DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2024/31**

Screening of seabed geological conditions for the Bornholm Syd offshore wind farm area

Desk study for the Danish Energy Agency

Technical report

Thomas Vangkilde-Pedersen & Niels Nørgaard-Pedersen

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Indhold

1. Dansk resume

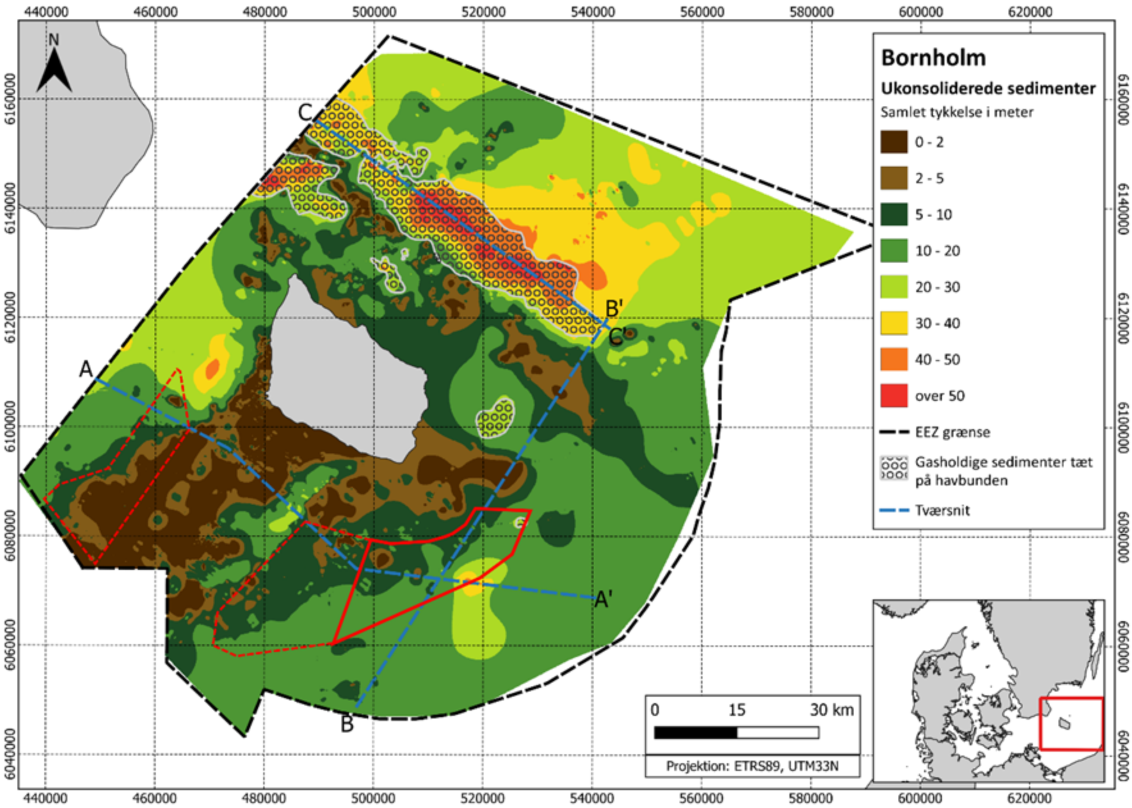
Energistyrelsen har bedt GEUS udføre et geologisk desk study af Bornholm Syd området baseret på eksisterende tilgængelige data med henblik på at vurdere områdets egnethed i forhold til etablering af havvind.

Opgaven har inkluderet kortlægning af den overfladenære geologi i forhold til fundering af havvindmøller med baggrund i en generel konceptuel geologisk model for Bornholmsbassinet samt relevante data. Resultatet af kortlægningen kan fremover benyttes som geologisk ramme for yderligere geologiske og geotekniske undersøgelser og tolkninger i området.

Arbejdet er baseret på en kombination af publicerede artikler, eksisterende seismiske data og sedimentkerner samt nærliggende geotekniske boringer og CPT forsøg og beskriver den generelle geologiske udvikling i området syd for Bornholm og specifikt i Bornholm Syd området.

Der findes kun få seismiske linjer og sedimentkerner i Bornholm Syd området, men ved at kombinere disse med den generelle konceptuelle geologiske model for Bornholmsbassinet (Jensen et al. 2021) og en geologisk/geoteknisk model for det nærliggende Bornholm II havvindområde baseret på detaljerede geofysiske og geotekniske undersøgelser (Rambøll 2024), er de geologiske og geotekniske forhold med betydning for etablering af havvind i området blevet beskrevet inklusiv en vurdering af potentielle marinarkæologiske interesser.

I Figur 1.1 er vist et generelt tykkelseskort for ukonsoliderede bløde Holocæne og senglaciale sedimenter i området omkring Bornholm, udarbejdet af GEUS i forbindelse med en igangværende geologisk screening for havvind for Energistyrelsen. Kortet viser, at Bornholm Syd området er meget sammenligneligt med Bornholm II havvindområdet med hensyn til tykkelsen af de bløde sedimenter. Dog skal man være opmærksom på, at det meget sparsomme datagrundlag i Bornholm Syd området betyder, at usikkerheden her er meget større end i Bornholm II området, hvor der er gennemført detaljerede undersøgelser.



Figur 1.1. Kortet viser den kombinerede tykkelse af unkonsoliderede bløde Holocæne og senglaciale sedimenter. Bornholm I og II havvindområderne er vist med stiplede røde polygoner og Bornholm Syd området med rød polygon. Opmærksomheden henledes på, at kortet i Bornholm Syd området er baseret på et meget sparsomt datagrundlag.

Følgende geologiske og geotekniske forhold med betydning for etablering af havvind i Bornholm Syd området er blevet identificeret:

- Vanddybden i området ligger omkring 40-70 m og stiger generelt fra vest mod øst med 40-60 m i den vestligste del og 60-70 m i den resterende del. Havbunden er generelt relativt jævn og med en svag hældning mod øst, men de få tilstedeværende seismiske linjer viser et højtliggende moræneområde i den nordvestlige del af området og en kanal eller lokal lavning i havbunden i den nordøstlige del af området. Her må de geologiske forhold forventes at adskille sig fra de generelle omgivelser.
- Fordelingen af sedimenter på havbunden afspejler til en vis grad vanddybderne i området med Holocænt mudder og mudret sand på større vanddybder og Kvartært ler og silt (senglaciale Baltiske Issø aflejringer) på lavere vanddybder mod vest og nord, hvor der enten ikke aflejres sedimenter eller foregår erosion af havbunden. Det betyder at der overordnet kan forventes meget bløde sedimenter i havbunden på større vanddybder og en lidt hårdere havbund på lavere vanddybder.
- Den kombinerede tykkelse af relativt bløde Holocæne og senglaciale sedimenter er generelt omkring 10-15 m, men større tykkelser på op til 20 m eller mere ses i udfyldte lavninger i den østlige-nordøstlige del af Bornholm Syd området. De Holocæne aflejringer forventes at bestå primært af blødt ler, men kan også inkludere løst sand. De øvre dele af de senglaciale Baltiske Issø aflejringer forventes også at bestå af blødt ler, mens de nedre dele forventes at bestå af mere hårdt ler eller ler som geoteknisk kan opføre sig mere som friktionsjord. Generelt forventes de Holocæne og senglaciale sedimenter at have relativt ringe geoteknisk styrke.

- Kvartære glaciale aflejringer ses dels som et ujævnt, mindre end 5 m tykt dække over de præ-Kvartære aflejringer og dels i store tykkelser på op til 50 m som fyld i glaciale tunneldale som kan være flere kilometer brede. De forventes at bestå af relativt hårdt moræneler og smeltevandssand. Aflejringerne er sandsynligvis overkonsoliderede (tidligere isbelastet) og kan potentielt indeholde store sten og blokke og være glacialtektonisk deformerede. Store sten og blokke kan potentielt være problematiske I forbindelse med nedramning af pælefundamenter i havbunden og glacialtektoniske deformationer kan øge heterogeniteten af de geologiske lag.
- En moræneryg med større tykkelser af glaciale aflejringer løfter sig omkring 15 m over den omkringliggende havbund i den nordvestlige del af Bornholm Syd området. Moræneryggen ser ud til at være en fortsættelse af en større ryg som kan ses i detaljerede batymetriske data fra Geodatastyrelsen og hvor GEUS' kort over havbundssedimenter også viser moræne på havbunden.
- Præ-Kvartære sedimenter optræder i dybder under havbunden varierende fra 10-50 m og kan forventes at bestå af Skrivekridt fra Øvre Kridt (som formentlig kan være relativt blødt) og løst cementeret sandsten og lersten fra Jura-Nedre Kridt. Lagdelingen i de præ-Kvartære aflejringer viser typisk hældninger på op til 5 grader og er præget af forkastninger og folder. Baseret på undersøgelserne i det nærliggende Bornholm II havvindområde kan de præ-Kvartære aflejringer fra Jura og Kridt i Bornholm Syd området formentlig forventes at variere mellem blød og svag til hård og stærk kalk/lersten, mellem blød til hård Skrivekridt og mellem blød og svag til hård og stærk sandsten og dermed udvise meget store variationer i geoteknisk styrke.

Baseret på de geotekniske vurderinger af Rambøll (2024) af enhederne i deres geologiske/geotekniske model for det nærliggende Bornholm II havvindområde og korrelationen mellem områderne i dette studie er følgende mulige geotekniske udfordringer i Bornholm Syd området blevet identificeret:

- De bløde Holocæne og senglaciale sedimenter i den øverste del af den geologiske lagserie i Bornholm Syd området har ikke nødvendigvis tilstrækkelig geoteknisk styrke i forhold til design af vindmøllefundamenter og kan medføre at f.eks. længere og dyrere pæle er nødvendige. Ringe bæreevne af sedimenterne kan desuden være et problem i forhold til for stor nedtrængning af benene på et evt. jack-up fartøj i installationsfasen og medføre behov for en anden type installationsfartøj.
- Sandaflejringer over blødt ler kan, hvis tilstede i området, potentielt være et problem i forhold til såkaldt punch-through af jack-up ben, hvor ringe bæreevne i den bløde ler kan forårsage hurtig og ukontrolleret nedtrængning af benene i overgangen fra sand til ler. Sådanne områder er ikke identificeret i de sparsomme data i Bornholm Syd området, men kan muligvis forekomme, f.eks. i de udfyldte kanalstrukturer.
- Overfladen af de hårdere glaciale sedimenter som ligger under de bløde Holocæne og senglaciale aflejringer kan lokalt udvise store topografiske variationer i Bornholm Syd området, hvor hældninger på op til 3-4 grader er observeret. Det kan potentielt medføre en risiko for udvikling af skævheder i vindmøllefundamenter især ved brug af fundamenttyper med flere ben/pæle.
- De glaciale aflejringer i Bornholm Syd området kan potentielt indeholde store sten og blokke som kan medføre en risiko for beskadigelse af stålet i pælefundamenter eller monopæle under nedramning.

- Den relativt lave, men meget varierende dybde til overfladen af de præ-Kvartære aflejringer i Bornholm Syd området betyder, at det er nødvendigt med særlig opmærksomhed på deres geotekniske egenskaber som potentielt kan udvise store variationer. De præ-Kvartære aflejringer inkluderer således bjergarter som formentlig varierer fra bløde og svage til hårde og stærke og sammen med variationerne i dybden til den præ-Kvartære overflade er det nødvendigt at tage i betragtning i forbindelse med valg af design, fundamenttype og installationsmetode.

Baseret på senglaciale og Holocæne relative kystforskydningskurver for den sydvestlige del af Østersøen er der foretaget en overordnet vurdering af potentielle marinarkæologiske interesser:

- I to meget korte tidsintervaller omkring ca. 12.800 og 11.700 år før nu, svarende til Bromme og Maglemose kulturerne, har de mest lavvandede dele af Bornholm Syd området mod vest og nord potentielt været tørt land eller ligget tæt på kysten. Potentielle kabelkorridor områder på den lavvandede del af Rønne Banke og nær Bornholm har formentlig været tørt land i længere perioder, men chancerne for at finde oversvømmede arkæologiske bosættelser er formentlig små i havområdet omkring Bornholm, som i dag er præget et højt energiniveau i vandsøjlen og hvor bølgerne kan opnå et langt stræk.

Ovenstående konklusioner i forhold til Bornholm Syd områdets egnethed til etablering af havvind kan ud fra et geologisk synspunkt sammenfattes i følgende udsagn:

De geologiske forhold i Bornholm Syd området, og dermed områdets egnethed i forhold til havvind forventes at være meget sammenlignelige med det nærliggende Bornholm II havvindområde, hvor der for nylig er udført detaljerede undersøgelser. Især vurderes det, at tykkelsen af de relativt bløde Holocæne og senglaciale sedimenter er sammenlignelig.

Baseret på de sparsomme data til rådighed og korrelation med Bornholm II havvindområdet, vurderes det at være muligt at etablere havvind i Bornholm Syd området fra et geologisk synspunkt. Der er dog, som i Bornholm II havvindområdet, observeret jordbundsforhold som kan udgøre udfordringer i forhold til installation af havvindmøller og øge udgifterne og som derfor må tages i betragtning. Disse udfordringer omfatter tykkelsen af bløde sedimenter, ujævn overflade af de hårdere glaciale aflejringer, risiko for sten og blokke i de glaciale aflejringer og potentielt meget store variationer i geoteknisk styrke af de præ-Kvartære aflejringer som optræder i relativt lave og varierende dybder under havbunden.

2. Summary

The Danish Energy Agency has asked GEUS to perform a geological desk study of the Bornholm Syd area based on existing data and with the aim to assess the suitability of the area for establishing offshore wind.

The desk study includes mapping the near-surface geology important for turbine foundations based on the general conceptual geological model for the Bornholm Basin as well as relevant existing data and may serve as the geological framework for future geological and geotechnical investigations and interpretations.

Based on a combination of published work, existing seismic data and sediment cores as well as nearby geotechnical boreholes and CPT data, the general geological development in the Bornholm Region and specifically the Bornholm Syd area have been described.

Only a few existing seismic lines and shallow vibrocores have been available for the geological mapping of the Bornholm Syd area but based on a general conceptual geological model for the Bornholm Basin (Jensen et al. 2021) and detailed geophysical and geotechnical investigations as well as an integrated ground model for the nearby Bornholm II OWF area (Rambøll 2024), the key geological and geotechnical conditions in the study area have been described, including an assessment of potential archaeological interests.

In Figure 2.1 a general thickness map of the unconsolidated soft sediments in the area around Bornholm, produced by GEUS in a current overall geological screening of Danish waters for offshore wind for the Danish Energy Agency, is shown. It appears from the map, that in terms of thickness of soft sediments, the Bornholm Syd area is very similar to the Bornholm II OWF area, but it should be kept in mind, that the amount of available data in the Bornholm Syd area has been very sparse, introducing a significant uncertainty compared to the detailed investigations in the Bornholm II OWF area.

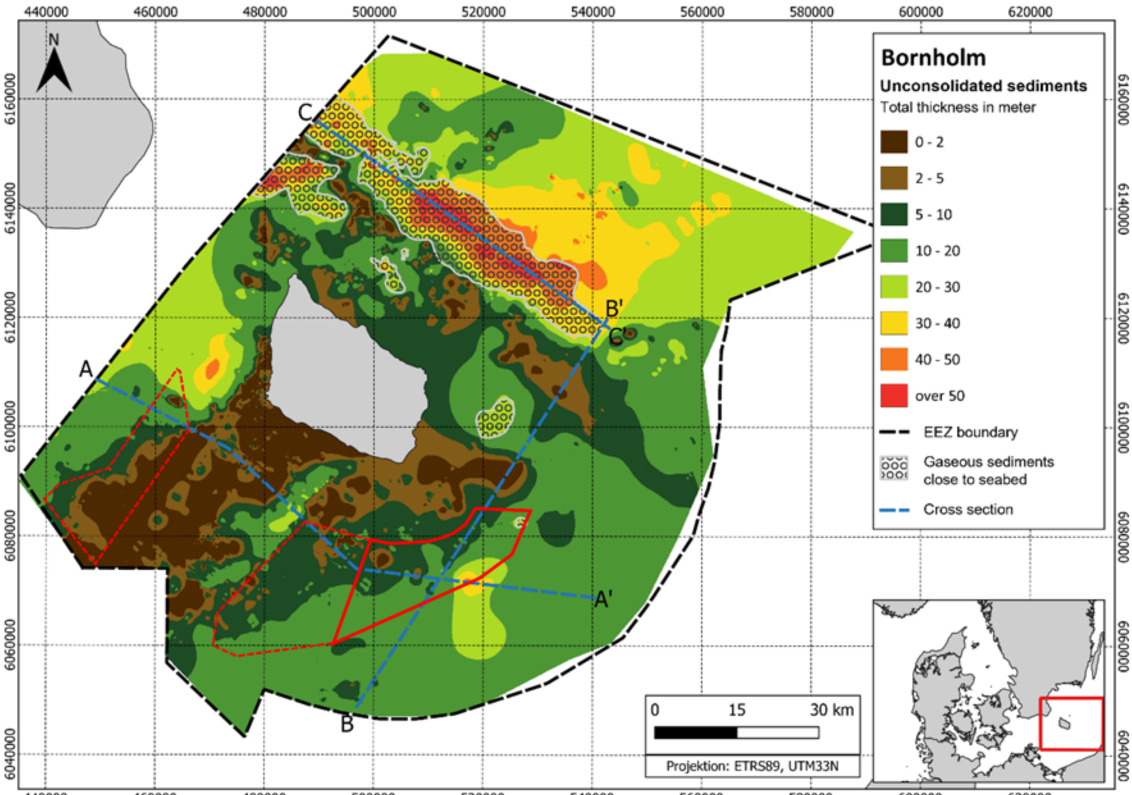


Figure 2.1. Map showing the combined thickness of unconsolidated soft sediments of Holocene and late glacial age. The Bornholm I and II OWF areas are shown with dashed red polygons and the Bornholm Syd area with a red polygon. Be aware that the map is based on very sparse data in the Bornholm Syd area.

The following key geological and geotechnical conditions with respect to offshore wind have been identified:

- The Bornholm Syd area is characterised by water depths of c. 40-70 m, with depths generally increasing from west to east with 40-60 m in the westernmost part and 60-70 m in the remaining area. The seabed is generally quite flat and with a gentle slope towards the east, but the few seismic lines reveal a higher lying moraine ground in the northwestern corner of the area and a channel or local depression in the seabed in the northeastern part of the area. Here it should be considered that the geological conditions can be expected to differ from the general surroundings.
- The distribution of seabed sediments reflects to some degree the bathymetry of the area with Holocene mud and muddy sand in the deeper parts and Quaternary clay and silt (late glacial Baltic Ice Lake deposits) in the shallower parts to the west and north, indicating non-deposition or erosion. This means a very soft seabed in the deeper parts and a harder seabed in the shallower parts.
- The combined thickness of the Holocene and late glacial relatively soft sediments is generally about 10-15 m but larger thicknesses of 20 m, or more, can be observed in filled-in depressions in the eastern-northeastern part of the Bornholm Syd area. The Holocene deposits are expected to be composed of mainly soft clay, but may also include loose sand, and the upper parts of the late glacial Baltic Ice Lake deposits are also expected to be composed of soft clay. The lower parts of the Baltic Ice Lake deposits are expected to be composed of transitional (geotechnically) clay and stiff clay. Generally, the Holocene and late glacial sediments can probably be expected to have relatively low geotechnical strength.

- Quaternary glacial deposits are partly found as an irregular, less than 5 m thick, cover on top of pre-Quaternary deposits, but also as in-filled glacial valley structures, up to 50 m in thickness and a few km wide. They are expected to be composed of stiff clay till and dense glaciofluvial sand, which are probably overconsolidated and may contain stones and boulders and with glaciotectonic structures. Stones and boulders can be a potential problem with regards to driving piles into the subsurface and glaciotectonic deformation can increase the heterogeneity of the geological layers.
- A moraine ridge of thicker glacial deposits, rising about 15 m above the surrounding seabed, can be observed in the northwestern part of the Bornholm Syd area. The ridge appears to be a continuation of a ridge structure seen in the detailed bathymetry map from Geodatastyrelsen and moraine is also indicated on the seabed sediment map of GEUS.
- Pre-Quaternary sediments are found about 10-50 m below the seabed and can be expected to consist of Upper Cretaceous chalk (can possibly be relatively soft) and Jurassic-Lower Cretaceous loosely cemented sandstone and mudstone. The stratification in the pre-Quaternary sediments is typically inclined with slopes up to 5 degrees, and faulted with folding structures observed along fault zones. Based on investigations in the Bornholm II OWF area, the Jurassic and Cretaceous deposits in the Bornholm Syd area can possibly be regarded as ranging from soft and weak limestone/mudstone to hard and strong limestone/mudstone, from soft chalk to hard chalk and from soft and weak sandstone to hard and strong sandstone and thus expectedly with large variations in geotechnical strength.

