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Geological screening of Kattegat Area A and B

Geological seabed screening in relation to possible location of windfarm areas

Jørn Bo Jensen & Ole Bennike

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

G E U S

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Client Danish Energy Agency

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G E U S

Table of contents

1. Summary

The Danish Energy Agency has requested that GEUS undertakes a geological screening study of the Kattegat Area A and B potential offshore wind farm (OWF) areas. The study has resulted in a general geological description and establishment of a geological model. The study is based on existing data and is to be used as a background for evaluation of wind farm potential sites and a background for future interpretations of new seismic data, geotechnical investigations and an archaeological screening.

In this study we have used a combination of published work, GEUS archive seismic data and sediment core data to assess the general geological development of the southern Kattegat area, including the potential Area A and B OWF.

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

As part of the geological desk study, we present a relative Late Glacial and Holocene sea-level curve for the area and describe the development that is relevant for an archaeological screening.

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

The geological model of the southern Kattegat is based on the previous geological screening report GEUS (2020) for Hesselø OWF, the seismic interpretation report Fugro (2021) and sediments geotechnical parameters from the Gardline (2021) report.

The mapping results are presented as seismic examples and general thickness maps of Area A and B geotechnical soft sediments (Figure 1.1), together with geotechnical soft sediment thickness maps for Hesselø OWF and Anholt OWF.

Several conclusions relevant for the future geotechnical and archaeological evaluations of Area A and B are presented and can be summed up in these statements:

From a geological viewpoint, the soft sediments in the northern and central parts of area A, with a thickness < 30m, are expected to be similar to the southeastern part of the Hesselø area with a thickness < 30m (Figure 1.1).

In the southern part of Area A and in all of Area B, there are expected similar soil conditions as in Anholt OWF meaning, from a geological point of view, it is most likely possible to establish OWF in these areas

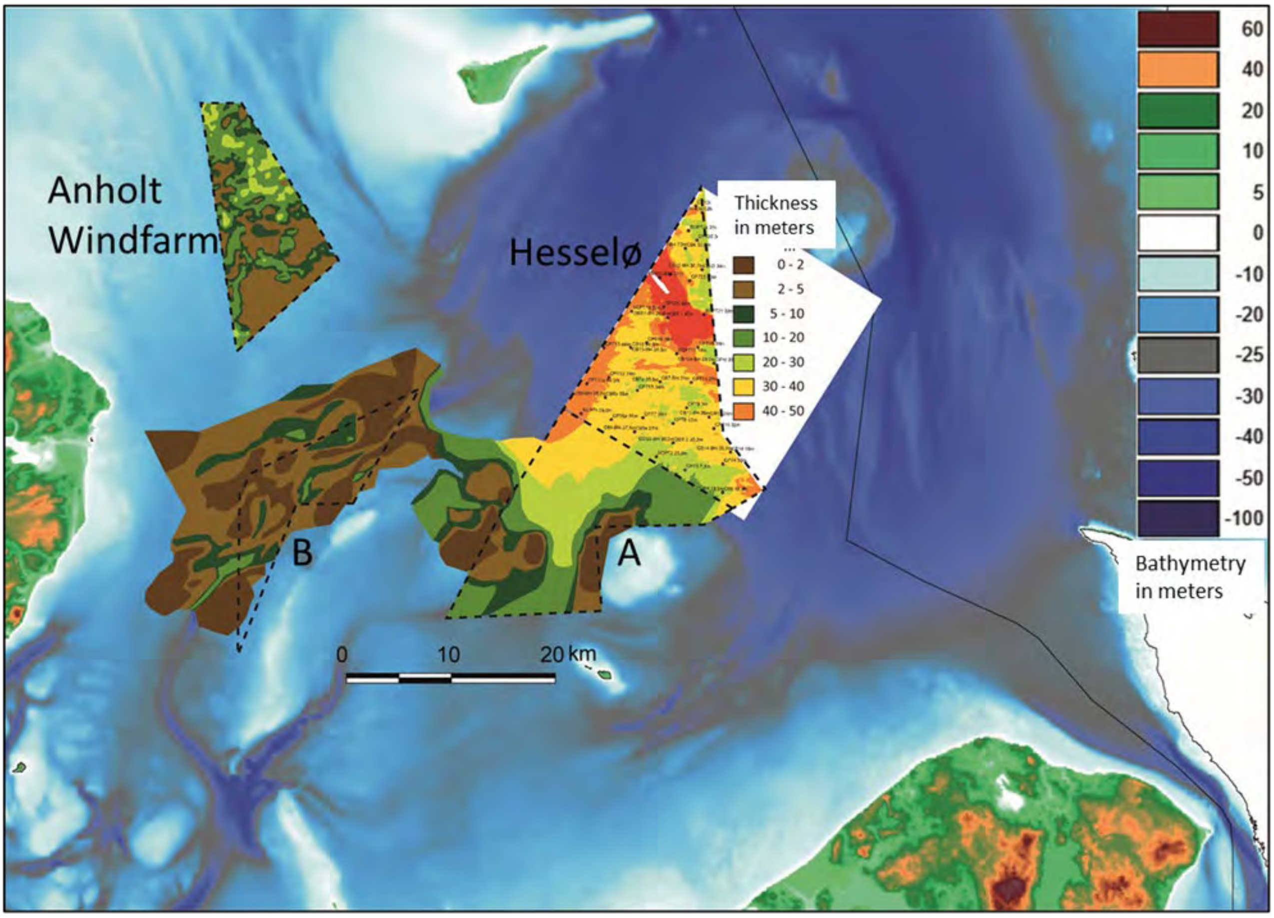


Figure 1.1 Thickness of geotechnical soft sediments in the southern Kattegat Anholt OWF and potential Hesselø, Area A and B. For details see Appendix C.

2. Resumé

Energistyrelsen har bedt GEUS om at udføre en geologisk screening af de potentielle havvindmølle parker områder A og B, i sydlige Kattegat. Undersøgelsen har resulteret i en generel geologisk beskrivelse og en geologisk model. Studiet er baseret på eksisterende data og er tænkt som baggrund for en vurdering af områdernes vindmølle potentiale, samt som baggrund for eventuelle fremtidige tolkninger af seismiske data, geotekniske undersøgelser og arkæologisk screening.

I studiet har vi benyttet en kombination af publicerede artikler og rapporter, samt GEUS-arkiv seismiske data og boringer, til at vurdere den generelle geologiske udvikling i den sydlige del af Kattegat, inklusive de potentielle havvindmølle områder A og B.

Der er give en geologisk beskrivelse og der er udviklet en geologisk model.

Som en del af studiet præsenterer vi en lokal relativ havniveaukurve der dækker de Holocæne og senglaciale perioder. Desuden beskriver vi udviklingshistorien, som er relevant for en efterfølgende arkæologisk screening.

Den generelle geologiske beskrivelse inkluderer en komplet succession fra den præ-Kvartære ramme, den præ-Kvartære overflade, glaciale aflejringer, den glaciale afsmeltning samt senglaciale og Holocæne aflejringer.

Den geologiske model omhandlende den sydlige del af Kattegat er baseret på den tidligere geologiske screening rapport (GEUS 2020) for Hesselø OWF, den seismiske tolkningsrapport Fugro (2021) og de sedimentologiske geotekniske parametre fra Gardline (2021) rapporten.

Kortlægningsresultaterne er præsenteret i form af seismiske eksempler og generelle kort over tykkelsen af geoteknisk set bløde sedimenter i område A og B (Figur 1.1), samt Hesselø OWF og Anholt OWF.

Der præsenteres adskillige konklusioner, som er relevante for fremtidige geotekniske og arkæologiske vurderinger af område A og B.

Konklusionerne kan i korthed sammenfattes til:

Set fra et geologisk synspunkt, kan det forventes at de bløde sedimenter i den nordlige og centrale del af område A (med tykkelser på< 30m), er sammenlignelig med de bløde sedimenter (med tykkelser < 30m) i den sydøstlige del af Hesselø området (Figure 1.1).

Jordbundsforholdene i den sydlige del af område A og hele område B forventes sammenlignelige med Anholt OWF. Dette indikerer, fra et geologisk synspunkt, at det er muligt at anvende disse områder til OWF.

3. Introduction

GEUS has been asked by the Danish Energy Agency to provide an assessment of the seabed in the Kattegat potential OWF areas A and B located south and southwest of the Hesselø OWF. The assessment consists of the establishment of a geological model based on existing data as a background for evaluation of suitability for wind farm establishment and a marine archaeological screening (Figure 3.1).

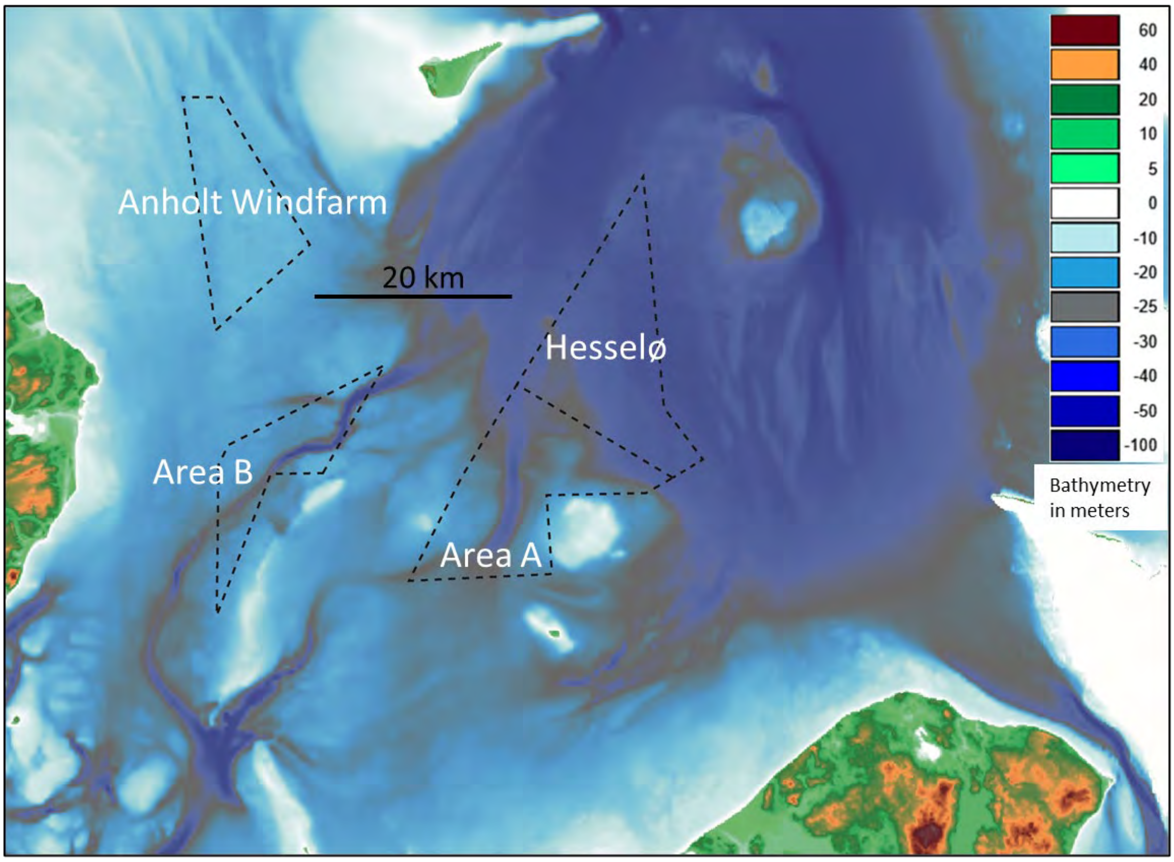


Figure 3.1. The location of the existing Anholt OWF, the planed Hesselø OWF and the potential OWF areas A and B in the southern part of the Kattegat region. Bathymetry from www.emodnet-bathymetry.eu.

4. Data background

As a basis for the desk study, existing background reports from The Danish Energy Agency https://ens.dk/en/our-responsibilities/wind-power/ongoing-offshore-wind-tenders/hesselo-offshore-wind-farm/preliminary have been used together with primary data from the GEUS Marta database (https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/marin-raastofdatabase-marta/), which is the main supply of shallow seismic data and vibrocore data (Figure 4.1). In addition, data not included in the Marta database have been used. These data comprise scientific multichannel data, data from IOPD core M0060, parasound sediment echosounder data and vibrocore data from the scientific cruise Maria S. Merian MSM62.

4.1 Background reports

In the geological screening report (GEUS 2020) the general geology of the region has been presented and existing seismic facies units have been described.

In the following detailed Hesselø OWF geophysical acquisition and interpretation report Fugro (2021) the seismostratigraphic units have been expanded with a few subunits, due to more information. The general stratigraphy remains but renamed to units A to I (Chapter 6, Table 1). In the present report the A to I names of the units are maintained.

Detailed information about the lithology and geotechnical parameters of the sediments from the coring activities in Hesselø OWF are found in the Gardline (2021) report and results from the report have been included in the present report evaluation of seismic units in the potential OWF areas A and B.

Seismic and coring information from the Hesselø export cable routes is reported by Rambøll (2021).

Soft sediments became an issue in the Hesselø OWF area and a summary of information from the previous reports has been presented in the Energinet (2021) Hesselø technical dialogue of soft sediments.

4.2 GEUS archive shallow seismic data and sediment cores

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

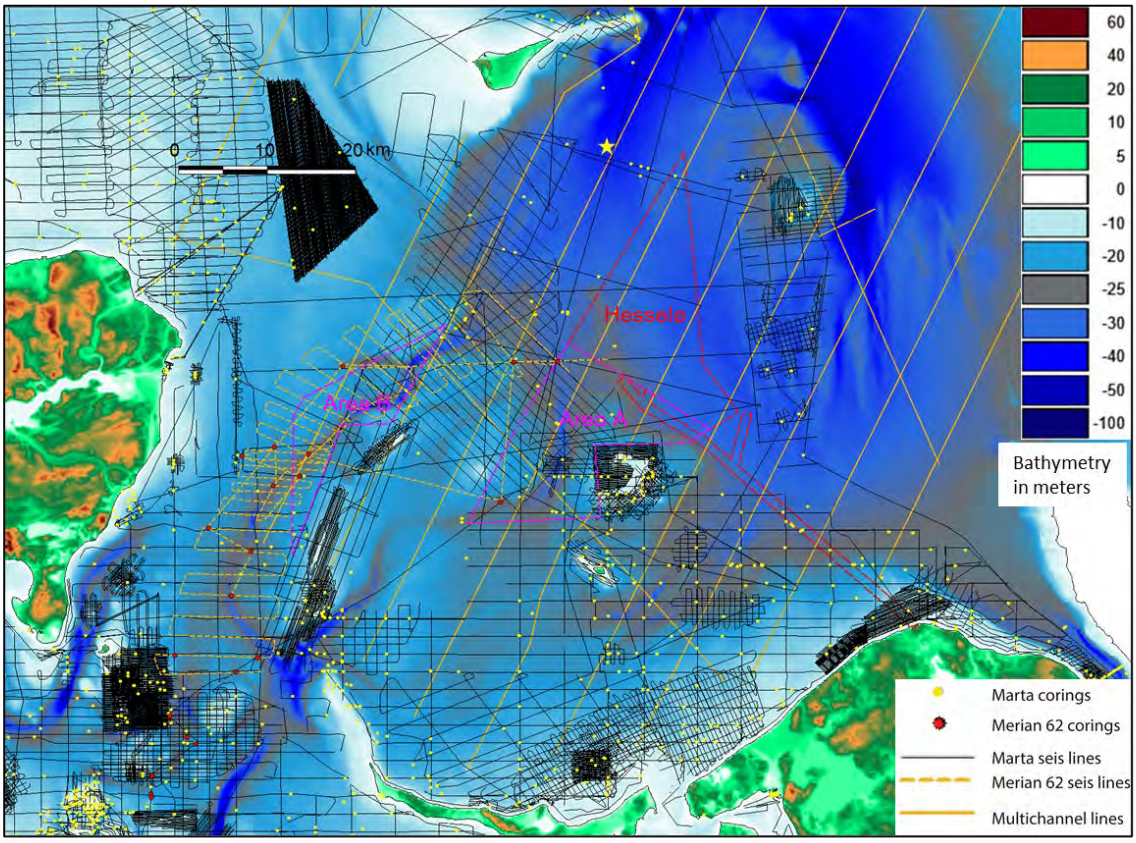


Figure 4.1. Distribution of Marta database seismic grid and core data in the southern and central Kattegat region. The planed Hesselø OWF and cable transects (red polygons) as well as the potential OWF areas A and B (purple polygons) the southern part of the Kattegat region. Bathymetry from www.emodnet-bathymetry.eu

4.3 Maria S. Merian MSM62 cruise data

An important part of the archive seismic and coring data background information comes from a scientific cruise in 2017 with the German research ship Maria S. Merian. Parasound sediment echosounder data supplemented with vibrocore data provide detailed information on the sediment distribution, especially in Area B.

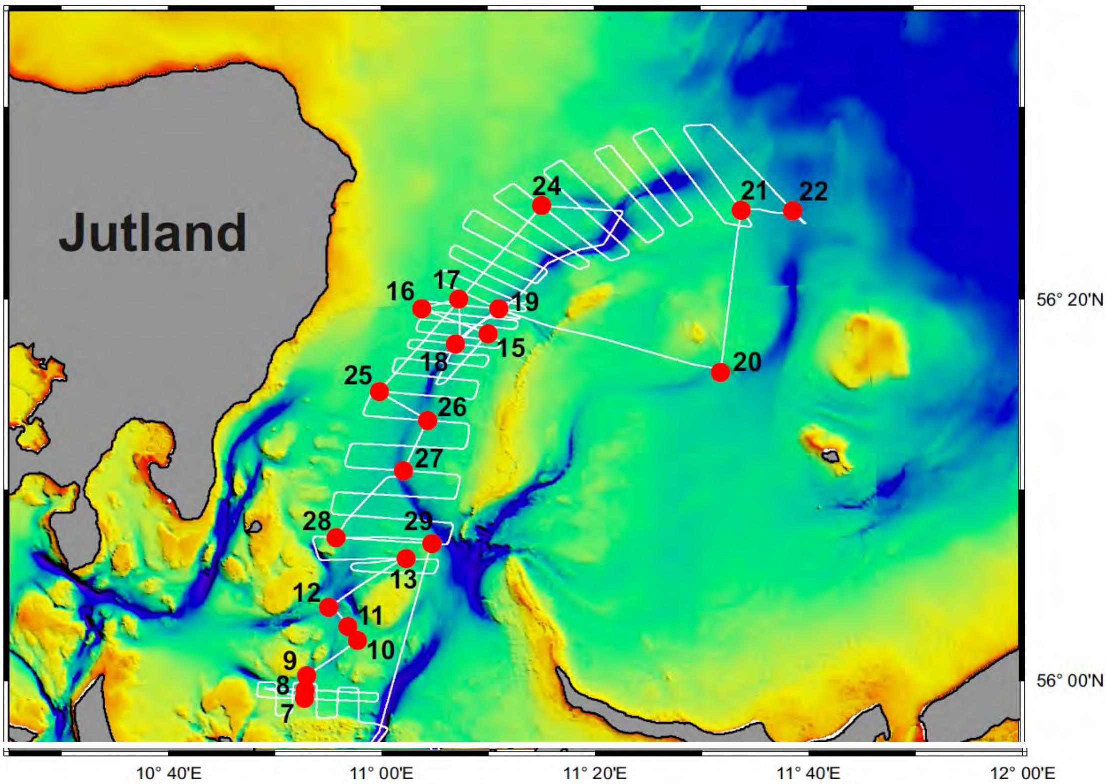


Figure 4.2 Maria S. Merian MSM62 cruise data from the southwestern Kattegat.

5. Geological setting

5.1 General pre-Quaternary framework

The Kattegat area of Denmark is dominated by the Sorgenfrei–Tornquist fault Zone with a south-east to north-west orientation, from Skåne in southern Sweden through Kattegat to northern Jylland (Figure 5.1). The fault system has been active since the Palaeozoic and even as late as the Quaternary (Jensen et al., 2002, GEUS 2020)), as a result of glacio-isostatic (re)adjustments following ice sheet advances and retreats. The major faults of the Sorgenfrei–Tornquist Zone, the Børglum and the Grenå–Helsingborg Faults dominate the pre-Quaternary setting in the wind farm areas with a south-east to north-west orientation (Figure 5.1).

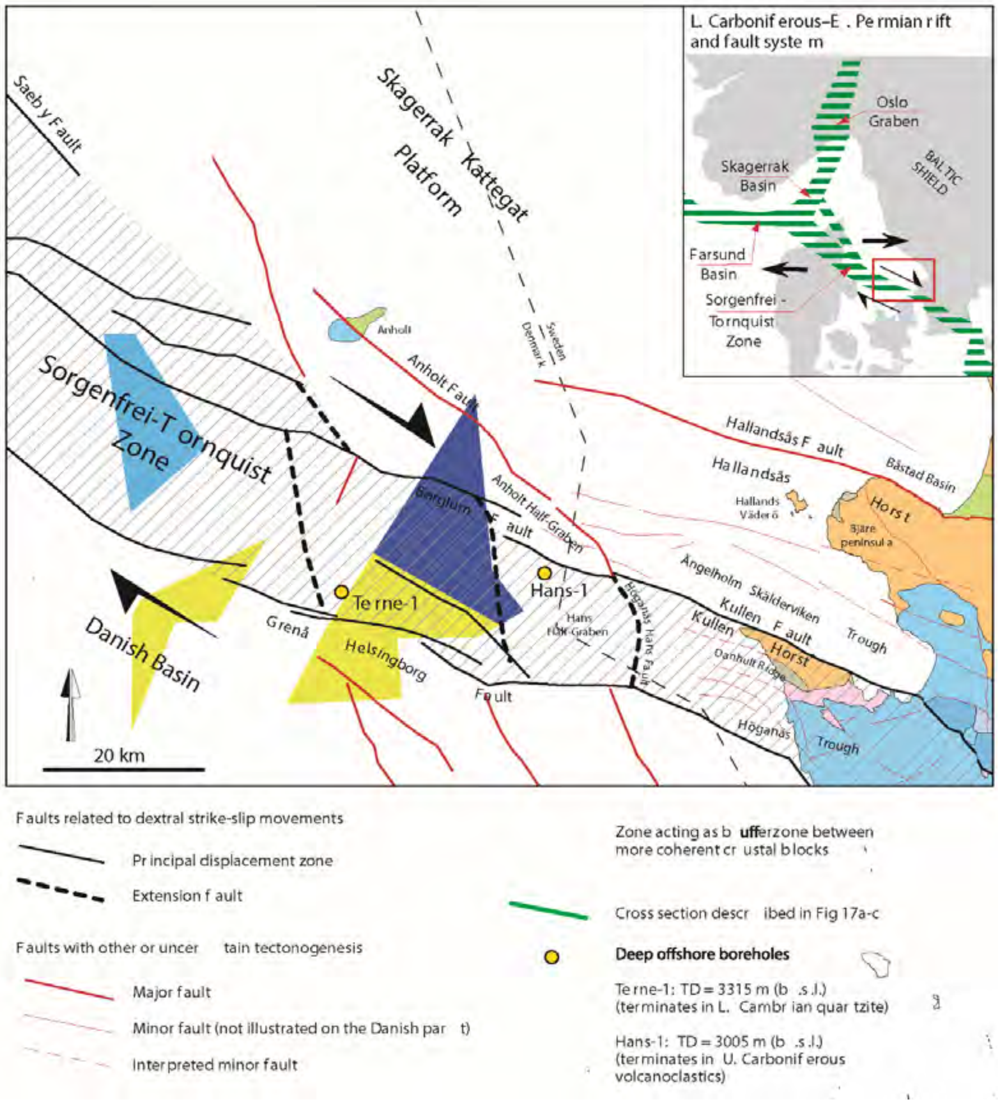


Figure 5.1. Regional structures in the southern part of the Kattegat (Erlström and Sivhed 2001). The locations of the existing Anholt OWF (light blue), the planed Hesselø OWF (dark blue) as well as the potential OWF areas A and B (yellow) are indicated.

