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Geology desk study offshore Bornholm, Baltic Sea

Windfarm investigations

Jørn Bo Jensen, Lasse Tésik Prins & Ole Bennike

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

GEUS

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Report for Energinet Eltransmission A/S

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G E U S

Contents

1. Summary

Energinet A/S has requested that GEUS undertakes a geological desk study of the Bornholm Offshore Wind Farms (OWFs) region. 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 have used a combination of published work, archive seismic data and sediment core as well as CPT data to assess the general geological development of the Adler Grund area, including the planned Bornholm OWFs.

A geological description is provided, and a geological model has been developed.

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

The general geological description includes the complete geological succession from the pre-Quaternary framework, the pre-Quaternary surface, glacial deposits, the deglaciation, and late glacial and Holocene deposits.

The geological model of the south-western Baltic Sea region is based on sequence stratigraphical studies by Jensen et al. (1997, 1999, 2017) customized to the Bornholm OWFs.

The Integrated Ocean Drilling Program (IODP) Expedition 347 in October 2013 carried out a 73.90 m deep drilling at site M0065 in the Bornholm Basin. The obtained sediment succession (down to 49.21 m) was divided into three different lithostratigraphical units and description of lithology and downhole core logging were performed including physical parameters.

In 2013, Energinet conducted surveys on six offshore near coastal areas. One of these areas (Rønne Banke Site 6) is located about 10km south of Rønne. Site 6 data gives information about lateglacial sands, till and Upper as well as Lower Cretaceous sediment distribution and geotechnical parameters.

In the south-western part of the Baltic Sea, studies of late glacial and early Holocene shore-level changes formed the basis for evaluation of the potential to find submerged settlements in the wind farm areas. The shore-level curve, in combination with the present bathymetry, indicate that the shallowest parts of the wind farm areas 1 and 2 were dry land during two short time intervals at ca. 12800 and 11700 years ago. This corresponds to the Bromme/Ahrensburg/Maglemose cultures. During younger cultures, the wind farm areas were transgressed, and continued being submerged during the Ancylus Lake and later by the Littorina Sea.

In relation to geotechnical challenges, a number of focal points has been raised such as neotectonics, recent earthquakes, gas in sediments, thick weakly consolidated glaciolacustrine clay and Holocene mud with high organic contents.

2. Introduction

GEUS has been asked by Energinet to provide an assessment of the Bornholm Offshore Wind Farms (OWFs), consisting of the establishment of a geological model based on existing data. The report will serve as a background for future interpretations of seismic data and a marine archaeological screening (Figure 2.1).

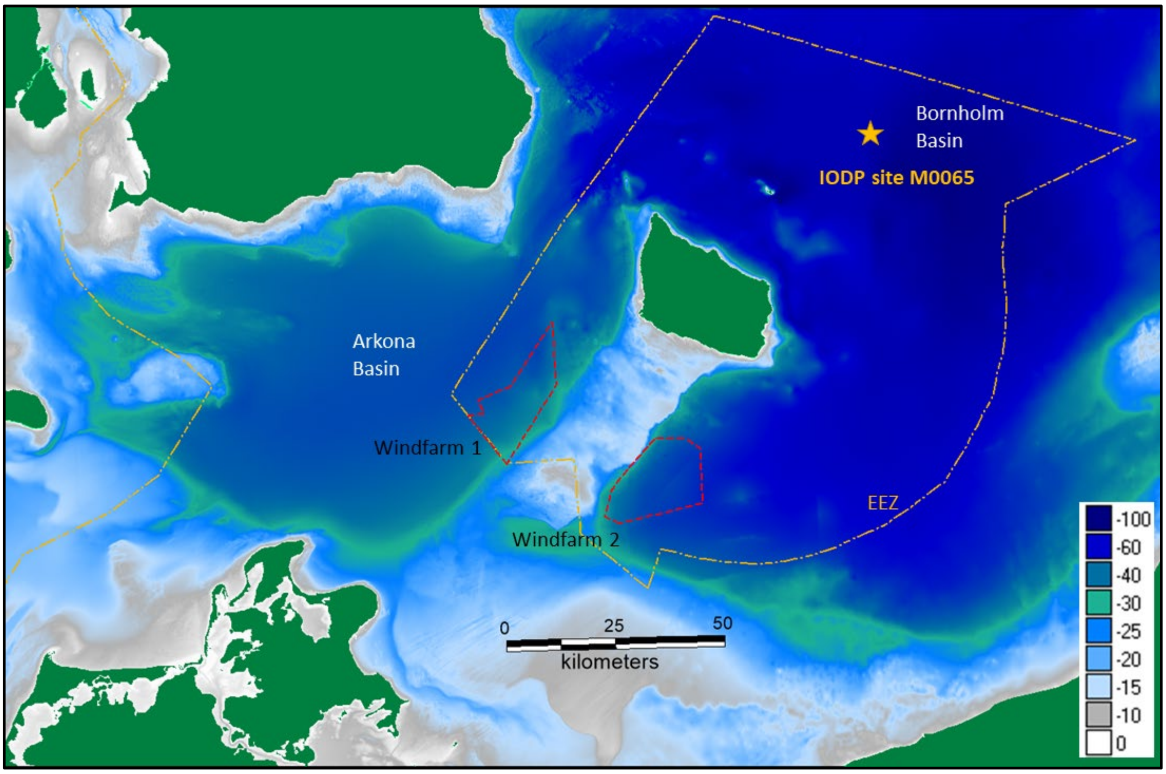


Figure 2.1. Overview map of the southwestern Baltic Sea with location of the Windfarm 1 and 2 study areas (polygons with red dashed lines). IODP site M0065 (yellow star). The yellow lines show the Exclusive Economic Zone. Bornholm Basin and Arkona Basin is indicated.

3. Data background

As a background for the desk study, deep seismic information has been compiled from scientific papers, but the seismic data are available from the GEUS Oil and Gas database (http://data.geus.dk/geusmap/?mapname=oil_and_gas&lang=en#baslay=baseMapDa&optlay=&extent=-741060,5683270,1783060,6766730), while the GEUS Marta database (https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/marin-raastofdatabase-marta/) is the main supply of shallow seismic data and vibro-core data (Figure 3.1). In addition, available data from IOPD core M0065 have been included.

3.1 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.

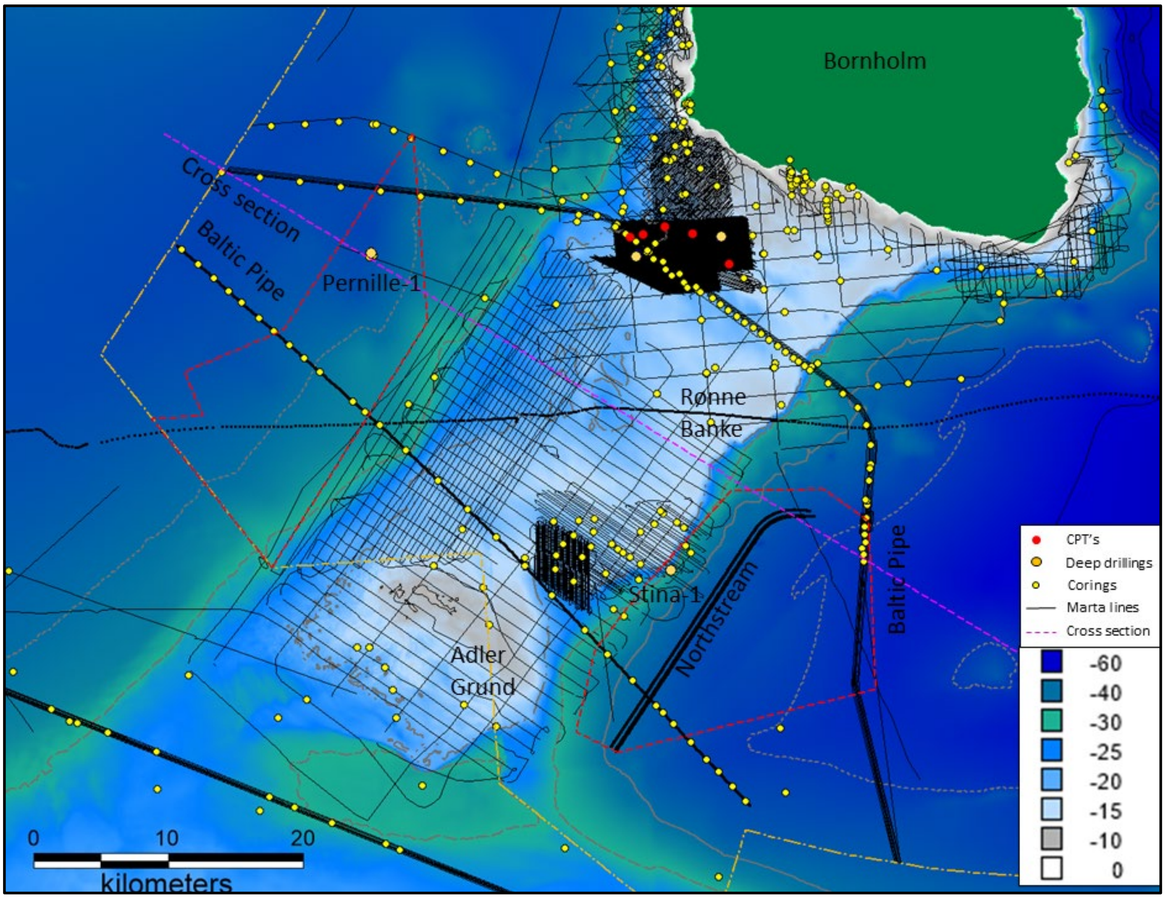


Figure 3.1. Distribution of Marta database seismic grid and core data southwest of Bornholm. The location of the proposed wind farms is indicated by polygons. The bathymetry is from Emodnet.

The existing seismic lines crossing Windfarm 1 and 2 have been collected by the Baltic Pipe and the Northstream projects and consists of side scan, sediment echosounder and boomer data. Multiple turning lines can be observed in the western rim of Windfarm 2. These data have been collected by GEUS in relation to raw material mapping and includes side scan, sediment echosounder and sparker data.

All the mentioned data are digital data and can be requested from GEUS for a small administrative fee.

The existing coring's in Windfarm 1 and 2 are all (except Stina-1), vibrocorings with up to 6m penetration. Most of the vibrocores relate to the Baltic Pipe project. Core descriptions are available in the Marta database while no samples have been preserved.

3.2 IODP Site M0065 data types

Important information about the sediment types in the Bornholm Basin can be obtained from the nearby IODP core M0065 (Figure 8.6). Andrén et al. (2015) provided descriptions that can be downloaded from the IODP homepage (Site M0065 (iodp.org). An overview paper of the drilling results is presented in Appendix A.

Descriptions of the drilling results include:

- Lithostratigraphy
- Biostratigraphy
- Geochemistry
- Physical properties
- Microbiology
- Stratigraphic correlations
- Downhole measurements

4. Pre-Quaternary geology

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 southwest (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; Mogensen & Korstgård 2003; Erlström & Sivhed 2001). The old crustal weakness zone was repeatedly reactivated during Triassic, Jurassic and Early Cretaceous times with dextral transtensional movements along the major boundary faults.

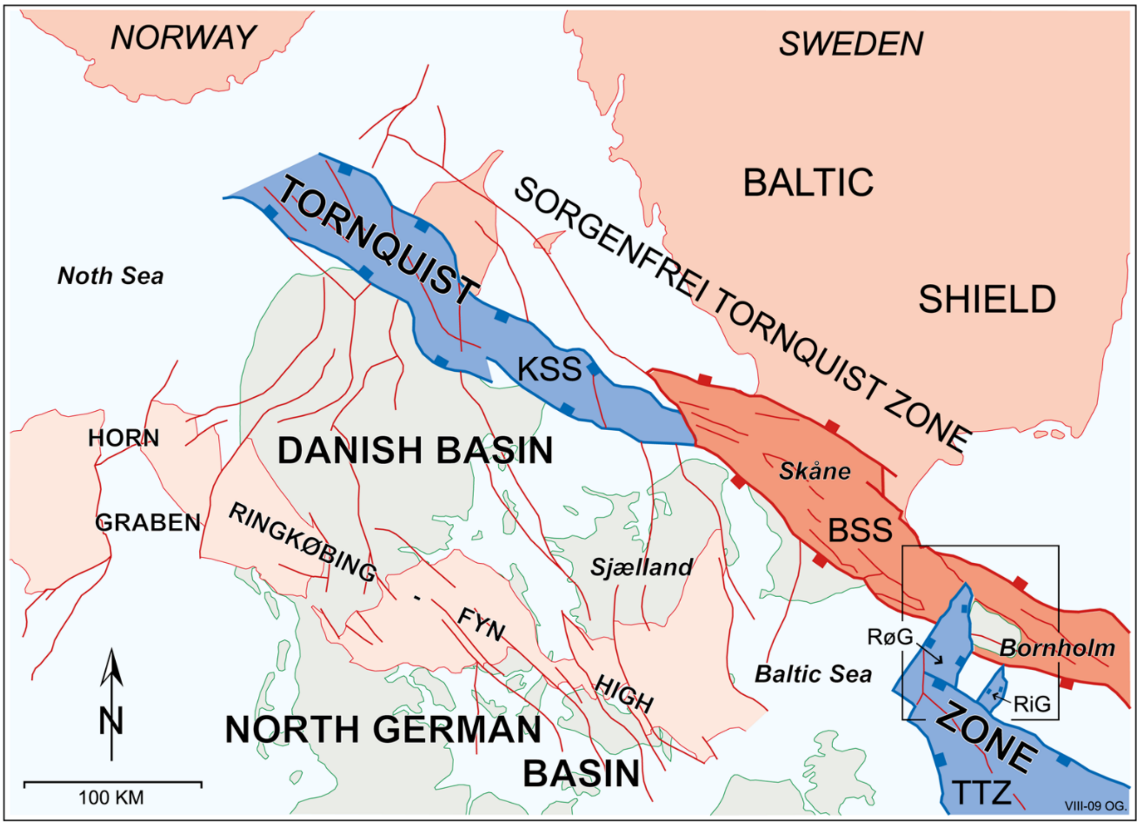


Figure 4.1. Position of the Bornholm area in the Tornquist Zone between the Baltic Shield/East European Platform and the Danish Basin/NW European craton (Graversen 2004, 2009).

In particular, the Rønne Graben (RøG) (Figure 4.2) has been studied in great detail, often in comparative studies along the Tornquist Zone (e.g. Liboriussen et al. 1987). Detailed descriptions were presented by Vejbæk (1985) and Graversen (2004, 2009) of the significant dextral wrench-faulting in the Late Carboniferous – Early Permian strike-slip pull-apart RøG basin, which was later lifted during the Late Cretaceous and early Tertiary regional inversion. The description of the block tectonics is based on deep seismic data and a few wells. In the shallow waters southwest of Bornholm, however, shallow seismic data have been used to describe in detail the inversion structures of the RøG basin (Jensen & Hamann 1989).

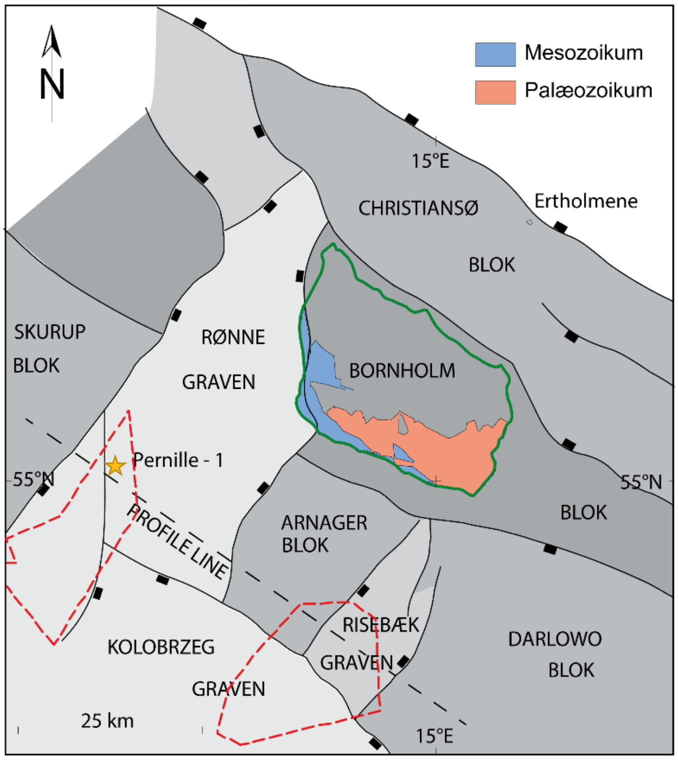


Figure 4.2. Major fault blocks of the Bornholm region. The fault pattern is based on Vejbæk & Britze (1994) and Vejbæk (1997). Profile line of Figure 4.3 is shown.

The tectonic history of the Tornquist Zone dates back to the Early Palaeozoic and repeated tectonic overprint characterizes the complex development of the zone. Changes in the stress field orientations through time resulted in shifting transtensional and transpressional strike-slip movements between the crustal blocks, where reactivation of old basement deep-seated fault zones caused dextral movements along the major boundary faults of the Tornquist Zone (Mogensen & Korstgård 2003).

In the Bornholm region, the RøG and the Bornholm Basin represent sedimentary basins, whereas Bornholm acts as a rigid diamond shaped block in the Tornquist Zone around which deformation was focused (Deeks & Thomas 2012).

Late Carboniferous – Early Permian large-scale intraplate tension resulted in dextral strike-slip faulting along the Tornquist Zone. The right stepping release step-over (Wu et al. 2009) resulted in the development of the NE–SW-orientated RøG pull-apart basin (Figure 4.2 and Figure 4.3) between opposing normal faults.

Expansion of the basins continued through the Triassic, Jurassic and Early Cretaceous (Vejbæk et al. 1994).

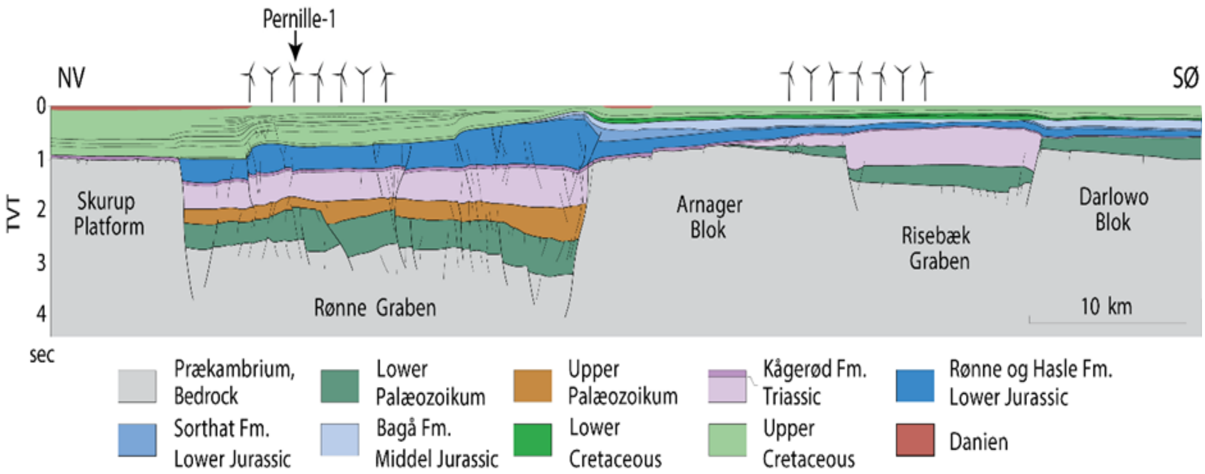


Figure 4.3. Cross section of the Sorgenfrei–Tornquist zone in the middle of the Bornholm OWFs (Mogensen & Korstgård 2003). The location of the section is indicated on Figure 4.2 and Figure 4.4

The following Late Cretaceous inversion phase that was associated with intraplate thrusting in central Europe (Kley & Voigt 2008) resulted in transpressional strike-slip tectonics along the Tornquist Zone during the Late Cretaceous and early Tertiary (Ziegler 1990). The Bornholm region was strongly affected by inversion tectonism caused by compressional strikeslip movements. This resulted in reverse faulting, uplift and erosion of former basin areas as described by Graversen (2004, 2009). The Rønne Graben is a key example of basin inversion (Figure 4.2, Figure 4.3 and Figure 4.4), with reactivation of faults and development of anticline flexure folds. Detailed studies of the near-surface part of the Rønne Graben (Jensen & Hamann 1989) revealed the presence of a number of en-echelon reverse faults approximately perpendicular to the main north–south reverse faults. The main fault can be classified as a dextral wrench fault with a reverse component. The presence of anticlinal flexural folds adjacent to the main fault requires a compressive component to the fault, which indicates that the system involved compressive dextral strike-slip movement.

The resulting present distribution of pre-Quaternary deposits in domino-shaped blocks and basins as a major puzzle of different ages is illustrated in Figure 4.4.

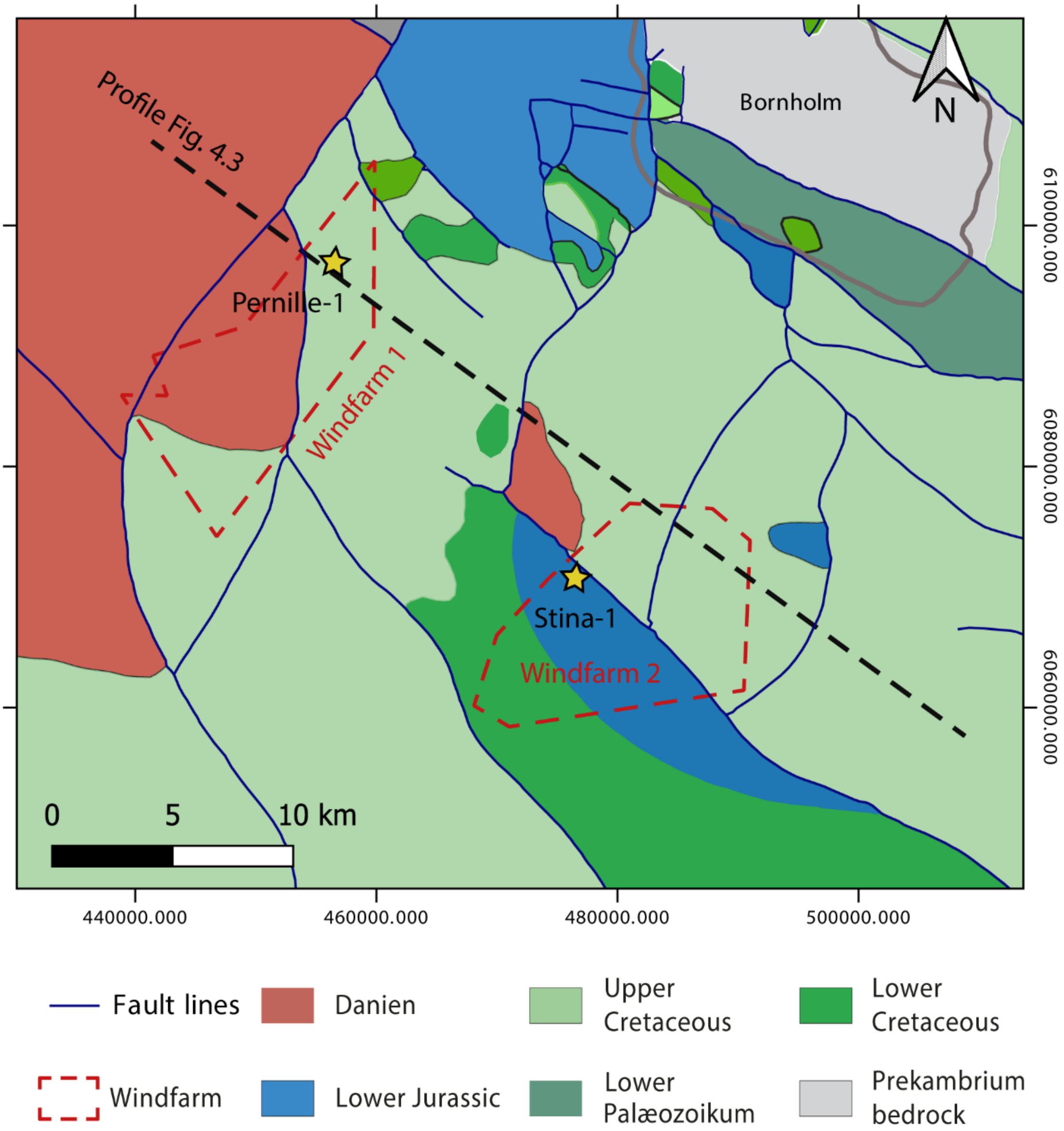


Figure 4.4. Major faults and pre-Quaternary stratigraphic units southwest of Bornholm. The stars indicate deep wells.