Based on the geotechnical assessments by Rambøll (2024) of the soil units in the Bornholm II OWF area and the correlation with the geological units mapped in this desk study, the following possible geotechnical implications for the Bornholm Syd area have been identified:

- The soft Holocene and late glacial sediments at the shallow subsurface in the Bornholm Syd area may not provide sufficient strength for foundation design, necessitating the use of longer and more expensive piles and low bearing capacity of the soil may also be problematic with respect to penetration of jack-up legs of an installation vessel and imply a need for another type of installation vessel.
- If present, areas with sand above soft clays may potentially also be problematic with respect to penetration of jack-up legs of an installation vessel during construction as low bearing capacity in soft clay below sand may cause rapid leg penetration due to so-called punch through. Such areas have not been identified in the sparse seismic and borehole data in the Bornholm Syd area but could be present e.g. in the channel structures.
- The surface of the stiff glacial sediments underlying the soft Holocene and late glacial deposits can locally have significant topography in the Bornholm Syd area, where slopes of up to 3-4 degrees have been observed. This could potentially induce local risk for foundation tilt development, especially in the case of multiple-legged foundations.
- The glacial deposits in the Bornholm Syd area may potentially contain blocks and boulders that can be a risk for foundations of driven piles or monopiles, as the steel can get damaged in the case of large size boulders.
- The relatively shallow, but varying, bedrock depths in the Bornholm Syd area means that specific attention must be paid to the geotechnical properties of the rocks which potentially may be very variable. Thus, the shallow bedrock includes

rock types probably ranging from soft and weak to hard and strong and these variations together with bedrock depth must be considered with respect to design, foundation type and installation method.

Based on a late glacial and Holocene relative shore level curve for the southwestern Baltic Sea an assessment of potential archaeological interests has been made:

- In two very short time intervals at c. 12.800 and 11.700 years ago, corresponding to the Bromme and Maglemose cultures, the shallowest parts of the Bornholm Syd area to the west and north may potentially have been dry land or near the coast. Potential cable corridor areas on the shallow-water parts of Rønne Banke and near Bornholm have probably been dry land for long periods but the chances of finding submerged archaeological settlements are probably small in the Bornholm area in general due to the long fetch and high energy environment of the present-day sea.

The above conclusions for the Bornholm Syd area with respect to the suitability of the area for offshore wind from a geological viewpoint, can be summed up in the following statements:

The geological conditions in the Bornholm Syd area, and thus the suitability for offshore wind of the area, are expected to be very similar to the Bornholm II OWF area where detailed investigations have recently been carried out. Especially it seems likely that the thickness of relatively soft Holocene and late glacial sediments is comparable.

Based on the sparse amounts of data and correlation with the Bornholm II OWF area, it is most likely possible to establish offshore wind in the Bornholm Syd area from a geological point of view. However, like in the Bornholm II OWF area, challenging ground conditions including the thickness of soft soils, irregular topography above stiff sediments, boulders in clay till and highly variable strength of bedrock found at a relatively shallow depth. These are conditions which potentially can increase the costs and must be taken into consideration.

3. Introduction

The Danish Energy Agency has asked GEUS to perform a geological desk study of the Bornholm Syd area based on existing data and with the aim to assess the suitability of the area for establishing offshore wind.

The desk study includes mapping the near-surface geology important for turbine foundations based on the general conceptual geological model for the Bornholm Basin as well as relevant existing data and may serve as the geological framework for future geological and geotechnical investigations and interpretations. The work largely builds on a desk study performed by GEUS for Energinet in 2021 of the Bornholm I and II OWF areas (Jensen et al. 2021) as well as a current overall geological screening of Danish waters for offshore wind carried out by GEUS for the Danish Energy Agency and geophysical and geotechnical investigations carried out by Energinet for the Bornholm II OWF area (Rambøll 2024). The Bornholm II OWF area is located immediately west of the Bornholm Syd area, and the Bornholm I OWF area further to the northwest, see Figure 3.1.

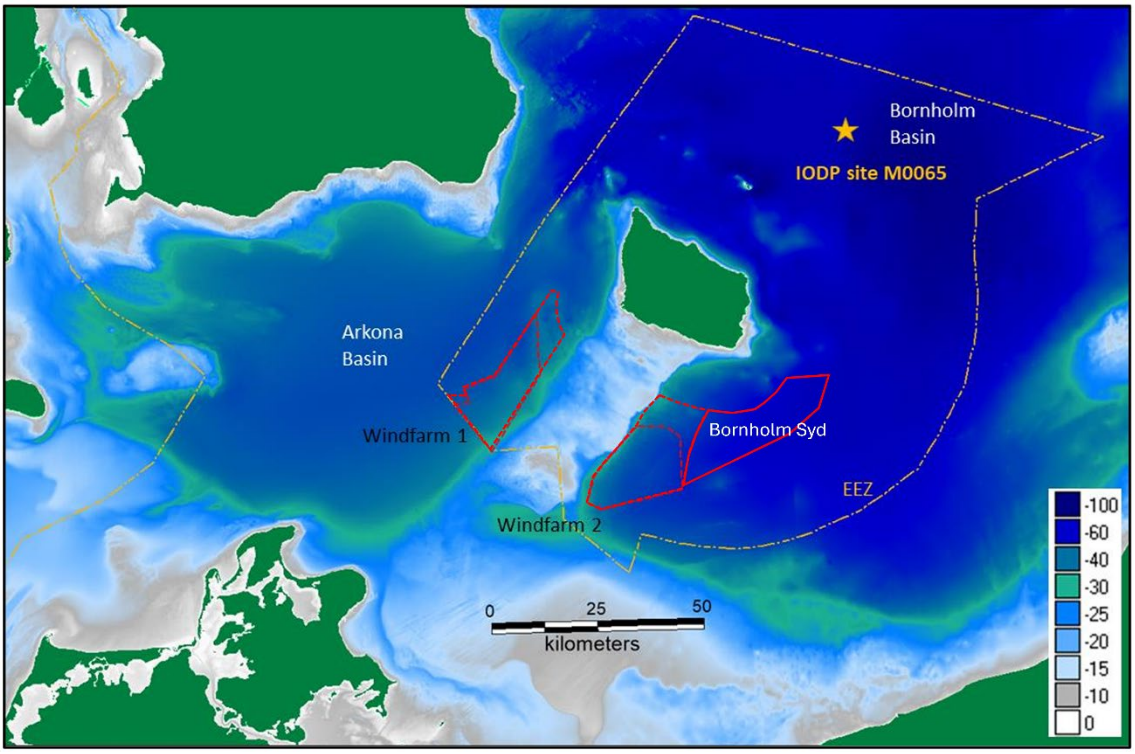


Figure 3.1. Overview map of the southwestern Baltic Sea with location of the Bornholm Syd area (red polygon) as well as the Bornholm I and II OWF areas (red dashed line polygons), IODP site M0065 (yellow star) and the Danish Exclusive Economic Zone (yellow line). Bornholm Basin and Arkona Basin are indicated, and the bathymetry is from EMODnet (2022).

4. Available data

A combination of published work, GEUS archive seismic data and sediment core data have been used as a basis for this geological desk study. The published work includes scientific papers and technical reports. Deep seismic information has been compiled from scientific papers, but the seismic data are available from GEUS' Deep Subsurface Data Portal, while primary shallow seismic data and vibrocores from GEUS' Marta database has been used directly in the geological interpretation and mapping. Especially new ultra-high resolution multichannel seismic sparker data and vibrocores, acquired for the Danish Energy Agency as part of an overall geological screening for offshore wind of Danish waters, has been contributing with new knowledge of the area (Figure 4.1). In addition, available data from IOPD core M0065 have been included (Andrén et al. 2015b). Last, but not least, ultra-high resolution multichannel seismic data and geotechnical information from recent geophysical and geotechnical investigations by Energinet of the Bornholm II OWF immediately west of the Bornholm Syd area (Rambøll 2024) has been used in the study.

4.1 GEUS shallow seismic and sediment core archive, Marta

The national Danish marine raw material database (Marta) is developed by GEUS in cooperation with the Danish Environmental Protection Agency and holds data from raw material investigations in Danish waters, subject to reporting obligations. The database includes seismic data, boreholes, grab samples and other sediment samples as well as relevant reports from primarily raw material studies since 1980, but also from other studies.

The seismic data include both older, originally analogue data (scanned and georeferenced) and newer data, originally in digital format. Some of the seismic data are still confidential, but an increasing part of the seismic lines (including scanned analogue data) can be downloaded directly from the web portal of the Marta database in SEG-Y file format.

The MARTA database further contains information on mapped raw material resource areas. This information is based on the results of processing and interpretation by GEUS of all reported raw material surveys and include the locations of the resource areas as well as the quality of the raw material deposits: resource type, geological formation type and resource certainty parameters (proven, probable, or speculative).

4.2 IODP Site M0065 data

Important information about the stratigraphy of the sediments in the Bornholm Basin can be obtained from the scientific IODP core M0065. Data, descriptions and results from the core are presented by Andrén et al. (2015b) and the paper can be downloaded from the IODP homepage (Site M0065 (iodp.org)). Descriptions of the drilling results include: Lithostratigraphy, biostratigraphy, geochemistry, physical properties, microbiology, stratigraphic correlations and downhole geophysical measurements.

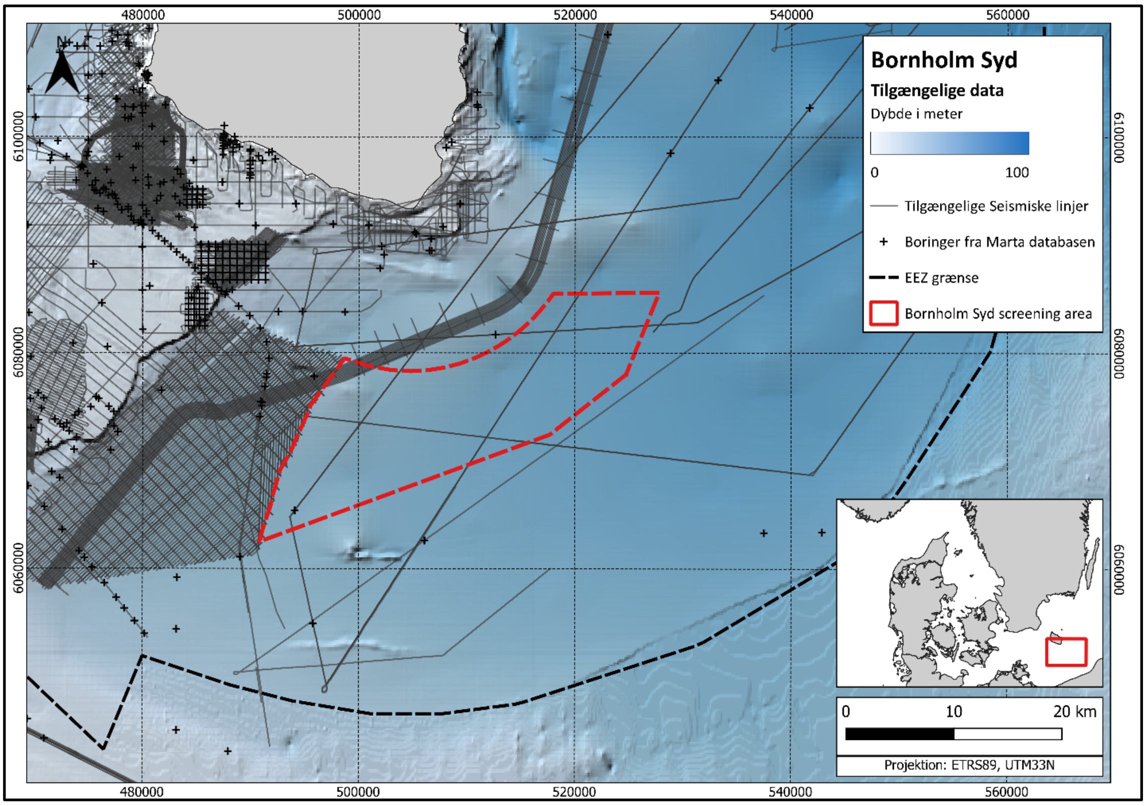


Figure 4.1. Overview map of available data (shallow seismic data and vibrocores) in the Bornhom Syd area (red polygon) from [GEUS' Marta database](#) and other sources. The bathymetry is from EMODnet (2022).

5. Pre-Quaternary geology

The southwestern 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 5.1). The Sorgenfrei–Tornquist Zone has been active during several phases after the Precambrian. The lineament is characterised by complex extensional and strike-slip faulting and structural inversion (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.

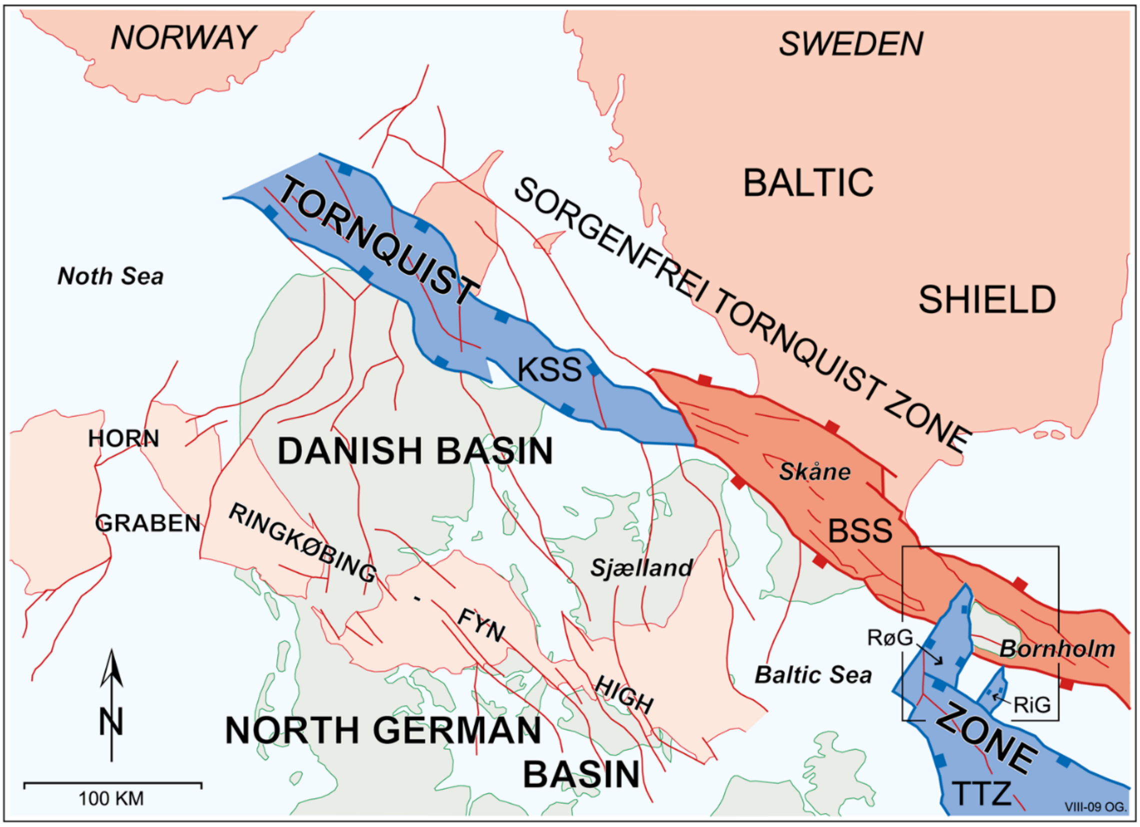


Figure 5.1. Position of the Bornholm area in the Tornquist Zone between the Baltic Shield/East European Platform and the Danish Basin/Northwest European craton (Graversen 2004, 2009).

In particular, the Rønne Graben (Figure 5.2) has been studied in 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 Rønne Graben 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 the inversion structures of the Rønne Graben basin in detail (Jensen & Hamann 1989).

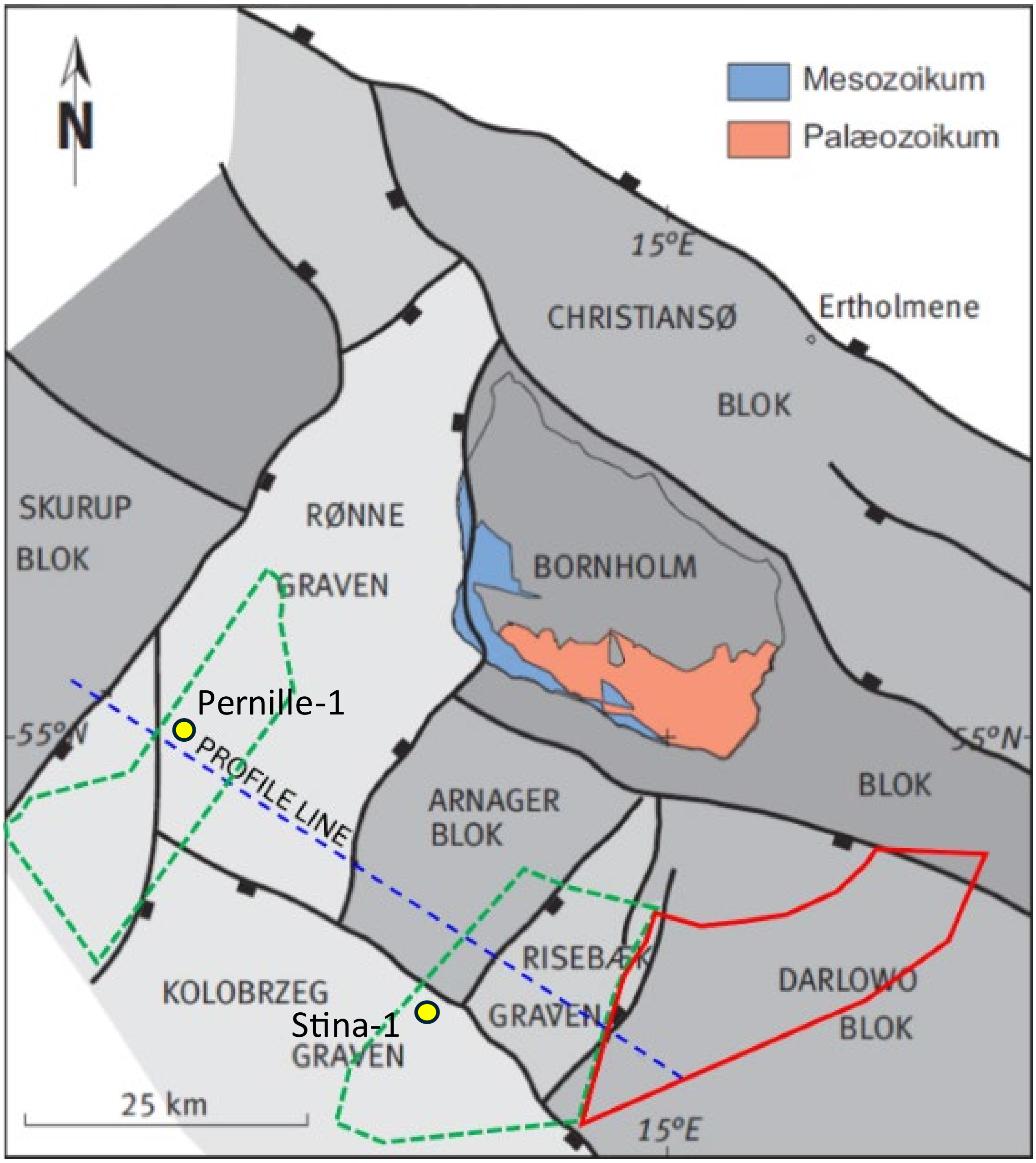


Figure 5.2. Major fault blocks of the Bornholm region. The fault pattern is based on Vejbæk & Britze (1994) and Vejbæk (1997). The Bornholm Syd area is shown with a red polygon, Bornholm I and II OWF areas with dashed green polygons, the profile line of Figure 5.3 with a dashed blue line and deep boreholes are shown with yellow dots.

The tectonic history of the Tornquist Zone dates 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 deep-seated basement fault zones caused dextral movements along the major boundary faults of the Tornquist Zone (Mogensen & Korstgård 2003).

In the Bornholm region, the Rønne Graben 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 Rønne Graben pull-apart basin (Figure 5.2 and Figure 5.3) between opposing normal faults.