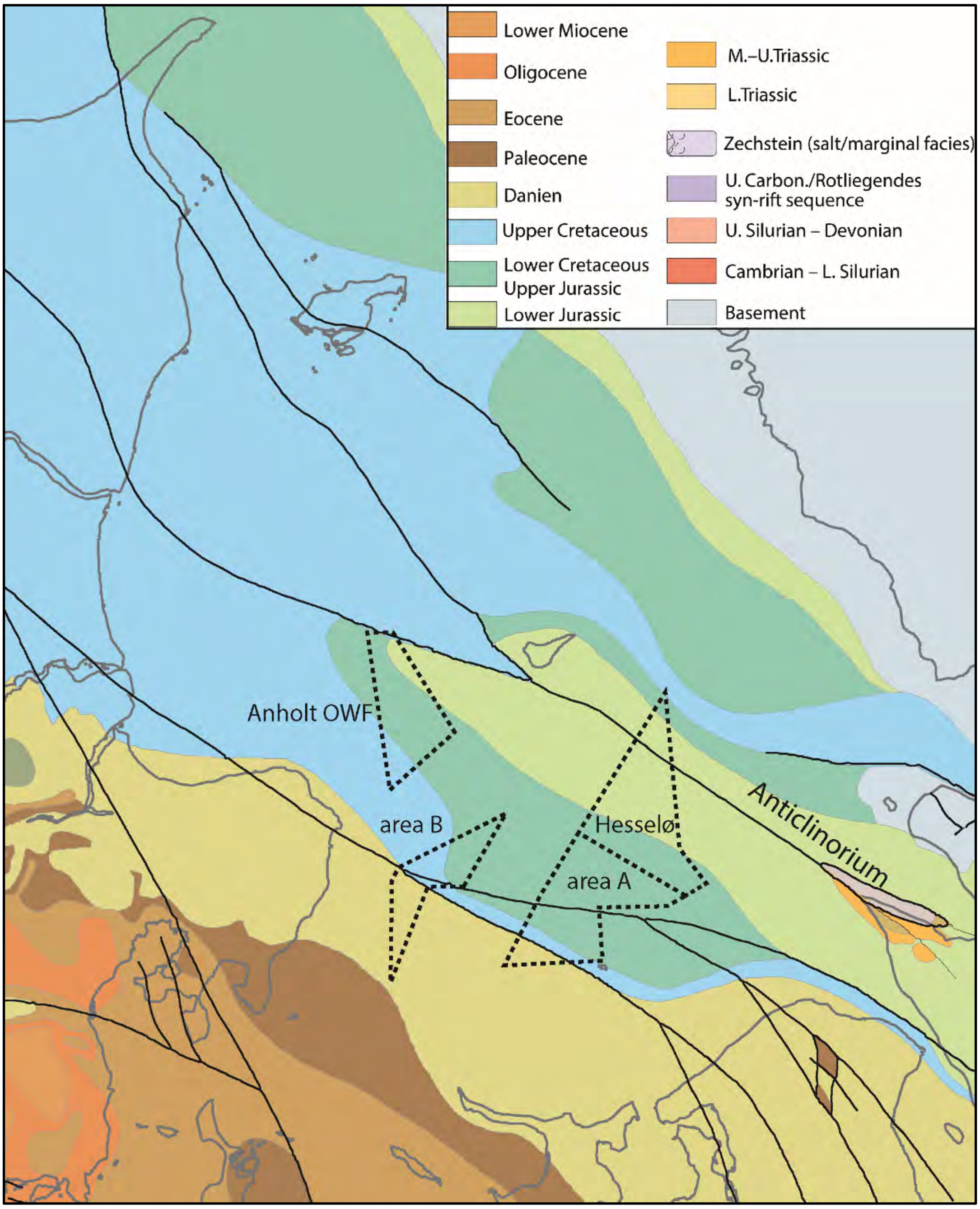


Figure 5.2. Pre-Quaternary surface geology and major faults in the Kattegat. The locations of the OWF's are indicated.

The pre-Quaternary stratigraphy and surface morphology have been studied by Gyldenholm et al. (1993), Lykke-Andersen et al. (1993) and Binzer & Stockmarr (1994). These studies show that the NW-dipping crystalline anticlinorium is bounded by Jurassic, Cretaceous and Tertiary sediment strata in a mainly fault-dominated structural setting (Figure 5.2). The bedrock at the OWF sites consists of Jurassic sandy mudstone and Upper Cretaceous limestone and glauconitic sandstone (Erlström and Sivhed, 2001).

5.2 Pre-Quaternary surface

The Børglum and Grenå Helsingborg Faults are associated with large pre-Quaternary depressions, which influenced the depositional patterns during the Quaternary and has resulted in a characteristic pre-Quaternary morphology (Binzer & Stockmarr 1994). The major faults reflect the motions within the fault blocks.

Model based studies show that elongated, pull-apart basins have developed in distinct narrow grabens. It is seen that the Hesselø OWF crosses deep faults and a pull-apart basin depocenter in the northern part of the wind farm, whereas areas A and B are dominated by shallower pre-Quaternary morphology (Figure 5.3).

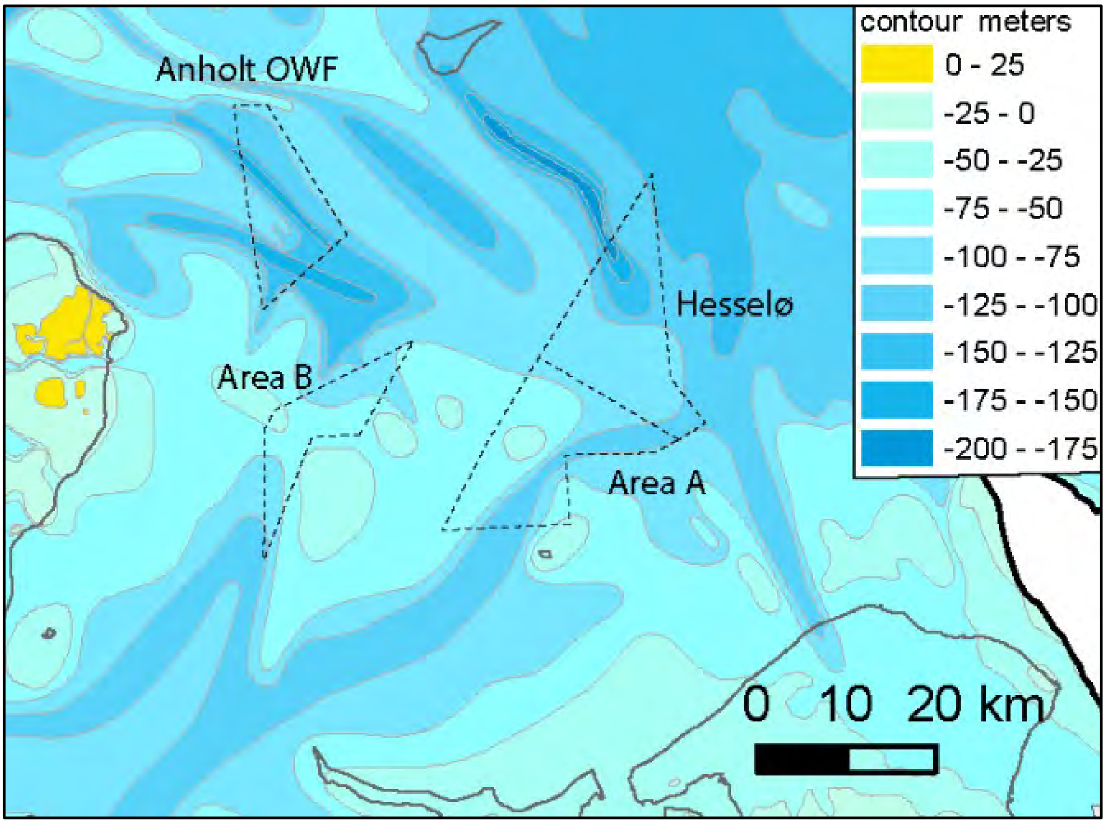


Figure 5.3. General pre-Qaternary morphology (Binzer & Stockmarr 1994). The location of the OWF's is indicated.

5.3 Glacial deposits and deglaciation

South of Anholt, till from the last Weichselian glaciation as well as Late Glacial and Holocene deposits are found. The Scandinavian Ice Sheet reached its maximum extent in western Denmark about 22 ka BP followed by stepwise retreat. The oldest deglaciation sediments have yielded ages of ca. 19 ka BP, but most deglaciation ages lie around 17 ka BP.

Around 18 ka BP the sea began to inundate northern Denmark. It led to the development of an archipelago in Vendsyssel (Richardt 1996) and to rapid deglaciation (Houmark-Nielsen & Kjær 2003; Figure 5.4).

In central Denmark ice from Sweden steadily retreated, which caused the opening of the Kattegat depression and transgression of the area. A glaciomarine environment was established with ice bergs, arctic seals, arctic whales and polar bears (Figure 5.4, Figure 5.5).

Shortly after 18 ka BP sea level regression caused by glacio-isostatic rebound is registered in Vendsyssel, the Kattegat and northern Øresund. During the general deglaciation, an ice stream readvance from the Baltic moved westward and reached the East Jylland ice marginal line at about the same time as the first marine inundation in Vendsyssel. This Young Baltic Ice advance created strong glaciotetonic deformations along the margin.

At ca. 17 ka BP the ice margin had retreated to the Halland coastal moraines along the Swedish west coast (Figure 5.4).

At ca. 15 ka BP, at the beginning of the Bølling Interstadial (Figure 5.4), calving along the ice margin in Skagerrak, near the present-day mouth of Oslo Fjord, sent ice bergs into the Norwegian Channel, with glaciers having abandoned the south Norwegian coast some thousand years earlier. In Sweden, ice had retreated to the central and southern uplands giving way to an ice-dammed lake in the southern part of the Baltic depression. As the ice stream in the Baltic was wasting, glacio-eustatic sea level rise characterised the Skagerrak and Kattegat southwards along the Swedish west coast into the northern Øresund region. From ca. 17 to 15 ka BP marine environments changed from arctic to boreo-arctic, and the mud-dominated Yoldia clay in Vendsyssel was generally succeeded by the littoral Saxicava Sand and Zirfaea Beds.

During the relative sea level rise in the Late Glacial period (Late Weichselian; 16.0 to 12.6 ka BP), a thick package of glaciomarine clay was deposited (Jensen et al. 2002; Houmark-Nielsen & Kjær 2003).

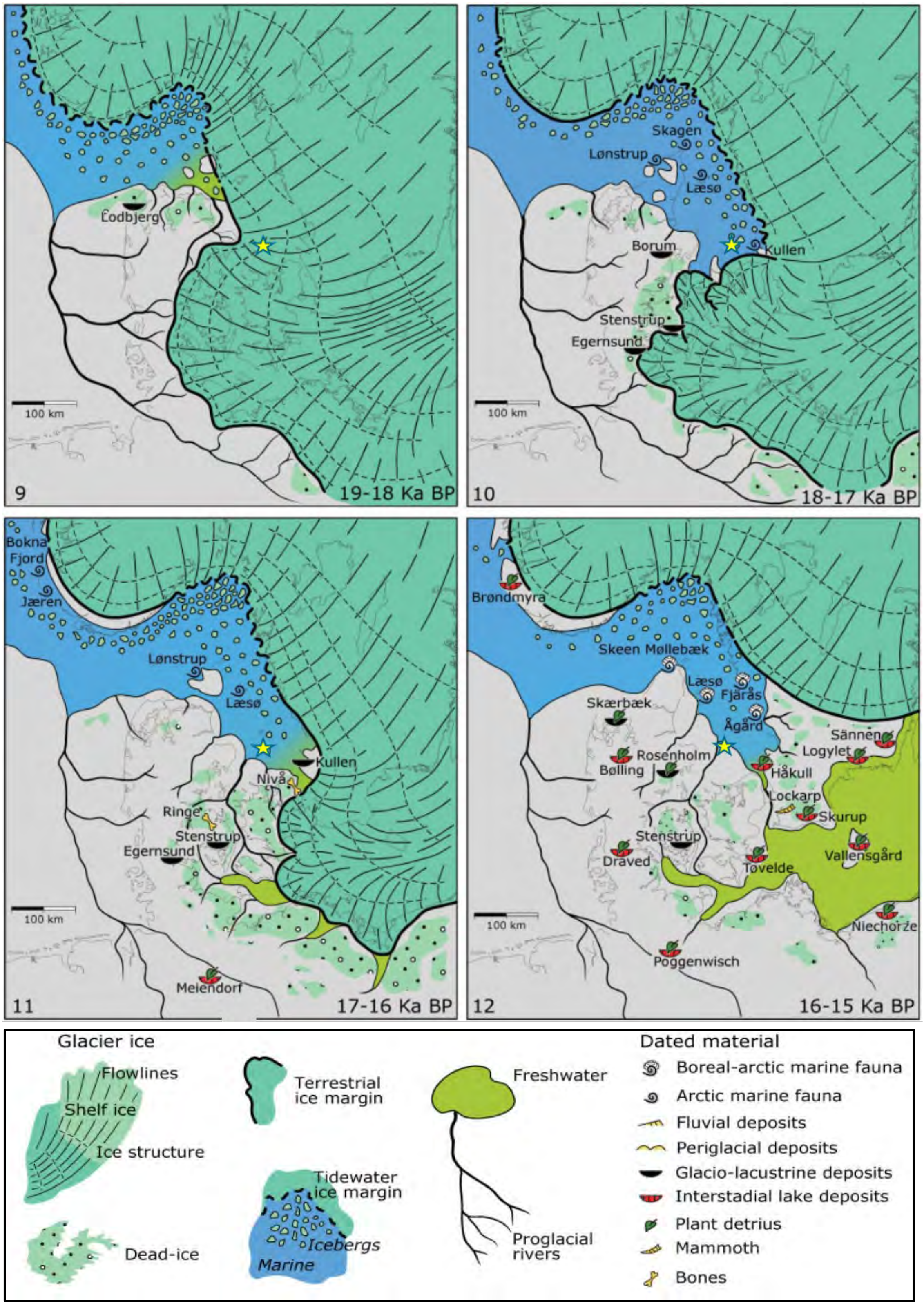


Figure 5.4. Palaeogeographical reconstructions of the last deglaciation of southern Scandinavia (19–15 ka BP; Houmark-Nielsen & Kjær 2003).

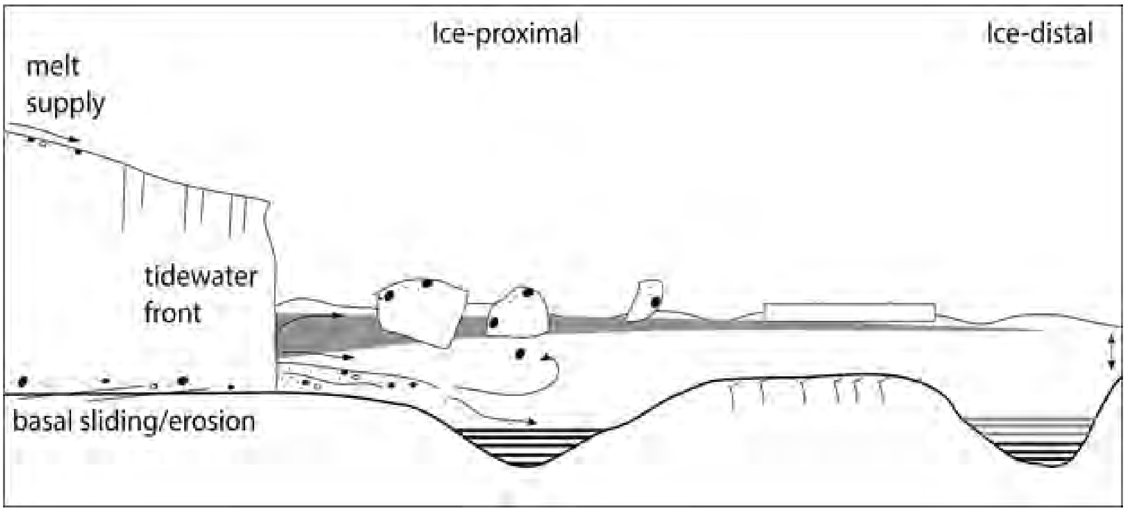


Figure 5.5. Illustration of a glaciomarine depositional environment.

Based on the GEUS archive data combined with the Emodnet bathymetry as well as the GEUS surface sediment map it is possible to revise earlier models of ice marginal ridges in the Hesselø Offshore Wind Farm, Area A and B study areas.

The morphological pronounced Sjællands Odde ice marginal ridge continues offshore in a big curve east of Area B and cuts Area A as well as the southernmost corner of the Hesselø Offshore Wind Farm area and continues northward to the Store Middelgrund area (Figure 5.6) where evidence of glaciotectonic deformations is seen on sparker line 5003 north of Store Middelgrund.

The interpretation of retreating ice marginal ridges is supported by the seabed surface sediment map (Figure 5.10) where the ridges in general consist of till, often superimposed by Holocene transgressive sand and gravel, coastal sediments eroded and redeposited on the margins of the till core.

The Hesselø OWF area is situated between two major ice marginal ridges in a basin with up to 100 m thick Late Glacial glaciomarine basin deposits (Figure 5.5) documented in IODP core M0060. Area A and B are situated in direct connection to the morphological pronounced Sjællands Odde ice marginal ridge.

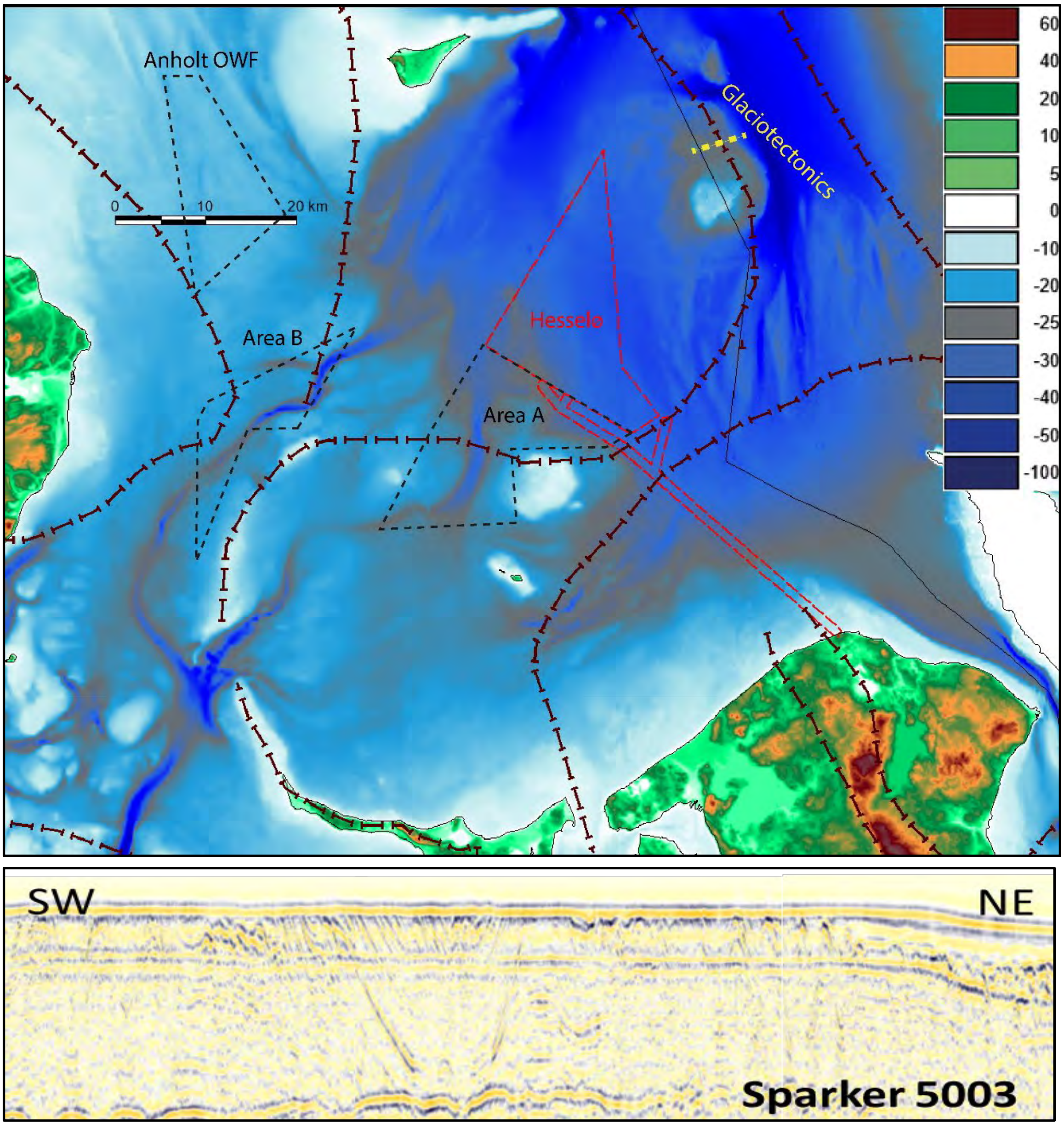


Figure 5.6. Upper figure: Interpreted ice marginal ridges in the southern part of the Kattegat. Lower figure: Sparker profiler showing evidence of glaciotectonic deformations north of Store Middelgrund (yellow dashed line on upper figure). Bathymetry from Emodnet. The location of the OWF's is indicated.

5.4 Late Glacial and Holocene

In the period after the deglaciation the southern Kattegat area was characterised by high-stand sea-level conditions, followed by a continuous moderate regression until the eustatic sea-level rise surpassed the glacio-isostatic rebound in the Early Holocene (Figure 5.7).

