests in a detailed geological model for the region between Bornholm and Køge Bugt, it is also of great interest for an archaeological screening to understand the development and distribution of land and lake/sea after the last deglaciation.

High-stand water-level characterised the initial period after the deglaciation of the south-western Baltic Sea. The region was deglaciated around 16,000 to 15,000 years ago and major parts of the planned cable route were covered by the glaciolacustrine Baltic Ice Lake. This corresponds to the archaeological Hamburg culture or Hamburgian (15,500–13,100 years BP) – 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 12800 years BP. During the lowstand period the water level was about 40 m below present sea level and reed plants were growing in parts of the Arkona Basin. Major parts of the cable route would have been dry land during this lowstand. However, the low-stand period was short-lived and followed by a rapid transgression. A new low-stand period is dated to ca. 11700 years BP, this time the water level was ca. 40–45 m below sea level and Bornholm was a peninsula connected to mainland Europe (Figure yy). Major parts of the cable route would have been exposed. However, this second low-stand period was also short-lived and soon followed by a new fairly rapid transgression. The new low-stand period corresponds to the early part of the Maglemose Culture (Figure 9.1).

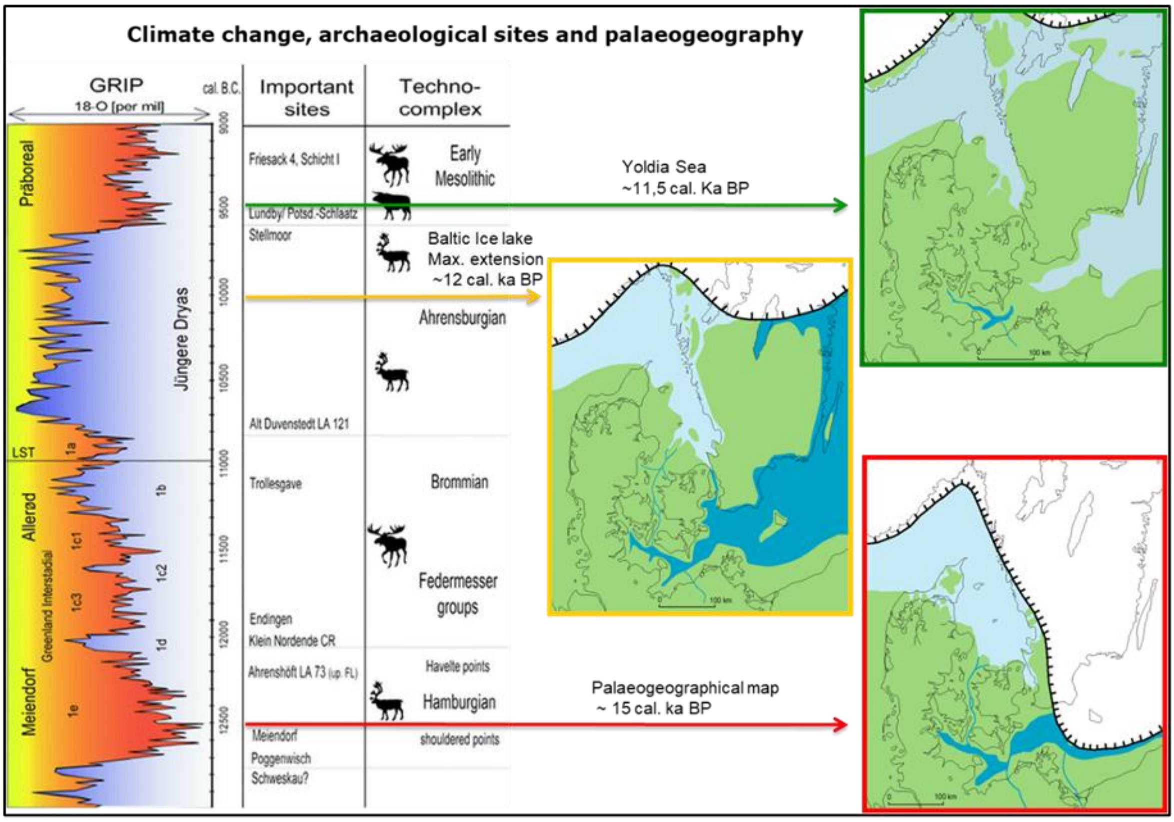


Figure 9.1 Late Glacial and Holocene general palaeogeography in the Danish area and related archaeological cultures. The maps are from Jensen et al. (2003).

The shallow-water parts of the cable corridors would have been dry land for long periods during the Late Glacial and Early Holocene. Late Glacial bones and antlers of reindeer, giant deer and other vertebrates have been recovered during sand dredging in Køge Bugt. Submerged archaeological sites from the Maglemose, Kongemose and Ertebølle Cultures are for example known from Mecklenburg Bucht off northern Germany (Schmölcke *et al.* 2006; Hartz *et al.* 2011; Lübke *et al.* 2011), from Køge Bugt, near Amager, from the former Free Port in Copenhagen and recently from Lynetteholm. Submerged fishing constructions made of hazel rods and dated to 9000-8400 cal. years BP have been reported from Hanö Bugt off Skåne (Hansson et al. 2018) and from Køge Bugt. Due to the fluctuating and dynamic shoreline history in the southern Baltic Basin, it is possible to find submerged landscapes and archaeological sites from the whole Holocene, but we consider the early and mid-Mesolithic the most likely. The chances to find submerged archaeological sites are probably small in areas with a long fetch and high energy environment. The chances are higher along the east coast of Sealand, which is protected from the dominating westerly winds.

10. Conclusions

In this study we used a combination of published work, archive seismic and sediment core as well as CPT data, to assess the general geological development of the south-western Baltic Sea region, including the planned Bornholm OWFs and cable transect From Bornholm to Køge Bugt. Detailed information has been acquired from The Baltic Pipe offshore pipeline transect, which over long stretches run parallel with the planned cable transects, so crucial information comes from seismic transects and vibrocores, reporting on the Baltic Pipe offshore pipeline transect studies.

A geological description has been provided and a geological model presented.

A surface sediment map has been compiled by a combination of Emodnet seabed substrate from the German and Swedish zones and the latest version (2020) of the Danish 1:100,000 seabed substrate map.

The planned cable transect will follow a complex line from Mesozoic Lower Jurassic sand and clay to Upper Cretaceous limestone at the seabed close to Bornholm, followed by glacial and Late Glacial clay on the margins of Rønne Banke. Arkona Basin is dominated by Late Glacial clay and Holocene mud, whereas Fakse Bugt and Køge Bugt are dominated by glacial till, with a patchy cover of Late Glacial and Holocene sand and mudy sand.