5. Earthquakes

Records of recent earthquake activity along the Fennoscandian Border Zone and the relationship to recent geological motion shows that the border zone is still an active zone (Gregersen et al. 1996). However, only few earthquakes have been recorded in the south-western Baltic Sea (Figure 5.1 Earthquake activity in southern Scandinavia (Gregersen & Voss 2014). The red dots show modern well-located earthquakes of the last 75 years, and green dots show the most important relatively larger earthquakes in 1759, 1841, 1904, 1985, 2004, 2008 and 2010. Danish observations of earthquakes through hundreds of years show no signs of greater earthquakes in the Sorgenfrei – Tornquist Zone than outside. The only exception to this is an area in the Kattegat region.

All observed earthquakes in the Danish and the Swedish part of the Sorgenfrei – Tornquist Zone are small and harmless, and only few can be felt by humans. It happens however, at yearly intervals. It is important to emphasize that the noticeable earthquakes occur more often outside the Sorgenfrei – Tornquist Zone than in the zone itself.

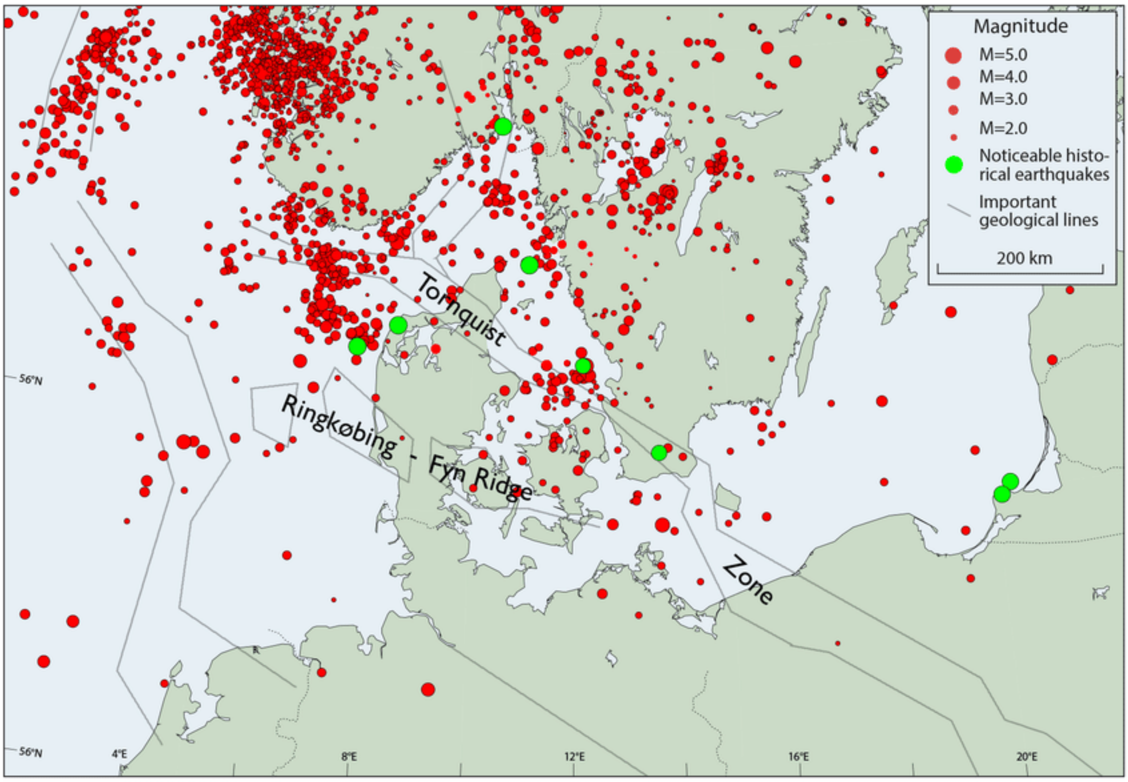


Figure 5.1 Earthquake activity in southern Scandinavia (Gregersen & Voss 2014). The red dots show modern well-located earthquakes of the last 75 years, and green dots show the most important relatively larger earthquakes in 1759, 1841, 1904, 1985, 2004, 2008 and 2010.

6. Pre-Quaternary surface

The general geological development of the study area has resulted in a characteristic pre-Quaternary morphology (Binzer & Stockmarr (1994; Figure 6.1). The major faults reflect the transtensional motions within the fault blocks.

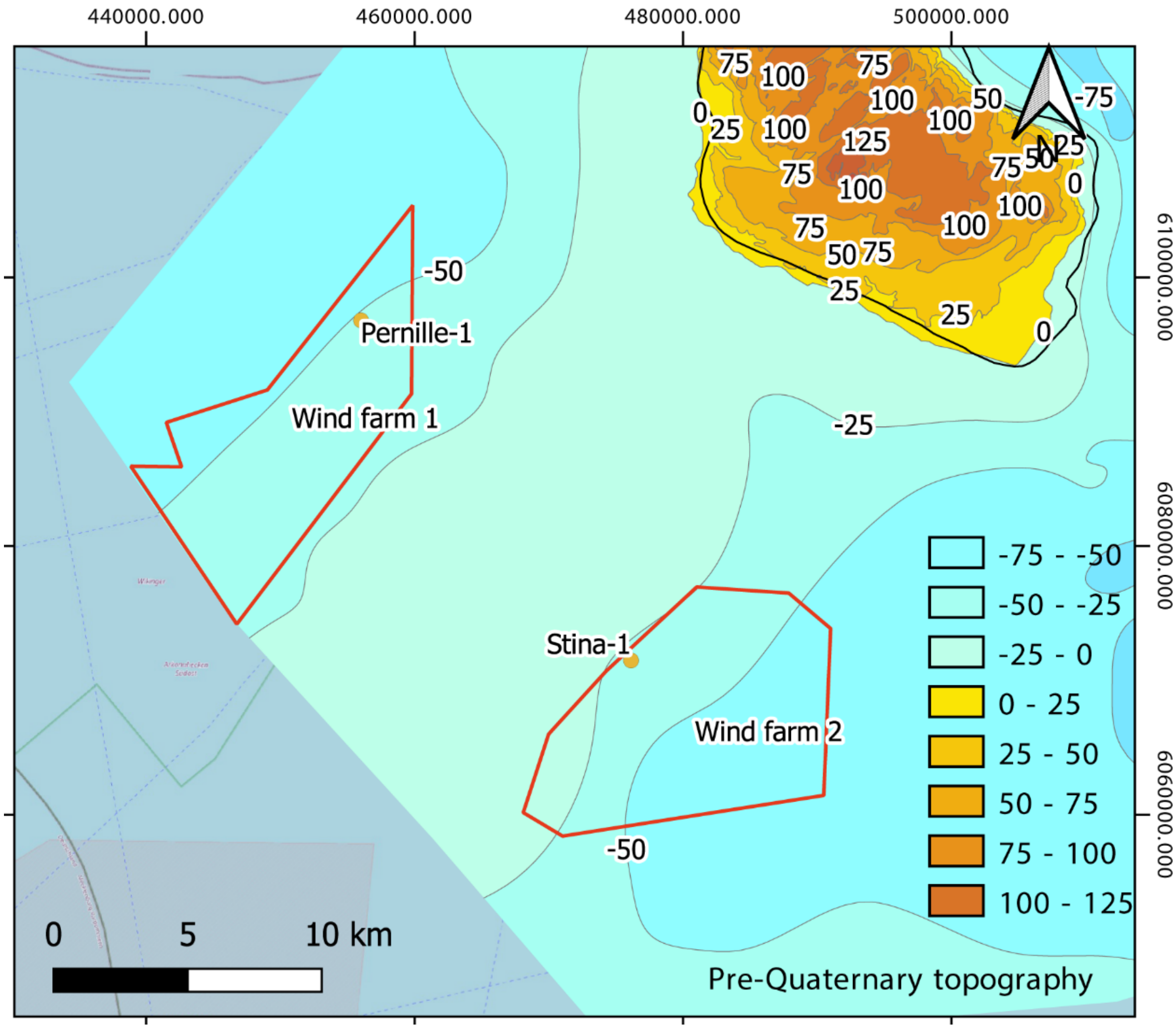


Figure 6.1. Pre-Qaternary topography (Binzer & Stockmarr 1994). The location of the Bornholm OWFs is indicated.

In a combined presentation of present bathymetry, major faults, and pre-Quaternary morphology (Figure 6.1 and Figure 6.2Figure 6.2) the close relationship between the wrench system faults and the depocenters is obvious. It is seen that the Bornholm OWFs crosses deep faults and pull-apart basin depocenter in the northern parts of the wind farms influenced by the Late Cretaceous and early Tertiary compressive dextral strike-slip inversion. The combined present bathymetry and pre-Quaternary surface morphology shows that only a thin Quaternary top unit of a few metres to about 30 m thickness can be expected. The seabed sediment map in Figure 11.2 shows that large areas expose pre-Quaternary sediments at the seabed.

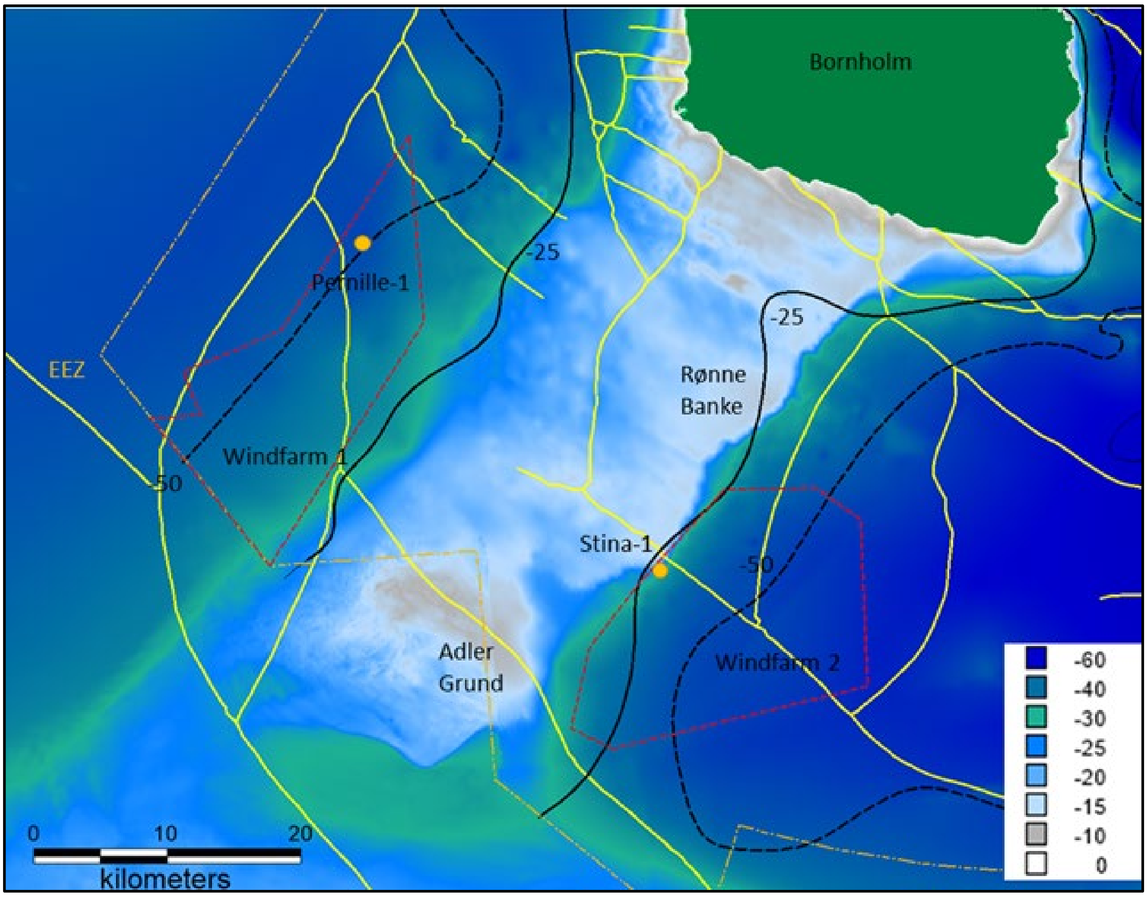


Figure 6.2. Present bathymetry, major faults (yellow lines) and Pre-Quaternary surface morphology curves -25 m and -50 m. The locations of the Bornholm OWFs are indicated.

7. Deep wells

Two deep wells, Pernille-1 and Stina-1 have been drilled in the windfarm areas.

- Pernille-1 is located in Windfarm 1, in the Rønne Graben (Figure 4.2). It mainly penetrated Mesozoic deposits (Figure 4.3 and Figure 4.4). Below about 16 m of Quaternary sandy to silty clay, the Pernille-1 well penetrated about 800 m of limestone from the Upper Cretaceous Chalk Group and Lower Jurassic Hasle and Rønne Formations sandstone, siltstone, mudstone and coal (Figure 7.1).

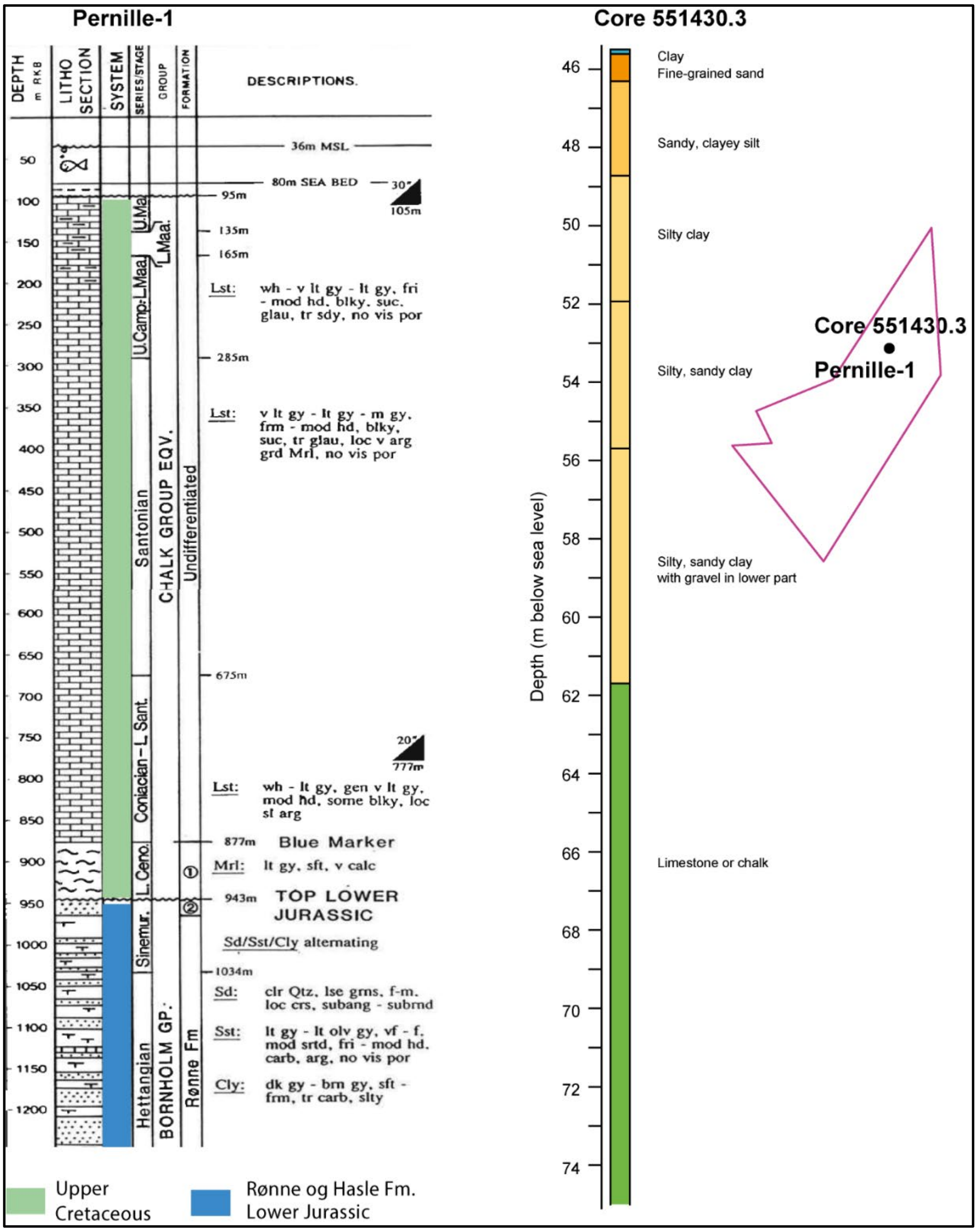


Figure 7.1. Lithological logs of deep well Pernille-1 (log report Appendix B) and a shallower core 551430.3 from the same position.

- The Stina-1 well was drilled on an inversion anticline, where a Jurassic package is identified directly below about 60 m of Quaternary sediments. The about 500 m of Jurassic sediments is interpreted as the Sorthat Formation on top of Hasle Formation and Rønne Formation in a succession of sandstones, siltstones, mudstones, and coals. Thick units of Triassic sediments are located below (Figure 7.2).

The stratigraphy of the wells was described by Graversen (2004) and log reports are attached as Appendix B and C.

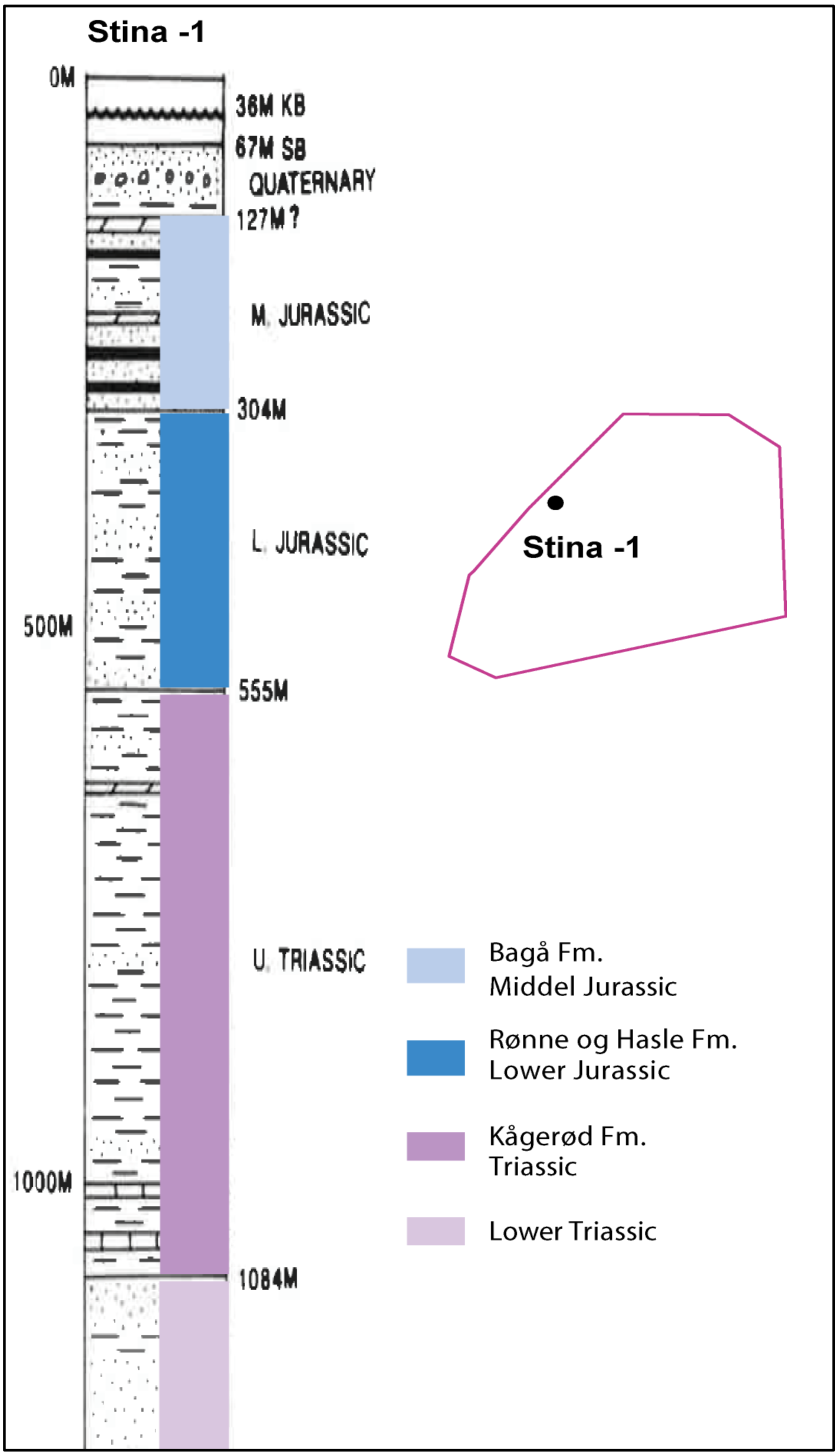


Figure 7.2. Lithological log of the deep well Stina-1 (log report Appendix C).

8. Quaternary geology of the Bornholm region

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 southwestern 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 22000 years BP followed by stepwise retreat.

The Bornholm region was probably deglaciated shortly after 15000 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 8.1).

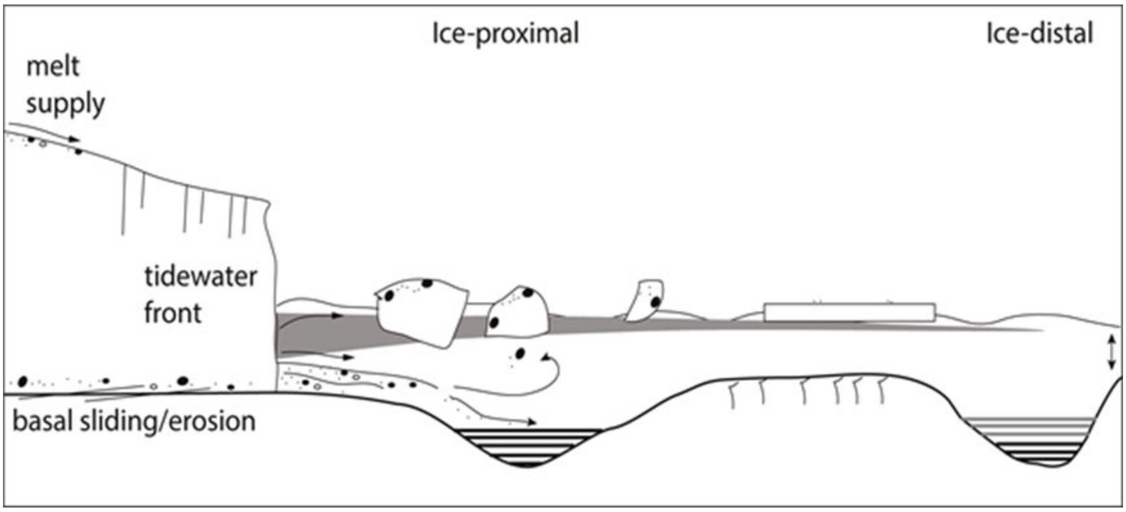


Figure 8.1. Illustration of a glaciolacustrine depositional environment.

Quaternary sedimentation in the Arkona and Bornholm Basins, has been intensively studied in relation to the development of the Late- and Postglacial Baltic Sea phases, 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).

8.1 The geological model

The Quaternary geological model for the region, builds on a network of seismic data recovered during 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 8.3, Figure 8.4, Figure 8.5 and Figure 8.6) 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 8.6.

A combined geological model based on seismic data and core data was established by Jensen et al. (2017) and will briefly be presented in the following sections.