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

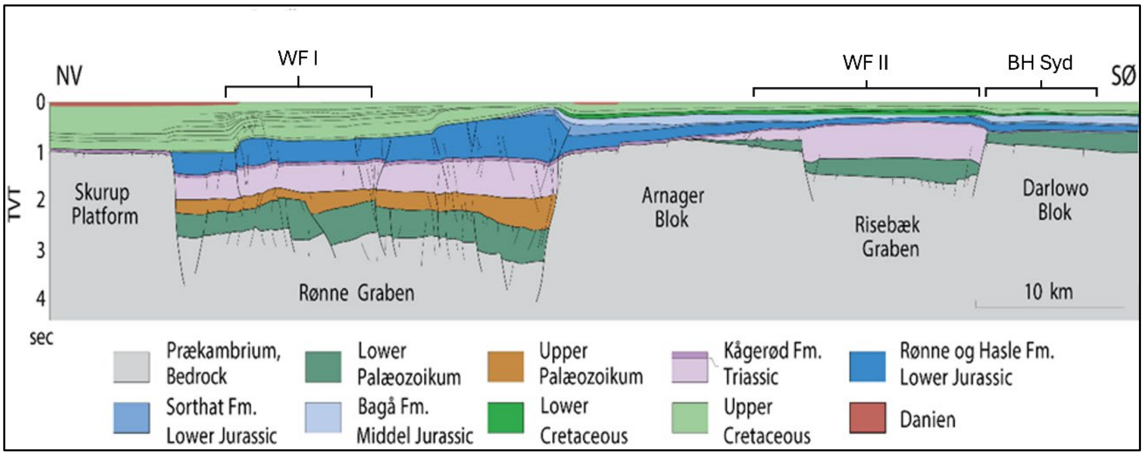


Figure 5.3. Cross section of the Sorgenfrei–Tornquist zone across the Rønne Graben and into the south-western part of the Bornholm Syd area (Mogensen & Korstgård 2003). The location of the Bornholm I and II OWF areas and the Bornholm Syd areas is indicated above the profile. The location of the section is shown on Figure 5.2.

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 strike-slip 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 5.2 and Figure 5.3), 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 several 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.

5.1 Deep wells

There are two deep wells from 1989 in the Bornholm Area: Pernille-1 and Stina-1. The stratigraphy of the wells is described by Graversen (2004).

Stina-1 is located west of the Bornholm Syd area (Figure 5.2). The well is drilled on an inversion anticline, where a c. 500 m thick Jurassic succession of sandstones, siltstones, mudstones, and coals underlies approx. 60 m of Quaternary sediments. Thick units of Triassic sediments are located below the Jurassic sediments.

Pernille-1 is located further to the northwest in the Rønne Graben (Figure 5.2) and mainly penetrates Mesozoic deposits. Below approx. 16 m of Quaternary sandy to silty clay, lies c. 800 m of limestone from the Upper Cretaceous Chalk Group above sandstone, siltstone, mudstone and coal of the Lower Jurassic Hasle and Rønne Formations.

In the Bornholm II OWF area west of the Bornholm Syd area, Energinet has carried out 20 geotechnical boreholes to a depth of 60-70 m in 2022. Pre-Quaternary bedrock of Cretaceous and Jurassic age has been encountered in twelve of these and mostly consists of limestone and mudstone, but also sandstone and chalk.

5.2 Pre-Quaternary surface

Figure 5.4 shows the topography (level in metres) of the pre-Quaternary surface in the area southwest of Bornholm. According to the map, the elevation of the surface in the Bornholm Syd area is roughly between -60 to -80 m.

The present-day bathymetry (Figure 8.1) with water depths ranging from 60 to 70 m in most of the area, and from 40 to 60 m in the western part, together with the topography of the pre-Quaternary surface, indicates that only a thin Quaternary top unit of a few metres to about 20-40 m thickness can be expected. The seabed sediment map in Figure 8.2 shows that around the island of Bornholm (north of the Bornholm Syd area and on Rønne Banke) large areas expose pre-Quaternary sediments at the seabed.

The general geological development of the area southwest of Bornholm has resulted in a characteristic pre-Quaternary morphology, where the major faults reflect the transtensional movements within the fault blocks. This tectonic and depositional history with a close relationship between the wrench system faults and the depocenters has resulted in a distribution of pre-Quaternary deposits of different ages in domino-shaped blocks and basins, making the geological map of the pre-Quaternary surface look like a large jigsaw puzzle as illustrated in Figure 5.5. It is, however, seen that the Bornholm Syd area is located outside the most intense block faulting.

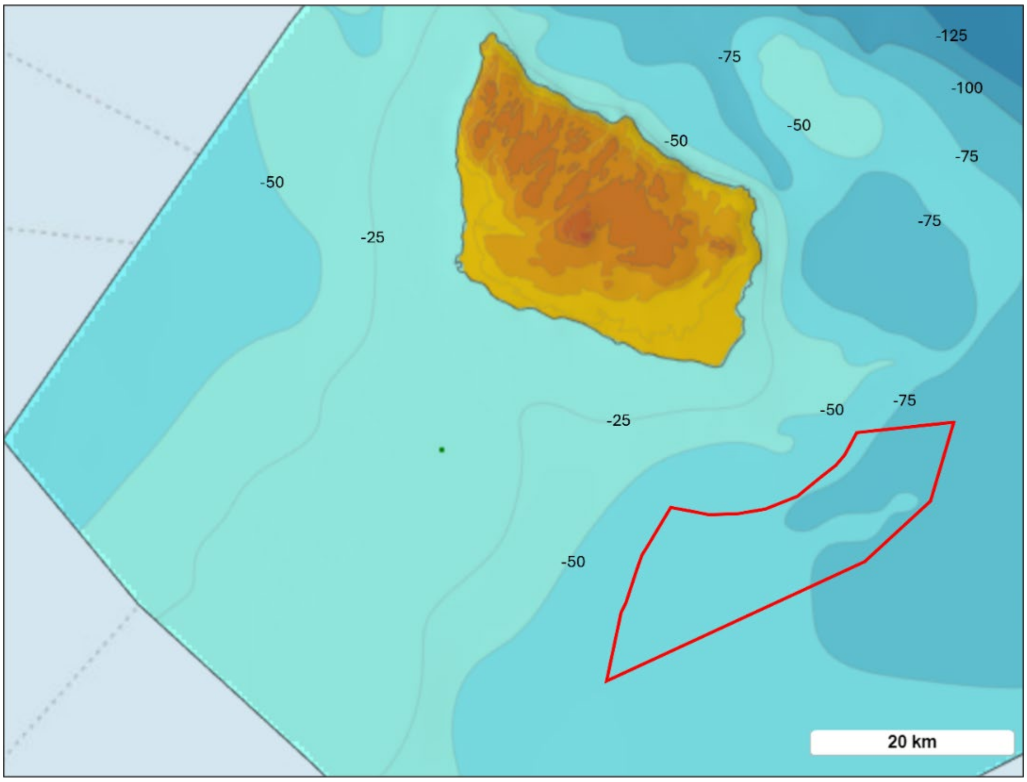


Figure 5.4. The topography (level in metres) of the pre-Quaternary surface (Binzer & Stockmarr 1994) southwest of Bornholm. Bornholm Syd area shown with red polygon.

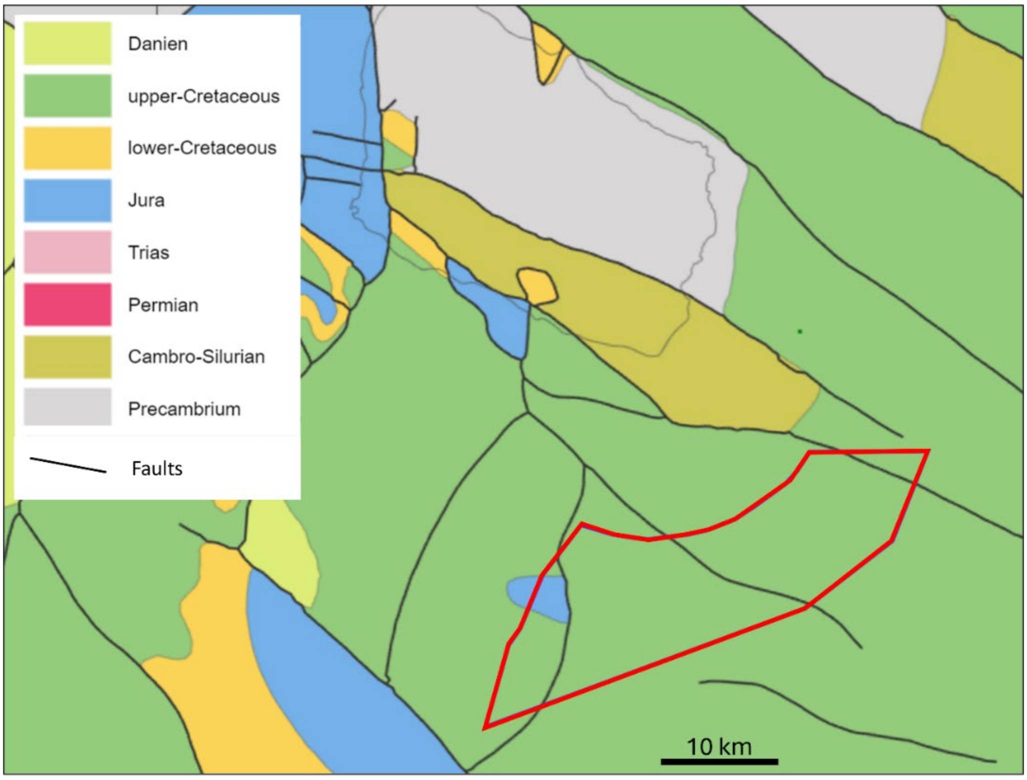


Figure 5.5. Major faults and pre-Quaternary stratigraphic units southwest of Bornholm. Bornholm Syd area shown with red polygon.

6. 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 6.1.), and except for the Kattegat region, Danish observations of earthquakes through hundreds of years show no signs of earthquakes being of larger magnitude in the Sorgenfrei–Tornquist Zone than outside.

All observed earthquakes in the Danish and Swedish parts 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.

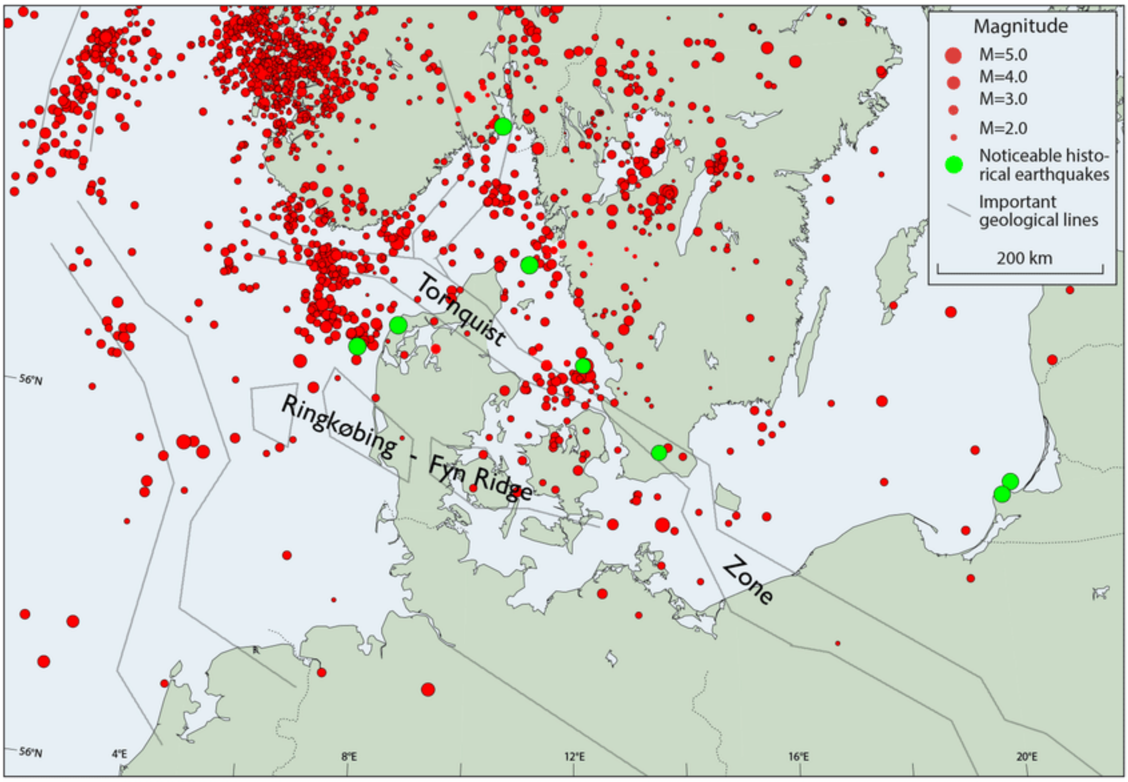


Figure 6.1. Earthquake activity in southern Scandinavia (Gregersen & Voss 2014). The red dots show modern well-located earthquakes of the last 75 years, and green dots show the most important relatively large earthquakes in 1759, 1841, 1904, 1985, 2004, 2008 and 2010.

7. 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 deep sediment basins (Jensen et al. 2017).

The Quaternary sedimentary succession in the Arkona Basin (west of Bornholm) and the Bornholm Basin (east of Bornholm), see Figure 3.1, has been intensively studied in relation to the development of the late- and postglacial Baltic Sea-phases based on the well-preserved Baltic Ice Lake clay, the Yoldia Sea clay and the 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).

In the following the palaeogeography of the deglaciation of Denmark and a seismic stratigraphy for the Bornholm Basin will be described.

7.1 Palaeogeography of the deglaciation of Denmark

The Scandinavian Ice Sheet reached its maximum extent in Denmark about 22.000 years BP followed by stepwise retreat.

During the general deglaciation, an ice stream re-advance from the Baltic moved westward and reached the East Jutland ice marginal line. 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 winter re-advances, formed during the general retreat of the ice margin. After the deglaciation, a glaciolacustrine environment, the Baltic Ice Lake, was established with icebergs (Figure 7.1).

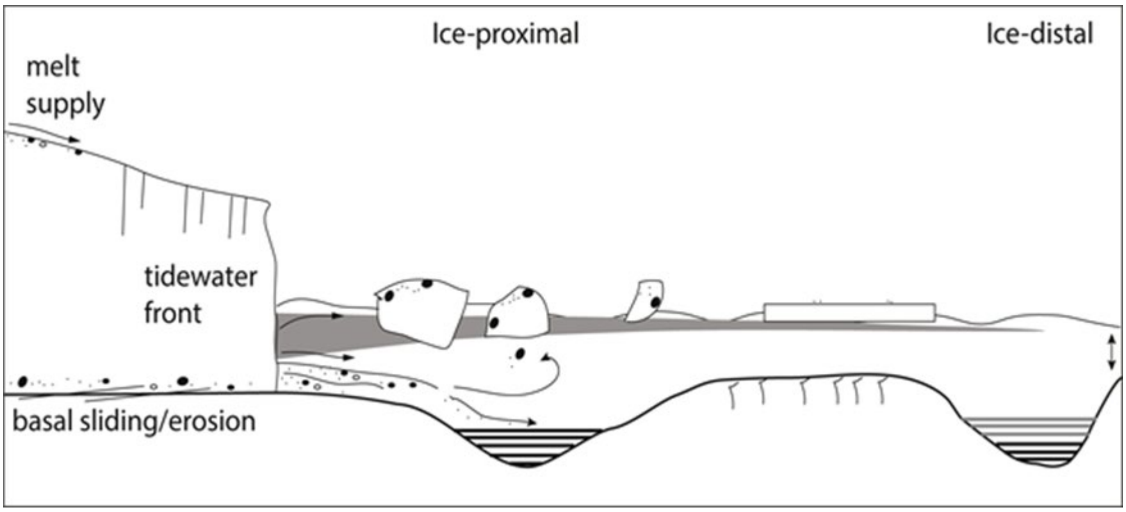


Figure 7.1. Illustration of a glaciolacustrine depositional environment.

The knowledge about the general deglaciation and postglacial history of the southwestern Kattegat and the western Baltic is presented as a series of palaeogeographical maps in Figure 7.2 and described below:

- About 18.000 years ago, the deglaciation after the maximum extent of the latest ice sheet in Jutland (Main Stationary Line) 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 after the load of the ice and the relative sea-level was high, with the sea covering 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 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 southwesternmost Baltic Sea.
- 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 documented 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 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 discharge event in south-central Sweden and the lake level dropped by about 25 m.

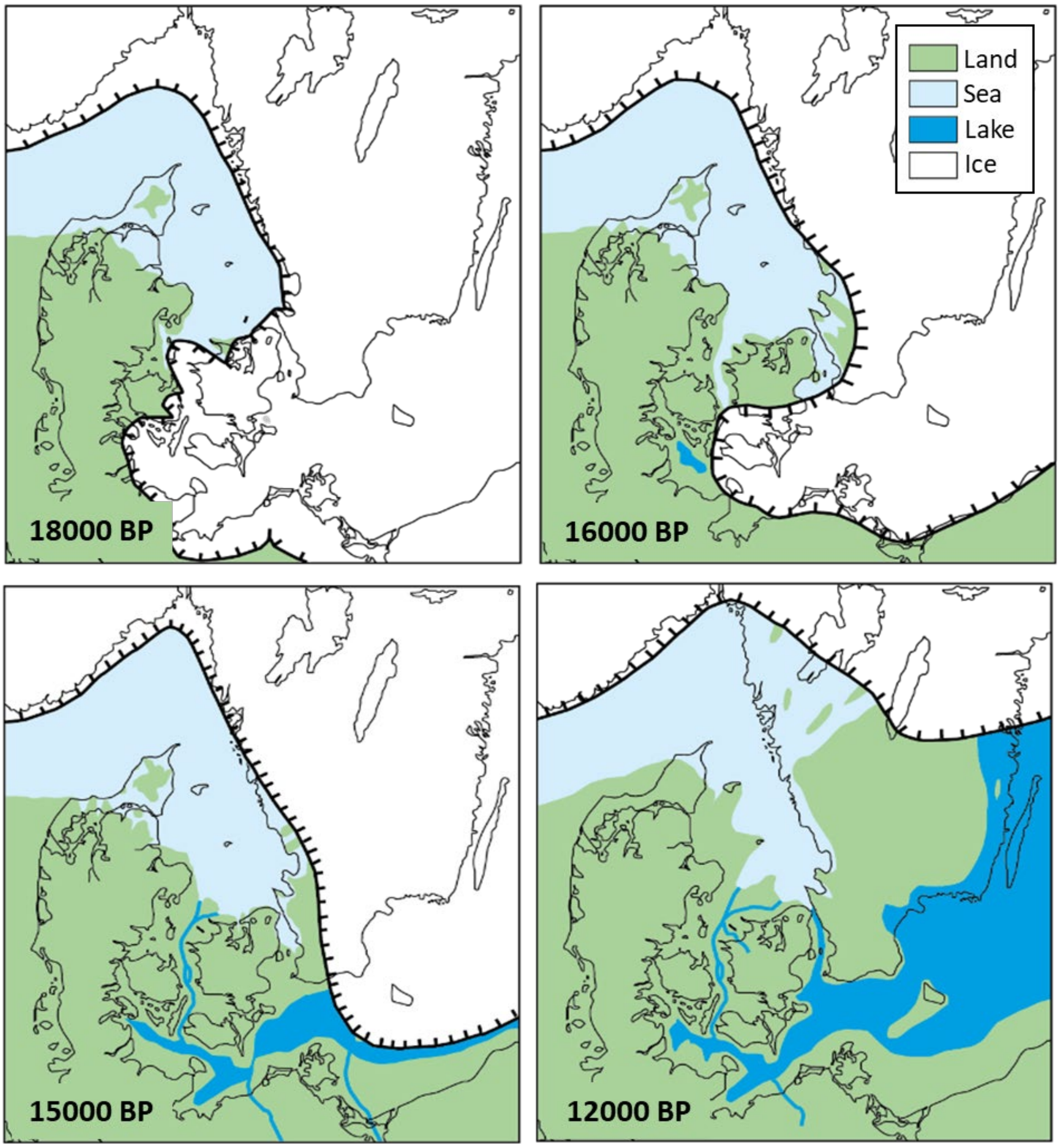
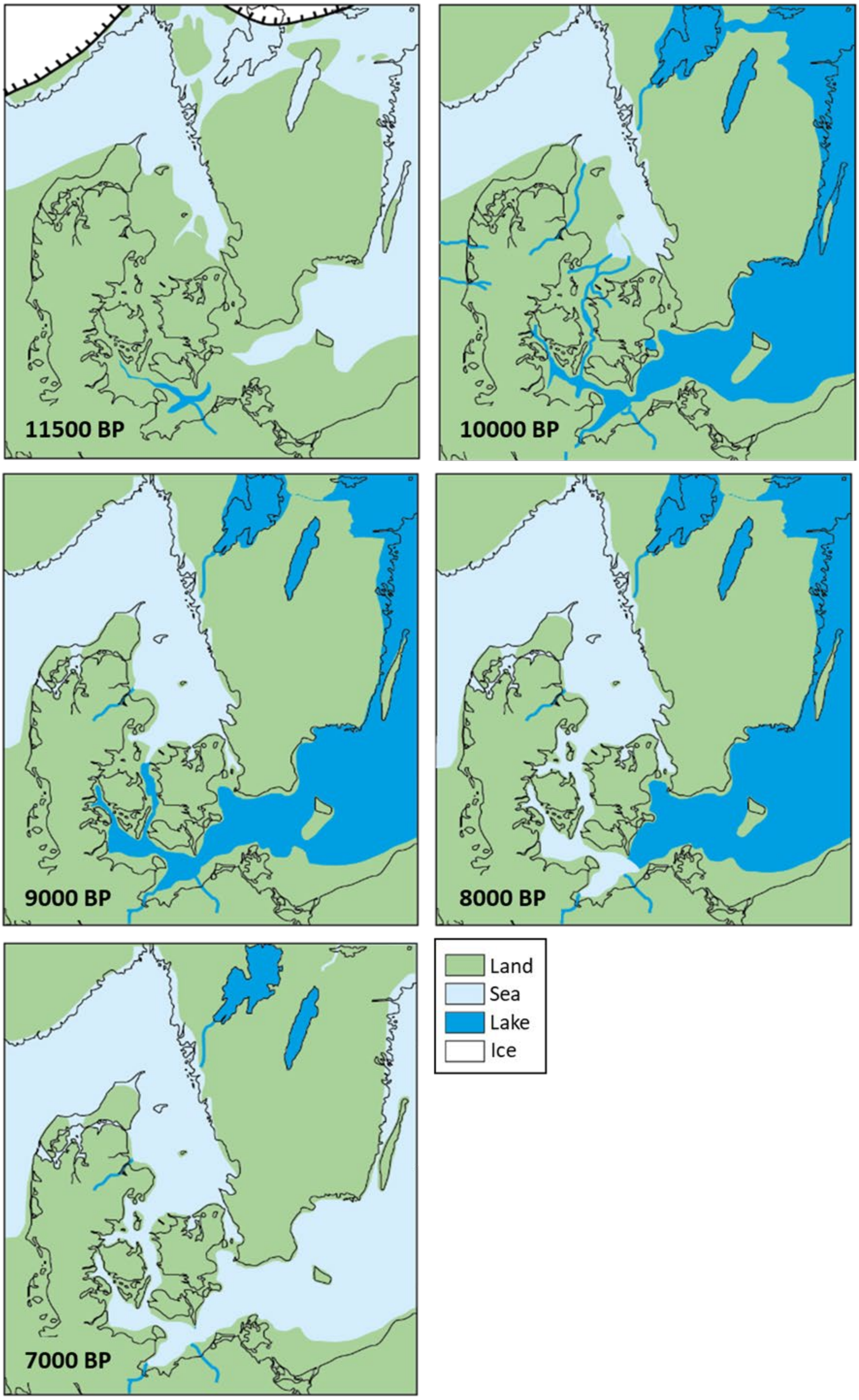


Figure 7.2. Palaeogeographical maps showing the development of the Danish area from approx. 18.000 to 7.000 years BP. Modified from Jensen et al. (2002). See also next page.