As a result of the geological desk study, it has been possible to present a relative Late Glacial and Holocene shore-level curve for the area and to describe the development relevant for an archaeological screening.

Detailed data are presented in the transect sections A–D among others described on the basis of profile sections A–M, modified from Baltic Pipe investigations (Rambøll 2020). Boomer and sediment echosounder data as well as vibrocore data form the background for the interpretations.

Several focal points are relevant for the future geotechnical and archaeological evaluations of the area:

- The study area is in the Fennoscandian border zone, which is characterised by pre-Quaternary dextral wrench faulting. A combination of archive data allows a tentative interpretation of the distribution of pre-Quaternary formations.

- In transect A near Bornholm, near-coastal seabed sediments and sedimentary rocks are dominated by Jurassic and Cretaceous bedrock deposits at the seabed, with patchy remnants of glacial and Postglacial boulders and sandy sediments.

- Transect A from the Danish part of Arkona Basin over Rønne Banke to the Bornholm Basin is characterised by basin deposits of a few metres mud and sandy mud on top of glaciolacustrine clay/silt and till. The northern Rønne Banke flank is characterised by 2–5 m patchy Holocene sand on top of stony till.

- Transect B from the Swedish part of Arkona Basin shows eastern dominance of Baltic Ice Lake clay and about 5 m Holocene mud/sandy mud. In the western part the Late Glacial clay thins and till with boulders is exposed at the seabed in larger areas.

- Transect C from outer Fakse Bugt is dominated by till with boulders and patchy cover of few metres of Holocene sand and muddy sand.

- Transect D from outer Fakse Bugt to northern Køge Bugt shows in the south Upper Cretaceous bedrock, with a thin layer of till and boulders, partly covered by Holocene sand and muddy sand. North-ward into Køge Bugt, increasing till thickness form a wedge-like structure and Late Glacial fine-grained basin fill, is overlain by a few metres of Holocene sand and muddy sand. Till ridges with boulders form the seabed in a mosaic pattern.

- Due to the fluctuating and dynamic shoreline history in the southern Baltic Basin, it is possible to find submerged landscapes and archaeological sites from the whole Holocene, but we consider the early and mid-Mesolithic the most likely.

- The chances to find submerged archaeological sites are probably small in areas with a long fetch and high energy environment. The chances are higher along the east coast of Sealand, which is protected from the dominating westerly winds.