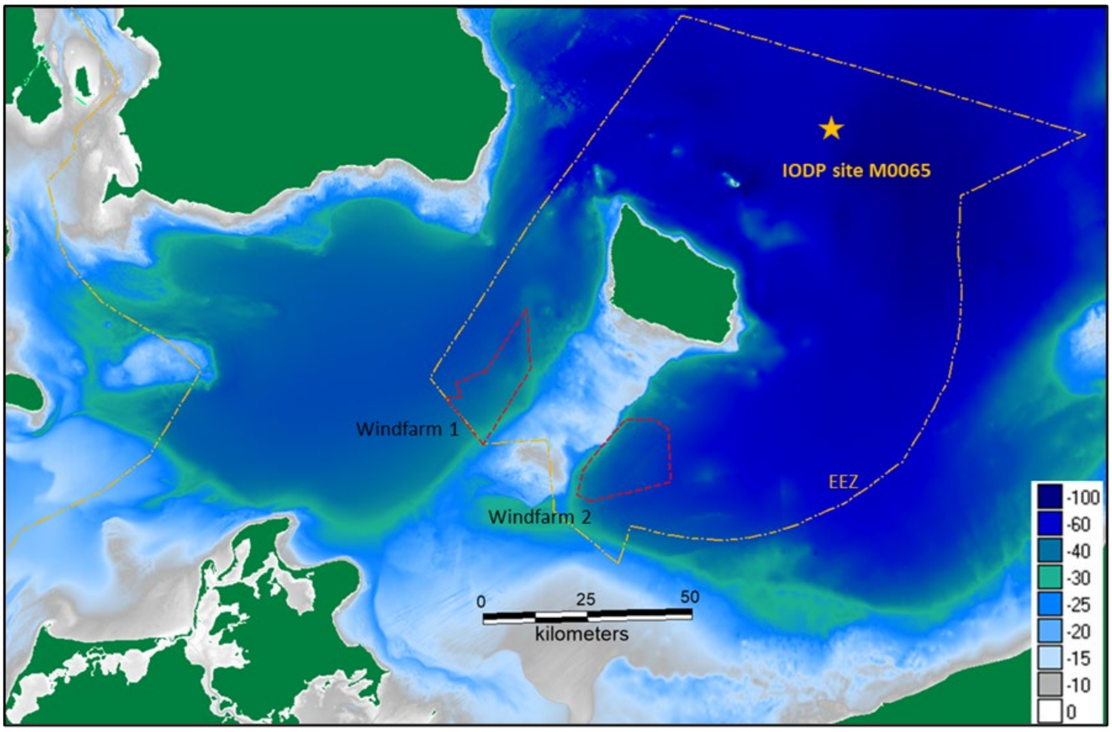


Figure 8.2. Map of the southwestern Baltic Sea with location of IODP sire M0065 (yellow star) in relation to the Windfarm 1 and 2 study areas (polygons with red dashed lines). EEZ yellow lines.

Six seismic units were described all separated by unconformities (Figure 8.3).

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 postglacial softer deposits are best seen on the sediment echo-sounder profiles (Figure 8.4).

The late- and postglacial Units III–I were deposited in basins with a changing shore level, well known in the southwestern Baltic Sea (Figure 8.3) (Uscinowicz 2006) and a close match can be expected between shore-level lowstands and allostratigraphical unconformities.

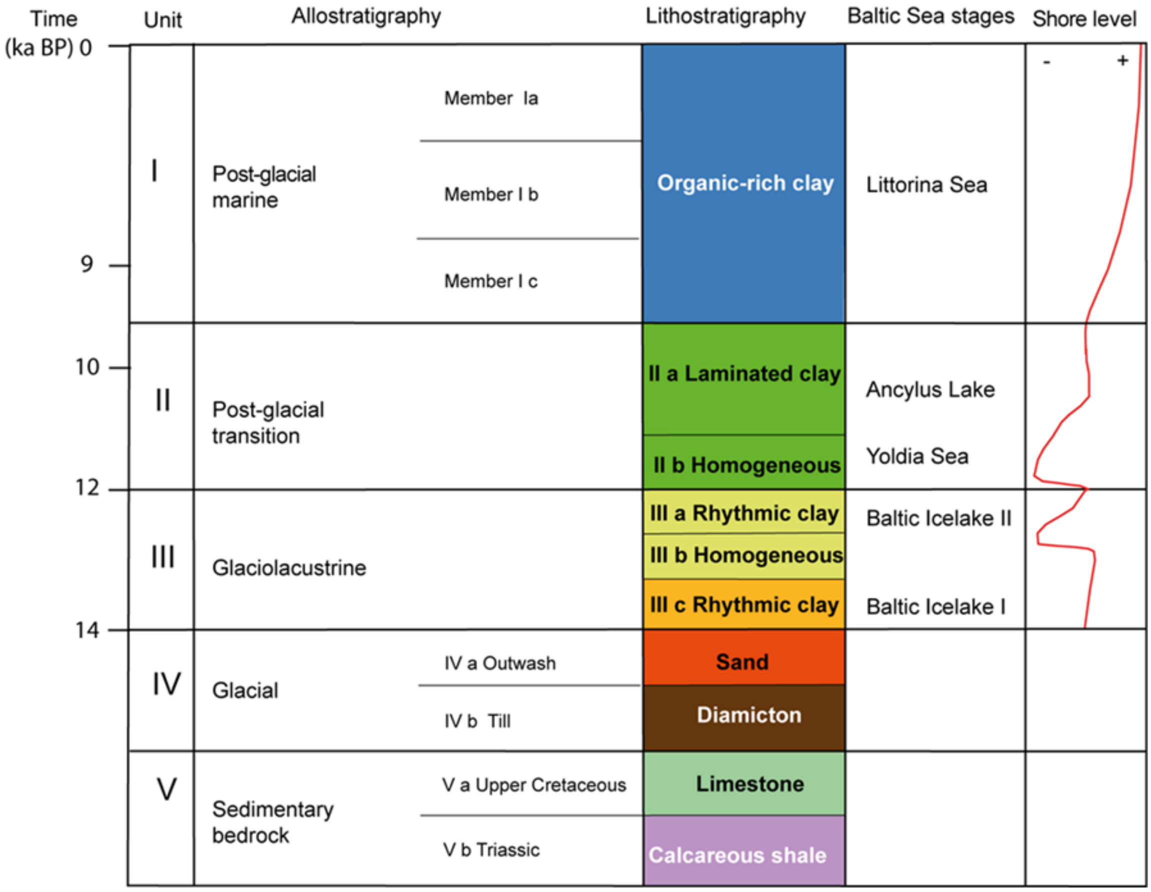


Figure 8.3. Stratigraphical subdivision of the Bornholm Basin (Jensen et al. 2017). The seismic Units I–VI represent allostratigraphical formations, some of which are divided into members, all bounded by unconformities. Mappable lithostratigraphical formations (informal) are identified within the allostratigraphical framework and Baltic Sea stages as well as the general Baltic Sea shore-level changes are correlated with the established allostratigraphy.

8.1.1 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 8.4) and Andrén (2014).

The distribution of glacial sediment facies is in general chaotic with alternating sections of clast-rich muddy diamicton and parallel-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.

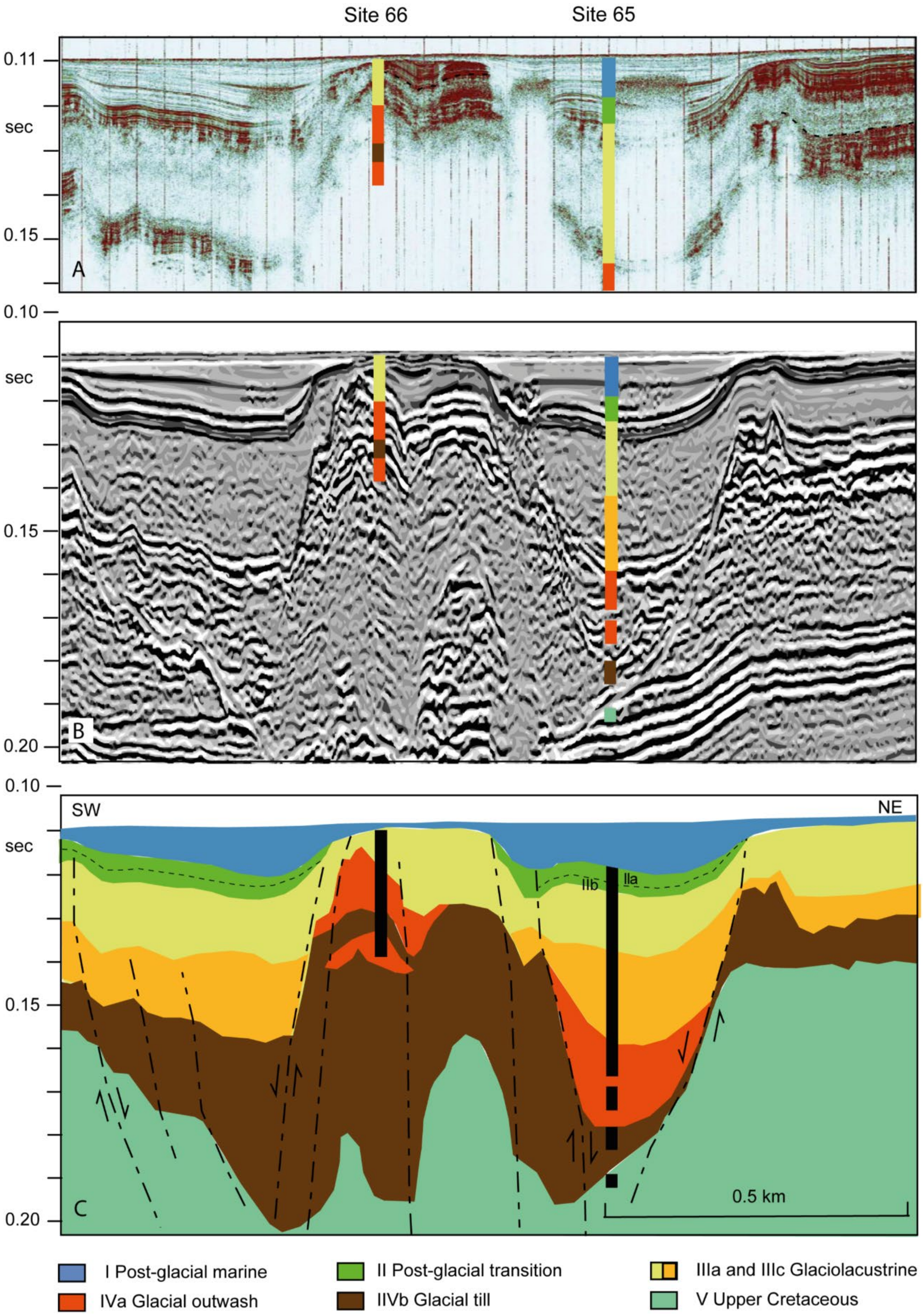


Figure 8.4. Seismic Line across Site M0065 (Jensen et al.2017). Original interpretation of the seismic transect: Airgun (A) and Atlas parasound (B) data (Andrén 2014), as well as sediment documentation for sites 65 and 66. The interpretation (C) follows the classification in seismic units described in Figure 8.3. The location of the IODP sites is shown in Figure 8.2.

8.1.2 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 8.4). 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 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 front 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 during the late Allerød (Figure 8.5). This drainage led to a 10-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 the changes in internal reflector configurations and the lithological shift to homogeneous clay.

- IIIa is the upper unit and consist of greyish brown, silty clay with parallel lamination, downwards coarsening to fine- to medium-grained sand with laminated silt; lowermost few metres massive, medium-grained sand with few dispersed pebbles, detrital carbonate in all grain sizes up to fine gravel. The indistinct lamination in formation 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 represents a proximal glacio-lacustrine environment.

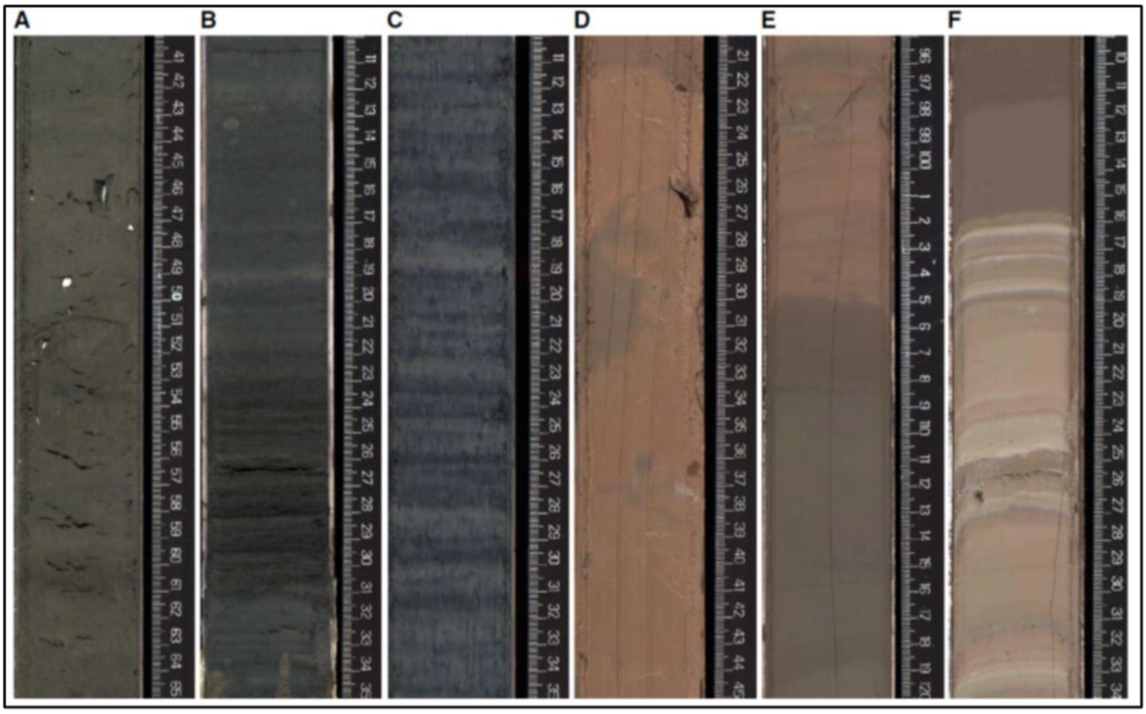


Figure 8.5. Examples of lithostratigraphic units, Hole M0065A. A. Unit I. B. Unit I. C. Unit II. D. Subunit IIIc. E. Subunit IIIb. F. Subunit IIIa.

8.1.3 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 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 8.4).

At IODP site 65, which is in one of the minor strike-slip fault basins (Figure 8.4), Unit II is 4 m thick and consists of grey to dark grey clay. In the lowermost part (formation 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.

8.1.4 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 8.4). 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 8.3). 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 8.4). 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., Zillen et al. 2008).

8.1.5 Physical properties

This section summarizes some of the preliminary physical property results from Site M0065. Gamma density was measured at 2 cm intervals (Figure 8.6). 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 8.6). 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 mbsf 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.

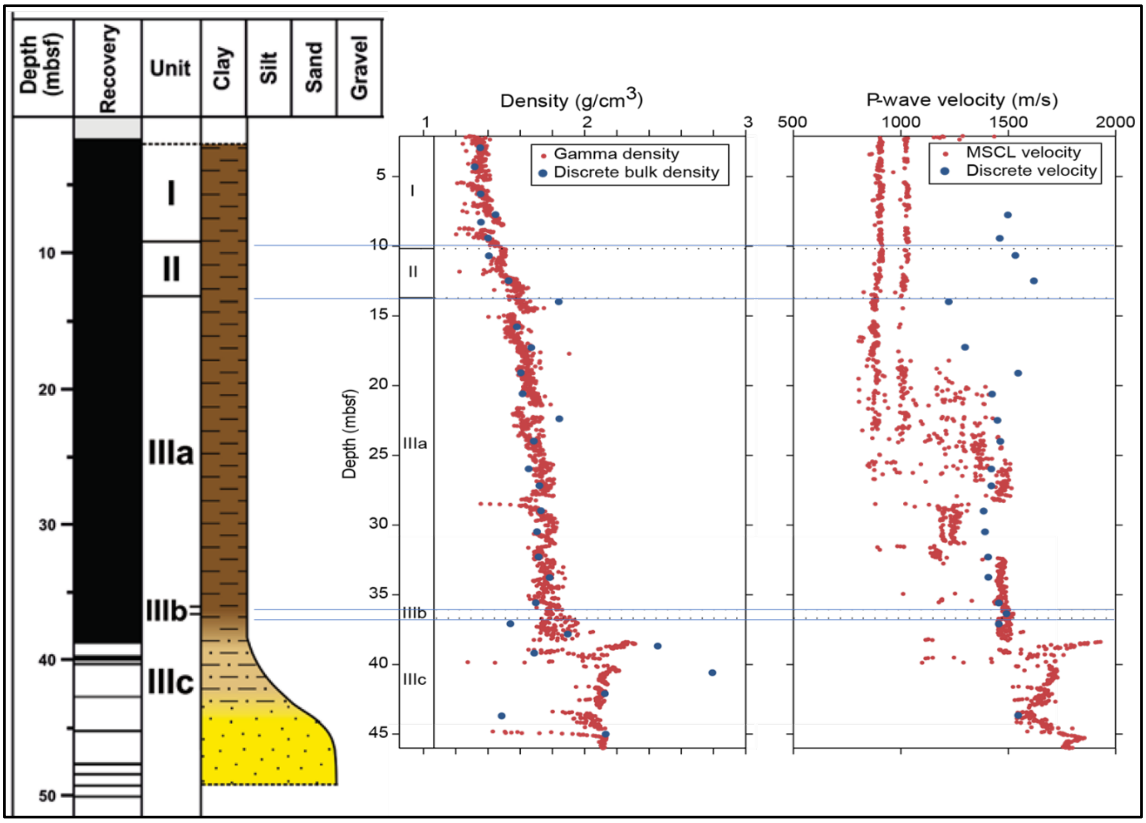


Figure 8.6. IODP Site M0065 core lithology, density and P-wave velocity. For details see Appendix A.

9. Palaeogeography of the deglaciation of Denmark

The Scandinavian Ice Sheet reached its maximum extent in Denmark about 22000 years BP followed by stepwise retreat.

During the general deglaciation, an ice stream re-advance from the Baltic moved westward and reached the East Jylland ice marginal line. The Bornholm region was probably deglaciated shortly after 15000 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 8.1).

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

Figure 9.1. a and b.

- About 18000 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 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, and the sea covered major parts of northern Jutland.
- At the next stage, about 16000 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 Zealand 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, while local lakes were under development along the ice margin in the south-westernmost Baltic Sea.
- A controversial stage of the deglaciation was reached about 15000 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 discharge events. The last and most extensive damming was at its maximum about 12000 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 discharge event in south-central Sweden and the lake level dropped by about 25 m.

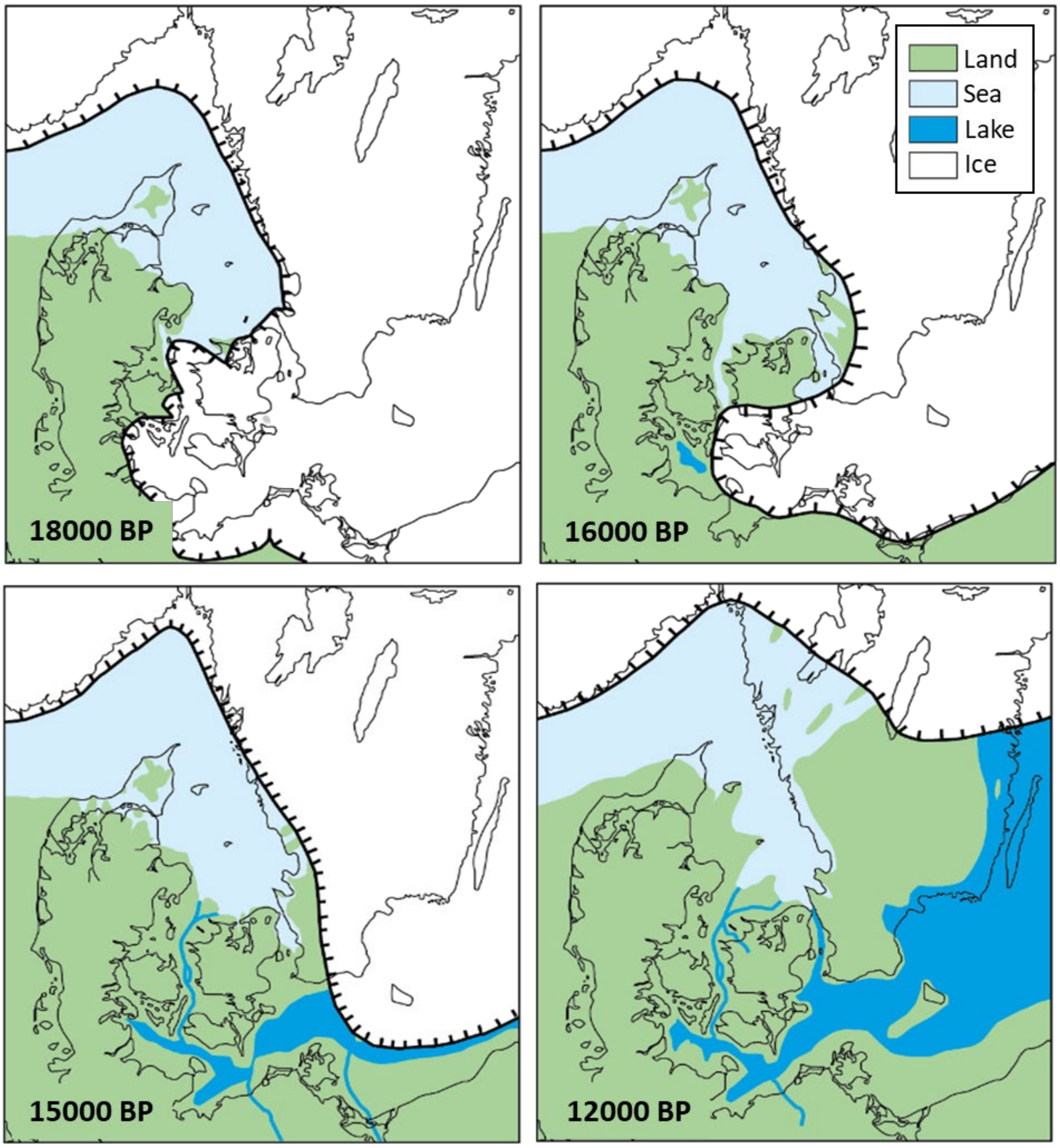
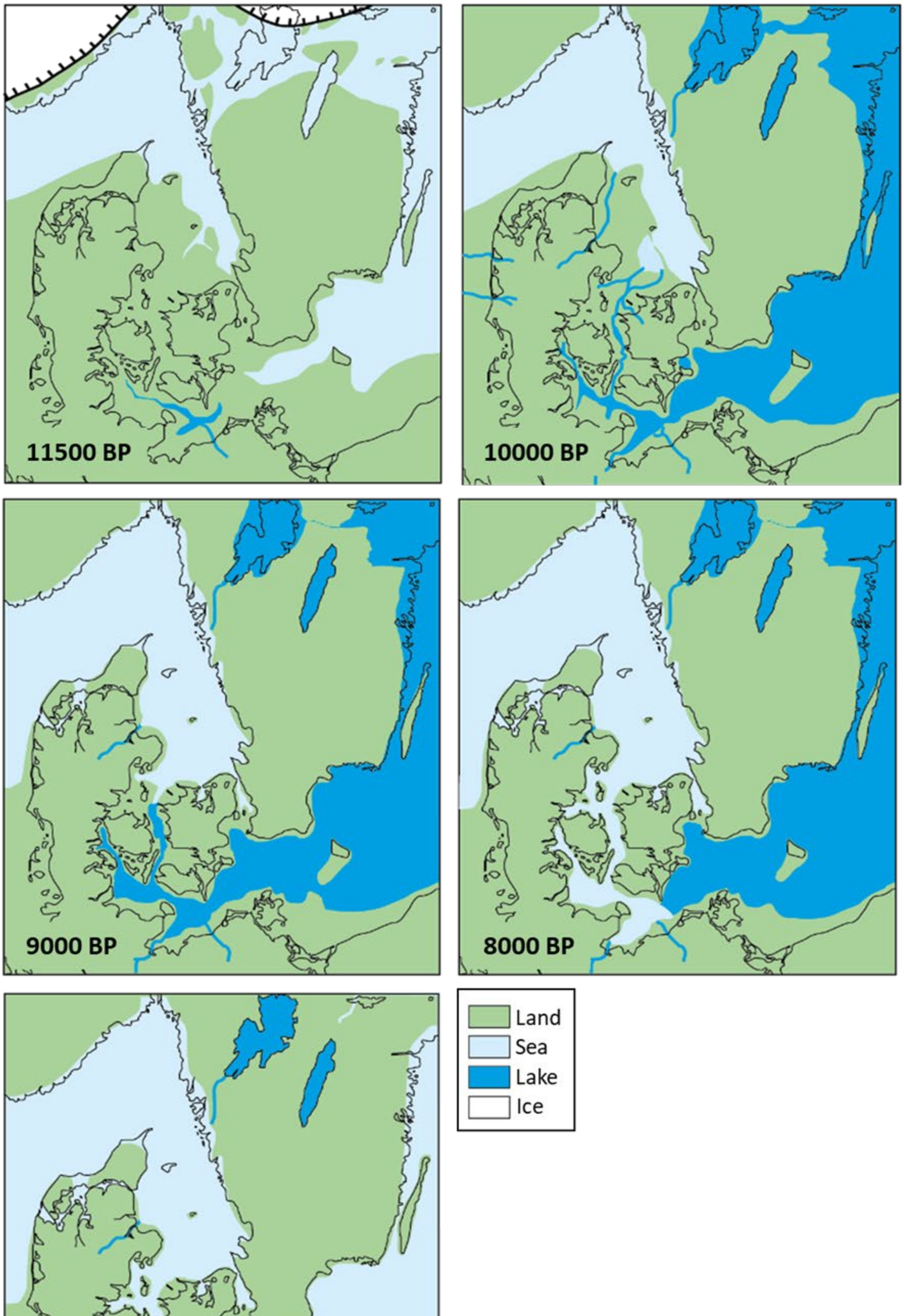


Figure 9.1. a and b. Palaeogeographical maps showing the development of the Danish area from ca. 18000 to ca. 7000 years BP. Modified from Jensen et al. (2002).