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

- 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 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 10.200 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, or estuary basin, partly blocked by transgressive coastal barriers. Remains of this system are preserved on the sea floor as reported by Bennike et al. (2000) and Bendixen et al. (2017).
- About 10.000 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, southeast of Langeland and in the southwestern 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 southwestern Kattegat.
- The calm lake sedimentation was followed by a gradual transgression and change into brackish conditions about 9.400 years ago and a fully marine environment was reached in the Great Belt 9.100 years ago marking the beginning of the Littorina transgression.
- About 8.000 years BP the transgression had reached the Darss Sill – Gedser Reef area.
- About 7.000 years BP also the western part of the Baltic Proper was marine.

7.2 Seismic stratigraphy for the Bornholm Basin

Based on a network of seismic data recorded during the last few decades a seismic stratigraphy has been established for the Bornholm Basin, mainly in connection with the EU BONUS project: Baltic Gas. Also in this project, core positions were selected and subsequently drilled during the Integrated Ocean Drilling Program IODP 347 (Andrén et al. 2015b) in October 2013, at Site M0065 see Figure 3.1. The total drilling depth was 73.9 m below sea floor where bedrock was encountered, but no samples were recovered from the lower part and only the upper 49.2 m could be described (Andrén et al. 2015b).

Based on the seismic stratigraphy and core data, a conceptual geological model for the Bornholm Basin was established by Jensen et al. (2017). The model includes five seismic units, all separated by unconformities, briefly described in the following sections and shown in Figure 7.3.

The crystalline basement and sedimentary bedrock Unit V as well as the glacial Unit IV were mainly identified on deeper airgun seismic data, whereas details of the more soft late- and postglacial sediments were best seen on Subbottom Profiler data (Figure 7.4).

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

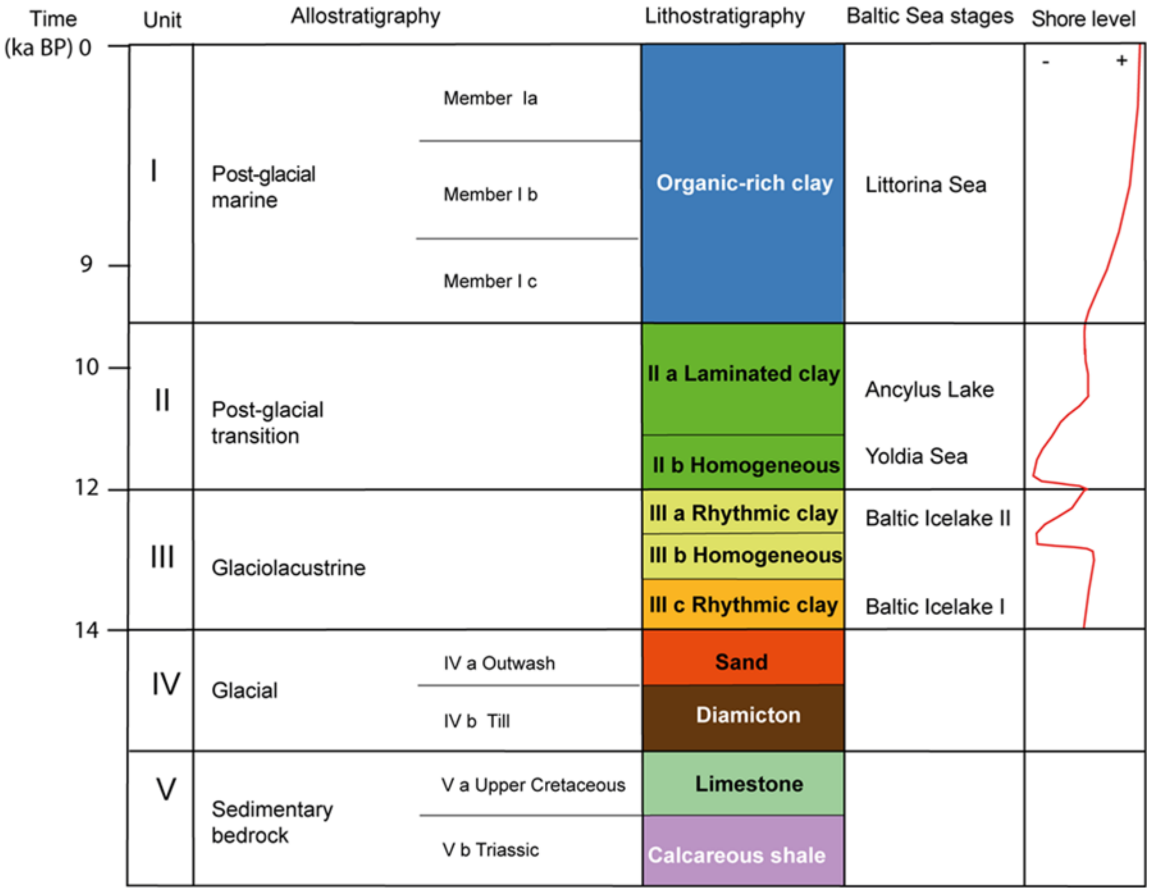


Figure 7.3. Stratigraphical subdivision of the Bornholm Basin (Jensen et al. 2017). The seismic Units I–V represent allostratigraphical formations, some of which are divided into members, and all bounded by unconformities. Mappable lithostratigraphical formations (informal) are identified within the allostratigraphical framework and Baltic Sea stages as well as the general Baltic Sea shore level changes are correlated with the established allostratigraphy.

7.2.1 Unit V crystalline basement and sedimentary bedrock

The seismic Unit V comprise crystalline basement and sedimentary bedrock. In the Bornholm Basin, the sedimentary bedrock is divided into member Va and Vb interpreted as Triassic shale and Upper Cretaceous limestone, respectively.

7.2.2 Unit IV glacial deposits

Unit IV consist of glacial deposits draping the irregular pre-Quaternary 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 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 M0066. However, IODP site M0065 is in a strike-slip fault basin, where there is a clear subdivision into a lower diamicton member (IVb) and an upper outwash member (IVa), separated by an unconformity.

7.2.3 Unit III late glacial glaciolacustrine deposits

Unit III comprise glaciolacustrine sediments covering the irregular unconformity of the glacial deposits in the Bornholm Basin, except in the topographically high Christiansø Ridge area, where the glacial deposits of 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 7.4). The internal reflection configuration varies through the basin.

Unit III is sub-divided into three subunits:

- The lower Unit IIIc corresponds to Baltic Ice Lake deposits in front of the retreating Weichselian glacier. It represents an early stable phase of the glaciolacustrine environment and show parallel reflectors and varved clay. The unit is fining upward indicating that the ice front became more and more distal to the Bornholm Basin.
- The middle Unit IIIb comprise homogeneous clay and is related to the first Baltic Ice Lake drainage occurring during the late Allerød. This drainage led to a 10-m drop in water level and to the formation of unconformities in the shallow parts of the southwestern Baltic Sea (Jensen et al. 1997; Bennike & Jensen 1998, 2013; Uscinowicz 2006). The relatively deep Bornholm Basin was, however, covered by water and the unconformity seen in shallow areas is replaced by a basin-correlative conformity.
- The upper Unit IIIa is fining upwards from massive, medium-grained sand to fine- to medium-grained sand with laminated silt and silty clay with parallel lamination. An indistinct lamination 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.

There are no diatoms, foraminifers or ostracods in the sediments of Unit III and the depositional environment is interpreted as a glacio-lacustrine environment. The sandy sediments in the lowermost part of the succession represents a proximal glacio-lacustrine environment.

7.2.4 Unit II Early postglacial transition clay

Unit II consist of postglacial clay conformably draping the glaciolacustrine sediments in the Bornholm Basin with a rather constant thickness of about 4 m. 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 7.4).

Unit II is sub-divided in two subunits:

- The lower Unit IIb consist of homogeneous brown clay, gradually changing upwards to grey clay with intervals of black spots and specks.
- The upper Unit IIa is laminated by colour with very fine dark grey iron sulphide-rich, 2–3 mm thick lamina. The density of laminae increases upwards.

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. 2000) documented the same lithological sequence and it has been interpreted to represent deposition in the Yoldia Sea (the lowermost homogeneous part) whereas the Ancylus Lake clay 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.

7.2.5 Unit I Mid- and late postglacial marine mud

Unit I comprise clay with indistinct colour lamination due to moderate bioturbation. 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.

In the central Bornholm Basin, northeast of the Christiansø Ridge, the basin infill of Unit I have an asymmetrical external wedge shape and Subbottom Profiler data show complex internal reflection patterns (Figure 7.4). Frequent low amplitude, concave and internal on-lap, parallel reflectors dominate the major synsedimentary down-faulting zone.

In the minor strike-slip fault basins, three members (Ic, Ib and Ia) are established. 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 northeastern 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.

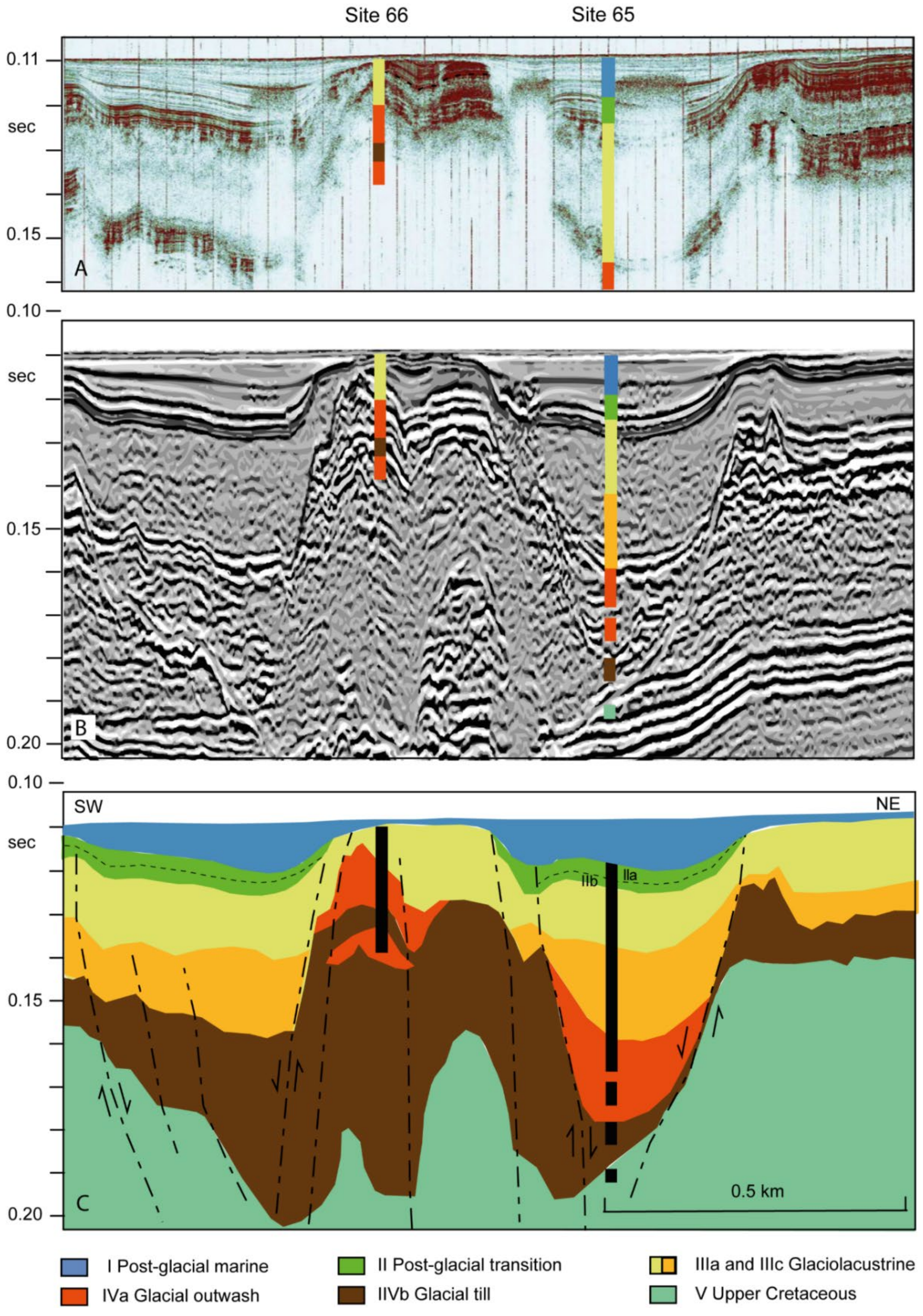


Figure 7.4. Seismic Line across Site M0065 (Jensen et al.2017). Profile A is Subbottom Profiler data and profile B is airgun seismic data, both with original interpretation and sediment core documentation for sites 65 and 66 (Andrén 2014). The interpretation in profile C follows the classification of seismic units described in Figure 7.3. The location of the IODP site is shown in Figure 3.1.

8. Geological mapping of the Bornholm Syd area

8.1 Bathymetry

Bornholm Syd is characterised by water depths of c. 40 to 70 m, with depths generally increasing from west to east (Figure 8.1). The seabed is generally quite even, but investigations of the seismic lines crossing the area reveal local higher- and lower lying parts. In the northwestern corner of the area, a higher lying moraine ground with a minimum depth of about 42 m is found. The moraine ground continues toward the WNW, where it becomes attached to Rønne Banke. Shallow seismic data investigated in the present study reveal a channel or local depression in the seabed in the northeastern part of the Bornholm Syd area. The ‘channel’ has an apparent width of about 800-900 m and a depth below the surrounding seabed of about 7-8 m. A similar size channel feature has been mapped in the Nord Stream 2 survey corridor immediately northwest of the Bornholm Syd area.

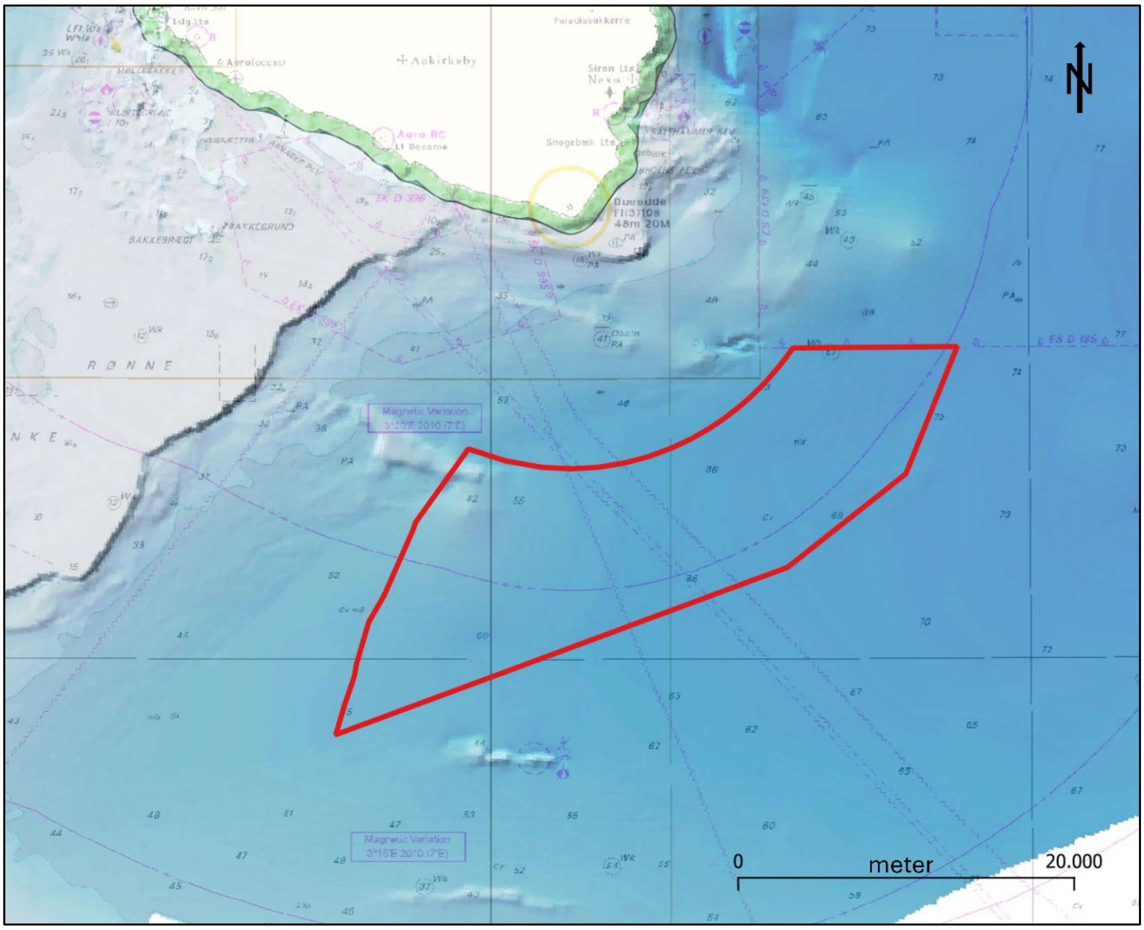


Figure 8.1. Bathymetric map of the Bornholm Syd area (red polygon) from the Danish Geodata Agency, with sea map depth values as a secondary layer.

8.2 Seabed sediments

The distribution of seabed sediments reflects to some degree the bathymetry of the region. Fine-grained mud has accumulated in the deeper parts of the Bornholm Basin, whereas areas with till and bedrock in the shallow parts indicate non-deposition or erosion (Figure 8.2). In the Bornholm Syd area Quaternary clay and silt (late glacial Baltic Ice Lake deposits) is found directly at, or very close to, the seabed in the western part of the area along a protruding moraine ridge as well as along the northwestern boundary. The top of the moraine ridge is characterised by till/diamicton with smaller and larger stones exposed at the seabed. Muddy sand and mud of Holocene age is found at the seabed in the remaining deeper part of the area, and the seabed sediments are generally becoming more fine-grained with increasing depth.