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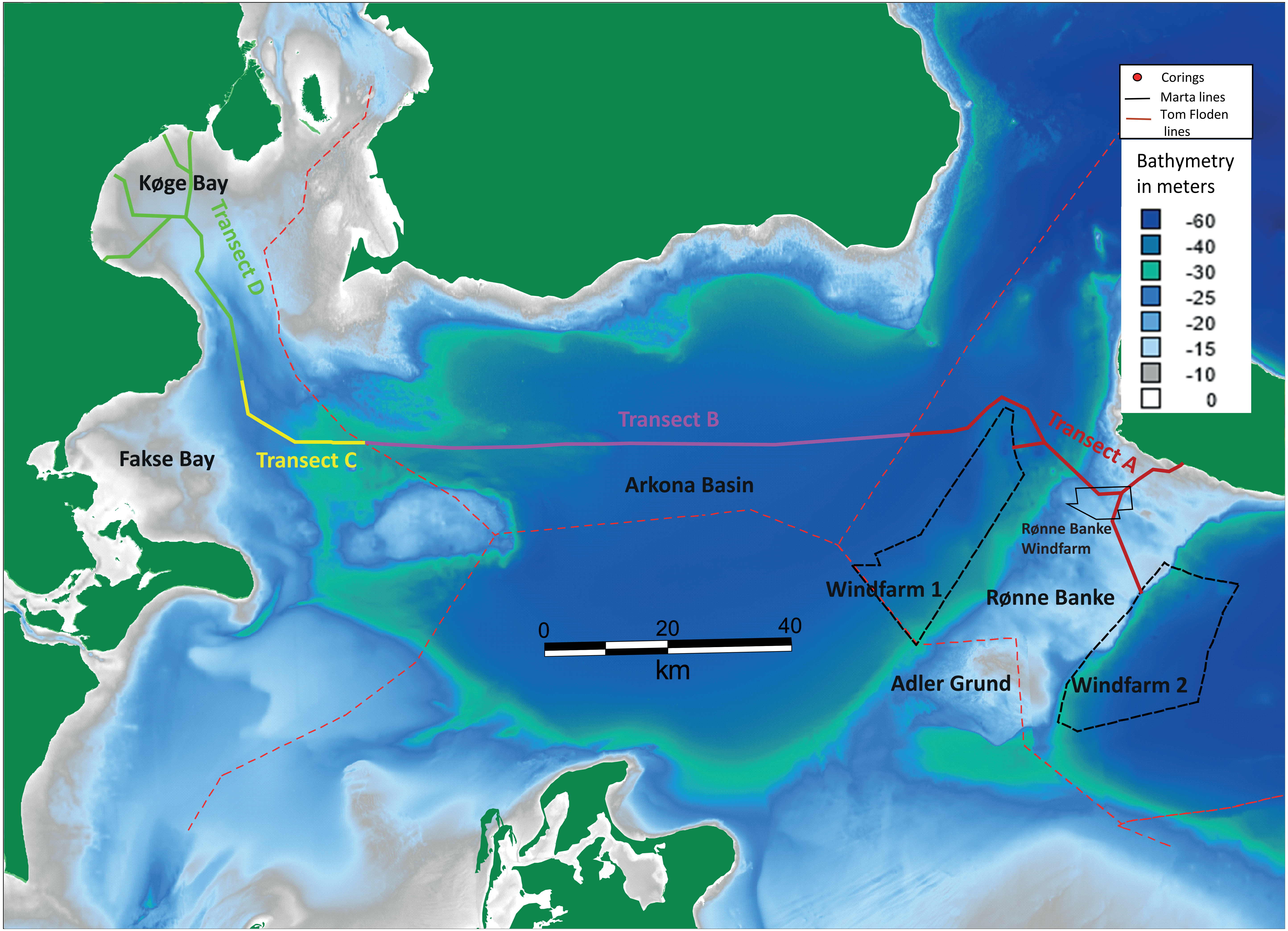
