DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2023/33**

Screening of seabed geological conditions for the offshore wind farm area Kattegat II and the adjacent cable corridor area

Desk study for Energinet

Jørn Bo Jensen, Ole Bennike,
Nicklas Christensen & Thomas Vangkilde-Pedersen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

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1. Dansk resumé

Energinet har bedt GEUS om at udføre en geologisk screening af Kattegat II havvind området og den mulige kabelkorridor til kysten af Djursland. Undersøgelsen er tænkt som baggrund for en vurdering af områdets potentiale for etablering af en havvindmøllepark. Denne rapport er en kompilering af en tidligere screeningsrapport som også dækker Kattegat II området (GEUS 2021) og et nyt studie som dækker kabelkorridoren.

Der er benyttet en kombination af publicerede artikler og rapporter, GEUS-arkiv seismiske data og boringer, forskningsdata samt nye seismiske data indsamlet i anden sammenhæng, til at vurdere den generelle geologiske udvikling i den sydlige del af Kattegat, inklusive Kattegat II området og kabelkorridoren.

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

Som en del af studiet er der præsenteret en lokal relativ havniveaukurve, der dækker de Holocæne og senglaciale perioder. Desuden er den geologiske udviklingshistorie med fordelingen af land og hav efter sidste istid beskrevet med henblik på en screening for arkæologiske interesser.

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 for den sydlige del af Kattegat er baseret på tidligere geologiske screeningsrapporter (GEUS 2020; GEUS 2021), den seismiske tolkningsrapport Fugro (2021) og den geotekniske rapport Gardline (2021).

Kortlægningsresultaterne er præsenteret i form af seismiske eksempler og generelle kort over tykkelsen af geoteknisk set bløde sedimenter i Kattegat II området sammen med tilsvarende kort over det tidligere Hesselø OWF område og andre tidligere OWF områder samt Anholt OWF.

Der præsenteres adskillige konklusioner, som er relevante for fremtidige geotekniske og arkæologiske vurderinger af Kattegat II området og kabelkorridoren. Konklusionerne kan i korthed sammenfattes til:

I Kattegat II havvind området kan der forventes jordbundsforhold som er sammenlignelige med forholdene i den sydlige del af Anholt OWF området. Dette indikerer, fra et geologisk synspunkt, at det er muligt at anvende området til OWF.

Jordbundsforholdene i det meste af kabelkorridoren er også sammenlignelige med forholdene i den sydlige del af Anholt OWF området. Dog findes der en større nordøst-sydvest gående begravet dal i den nordlige del af korridoren med fyld af forventede bløde sedimenter af 20-30 meters tykkelse og lokalt op til 40-50 m.

2. Summary

Energinet has asked GEUS to perform a geological desktop screening study of the offshore wind farm (OWF) area Kattegat II and the potential cable corridor to the coast of Djursland. The results are to be used as background for evaluation of the suitability of the areas for a wind farm site and cable corridor to land. This report compiles the results of a previous screening study also covering the current OWF area Kattegat II (GEUS 2021) and a new study covering the potential cable corridor.

A combination of published work, GEUS archive seismic data and sediment core data, research data and new seismic data from other projects have been used to assess the general geological development of the southern Kattegat area, including the current Kattegat II OWF area and the potential cable corridor.

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

As part of the geological desk study, a relative Late Glacial and Holocene sea-level curve for the area is presented and a screening for archaeological interests has been performed based on the development of the distribution of land and sea after the last deglaciation.

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 previous geological screening reports (GEUS 2020; GEUS 2021), the seismic interpretation report Fugro (2021) and the geotechnical report Gardline (2021).

The mapping results are presented as seismic examples and general thickness maps of geotechnical soft sediments in the current Kattegat II OWF area and cable corridor, together with thickness maps of geotechnical soft sediment for the previous Hesselø OWF area and other previous OWF areas as well as the Anholt OWF.

Several conclusions relevant for the future geotechnical and archaeological evaluations of the Kattegat II OWF area are presented and can be summarized in these statements:

The soil conditions in the Kattegat II OWF area are expected to be similar to the soil conditions in the southern part of the Anholt OWF. This means, from a geological point of view, that it is most likely possible to establish an OWF in the Kattegat II OWF area.

Also, the soil conditions in most of the cable corridor is similar to the soil conditions in the southern part of the Anholt OWF. However, in the northern part of the area a large northeast–southwest-oriented incised valley with infill of soft sediments up to 20-30 m in thickness and locally up to 40-50 m is found.

3. Introduction

Energinet has asked GEUS to perform a geological desktop screening study of the offshore wind farm (OWF) area Kattegat II and the potential cable corridor to the coast of Djursland. The results are to be used as background for evaluation of the suitability of the areas for a wind farm site and cable corridor to land. This report compiles the results of a previous screening study also covering the current OWF area Kattegat II (GEUS 2021) and a new study covering the potential cable corridor.

The Kattegat II OWF area is located c. 20 km east of the east coast of Djursland and the cable corridor extends from the northeastern and southern corners of the area to the coast of Djursland north and south of Grenaa (Figure 3.1).

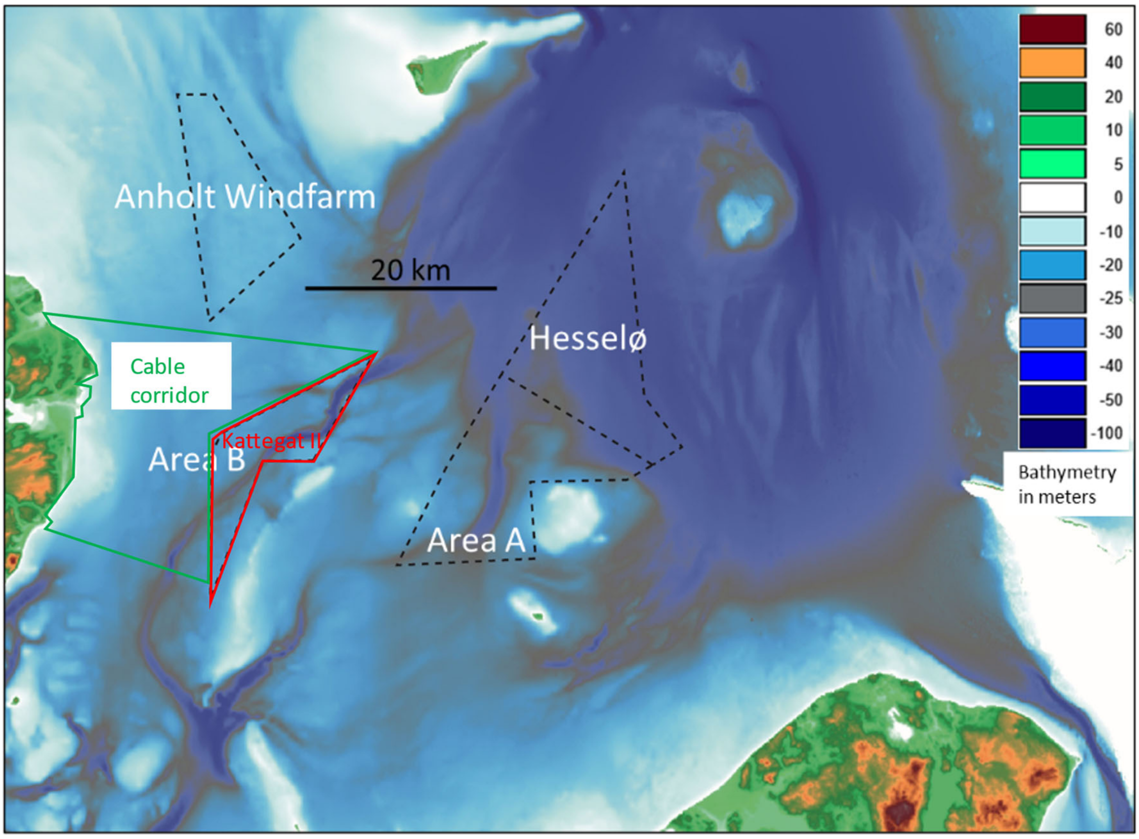

Figure 3.1. The location of the current Kattegat II OWF area (in red) and cable corridor (in green) in the southern part of the Kattegat region as well as the existing Anholt OWF and OWF areas covered in previous screening reports (hatched black lines). Bathymetry from www.emodnet-bathymetry.eu.

The screening study include a description of the regional geological development of the Kattegat area and the establishment of a conceptual geological model for the understanding of the local geological conditions and possible implications for geotechnical conditions and archaeological interests. The work is based on a combination of published reports, publications and archive seismic and sediment core data, and especially the GEUS report (GEUS 2021) mentioned above and covering the previous Kattegat Area A and B OWF areas.

4. Data background

As a basis for the desk study, existing background reports from The Danish Energy Agency have been used together with primary data from the GEUS Marta database, which is the main source of shallow seismic data and vibrocore data (Figure 4.1). In addition, data not included in the Marta database have been used. The latter data comprise scientific multi-channel seismic data, data from IODP core M0060, and a few Parasound sediment echo-sounder data and vibrocore data from the scientific cruise Maria S. Merian MSM62 as well as new and unpublished seismic data from investigations for the Danish Energy Agency as part of a geological screening for offshore wind of the Danish Sea territory.

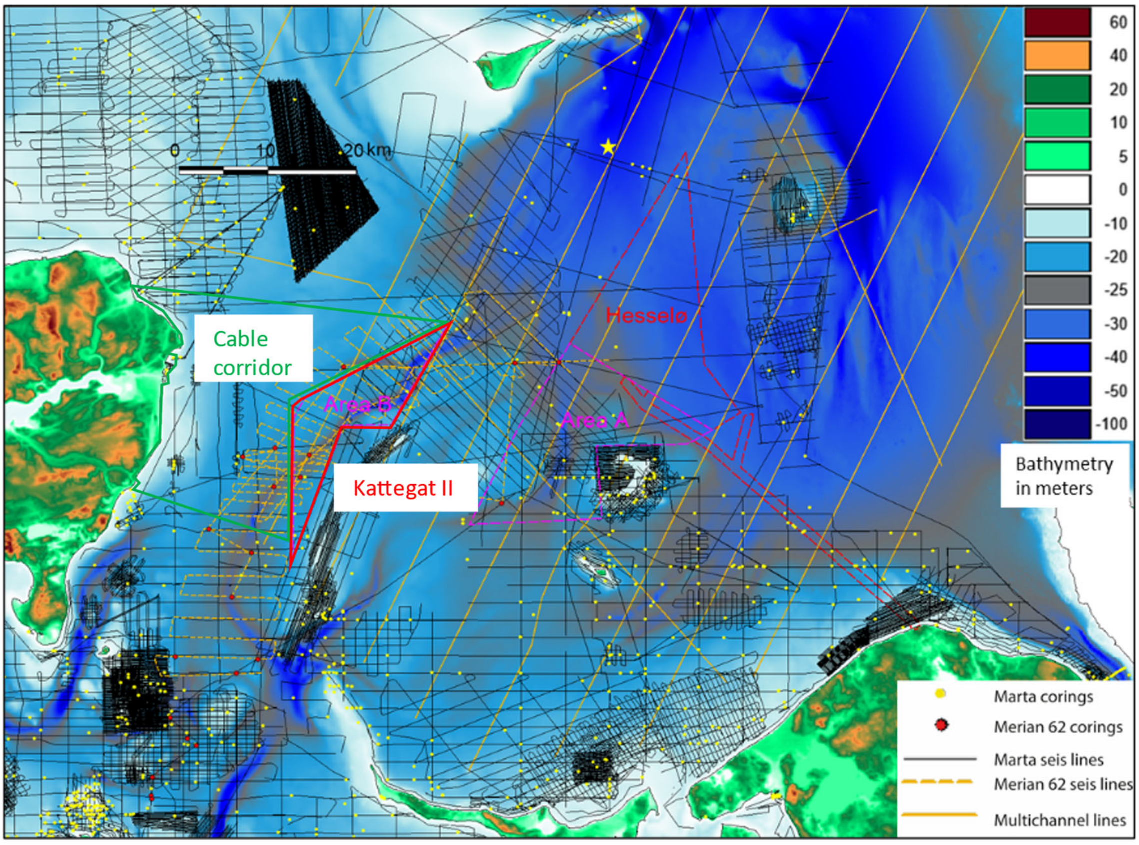

Figure 4.1. Distribution of Marta database seismic grid and core data in the southern and central Kattegat region. The Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (purple and red hatched lines). Bathymetry from www.emodnet-bathymetry.eu.