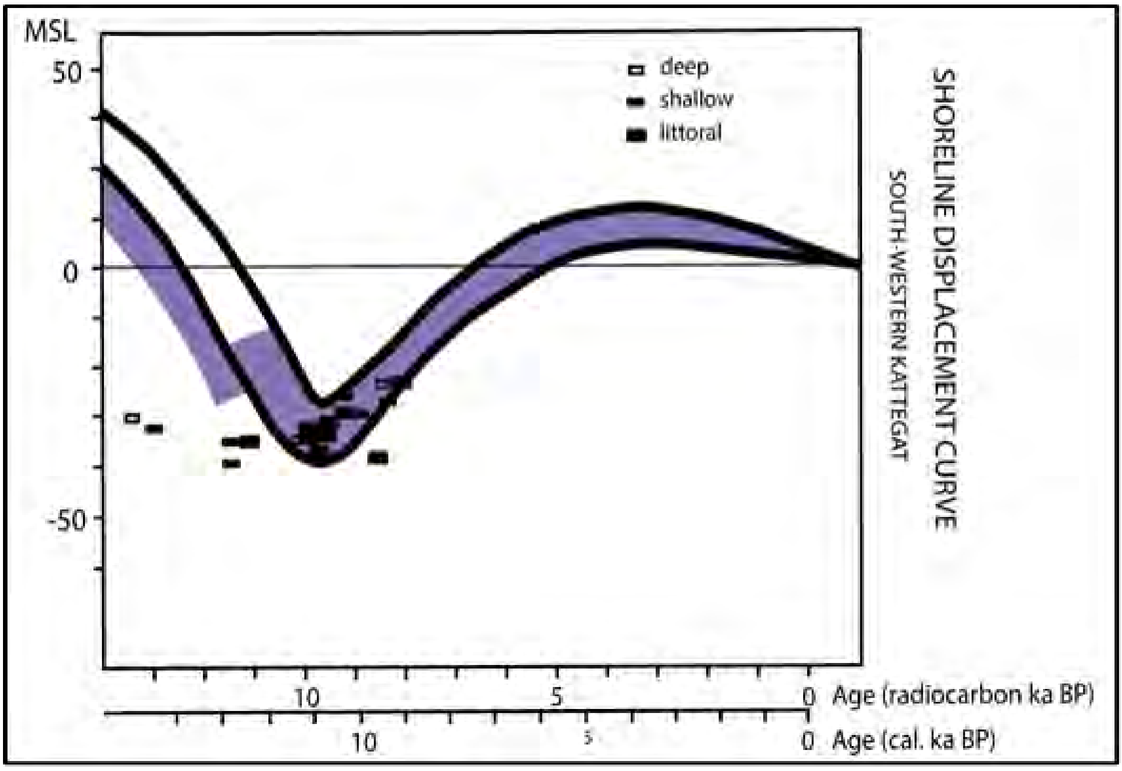


Figure 5.7. Shoreline displacement curves for the southern Kattegat. The two solid black lines indicate the range of shoreline displacements in non-faulted regions of the study area (modied from Mörner 1983). The purple area indicates the relative sea level changes interpreted from the sequence stratigraphy in the down-faulted NW–SE-striking depression. Radiocarbon dated samples are indicated as deep >10 m, shallow 2–10 m or littoral 0–2 m.

Late Weichselian subaqueous sediments occur typically as basin infill in the area north of the anticlinorium, or in local depressions elsewhere.

In the Early Holocene the relative sea level began to rise, as the eustatic sea-level rise surpassed the isostatic uplift of the crust. Mörner (1969, 1983) made comprehensive pioneer studies of the relative sea-level changes in the Younger Dryas–Holocene Kattegat, whereas later studies have resulted in more detailed palaeogeographical reconstructions based on sequence stratigraphical studies (Bennike et al. 2000; Jensen et al. 2002; Bendixen et al. 2015, 2017).

The Hesselø OWF area has been submerged most of the time after the last deglaciation, but in the lowstand period around 10.5 ka BP only partly, and lowstand sediments must be expected (Figure 5.8). Already in the initial phase of the Holocene transgression the Hesselø OWF area was fully submerged, whereas the cable corridor as well as Area A and B have a longer transgression history.

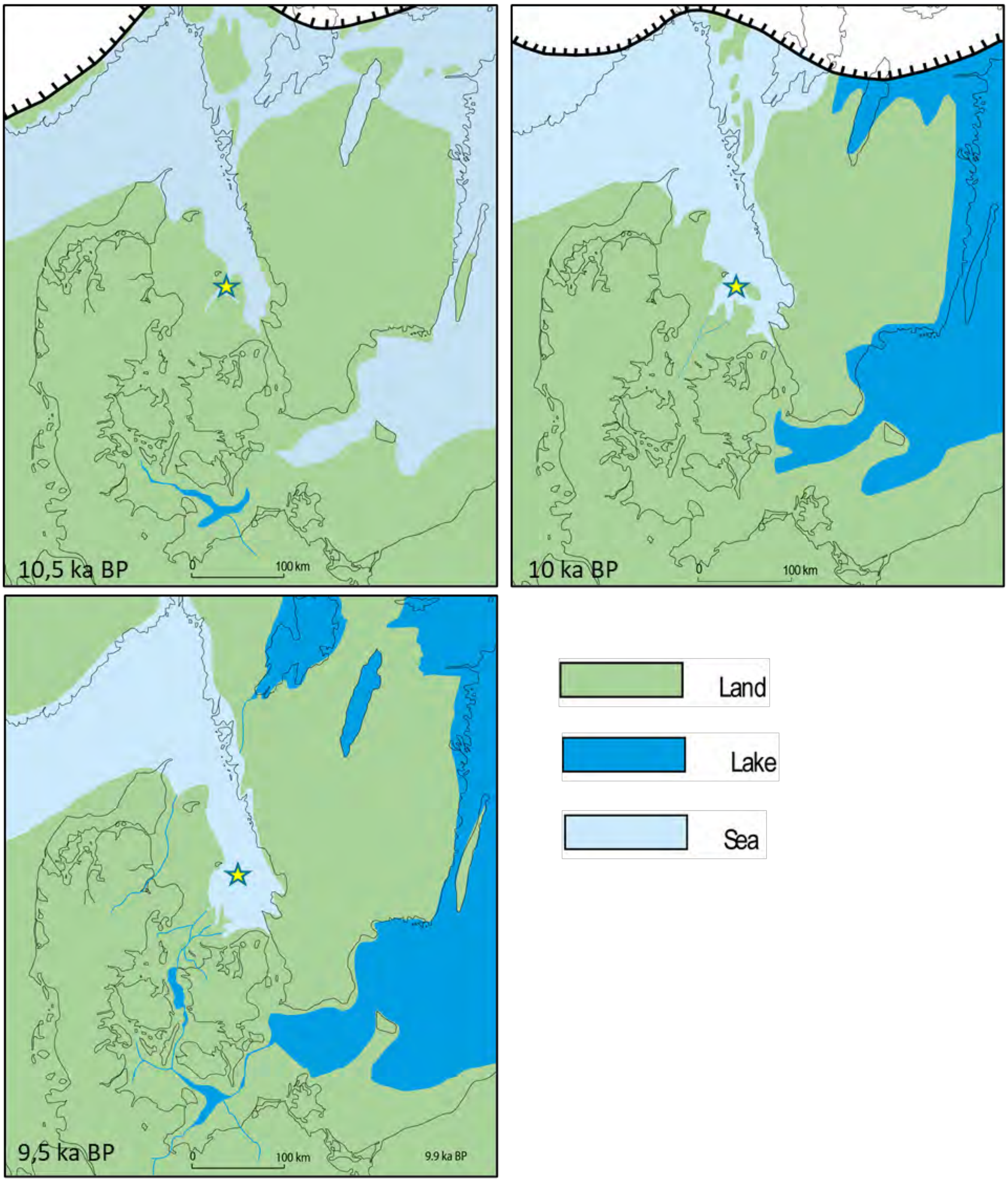


Figure 5.8. Palaeogeographical scenarios for the Kattegat region. There was a lowstand at 10.5 ka BP followed by a transgression (Jensen et al 2002). The yellow star shows the location of IODP core M0060.

5.5 Seabed morphology and surface sediments

In the Hesselø OWF site water depths range from 24.7 m to 33.5 m MSL. The minimum water depth is seen in the south-western part of the site and the maximum depth is recorded in the east.

The Hesselø OWF site is characterised by gentle seafloor slopes, on average between approximately 0˚ and 3˚.

Area A water depths range from about 16 m to 35 m MSL. The minimum water depths on the Store- and Lille Lysegrund banks are divided by a channel with greater depths.

Area B water depths range from about 15 m to 35 m. The shallowest area is found on the northern flank of the Sjællands Odde ice marginal ridge. The deepest area is found in the northeast–southwest-oriented Great Belt incised channel.

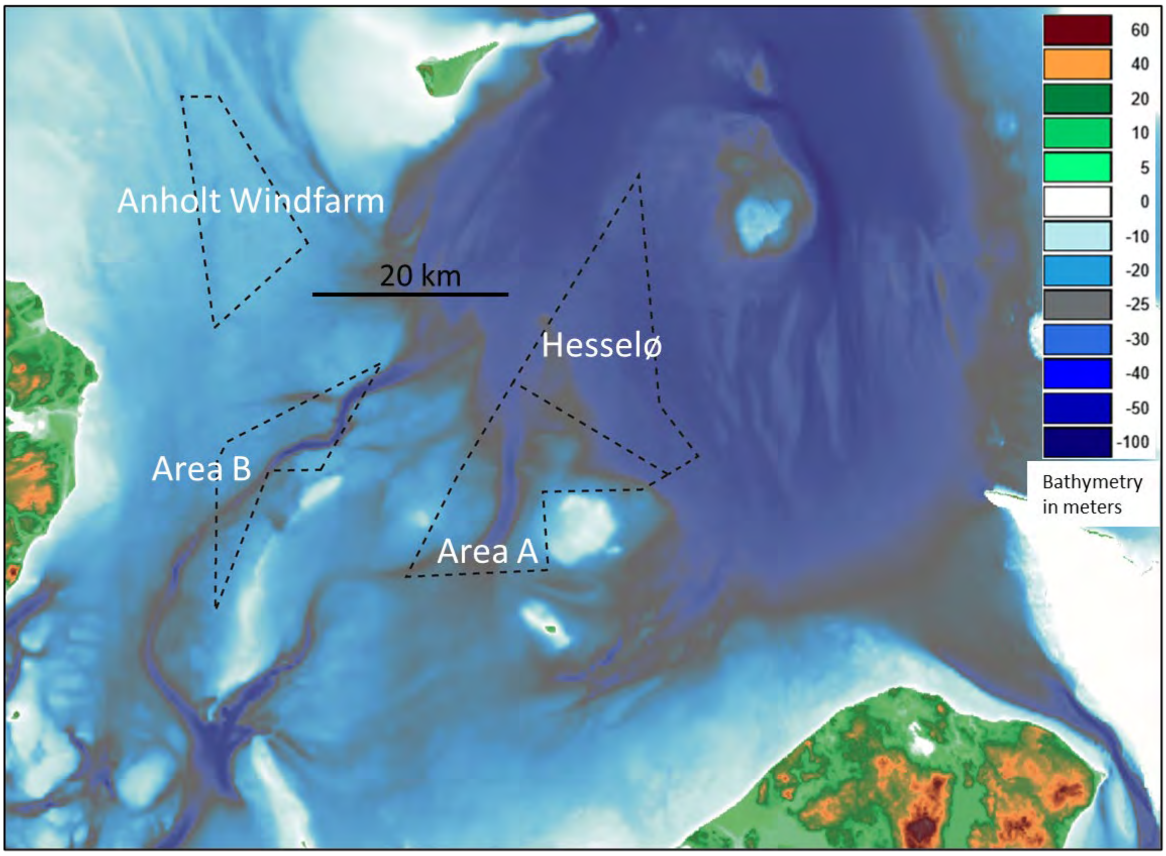


Figure 5.9 Southern Kattegat bathymetry. The locations of the existing Anholt OWF, the planed Hesselø OWF and the potential OWF areas A and B in the southern part of the Kattegat are indicated. Bathymetry from www.emodnet-bathymetry.eu.

The surface sediments in the Hesselø OWF were mapped in detail in the Fugro (2021) report and a mixture of Late Glacial clay, mud and muddy sand dominates, with a concentration of gravel/sand in the northern part close to Store Middelgrund (Figure 5.10).

The northern part of Area A is expected to have a similar pattern, but the central and southern part of Area A is in the ice marginal ridge area, and consist mainly of till and gravel interrupted by muddy sand in the central north-south channel.

Area B is dominated by till and gravel in the northern semi-detailed mapped area, whereas the southernmost part is mapped as muddy sand located west of the Sjællands Odde ice marginal ridge. It is expected that a detailed mapping of the southern part of Area B will reveal larger areas with till and gravel.

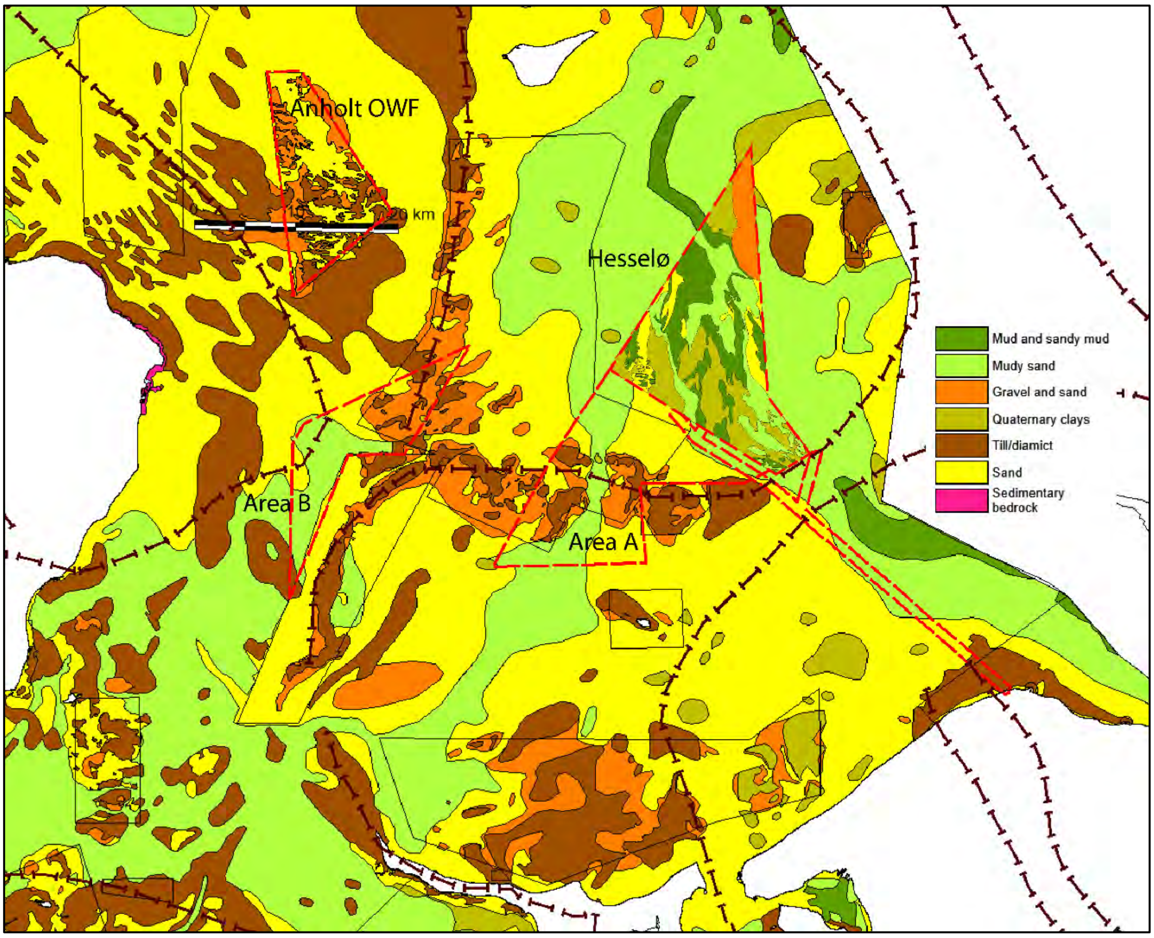


Figure 5.10. Seabed surface sediment map, interpreted ice marginal ridges. The locations of the existing Anholt OWF, the planed Hesselø OWF and the potential OWF areas A and B in the southern part of the Kattegat are indicated (red stippled polygons). Updated detailed sediment data from Fugro (2021) is presented in Hesselø OWF. (Black lined polygons marks margins of detailed mapped subareas).

6. Hesselø OWF seismostratigraphic and lithological units

In the geological screening report (GEUS 2020) the general geology of the region has been presented and existing seismic facies units have been described.

The detailed Hesselø OWF investigations (Fugro 2021) confirm the general stratigraphy. The geophysical seismostratigraphic units have been expanded with a few subunits, due to more information. The general stratigraphy remains but is renamed to units A to I (Table 1).

UNIT	Expected soil type	Age	Environment	Thickness	Unit Base BSF
A	Clay to clayey medium sand or sandy gyttja with shells and shell fragments and organic material	Holocene	Marine	1-3 m	1-3 m
B	Interlaminated to interbedded clay and silt with shells and shell fragments	Early Holocene	Deltaic	0-14 m	1-17 m
C	Medium sand with abundant shells and shell fragments	Early Holocene	Shallow marine (Spit or Barrier Island)	0-3 m	0-17 m
D	Clay with occasional laminae of silt and/or sand, locally sandy	Weichselian	Glaciomarine, glaciolacustrine to fluvial	0-66 m	1-72 m
E	Clay, locally with sand beds	Weichselian	Glaciomarine and/or glacial deposits	0-66 m	9-122 m
F	Clay with laminae or thin beds of silt or sand	Pleistocene	Glaciomarine	0-39 m	14-113 m
G	Poorly sorted gravelly and sandy CLAY, sandy till or clayey till	Pleistocene	Glaciomarine and/or glacial till	0-94 m	27-166 m
H	Sand, clay, clayey till and/or sandy till	Pleistocene	Glacial, periglacial and/or glaciomarine	0-80 m	40-111 m
I	Sandy mudstone, limestone and glauconitic sandstone	Jurassic to Cretaceous	Marine	-	-

Table 1. Overview of seismostratigraphic units adapted from GEUS (2020) and Fugro (2021). For details see Appendix A.

In the following, the description of the units in the geological development history will be presented in chronological order.

The seismic facies units present a subdivision into bedrock (I) and glacial (H–G) deposits, underlying tree different Late Weichselian (F, E and D) units, which form basin infill with a total maximum thickness of ca. 100 m. The Early Holocene low sea level shallow marine sediments are represented by unit C whereas early transgression deltaic/estuarine sediments are represented by unit B. Younger Holocene sediments are represented by unit A.

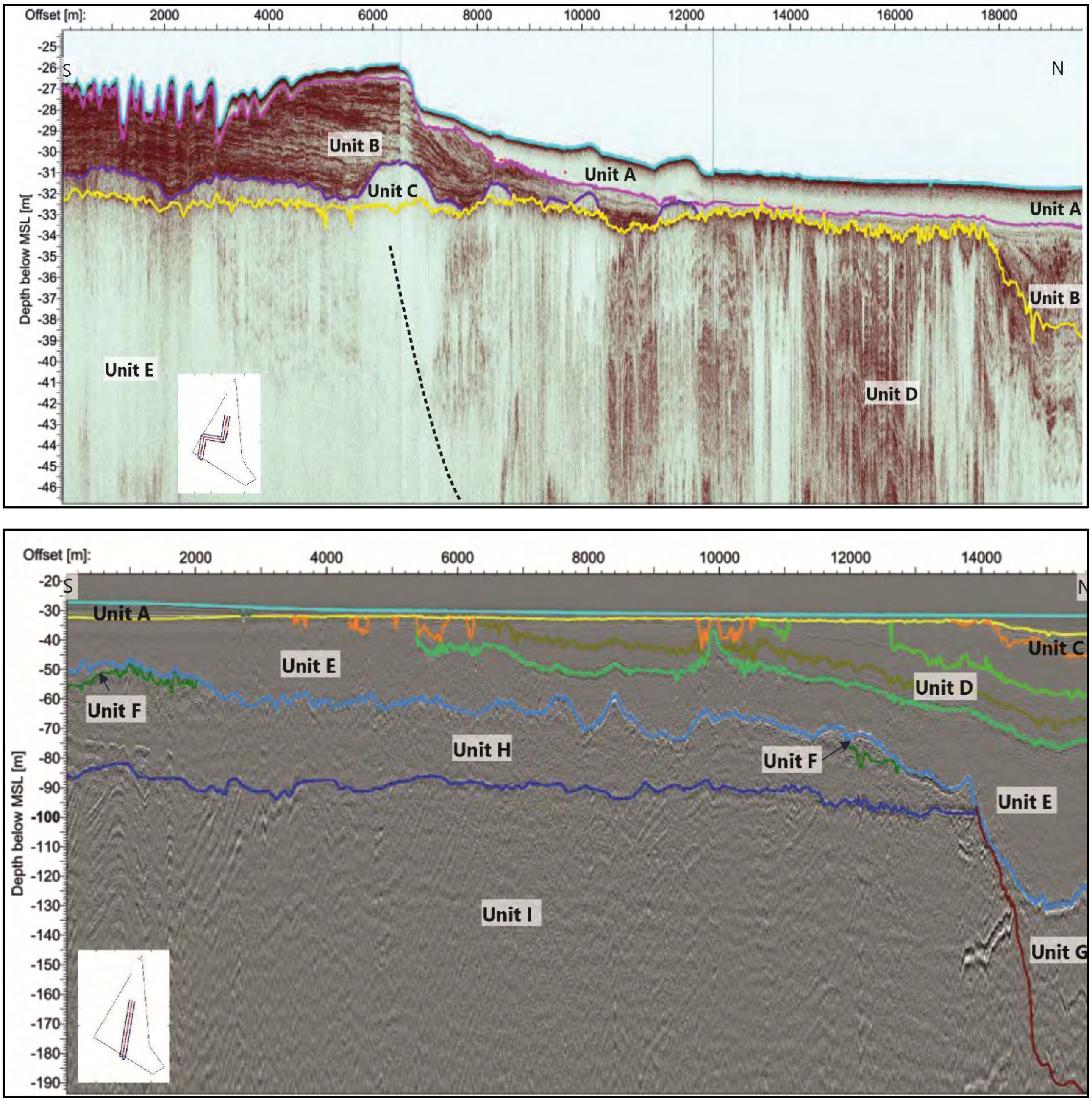


Figure 6.1. Overview of seismostratigraphic units interpreted in the Hesselø OWF study area.

6.1 Unit I bedrock

The internal seismic character shows predominantly low to medium-amplitude, large wavelength parallel reflectors (Figure 6.1). Where Unit I shows parallel inclined (possibly folded) reflectors, the horizon marking the top of Unit I represents an angular unconformity with the overlying units. Due to the tectonic history of the general area, the presence of faults can be expected.

The bedrock consists of Jurassic sandy mudstone to Lower Cretaceous limestone and glauconitic sandstone, deposited in a marine environment (GEUS 2020; Figure 4.2).

The bedrock forms the acoustic basement. Earlier studies of the pre-Quaternary surface topography (Gyldenholm et al. 1993; Binzer & Stockmarr 1994) showed that elongated NW–SE-trending depressions (Figure 5.3 and Figure 5.1) follow the general dextral wrench fault pattern in the Fennoscandian Border Zone (Liboriussen et al. 1987). These studies also reported that the central northwest-dipping crystalline anticlinorium is bounded by Jurassic, Cretaceous and Tertiary sedimentary strata, which are generally associated with major faulting (Figure 5.2). The top of the bedrock has a high intensity return, and for the Jurassic strata strongly dipping internal reflectors are seen, whereas the crystalline bedrock shows no true internal reflections.

6.2 Unit H clayey till and/or sandy till

The Unit H till is only absent in the large pre-Quaternary depression. The unit shows typical thicknesses of 25 m to 35 m south of the depression and reaches a thickness of ca. 80 m north of the depression.