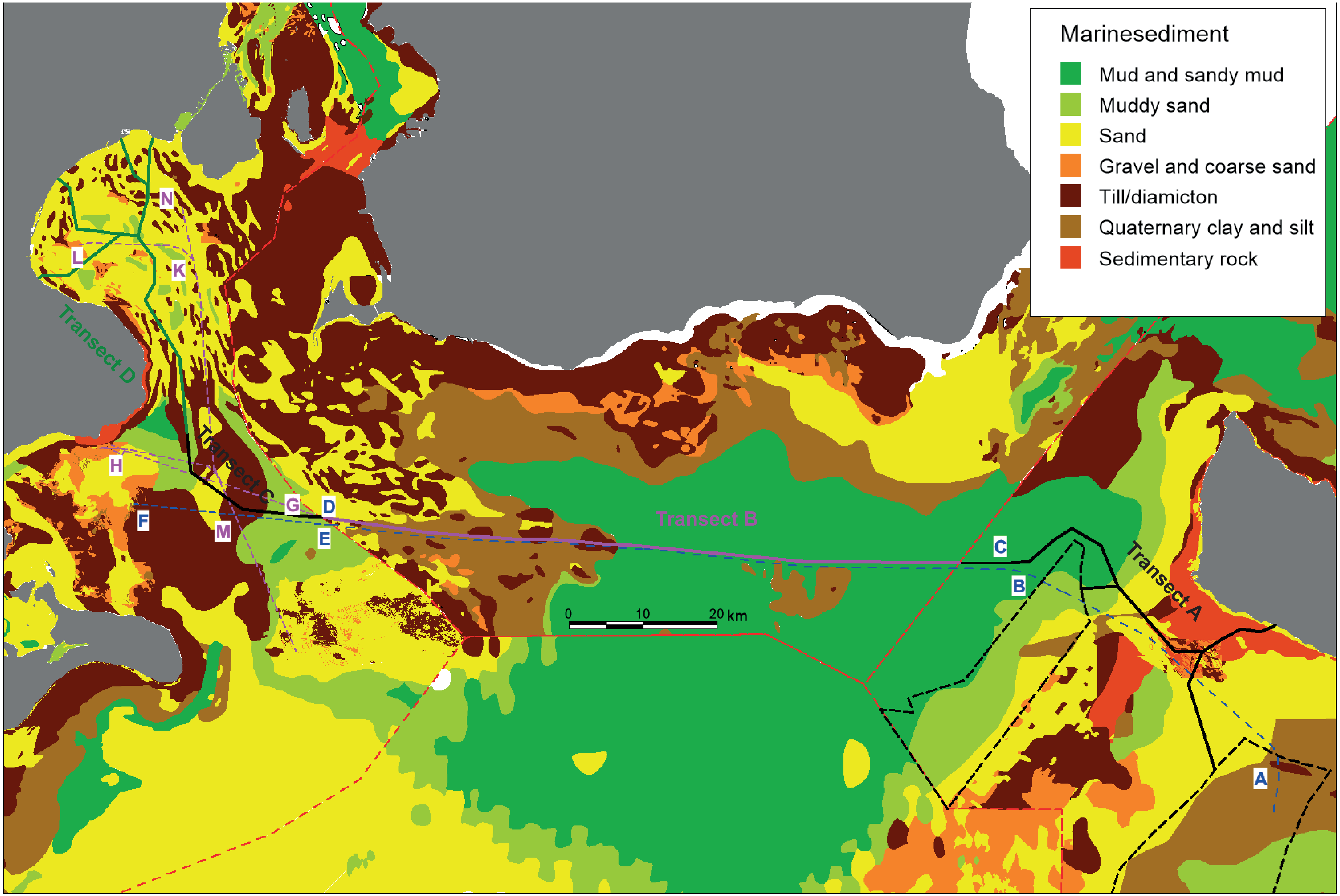
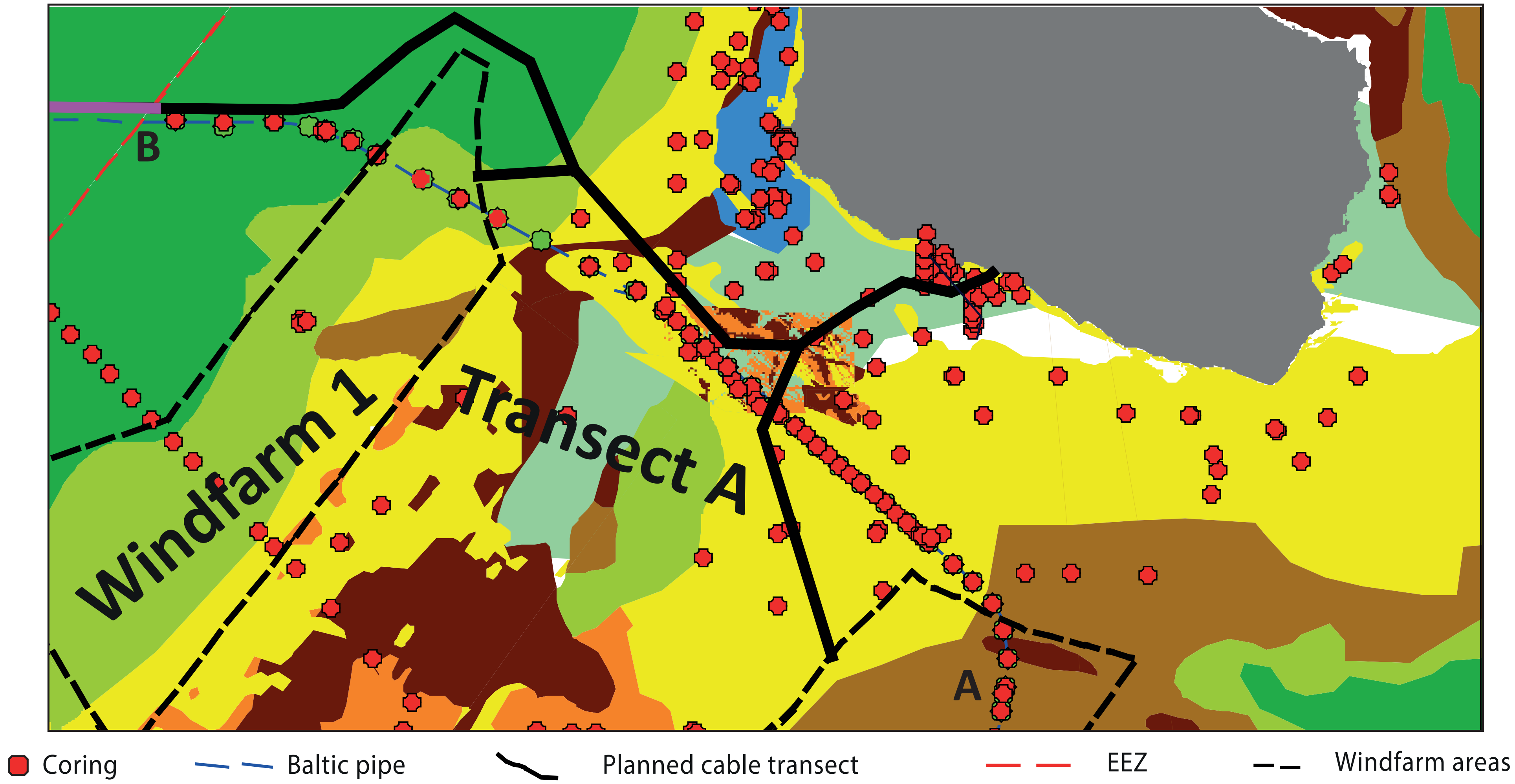