4.1 Background reports

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

In the geophysical acquisition and interpretation report (Fugro 2021) for the Hesselø OWF, the seismostratigraphic units described in GEUS (2020) have been expanded with a few subunits, due to more detailed information. The general stratigraphy remains but the units have been renamed to unit A to I (Chapter 6, Table 1). In the geological screening report of the Kattegat Area A and B (GEUS 2021), and the present report, the names of unit A to I 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 work have been included in the present evaluation of seismic units in the Kattegat II OWF area.

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.

4.3 New seismic data

New and unpublished seismic data in the area appears from investigations for the Danish Energy Agency as part of a geological screening for offshore wind of the Danish Sea area and have been used in the present study, especially in the cable corridor where few existing data were available.

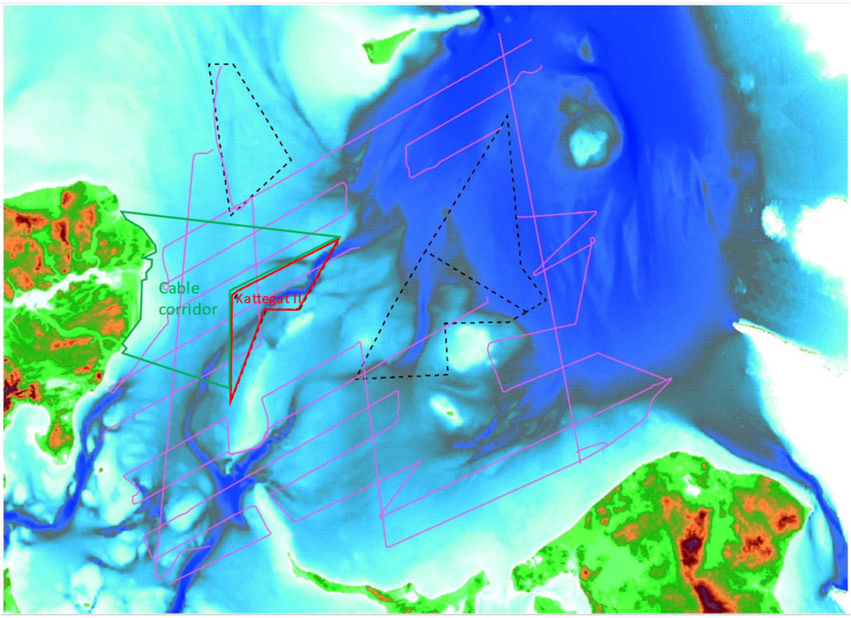

Figure 4.2 New and unpublished seismic data (in purple) used in the present study. The data are from investigations for the Danish Energy Agency as part of a geological screening for offshore wind of the Danish Sea area. The location of the Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines).

4.4 Maria S. Merian MSM62 cruise data

Part of the background information comes from seismic and coring data from a scientific cruise in 2017 with the German research ship Maria S. Merian (Figure 4.3). Parasound sediment echosounder data supplemented with vibrocore data from the investigations provide detailed information on the sediment distribution.

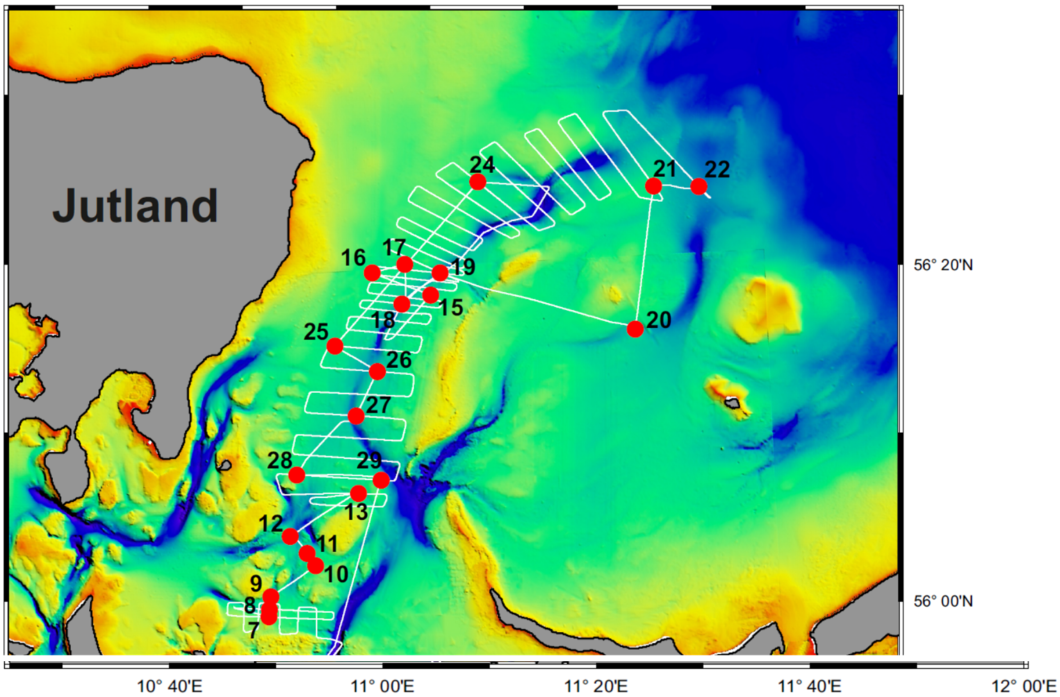

Figure 4.3 Maria S. Merian MSM62 cruise data in the southwestern Kattegat.

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 lie north of, and in the northern part of the area, respectively and dominate the pre-Quaternary setting with a south-east to north-west orientation (Figure 5.1).

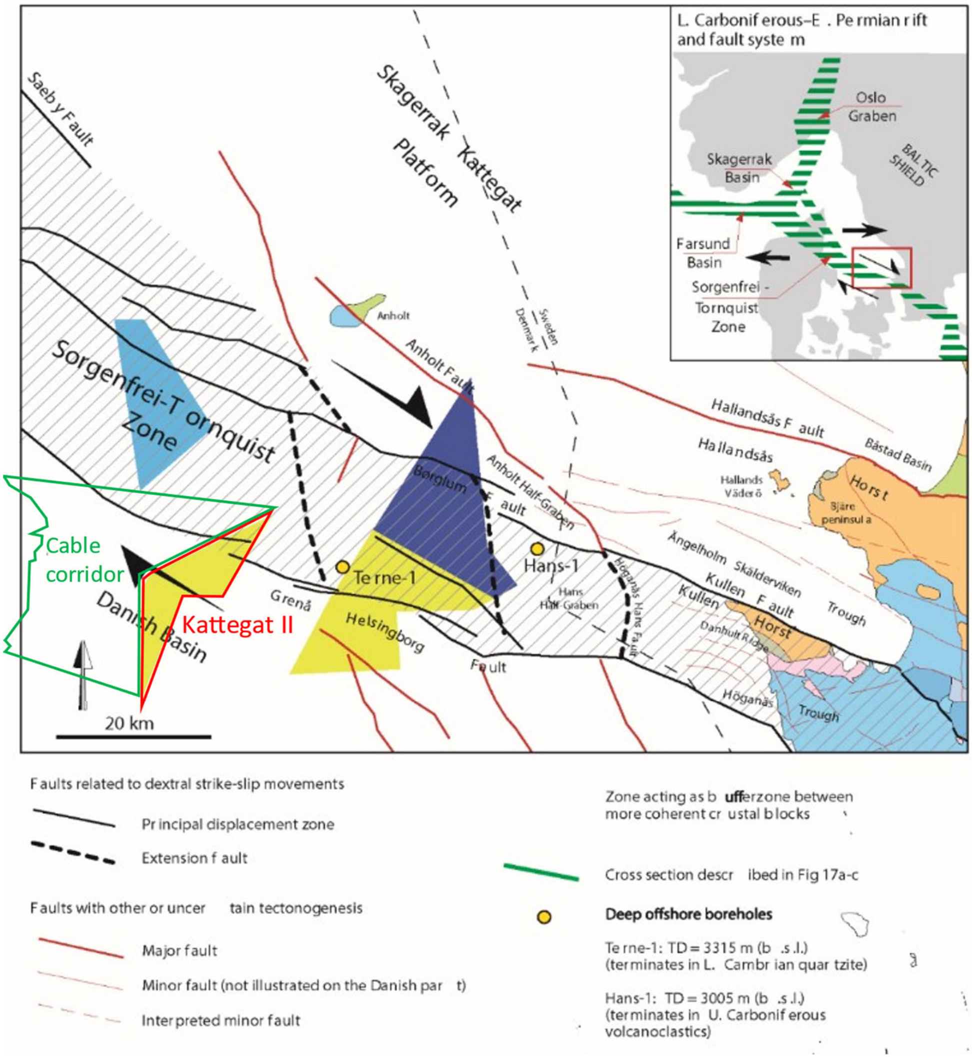

Figure 5.1. Regional structures in the southern part of the Kattegat (Erlström & Sivhed 2001). The location of the Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF (light blue) and OWF areas covered in previous screening reports (yellow and dark blue).

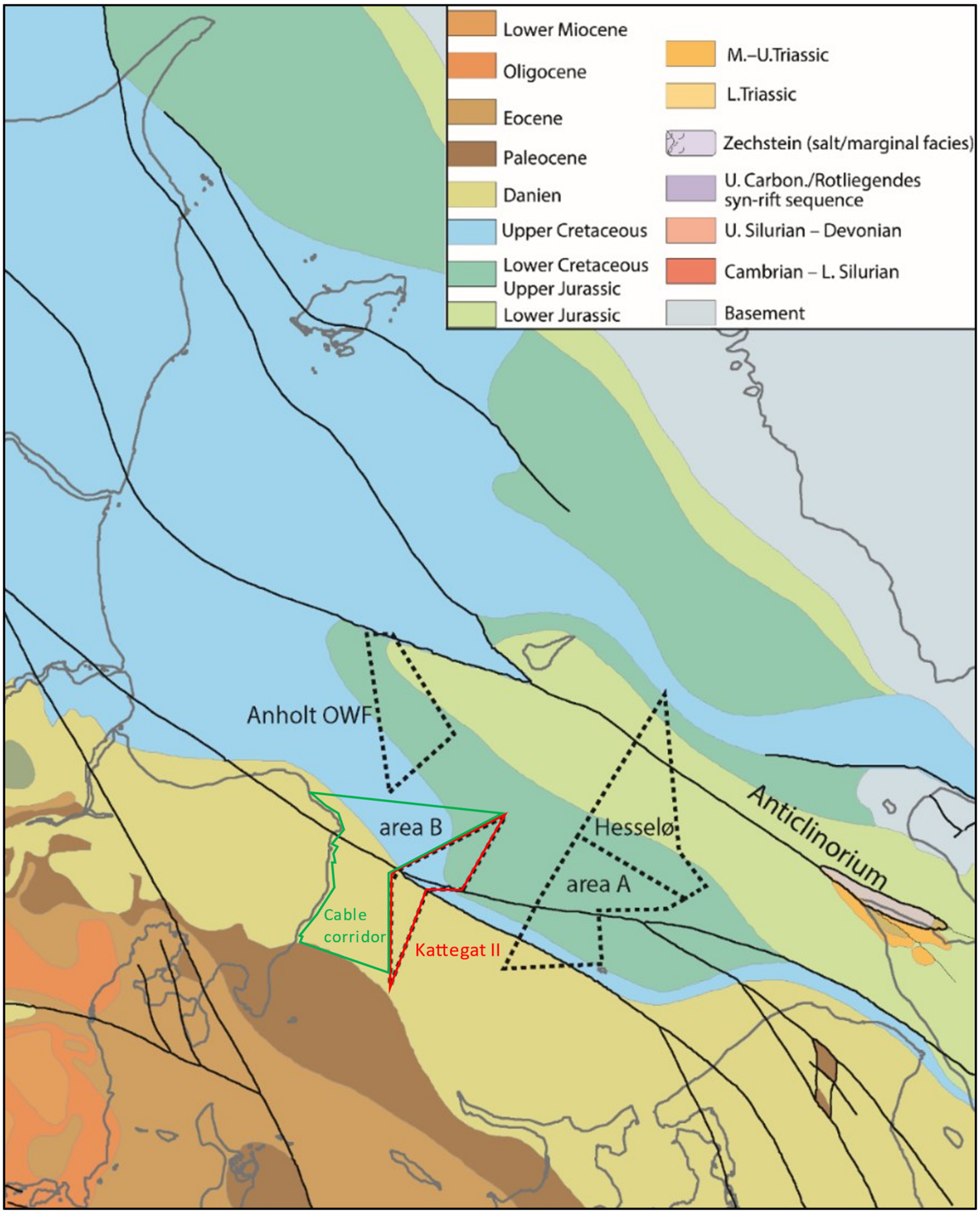

Figure 5.2. Pre-Quaternary surface geology and major faults in the Kattegat. The location of the Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines).