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

- About 11500 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 called *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 10200 years ago with only a narrow drainage pathway through the Great Belt into the southern Kattegat. Initial transgression had 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 as it is reported by Bennike et al. (2000) and Bendixen et al. (2017).
- About 10000 years ago the Ancylus Lake level dropped about 9 m within few hundred years. The traditional opinion was 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 could be provided by this drainage route. Moreover, for the time of drainage calm lake and estuarine sedimentation is recorded in the Great Belt and south-western Kattegat.
- The calm lake sedimentation was followed by a gradual transgression and change into brackish 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.

10. Late glacial and Holocene fluctuating water levels

During the period after the last deglaciation, the south-western Baltic Sea region was characterised by highly fluctuating water levels (Figure 10.1). 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. 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 increased rapidly, and water level continued to increase rapidly during the early part of the Ancylus Lake Stage. The rapid increase was followed by a period with relatively stable water level. Water level soon continued to rise, and at ca. 7000 years BP marine waters inundated the region: The Littorina Sea Stage began. 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 are submerged.

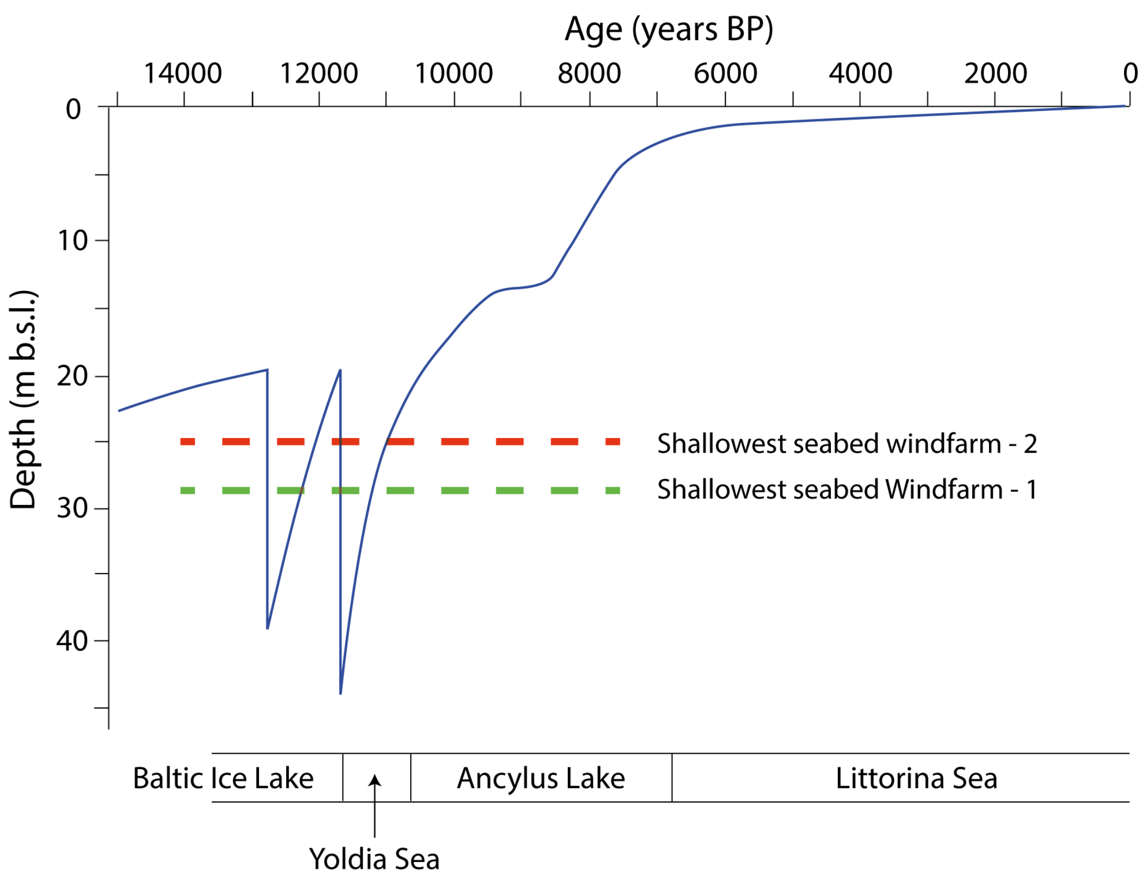


Figure 10.1. Shoreline displacement curve for the south-western Baltic Sea. The curve is based on radiocarbon dating of samples collected from vibrocores (

Table1).

Core	N. lat. °	E. long. °	Laboratory number	Material	Depth (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
526188	54.792	14.554	Ua-4861	*Mytilus edulis*	410	5185±90	5508
526189	54.806	14.50	Ua-4862	*Mytilus edulis*	340	1980±75	1539
Lake deposits							
526187	54.804	14.53	Ua-4859	Land plants	365-380	8050±100	8912
526187	54.804	14.53	Ua-4860	*Pinus sylvestris*	480	9095±140	10261
526189	54.806	14.50	Ua-4863	*Pinus sylvestris, B. Albae*	540	9230±85	10404
200540	54.725	12.766	AAR-2637	*B. nana, S. herbacea*	27.7	12700±110	15132
258000	54.750	13.765	KIA-21680	*Cladium mariscus*	45.2	10980±55	12896
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
BP09 ext 11	54.946	14.744	Beta-560826	*Populus tremula*	23.0	9240±30	10407
RAM-05-09	54.942	14.754	Beta-560827	*Cladium, Scirpus*	19.6	8070±30	9002
222810	54.457	15.156	KIA-9342	*Scirpus, Pinus*	35.9	9930±45	11337
222810	54.457	15.156	KIA-9341	*Menyanthes, Phragmites*	34.5	9365±50	10583
222820	54.483	15.172	KIA-9343	*Pinus, Betula Albae*	36.1	9740±55	11177
5775/01	54.913	13.05	AAR-1923	*Cladium mariscus*	44.3	9360±90	10574
258010	54.920	13.151	KIA-21682	*Phragmites*	46.3	7880±50	8522

[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).

Table 1. Selected radiocarbon ages from the Rønne Banke, Arkona Basin and Bornholm Basin region.

The Bornholm wind farm areas have been submerged most of the time after the last deglaciation, but in the lowstand periods around 12800 and 11700 years BP the shallowest parts were dry land.

11. Details from the windfarm areas

11.1 Bathymetry

To the southwest of Bornholm, a shallow water area with Adler Grund and Rønne Banke separates the Arkona and Bornholm Basins (Figure 11.1). The Water depths on Rønne Banke is about 20 m, 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 wind farm 1 area the water depth increases towards the northwest, from ca. 35 to ca. 45 m and in the wind farm 2 area the water depth increases towards the south-east, from ca. 30 m to ca. 50 m.

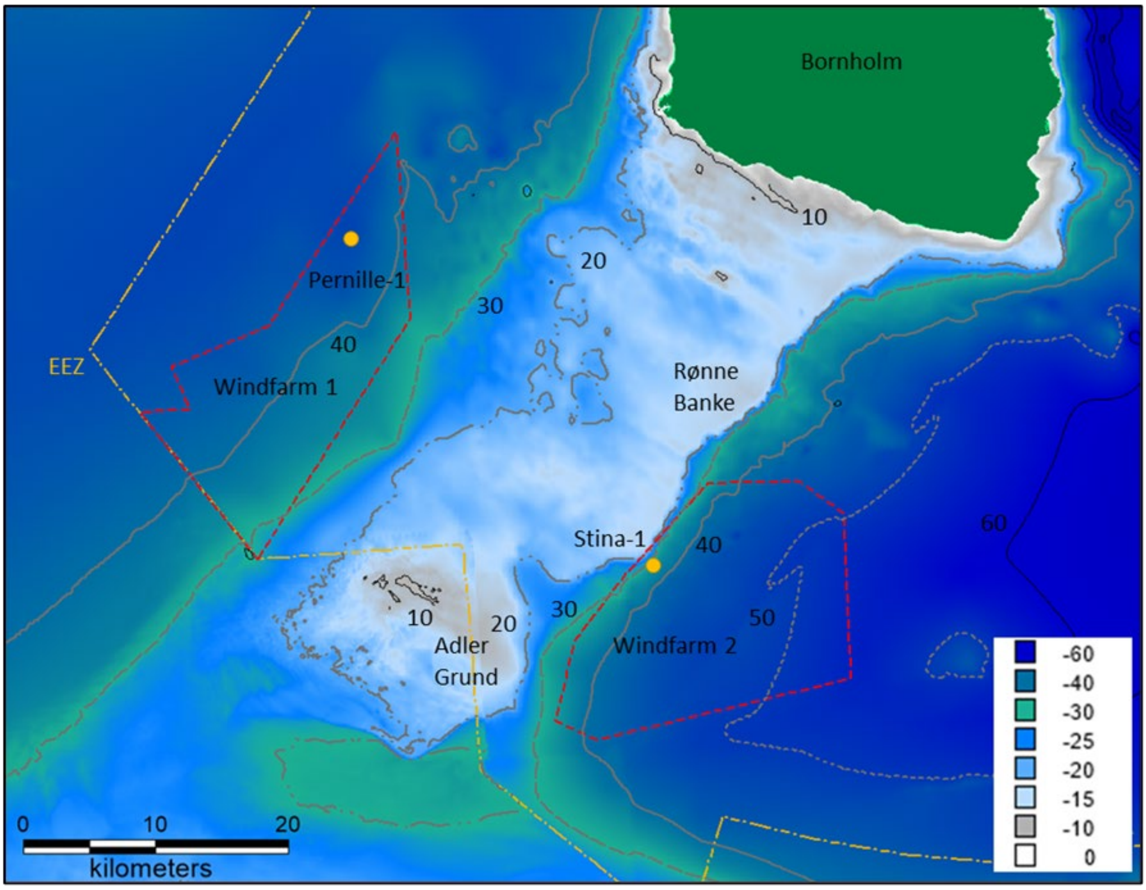


Figure 11.1 Bathymetry in the proposed windfarm areas (red polygons) southwest of Bornholm in the Baltic Sea. EEZ yellow lines, Bathymetry from Emodnet and the 2 deep drillings Pernille-1 and Stina-1 as yellow dots.

11.2 Seabed sediments

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 (Figure 11.2). In the wind farm 1 area sand is found in the shallowest areas but muddy sand dominates. Small areas mapped as mud and clay and silt are also found. The wind farm 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 wind farm 1 area and late glacial clay deposited in the Baltic Ice Lake is found in the north. Vibrocore data from the wind farm 2 area indicate marine sand and silt in the south and late glacial glaciolacustrine clay in the northeast (Figure 11.2).

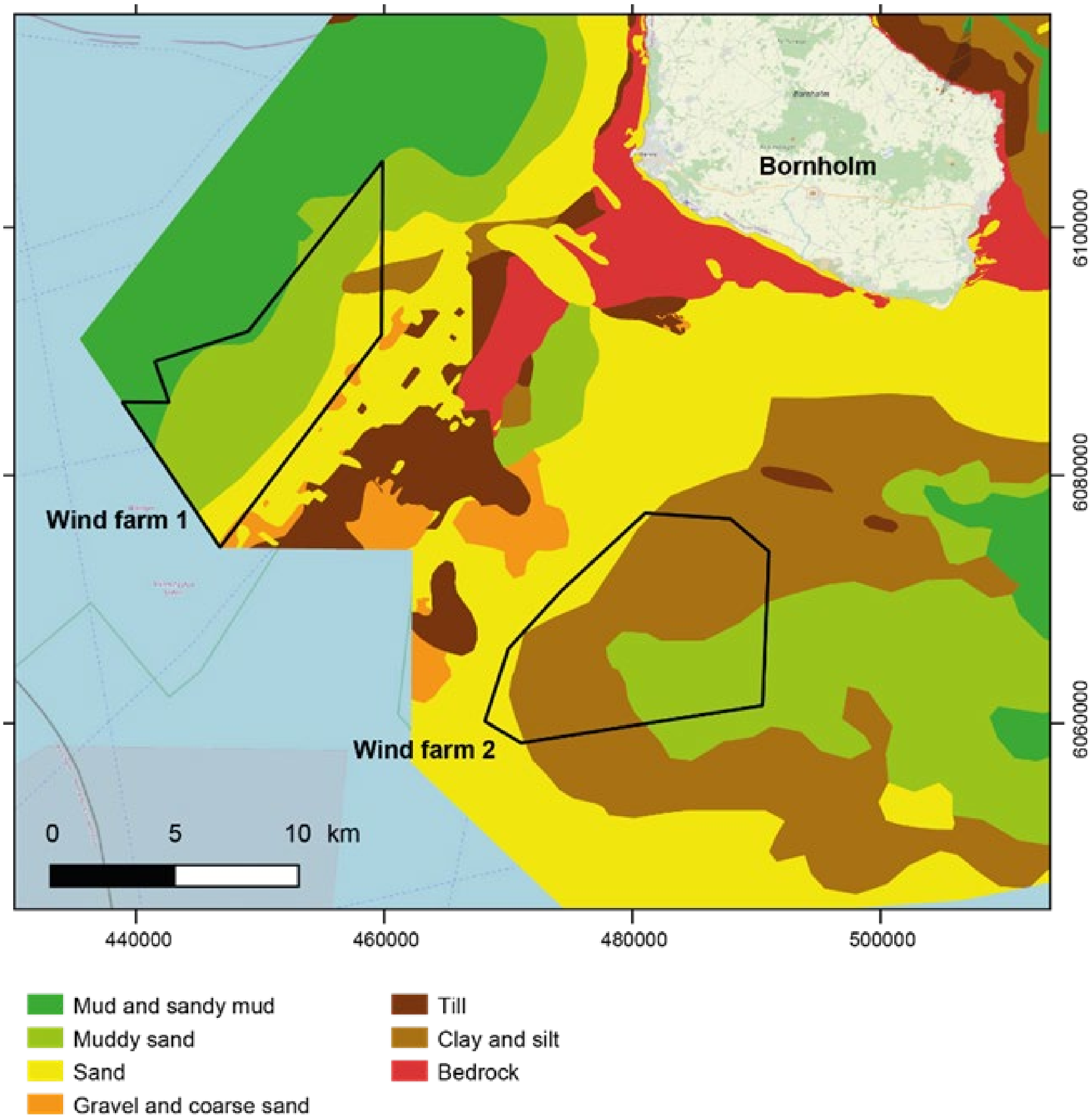


Figure 11.2. Seabed sediments in the Bornholm OWFs region, according to the Marta database. The map gives only a general impression of the seabed sediments.

11.3 Shallow sediments in Windfarms 1 and 2

A few representative boomer seismic lines and data from vibrocores from the windfarm areas have been interpreted and a short description will be presented in the following chapters.

The boomer seismic lines show a combination of near surface pre-Quaternary deposits covered by Quaternary glacial, late glacial and Holocene sediments.

The location of the seismic examples, deep wells and vibrocores, in the wind farm areas southwest of Bornholm, is illustrated on a bathymetric map in Figure 11.3 and in relation to the major faults and pre-Quaternary stratigraphic units in Figure 11.4.

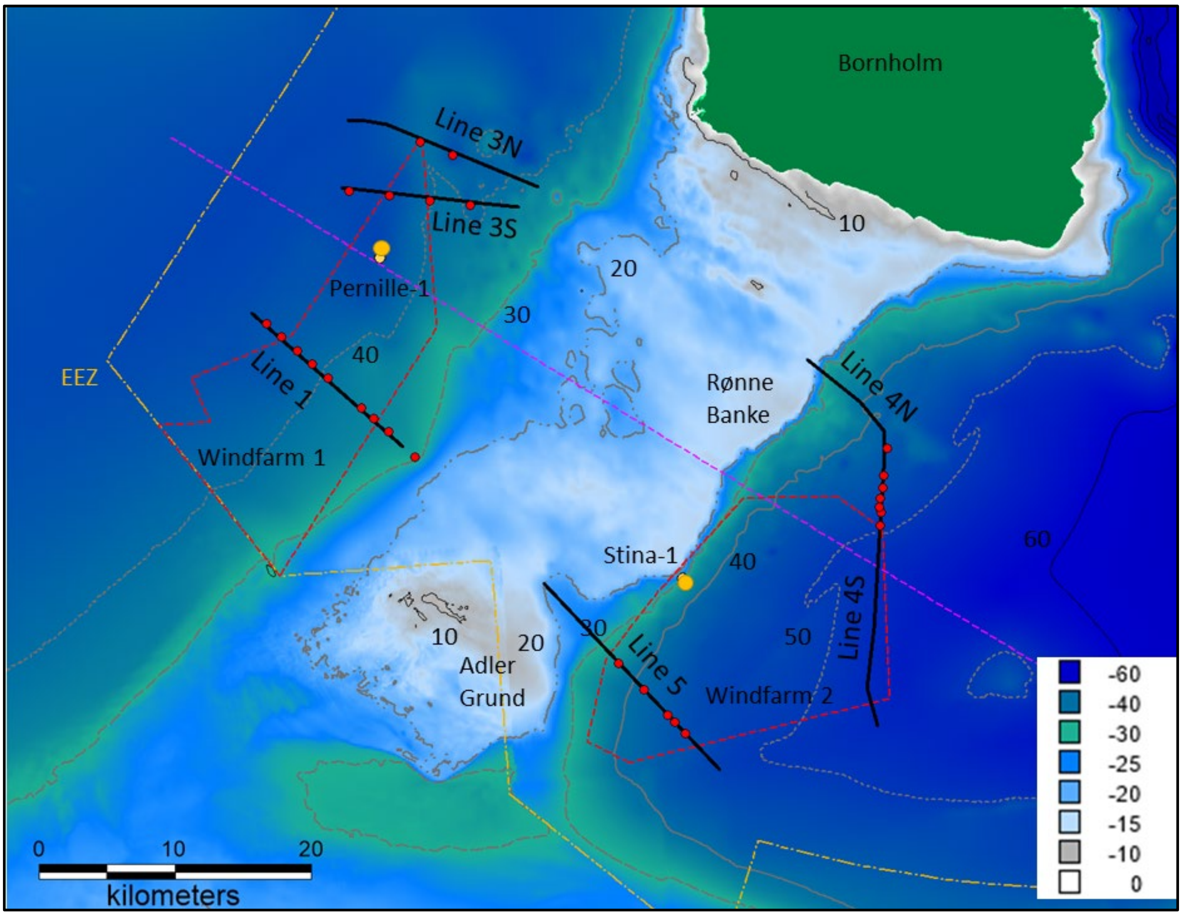


Figure 11.3. Location of deep wells (yellow dots), Boomer seismic examples (black lines) and vibrocores (red dots) southwest of Bornholm. The location of the proposed wind farms is indicated by polygons. The bathymetry is from Emodnet.

As described in chapter 4 the pre-Quaternary geology southwest of Bornholm is dominated by block faulting in a lineament characterised by complex extensional and strike-slip faulting followed by structural inversion. The overall graben and block structures are shown in Figure 4.1, Figure 4.2 and Figure 4.3 and the detailed blocks and pre-Quaternary stratigraphy is presented in Figure 11.4. together with the locations of windfarms and seismic as well as core examples described in the following chapters.

The pre-Quaternary interpretation on the boomer profiles is based on published structures and stratigraphy, the two deep wells Pernille-1 and Stina-1 (Figure 7.1 and Figure 7.2) as well as the characteristic seismic reflection patterns described by Jensen and Hamann (1989) (Figure 11.5 and Figure 11.6). The windfarm boomer profiles interpretations must be seen as a tentative proposal of possible faults and stratigraphic distribution of Mesozoic sed-iments.

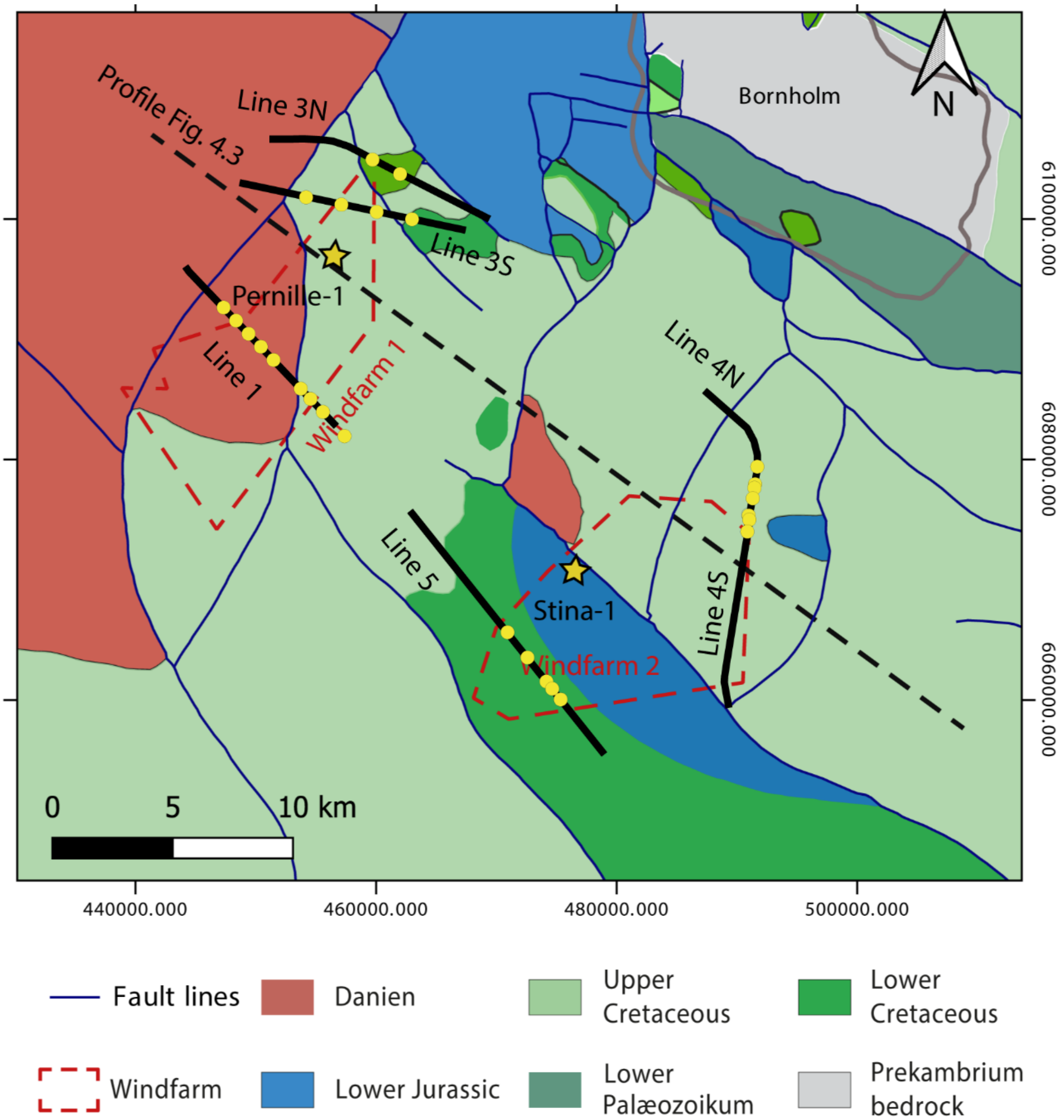


Figure 11.4. Major faults and pre-Quaternary stratigraphic units southwest of Bornholm. Stars represent deep wells. Dots represents vibrocores and thick black lines boomer seismic examples.