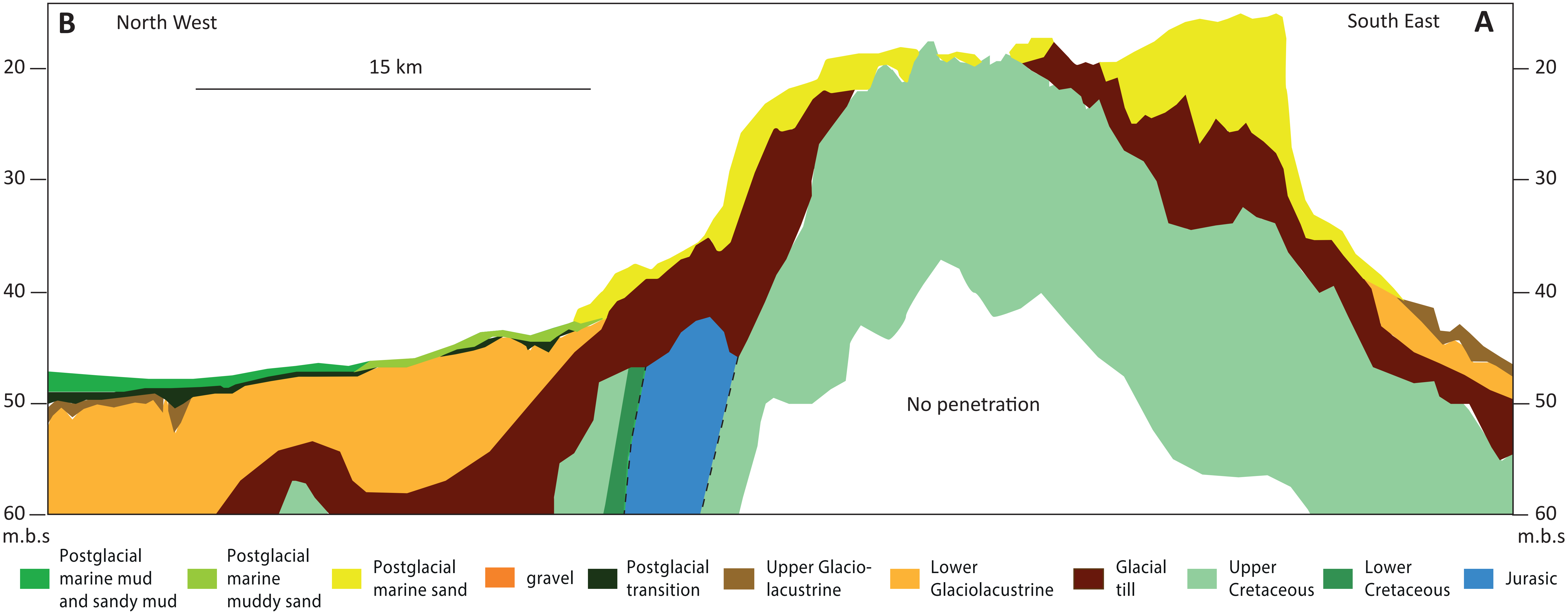
Appendix A.
Overview map of southwestern Bal c Sea Bathymetry
and location of cable transects A - D



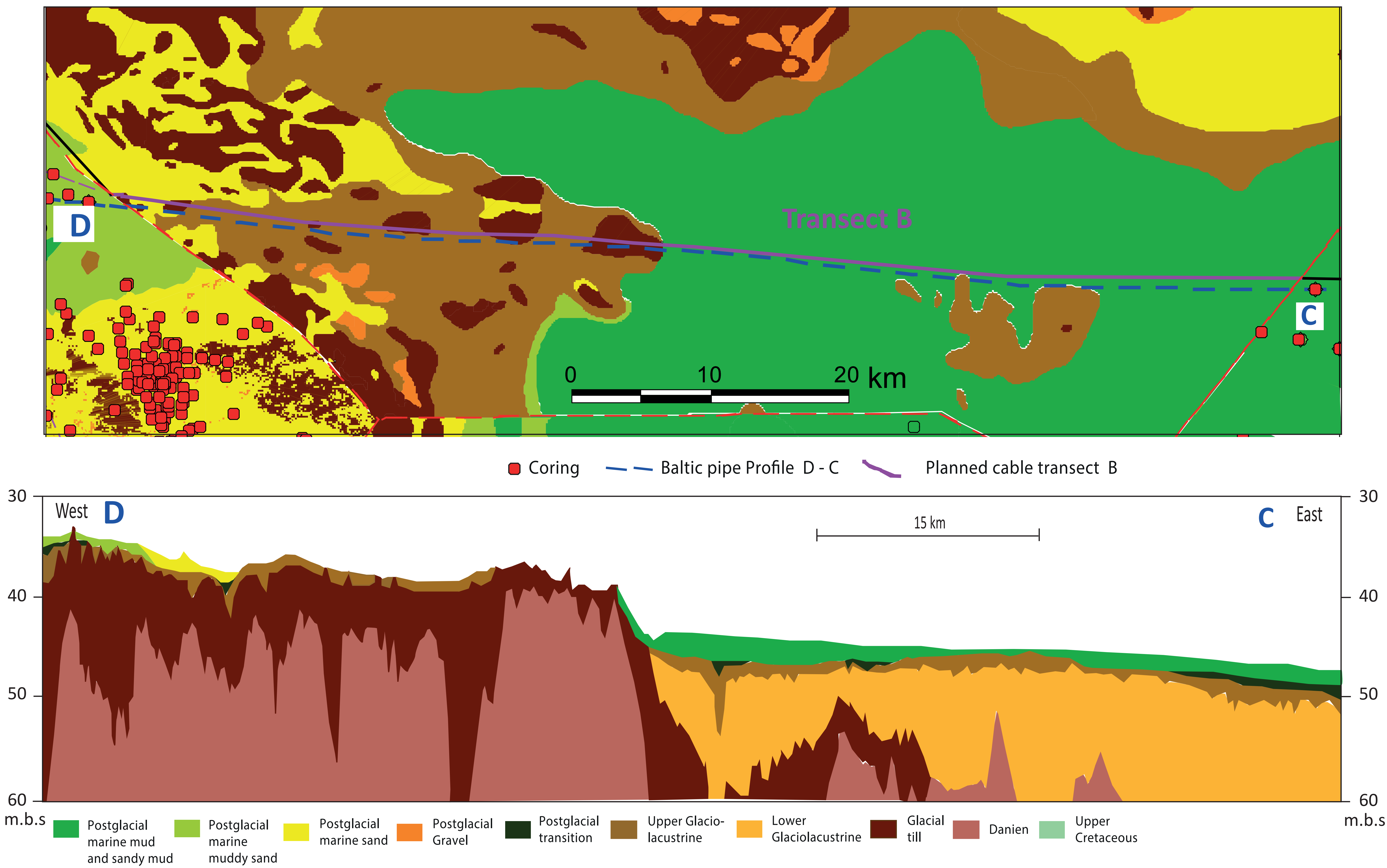
Appendix B.
Overview map of seabed sediments southwestern Baltic Sea
with location of cable transect profiles, A-B, C-D, E-F, G-H, K-L and N-M.