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 Kattegat II area and cable corridor consists of Jurassic and Upper Cretaceous sandy mudstone in the northeastern part and Danien limestone in the southwestern part (Erlström & 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. North and northeast of the Kattegat II OWF area and cable corridor such pull-apart basins have their depocenter, whereas the Kattegat II OWF area is dominated by shallower pre-Quaternary morphology (Figure 5.3).

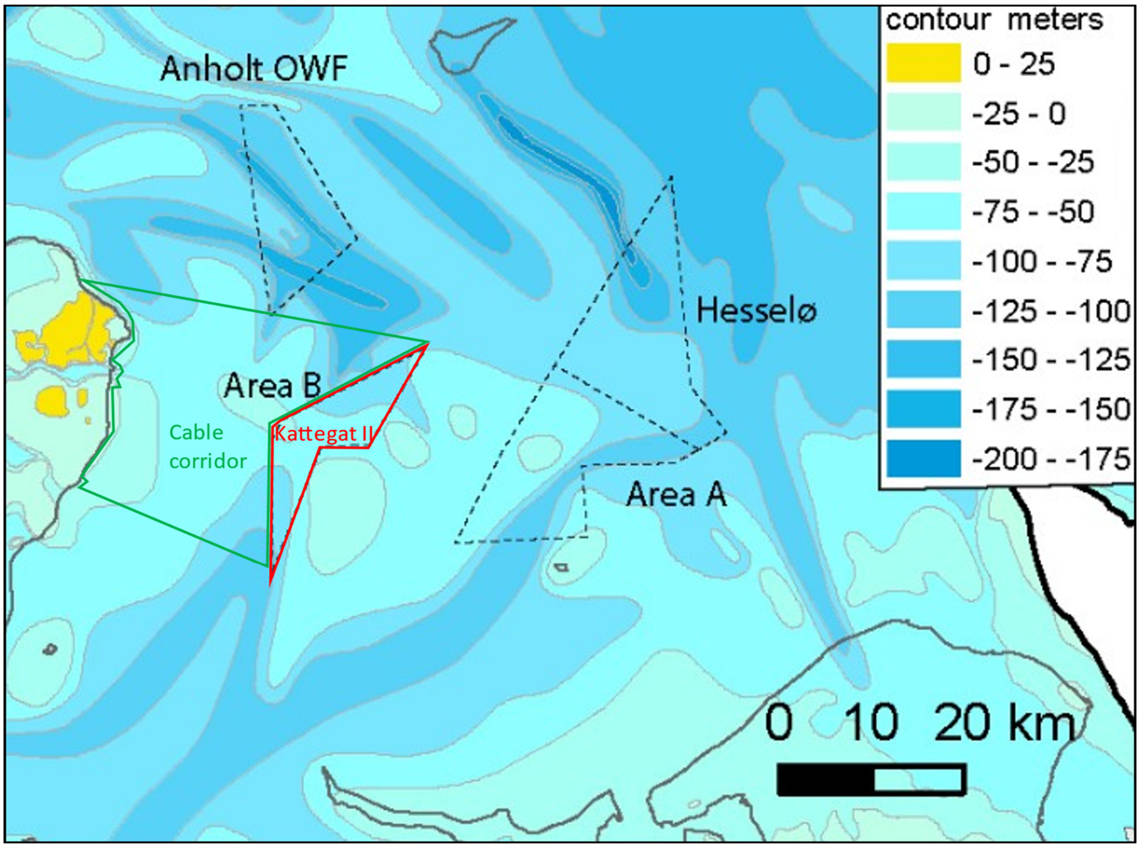

Figure 5.3. General pre-Qaternary morphology (Binzer & Stockmarr 1994). The location of the Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines).

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

At c. 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 c. 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).

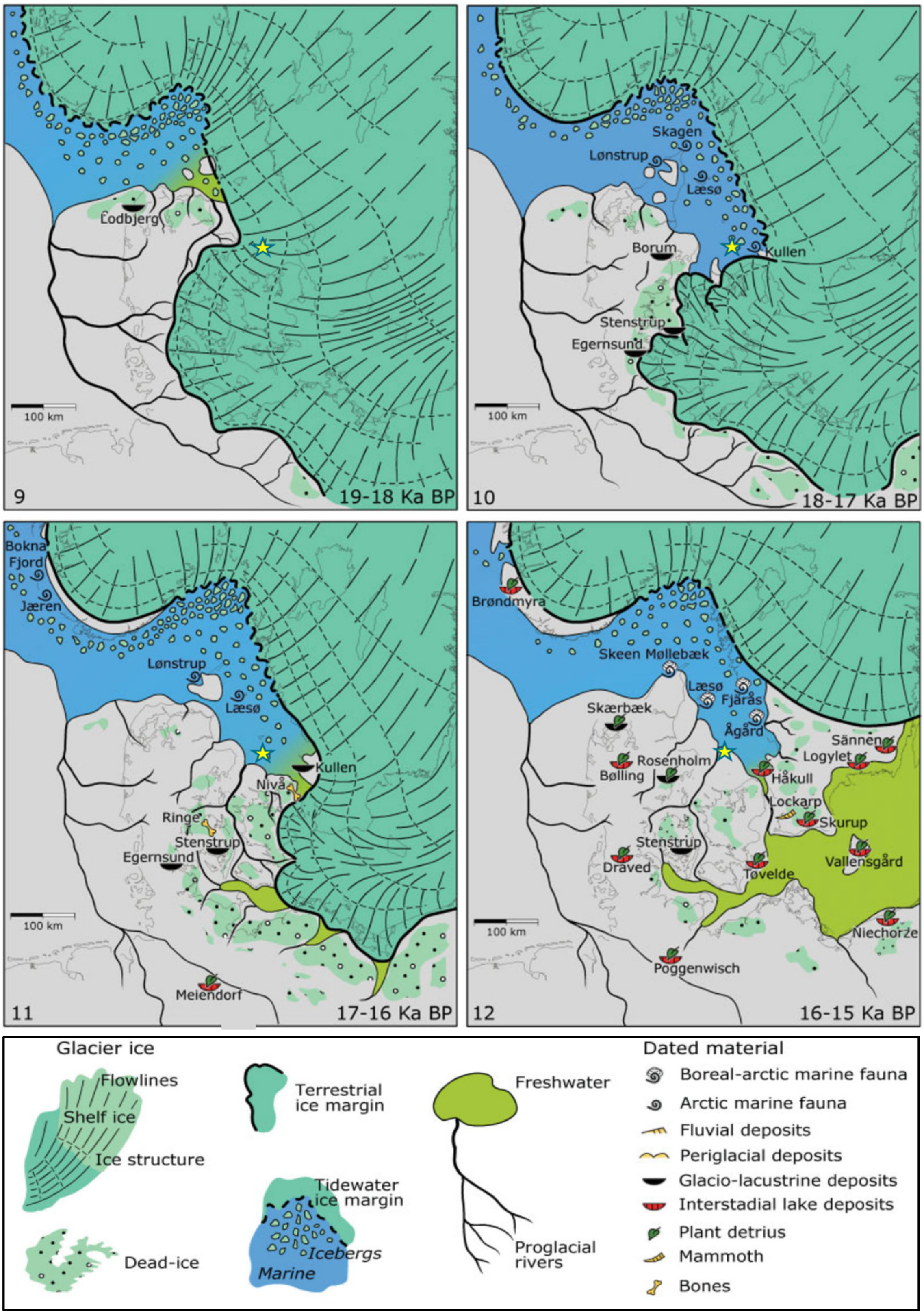

Figure 5.4. Palaeogeographical reconstructions of the last deglaciation of southern Scandinavia (19–15 ka BP; Houmark-Nielsen & Kjær 2003).

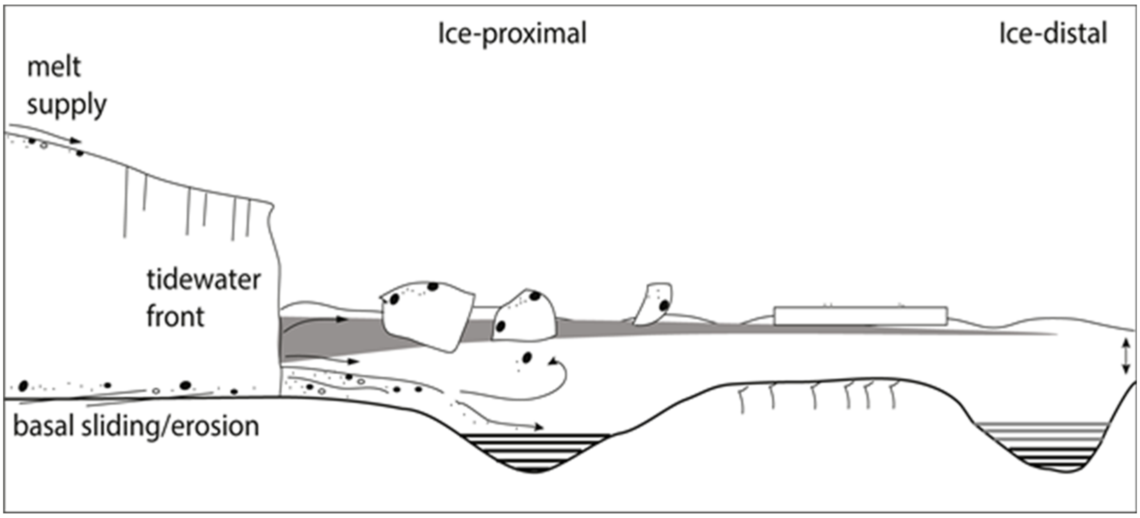

Figure 5.5. Illustration of a glaciomarine depositional environment.

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 Kattegat II OWF area.

The morphological pronounced Sjællands Odde ice marginal ridge continues offshore in a big curve southeast of the Kattegat II OWF 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 area to the northeast is dominated by a basin with up to 100 m thick Late Glacial glaciomarine basin deposits (Figure 5.6) documented in IODP core M0060, while the Kattegat II OWF area is situated in direct connection to the morphological pronounced Sjællands Odde ice marginal ridge.

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 5.6) documented in IODP core M0060. Area A and B are situated in direct connection to the morphological pronounced Sjællands Odde ice marginal ridge.