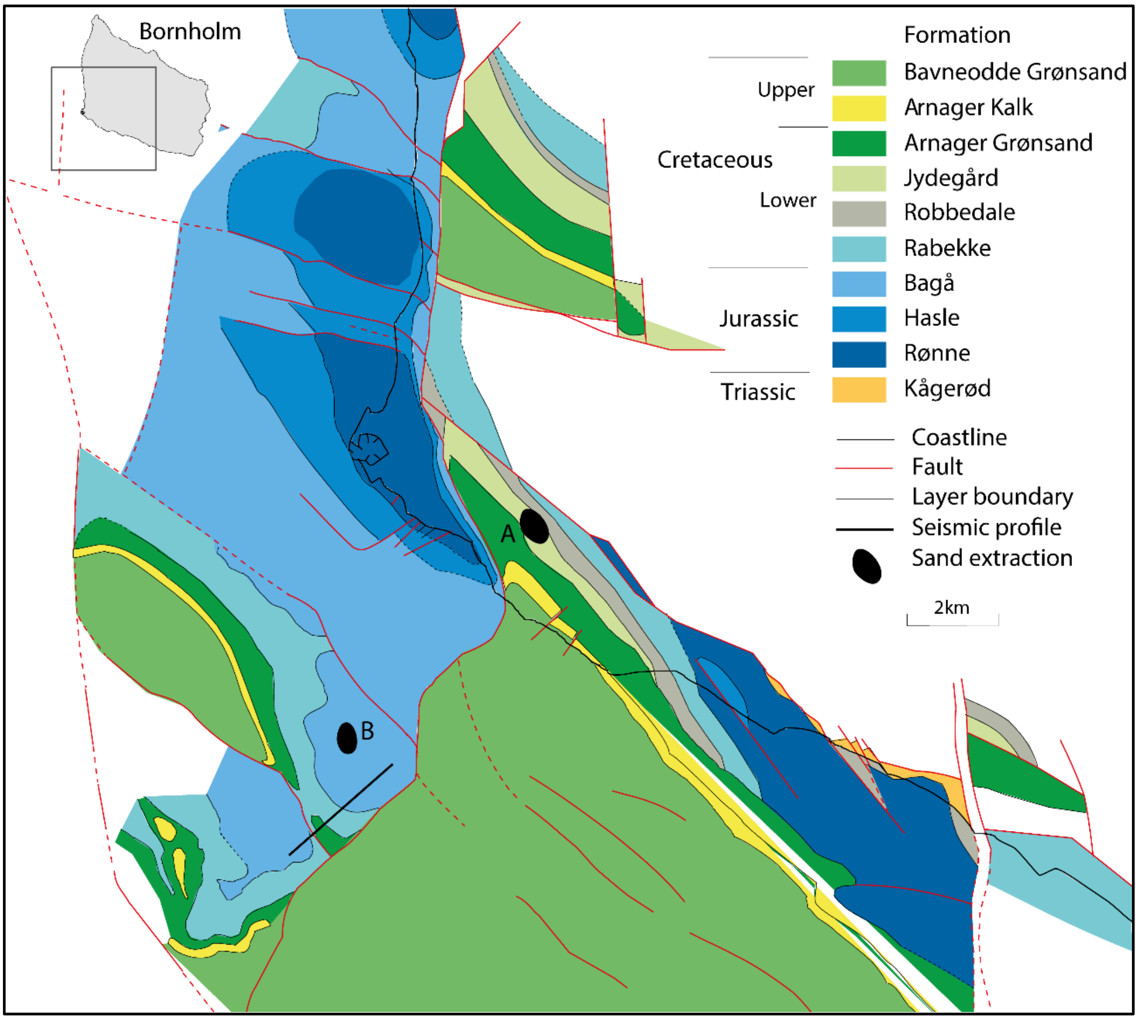


Figure 11.5. The pre-Quaternary Mesozoic surface, exposed at the seabed near coastal offshore Bornholm. (Jensen and Hamann 1989).

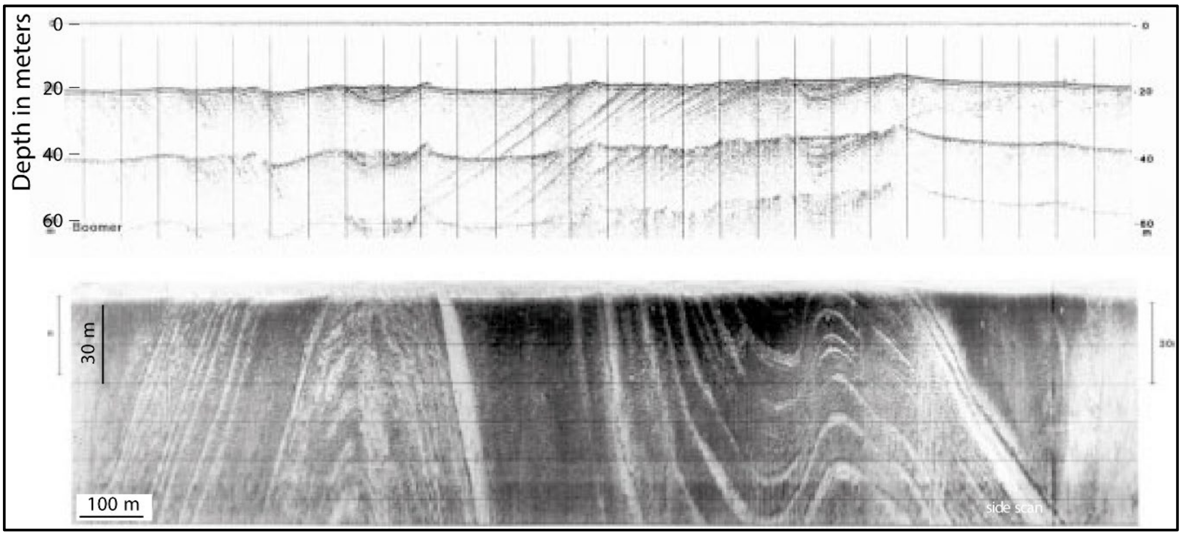


Figure 11.6. Boomer profile and side scan sonar image of the seabed south west of the seismic profile. Exposed Cretaceous sediments at the seabed. Location of profile se Figure 11.5. (Jensen & Hamann 1989).

11.3.1 Windfarm 1

Line 1, Line 3S and Line 3 N Line 1 crosses the central part of the area and transects a pre-Quaternary fault zone with normal faults (Figure 11.7). It results in a change from the south-eastern Upper Cretaceous (Maastrichtian) limestone as documented in Pernille-1 (Figure 7.1) to the north-western Danien limestone (Figure 11.4, Figure 11.7, Figure 11.8 and Figure 11.9) describe the sediments down to 120 ms in Wind farm 1.

11.3.1.1 Pre-Quaternary setting

Line 1 crosses the central part of the area and transects a pre-Quaternary fault zone with normal faults (Figure 11.7). It results in a change from the south-eastern Upper Cretaceous (Maastrichtian) limestone as documented in Pernille-1 (Figure 7.1) to the north-western Danien limestone (Figure 11.4 and Figure 11.7).

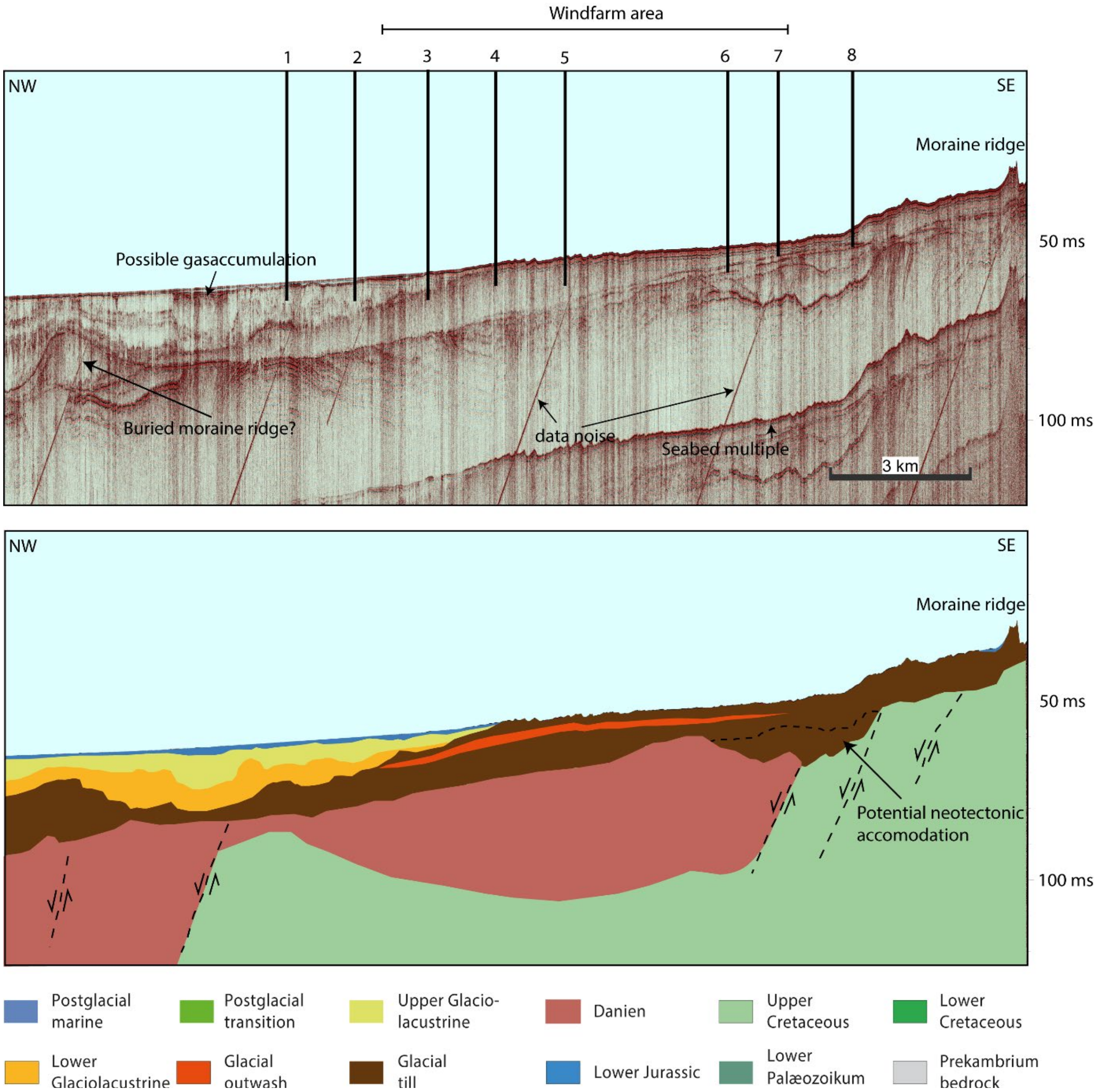


Figure 11.7. Seismic Line 1 from the central part of Wind farm 1. See Figure 11.3 and Figure 11.4 for location. The numbers refer to cores shown in Figure 11.8.

Line 3 S and 3 N represent the northern part of windfarm 1 but show different pre-Quaternary sediments.

Line 3S (Figure 11.8) shows faults combined with drag folding in-between. The result is a pre-Quaternary surface that consists of north-eastern lower Cretaceous probably Rabække Formation characterised by folded strong parallel reflectors, probably related to kaolinitic clay and coal-bearing clay horizons interbedded with fine-grained sand units overlain by Arnager Greensand with few strong reflectors consisting of phosphorite conglomerates in a glauconitic marine sand.

In the central part of the section, between the two faults, Upper Cretaceous (Maastrichtian) limestone is expected as documented in Pernille-1 (Figure 7.1) and southwest of the faults Danien limestone is likely.

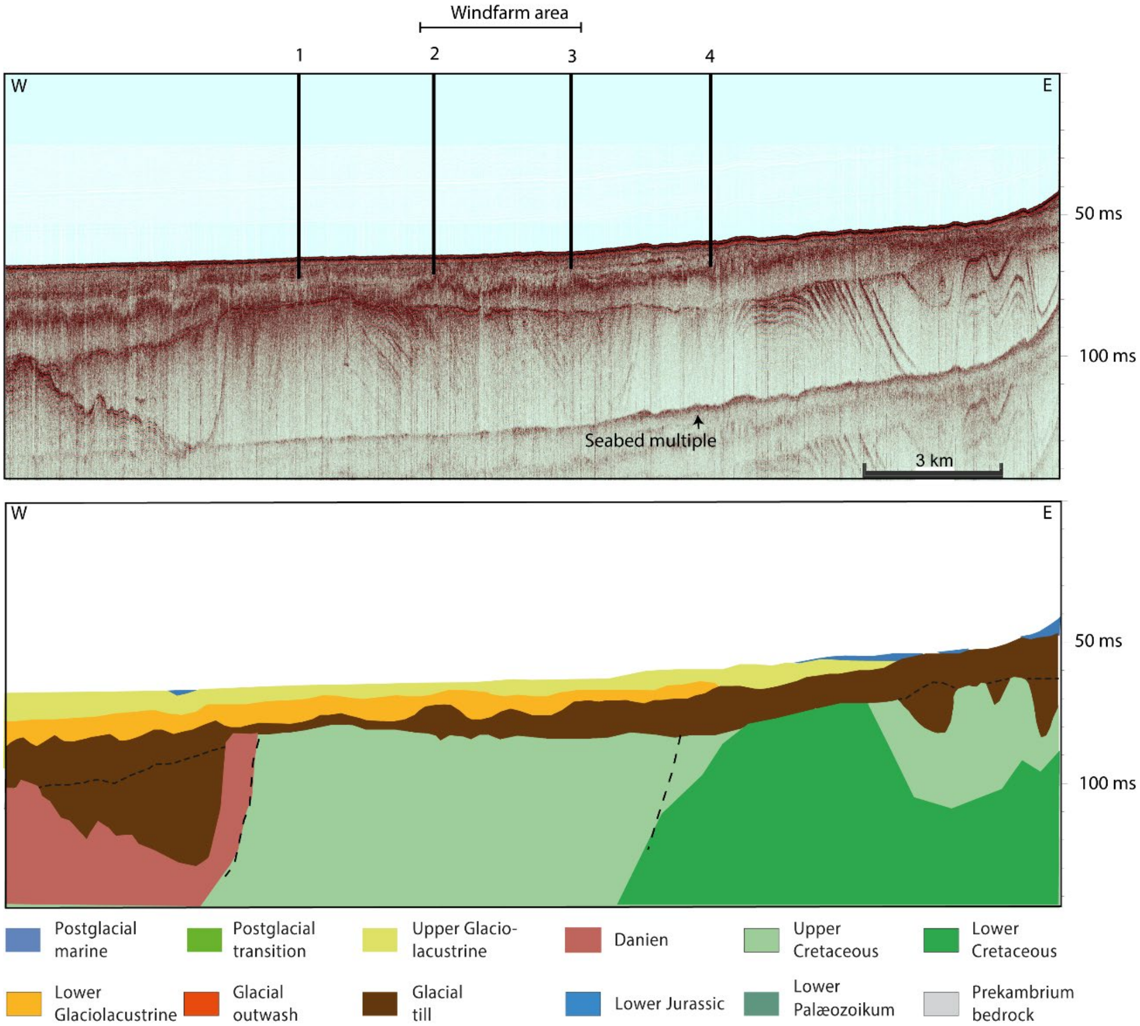


Figure 11.8. Seismic Line 3S from the northern part of Wind farm 1. See Figure 11.3 and Figure 11.4 for location. The numbers refer to cores shown in Figure 11.11.

Line 3N (Figure 11.9) crosses three faults and the pre-Quaternary surface consists of north-eastern lower Jurassic probably Bagå formation of alternating layers of sand, clay and coal.

In the middle section lower Cretaceous Rabække Formation with strong parallel reflectors reflects kaolinitic clay and coal-bearing clay horizons interbedded with fine-grained sand units overlain by Arnager Greensand and followed by Upper Cretaceous (Maastrichtian) limestone. Southwest of the faults Danien limestone is likely present.

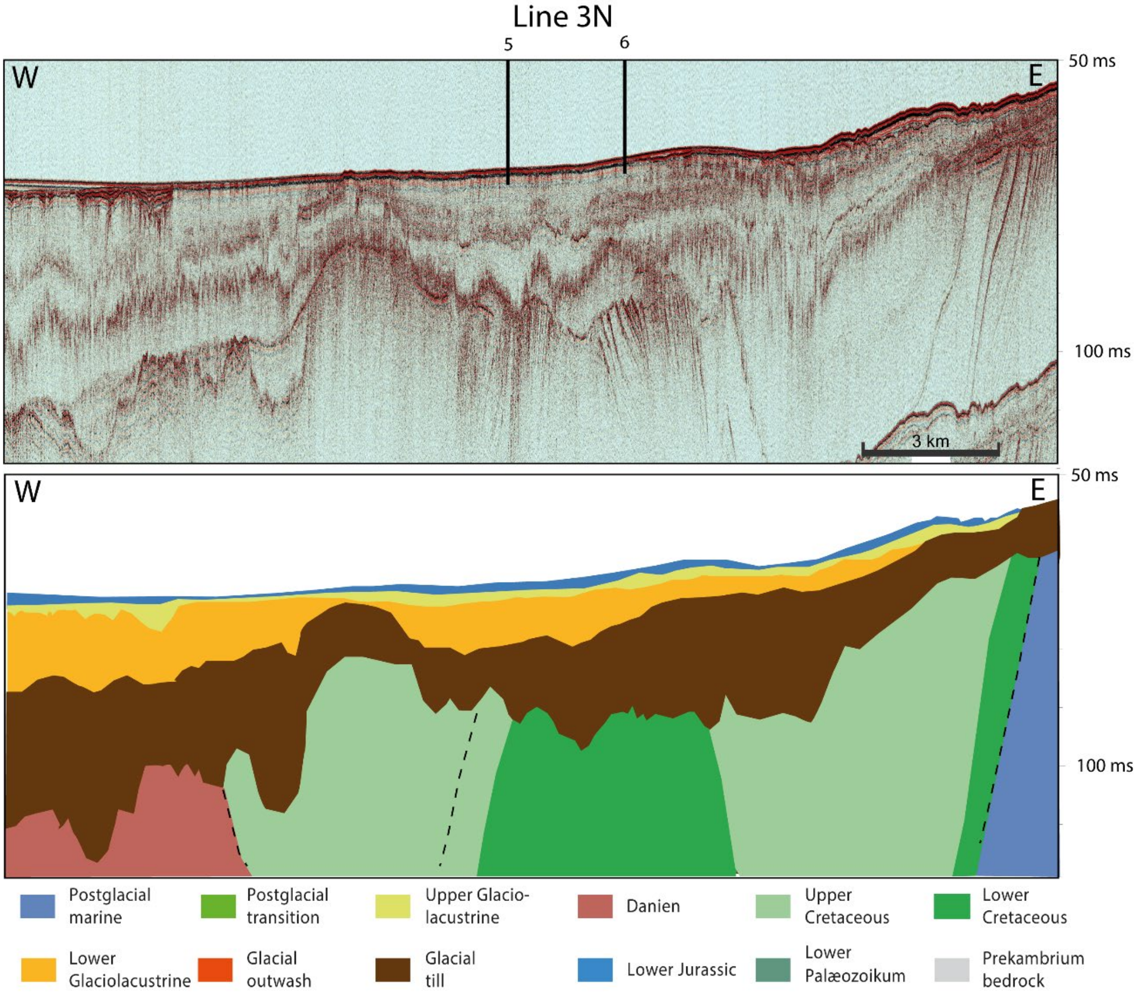


Figure 11.9. Seismic Line 3N just north of Wind farm 1. See Figure 11.3 and Figure 11.4 for location. Numbers refer to cores shown in Figure 11.11.

11.3.1.2 Quaternary sediments

The glacial unit includes a package of sandy meltwater deposits interpreted in the core logs in Line 1 (Figure 11.10). This unit is deposited in front of a moraine ridge, present in the south-eastern end of the line and there is another potential buried moraine ridge in the north-western end of the line, beneath the younger lacustrine deposits. There are multiple internal reflections within the interpreted glacial unit in all three lines (Figure 11.7, Figure 11.8 and Figure 11.9). Especially within the depressions in the pre-Quaternary surface above the fault zones (e.g., Line 1). These may represent accommodation space provided by neotectonic movements in the deeper faults, similar to observations in the Bornholm Basin (Jensen et al. 2016) Neotectonic movements have also been attributed to the formation of depressions and subsequent infill south of the island of Anholt (Jensen et al. 2008), which is also situated in the Tornquist zone. There are, however, no lithological evidence of the infill within these depressions, nor dating from the deposits. Neotectonic movement is thus speculative but a possible scenario.

The late glacial units represent the two lake stages described in chapter 8.1.2; the Baltic Ice Lake I and II (Figure 8.3). They are separated by a thin (below vertical seismic resolution) homogenous clay deposit (Figure 8.5). The two units (IIIa and IIIc) thus represent lake level highstands separated by a drainage event, and deposition of a lowstand homogenous clay unit (IIIb). The glacial lake deposits thickens towards the north. It thus follows the general trend of the pre-Quaternary surface, which deepens towards the north. The late glacial lacustrine units are expected to be present in most of the Wind farm 1 area and are documented in the vibrocores (Figure 11.10 and Figure 11.11).

There are potential gas accumulations within these deposits, as indicated on seismic Line 1 (Figure 11.7). There are no remnants of the Ancylus lake in Wind farm 1, and the ice lake deposits are overlain by a thin layer of Holocene marine muddy sand. Towards the southeast, the glacial surface crops out on the sea floor.

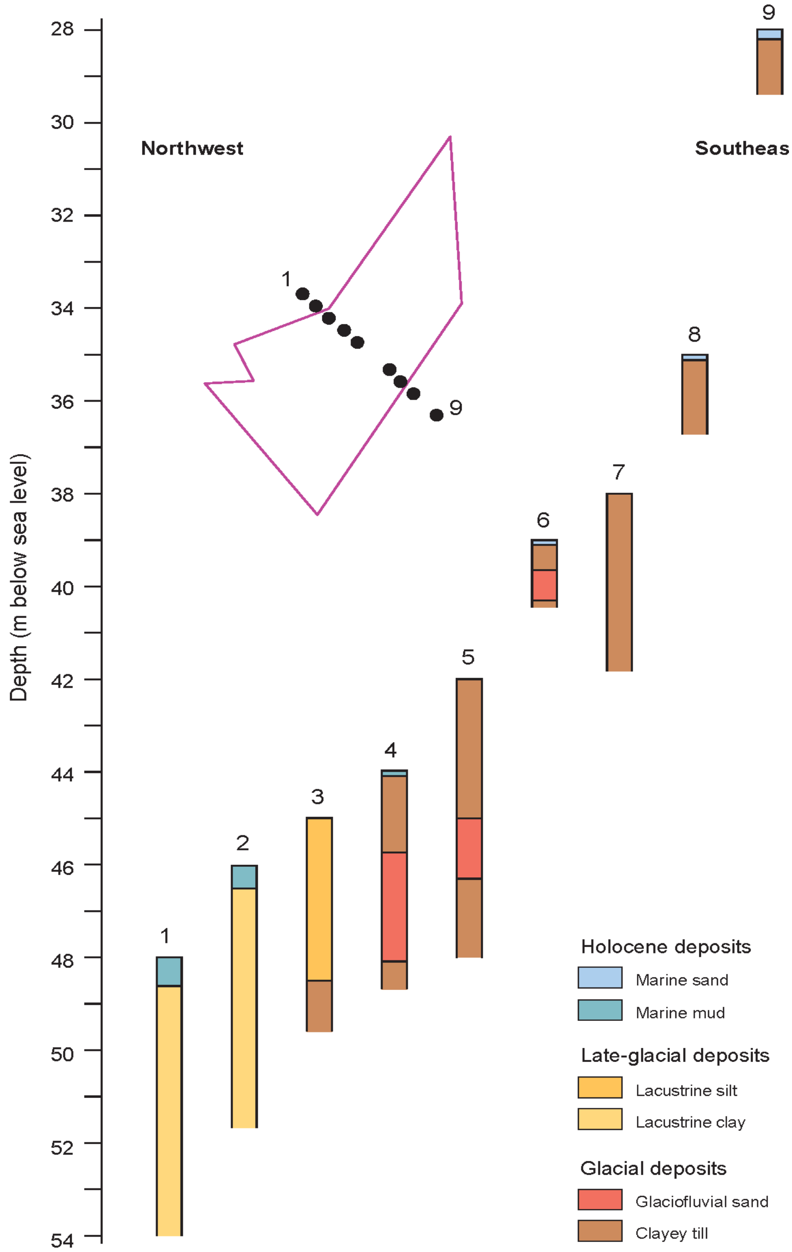


Figure 11.10. Lithological logs based on vibrocores from wind farm 1 (Line 1, Figure 11.5) southwest of Bornholm.