Appendix C : Transect A

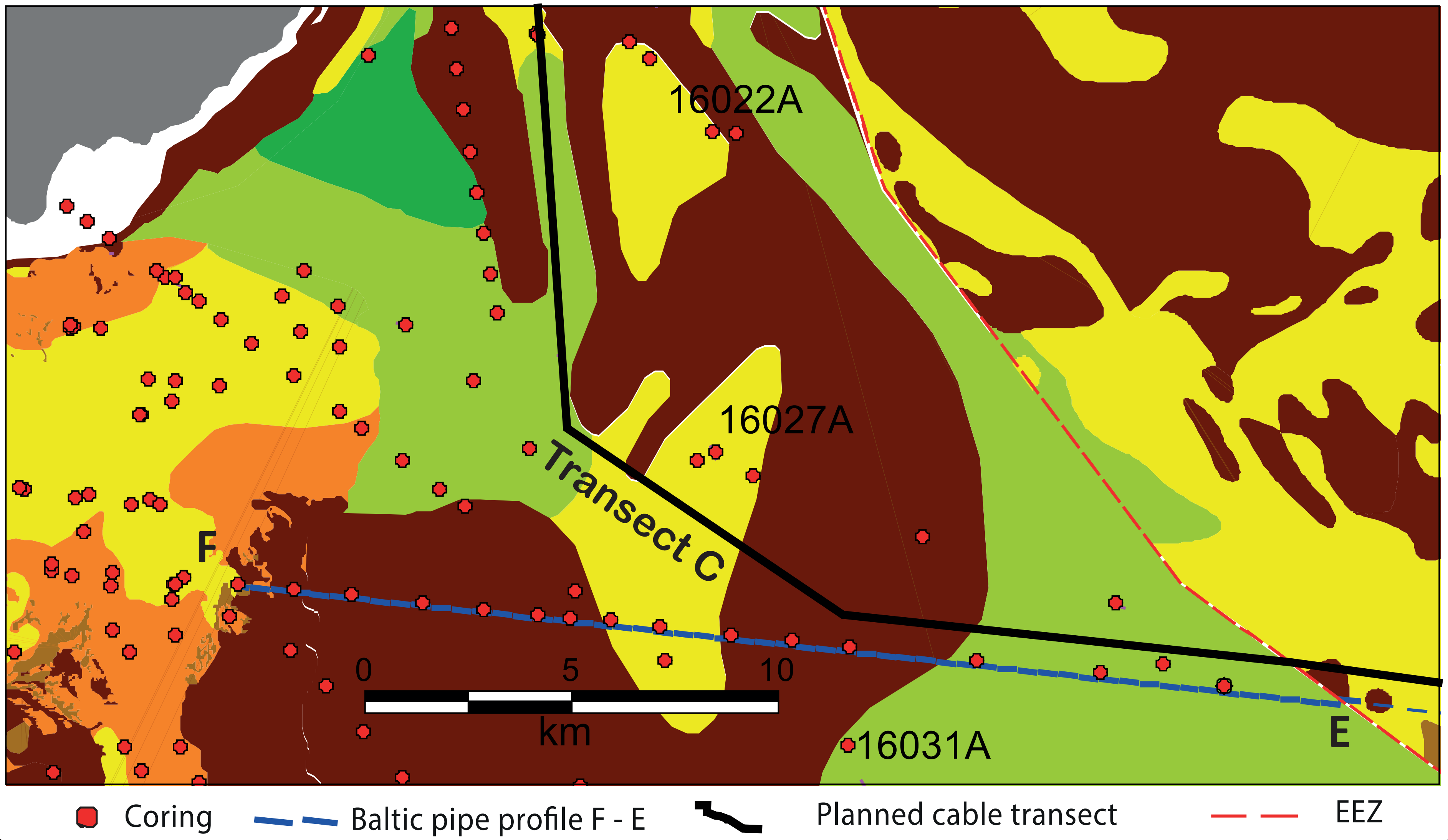


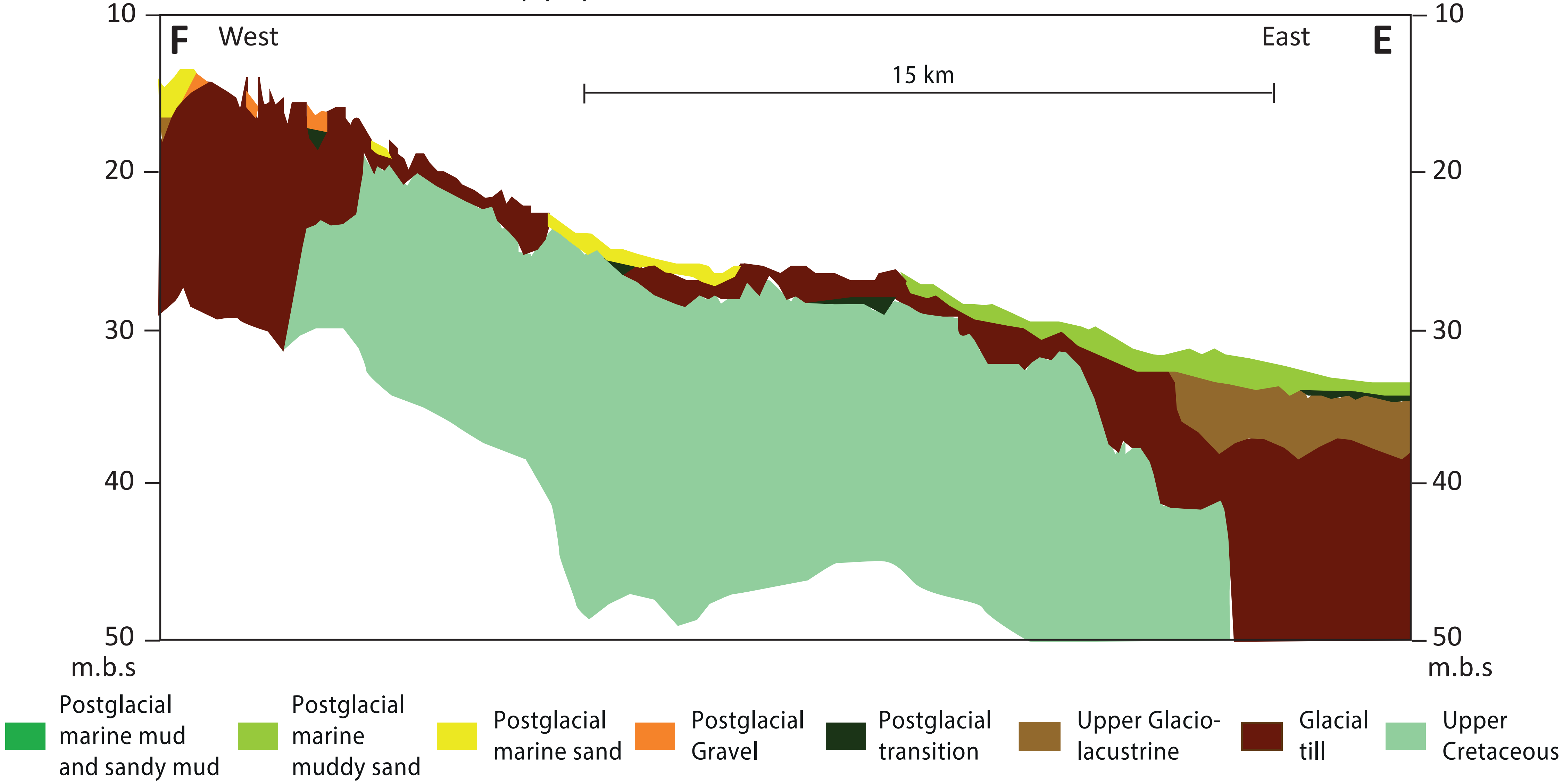


Appendix D : Transect B

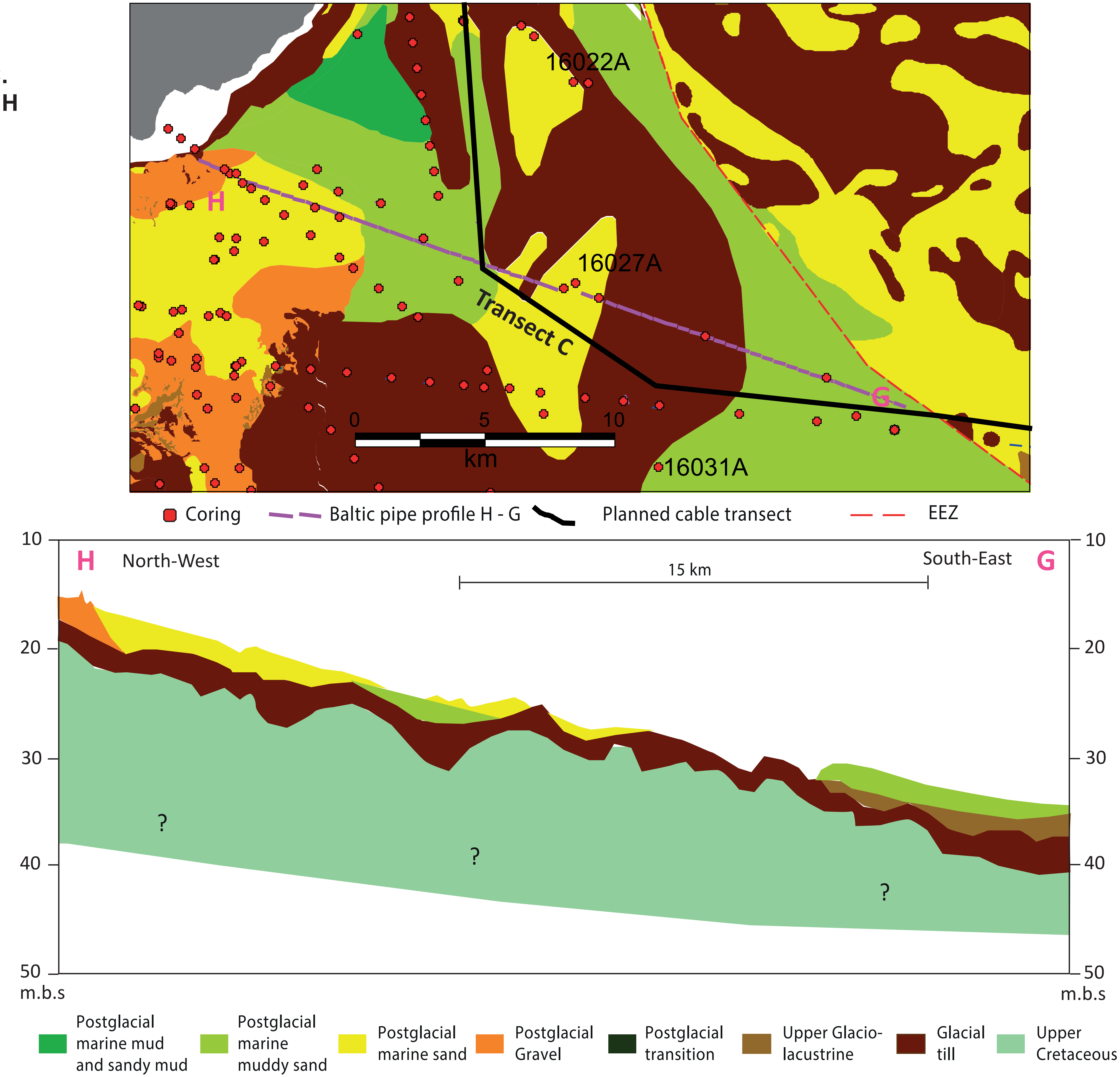


Appendix E: Transect C.
Profile F - E