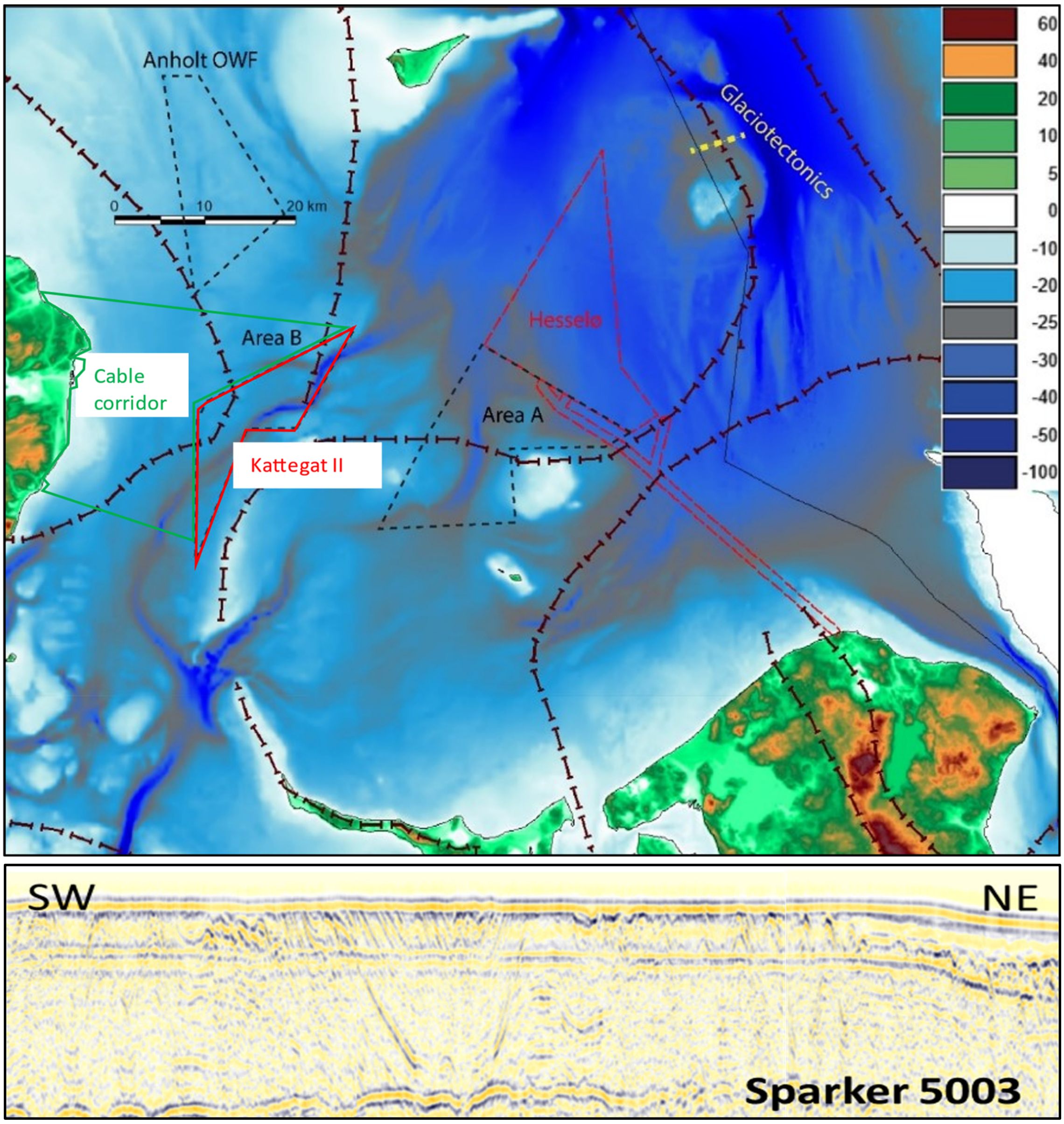

Figure 5.6. Upper figure: Interpreted ice marginal ridges in the southern part of the Kattegat. Lower figure: Sparker profiles showing evidence of glaciotectonic deformations north of Store Middelgrund (yellow dashed line on upper figure). The Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black and red hatched lines). Bathymetry from [www.emodnet-bathymetry.eu.](www.emodnet-bathymetry.eu)

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).

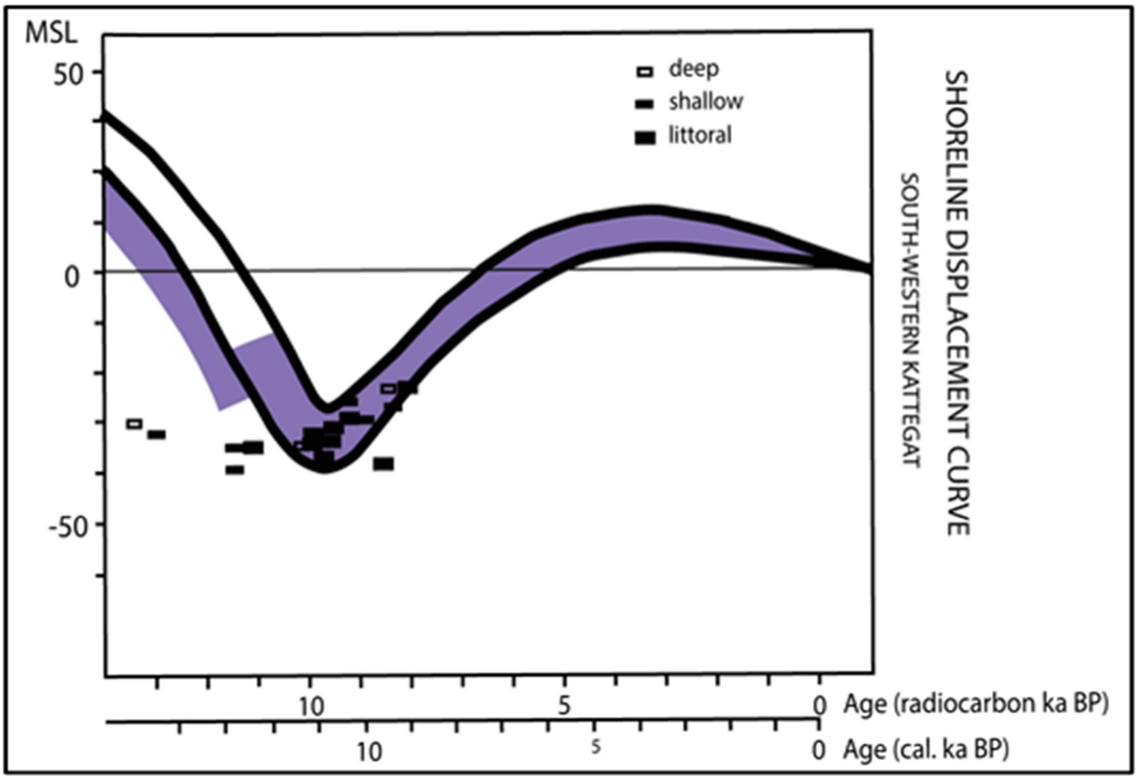

Figure 5.7. Shoreline displacement curves for the southern Kattegat. The two solid black lines indicate the range of shoreline displacements in non-faulted regions of the study area (modified from Mörner 1983). The purple area indicates the relative sea level changes interpreted from the sequence stratigraphy 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 area to the northeast 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 this north-eastern area was fully submerged, whereas the Kattegat II OWF area and cable corridor have a longer transgression history.

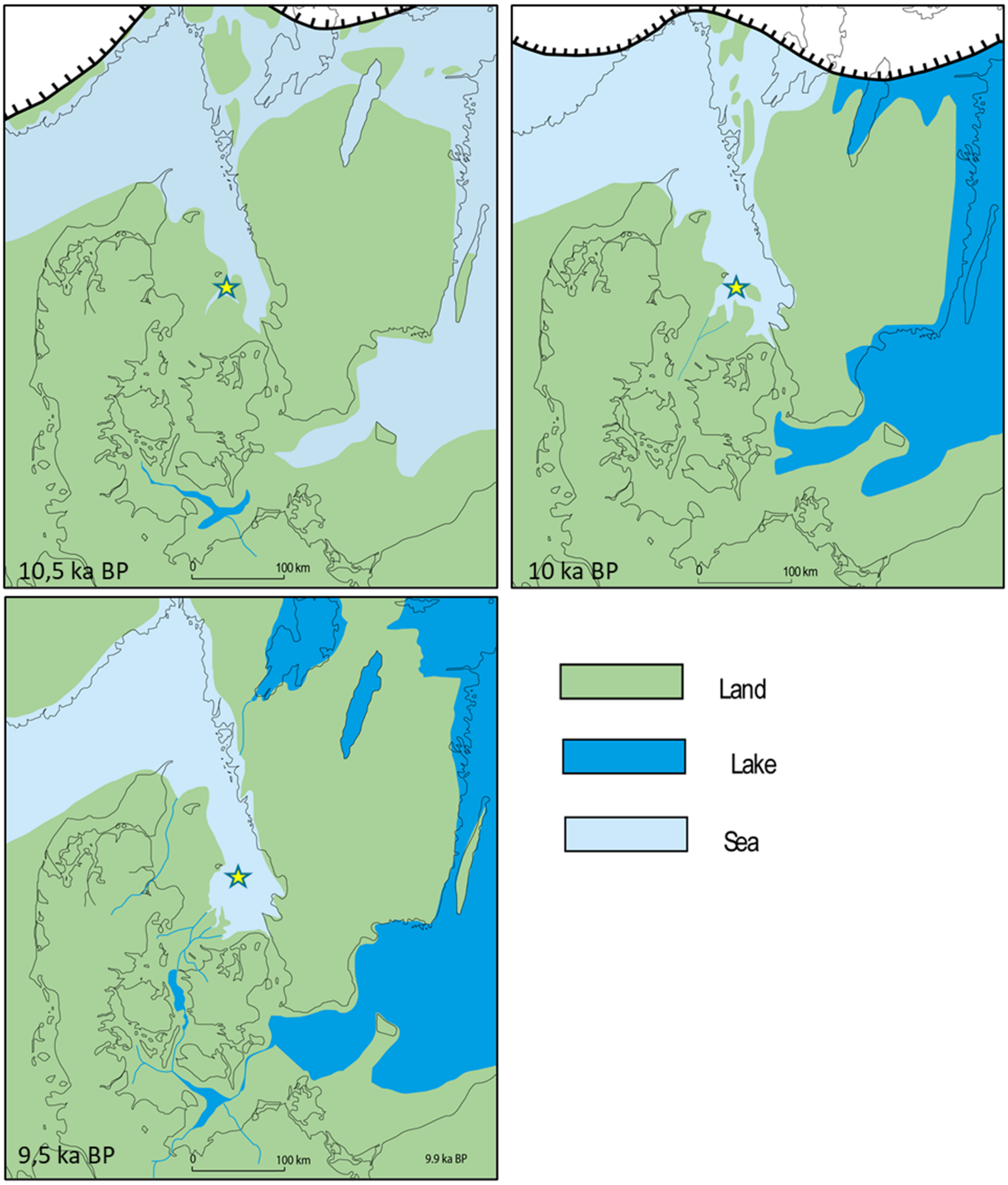

Figure 5.8. Palaeogeographical scenarios for the Kattegat region. There was a lowstand at 10.5 ka BP followed by a transgression (Jensen et al 2002). The yellow star shows the location of IODP core M0060.

5.5 Seabed morphology and surface sediments

The water depths in the Kattegat II OWF area 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. In the cable corridor the water depth is generally ranging from 15 m to 20 m, decreasing towards the coast of Djursland and with up to 25-30 m in the Great Belt incised channel (Figure 5.9).