The internal seismic reflectors vary from medium-amplitude parallel reflectors (Figure 6.1), dominantly observed south of the large pre-Quaternary depression to acoustically transparent and chaotic with short internal reflectors, observed north of the depression.

A low to medium positive amplitude reflector marks an angular unconformity, where the underlying bedrock (Unit I) is clearly folded. This is most prominently visible south of the depression.

Unit H is interpreted as Pleistocene sediments deposited in glacial, periglacial and/or glaciomarine conditions (Table 1).

Earlier studies in the region indicate that the unit represents Weichselian and older glacial deposits (SGU 1989; Nielsen & Konradi 1990; Gyldenholm et al. 1993).

6.3 Unit G, sandy or clayey till/diamicton

Unit G is mainly present in the large pre-Quaternary depression and locally in other parts. The unit reaches a maximum thickness of approximately 94 m in the deepest parts of the depression. In the shallower parts of the depression and in the other parts of the site, it shows a typical thickness of approximately 10 m.

The base of Unit G is an erosional surface cutting deeply into the underlying Unit H and Unit I. The internal seismic character of Unit G varies from acoustically semi-transparent with occasional inclined discontinuous internal reflectors where Unit G is thick, to more chaotic where Unit G is thin (Figure 6.1).

Unit G is interpreted as a diamicton valley infill. A similar valley was penetrated by an IODP borehole (Andrén 2015a, b), where similar fill was interpreted as debris flow deposits. However, the fill may also represent glacial till.

6.4 Unit F glaciomarine laminated clay, silt or sand

Unit F is present locally, in the north and in the western part of the site (Figure 6.1). The unit is typically less than 10 m thick, but locally reaches a thickness up to 39 m in the eastern east–west oriented channel towards the large pre-Quaternary depression.

The internal seismic character of Unit F shows closely spaced medium to high amplitude parallel reflectors similar to the dominant seismic character of Unit D. Unit E is stratigraphically found between Unit D and F in the central and southern part of the site.

Unit F is interpreted as glaciomarine deposits due to its bedded seismic character and similarity to the bedded facies of the overlying Unit D.

6.5 Unit E glaciomarine clay, locally with sand beds

Unit E is present across the Hesselø OWF. The unit shows a typical thickness of 10 m to 20 m and reaches a maximum of approximately 62 m within the pre-Quaternary depression and approximately 40 m in the south.

The internal seismic character of Unit E is semi-transparent to chaotic (Figure 6.1). Locally, laterally limited steep internal reflectors can be present.

In the south-western part of the site, the top of the unit is fading out and it becomes difficult to properly differentiate this unit from the overlying unit.

Unit E is interpreted as a unit of glacio-tectonised deposits. In the south-west, where Unit E increases in thickness, it is present directly below the Holocene.

The sedimentological characteristics in the central part of the study area are illustrated by core 572007 (Figure 6.2 and Figure 6.3), which contains 5 m of weakly laminated to structureless clay with dropstones, without macroscopic evidence of marine influence.

In the southernmost part of the area, where interlayering of fine sand and clay suggests a more proximal setting, a few shells of the marine bivalve species *Hiatella arctica* were found. AMS radiocarbon dating of a shell yielded an age of about 16 cal. ka BP (Jensen et al. 2002), demonstrating that the basal part of the unit was deposited shortly after the deglaciation of the area. This is supported by previous indications of a glaciomarine fauna in the same unit, as described by Nielsen & Konradi (1990) and by Bergsten & Nordberg (1992). The latter authors described similar lithological facies types (facies IV and III) and characterized these as ice-proximal to shelf sediments with a high-arctic fauna referred to the same period.

6.6 Unit D glaciomarine clay with occasional laminae of silt

Unit D is absent in the south and south-western part of Hesselø OWF. The unit has a typical thickness of approximately 20 m to 30 m and reaches a maximum thickness of approximately 66 m in the large pre-Quaternary depression. It thins to less than 10 m in the south, where the underlying Unit E substantially increases in thickness.

The dominant seismic character of Unit D is low to high-amplitude parallel reflectors. These reflectors become increasingly distorted towards the southern part of the site.

Evidence of mass transport deposits was observed in the upper part of Unit D.

Based on historical geotechnical data (GEUS 2020), Unit D consists of clay with occasional laminae of silt and/or sand and can be locally sandy. The channel-fills consist of medium coarse sand interbedded with silty clay (GEUS 2020) (Figure 6.2. Boomer seismic section 572008.

Based on its seismic character, stratigraphic position and geotechnical properties, Unit D is interpreted as predominantly Late Glacial clay deposited in a glaciomarine environment. Channel infill found at the base is interpreted as deposited in a fluvial environment and the channelling features are interpreted as mass-transport deposits within the Late Glacial deposits.

The internal reflection pattern points to a lower transgressive systems tract with reflectors onlapping in the shallow part and downlapping towards the basin. Furthermore, an upper highstand systems tract is indicated, bounded below by the maximum transgression surface (maximum flooding surface) and above by a type I sequence boundary (Posamentier et al. 1992).

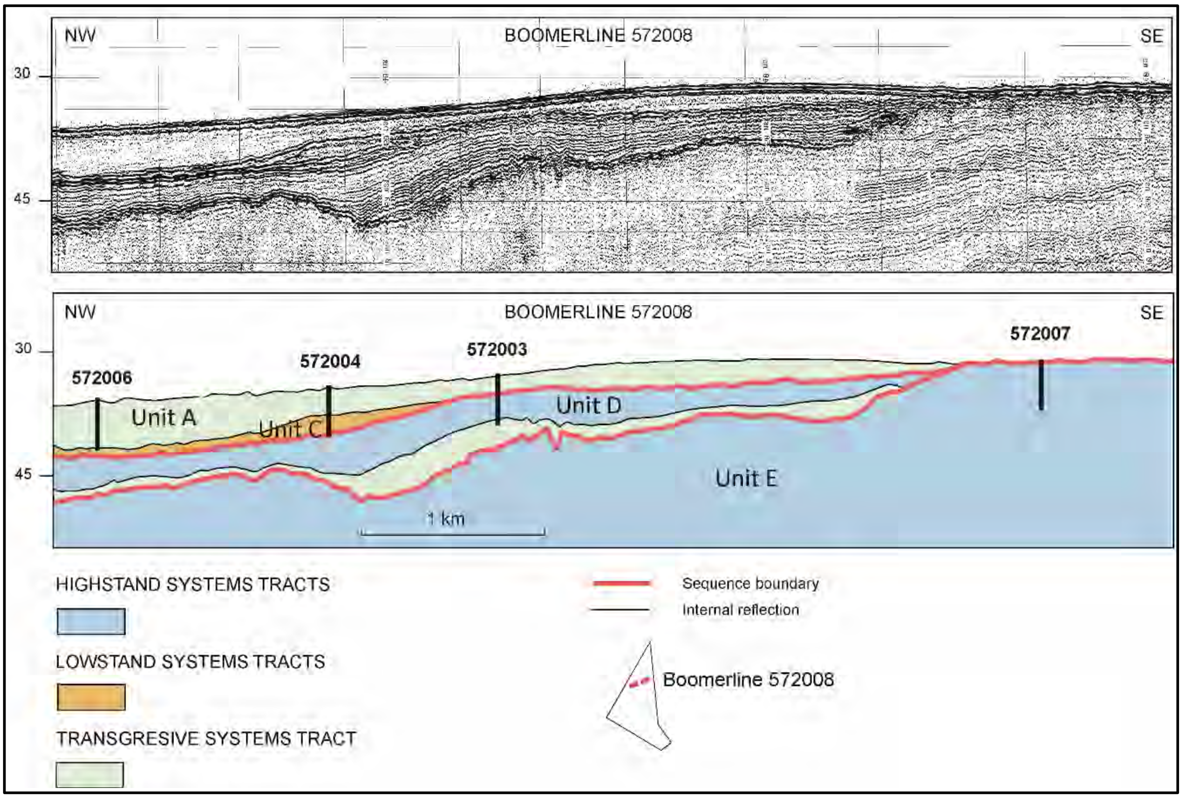


Figure 6.2. Boomer seismic section 572008.

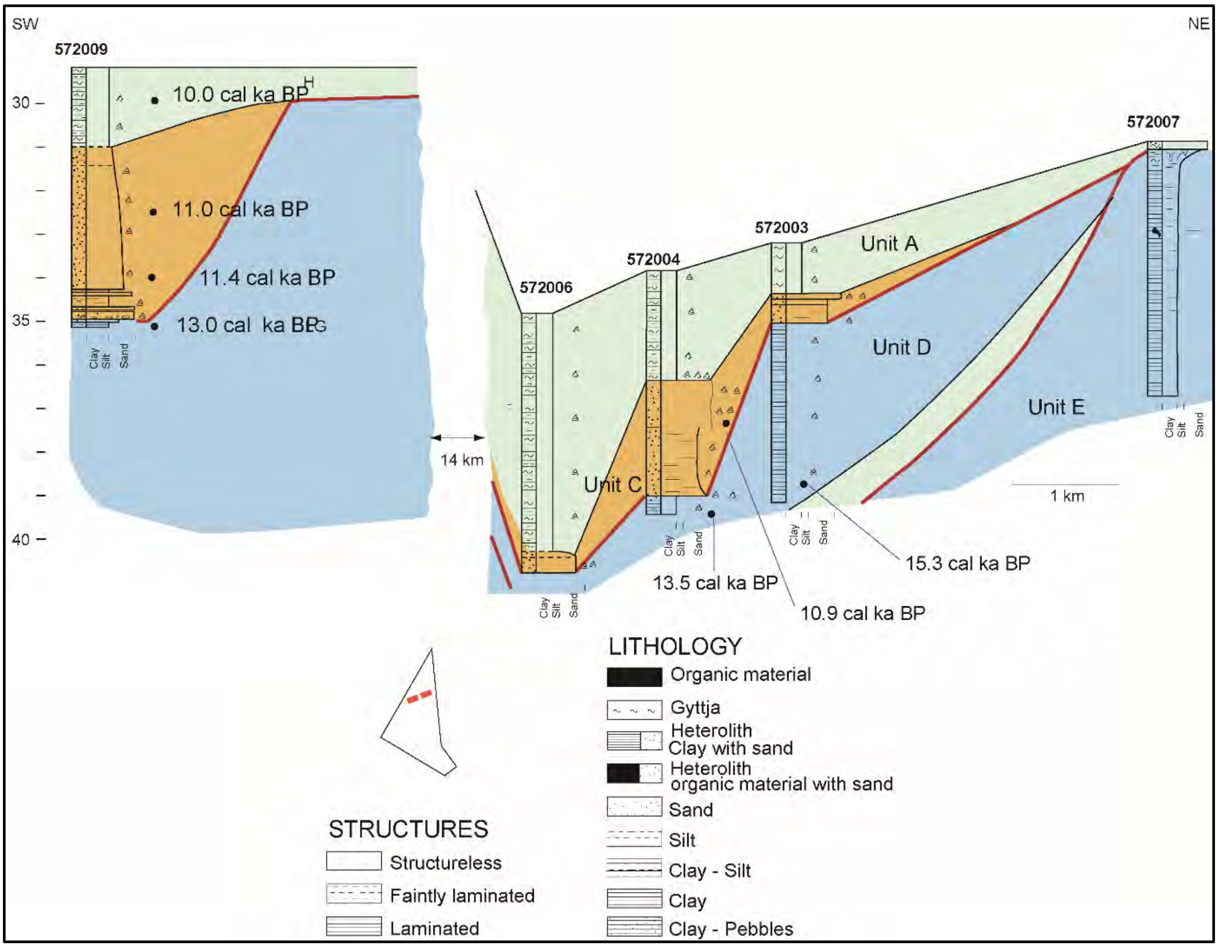


Figure 6.3. Sedimentological logs and log correlations. Sedimentological signatures are indicated; for description of stratigraphical signatures see Table 1. Detailed information on C-14 ages is given in Jensen et al. (2002).

The internal reflectors are distinct and show onlap in the shallow, landward direction and downlap in the basin-ward direction.

Vibrocores 572003 and 572004 (Figure 6.3) penetrated the highstand sediments, which consist of structureless clay with marine shells and a mixture of silt and fine sand. Distinct bioturbation is also observed.

Age determinations of a shell of *Portlandia arctica* (572003) from the unit's lower part and of a shell of *Astarte borealis* from the upper part gave ages for the highstand sedimentation period of 15.0–13.5 cal. ka BP.

6.7 Unit C Holocene shallow marine medium sand with abundant shells

Unit C is present in the south-western part of the site, where it forms hummocks/ridges with approximately a north–south orientation. The unit is also present in the pre-Quaternary depression in the north of the site.

The unit is often acoustically (semi-)transparent to chaotic. However, where the unit is thicker, it may show stratification, with low-amplitude parallel reflectors oriented in various directions. The base of Unit C has an irregular and erosional character.

Unit C is interpreted to be near coastal deposits, such as coast-parallel spits or barrier islands formed during the marine transgression in the Early Holocene.

Based on the internal reflection pattern, the sequence is divided into a lower lowstand systems tract and an upper transgressive systems tract. The lowstand systems tract is developed as wedge-shaped structures in the basin areas (Figure 6.2) and as a beginning infill of the incised palaeo-Great Belt valleys (Figure 6.3; vibrocore 572009). In both cases the systems tract is characterized by rather chaotic internal reflection patterns. The transgressive systems tract consists of basin deposits with reflectors that onlap in the landward direction, and downlap in the basin-ward direction (Figure 6.2). The lowstand wedge structures are lithologically documented by vibrocores 572003, 572004 and 572006 (Figure 6.3). The sediments consist mainly of weakly laminated, medium- to coarse grained sand with abundant shallow-water marine molluscs and foraminifers. Radiocarbon dating of *Mytilus edulis* from core 572004 shows that the lowstand sedimentation took place in the Early Holocene (Jensen et al. 2002). The infill of the incised palaeo-Great Belt valley found in vibrocore 572009 (Figure 6.3) consists of a basal, 1 m thick unit of interlayered medium and coarse-grained sand layers and laminated silt containing littoral and shallow-water marine molluscs and foraminifers. The sediment succession as well as the dating of *Betula nana* bark fragments point to an initial lowstand littoral deposition at about 13 cal. ka BP. The sedimentary conditions ranged from a normal low-energy environment upstream to a high-energy environment exposed to storm surges in the estuary. This initial phase was followed by an interval represented by about 3.5 m of structureless, fining upwards, medium- to fine-grained sand also with abundant littoral and shallow-water marine molluscs and foraminifers. Dating results (Jensen et al. 2002) demonstrate that the incised valley infill corresponds to the basin lowstand wedge sedimentation from the Early Holocene. The uppermost 1.5 m of vibrocore 572009 consists of structureless clay to fine sand, with shells of marine molluscs and foraminifers that indicate shallow to deeper-water marine environments. These sediments are dated to about 10 cal. ka BP.

6.8 Unit B Early Holocene interlaminated to interbedded clay and silt with shells, deltaic environment

Unit B is present in the central and western part of the site (Figure 6.1). In general, the unit is thin, on average approximately 1 m. It reaches locally greater thickness of approximately 6 m in the shallower south-western part of the site (Figure 6.1) and a maximum thickness of approximately 14 m in the large pre-Quaternary depression in the north-eastern part of the site.

Internally the unit is stratified, with low to high-amplitude, parallel reflectors. Where Unit B is thickest in the south-western part of Hesselø OWF, the stratification has an eastward directed inclined orientation and high amplitudes. In the east where Unit B is thin, the stratification is sub-horizontal and associated with low amplitudes.

Within the large pre-Quaternary depression, the stratification in Unit B has a dominant westward orientation and shows abundant high-amplitude reflectors of variable lateral extent.

They are interpreted as possible pockets of peat or organic clay. Acoustic blanking is observed in Unit B in the deepest parts of the large pre-Quaternary depression.

The character of the base of Unit B is either undulating or irregular. The top of unit B marks a change in seismic character between acoustically transparent (Unit A) above and a stratified character (Unit B) below. At the south-western part of the site, with shallower waters, the internal stratification of Unit B shows an angular unconformity with the overlying Unit A.

Unit B is interpreted to be deposited in a deltaic environment, at the mouth of the Dana River System (Great Belt palaeo-river) through which the Ancylus Lake drained into the Kattegat (Figure 6.4).

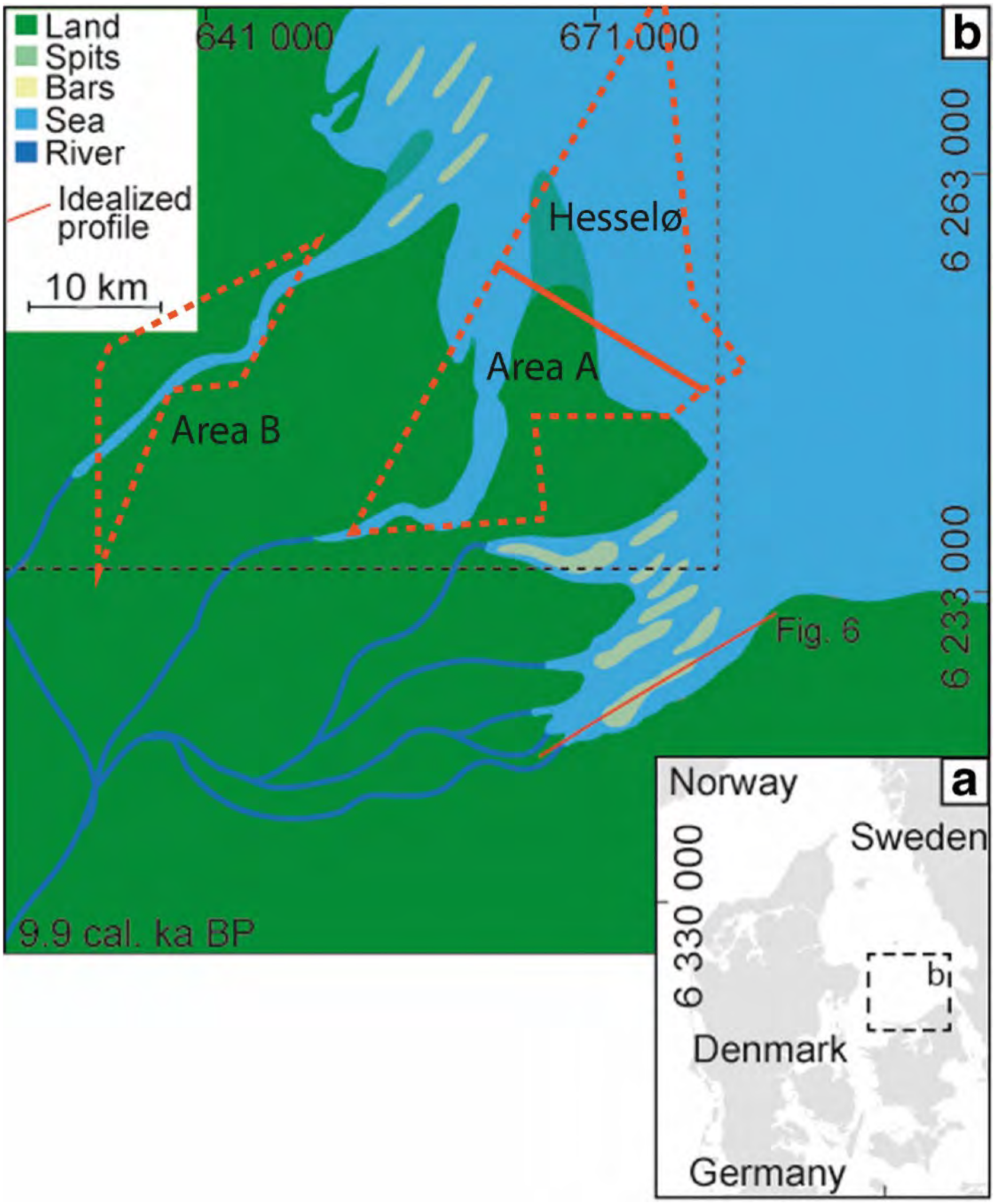


Figure 6.4 Dana River System Great Belt palaeo-river (Bendixen et al. 2015, 2017)

6.9 Unit A Holocene marine clay to clayey, medium sand or sandy gytja with shells and organic material

This unit is present across the entire Hesselø OWF, except for small areas with erosional escarpments. The unit generally forms a thin draping layer. The maximum thickness is observed in the centre of the site, where it reaches approximately 3 m and decreases to less than 1 m towards the eastern and western margins of the site.

Internally the unit is acoustically transparent, but vague internal reflector is seen locally.

Where the unit overlies Unit B, the base is regular and varies from flat to undulating. Where the unit overlies Unit D (mostly in the east), the base has an irregular, rugose character. In the eastern part of the site, the unit overlies Unit C.

In the western part of the site, Unit A is locally in erosional contact with the underlying Unit B, forming gullies 1 m to 3 m deep and 80 m to 200 m wide with a west–east orientation. Because the overlying Unit A is thin and drapes Horizon H01, these gullies can still be observed in the present-day seafloor morphology.

In the western part of the site, the base of Unit A forms the eastern margin of a wide channel with a north–south orientation. Potentially these gullies and the channel were formed by the Dana River (Great Belt palaeo-river; Bendixen et al. 2015, 2017).

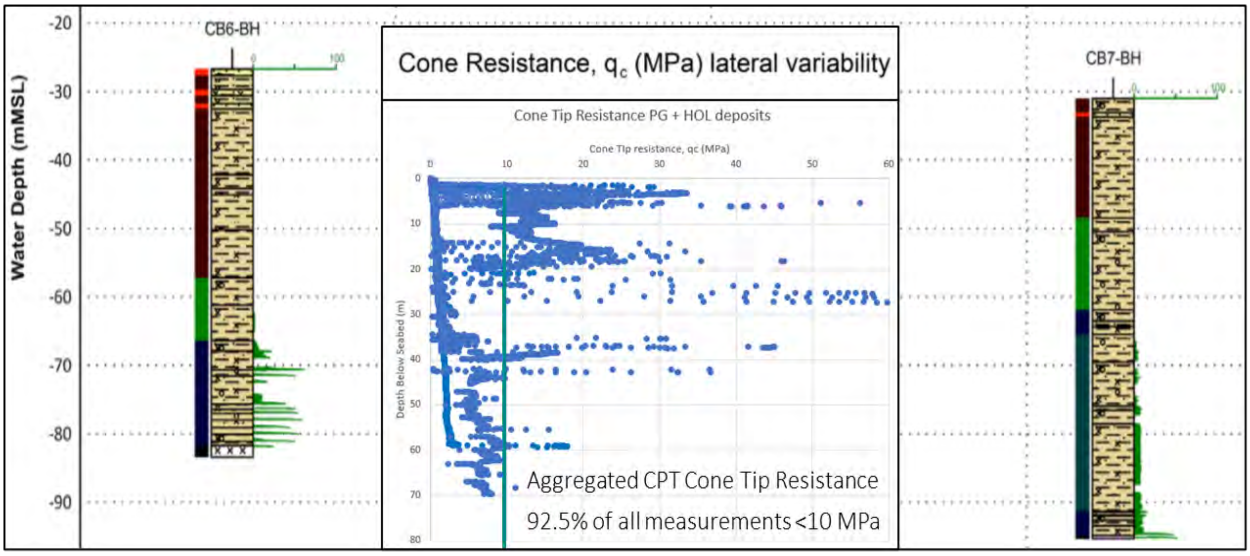
In the eastern part of the site, where the Holocene cover is generally thin, Unit A appears to fill in the depressional remnants of iceberg plough marks from the underlying Unit D.