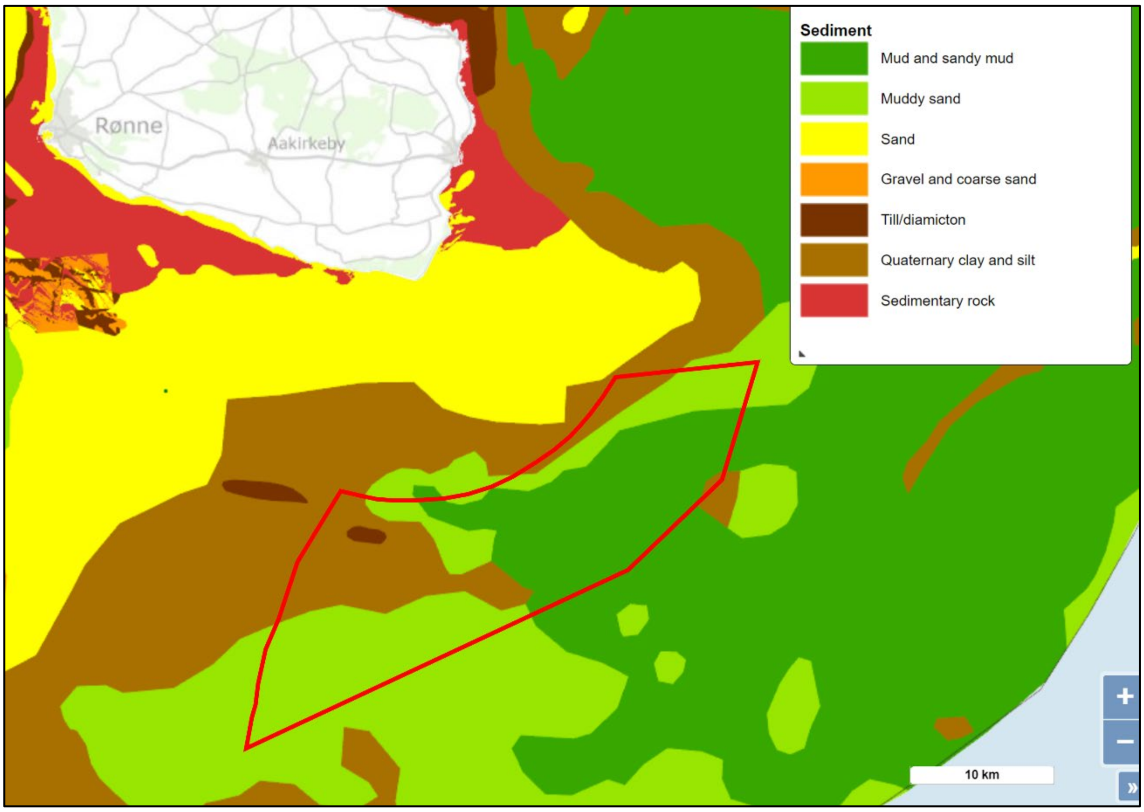


Figure 8.2. Seabed sediments south of Bornholm, according to the Marta database. The Bornholm Syd area is indicated by the red polygon. The map gives only a general impression of the seabed sediment distribution.

8.3 Sediment cores

A number of vibrocores of max. 6 m length were taken in 2023 by GEUS in connection to the ongoing large scale windfarm screening for Energistyrelsen. Relevant other sediment cores are known from the Bornholm II OWF area (Rambøll, 2024), and from the Nord Stream 2 and Baltic Pipe alignment areas to the west of Bornholm Syd.

Only one short sediment core, BO-13, is found within the Bornholm Syd area. Core BO-13 shows 3 m of clayey Ancylus Lake deposits with 2 m of marine mud on top (Figure 8.3).

Another core, BO-08, from close to the northwestern margin of the Bornholm Syd area, show about 5.9 m of stratified Baltic Ice Lake sediments, with typical fine layering of reddish brown and grey clay (Figure 8.4.). In that area, presently characterised by non-deposition, Baltic Ice Lake deposits are exposed directly at the seabed, as shown on the seabed sediment map in Figure 8.2.

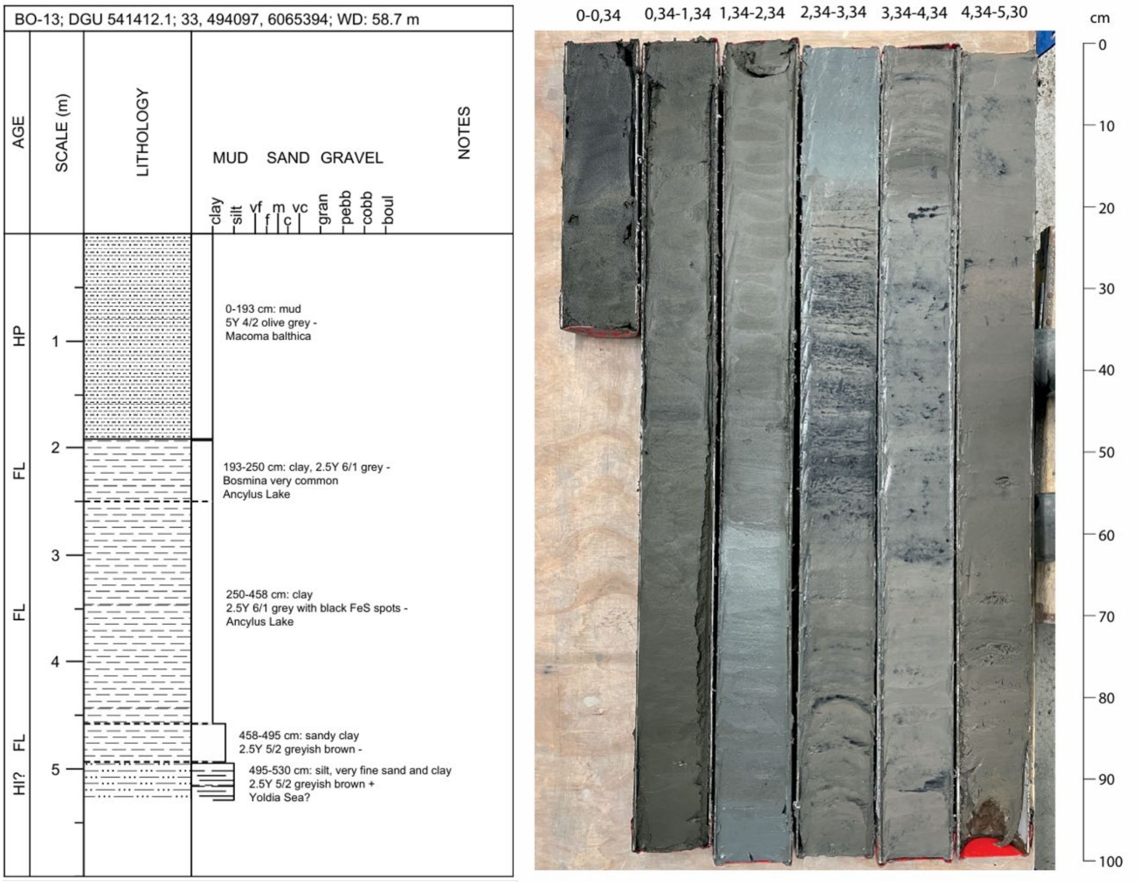


Figure 8.3. Lithology log and photo of vibrocore BO-13 from the southwestern part of the Bornholm Syd area. The top section of the core (0-34 cm) is to the left on the photo. The core log represents seismic unit 1 in the present study, Holocene soft lacustrine clay and marine mud deposits.

A number of 60-70 m deep geotechnical boreholes and shallow CPT's (generally 5-10 m, but occasionally up to 20 m) were carried out in 2022 in the Bornholm II OWF area immediately to the west of the Bornholm Syd area (Rambøll, 2024). These ground truthing data can be considered as the best analogues for sediment lithologies and geotechnical properties in the Bornholm Syd area. An example of borehole/CPT site BH-217 is shown in Figure 8.5.

Figure 8.4. Lithology log and photo of vibrocore BO-08 to the northwest of the Bornholm Syd area. The top section of the core (0-93 cm) is to the left on the photo. The core log represents seismic unit 2 in the present study, late glacial Baltic Ice Lake deposits of firm, fine stratified brownish to greyish clay.

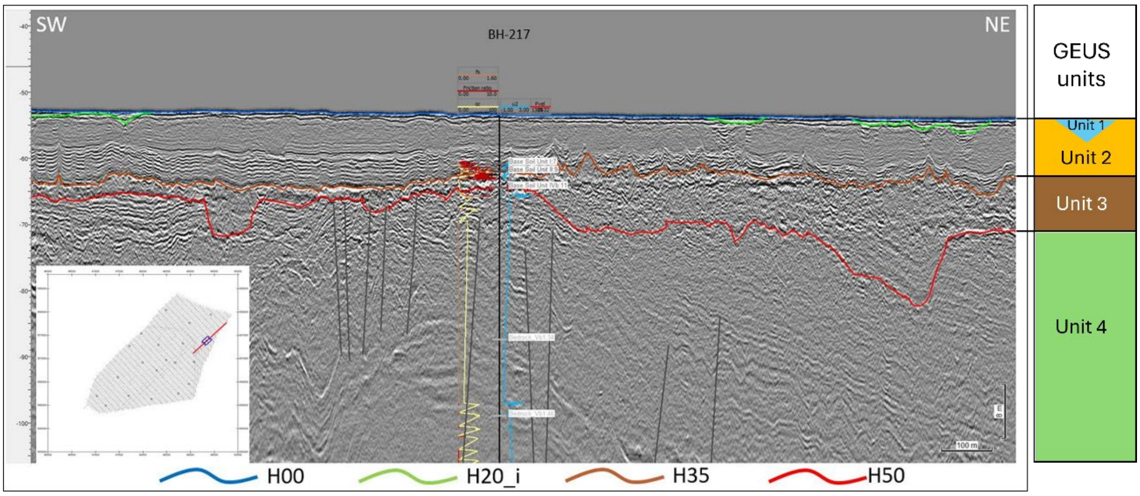


Figure 8.5. Seismic profile with long core BH-217 from the western part of the Bornholm II OWF area adjacent to the Bornholm Syd area (Rambøll, 2024). Seismic units 1-4 defined in the present study are shown to the right. H00 indicates the seabed. H20 corresponds to top of seismic unit 2 (Baltic Ice Lake deposits). H35 corresponds to top of seismic unit 3 (glacial deposits). H50 corresponds to top of seismic unit 4 (pre-Quaternary bedrock). According to borehole data, the pre-Quaternary deposits consist of soft chalk (upper Cretaceous) and, in the lower part, soft sandstone (Lower Cretaceous or Jurassic).

8.4 Seismic profiles

Only four shallow seismic lines are crossing the Bornholm Syd area (Figure 4.1 and Figure 8.6.). The lines ENS22_BO-01, -04, -09, and -11 were recorded by GEUS with Sparker equipment (single- and multichannel streamer), Subbottom Profiler (Innomar Medium system) and combined Side Scan Sonar/Multibeam system during a large-scale windfarm screening survey for the Danish Energy Agency in 2022 (Perez et al., 2023). The data are of high quality and post-processing has further enhanced the signal/noise ratio.

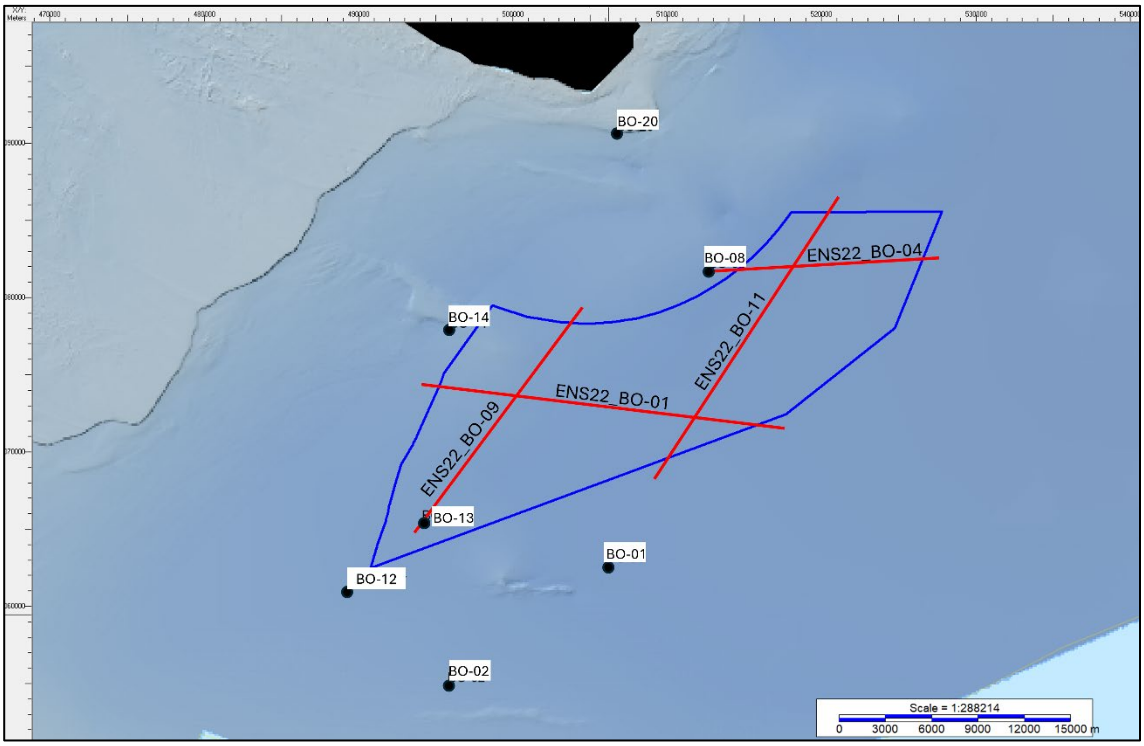


Figure 8.6. Location of the four available shallow seismic lines (in red) crossing the Bornholm Syd area (in blue). Vibrocores in or near the area is shown as black dots. The bathymetry is from EMODnet (2022).

The lower frequency Sparker equipment can penetrate about 50-150 m below the seabed depending on specific lithologies and hardness of the underground. In this respect, thicker glacial units, the top pre-Quaternary surface and internal structures in the upper part of the pre-Quaternary can be clearly observed. The higher frequency Subbottom Profiler signals, on the other hand, can resolve detailed structures on decimeter-scale in the upper softer part of the seabed (late glacial and Holocene deposits). By combining data from both instruments along the same lines, interpretations of sediment structures and identification of specific seismic units can be optimised.

After processing, the seismic data were imported into IHS Kingdom interpretation software. Four regional seismic units (1-4) were identified, and boundaries between the units were traced on the seismic sections. Hereby, extent and thickness of units have been mapped out.

Side-Scan Sonar data were inspected along lines in Sonarwiz interpretation software with special emphasis on locating areas with stone concentrations on the seabed.

The seismic units are described below in section 8.4.1 and the geological interpretation of Sparker seismic and Subbottom Profiler (SBP) data from the four survey lines are described in section 8.4.3 to 8.4.6. The location of the seismic lines and selected vibrocores are shown in Figure 8.6.

8.4.1 Seismic units

The following seismic units (from seabed and downward), corresponding to the seismic units of Rambøll (2024) in the Bornholm II OWF area, have been mapped:

Unit 1:
The youngest unit shows medium amplitude parallel reflections, often with higher amplitudes at the base. In expanded sections a trend from conformably layering in the lower part to more dynamic down-lap and on-lap structures in the upper part can be observed.

Unit 1 is interpreted as Holocene deposits encompassing Ancylus Lake deposits in the lower part and transitioning into marine Littorina Sea deposits in the upper part.

Unit 2:
The unit shows characteristic variable bands of high amplitude parallel reflections alternating with lower amplitude reflections. The layering is typically conform and wavy reflecting deposition on top of an irregular surface. Internal offset layering possibly related to small scale faulting is frequently seen. In the western part of the area, a sub-unit with a more chaotic to homogeneous appearance and with an erosive base can be observed interspersed between the more characteristic layered parts of Unit 2.

Unit 2 is interpreted as late glacial Baltic Ice Lake deposits. The more chaotic layered subunit in the shallower western part is interpreted as a low-stand unit related to the first dramatic drainage of the Baltic Ice Lake at about 12.800 years BP.

Unit 3:
The unit show variable chaotic reflections alternating with sectors of high amplitude reflections. The lower boundary is highly irregular and in parts channelised. The upper boundary is likewise irregular with some parts forming ridges.

Unit 3 is interpreted as Quaternary glacial deposits consisting of till and meltwater deposits. The unit forms generally a rather thin cover on top of the pre-Quaternary bedrock, but some sectors of the profiles are characterised by deeply incised (50 m or so) and filled-in glacial valleys. A multistorey fill observed in some of the larger buried valleys, suggests reactivation of glacial erosion and deposition in the valley structures during several glacial episodes.

Unit 4:
The unit shows inclined layering with slopes up to 5 degrees, in some places with large scale folds and fault structures. Reflections are quite variable from low to high amplitudes characterising different parts of the internal stratigraphy.

Unit 4 is interpreted as pre-Quaternary bedrock, which have been folded and faulted along older fault blocks during the Late Cretaceous tectonic inversion phase. The pre-Quaternary bedrock in the upper 100 m of the sections most likely consists of Upper Cretaceous Chalk, but along fault structures, Jurassic and lower Cretaceous sandstones and mudstones can also be expected.

The general characteristics and geological interpretations of the units are presented in Table 7.1.

Table 8.1. Description of four identified seismo-stratigraphic units.

Unit	Stratigraphic Unit	Acoustic character	Depositional environment	Lithology
1	Holocene Littorina Sea, Ancylus Lake, Yoldia Sea deposits	Fine layering with medium amplitude reflections	Marine - brackish - lacustrine	Clay - sandy mud with some organic content
2	Late glacial Baltic Ice Lake deposits	Variable fine layering with high amplitude reflections and more homogenous low amplitude parts	Ice-proximal to ice distal lake deposits	Silty clay with some ice-rafted debris in lower part
3	Glacial Weichselian or older	Crude high amplitude reflections alternating with homogenous or chaotic parts	Subglacial-glacial lacustrine, glaciofluvial, and glaciotectonic deformation	Till alternating with sand and gravel
4	Pre-Quaternary Cretaceous or older	Inclined, folded and faulted layering with variable amplitude reflections	Open marine to coastal deposits (tropical-subtropical climate)	Chalk, sandstone, and mudstone (lithified to unlithified)

8.4.2 Correlation with the Bornholm Basin seismic stratigraphy

Seismic Unit 1 in the present study corresponds to Seismic Unit I and II in the seismic stratigraphy for the Bornholm Basin, see section 7.2 and Figure 9.1.

Seismic Unit 2 in the present study corresponds to Seismic Unit III in the seismic stratigraphy for the Bornholm Basin.

Seismic Unit 3 in the present study corresponds to Seismic Unit IV in the seismic stratigraphy for the Bornholm Basin.

Seismic Unit 4 in the present study corresponds to Seismic Unit V in the seismic stratigraphy for the Bornholm Basin.

8.4.3 Line ENS22_BO-01

The line crosses the central part of the Bornholm Syd area from west to east and the line segment is about 21 km long with water depths increasing from about 49 m at the western side to about 61 m at the eastern side (Figure 8.7.).

Baltic Ice Lake sediments (Unit 2) with only a thin sporadic cover of Holocene sediments (Unit 1) characterises the upper 10-15 m below the seabed. Only in the westernmost part the Holocene unit increases markedly to about 10 m thickness in a large, infilled channel structure encompassing late glacial and glacial units 2 and 3. Glacial Unit 3 is variable from a few metres in thickness to thick buried valley units with a thickness of up to 40-50 m and an apparent width of about 1-4 km eroding into the pre-Quaternary bedrock (Unit 4). In the central part of the section, a buried moraine high appears to rise to the seabed. The pre-Quaternary can be expected to consist of Upper Cretaceous chalk based on the pre-Quaternary surface map (Figure 5.5). The internal structures show inclined layering, folding and faulting. The fault structure observed in the central part, is most likely related to the WNW-ESE trending fault zone indicated in Figure 5.5.