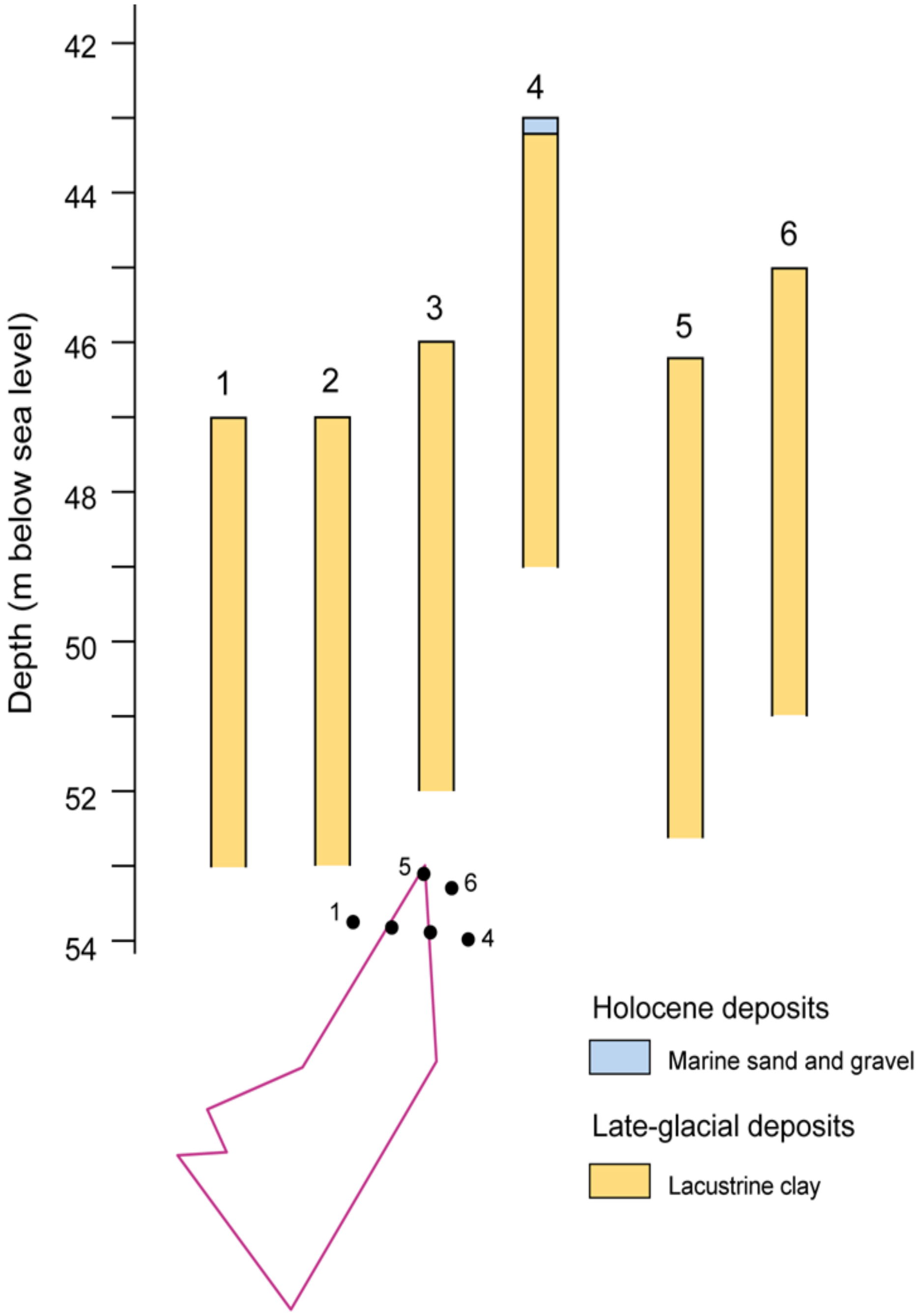


Figure 11.11 Lithological logs based on vibrocores from the northern part of wind farm 1 (Line 3N and 3S Figure 11.8 and Figure 11.9) southwest of Bornholm. The area is dominated by late glacial silty clay deposited in the Baltic Ice Lake. A thin layer of sand and gravel deposited during the Littorina Sea Stage is recorded at the shallowest site.

11.3.2 Wind farm 2

Line 4N1, Line4S and Line 5 (Figure 11.12, Figure 11.13 and Figure 11.14) describe the sediments down to 120 ms in Wind farm 2.

11.3.2.1 Pre-Quaternary setting

The Wind farm 2 area is described from Line 4 S and Line 5 primarily, which show the trends in the area, but also Line 4N, located just north of the windfarm 2 area. The pre-Quaternary surface represents both Lower Cretaceous (southern part), Jurassic (central part) and Upper Cretaceous deposits (northern part) (Figure 11.4). The Jurassic deposits are not represented in the seismic sections presented here. The Upper Cretaceous is represented in the lines 4N and 4S.

Line 4N (Figure 11.12) is dominated by strong parallel reflector bundles with a strong imprint of folding. Studies by Jensen & Hamann (1989) shows that the lithology represented by strong reflectors most likely is Bavneodde Greensand Formation cemented glauconitic quartz sandstone and occasionally conglomerates, while unconsolidated glauconitic sand gives rise to weak reflectors.

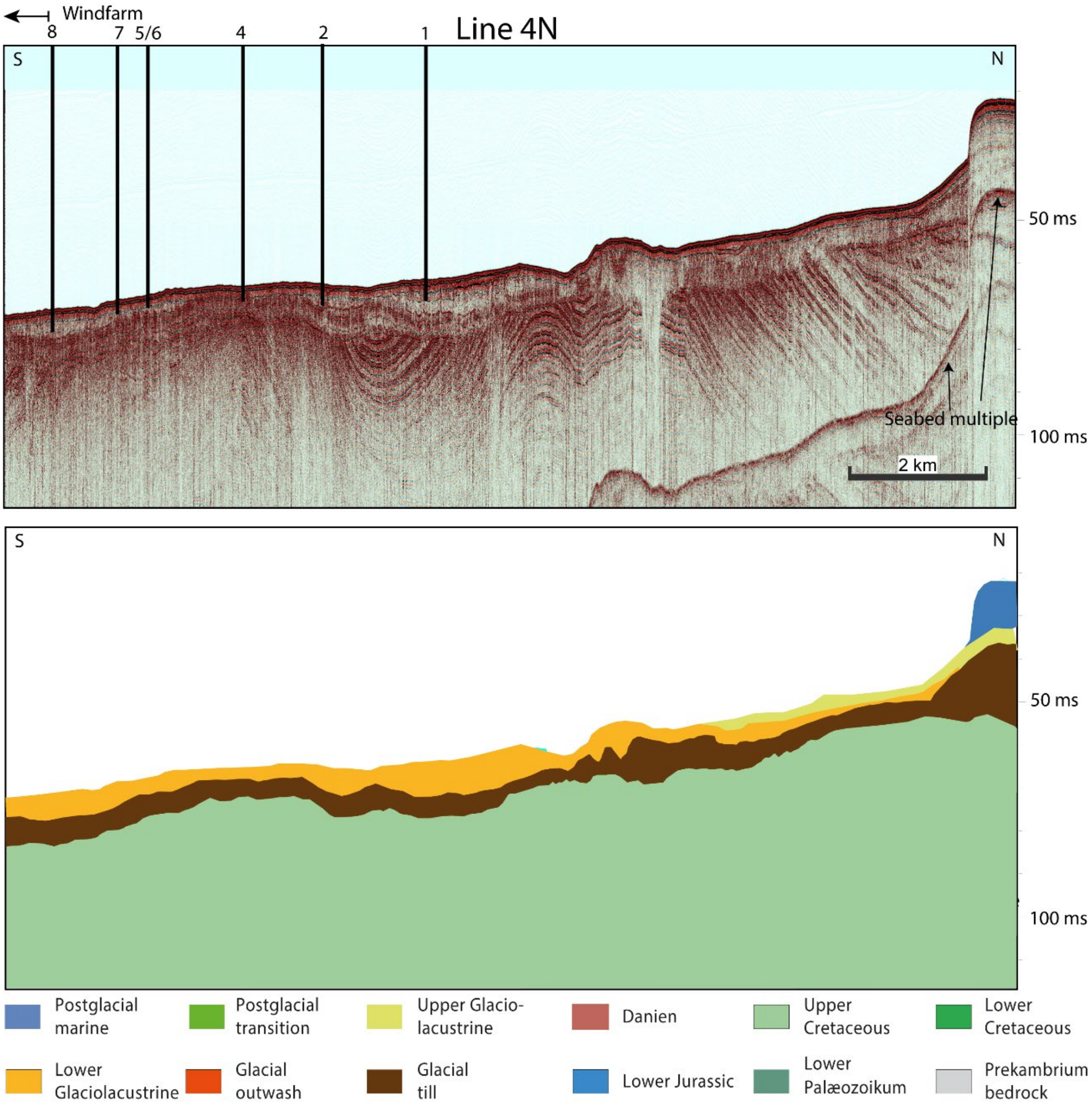


Figure 11.12. Seismic Line 4N from the northern part of Wind farm 2. see (Figure 11.3 and Figure 11.4) for location. (The numbers refer to cores shown in Figure 11.15)

Line 4S inside windfarm 2 only have bundles of strong parallel reflectors in the northern part while the southern part is dominated by weak reflectors. This indicates a change from quarts sandstone to glauconitic sand.

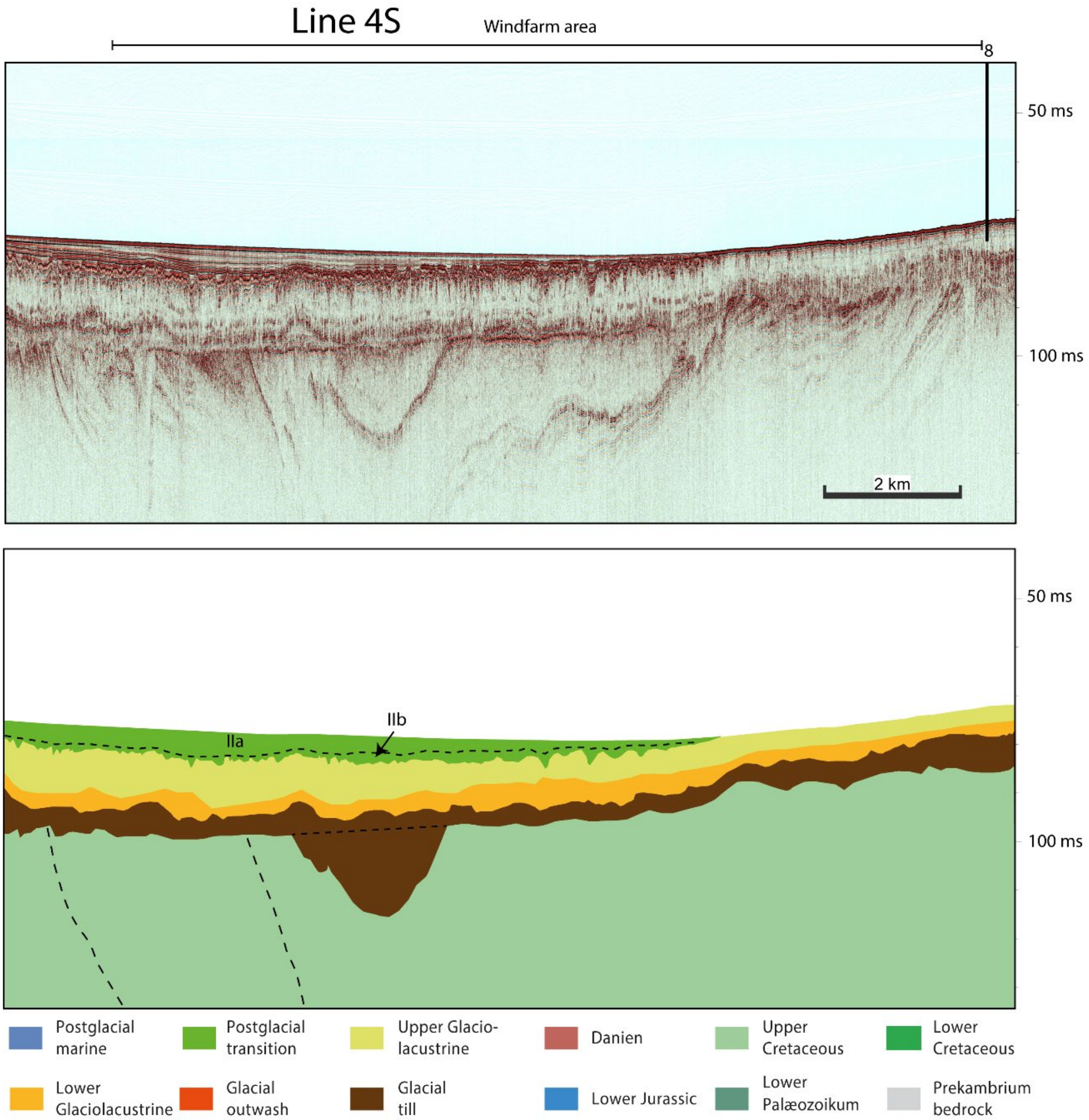


Figure 11.13. Seismic Line 3N just north of Wind farm 1. see (Figure 11.3 and Figure 11.4) for location. (The number refers to core shown in Figure 11.15).

Line 5 apparently shows Lower Cretaceous pre-Quaternary sediments in the southeast and a gradual transition to north-western Upper Cretaceous deposits. No information has been obtained about the sediment types.

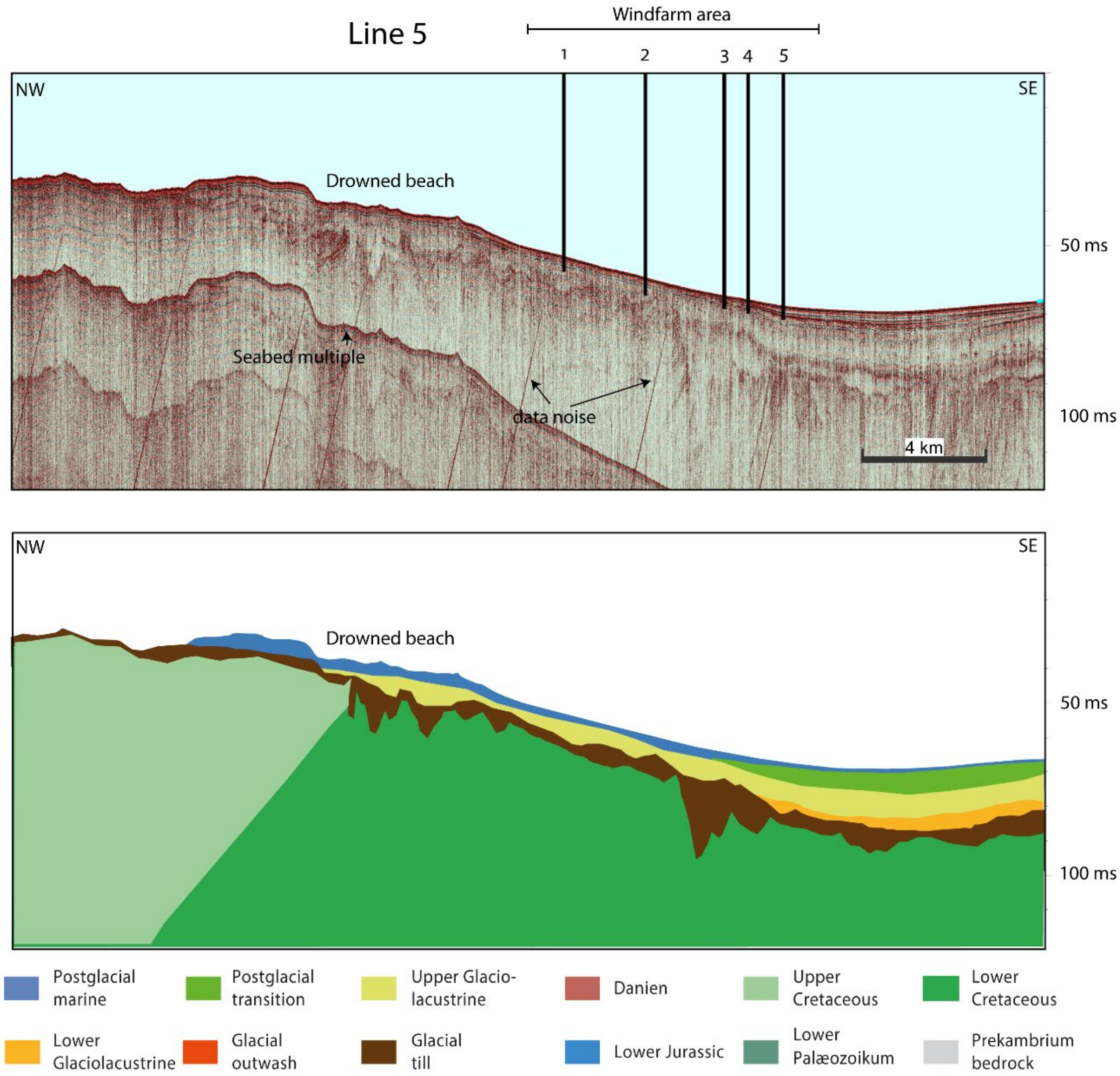


Figure 11.14. Seismic Line 5 south-western part of Wind farm 1. see (Figure 11.3 and Figure 11.4) for location. (Numbers refer to cores shown in Figure 11.16).

11.3.2.2 Quaternary sediments

The glacial unit is relatively thin compared to the deposits in the Wind farm 1 area. In general, only few metres of draping on the pre-Quaternary surface interrupted by few depressions. There are fewer internal reflections within the unit, suggesting layering of the till. Seasonal melting and resulting seasonal moraines may also have affected the wind farm 2 area in the same way as the Wind farm 1 area.

The late glacial unit shows the same pattern as in the Wind farm 1 area, with two high stand units separated by a low stand unit, below seismic resolution, but documented in the vibrocores. Towards the north-east, erosion or nondeposition has exposed late glacial unit IIIc, this is however outside the windfarm area. The top reflector of the late glacial units is characterized by a high amplitude, that may be associated with development of unconformities during low stand periods.

On top of the late glacial unit, a Holocene lacustrine unit is deposited. The seismic section shows a nicely laminated unit (unit II), with medium amplitude reflections. This unit was deposited primarily in the Ancylus Lake, with possible remnants of Yoldia clay deposits at the base.

Northwest of windfarm 2 in the northern part of Line 4N (Figure 11.12. Seismic Line 4N from the northern part of Wind farm 2. see (Figure 11.3 and Figure 11.4) for location. (The numbers refer to cores shown in Figure 11.15), there is a thick marine sandy unit that represents a drowned beach. This unit is not found in the wind farm area.

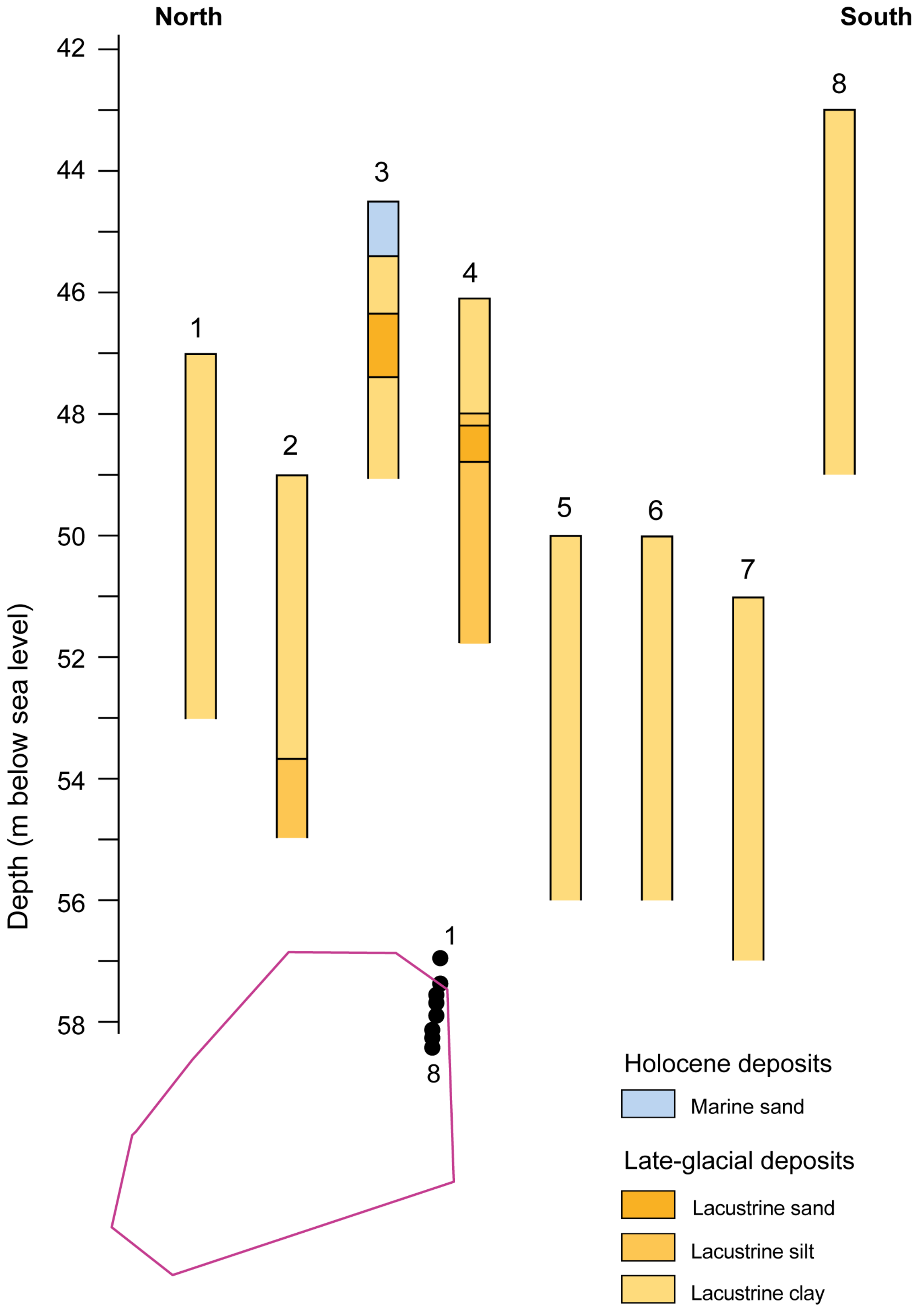


Figure 11.15. Lithological logs based on vibrocores from wind farm 2 (Line 4N and 4S) (Figure 11.12 and Figure 11.13) south-west of Bornholm.