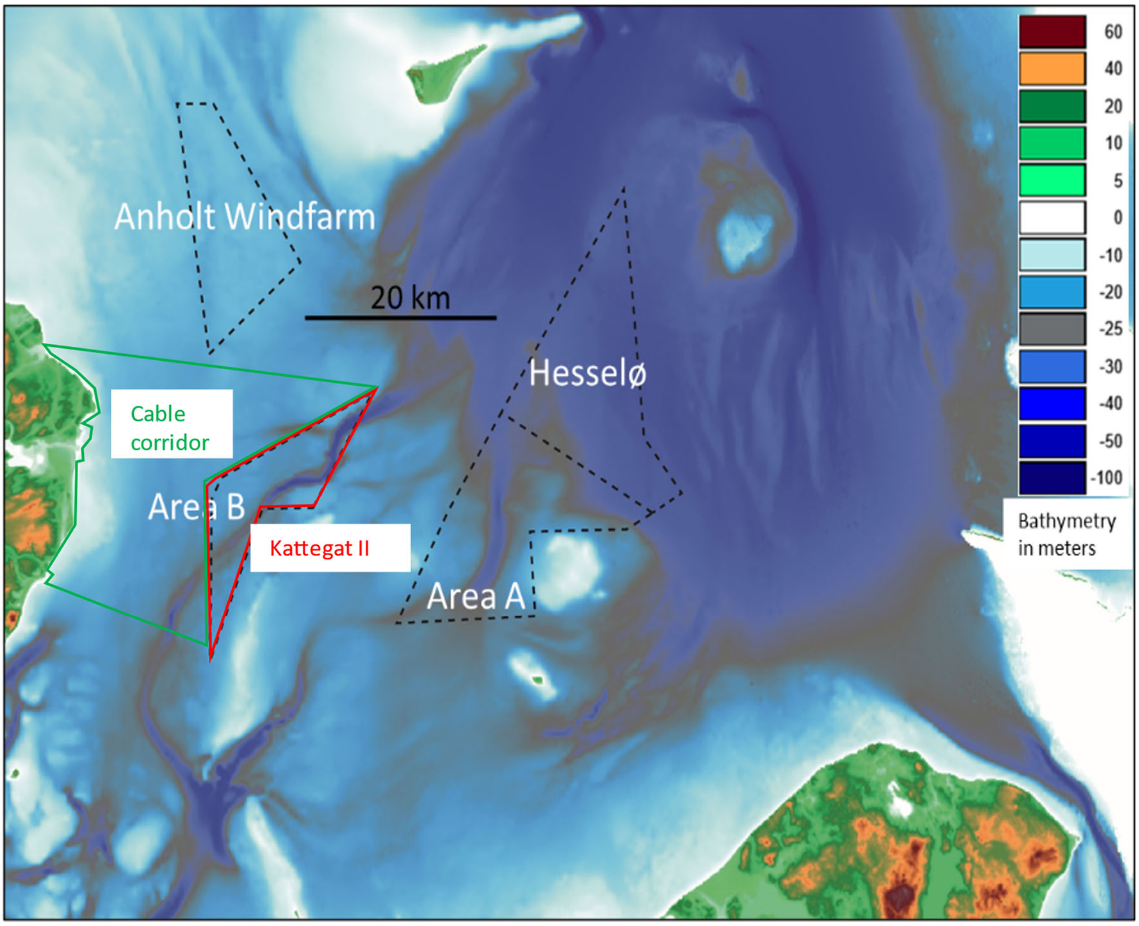

Figure 5.9 Southern Kattegat bathymetry. The Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines). Bathymetry from [www.emodnet-bathymetry.eu.](http://www.emodnet-bathymetry.eu)

The surface sediments to the northeast were mapped in detail by Fugro (2021). 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 Kattegat II OWF area 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.

The cable corridor is dominated by sand and till and muddy sand and till to the southeast.

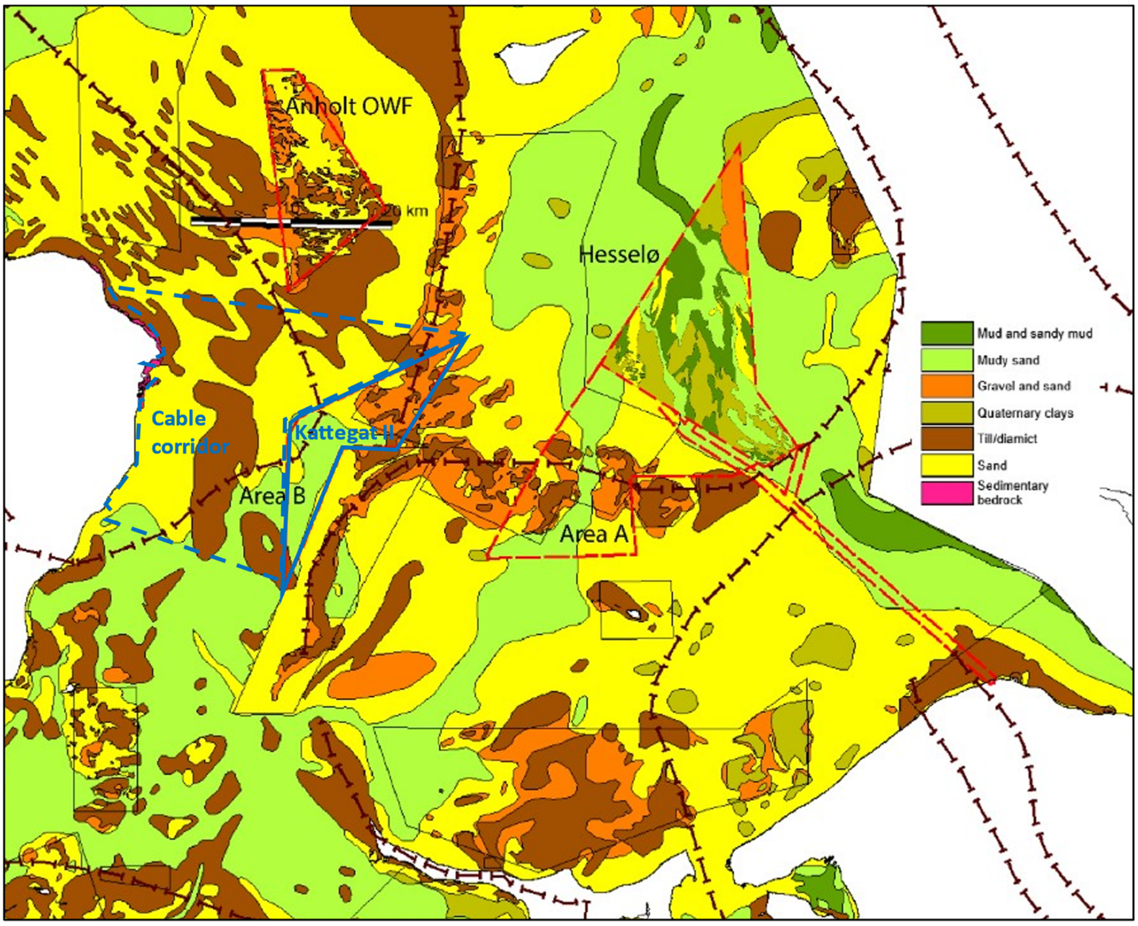

Figure 5.10. Seabed surface sediment map with interpreted ice marginal ridges. The Kattegat II OWF area is shown in blue, and the cable corridor in hatched blue, together with the existing Anholt OWF and OWF areas covered in previous screening reports (red hatched lines). Updated detailed sediment data from Fugro (2021) is presented northeast of the Kattegat II OWF area and thin black lined polygons marks margins of detailed mapped subareas. Bathymetry from www.emodnet-bathymetry.eu.

6. 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 previous detailed Hesselø OWF investigations (Fugro 2021) confirm the general stratigraphy, but the geophysical seismostratigraphic units have been expanded with a few subunits, due to more information and the general stratigraphy remains but is renamed to units A to I (Table 1) compared to the GEUS (2020) report.

UNIT	Expected soil type	Age	Environment	Thickness	Unit Base BSF
A	Clay to clayey medium-grained 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-grained 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	Late Weichselian	Glaciomarine, glaciolacustrine to fluvial	0-66 m	1-72 m
E	Clay, locally with sand beds	Late Weichselian	Glaciomarine and/or glacial deposits	0-66 m	9-122 m
F	Clay with laminae or thin beds of silt or sand	Late Weichselian	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).

In the following, descriptions of the units in the geological development history will be presented in chronological order, based on the interpretations in the previous Hesselø OWF area. In chapter 8 and 9 the mapping and geological screening of the current Kattegat II OWF area, based on these seismiostratigraphic units, is described.

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 c. 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.

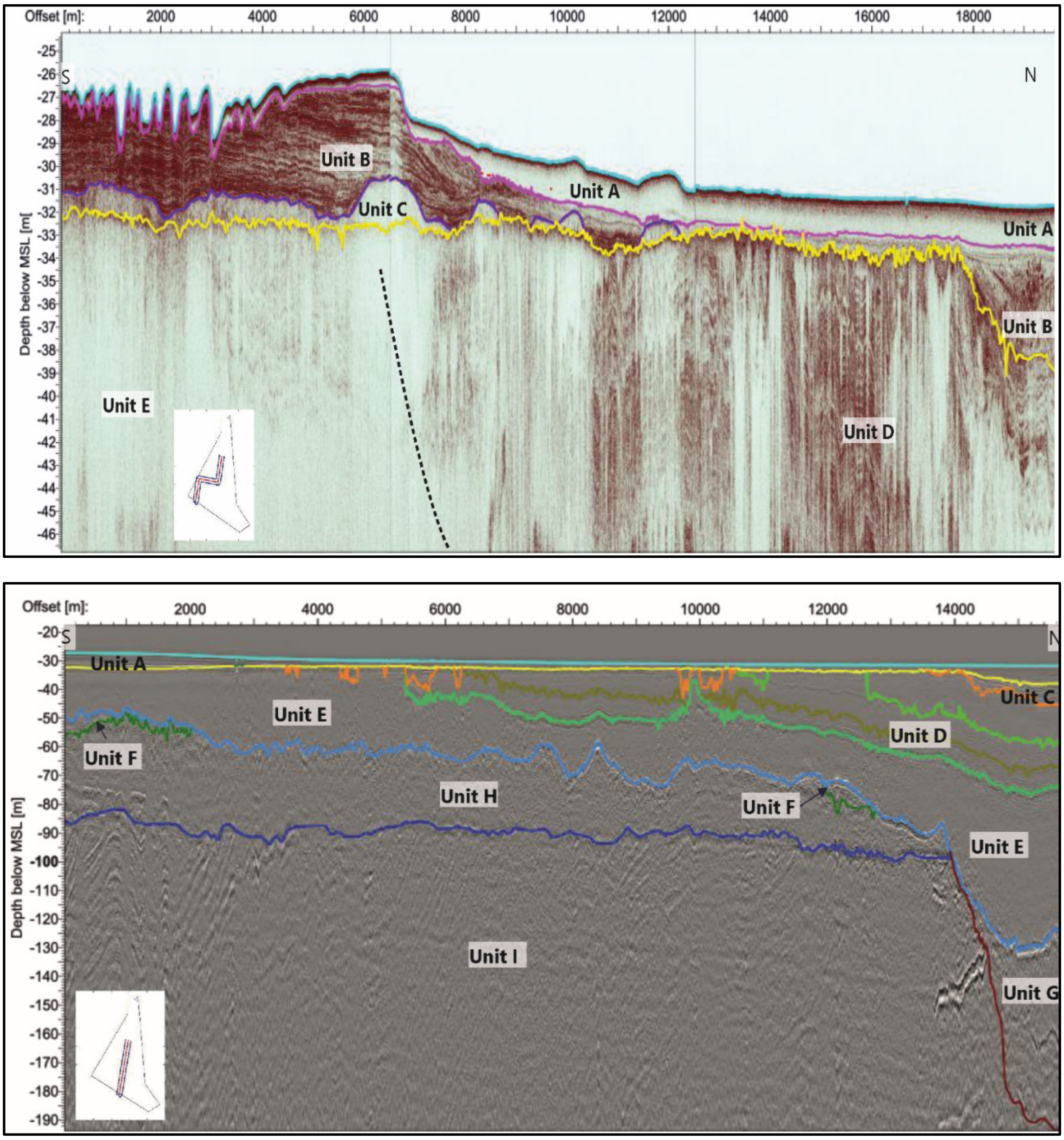

Figure 6.1. Overview of seismostratigraphic units interpreted in the previous Hesselø OWF study area.