Unit A is interpreted as a Holocene marine sediment.

7. Geotechnical soft sediments in Hesselø OWF

Geotechnical acquired data in the Hesselø OWF include 14 long sediment cores and three short cores, 33 CPT, 7 SCPT and 5 PS-logging with investigations to 70 m below seafloor.

The geotechnical results show that major parts of Hesselø OWF contains soft Late Glacial and Holocene clay–sand clay sediments (seismic units A–E/F) (Table 1). These types of sediments dominate the uppermost 0 to >50 m below seabed, with very low cone resistance and undrained shear stress values covering the seismic units G and H interpreted as well consolidated glacial tills.



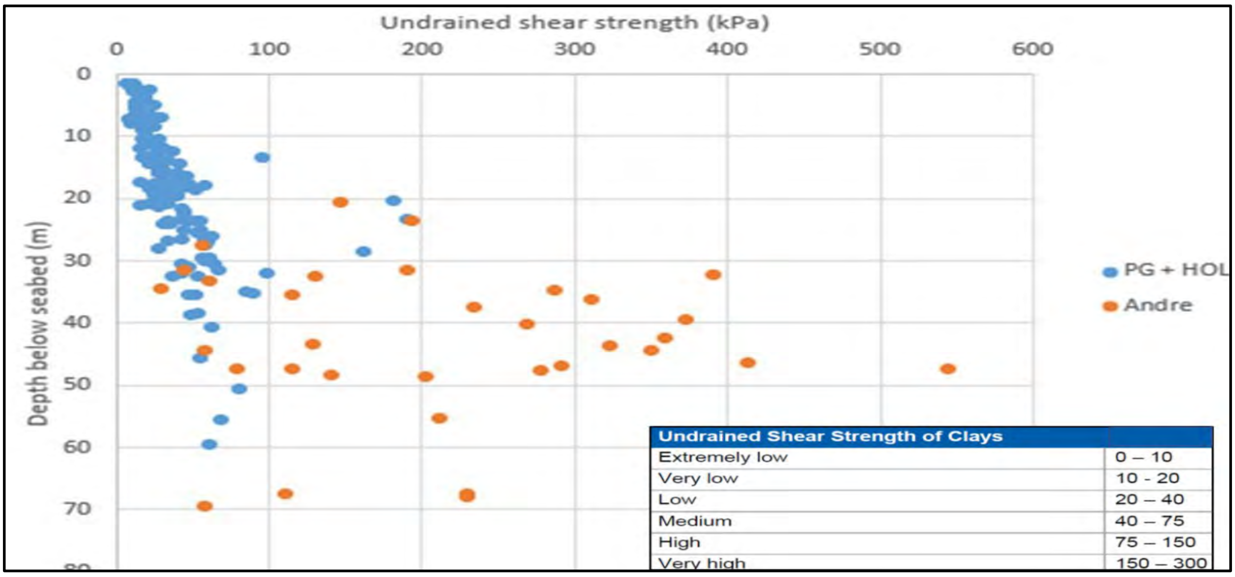


Figure 7.1 Geotechnical sediment cores CB6-BH and CB7-BH, with indication of very low cone resistance to more than 40 m below seabed and evidence of 92,5% of total CPT measurements <10 MPa. The location of CB6-BH and CB7-BH is indicated on Figure 7.3.

Figure 7.2 Undrained shear stress measurements showing low Unit A - E/F values and higher values for the lower units G–H.

The cone resistance measurements shows that 92,5 % of the tests have values <10 MPa (Figure 7.1) and the soft Late Glacial and Holocene clay–sand clay sediment also have very low undrained shear strength values below 100 kPa. In general, values below 40 kPa are in the range of low to extremely low undrained shear stress of clay (Figure 7.2).

The distribution of the uppermost soft sediments is illustrated in Figure 6.3 presented by Energinet (2021). The seismic interpretation of the combined Units A–E/F shows more than 50 m of soft sediments in the north-central part of the Hesselø OWF, gradually thinning to about 20–30 m in the south-eastern part of the area. Correlation of the seismic data to coring data is in general good, but local areas show less good correlation.

One possible explanation could be that the southernmost part of the area may be influenced by glacial disturbance from a minor glacial readvance. Limited increase in strength parameters can be expected in this area.

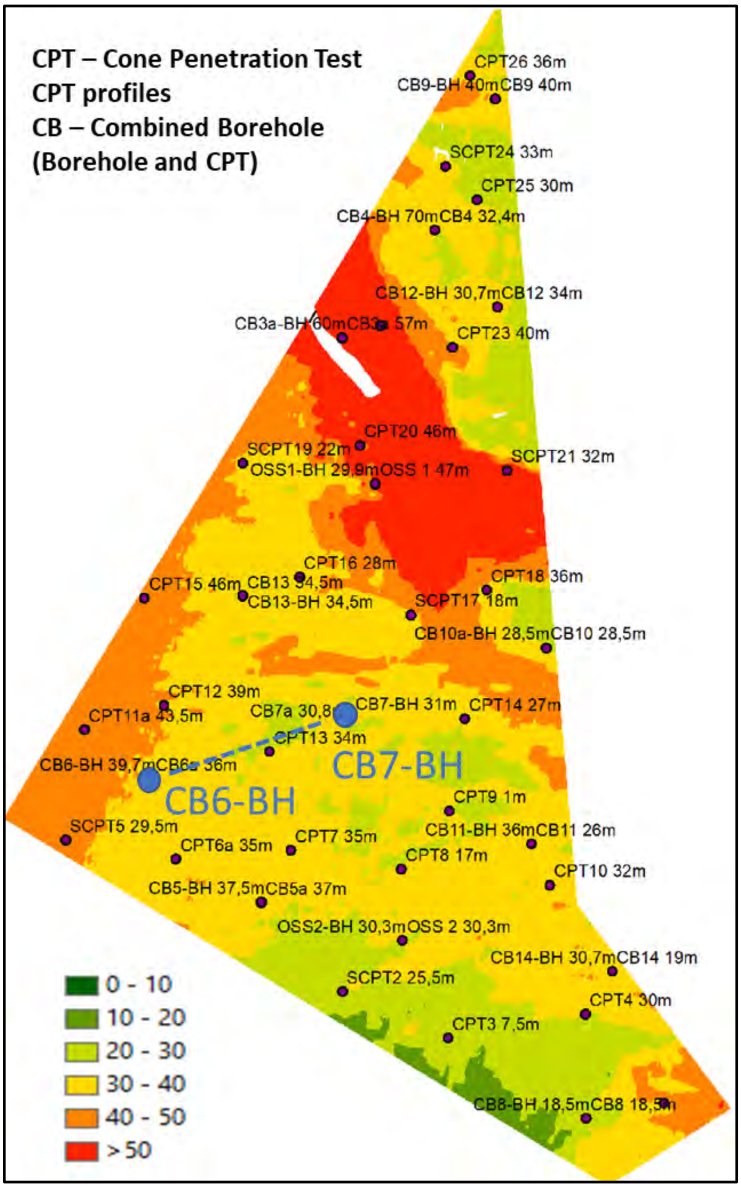


Figure 7.3 Thickness of geotechnical soft sediments (thickness of Unit A–E/F Seismic data) in the Hesselø OWF. Point data shows thickness of soft sediment (CPT and boreholes). There is generally a good correlation between the data sets. Local areas without correlation could be related to glacial disturbance of Unit E/(F). Figure from Energinet (2021).

8. Mapping procedures of Area A and B archive data

As a background for the evaluation of Geotechnical soft sediments in Area A and B we have used the results from the geotechnical soft sediment mapping in the Hesselø OWF presented in chapter 7 (Figure 7.1 to Figure 7.3).

The detailed mapping of geotechnical soft sediments in Hesselø OWF will be expanded to a more general mapping of thickness of expected geotechnical soft sediments in Area A and B. This is carried out to enable us to give a general evaluation of the potential for OWF foundations in Area A and B.

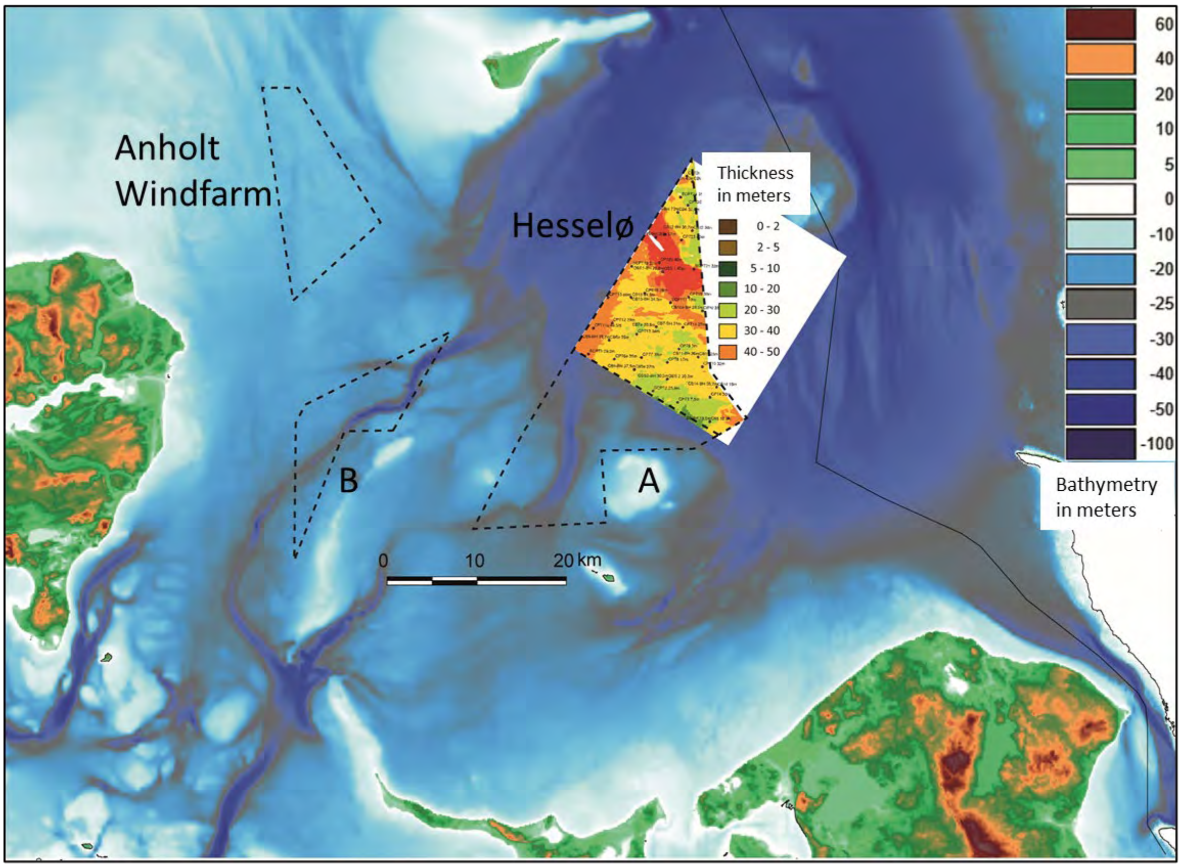


Figure 8.1 Detailed mapping of geotechnical soft sediments in Hesselø OWF, presented in relation to the optional study areas A and B as well as the existing Anholt OWF.

In the geological screening process of Area A and B, we have used the datatypes presented in chapter 4 (Data background).

On the basis of information from GEUS (2020) and Fugro (2021) it was decided to use the seismostratigraphic units presented in Table 1, for interpretation of archive data in Area A and B.

In Area A and B, we have used ‘Marta Database’ sparker data from raw material survey Anholt-Syd-R3-NST 2011 as well as scientific data not yet stored in Marta.

The scientific data include a few multichannel data from a DAN-IODP-SEIS KAT2013 High Resolution 2D seismic survey, single channel lines from 1999 acquired in a cooperation with Institut für Ostsee Forschung in Warnemünde and Parasound subbottom profiles from the Maria S. Merian MSM62 cruise.

The following steps have been followed for the mapping in Area A and B:

- Seismic data were converted to SGY format
- A harmonised processing of seismic data was made in GeoSuite AllWorks.
- SGY files were loaded in the seismic interpretation software Geographics
- Interpretation of seismic profiles was according to the seismostratigraphic units in Table 1
- Calculation of the thickness of soft sediment (bottom unit E/F minus seabed)
- Export of thickness in ascii format
- Georeference of soft sediment thickness
- GIS presentation of soft sediment thickness
- Soft sediment thickness comparison with Hesselø OWF and Anholt OWF

The final product is thickness and distribution maps of expected geotechnical soft sediments in Area A and B.

9. Geological screening of Area A

In Area A we have used a few seismic lines with track lines that cover parts of Hesselø OWF and Area A. Profiles of two examples (Figure 9.1 (Sparker lines 572013A and R3_017A) and an example of a Fugro 2D UHRS sparker line (HAX2499P01) are presented as a background for visualisation of the Table 1 seismic units.

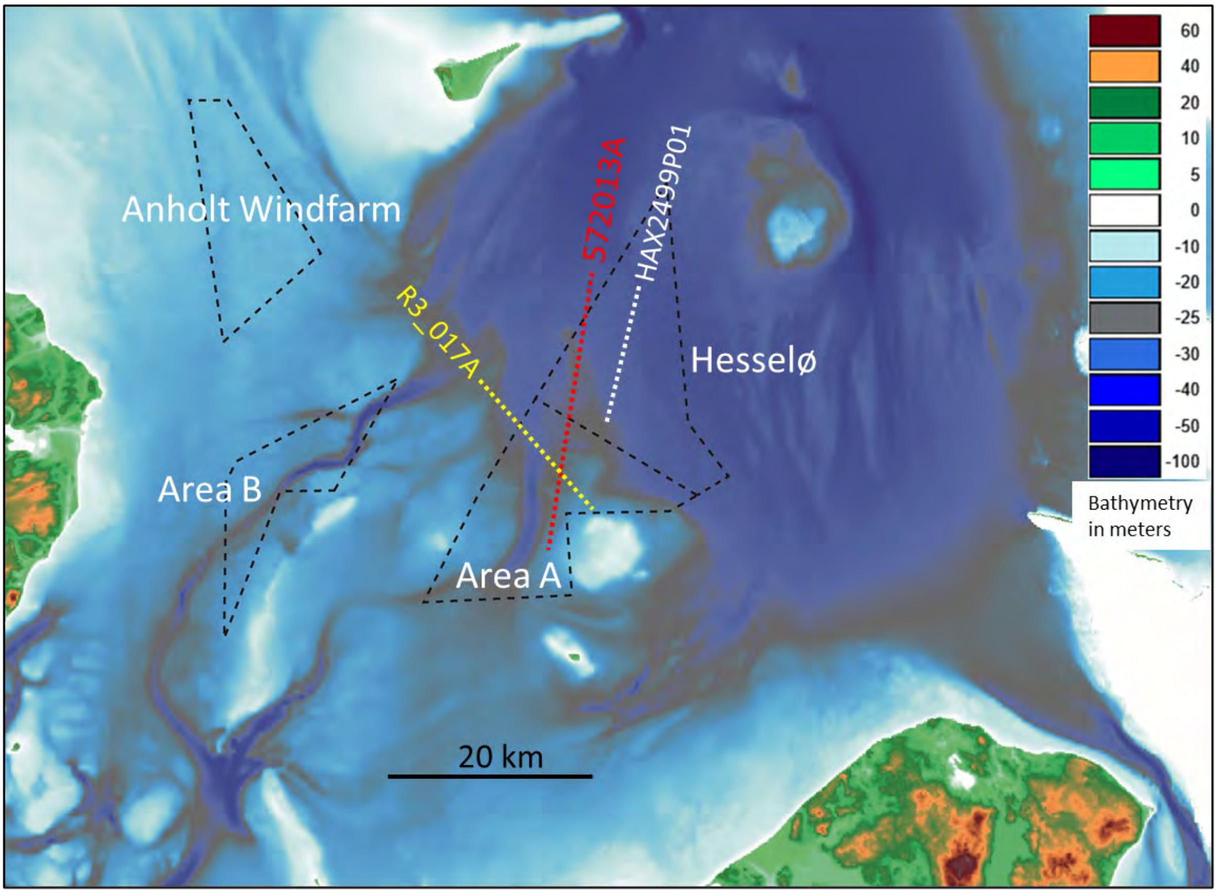


Figure 9.1 Bathymetry and location of seismic examples from Hesselø OWF and Area A.

Fugro line HAX2499P01 is a north to south profile in Hesselø OWF and archive line 572013A is sub-parallel to it but continues southward through Area A (Figure 9.1, Figure 9.2 and Appendix A).

Both profiles show the same units in Hesselø OWF, from unit H till to unit E/F Late Glacial soft clay and C to A Holocene clay to sand.

9.1 Seismic interpretation in Area A.

By following archive line 572013A southward it is possible to verify that the seismic units continue into Area A with a gradual thinning of the combined geotechnical soft sediment units D and E (in the south unit D fills in a depression) and with varying thicknesses of the unit B deltaic soft sediments (Figure 9.2). The combined geotechnical soft sediments are in general more than 20 m thick along line 572013A.

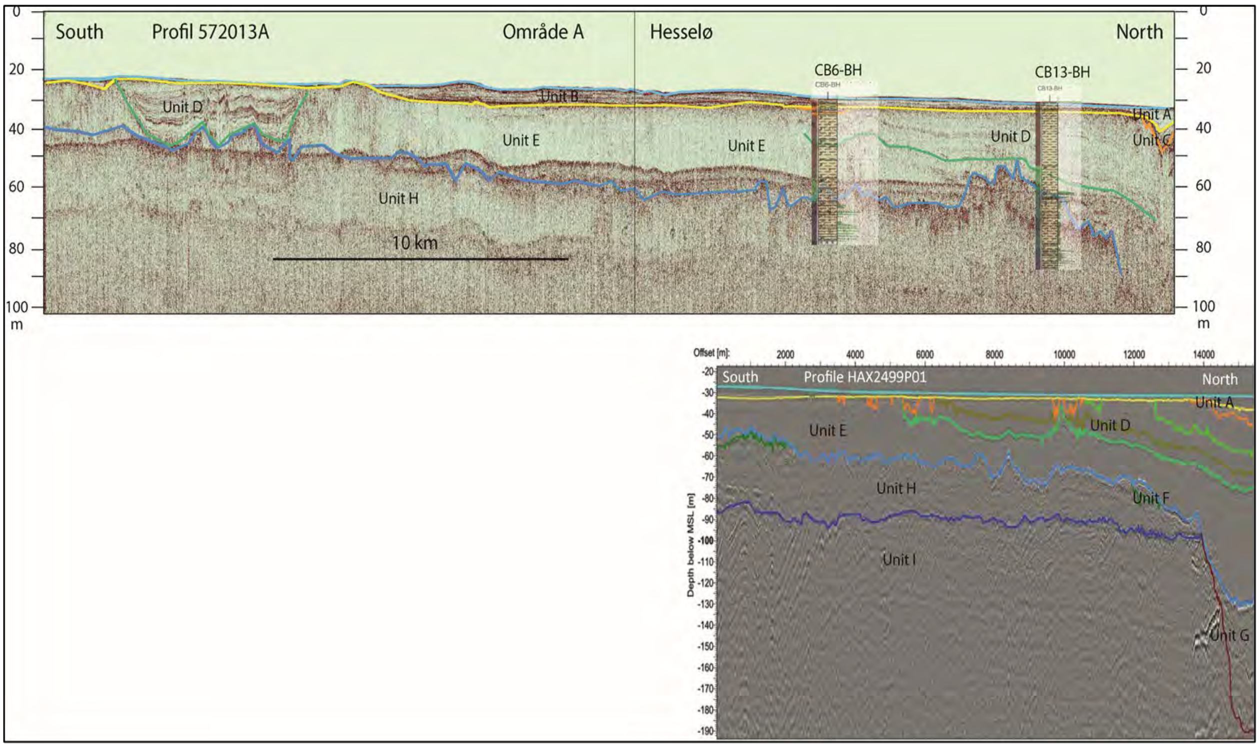


Figure 9.2 North-south seismic profiles Fugro line HAX2499P01 in Hesselø OWF and archive line 572013A continuing southward through Area A. For details see Appendix A. Location see Figure 9.1 and seismostratigraphic units presented in Table 1.

Cross line R3_017A (Figure 9.3 and Appendix B) documents that the Unit H till comes to the seabed surface in the south-eastern part and that the north-central and western part along line 572017A has a combined geotechnical soft sediment in general of more than 20 m thickness along line 572017A.

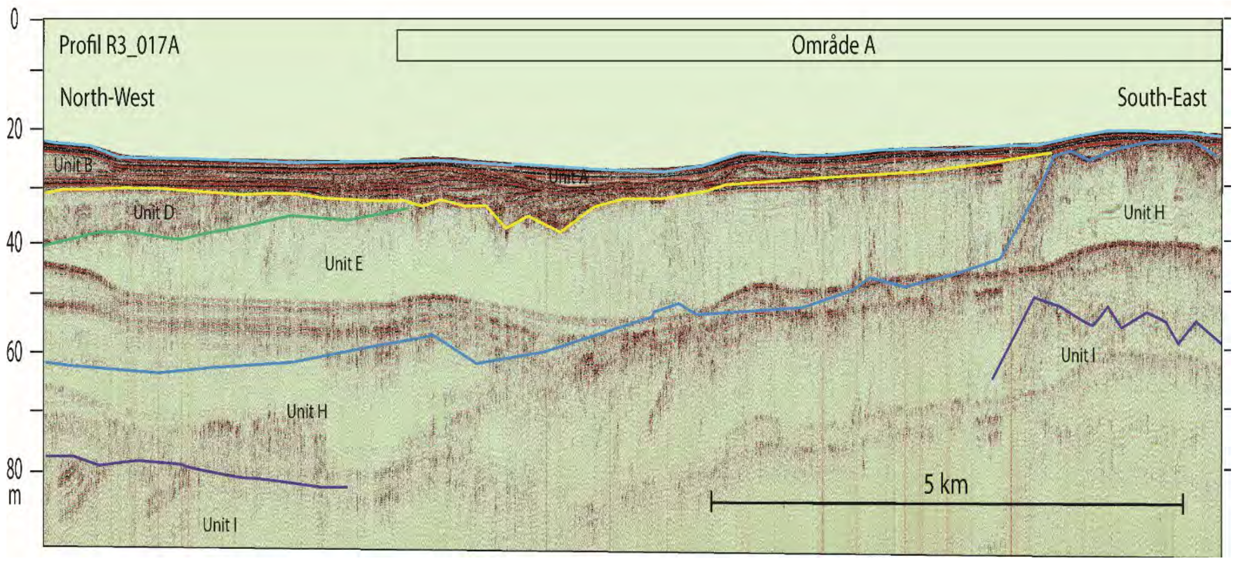


Figure 9.3 North-west to south-east section from the northern part of Area A. For details see Appendix B. Location see Figure 9.1. The seismostratigraphic units are presented in Table 1.

9.2 Thickness map of geotechnical soft sediments in Area A

With the stratigraphy in place all available lines have been interpreted and a general thickness map of geotechnical soft sediments in Area A have been produced and compared to the detailed mapping of Hesselø OWF (Figure 9.4).