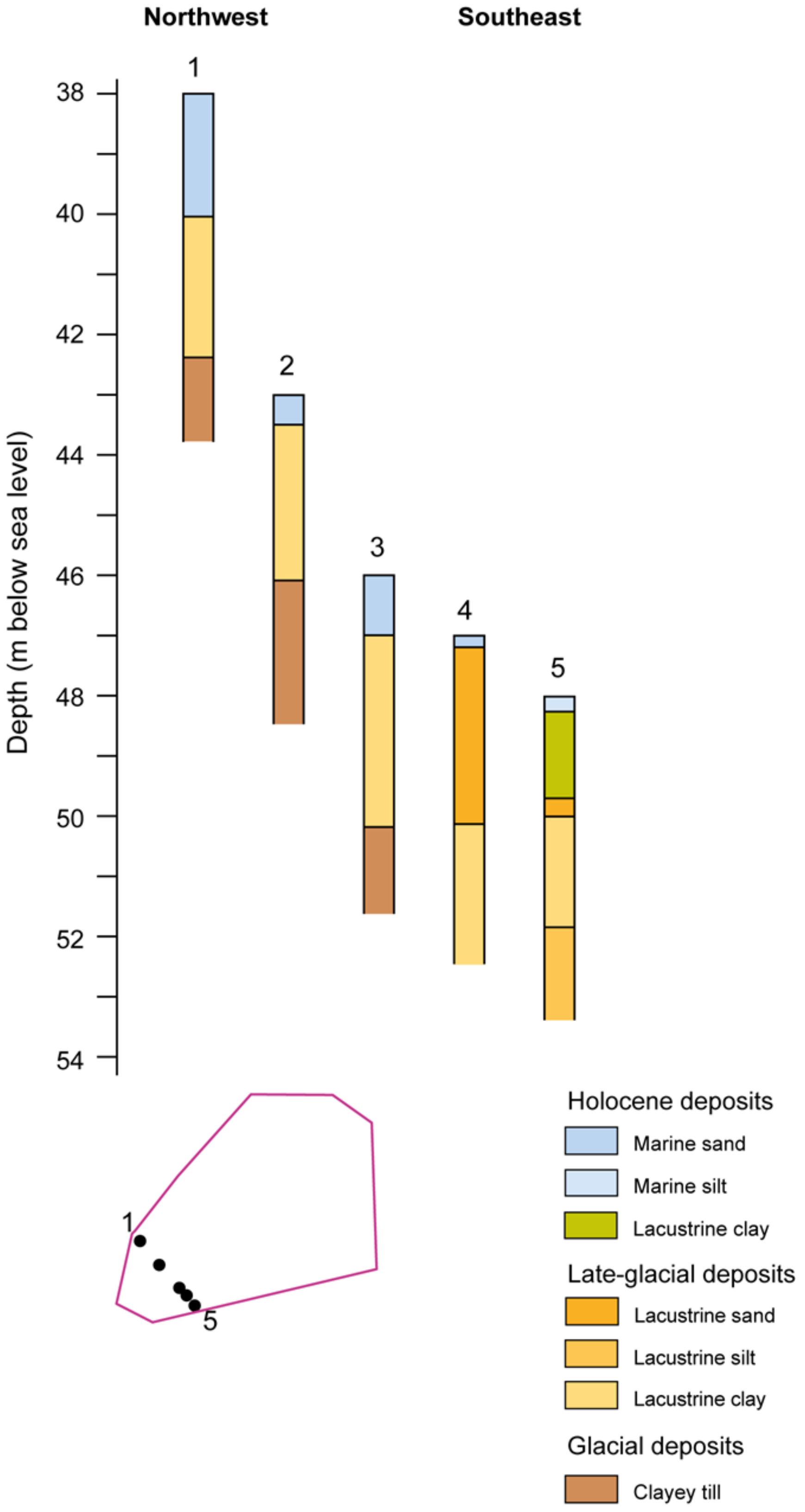


Figure 11.16 Lithological logs based on vibrocores from the southern part of wind farm 2 (Line 5, Figure 11.14) southwest of Bornholm.

12. Danish windfarm Site 6. Rønne Banke

In 2013, Energinet conducted surveys on six offshore near coastal areas planned by the Danish Energy Agency towards licensing for a total of 500MW OWF. One of these areas (Site 6 Rønne Banke) covers 45km^2 and is located about 10km south of Rønne. Site 6 is located at water depths between 9 and 24m, in general shallower than Windfarm 1 and 2 (Figure 12.1). Only the north-western most part of Windfarm 2 reaches 22m water depths in a few hundred meters narrow rim.

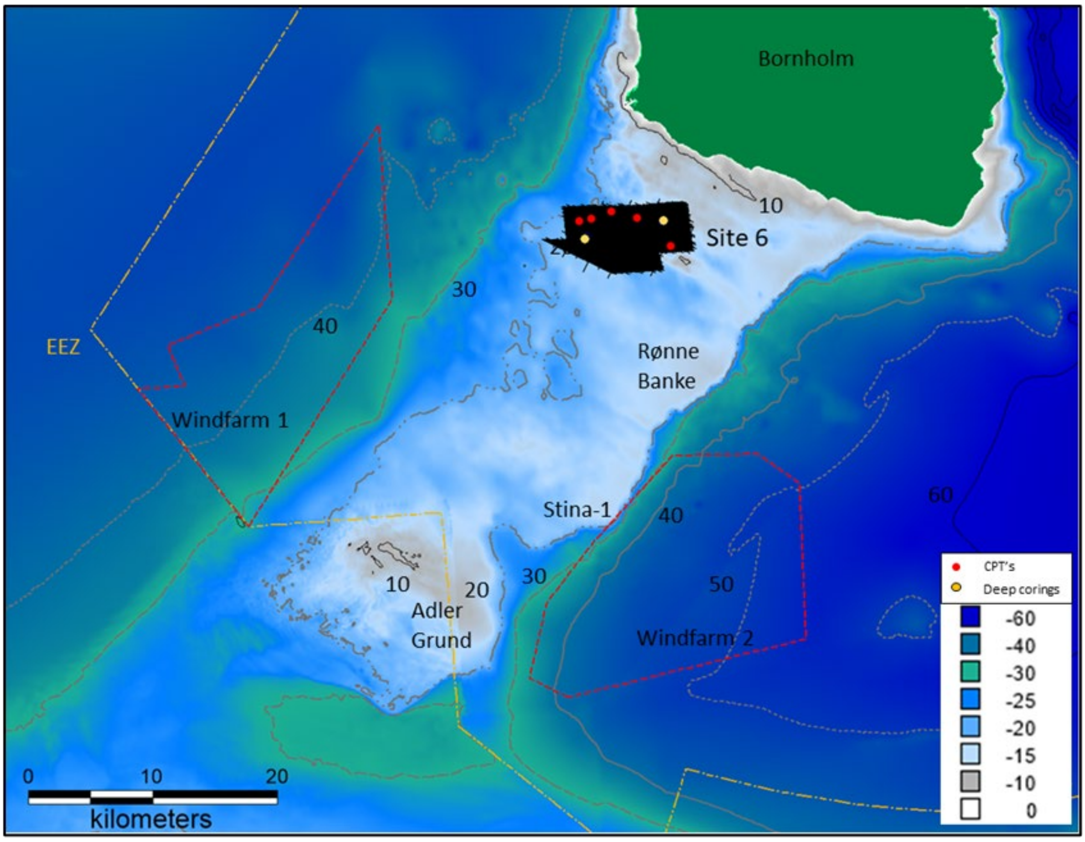


Figure 12.1 Location of Site 6 Rønne Banke in relation to Windfarm 1 and Windfarm 2. The location of 2 combined deeper cores and CPTs (yellow dots) and 5 CPTs (red dots) is indicated in site 6.

The general distribution of seabed sediments in Rønne Banke site 6 is described in the GEUS Marta database as dominated by bedrock at the seabed (Figure 12.2) with thin sand and glacial deposits in the southernmost margin areas. It also clearly shows that the lateglacial and Holocene basin deposits in the deeper Windfarm 1 and 2 areas are not represented in the Rønne Banke Site 6 area.

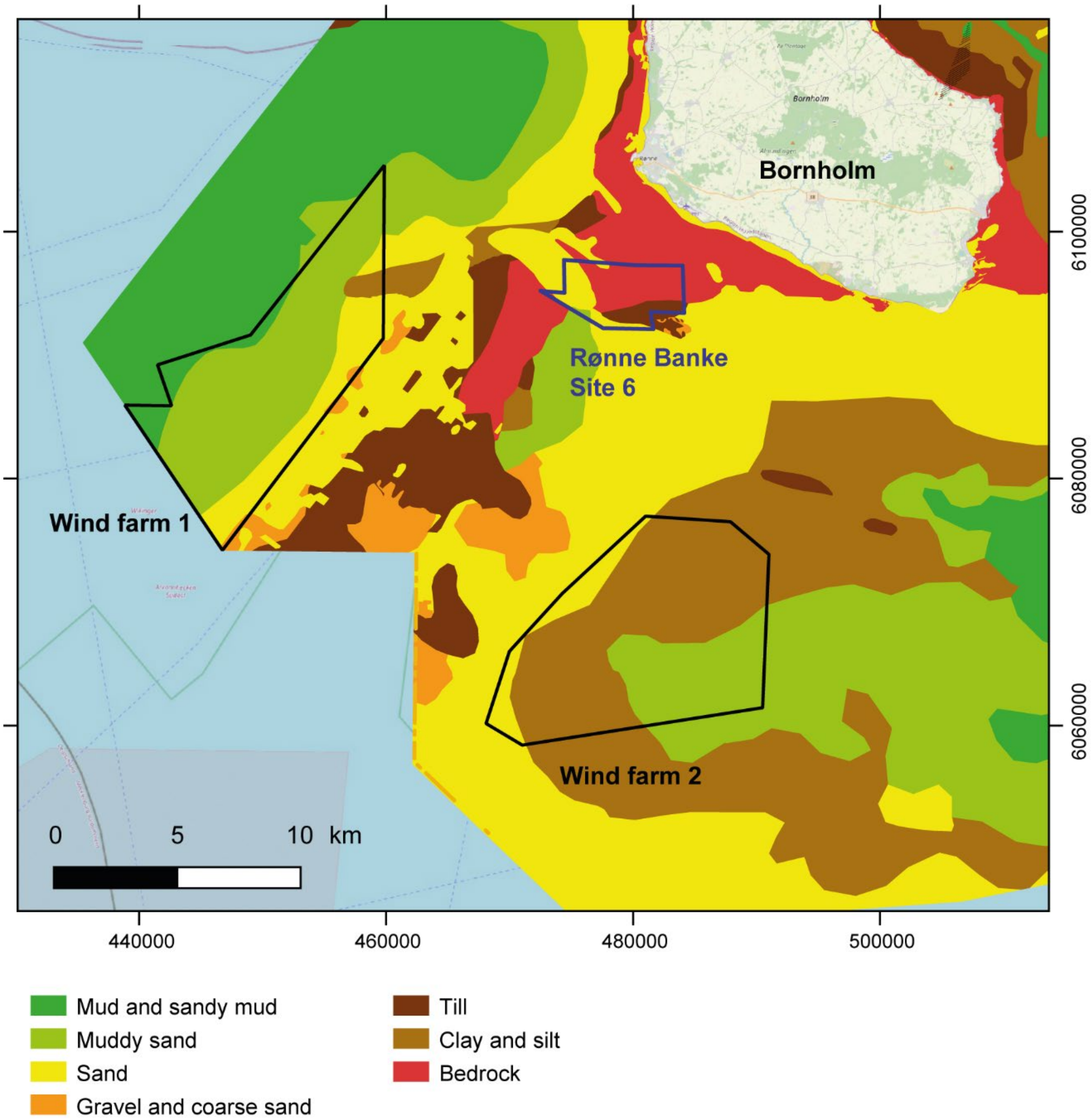


Figure 12.2 Seabed sediments in the Bornholm OWFs region, according to the Marta database. The map gives only a general impression of the seabed sediments. The location of OWF site 6 is located in an area dominated by bedrock at the seabed.

Energinet carried out an assessment and an initial evaluation of the foundation of wind turbines, to lower the risk for companies with interest in acquiring the license to build and operate the wind farms providing a general assessment of the areas.

The studies were divided in a geophysical survey and a geotechnical coring survey:

12.1 Geophysical survey

A geophysical survey was carried out in 2013 by EGS (International) Limited and reported in their report “Danish Wind Farm Site Surveys, Site 6, Rønne Banke” (Energinet 2014 (a) and (b)).

The survey included the following:

- Bathymetric mapping.

- Side-scan sonar mapping
- Sub-bottom profiling with two systems,
- high resolution pinger (chirp) single channel system
- deep penetration sparker multi-channel system.
- Magnetic profiling.
- Grab sampling to support seabed interpretation.

Survey lines with 65m line spacing has been collected over an approximate area of 45km^2. This equated to a total planned line length of 755km. Data were acquired, processed and interpreted resulting in the interpretation of bathymetry, seabed features and shallow geological profiles. Full data coverage was achieved during survey operations. A total of 26 grab samples were taken to provide ground-truth data.

Products from the survey are:

- A vessel track chart plot
- A Full coverage multibeam bathymetric chart
- SSS mosaic charts displaying elements of the seabed features, morphology and sediments.
- An overview SBF chart has also been created at a scale of 1:25,000 and
- Sub-seabed geological components were also charted as example geological interpretation of 6 mainlines and 5 cross lines

The sub-surface sediments have been mapped based on seismic evidence. The distribution of the most significant geological units has been mapped (Figure 12.8) as a background for the geotechnical evaluations of the turbines.

The interpretations are mainly made on basis of the seismic reflection pattern.

12.2 Geotechnical investigations

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

The purpose of the ground investigations was to provide preliminary geotechnical data to allow for the evaluation of the site for further investigations and development into a nearshore wind farm.

Base on the seismic data, sites for ground investigation locations were selected (Figure 12.7 and Figure 12.3):

- Two combined borehole and CPT locations (RNB-BH001/CPT001 and RNB-BH002/CPT002). Both with core penetration 50m below seabed and CPT depth of recovery of 8,5m (CPT001) and 49m (CPT002).
    - The two borehole studies include:
        - Sediment description
        - Moisture
        - Atterberg Limits

- Particle size distribution
- Minimum and maximum density
- Undrained shear strength
- Isotropically consolidated drained triaxial tests
- Termal resistivity
- Unixial compressive strength
- Carbonate content
- Sulphate content
- Chloride content

- Five CPT locations (RNB-CPT003 to RNB-CPT007) with depth of recovery up to 24m.
  - CPT results ae presented in three plot types
    - Plot1. Cone end resistance, sleeve friction, friction rate, porewater pressure, penetration speed.
    - Plot2. Net cone resistance, excess porewater pressure ratio, friction ratio, estimated soil type
    - Plot3. Net cone resistance, friction ratio, derived relative density, derived angle of internal friction and derived undrained shear strength.

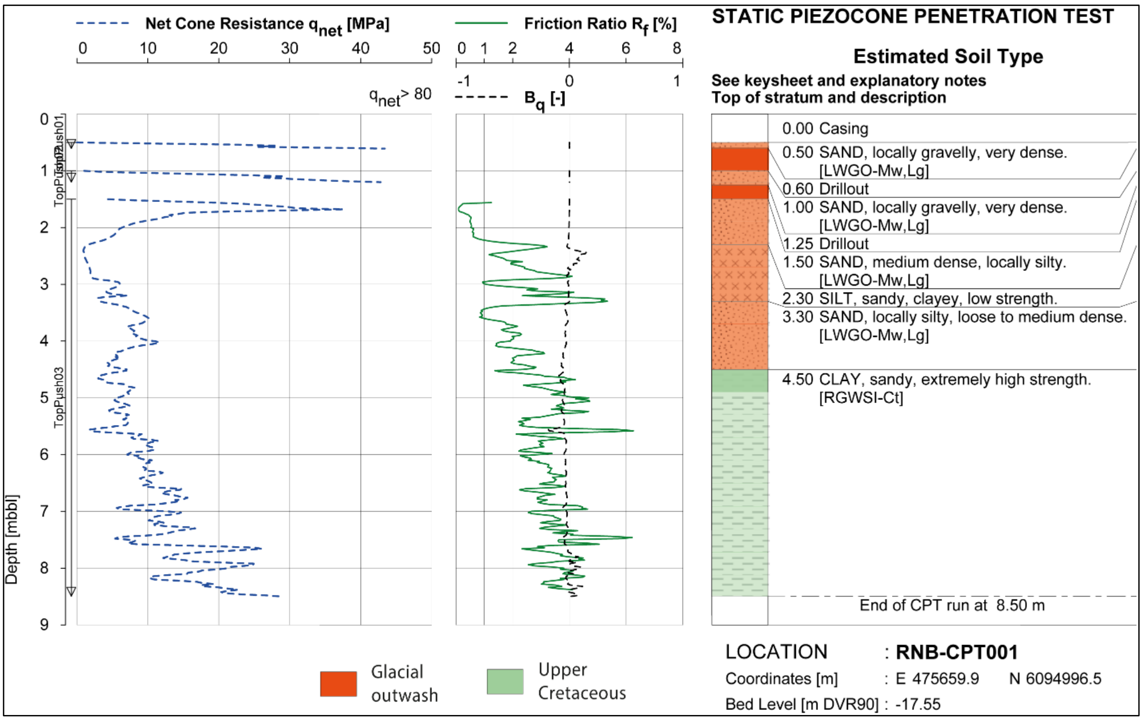


Figure 12.3 Example on CPT test with lithological interpretation on location RNB-CPT001. (ref. Energinet 2014 (d)).

12.3 Interpretations

12.3.1 Sediment distribution

The Rønne Banke Site 6 survey 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 12.4).

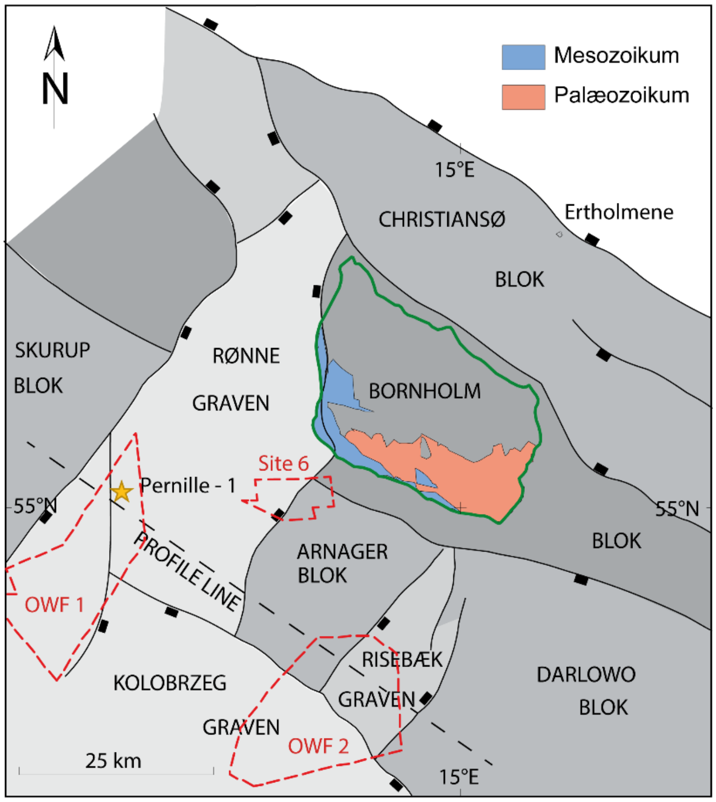


Figure 12.4 Major fault blocks of the Bornholm region. The fault pattern is based on Vejbæk & Britze (1994) and Vejbæk (1997). Location of Windfarm 1 and 2 as well as Site 6 is indicated. Profile line of Figure 4.3 is shown.

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 12.5).

The structural history has resulted in severe folding of the sediments on both sides of the fault. The sediments occurring at and within 50m of the seabed on the West side (Rønne Graben) consist predominantly of Early Jurassic to Late Cretaceous SANDS and SANDSTONES (variably consolidated) with occasional LIMESTONE and SHALE also with a possiblility of CLAY and COAL (Figure 12.6). On the Eastern side of the Rønne Fault the sediments consist of interbedded, cemented SANDSTONES and unconsolidated SANDS. 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 SANDS have been eroded (Figure 12.7). 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.

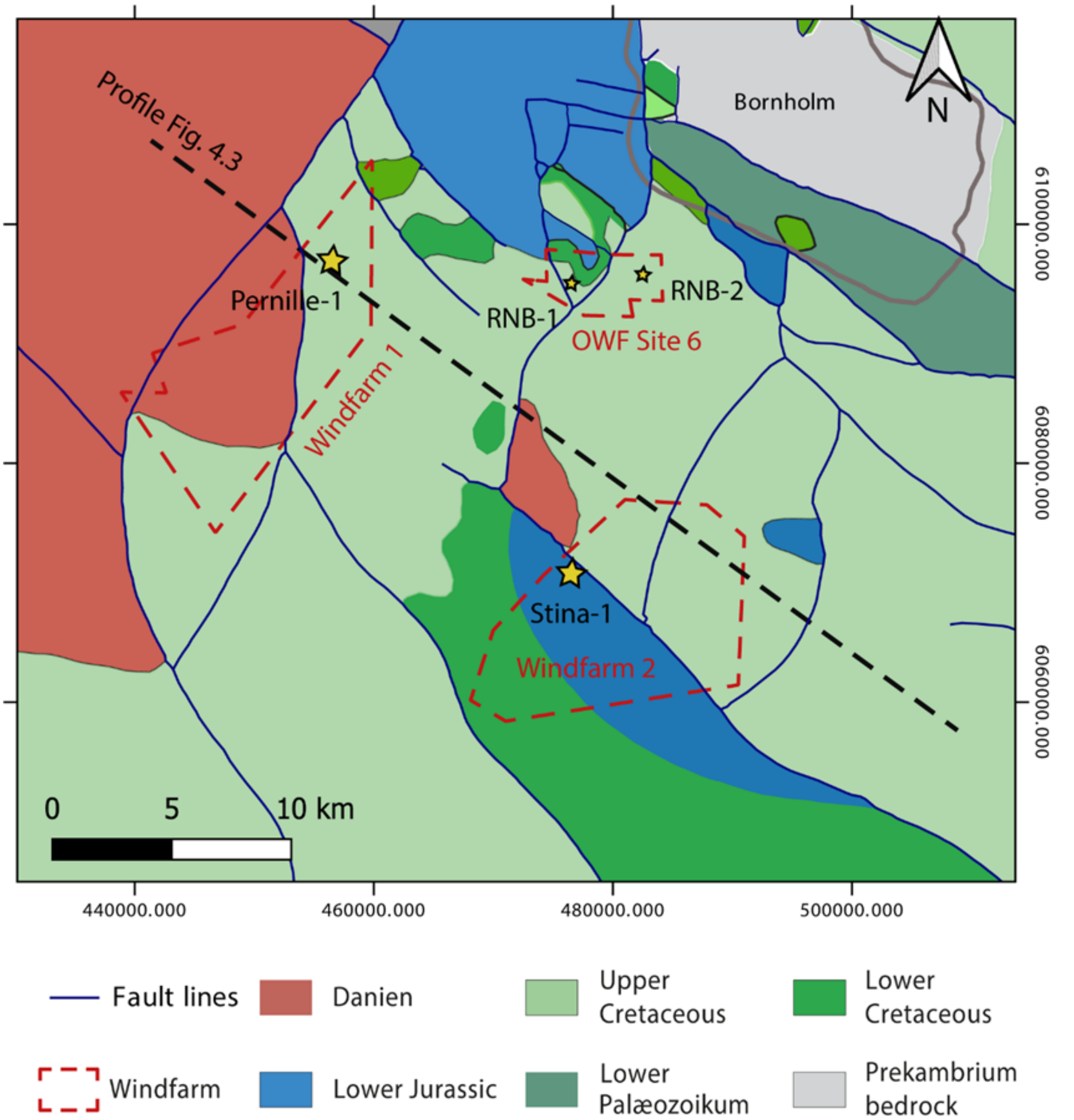


Figure 12.5 Major faults and pre-Quaternary stratigraphic units southwest of Bornholm. The location of Rønne Banke Site 6 survey area is located. The stars indicate deep wells.

Variable thickness of a glacial unit occurs at the seabed over most of the survey area where bedrock 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 12.10). The glacial unit is expected to consist of SAND, GRAVEL and TILL in variable concentrations and reaches a maximum thickness of 43m in an extended channel orientated east-west across the northern half of the survey area (Figure 12.10). More localised eroded depressions infilled with glacial sediments occur at the southern and eastern margins of the survey area (Figure 12.6). 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 4m near the western margin of the area and pinches out towards the north and east (Figure 12.9).