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 northeast of the current Kattegat II OWF area. The unit shows typical thicknesses of 25 m to 35 m south of the depression and reaches a thickness of c. 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 seen south of the depression.

Unit H is interpreted as Pleistocene sediments deposited in glacial, periglacial and/or glaciomarine conditions (Table 1. Overview of seismostratigraphic units adapted from GEUS (2020) and Fugro (2021).

Earlier studies 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 area, 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 the IODP M0060 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 previous Hesselø OWF area (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 F is interpreted as glaciomarine deposits due to its bedded seismic character and similarity to the bedded facies of the overlying Unit D (with unit E stratigraphically found between Unit D and F in the central and southern part of the previous Hesselø OWF area).

6.5 Unit E glaciomarine clay, locally with sand beds

Unit E is present across the previous Hesselø OWF area. 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 previous area, 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 previous 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 previous area, where interlayering of fine-grained 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 the previous Hesselø OWF area. 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 area. 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- and coarse-grained 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).

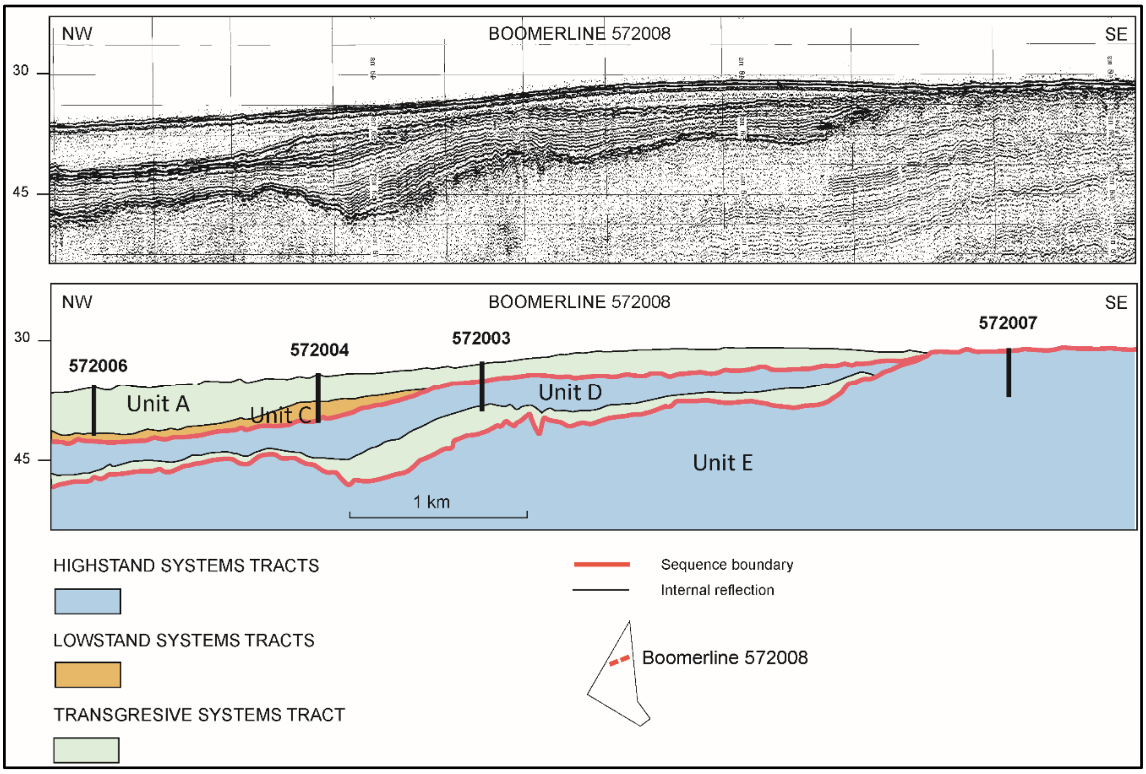

Figure 6.2. Boomer seismic section 572008.

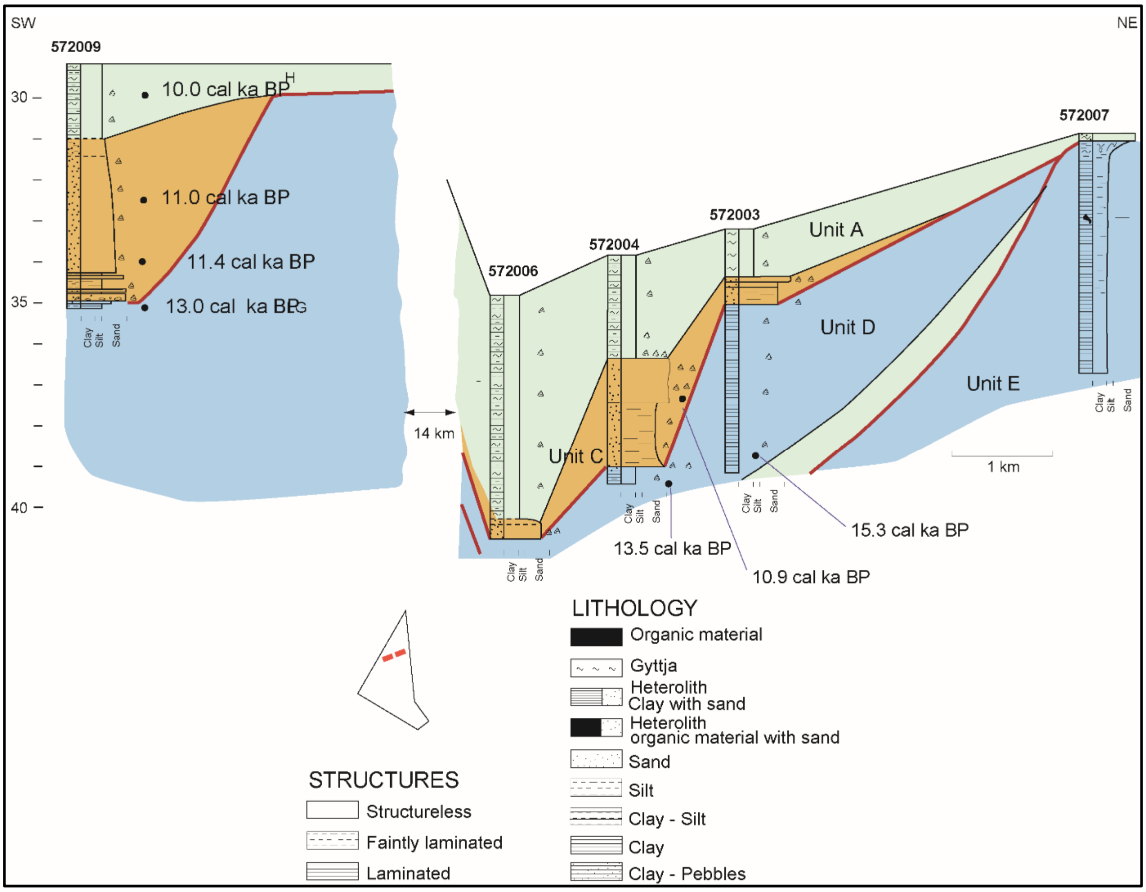

Figure 6.3. Sedimentological logs and log correlations. Sedimentological signatures are indicated; for description of stratigraphical signatures see Table 1. Overview of seismostratigraphic units adapted from GEUS (2020) and Fugro (2021).Detailed information on C-14 ages is given in Jensen et al. (2002).

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-grained 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-grained sand with abundant shells

Unit C is present in the south-western part of the previous Hesselø OWF area, 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 previous area.

The unit is often acoustically (semi-)transparent to chaotic where the unit is thin. 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 spits or coast-parallel 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). 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-grained 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 previous Hesselø OWF area (Figure 6.1). In general, the unit is thin, on average approximately 1 m. It reaches locally a greater thickness of approximately 6 m in the shallower south-western part of the previous area (Figure 6.1) and a maximum thickness of approximately 14 m in the large pre-Quaternary depression in the north-eastern part of the previous area.

Internally the unit is stratified, with low to high-amplitude, parallel reflectors. Where Unit B is thickest in the south-western part of the previous Hesselø OWF area, 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 previous area, 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).

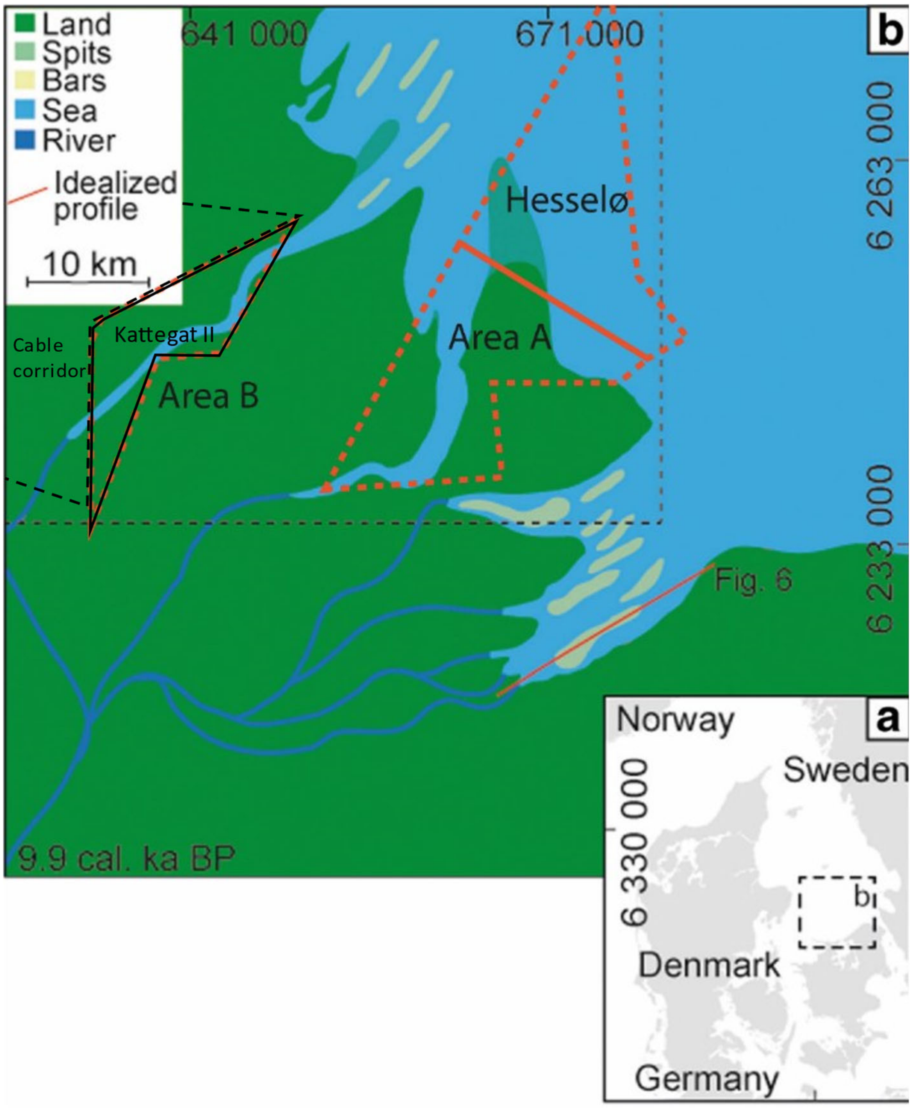

Figure 6.4 Dana River System Great Belt palaeo-river (Bendixen et al. 2015, 2017). The Kattegat II OWF area is shown in black, and the cable corridor in hatched black, together with the existing Anholt OWF and OWF areas covered in previous screening reports (red hatched lines).