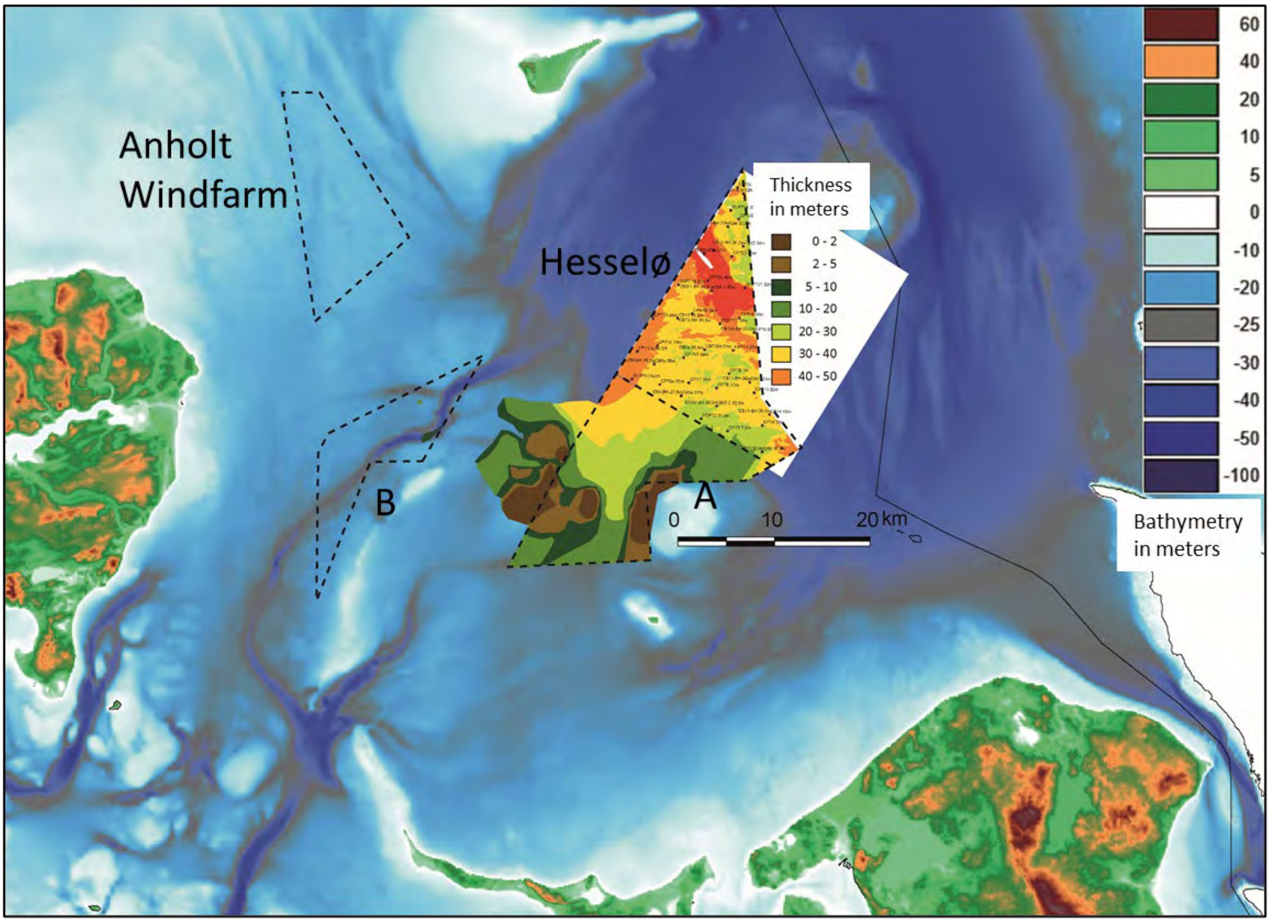


Figure 9.4 General thickness of geotechnical soft sediments (combined thickness of Unit A–E/F Seismic data) in Area A compared with the detailed mapping of Hesselø OWF.

In Area A the more than 20 m thick geotechnical soft sediment package continues in the northern and western part as well as in a southward trending central channel. In the south-western and south-eastern parts, the geotechnical soft sediment thickness above unit H till, diminishes to be few metres.

10. Geological screening of Area B

In Area B it was possible to locate both sparker lines from raw material investigations and parasound sediment echosounder lines from the Maria S. Merian cruise MSM62. The sparker lines penetrate units A–E and into the till unit H. Therefore, we can document that the stratigraphy from Table 1 is also valid for Area B. The parasound data only penetrate the uppermost part of the till, but with a high resolution. These data are also supported by vibrocore documentation.

10.1 Sparker line interpretation in Area B

Sparker lines R3_035 and R3_029 (Figure 10.1and Figure 10.2) are located in the northern part of Area B and show a hummocky till surface with infill of larger northeast–southwest oriented depressions, with Unit E Late Glacial possibly soft clay up til 10 m thick. Holocene soft, muddy and sandy sediments, occasionally with acoustic signs of methane content, are found in connection with the present Great Belt channel, incised in the seabed, in restricted areas and up to 10 m thick, locally even more.

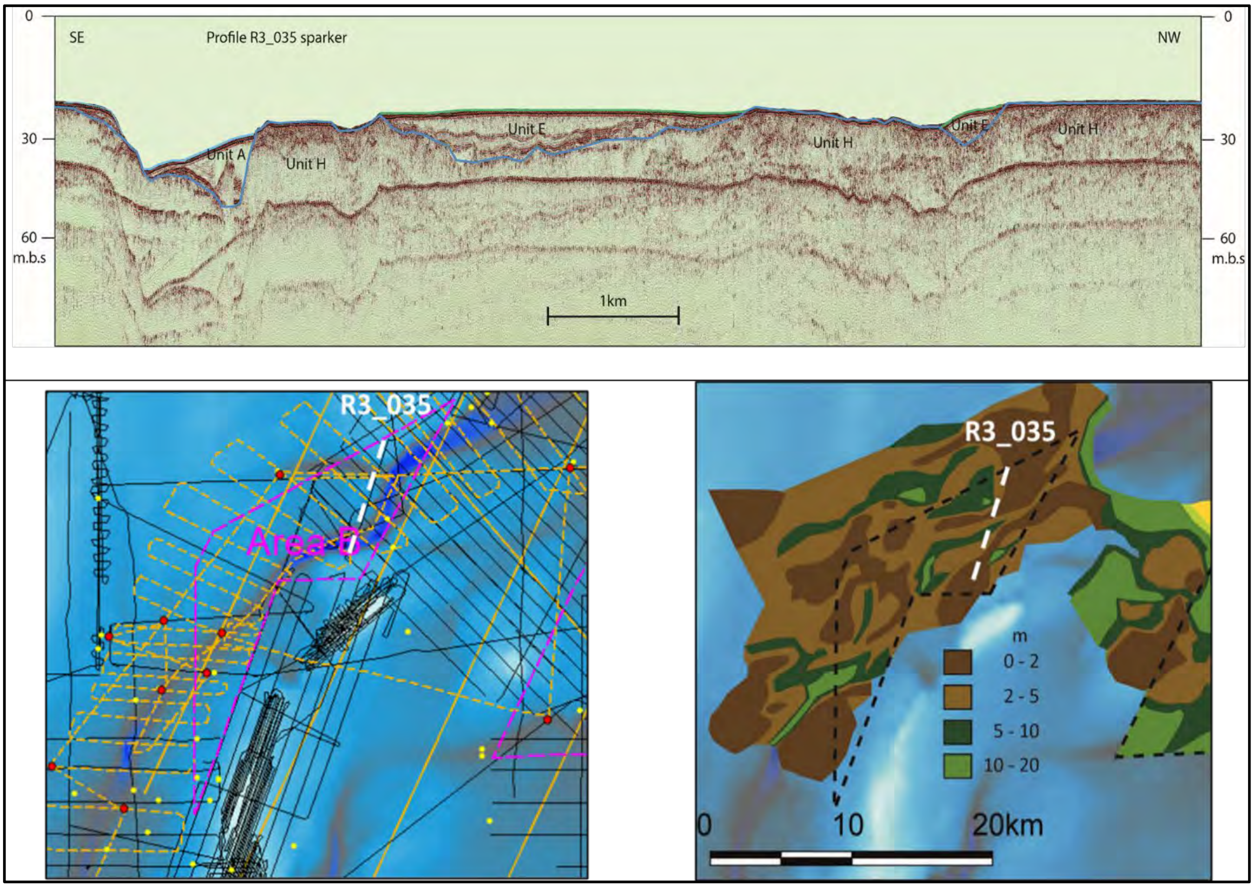


Figure 10.1 South-east to north-west Sparker profile R3_035 with documentation for location in relation to the seismic archive data grid and the geotechnical soft sediment thickness map.

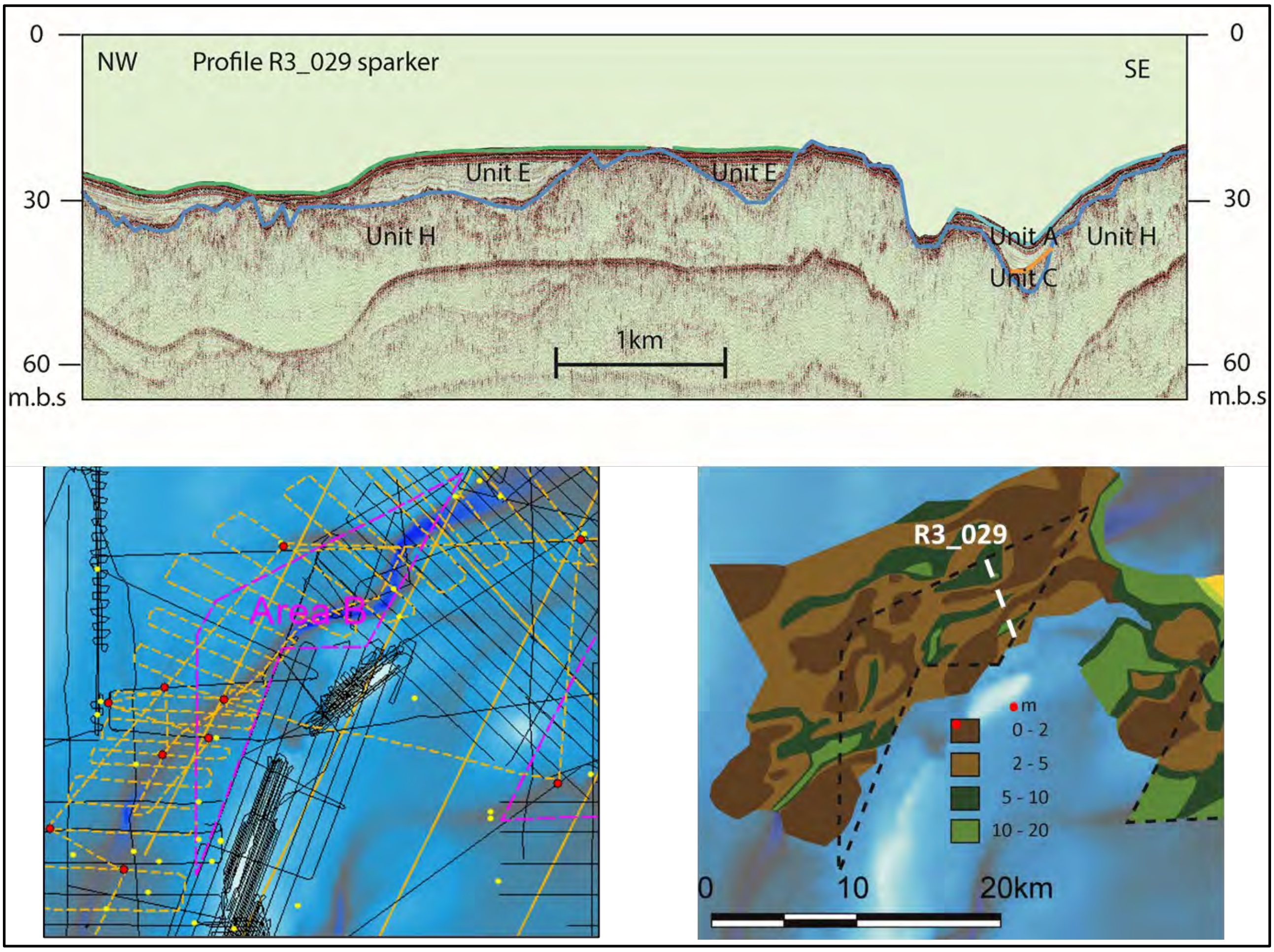


Figure 10.2 North-west to south-east Sparker line R3_035 with documentation for location in relation to the seismic archive data grid (black lines are sparker lines) and the geotechnical soft sediment thickness map.

10.2 Parasound and vibrocore interpretation in Area B

A series of parasound examples from Area B are presented to visualise the areal distribution of the geotechnical soft sediments (Figure 10.3, Figure 10.4 and Figure 10.5).

The high-resolution seismic data supported by vibrocores confirm that Unit H (glacial till) underlies unit E represented by partly draping Late Glacial deposits that consist of soft clay. The Late Glacial clay covers large areas whereas uppermost Holocene muds and fine sand are confined to the northeast–southwest channel depression, seen on the bathymetric map.

Parasound examples from the northern and central part of Area B (Figure 10.3) show nice examples of till (Core 24) Unit H (hummocky surface with chaotic seismic internal reflections) with infill between the hummocks of Late Glacial clay (Core 19) unit E (stratified seismic reflections) followed by channel erosion and infill of Unit B muddy clay and silt (stratified seismic reflections) and Unit A (structureless to transparent) sandy mud.

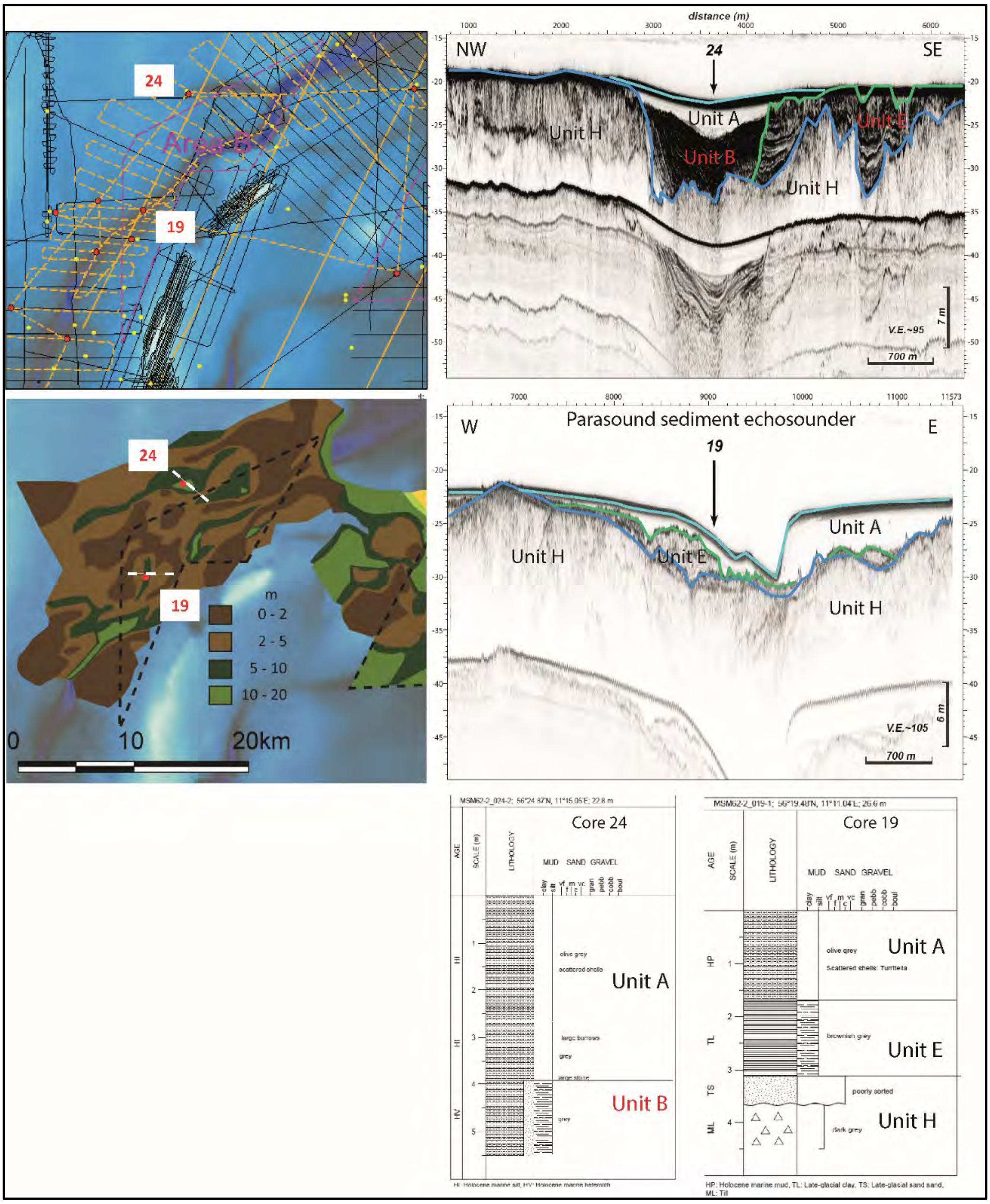


Figure 10.3 Parasound echosounder profiles from the northern and central parts of Area B, with documentation for location in relation to the seismic archive data grid (yellow lines are parasound grid). The positions of the seismic examples and vibrocores 24 and 19 are indicated on the geotechnical soft sediment thickness map. Core descriptions with indication of seismic units are seen in the lower right of the figure.

A parasound example from the central-western part of Area B (Figure 10.4) shows the top of till (core 17) Unit H (hummocky surface with chaotic seismic internal reflections) with infill between the hummocks of Late Glacial clay and silt (Core 16 and 17) unit E (stratified seismic reflections). This example is outside the channel area and shows draping Unit A (structureless to transparent) fine sand to muddy sand.

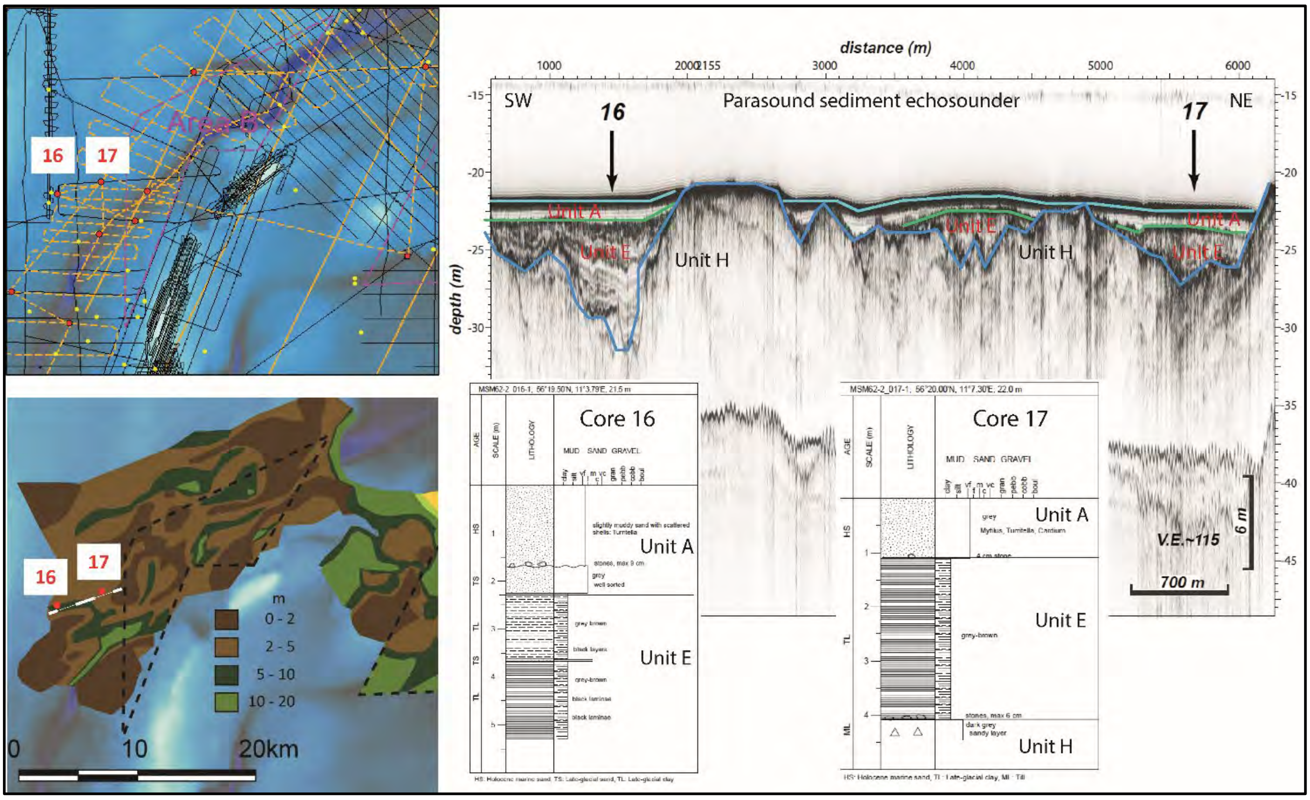


Figure 10.4 Parasound echosounder lines west of Area B, with documentation for location in relation to the seismic archive data grid (the yellow lines show the parasound grid). The positions of the seismic examples and vibrocores 16 and 17 are indicated on the geotechnical soft sediment thickness map. Core descriptions with indication of seismic units.

Parasound examples from the south of Area B (Figure 10.5) also show till as the basis, Unit H (chaotic seismic internal reflections) with partly infill of Late Glacial clay and silt unit E (stratified seismic reflections). The Figure 10.5 examples show on the paleo Great Belt channel incision and the channel infill of more than 10 m Unit A (lower part parallel infill reflectors and upper part structureless to transparent) Holocene sandy clay to mud (Core 15 and 18).