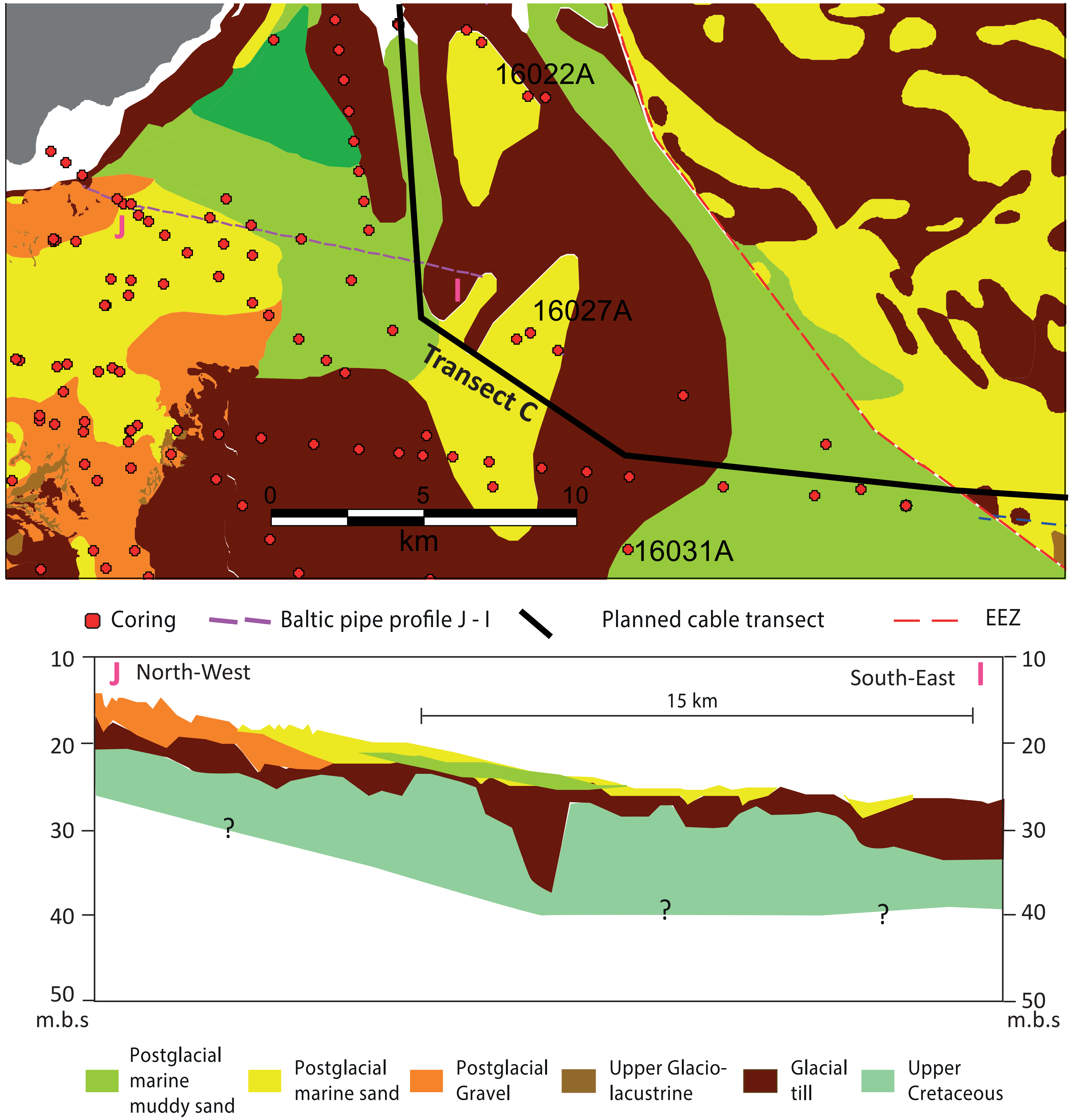




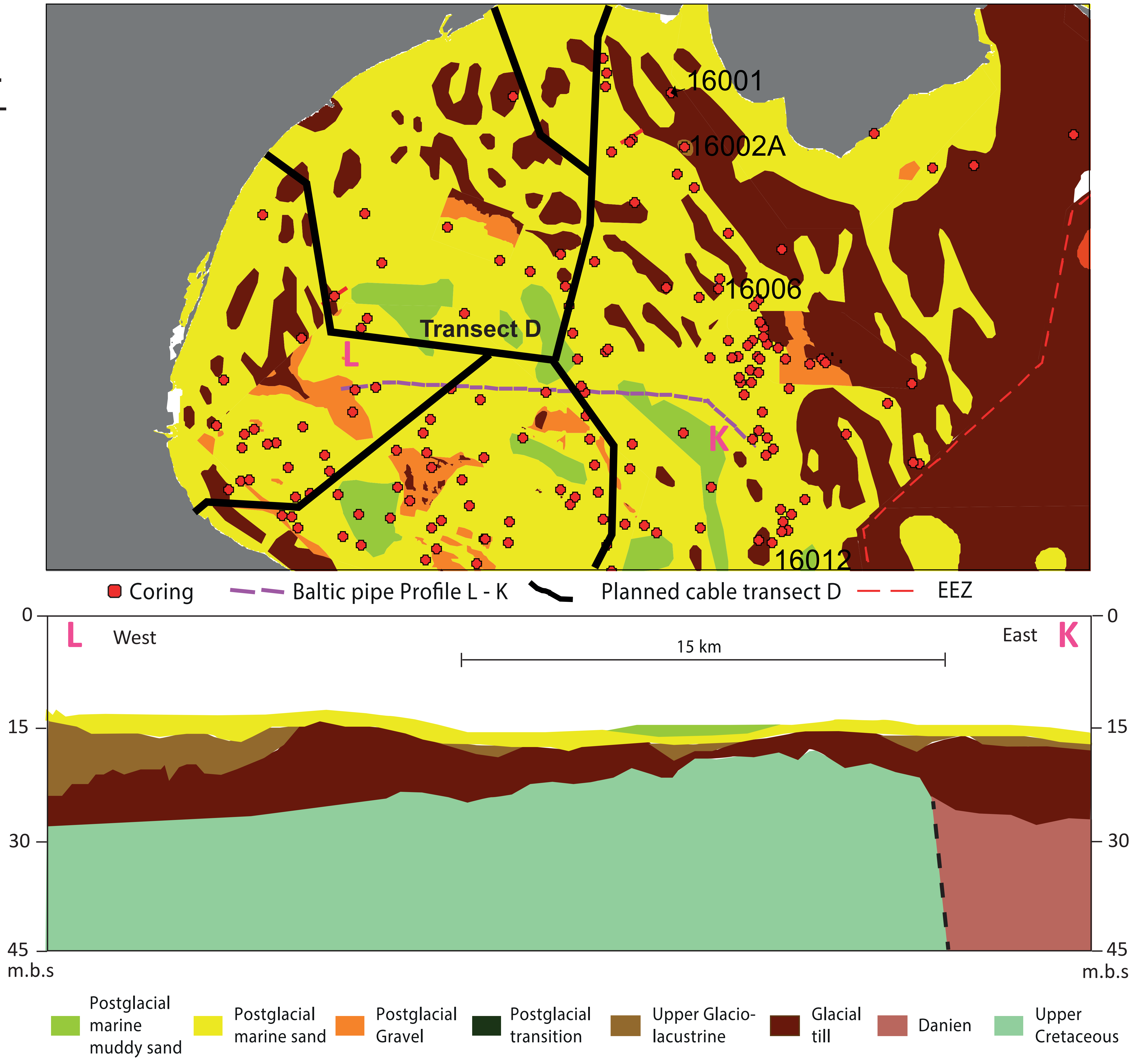
Appendix F: Transect C.
Profile G - H

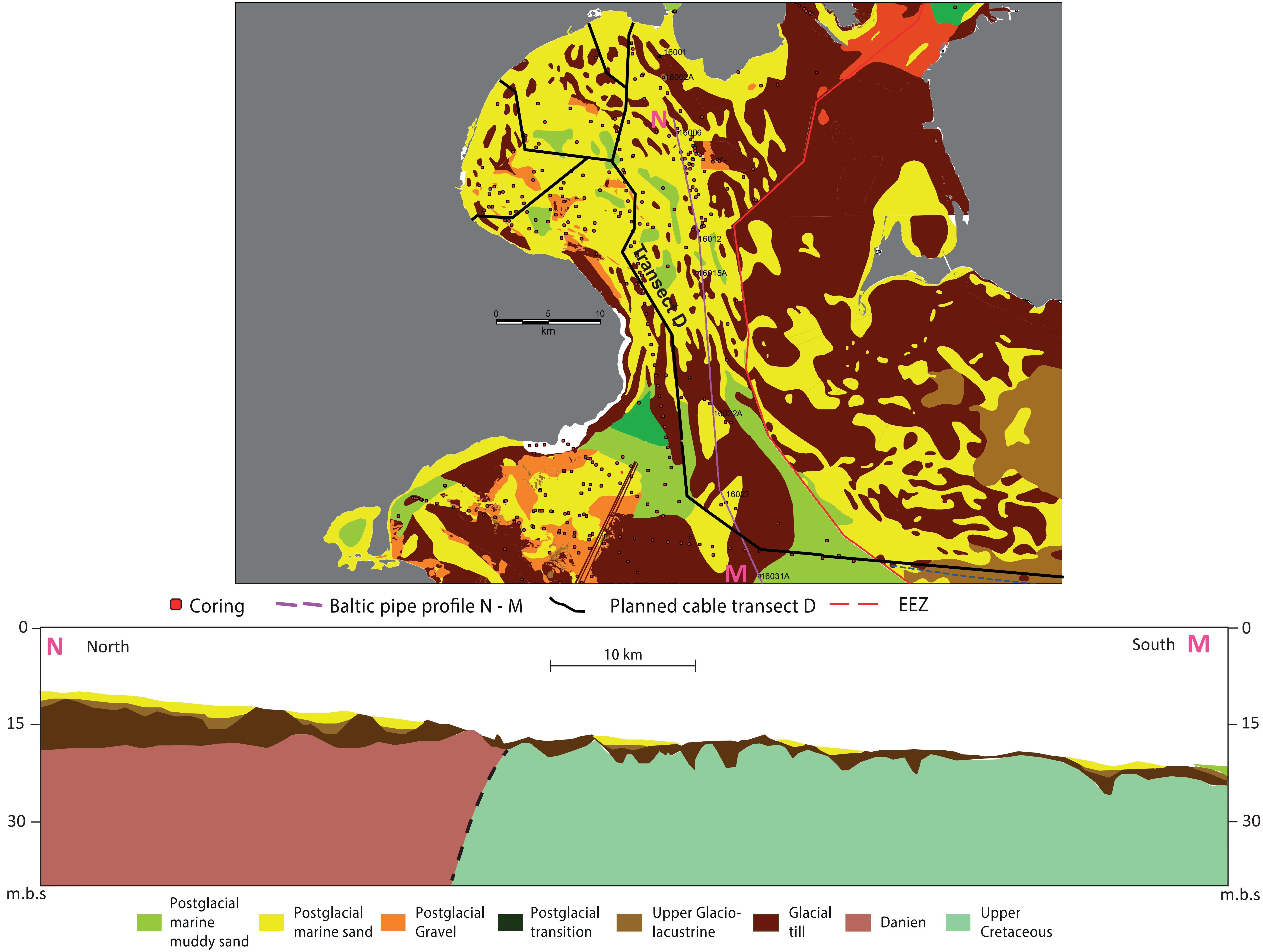


Appendix G: Transect C.
Profile I - J



Appendix H: Transect D.
Profile K - L

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Postglacial marine sand
Postglacial Gravel
Postglacial transition
Upper Glacio-lacustrine
Glacial till
Danien
Upper Cretaceous

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