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

This unit is present across the entire previous Hesselø OWF area, 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 area, where it reaches approximately 3 m and decreases to less than 1 m towards the eastern and western margins of the area.

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 area, the unit overlies Unit C.

In the western part of the previous area, 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 previous area, 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 previous area, 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 the Hesselø OWF

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

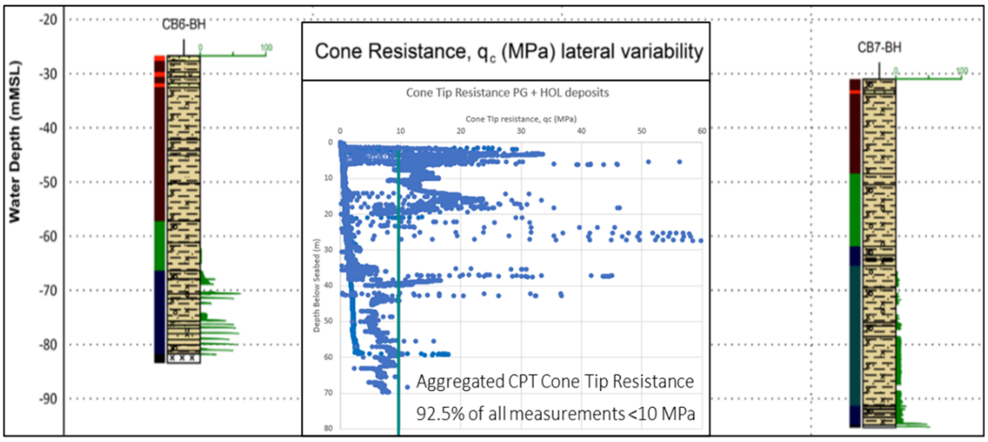

Figure 7.1 Geotechnical sediment cores CB6-BH and CB7-BH, with indication of very low cone resistance to more than 40 m below seabed and evidence of 92,5% of total CPT measurements below 10 MPa. The location of CB6-BH and CB7-BH is indicated on Figure 7.3.

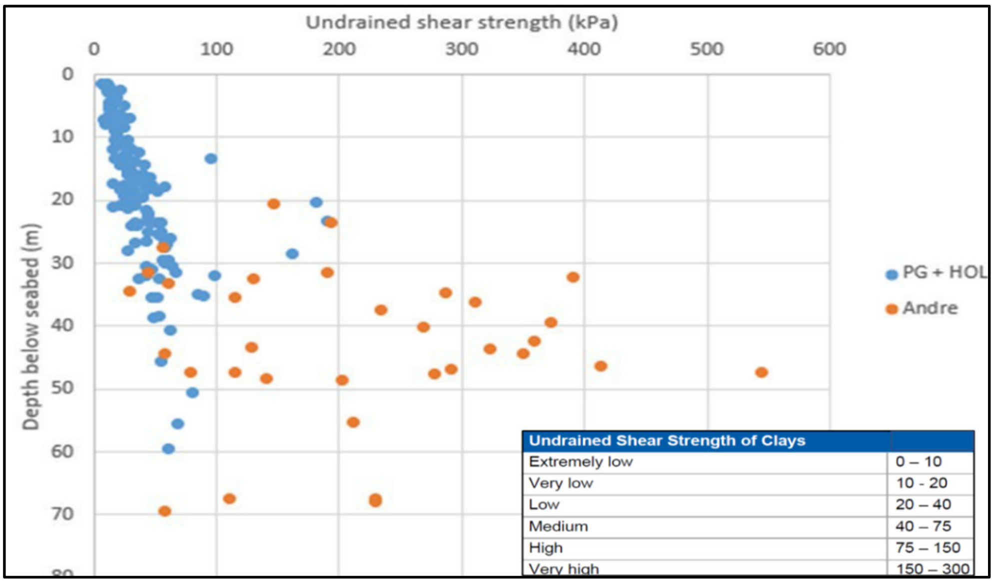

Figure 7.2 Undrained shear stress measurements showing low Unit A - E/F values and higher values for the lower units G–H.

The cone resistance measurements show that 92,5 % of the tests have values below 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 in the previous Hesselø OWF area is illustrated in Figure 7.3 from the Energinet (2021) report. 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 previous area, 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.

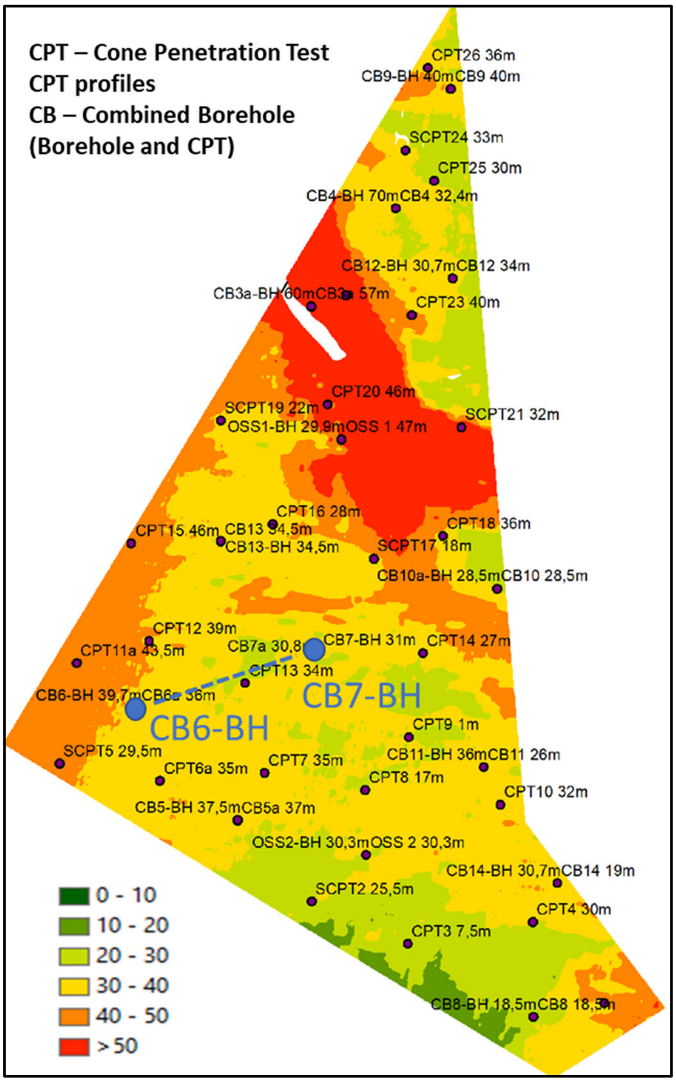

Figure 7.3 Thickness of geotechnical soft sediments (thickness of Unit A–E/F Seismic data) in the previous Hesselø OWF area. Point data show thickness of soft sediments (CPT and boreholes). There is generally a good correlation between the data sets. Local areas without correlation could be related to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

8. Mapping of the Kattegat II OWF area and cable corridor

As a background for the evaluation of Geotechnical soft sediments in the current Kattegat II OWF area and cable corridor, the results from the mapping of geotechnical soft sediments in the previous Hesselø OWF area presented in chapter 7 (Figure 7.1 to Figure 7.3), have been used.

The detailed mapping of geotechnical soft sediments in the previous area is expanded to a more general mapping of thickness of expected geotechnical soft sediments in the Kattegat II OWF area and cable corridor in order to enable a general evaluation of the potential for OWF foundations and cable corridor.

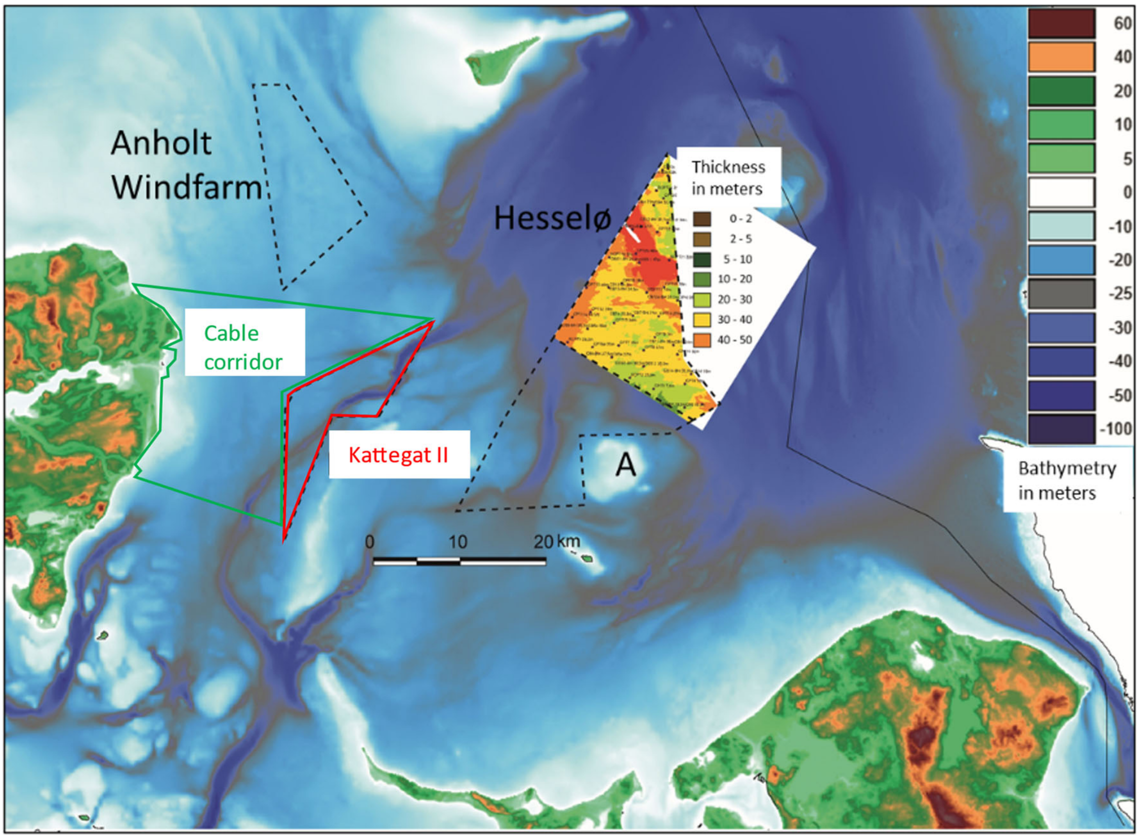

Figure 8.1 Detailed mapping of geotechnical soft sediments in the previous Hesselø OWF area. The Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines).

In the geological screening process of the current Kattegat II OWF area and cable corridor, the datatypes presented in chapter 4 (Data background) have been used.

For the interpretation of archive data in the area, the seismostratigraphic units presented in Table 1, and based on information from GEUS (2020) and Fugro (2021), have been used.

Sparker data in the Marta database from the raw material survey Anholt-Syd-R3-NST 2011 have been used as well as scientific data not yet stored in Marta.

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

In addition, new and unpublished seismic data from investigations for the Danish Energy Agency as part of a geological screening for offshore wind of the Danish Sea area have been used, especially in the cable corridor where few existing data were available.

The mapping procedure included the following steps:

- 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 Kingdom Suite
- Seismic Interpretation was based on the seismostratigraphic units in Table 1
- Calculation of the thickness of soft sediments: 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 area and Anholt OWF

The final product is thickness and distribution maps of expected geotechnical soft sediments in the Kattegat II OWF area and cable corridor.

9. Geological screening of the Kattegat II OWF area and cable corridor

In the Kattegat II OWF area, Sparker seismic lines penetrate units A–E and into the till unit H. Thus, it can be verified that the stratigraphy from Table 1, established in the previous Hessel OWF area, is also valid for the Kattegat II OWF area. The Parasound data only penetrate the uppermost part of the till, but with a high resolution. These data are also supported by vibrocore documentation.