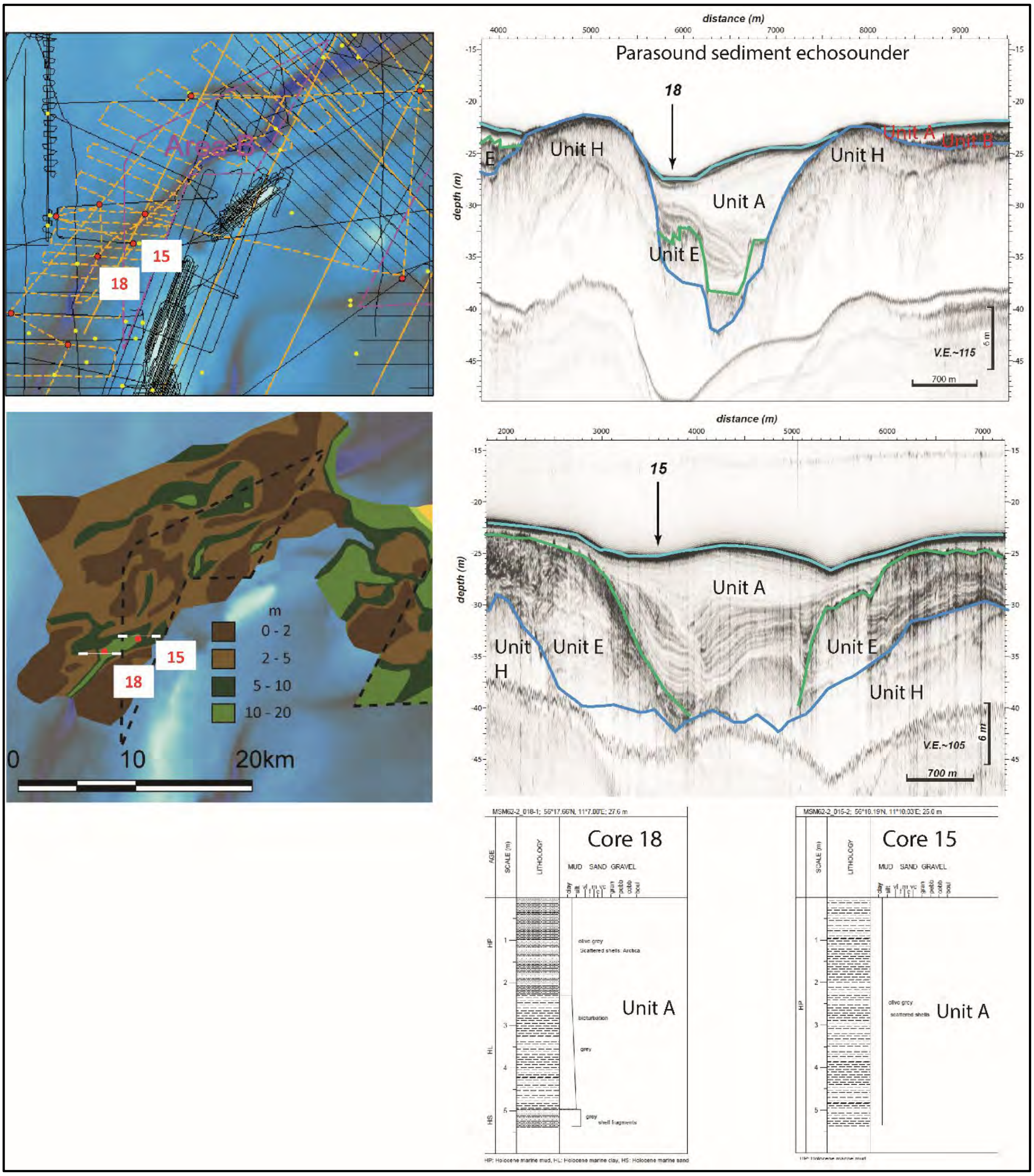


Figure 10.5 Parasound echosounder profiles from the southernmost part of Area B, with documentation for locations in relation to the seismic archive data grid (yellow lines are parasound grid). The positions of the seismic profiles and vibrocores 18 and 15 are indicated on the geotechnical soft sediment thickness map. Core descriptions with indication of seismic units.

10.3 Thickness map of geotechnical soft sediments in Area B

In Area B a hummocky till surface with infill of larger northeast–southwest-oriented depressions have infill of Unit E Late Glacial possibly soft clay up til 10 m thick, whereas a paleo Great Belt Channel has infill of Holocene soft, muddy, and sandy sediments in restricted areas and up to 10 m thick, locally even more.

The combined thickness of geotechnical soft sediment is shown in Figure 10.6. The general impression is that the soft sediments are thinner than in Hesselø OWF and Area A. In most of Area B, the thickness of soft sediment is between 2 and 5 m, but in the northeast to southwest elongated depressions there are 5–10 m of soft sediment and locally 10–20 m.

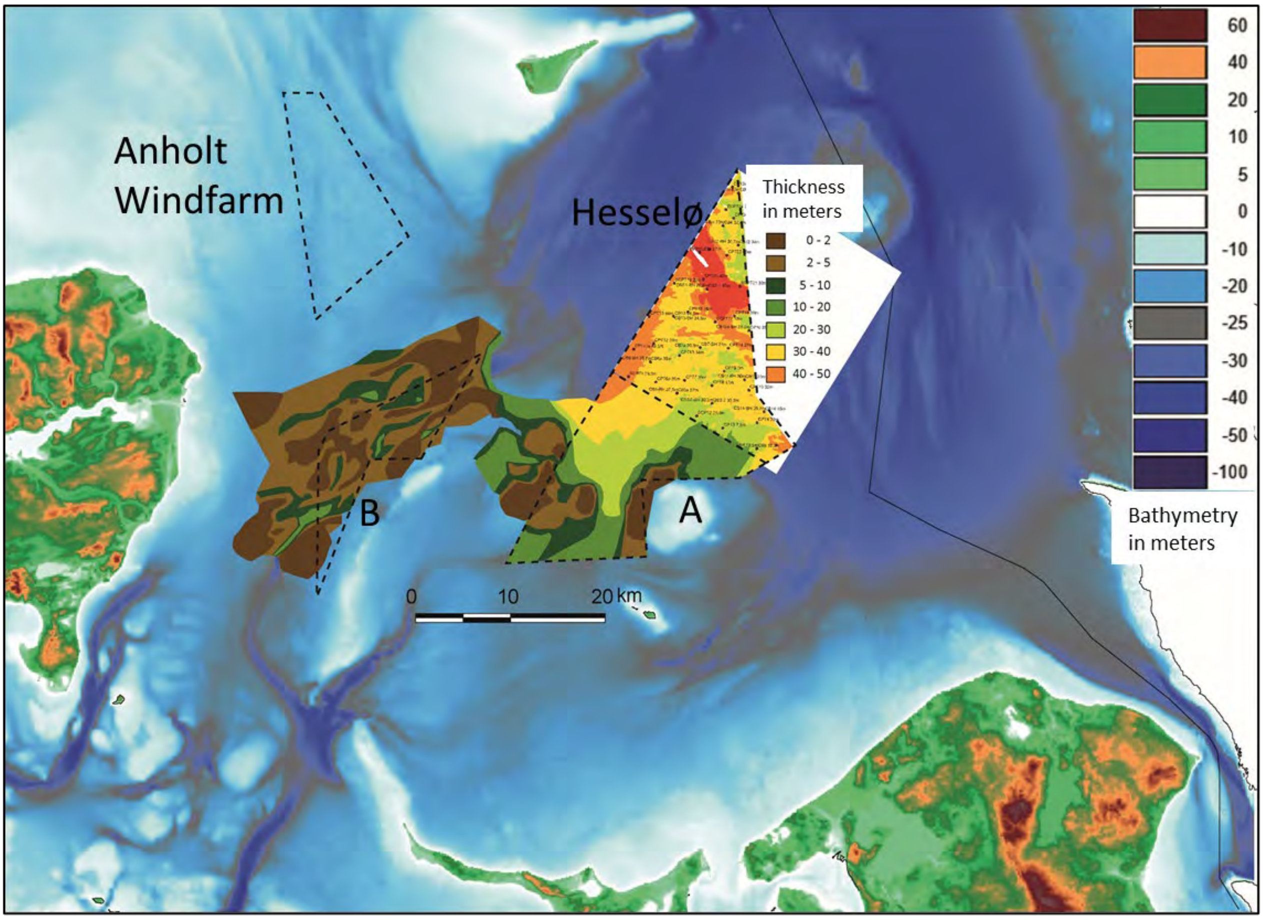


Figure 10.6 General thickness of geotechnical soft sediments (combined thickness of Unit A–E/F Seismic data) in Area A and B, compared to the detailed mapping of Hesselø OWF.

11. Anholt OWF as an analog for Area A and B

Hesselø OWF is in the preparation phase and Area A and B are in the screening phase.

Anholt OWF is however in function and all geological basis information is available and of great importance for the geotechnical evaluation of Area A and B.

In 2009, GEUS conducted a geophysical survey of the Anholt OWF (Leth et al. 2009; Leth & Novak 2010), which, together with cone penetration tests and data from boreholes, lead to a good understanding of the geological architecture and development of the 144 km^2 survey area.

The geological setting of the Anholt OWF is the same as in Hesselø OWF, Area A and B with the same seismic units described in Table 1.

A schematic geological profile of Anholt OWF and a general map of the thickness of geotechnical soft sediments (Figure 11.1) show a southern area comparable to Area A with a hummocky till surface draped by Unit D and E Late Glacial soft clay, overlain by Holocene A, B and C muddy channel fills and fine-grained muddy sand.

The southern Anholt OWF area is dominated by 0–5 m soft sediments above till and as such comparable to Area B.

The northern Anholt OWF area is dominated by 10–30 m soft sediments above till, corresponding to the central part of Area A.

A detailed geotechnical evaluation of the Anholt OWF is outside the scope of this preliminary screening and evaluation of possible foundation problems. However, it is interesting to study the distribution of windmills in the Anholt OWF (Figure 11.1). The windmills show an overall northwestern pointed shape, but with obvious considerations to soft bottom, with missing windmills in the areas with the thickest layers of soft sediments.

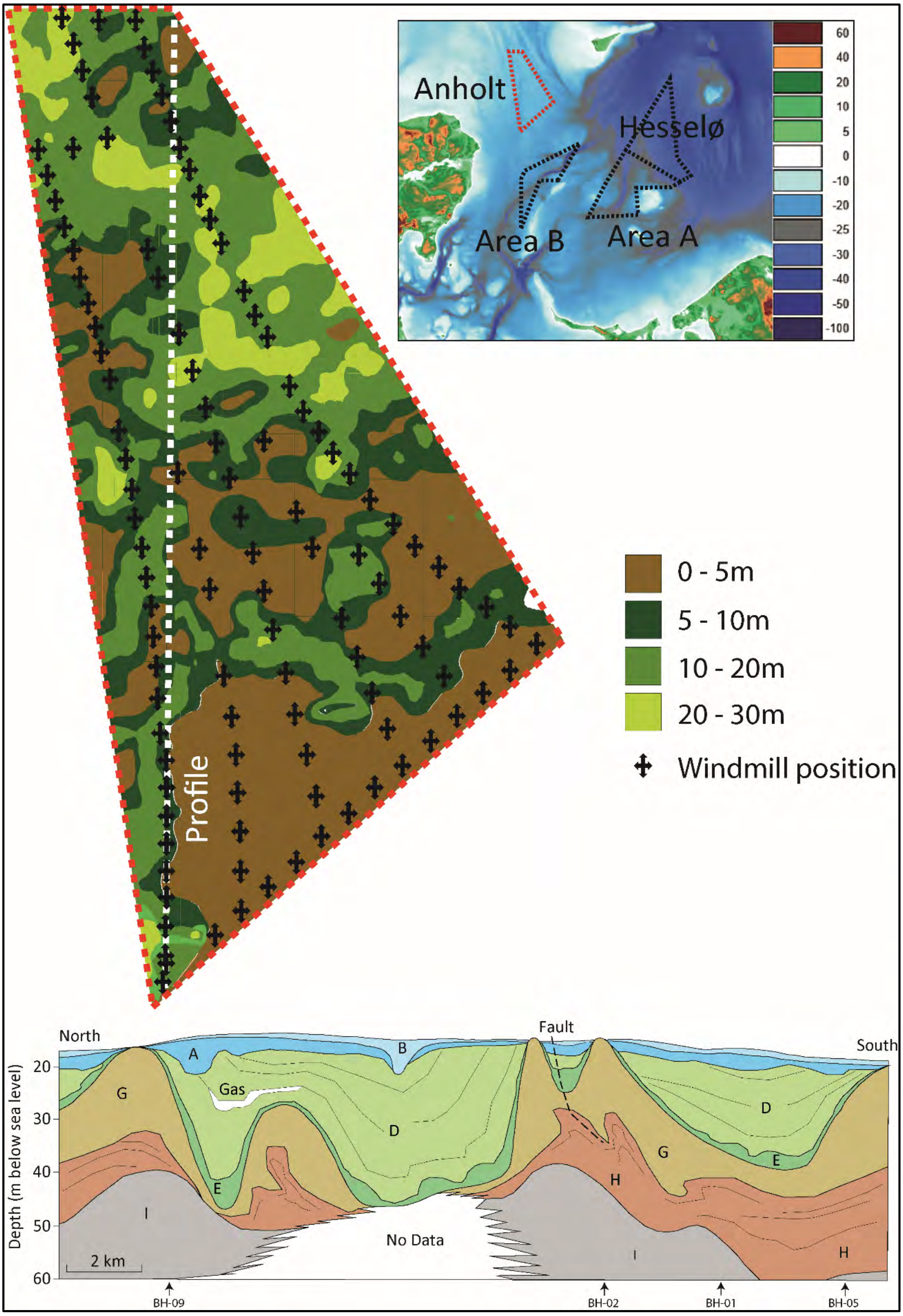


Figure 11.1 Anholt OWF general map of thickness of geotechnical soft sediment, with indication of location of schematic profile and windmill positions. Details of seismic units A–I in the schematic profile are provided in Table 1.

12. Archaeological interests

In addition to geotechnical interests in a detailed geological model for Area A and B, to be able to plan the detailed geotechnical investigations, it is also of great interest for an archaeological screening, to understand the development and distribution of land and sea after the last deglaciation.

As described in Chapter 5.4, highstand sea-level characterised the initial period after the deglaciation of central and southern Kattegat. Around 15 cal. ka BP Kattegat was deglaciated and all the planned Area A and B, were covered by the glaciomarine Younger Yoldia Sea (Figure 12.1). This corresponds to the archaeological Hamburg culture or Hamburgian (15.5–13.1 ka BP)–a Late Upper Palaeolithic culture of reindeer hunters.

The highstand period was followed by a regression and development of an erosional unconformity. Around 12 cal. ka BP, the Baltic Ice Lake reached its maximum shore level in the Baltic and the Kattegat regression continued. Possibly, parts of Store Middelgrund and Area A and B emerged from the sea (Figure 12.1) in the time period of the Ahrensburg culture or Ahrensburgian (12.9 to 11.7 ka BP)–a late Upper Palaeolithic nomadic hunter culture.

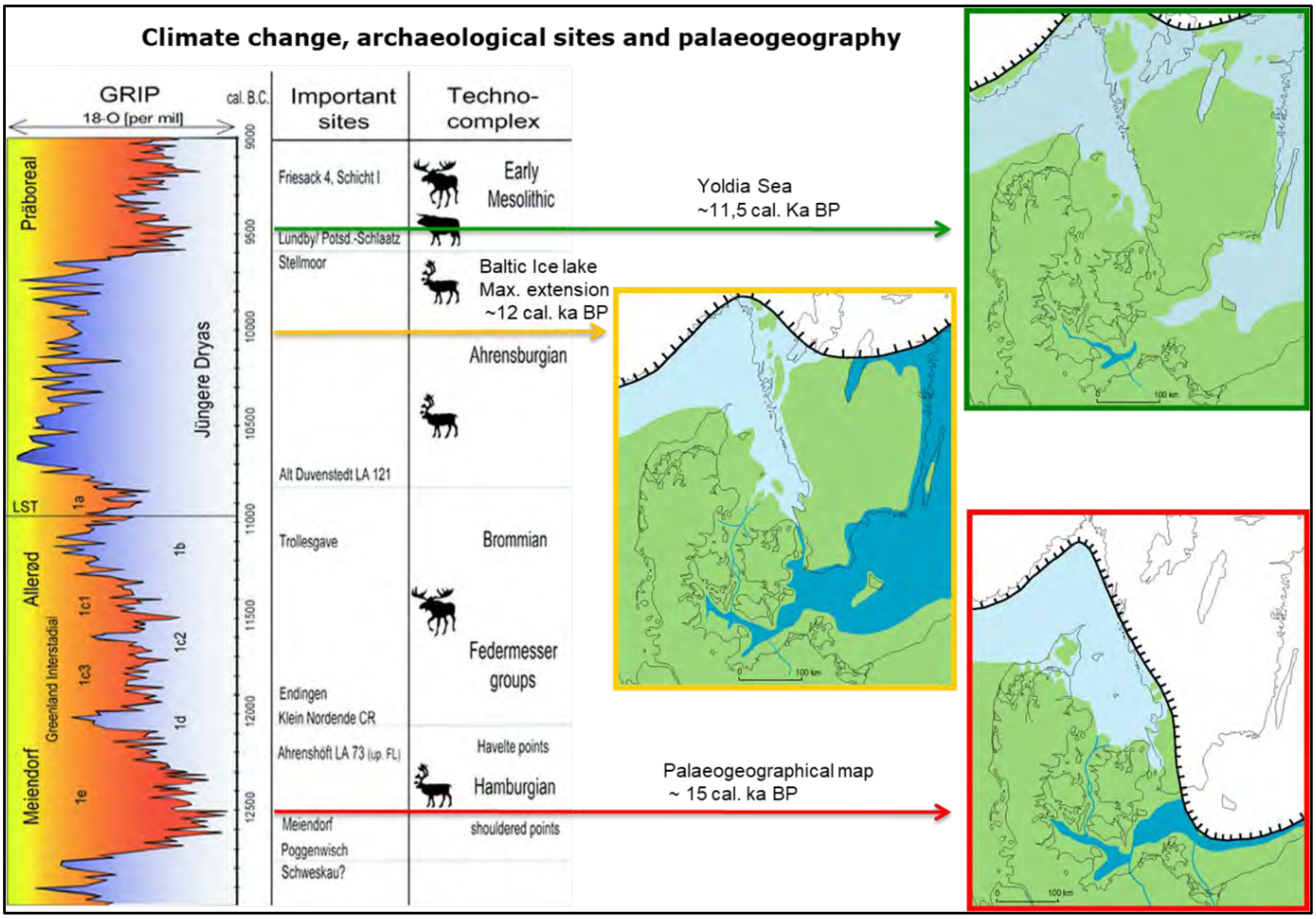


Figure 12.1. Late Glacial and Holocene general palaeogeography in Kattegat and related archaeological cultures. (the maps are from Jensen et al. 2003).

The regression reached its maximum lowstand about 11.5 cal. ka BP, during a period when the Baltic was connected to the Kattegat via south-central Sweden (Figure 12.1). Large parts of Area A and B was land but with N–S-oriented channels in the Area B Lyse Grund Area and the palaeo Great Belt channel in Area B. The northern part of Area B crosses the mouth of a possible fjord system. The lowstand coincides with the Early Maglemosian culture from 11.0 to 8.8 ka BP, a hunting and fishing culture with tools made from wood, bone and flint.

The regression was followed by the initial Holocene transgression and a major spit barrier/estuary system developed in large areas in the southernmost part of the Kattegat. About 9.9 cal. ka BP, the system was fully developed with a large tidally dominated river mouth system with a southward fluvial connection to the Baltic Ancylus Lake (Figure 5.4). A major fine-grained sand spit and back barrier estuary clay dominates the northwestern part of Area A. The large spit barrier/estuary phase developed in the transition period between the Early Maglemosian culture 11.0–9.0 ka BP and the Middle Maglemosian culture 9.8–9.0 ka BP.

The present bathymetry (Figure 3.1) shows that the spit/ barrier/estuary has to a large degree been preserved, with only minor modification by the continued Holocene transgression. This leads to the conclusion that the following steep transgression (Figure 5.7) resulted in a coastal back-stepping over a relatively flat platform with a fast retreat of the coastline and only minor erosion of the spit barrier/estuary system.

Coastal deposits of the younger phases of the Holocene transgression is not represented in the Area a and B and will only be of relevance in the future cable corridors close to the present coastline.

13. Conclusions

In this screening study of Area A and B potential OWF, we have used a combination of published work and archive seismic and sediment core data to assess the general geological development of the southern Kattegat area, including the planned Area A and B OWF.

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

As part of the geological desk study, we present a relative Late Glacial and Holocene sea-level curve for the area and describe the development that is relevant for an archaeological screening.

The Hesselø OWF seismostratigraphic and lithological units as well as the thickness of geotechnical soft sediments have been used as a background for mapping of archive data from Area A and B.

The results of the mapping are presented as seismic examples. A map showing the general thickness of geotechnical soft sediments in Area A and B, in the Hesselø OWF and the Anholt OWF is presented in Figure 13.1.

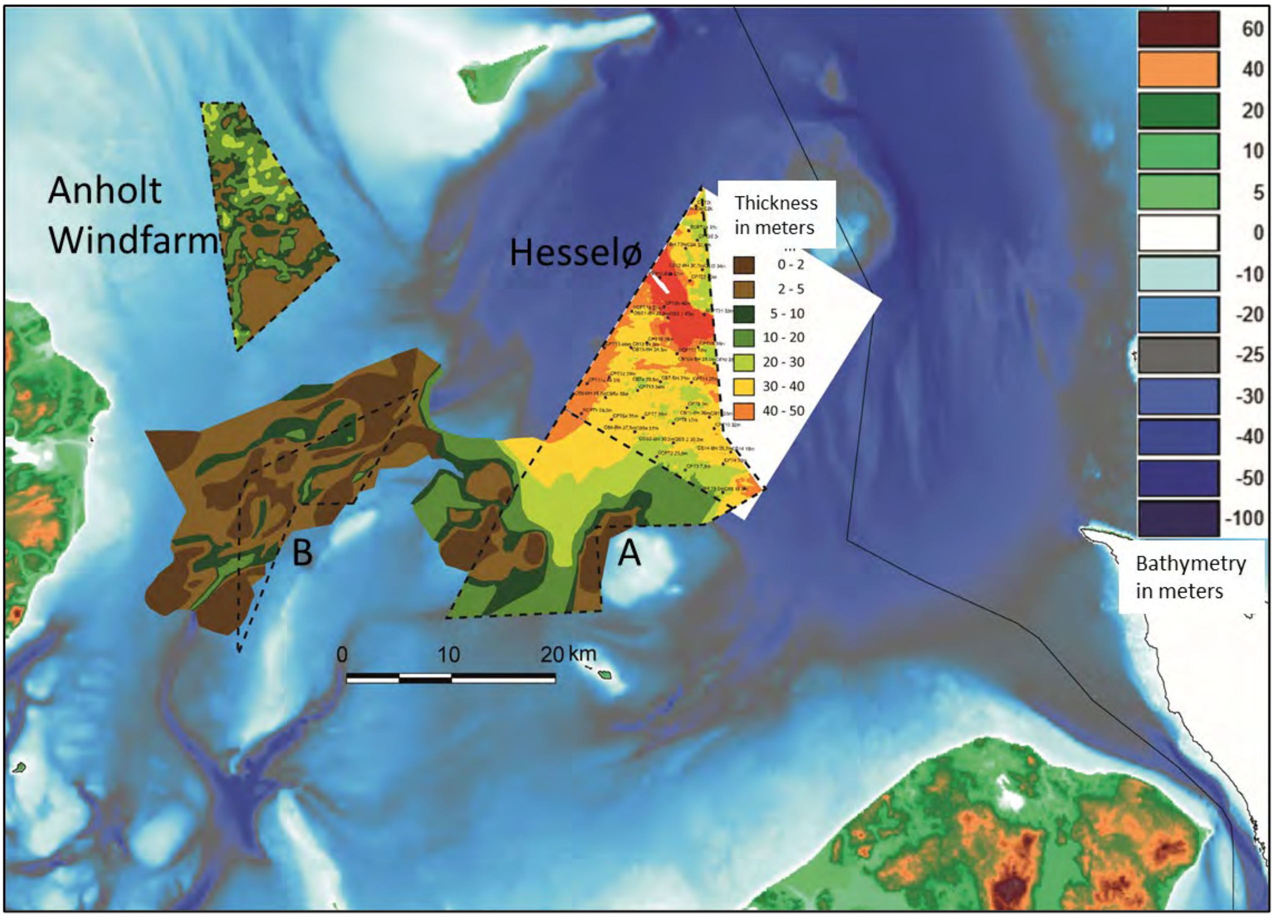


Figure 13.1 Thickness of geotechnical soft sediments in the southern Kattegat Anholt OWF and potential Hesselø, Area A and B. For details see Appendix C.