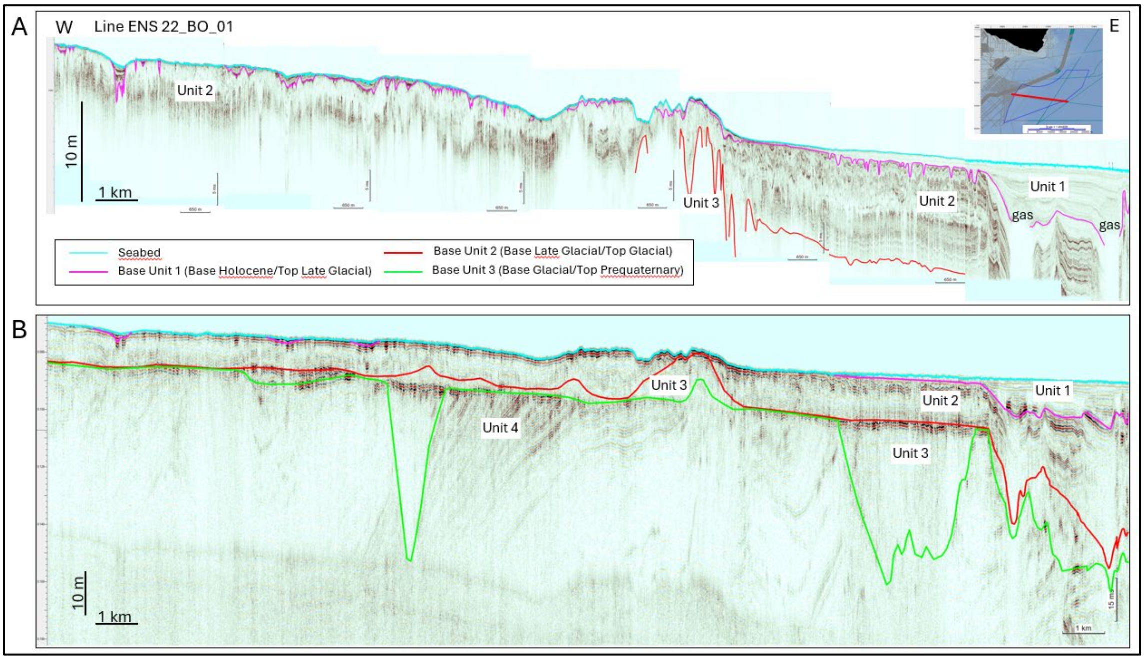


Figure 8.7. Line ENS22_BO-01 SBP profile (A) and Sparker profile (B) with unit base/top interpretation marked by colour. Note the different vertical resolution of the two data types

8.4.4 Line ENS22_BO-04

The line crosses the northern part of the Bornholm Syd area from west to east and the line segment is about 12 km long with water depths increasing from about 56 m at the western side to about 75 m at the eastern side (Figure 8.8.).

Baltic Ice Lake sediments (Unit 2) with no or only a thin sporadic cover of Holocene sediments (Unit 1) characterises the upper 10-12 m below the seabed in the western part. The seabed there appears to be erosional with erosion truncating the layering in the Baltic Ice Lake sediments. Toward the eastern part of the section, increasing thickness of Holocene sediments up to 10-15 m is found. Where line ENS_BO-04 crosses line ENS_BO-11 a conspicuous depression in the seabed is found with shallow gas in the sediments masking reflections below. The depression is about 6-8 m below the surrounding seabed and appear to be about

500-1000 m wide. A channel structure of similar dimensions has been documented from the Nord Stream 2 alignment to the northwest of the structure and it appear likely, that the depression reflects an only partly infilled older channel structure crossing the Bornholm Syd area. A buried glacial valley structure is thus located below the depression in the seabed.

Only in the easternmost part the Holocene unit increases markedly to about 10 m thickness in a large, infilled structure encompassing late glacial Unit 2 and glacial Unit 3. Glacial Unit 3 is variable from a few metres in thickness to thick buried valley units with a thickness of up to 30 m and an apparent width of about 2-3 km eroding into the pre-Quaternary bedrock (Unit 4).The pre-Quaternary can be expected to consist of Upper Cretaceous chalk based on the pre-Quaternary surface map (Figure 5.5). The internal structures show inclined layering, folding and faulting.

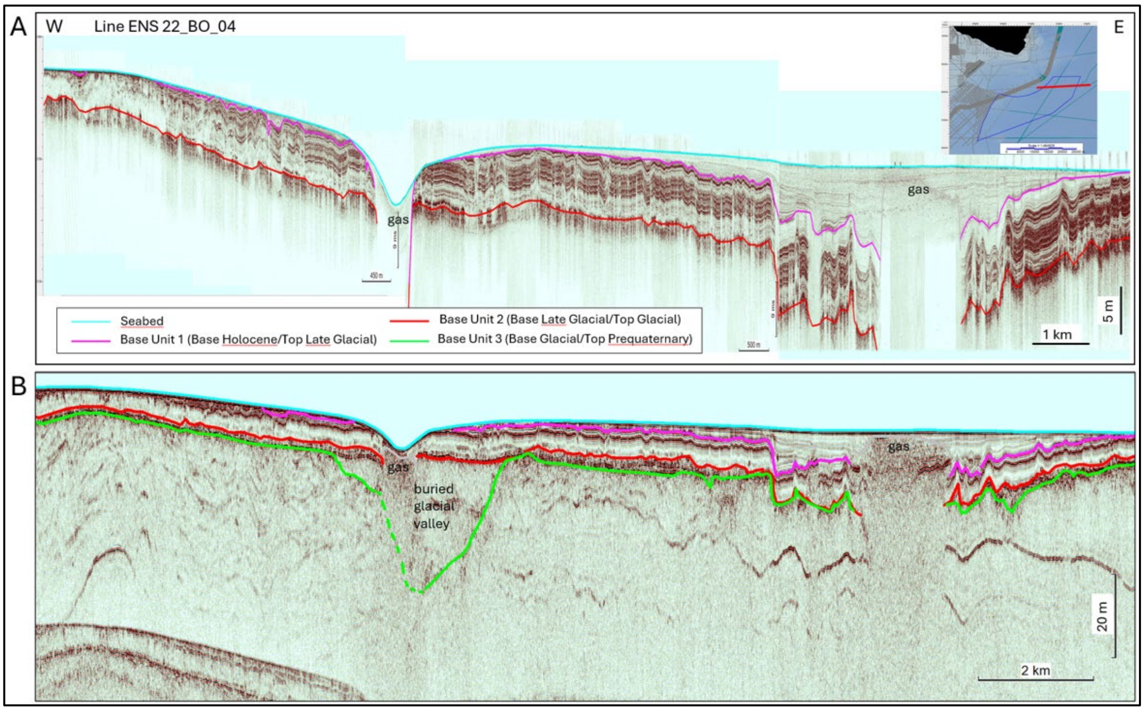


Figure 8.8. Line ENS22_BO-04 SBP profile (A) and Sparker profile (B) with unit base/top interpretation marked by colour. Note the different vertical resolution of the two data types.

8.4.5 Line ENS22_BO-09

The line is crossing the western part of the Bornholm Syd area from southwest to northeast and the line segment is about 17 km long with water depths of about 53 m at the southwestern part decreasing to about 41 m at the top of a ridge structure in the northeastern part (Figure 8.9.).

Holocene deposits (Unit 1) and Baltic Ice Lake deposits (Unit 2) have a thickness of about 12-13 in the southwestern part but thins progressively toward the peak of the ridge structure where moraine deposits appear to be exposed directly at the seabed. The moraine deposits contain stones of variable sizes as verified by side scan sonar data from the top of the ridge. Northwest of the moraine ridge Baltic Ice Lake deposits in general are found right up to the seabed. Glacial deposits (Unit 3) form a several kilometres wide and about 40 m deep buried valley dissecting the pre-Quaternary deposits in the southwestern part of the section. Toward the central and northeastern part of the section, the pre-Quaternary surface rises to about 10-20 m below the seabed. Steepened dip and smaller fold structures in the northwestern-most part of the section indicate proximity to fault structures transversing the Bornholm Syd area.

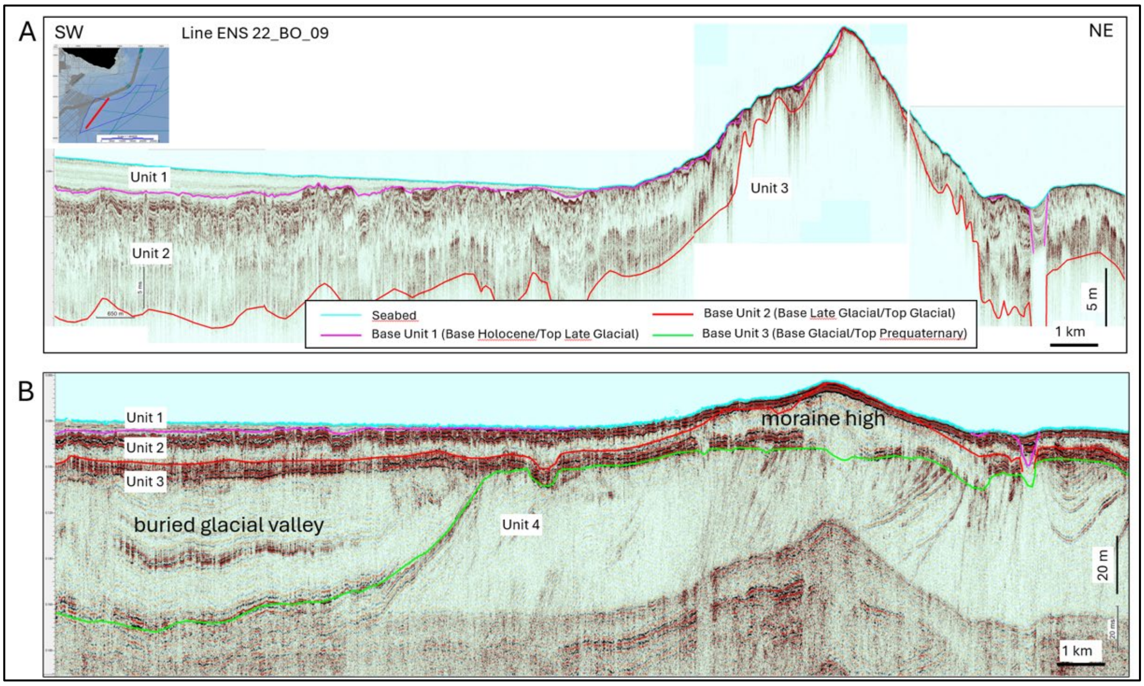


Figure 8.9. Line ENS22_BO-09 SBP profile (A) and Sparker profile (B) with unit base/top interpretation marked by colour. Note the different vertical resolution of the two data types.

8.4.6 Line ENS22_BO-11

The line is located in the eastern part of the Bornholm Syd area and orientated from southwest to northeast (Figure 8.10.). The line segment is about 19 km long with water depths of about 57-59 m interrupted by the about 7-8 m deeper channel feature in the northeastern part, as also observed along the crossing line ENS_BO-04.

Holocene deposits (Unit 1) generally show a thickness of about 2 m, but at three about 500-800 wide parts of the section, the Holocene deposits show thickened sections of more than 5 m and gas masking. Baltic Ice Lake deposits (Unit 2) show a thickness of about 10-12 m, slightly thicker in the southwestern part. Glacial deposits (Unit 3) vary between less than 5 m in thickness and a much thicker infilled glacial valley structures about 1-3 km wide and 30-40 m deep along the section. Where not dissected by glacial infilled valleys, the pre-Quaternary surface is found about 10-15 m below the seabed. The pre-Quaternary deposits show inclined bedding and folding indicating proximity to fault structures transversing the Bornholm Syd area.

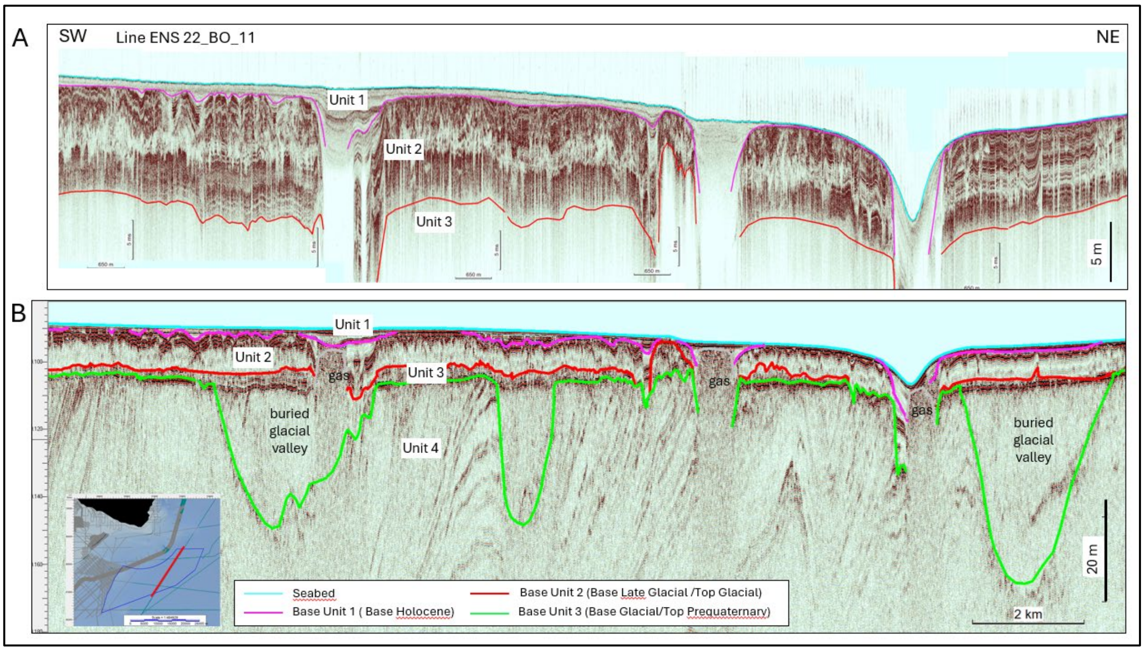


Figure 8.10. Line ENS22_BO-11 SBP profile (A) and Sparker profile (B) with unit base/top interpretation marked by colour. Note the different vertical resolution of the two data types.

8.5 Thickness of units

Based on seismic interpretation and tracing of boundaries between seismic units 1, 2, 3 and 4, thickness distribution maps have been produced. Due to the scarcity of available seismic lines in the Bornholm Syd area, the thickness distribution is only shown along lines and not as gridded maps.

A velocity of 1600 m/s has been used for transforming seismic two-way-traveltimes to depth of layer boundaries and thickness of units. As velocity may vary between units depending on water content and consolidation of sediments, it introduces an uncertainty concerning the calculated thickness of units. The uncertainty is more limited concerning mapped thicknesses of unit 1 and 2 which is mostly normal consolidated clays. Higher uncertainties can be expected for the mapped thickness of unit 3 and the subsurface depth to the top of unit 4, as these units consist of variable lithologies such as ice-loaded till and glaciofluvial sand.

Due to the scarcity of available seismic lines in the Bornholm Syd area, the mapped thickness distribution of the individual units is only shown along the actual lines in Figure 8.11 to Figure 8.13.

The thickness of Unit 1, Holocene sediments, shown in Figure 8.11, is generally only up to a few metres. However, in the easternmost part, the thickness appears to increase to about 10 m in larger filled-in depressions. Moreover, along line ENS22_BO-11, discrete sections less than 1 km wide show markedly larger thicknesses of Holocene sediments. The features probably represent older filled-in channels, which may cross the central to northern part of the Bornholm Syd area.

The combined thickness of Unit 1 and 2, Holocene and late glacial sediments which have not been ice-loaded, is shown in Figure 8.12. The thickness is generally about 10-15 m, being thinner in the northwestern part where subrecent erosion has taken place, and somewhat thicker in the eastern and southern part where subrecent erosion appear to have been absent. In the easternmost part of lines ENS22_BO-01 and -04, the thickness increases to 20-30 m.

The thickness of Unit 3, glacial sediments, shown in Figure 8.13., is quite variable, from only a few metres to more than 50 m. This reflects the local occurrence of buried glacial valleys. A particular large and deep one (more than 10 km wide, about 60 m deep) is observed in the southern part of the Bornholm Syd area. The other buried valleys observed, appear to be not more than a few kilometres wide and about 30-40 m deep.

The depth below seabed to the top of Unit 4, the pre-Quaternary, shown in Figure 8.14., is varying from less than 10 m to more than 70 m. The depth variation is obviously reflecting the local occurrence of glacial erosion into the pre-Quaternary surface in connection with tunnel valley formation.

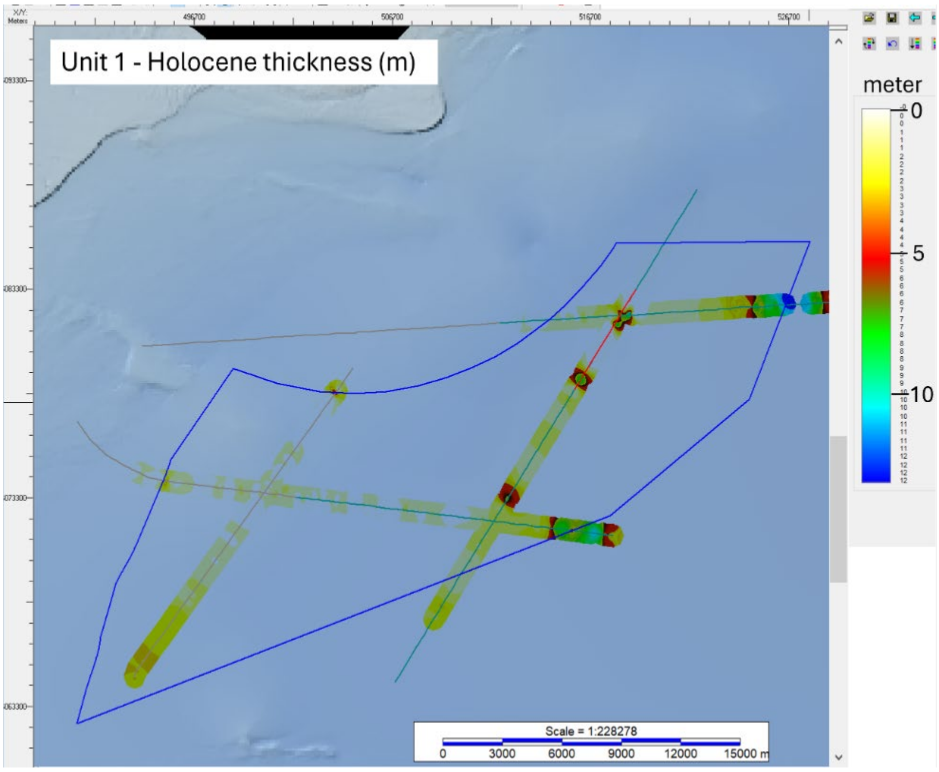


Figure 8.11. Mapped thickness of Unit 1 (Holocene sediments) along interpreted seismic lines.

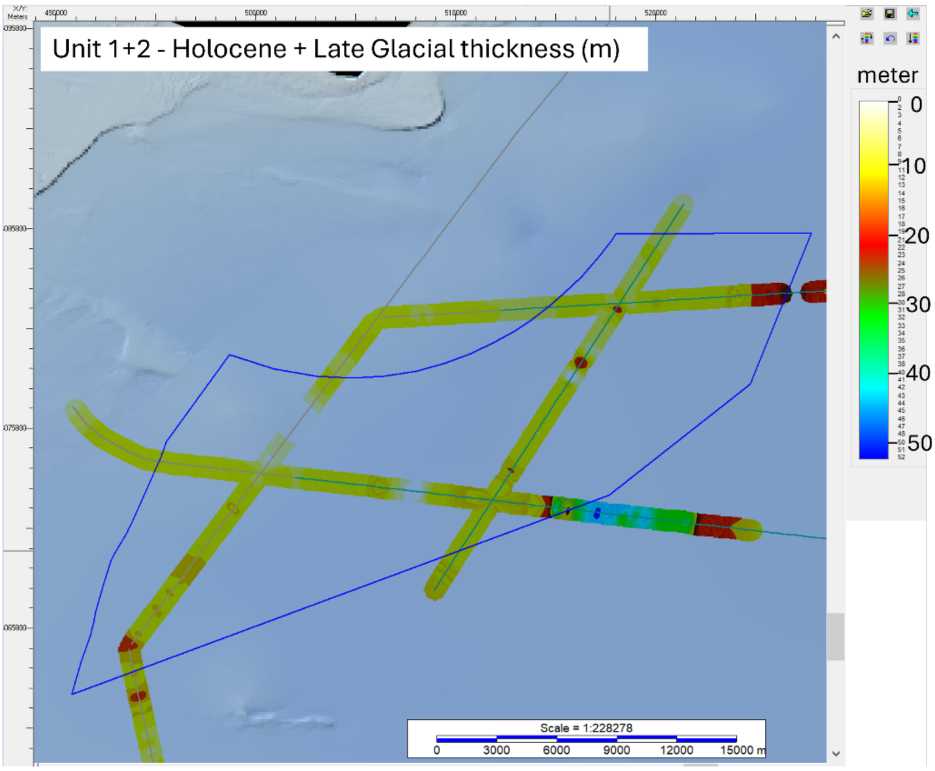


Figure 8.12. Mapped combined thickness of Unit 1 and 2 (Holocene and late glacial sediments) along interpreted seismic lines.