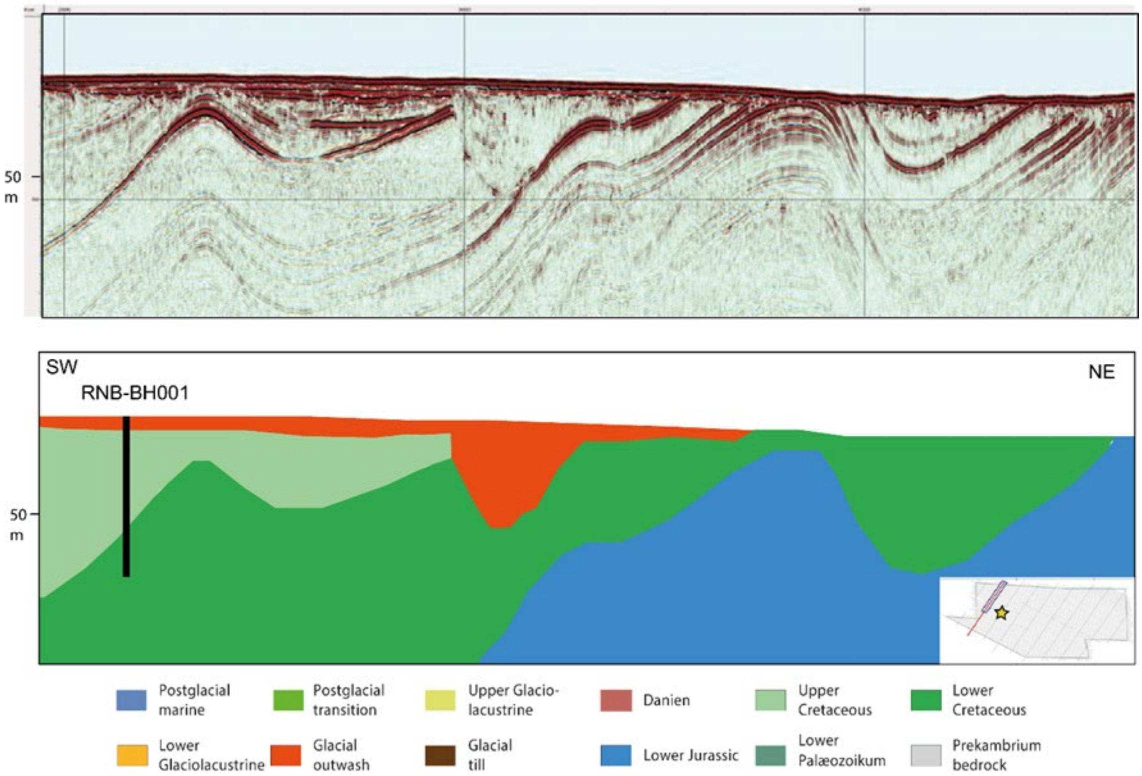


Figure 12.6 High Resolution Sparker multi-channel line XL_010 and below geological interpretation. Location is indicated at inset chart in lower right corner.

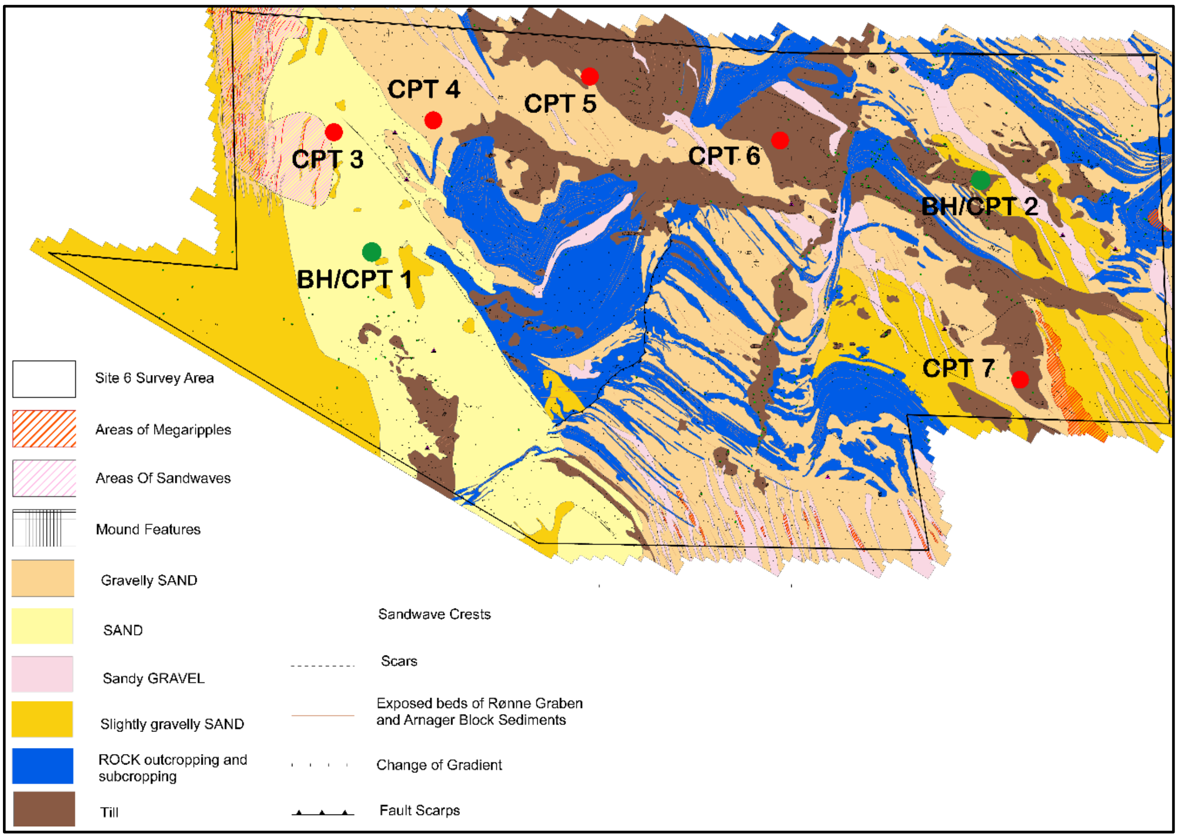


Figure 12.7 Seabed sediment map Rønne Banke Site 6. Surface sediment types and features are indicated as well as location of boreholes (BH 1 and BH 2) and CPT's (CPT 1 to CPT 7)

12.3.2 Sediment types and composition

The coring and CPT results revealed several sediment types that improves the understanding of the layers (detailed results in Energinet 2014 (c) and (d)). The combination of lithology geotechnical parameters and stratigraphy (Figure 12.8) 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 12.8 Stratigraphic diagram of Rønne Banke Site 6 on both sites of the Rønne Fault.

12.3.2.1 Holocene marine deposits

Thickness of Holocene marine deposits has been mapped in the southwestern part of Site 6 on basis of the seismic survey (Figure 12.9) and the geotechnical studies encountered, sand, clays, and possible organic clays in RNB-CPT003, RNB-CPT004, RNB-CPT005, RNB-CPT006 to a maximum depth of 4m below seabed (RNB-CPT003). The sediments consist of very loose to very dense occasionally silt, gravelly sand, to medium to extremely high strength sandy clays.

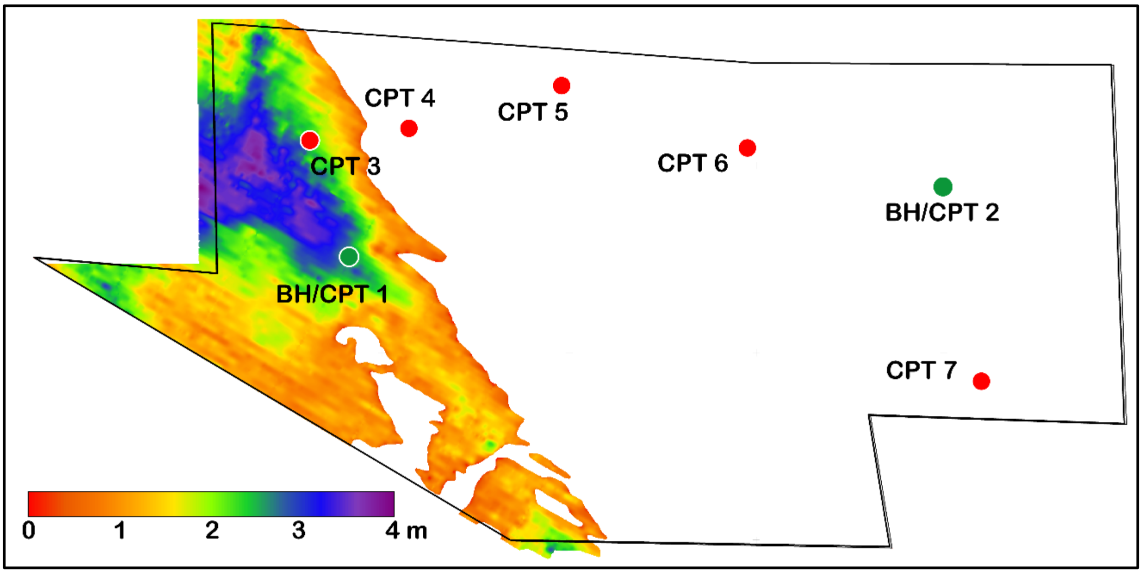


Figure 12.9 Thickness of Holocene marine deposits mapped form chirp seismic data. Locations of Boreholes and CPT's are indicated.

12.3.2.2 Late glacial outwash deposits

The thickness of glacial to late glacial meltwater sand and till has been mapped (Figure 12.10) on basis of the seismic data and the geotechnical studies. Meltwater sand deposits in RNB-BH001, RNB-BH002 and RNB-CPT001 has been mapped to a maximum depth of 6m below seabed. The fine and medium sand and gravel contains a variable content of clay and the gravel consist of granite, flint sandstone and siltstone.

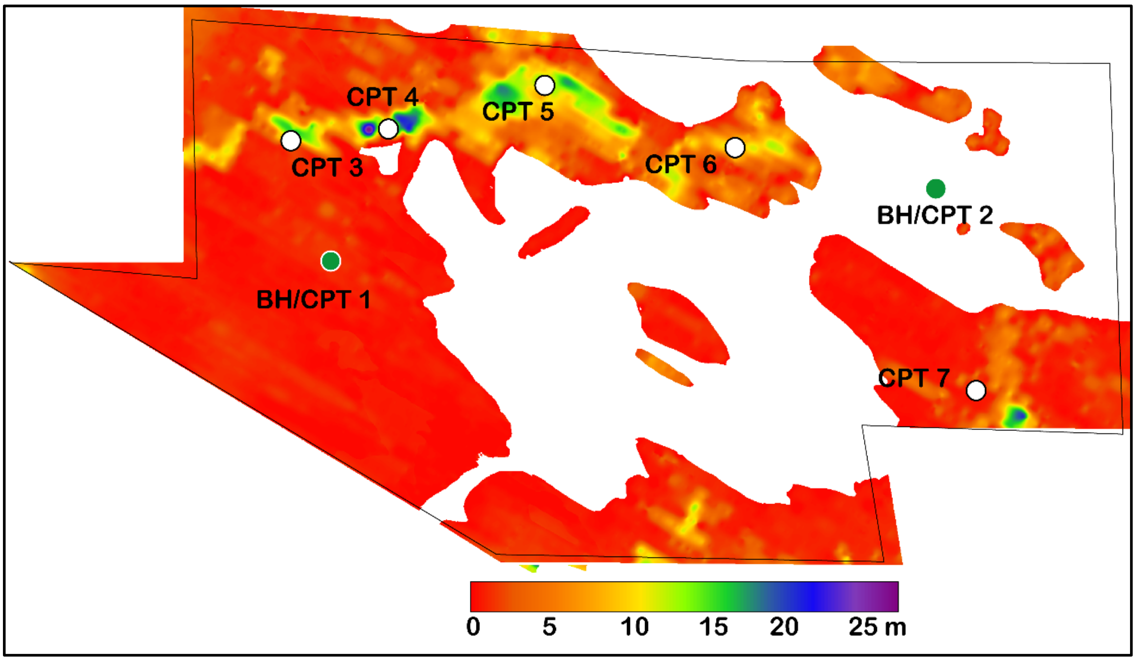


Figure 12.10 Combined thickness of glacial meltwater sand and till. Locations of Boreholes and CPT's are indicated.

12.3.2.3 Arnager Block weathered mudstone (possibly Till)

Arnager Block Weathered Mudstones is observed in positions RNB-CPT006 and RNB-CPT007 with a maximum thickness of 10m (RNB-CPT006). Based on interpretation of cone penetration tests it is anticipated that the mudstone generally comprises high to extremely high strength clays 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 may be clay till (Figure 12.7 and Figure 12.11).

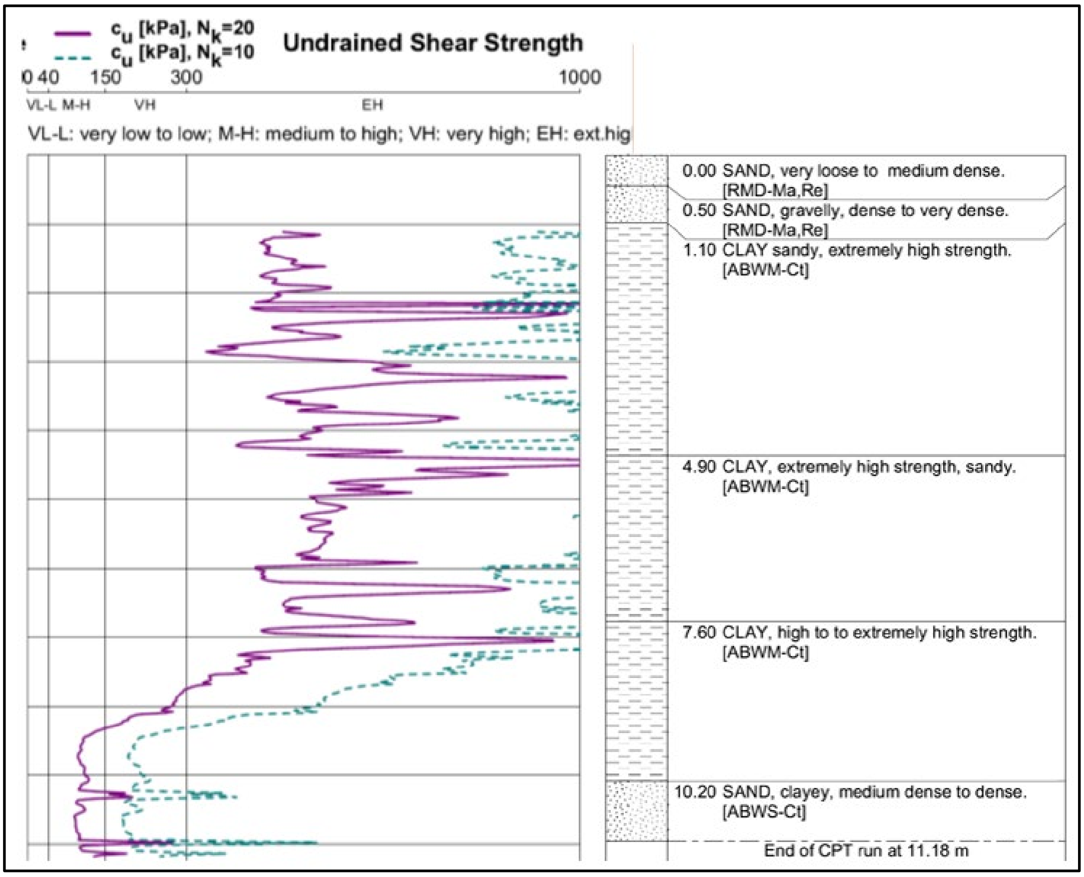


Figure 12.11 Undrained shear strength of RNB-CPT006 showing extremely high strength clay (till) to 10 m and medium high to high in the Bavneodde Greensand below (ref. Energinet 2014 (d)).

12.3.2.4 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. The sandstone was encountered in positions RNB-BH/CPT002, RNB-CPT6a and RNB-CPT7a, b.. Recorded to the bottom of RNB-BH002a 50m below seabed. Interpreted to be Upper Cretaceous Bavneodde Greensand Formation.

Medium high to high undrained shear strength is observed (Figure 12.11).

12.3.2.5 Rønne Graben Weathered Siltstone (Bavneodde Greensand Formation)

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

12.3.2.6 Rønne Graben Limestone (Arnager Limestone Formation).

The limestone was encountered in RNB-BH001 35m below seabed, with a thickness of about 2m and described as a weak brecciated limestone, considered to be the Arnager Limestone Formation (Figure 12.8).

12.3.2.7 Rønne Graben Weathered Mudstone (Arnager Greensand Formation)

The mudstone is observed at locations RNB-CPT003a and RNB-CPT004a with a maximum penetrated depth of 24m below seabed (RNB-CPT003a). The cone test data indicate medium to very high strength sandy and silty clays. Stratigraphically the unit is referred to as Lower Cretaceous Arnager Greensand Formation (Figure 12.8).

12.3.2.8 Rønne Graben Weathered Sandstone (Arnager Greensand Formation)

The 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 with interbedded cemented and unconsolidated glauconitic sands (Figure 12.8).

12.4 Correlation of Rønne Banke Site 6 results to windfarm 1 and 2

Rønne Banke Site 6 is located close to Windfarm 1 and 2 with the obvious possibility of obtaining useful information from the Site 6 previous work.

- Site 6 is located at water depths between 9 and 24m, in general shallower than Windfarm 1 and 2 (Figure 12.1). Only the north-western most part of Windfarm 2 reaches 22m water depths in a few hundred meters narrow rim.
- Due to the shallow water depths, unit II Early postglacial transition Yoldia clay and Ancylus clay, as well as unit III Late glacial glaciolacustrine Baltic Icelake deposits, from Windfarm 1 and 2 are not represented in the Rønne Banke Site 6 area.
- Until 4m thick Holocene marine sands from site 6 may be correlated to similar deposits in Windfarm 1 and 2.
- Seismic data from Site 6 reveal until 10m of till with geotechnical parameters described in RNB-CPT006, probably well suited for comparison with Windfarm 1 and 2 till deposits.
- Pre-quaternary deposits represented by coring and CPT’s includes Upper Cretaceous Bavneodde Greensand and Arnager Limestone as well as Lower Cretaceous Arnager

Greensand. Detailed information of geotechnical parameters may be found in reference Energinet 2014 (c) and (d), possibly well representing similar deposits in Windfarm 1 and 2.

13. Archaeological interests

In addition to geotechnical interests in a detailed geological model for the Bornholm OWF areas, 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.

As described in Chapters 9 and 10, highstand water-level characterised the initial period after the deglaciation of the Bornholm area. The Bornholm area was deglaciated shortly after 15000 years BP and the planned Bornholm OWF areas were covered by the glaciolacustrine Baltic Ice Lake (Figure 12.1). This corresponds to the archaeological Hamburg culture or Hamburgian (15500–13100 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. This means that the shallowest parts of the wind farm areas would have been dry land. However, the lowstand period was short-lived and followed by a rapid transgression. A new lowstand period is dated to ca. 11700 years BP, this time the water level was ca. 45 m below sea level and Bornholm was a peninsula connected to mainland Europe ((Figure 12.1). Larger parts of the wind farm areas would have been exposed. However, this second lowstand period was also short-lived and soon followed by a new rapid transgression. The new lowstand period corresponds to the early part of the Maglemose Culture (Figure 12.1).

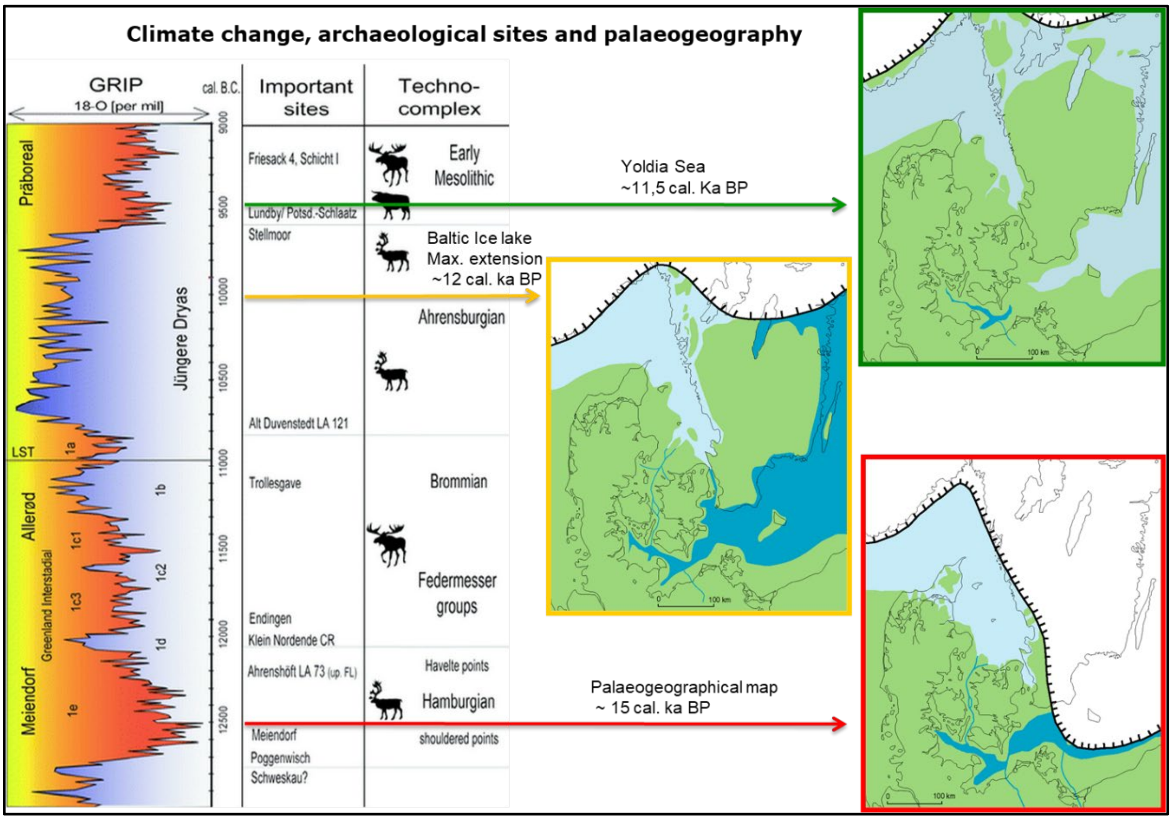


Figure 13.1. Late glacial and Holocene general palaeogeography in the Danish area and related archaeological cultures. The maps are from Jensen et al. (2003).

In contrast to the wind farm areas, the shallow-water parts of the cable corridors and the Rønne Banke Site 6 survey area would have been dry land for long periods. Submerged archaeological settlements from the Maglemose, Kongemose and Ertebølle Cultures are for example known from Mecklenburg Bay off northern Germany (Schmölcke *et al.* 2006; Hartz *et al.* 2011; Lübke *et al.* 2011). The chances to find submerged archaeological settlements are probably small in the Bornholm area due to the fetch and high energy environment. The chances are much higher along the east coast of Zealand, which is protected from the dominating westerly winds - and submerged finds have for example been made in Køge Bugt and near Amager.

14. Conclusions

In this study we have 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.

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

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

A number of focal points are relevant for the future geotechnical and archaeological evaluation of the area:

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

- Rønne Banke Site 6 coring and CPT data gives information about Upper and Lower Cretaceous sediment geotechnical parameters.

- Studies of the Bornholm Basin indicate that late glacial clay shows that neotectonic activities has created elongated restricted basins with syn-sedimentary infill that has continued into the Holocene. Recent earthquakes are rare in the area and points to limited recent seismological activity.

- Traces of acoustic disturbance on seismic profiles has been observed in the Quaternary sediments above fault zones and may be related to thermogenic degassing from deeper structures. Acoustic gas indications in Holocene sediments may be related to Neogene degassing.

- Glacial till ridges has been recorded at Adler Ground south east of the Bornholm OWF 1 area and similar features may be found in other areas.

- Till deposits has been mapped in Rønne Banke Site 6 and CPT data gives information on possible geotechnical parameters in Windfarm 1 and 2.

- Weakly consolidated late glacial clay (Baltic Ice lake I and II) with a thickness of up to 20 m covers most of the Bornholm OWFs area and must be taken into consideration.

- In OWF 2 early Holocene freshwater unconsolidated lake clay is deposited, it attains a thickness of up to 10 m.

- In connection with the Holocene transgression of the area, the deeper parts of the OWF's have been draped by a relatively thin layer of mud and sandy mud, with high contents of organic material and geotechnical challenges must be expected.

- The late glacial and early Holocene coastal zone development of the Bornholm OWFs area and eastern cable corridor opens for an archaeological interest window in the time period for the Ahrensburg and Maglemosian cultures, whereas the area was transgressed by the sea under the time windows of younger cultures.

15. Literature

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