The geological screening leads to several conclusions relevant for the future geotechnical and archaeological evaluation of the area:

- The study area in the Fennoscandian border zone is characterised by pre-Quaternary faulting. Studies of the distribution of Late Glacial soft clay show that faulting has created elongated restricted basins with soft sediment infill above till.
- Weakly consolidated glaciomarine clay with a thickness of more than 30 m covers a majority of the Hesselø OWF area and continues southward into Area A.
- An Area A 20–40 m thick geotechnical soft sediment package is mapped in the northern and western part as well as in a southward trending central channel. In the south-western and south-eastern parts, the geotechnical soft sediment thickness above till, diminishes to be few metres.
- Area B has thinner, soft sediments than Hesselø OWF and Area A, in most of the area between 2 and 5 m, but in the northeast to southwest elongated depressions there are 5–10 m of soft sediment and locally 10–20 m.
- Anholt OWF is a relevant analogue for Area A and B with obvious similarities in relation to geotechnical considerations concerning the thickness of geotechnical soft sediments.
- Glaciotectonic deformations have been recorded at store Middelgrund east of the Hesselø OWF area and similar features may be found in Area A close to Lysegrund.
- In connection with the Holocene transgression the north-western part of Area A was transformed into a spit/estuarine system with fine-grained sand and clay and with high contents of organic material. In this area geotechnical challenges are expected.
- The Late Glacial and Early Holocene coastal zone development of the northern Area A opens for archaeological interests in the time period for the Ahrensburgian and Maglemosian cultures whereas the area was transgressed by the sea during younger cultures.
- Bathymetrical data highlight that channels are found in Area A and B, in contrast to the relatively flat seabed in the Hesselø OWF.

An overall conclusion from a geological viewpoint is that the soft sediments in the northern and central parts of area A, with a thickness < 30m, are expected to be similar to the south-eastern part of the Hesselø area with a thickness < 30m of soft sediments.

In the southern part of Area A and in all of Area B, there are expected similar soil conditions as in Anholt OWF meaning, from a geological point of view, it is most likely possible to establish OWF in these areas.

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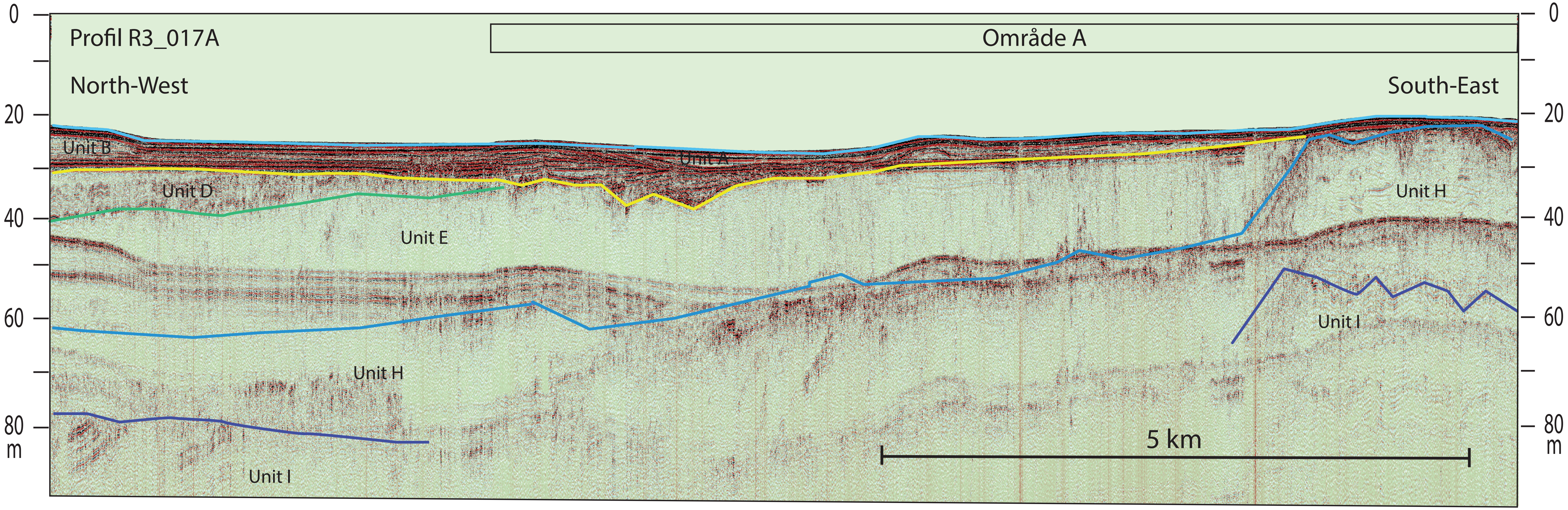
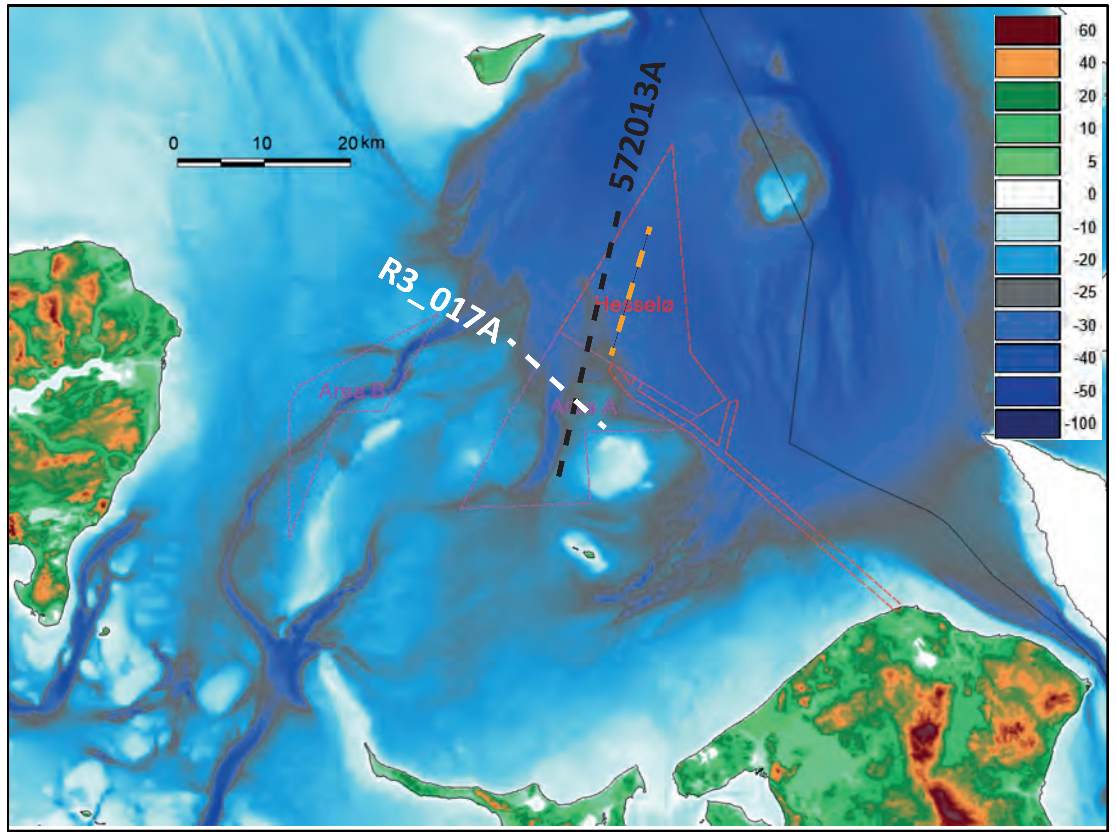
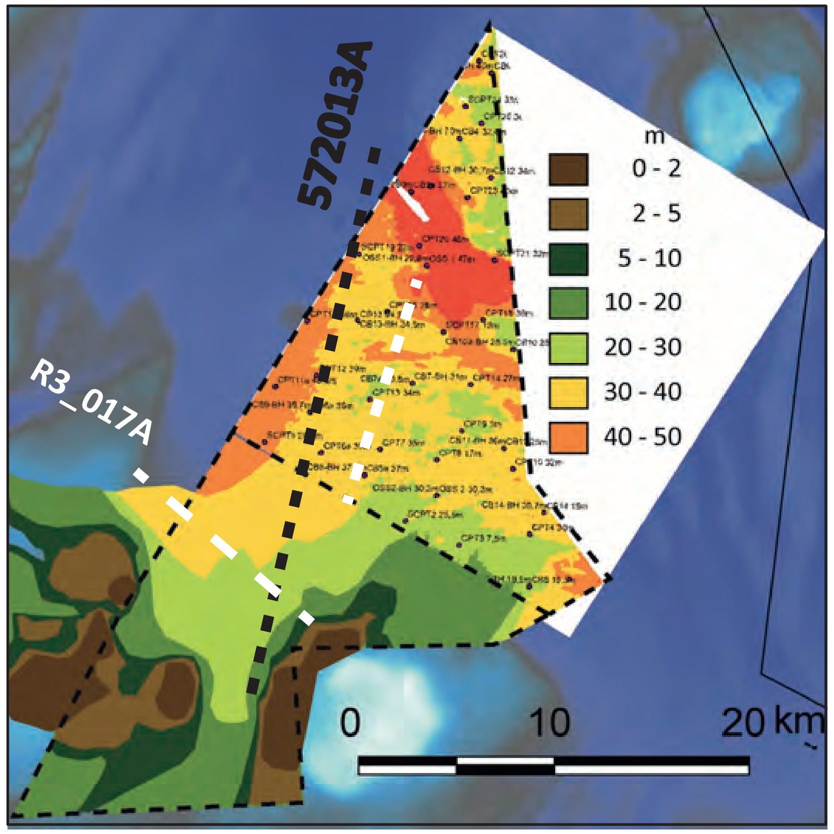
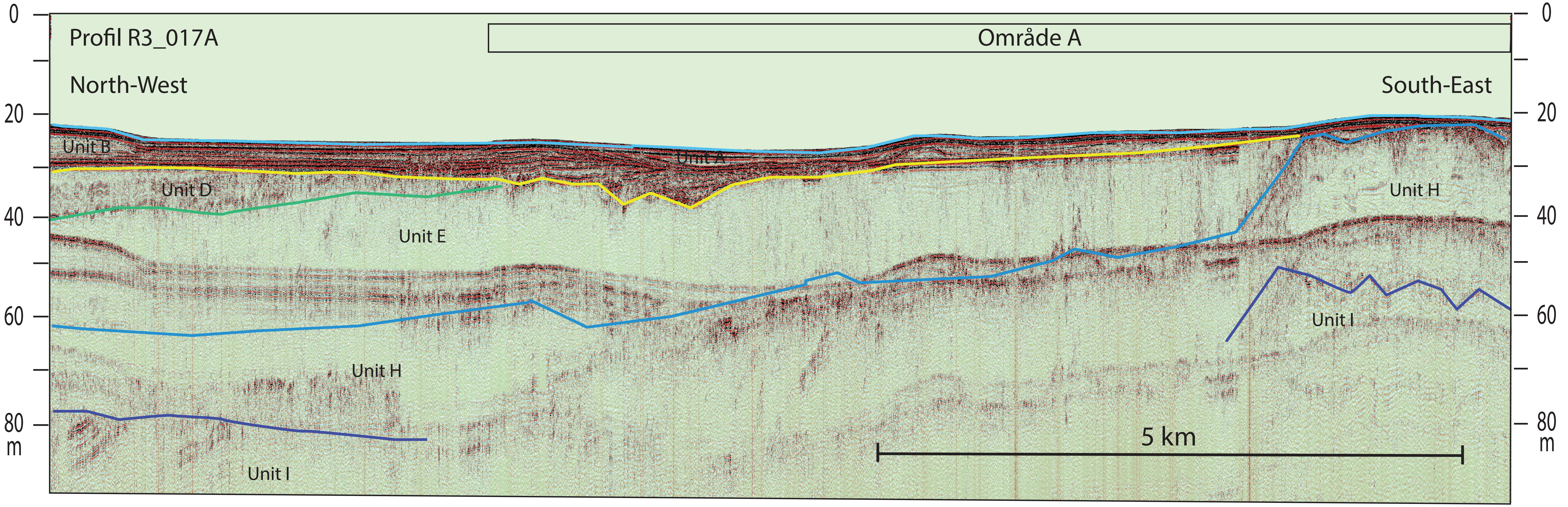


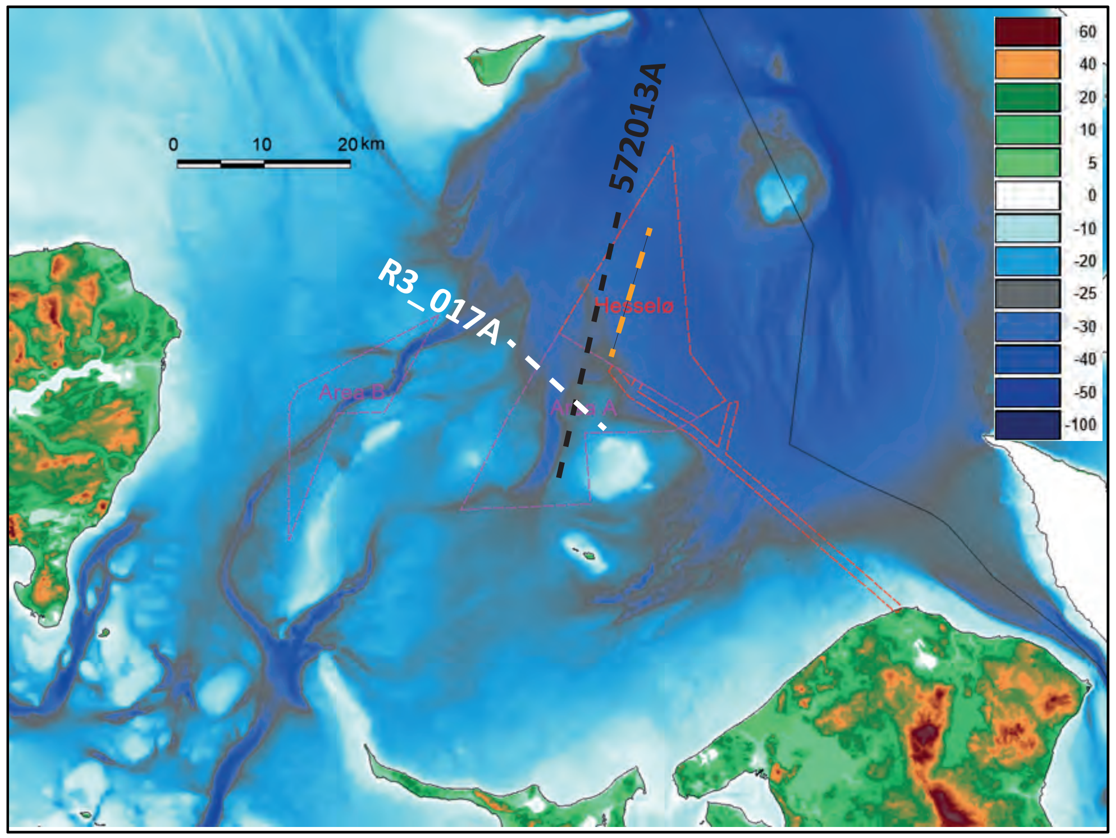


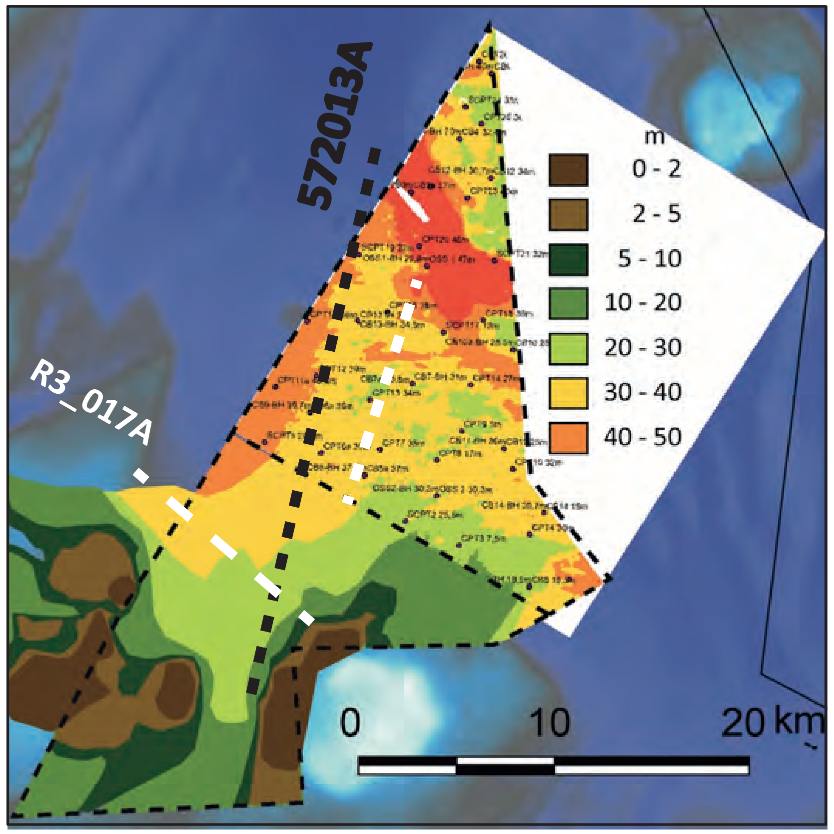


UNIT	Expected soil type	Age
A	CLAY to clayey medium SAND or sandy GYTTJA with shells and shell fragments and organic material	Holocene
B	Interlaminated to interbedded CLAY and SILT with shells and shell fragments	Early Holocene
C	Medium SAND with abundant shells and shell fragments	Early Holocene
D	CLAY with occasional laminae of SILT and/or SAND, locally sandy	Weichselian
E	CLAY, locally with sand beds	Weichselian
F	CLAY with laminae or thin beds of SILT or SAND	Pleistocene
G	Poorly sorted gravelly and sandy CLAY, SAND TILL or CLAY TILL	Pleistocene
H	SAND, CLAY, CLAY TILL and/or SAND TILL	Pleistocene
I	Sandy MUDSTONE, LIMESTONE and glauconitic SANDSTONE	Jurassic to Cretaceous

Appendix B: Profile R3_017A
Hesselø OWF and Area A seismic Units







UNIT	Expected soil type	Age
A	CLAY to clayey medium SAND or sandy GYTTJA with shells and shell fragments and organic material	Holocene
B	Interlaminated to interbedded CLAY and SILT with shells and shell fragments	Early Holocene
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E	CLAY, locally with sand beds	Weichselian
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G	Poorly sorted gravelly and sandy CLAY, SAND TILL or CLAY TILL	Pleistocene
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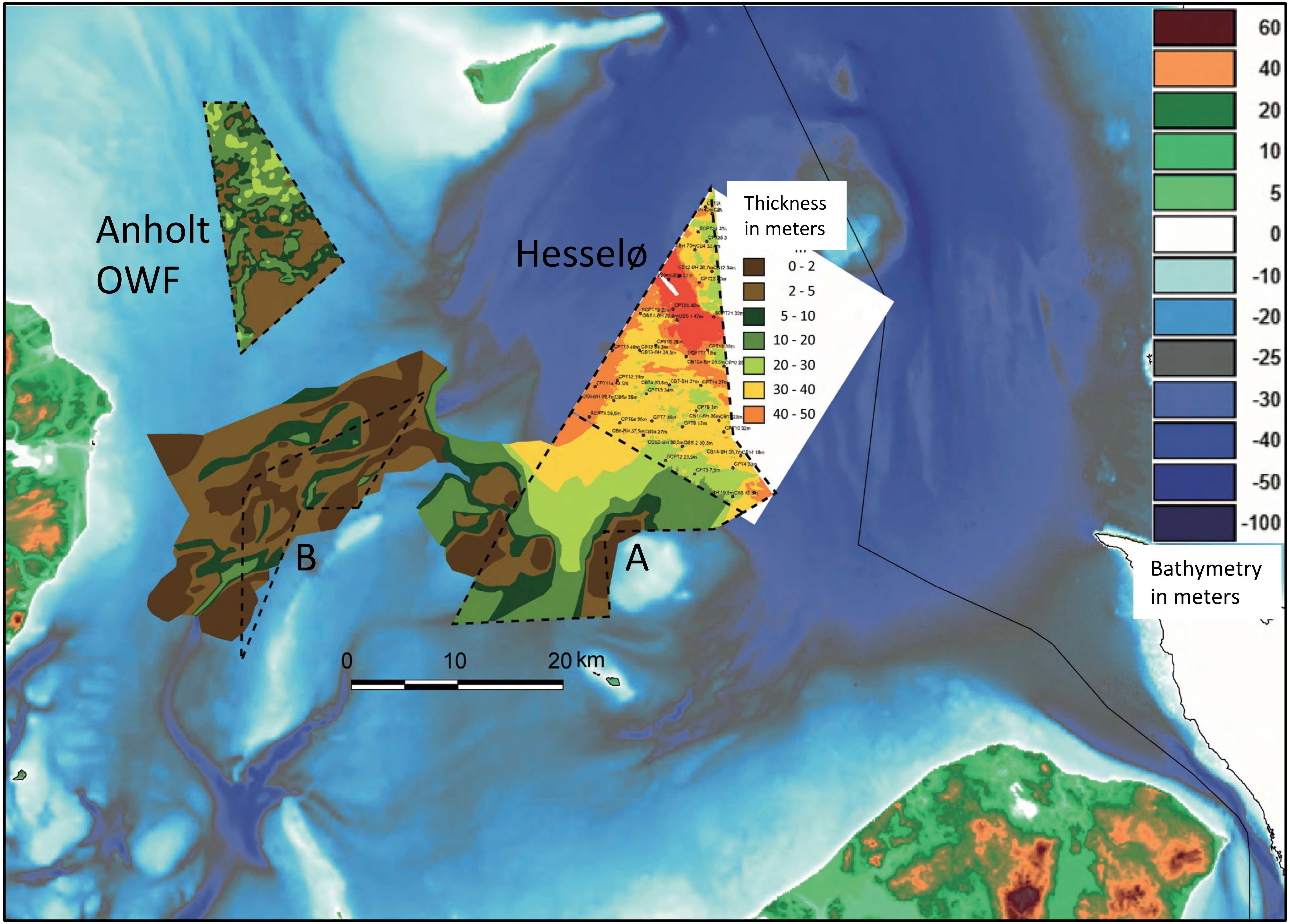
Appendix B: Profile R3_017A
Hesselø OWF and Area A seismic Units



Appendix C. Hesselø, area A, B and Anholt Windfarm soft sediment thickness

Danish Ministry of Climate,
Energy and Utilities

Geological survey of
Denmark and Greenland (GEUS)

Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

GEUS is a research and advisory
institution in the Danish Ministry
of Climate, Energy and Utilities