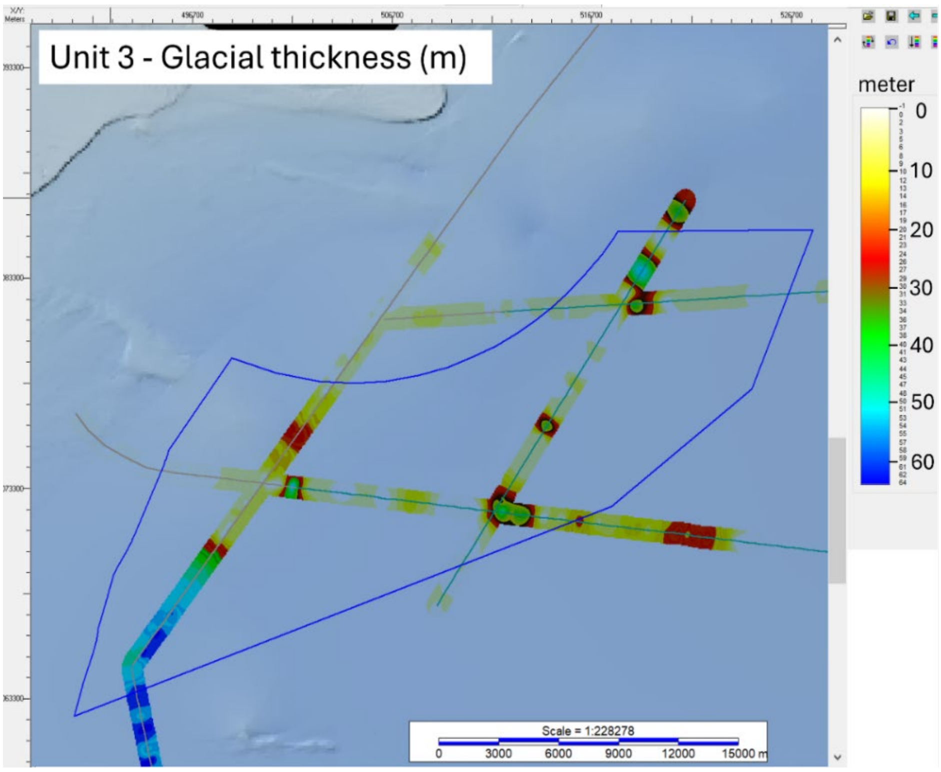


Figure 8.13. Mapped thickness of Unit 3 (glacial sediments) along interpreted seismic lines.

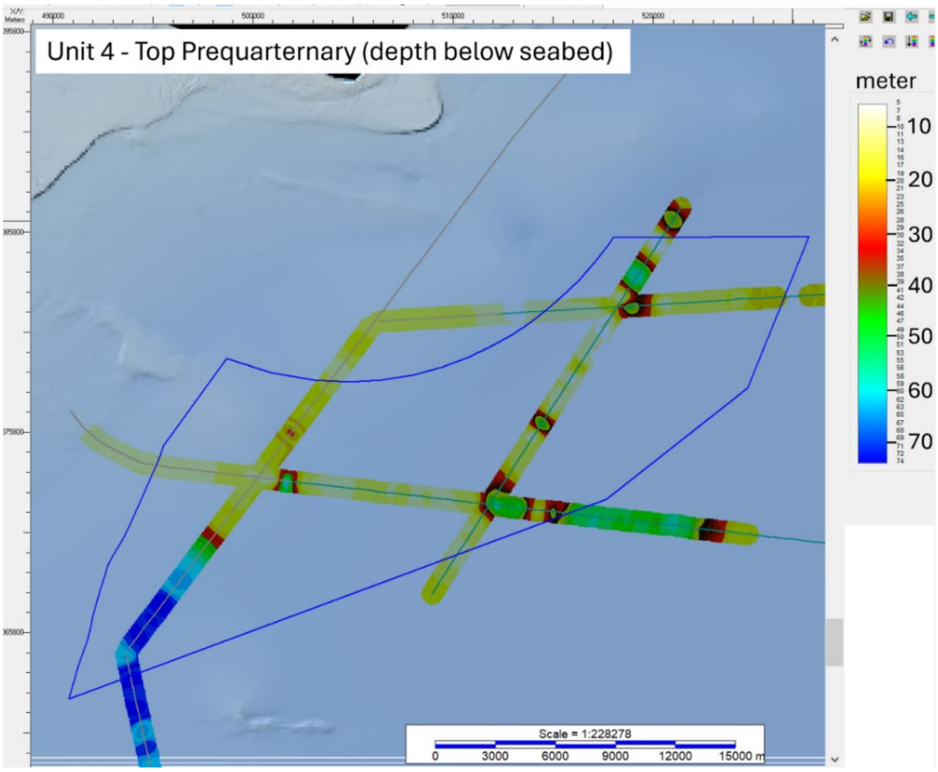


Figure 8.14. Depth below seabed of top of Unit 4, pre-Quaternary sediments.

9. Key geological and geotechnical conditions

The Bornholm Syd desk study has revealed geological and geotechnical conditions and sediment characteristics that may have implications for the assessment of wind farm foundation conditions. These are described in more detail in section 9.1 to 9.4 below. But first, a number of typical Danish sediment types/geological conditions and their general implications for offshore wind are shortly discussed here:

- Soft silty clays and gyttja
- Peat layers
- Marine dynamic sand deposits
- Overconsolidated glacial sediments
- Glaciotectonic deformations
- Buried Quaternary valleys/paleo-channels
- Shallow gas
- Shallow bedrock

With reference to Velenturf et al. (2021), some of the possible geotechnical implications of these geological conditions are described below.

Soft sediments (e.g. soft clay, mud, gyttja, peat) can imply a risk for low geotechnical strength and be a challenge for both the foundation design and for e.g. large jack-up rigs in the construction phase, while sand deposits normally are well suited.

Marine dynamic sand deposits may imply migrating erosional and depositional bedforms that can change the seabed topography over the operational lifetime of an OWF site in terms of scouring or burial of e.g. piles or cables or even jack-up legs in the construction phase.

Old glacial deposits may represent overconsolidated sediments with high geotechnical strength but can also provide a difficulty during construction e.g. for driving piles. They may also comprise more specific hard, potentially heterogeneous, coarse lag deposits (gravel to boulders) that can be difficult to penetrate and may lead to refusal of foundation infrastructure or damage of equipment. Near the seabed, a hard, heterogeneous surface can make it more difficult to predict scour behavior. Furthermore, the sediment thickness and lithology may vary abruptly over short distances especially in the glacial deposits, and the Quaternary deposits in general, complicating turbine siting and cable routing as well as foundation design(s). In glaciotectonically deformed areas, steeply dipping and alternating layering may occur with dislocated floes of soft sediments and abrupt changes in geotechnical properties.

The occurrence of paleochannels or buried valleys with steep sides may also imply sharp variations in sediment composition in either side and within the channel fill, potentially complicating foundation design.

Shallow gas (or over-pressured pore fluids) may lead to blow outs when drilling for sediment sampling and infrastructure construction. The presence of shallow gas/pressured fluids may be indicated by pockmarks in the seabed and can also be indicated by acoustic blanking of seismic reflection data, preventing interpretation of units below. Pockmark areas can be unstable and should be avoided for turbine locations and cable routing.

Shallow bedrock will often have high geotechnical strength that potentially may be problematic but can also be weathered and with lower strengths at the interface with Quaternary sediments.

In Table 9.1 an overview of sediment types identified in the screening area, related potentially critical geotechnical conditions and general foundation suitability is given.

Table 9.1. Overview of typical Danish sediment types and related potentially critical geotechnical conditions and general foundation suitability.

Sediment type	Critical geotechnical conditions/challenges	Foundation suitability
Marine sand	n.a.	Well suited
Marine clay/soft mud	Low geotechnical strength	Not well suited if thick
Peat	High compressibility, low geotechnical strength	Not well suited
Glaciofluvial sand	n.a.	Well suited
Glaciolacustrine clay	Low geotechnical strength if not overconsolidated by ice sheet loading	Not well suited if thick
Moraine clay/till	Often, but not always, overconsolidated, potentially heterogeneous, can contain coarse lag deposits, boulder stones and dislocated slabs of older sediments	Potentially problematic
Buried valley sediments	Potentially heterogeneous with both glacial and non-glacial deposits, sharp variations in sediment composition across flanks and internally with abrupt changes in geotechnical properties	Potentially problematic
Glaciotectonic deformations	Often steeply dipping layers and very alternating layering, dislocated slabs of older sediments may occur and potentially abrupt changes in geotechnical properties	Potentially problematic
Gas or fluids in the sediments	Can lead to blow outs when drilling for sediment sampling and infrastructure construction, can cause acoustic blanking of seismic reflection data, preventing interpretation of units below	Potentially problematic
Overconsolidated sediments	Ice sheet loading or subaerial exposure and desiccation, can lead to overconsolidation of sediments and difficult testing and construction conditions	Potentially problematic
Shallow bedrock	Typically, high geotechnical strength that potentially may be problematic, can also be weathered with lower strengths at the interface with Quaternary sediments	Potentially problematic

9.1 Key geological conditions

Below the key geological conditions in the Bornholm Syd area with respect to offshore wind is described. It shall be noted that generalisations are made based on the investigation of only four seismic lines crossing the area.

- The thickness of the postglacial (Unit 1) and late glacial (Unit 2) relatively soft sediments is generally about 10-15 m. Thicknesses of 20 m or more, can be observed in filled-in depressions in the eastern-northeastern part of the Bornholm Syd area.

One seabed depression observed in the northern part of the Bornholm Syd area is still partly unfilled, showing a bathymetric low of about 5-8 m below the surrounding seabed. The structure appears to be connected to a similar channel structure in the Nord Stream 2 survey zone to the northwest and has also been located on seismic lines closer to Bornholm. It is unclear whether the observed filled-in depressions originate from older channel structures crossing the area, or if they represent local infilled seabed depressions.

- Glacial deposits (Unit 3), which can be expected to be overconsolidated, rock-bearing, and with glaciotectonic structures, are partly found as an irregular less than 5 m thick cover on top of pre-Quaternary deposits, but also as in-filled glacial valley structures, up to 50 m in thickness and a few km wide.
- A moraine ridge of thicker glacial deposits, rising about 15 m above the surrounding seabed, can be observed in the northwestern part of the Bornholm Syd area. The ridge appears to be a continuation of the ridge structure seen on the bathymetry map from Geodatastyrelsen and a moraine area indicated on the seabed sediment map of GEUS.
- Pre-Quaternary sediments (Unit 4), found about 10-50 m below the seabed, can be expected to consist of Upper Cretaceous chalk (can possibly be relatively soft) and Jurassic-Lower Cretaceous loosely cemented sandstone and mudstone. Stratification in the pre-Quaternary sediments is typically inclined with slopes up to 5 degrees, and faulted with folding structures observed along fault zones.
- Geotechnical risks and hazards in the Bornholm Syd area are likely to be comparable with the conditions in the Bornholm II OWF as reported by Rambøll (2024).

9.2 Correlation with the Bornholm II OWF area

In 2021 GEUS performed a desk study for Energinet of the Bornholm I and II OWF areas (Jensen et al. 2021), see Figure 3.1, and presented a seismic stratigraphy for the Bornholm Basin, see Figure 7.3. Subsequently in 2022, Energinet has performed comprehensive geophysical and geotechnical surveys in the Bornholm II OWF area, and the seismic units and geotechnical soil units in the integrated ground model established by Rambøll (2024), is to some extent following the seismic stratigraphy for the Bornholm Basin, see section 8.4.2, but is not identical. In Figure 9.1 is shown a comparison of the units in the two studies.

The geophysical mapping of the Bornholm II OWF area includes approx. 7107 km ultra-high resolution multichannel seismic data in a 250 x 1000 m line grid. The geotechnical data comprise 20 geotechnical boreholes to a depth of 60-70 m and 53 shallow CPT tests, generally 5-10 m, but occasionally up to 20 m deep. Both the seismic data density and borehole information is thus incomparable with the few seismic lines and shallow vibrocores in the Bornholm Syd area and a much more detailed mapping has been possible in the Bornholm II OWF area. However, the conceptual geological model for the Bornholm Basin is well described and it seems reasonable to correlate the geotechnical results from the Bornholm II OWF area with the corresponding units mapped in the Bornholm Syd area.

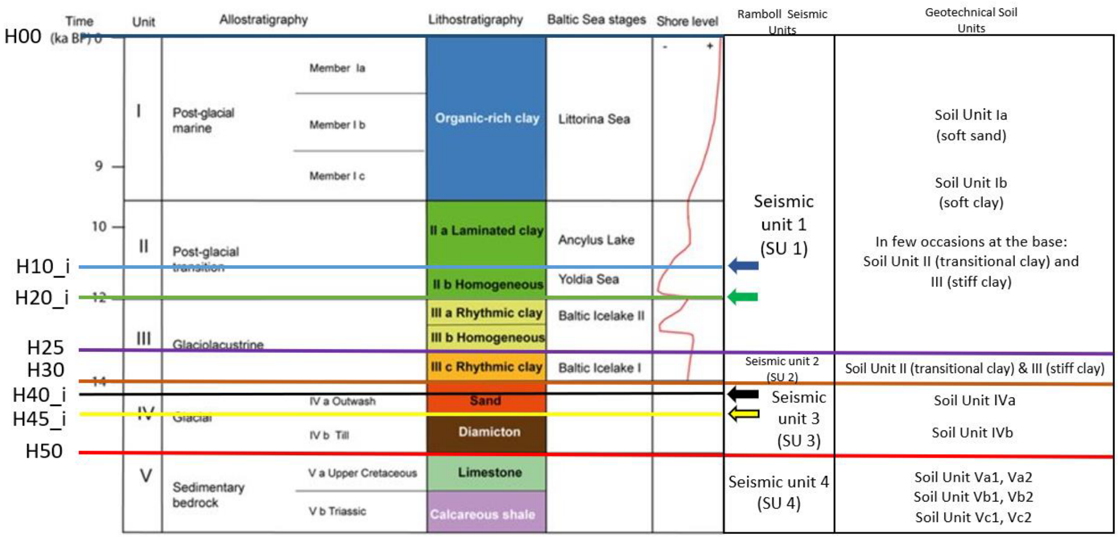


Figure 9.1. Overview of seismic units and geotechnical soil units in the integrated ground model established for the Bornholm II OWF area by Rambøll (2024) and compared to the seismic stratigraphy for the Bornholm Basin. The seismic units 1-4 in the present study corresponds to seismic units 1-4 in the figure with the exception that Seismic Unit 2 in the presents study include the lower part of Seismic Unit 1 in the figure, i.e. both Baltic Icelake II and I.

Seismic Unit 1 in the present study corresponds to the upper parts of Seismic Unit 1 in the Bornholm II OWF area and does not include the upper parts of the late glacial Baltic Ice Lake deposits as Seismic Unit 1 by Rambøll (2024) does.

Seismic Unit 2 in the present study hence include both the lower parts of Seismic Unit 1 and Seismic Unit 2 in the Bornholm II OWF area, while Seismic Unit 3 and 4 corresponds to the respective Seismic Units 3 and 4 in the Bornholm II OWF area.

In the following, the main geotechnical results from the Bornholm II OWF area will be correlated with the seismic units mapped in the Bornholm Syd area.

9.3 Key geotechnical conditions

As it can be seen from Figure 9.1 the seismic units in the Bornholm II OWF area have been divided into soil units.

Seismic Unit 1 in the present study corresponds to Soil Unit Ia and Ib in the integrated ground model established by Rambøll (2024).

The upper parts of Seismic Unit 2 also correspond to Soil Unit Ia and Ib and the lower parts corresponds to Soil Unit II and III. Seismic Unit 3 corresponds to Soil Unit IVa and IVb and Seismic Unit 4 corresponds to Soil Units Va1, Va2, Vb1, Vb2, Vc1 and Vc2.

Below a correlation is made between the seismic units and soil units and their properties in the Bornholm II OWF area (Rambøll 2024) and the seismic units mapped in this desk study. The lithological and geotechnical information are extracted from borehole and CPT locations in the Bornholm II OWF area as described by Rambøll (2024).

9.3.1 Seismic Unit 1 – Soil Units Ia and Ib

Seismic Unit 1 represents the post-glacial clay and marine sediments, deposited during the Yoldia Sea and Ancylus Lake stages in early Holocene and the Littorina Sea period in late Holocene. The thickness is generally a few metres, but up to 10 m in local depressions/channels.

The unit is primarily composed of clay and sandy mud with some organic content but may also locally include marine sand. It mainly corresponds to Soil Unit Ib in the Bornholm II OWF area, described as soft clay, and locally to Soil Unit Ia described as loose, low to medium strength sand.

9.3.2 Seismic Unit 2 – Soil Units Ia, Ib, II and III

Seismic Unit 2 represents late glacial Baltic Ice Lake clay deposited in a glaciolacustrine environment at the time of the retreat of the last Weichselian ice sheet and during the late glacial period. The thickness is generally 10-15 m, but thinner to the northwest and thicker to the southeast, locally up to 20-30 m.

The unit is composed of silty clay with some ice-rafted debris in the lower parts. The upper parts correspond to Soil Unit Ib in the Bornholm II OWF area, described as soft clay, while the lowermost part probably corresponds to Soil Unit II and III in the Bornholm II OWF area, described as transitional and stiff clays (geotechnically, transitional clay is a soil type which in terms of strength may behave more like a frictional soil than a cohesive soil).

9.3.3 Seismic Unit 3 – Soil Units IVa and IVb

Seismic Unit 3 represents glacial deposits, probably from several glaciations, with alternating layers of clay till and glaciofluvial sand, burying the topography of the underlying bedrock. In general, glaciofluvial sand is interpreted to cover the glacial till in large parts of the area. The thickness is generally a few metres, but up to 30-40 m in buried valleys and to the southwest more than 50 m in a very large buried glacial valley.

The unit is mainly composed of clay till alternating with sand and gravel. The clay till corresponds to Soil Unit IVb in the Bornholm II OWF area, described as very stiff clay till, while the glaciofluvial sand and gravel corresponds to Soil Unit IVa, described as dense glacial sand.

9.3.4 Seismic Unit 4 – Soil Units Va1, Va2, Vb1, Vb2, Vc1 and Vc2

Seismic Unit 4 represents pre-Quaternary Jurassic and Cretaceous deposits. The depth below seabed of the top of the unit is varying from less than 10 m to more than 70 m, reflecting local glacial erosion into the pre-Quaternary surface in connection with tunnel valley formation (buried valleys). The base of Seismic Unit 4 is below the seismic penetration and has not been mapped.

The unit is composed of chalk, sandstone, and mudstone (lithified to unlithified). In the Bornholm II OWF area, Seismic Unit 4 is subdivided into six soil units (or rock units). Soil Unit Va1 is described as soft, ranging from very weak to medium weak limestone/mudstone, whereas Soil Unit Va2 is described as hard, ranging from weak to extremely strong limestone/mudstone. Soil Unit Vb1 is described as soft chalk, while Soil Unit Vb2 is described as hard chalk. Soil Unit Vc1 is described as soft, extremely weak to weak sandstone, and Soil Unit Vc2 is described as hard, medium-strong to strong sandstone. It is likely, that the pre-Quaternary Jurassic and Cretaceous deposits mapped as Seismic Unit 4 in the Bornholm Syd area can also be regarded as ranging from soft and weak limestone/mudstone to hard and strong limestone/mudstone, from soft chalk to hard chalk and from soft and weak sandstone to hard and strong sandstone.

9.4 Geotechnical implications

Based on the geotechnical assessments by Rambøll (2024) of the soil units in the Bornholm II OWF area and the correlation with the geological units mapped in this desk study, the possible geotechnical implications for the Bornholm Syd area are described below.

The geological units and their distribution mapped in the area, together with the expected geotechnical properties, gives rise to the following conditions that should be noted for the Bornholm Syd area:

- Very soft sediments at shallow depths
- Sand overlying soft clays
- Irregular topography above very stiff sediments
- Potential boulders and block fields
- Shallow gas
- Shallow bedrock depths
- Very variable bedrock conditions at short lateral distances due to inclined bedding, faults and folding

9.4.1 Very soft sediments at shallow depths

Soft Holocene and late glacial sediments at the shallow subsurface are present throughout the entire Bornholm Syd area. The general thickness is around 10-15 m, but especially to the east the thickness can reach up to 20-30 m. According to Rambøll (2024) they may not provide sufficient strength for foundation design and may pose risks during pile installation and inadequate bearing capacity, necessitating the use of longer piles. Furthermore, very soft sediments may also be problematic with respect to penetration of jack-up legs of an installation vessel during construction because of the low bearing capacity and may imply a need for another type of installation vessel (Rambøll 2024).

9.4.2 Sand overlying soft clays

In the Bornholm II OWF area, Rambøll (2024) have identified areas with sand above soft clays from analyzing the CPT and borehole data, but it has not been possible to identify such sand areas based on the seismic data alone. If present, areas with sand above soft clays may potentially be problematic with respect to penetration of jack-up legs of an installation vessel during construction because of rapid penetration due to so-called punch through (Rambøll 2024). In the Bornholm Syd area such areas have also not been identified in the sparse seismic and borehole data but could be present e.g. in the channel structures.

9.4.3 Irregular topography above very stiff sediments

The surface of the stiff glacial sediments underlying the soft Holocene and late glacial deposits can locally have significant topography in the Bornholm Syd area and probably marks the change between the transitional clays (from soft towards stiff), and the very dense sand and clay tills. In the Bornholm II OWF area Rambøll (2024) describe that the irregular topography above very stiff glacial sediments may induce a risk for foundation tilt development, especially in the case of multiple-legged foundations. Slopes of up to 3-4 degrees have been observed in the Bornholm Syd Area.

9.4.4 Potential boulders and block fields

The surface of the glacial deposits marks a change in the depositional environment in the area where hummocky moraines were created during the retreat of the last Weichselian ice sheet from the Bornholm region. The depositional setting changed from one being influenced by the direct action of ice and/or ice melt, to deposition in a standing water body. It is very likely that blocks, boulders and even rafts of semi-coherent rock were deposited as the ice sheet retreated. The glacial deposits therefore not only have a very irregular surface topography but may potentially also contain blocks and boulders. In the Bornholm II OWF area, boulders have been mentioned/identified in four geotechnical boreholes and according to Rambøll (2024) they can be a risk for foundations of driven piles or monopiles, as the steel can get damaged in the case of large size boulders. Consequently, this may also be a potential hazard in the Bornholm Syd area, where scattered stones have been observed at the seabed on side-scan sonar data from the top of the moraine ridge in the northwestern part of Bornholm Syd. This may support that the glacial till unit mapped in the Bornholms Syd area in general is stone carrying.

9.4.5 Shallow gas

Shallow gas has been observed on all the seismic lines along sections with increased thickness of Holocene sediments in partly infilled older channel structures. Other areas with similar channels and/or shallow gas cannot be ruled out and should be taken into consideration.

9.4.6 Shallow bedrock depths

The relatively shallow bedrock depths in the Bornholm Syd area means that specific attention must be paid to the geotechnical properties of the bedrock which as described below, according to Rambøll (2024) potentially may be very variable. Furthermore, variations in bedrock depth may have an impact on choice of foundation type.

9.4.7 Variable bedrock conditions due to faults and folding

In the Bornholm II OWF area, very variable geotechnical conditions were identified with rock types ranging from soft and weak to hard and strong (Rambøll 2024). These variations can probably also be expected in the Bornholm Syd area and must be considered with respect to design and installation method.

10. Archaeological interests

The geological mapping is not only essential in the assessment of possible geotechnical implications. The geological development and distribution of land and lake/sea after the last deglaciation is also essential for the evaluation of potential archaeological interests.

During the period after the last deglaciation, the southwestern Baltic Sea region was characterised by highly fluctuating relative shore levels as seen in Figure 10.1. The relative shore level curve in the figure is based on radiocarbon dating of a number of samples collected from vibrocores in the region, see Table 10.1. Transgressions were interrupted by two abrupt forced regressions, the first around 12.800 years BP and the second around 11.700 years BP. Prior to these regressions, the Baltic Ice Lake was dammed by glacier ice in south-central Sweden. Following the retreat of the Scandinavian Ice Sheet, the dam was broken twice, and the shore level dropped by 20-25 metres over a few years. In the early Holocene, during the Yoldia Sea stage, the shore level increased rapidly, and continued to increase rapidly during the early part of the Ancylus Lake stage. The rapid increase was followed by a period with relatively stable shore level, but soon the rise continued, and around 7.000-8.000 years BP marine waters inundated the region, initiating the Littorina Sea stage. During the past 6.000 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 have been submerged.

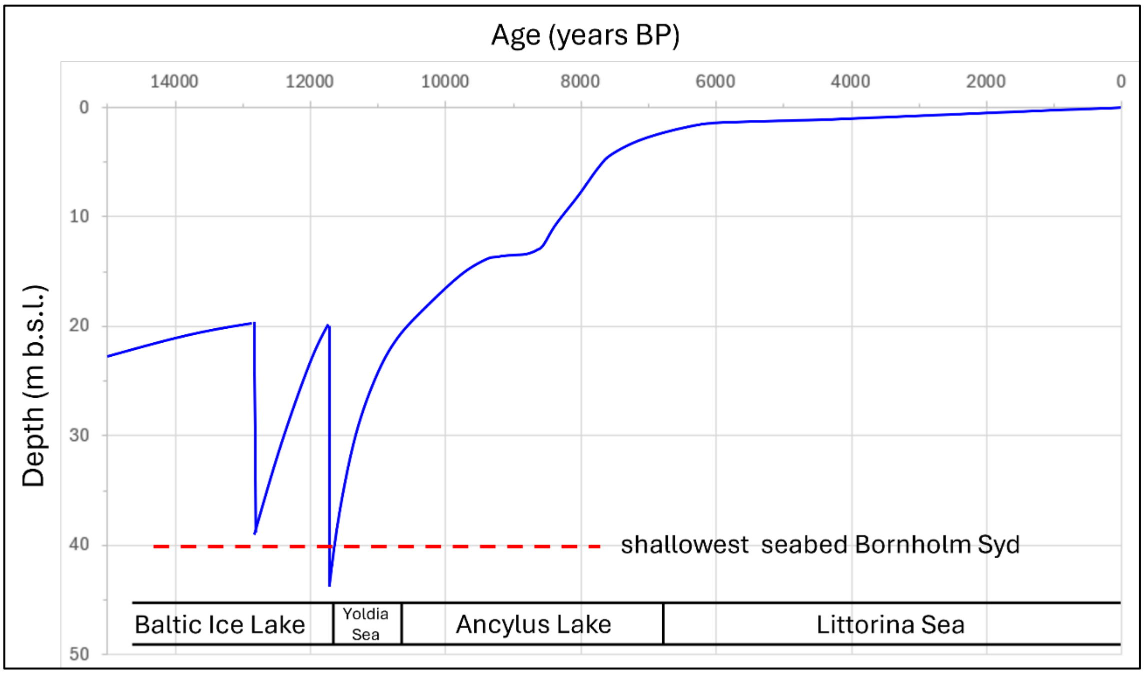


Figure 10.1. Shoreline displacement curve for the southwestern Baltic Sea. The curve is based on radiocarbon dating of samples collected from vibrocores, see Table 10.1.

Table 10.1. Selected radiocarbon ages from the Rønne Banke, Arkona Basin and Bornholm Basin region.

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).

The Bornholm area was deglaciated shortly after 15.000 years BP and high stand water-level characterised the initial period after the deglaciation. This corresponds to the archaeological Hamburg culture or Hamburgian (15.500–13.100 years BP) – a Late Upper Palaeolithic culture of reindeer hunters, but in this period, the Bornholm Syd area was covered by the glaciolacustrine Baltic Ice Lake (Figure 10.2).

The high stand period was followed by an abrupt regression and development of an erosional unconformity at around 12.800 years BP. During the low stand period the water level was about 40 m below present sea level. This means that the shallowest parts of the Bornholm Syd area, represented by the moraine ridge in the western part, would have been situated at the lake margin, whereas the remaining parts would have been lake-covered. The period corresponds to the Bromme culture, but the low stand period was short-lived and followed by a rapid transgression.

A new low stand period is dated to about 11.700 years BP, this time the water level was approx. 45 m below sea level and Bornholm was a peninsula connected to mainland Europe (Figure 10.2). In this period parts of the moraine ridge in the Bornholm Syd area, together with the shallower Rønne Banke would probably have been dry land. However, this second low stand period, corresponding to the early part of the Mesolithic period and the Maglemose culture in Denmark was also short-lived and followed by a new rapid transgression and the area was covered by the sea during the time windows of younger cultures.

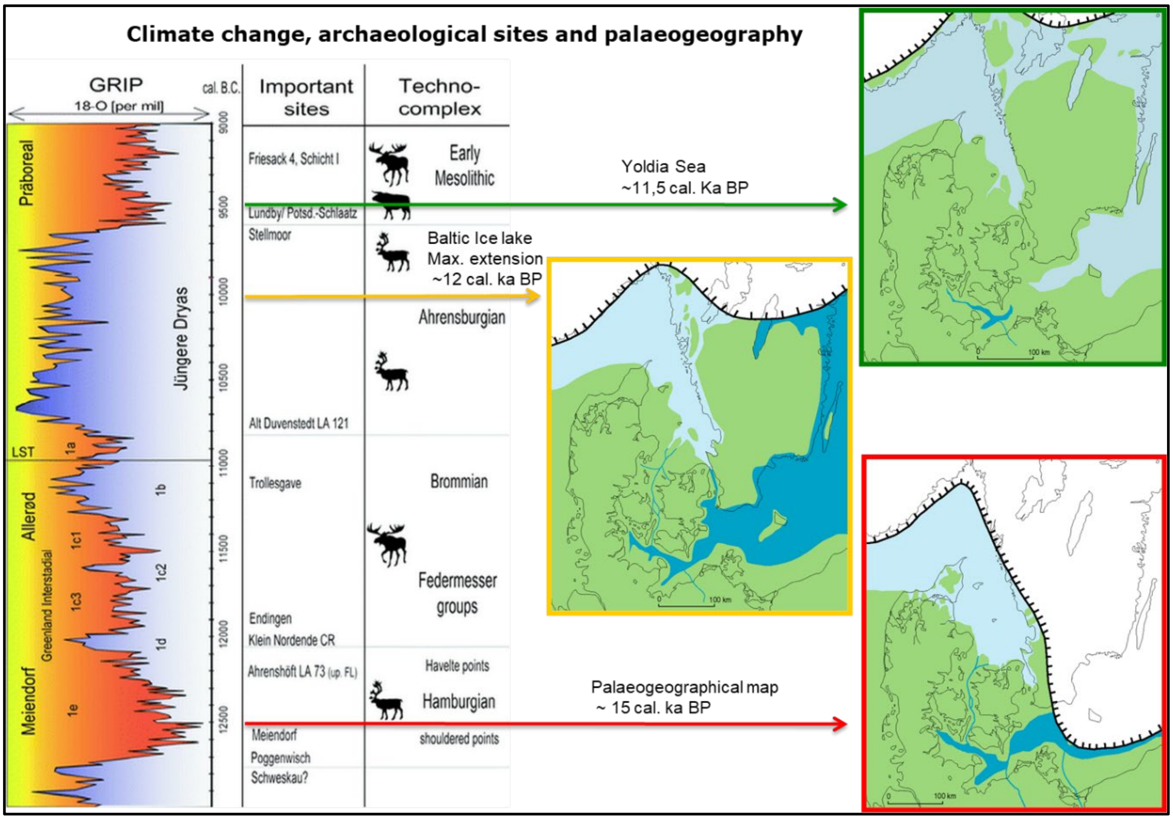


Figure 10.2. Late glacial and Holocene general palaeogeography in the Danish area and related archaeological cultures. The maps are from Jensen et al. (2003).

In contrast to the Bornholm Syd area, the shallow-water parts of Rønne Banke and potential cable corridor areas for a connection to Bornholm, would have been dry land for long periods. Submerged archaeological settlements from the Maglemose, Kongemose and Ertebølle Cultures are for example known from Mecklenburger Bucht off northern Germany (Schmölcke et al. 2006; Hartz et al. 2011; Lübke et al. 2011). However, the chances of finding submerged archaeological settlements are probably small in the Bornholm area in general due to the long fetch and high energy environment of the present-day sea.

11. Conclusions

Based on a combination of published work, existing seismic data and sediment cores as well as nearby geotechnical boreholes and CPT data, the general geological development in the Bornholm Region and specifically the Bornholm Syd area have been described.

Only a few existing seismic lines and shallow vibrocores have been available for the geological mapping of the Bornholm Syd area but based on a general conceptual geological model for the Bornholm Basin (Jensen et al. 2021) and detailed geophysical and geotechnical investigations as well as an integrated ground model for the nearby Bornholm II OWF area (Rambøll 2024), see Figure 3.1, the key geological and geotechnical conditions in the study area have been described, including an assessment of potential archaeological interests.

In Figure 11.1 a general thickness map of the unconsolidated soft sediments in the area around Bornholm, produced by GEUS in a current overall geological screening of Danish waters for offshore wind for the Danish Energy Agency, is shown. It appears from the map, that in terms of thickness of soft sediments, the Bornholm Syd area is very similar to the Bornholm II OWF area, but it should be kept in mind, that the amount of available data in the Bornholm Syd area has been very sparse, introducing a significant uncertainty compared to the detailed investigations in the Bornholm II OWF area.

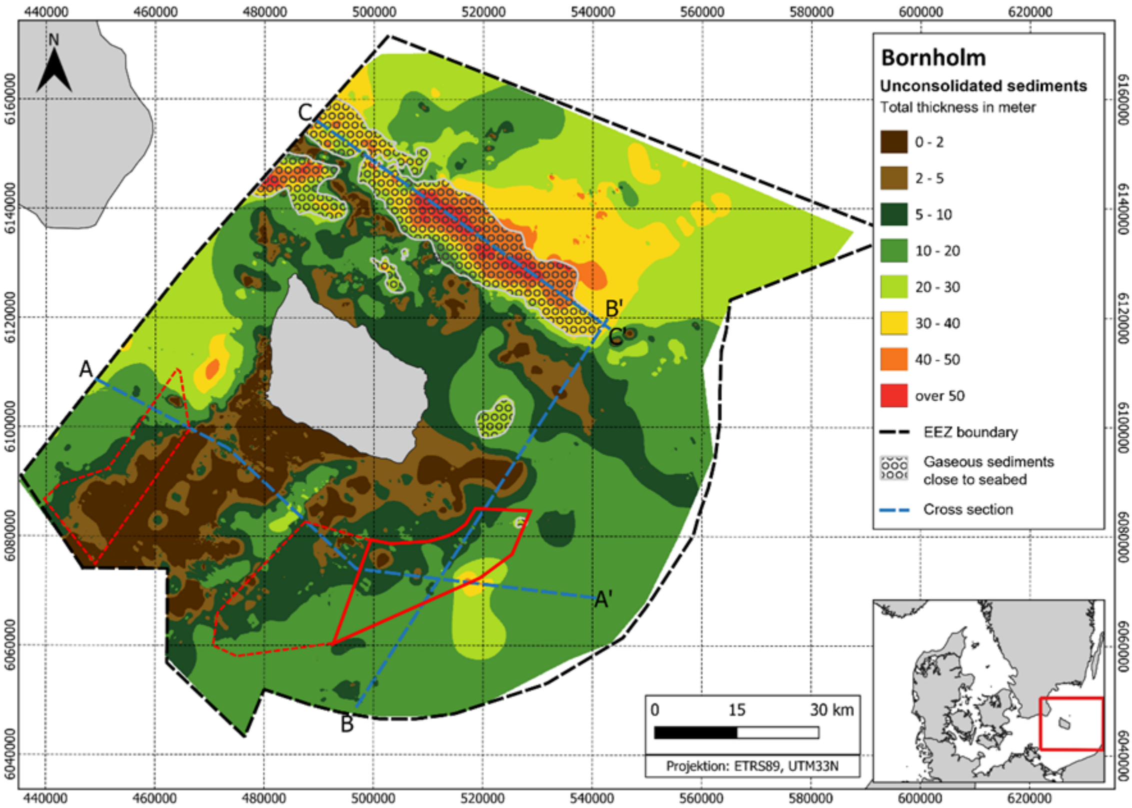


Figure 11.1. Map showing the combined thickness of unconsolidated soft sediments of Holocene and late glacial age. The Bornholm I and II OWF areas are shown with dashed red polygons and the Bornholm Syd area with a red polygon. Be aware that the map is based on very sparse data in the Bornholm Syd area.

The following key geological and geotechnical conditions with respect to offshore wind have been identified:

- The Bornholm Syd area is characterised by water depths of c. 40-70 m, with depths generally increasing from west to east with 40-60 m in the westernmost part and 60-70 m in the remaining area. The seabed is generally quite flat and with a gentle slope towards the east, but the few seismic lines reveal a higher lying moraine ground in the northwestern corner of the area and a channel or local depression in the seabed in the northeastern part of the area. Here it should be considered that the geological conditions can be expected to differ from the general surroundings.
- The distribution of seabed sediments reflects to some degree the bathymetry of the area with Holocene mud and muddy sand in the deeper parts and Quaternary clay and silt (late glacial Baltic Ice Lake deposits) in the shallower parts to the west and north, indicating non-deposition or erosion. This means a very soft seabed in the deeper parts and a harder seabed in the shallower parts.
- The combined thickness of the Holocene and late glacial relatively soft sediments is generally about 10-15 m but larger thicknesses of 20 m, or more, can be observed in filled-in depressions in the eastern-northeastern part of the Bornholm Syd area. The Holocene deposits are expected to be composed of mainly soft clay, but may also include loose sand, and the upper parts of the late glacial Baltic Ice Lake deposits are also expected to be composed of soft clay. The lower parts of the Baltic Ice Lake deposits are expected to be composed of transitional (geotechnically) clay and stiff clay. Generally, the Holocene and late glacial sediments can probably be expected to have relatively low geotechnical strength.
- Quaternary glacial deposits are partly found as an irregular, less than 5 m thick, cover on top of pre-Quaternary deposits, but also as in-filled glacial valley structures, up to 50 m in thickness and a few km wide. They are expected to be composed of stiff clay till and dense glaciofluvial sand, which are probably overconsolidated and may contain stones and boulders and with glaciotectonic structures. Stones and boulders can be a potential problem with regards to driving piles into the subsurface and glaciotectonic deformation can increase the heterogeneity of the geological layers.
- A moraine ridge of thicker glacial deposits, rising about 15 m above the surrounding seabed, can be observed in the northwestern part of the Bornholm Syd area. The ridge appears to be a continuation of a ridge structure seen in the detailed bathymetry map from Geodatastyrelsen and moraine is also indicated on the seabed sediment map of GEUS.
- Pre-Quaternary sediments are found about 10-50 m below the seabed and can be expected to consist of Upper Cretaceous chalk (can possibly be relatively soft) and Jurassic-Lower Cretaceous loosely cemented sandstone and mudstone. The stratification in the pre-Quaternary sediments is typically inclined with slopes up to 5 degrees and faulted with folding structures observed along fault zones. Based on investigations in the Bornholm II OWF area, the Jurassic and Cretaceous deposits in the Bornholm Syd area can possibly be regarded as ranging from soft and weak limestone/mudstone to hard and strong limestone/mudstone, from soft chalk to hard chalk and from soft and weak sandstone to hard and strong sandstone and thus expectedly with large variations in geotechnical strength.

Based on the geotechnical assessments by Rambøll (2024) of the soil units in the Bornholm II OWF area and the correlation with the geological units mapped in this desk study, the following possible geotechnical implications for the Bornholm Syd area have been identified:

- The soft Holocene and late glacial sediments at the shallow subsurface in the Bornholm Syd area may not provide sufficient strength for foundation design, necessitating the use of longer and more expensive piles and low bearing capacity of the soil may also be problematic with respect to penetration of jack-up legs of an installation vessel and imply a need for another type of installation vessel.
- If present, areas with sand above soft clays may potentially also be problematic with respect to penetration of jack-up legs of an installation vessel during construction as low bearing capacity in soft clay below sand may cause rapid leg penetration due to so-called punch through. Such areas have not been identified in the sparse seismic and borehole data in the Bornholm Syd area but could be present e.g. in the channel structures.
- The surface of the stiff glacial sediments underlying the soft Holocene and late glacial deposits can locally have significant topography in the Bornholm Syd area, where slopes of up to 3-4 degrees have been observed. This could potentially induce local risk for foundation tilt development, especially in the case of multiple-legged foundations.
- The glacial deposits in the Bornholm Syd area may potentially contain blocks and boulders that can be a risk for foundations of driven piles or monopiles, as the steel can get damaged in the case of large size boulders.
- The relatively shallow, but varying, bedrock depths in the Bornholm Syd area means that specific attention must be paid to the geotechnical properties of the rocks which potentially may be very variable. Thus, the shallow bedrock includes rock types probably ranging from soft and weak to hard and strong and these variations together with bedrock depth must be considered with respect to design, foundation type and installation method.

Based on a late glacial and Holocene relative shore level curve for the southwestern Baltic Sea, an assessment of potential archaeological interests has been made:

- In two very short time intervals at c. 12.800 and 11.700 years ago, corresponding to the Bromme and Maglemose cultures, the shallowest parts of the Bornholm Syd area to the west and north may potentially have been dry land or near the coast. Potential cable corridor areas on the shallow-water parts of Rønne Banke and near Bornholm have probably been dry land for long periods but the chances of finding submerged archaeological settlements are probably small in the Bornholm area in general due to the long fetch and high energy environment of the present-day sea.

The above conclusions for the Bornholm Syd area with respect to the suitability of the area for offshore wind from a geological viewpoint, can be summed up in the following statements:

The geological conditions in the Bornholm Syd area, and thus the suitability for offshore wind of the area, are expected to be very similar to the Bornholm II OWF area where detailed investigations have recently been carried out. Especially it seems likely that the thickness of relatively soft Holocene and late glacial sediments is comparable.

Based on the sparse amounts of data and correlation with the Bornholm II OWF area, it is most likely possible to establish offshore wind in the Bornholm Syd area from a geological point of view. However, like in the Bornholm II OWF area, challenging ground conditions including the thickness of soft soils, irregular topography above stiff sediments, boulders in clay till and highly variable strength of bedrock found at a relatively shallow depth. These are conditions which potentially can increase the costs and must be taken into consideration.

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