9.1 Sparker line interpretation in the Kattegat II OWF area

Sparker lines R3_035 and R3_029 (Figure 9.1and Figure 9.2) are located in the northern part of the Kattegat II OWF area and show a hummocky till surface with larger northeast–southwest oriented depressions, with infill of Unit E Late Glacial, possibly soft, clay up to 10 m thick. Unit A 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.

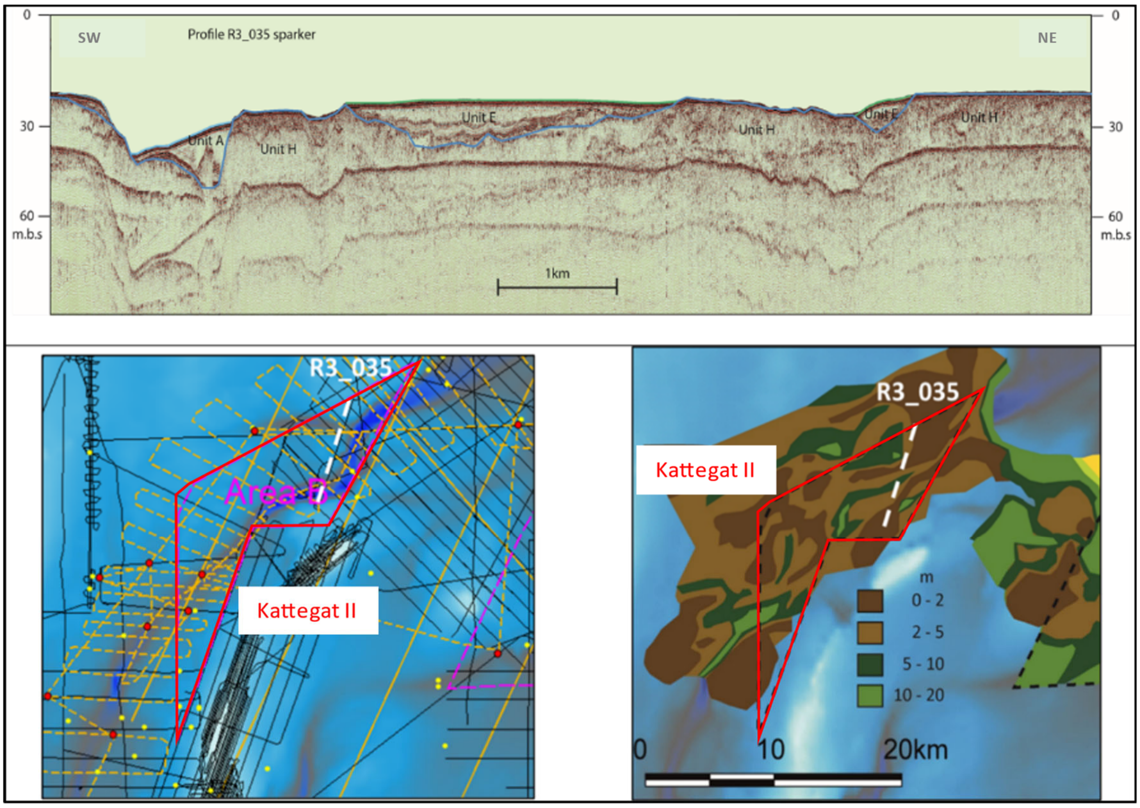

Figure 9.1 Southwest to northeast Sparker profile R3_035 with location in relation to the seismic archive data grid (black lines are Sparker data) and the geotechnical soft sediment thickness map.

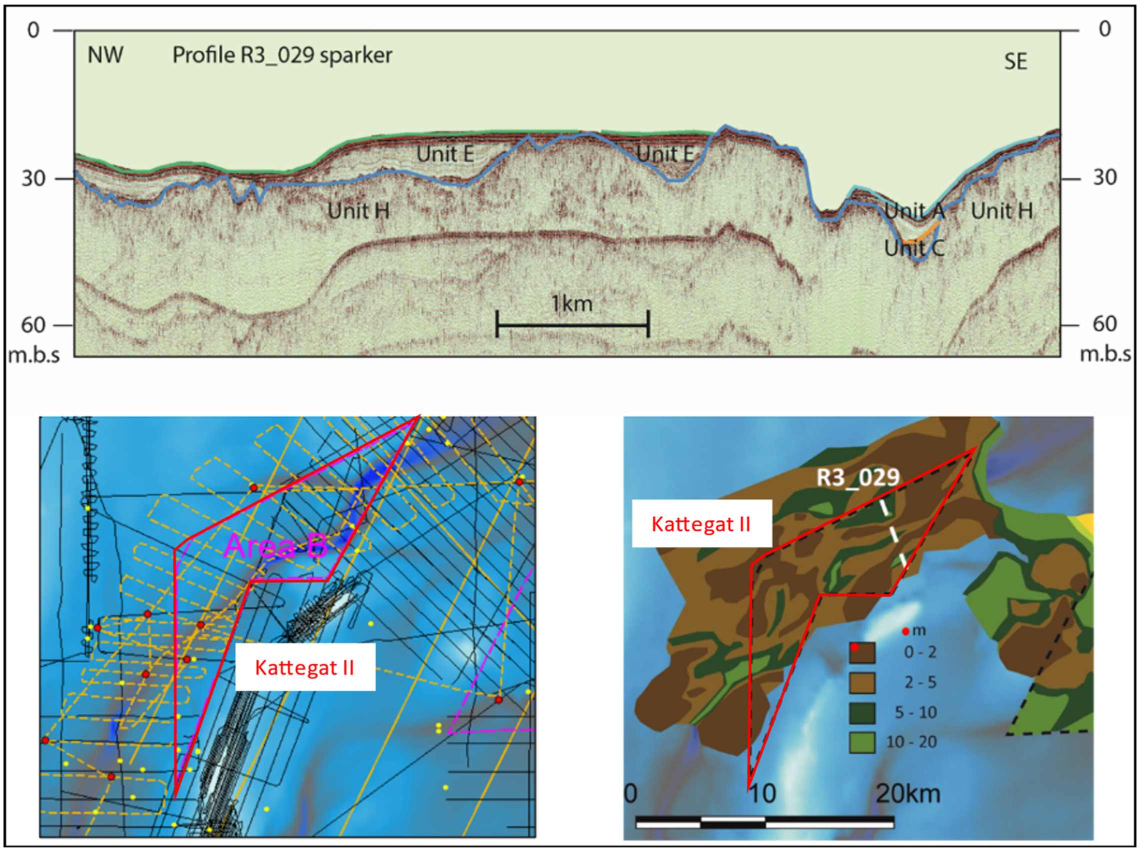

Figure 9.2 Northwest to southeast Sparker line R3_035 with location in relation to the seismic archive data grid (black lines are Sparker data) and the geotechnical soft sediment thickness map.

9.2 Parasound and vibrocore interpretation in the Kattegat II OWF area

A series of Parasound examples from the Kattegat II OWF area are presented to visualize the areal distribution of the geotechnical soft sediments (Figure 9.3, Figure 9.4 and Figure 9.5).

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 cover large areas whereas the uppermost Unit A and C Holocene mud and fine-grained sand are confined to the northeast–southwest-trending channel, seen on the bathymetric map.

Parasound data from the northern and central part of the Kattegat II OWF area (Figure 9.3) show the Unit H till (verified in core 24) with a hummocky surface and chaotic internal seismic reflection pattern. The infill between the hummocks are Unit E Late Glacial clay (verified in core 19) with stratified seismic reflections and followed by channel erosion and infill of Unit B muddy clay and silt, also with stratified seismic reflections and Unit A structureless to transparent, sandy mud.

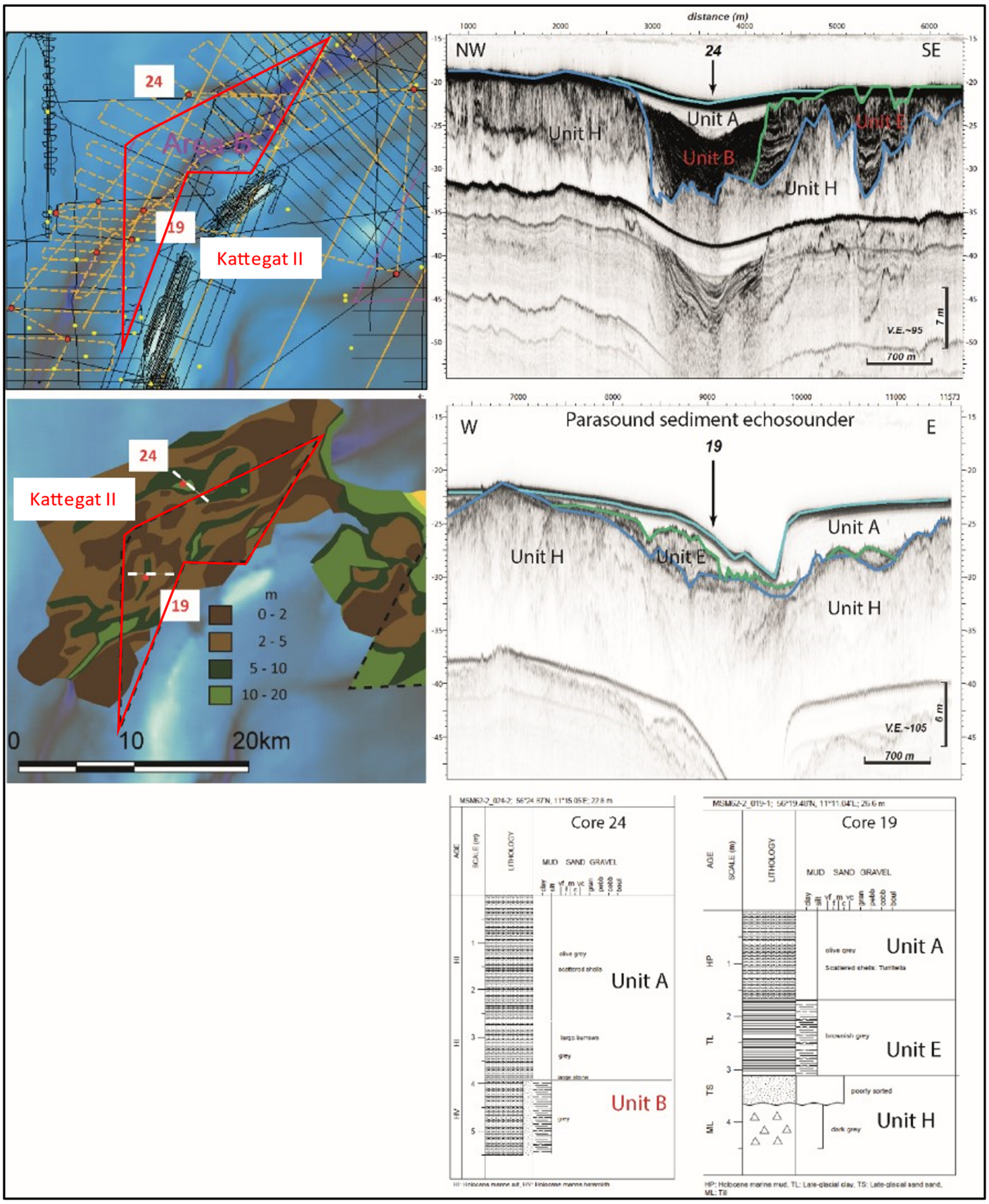

Figure 9.3 Parasound echosounder profiles from the northern and central parts of the Kattegat II OWF area with location in relation to the seismic archive data grid (yellow lines are Parasound data). The position of the seismic examples and vibrocores 24 and 19 are indicated on the geotechnical soft 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 the Kattegat II OWF area (Figure 9.4) also shows the Unit H till (core 17) with a hummocky surface and chaotic internal seismic reflection pattern and with infill between the hummocks of Unit E Late Glacial clay and silt (core 16 and 17) with stratified seismic reflections. This example is outside the channel area and shows the structureless/transparent fine-grained sand to muddy sand of Unit A draping the surface of Unit H and E.

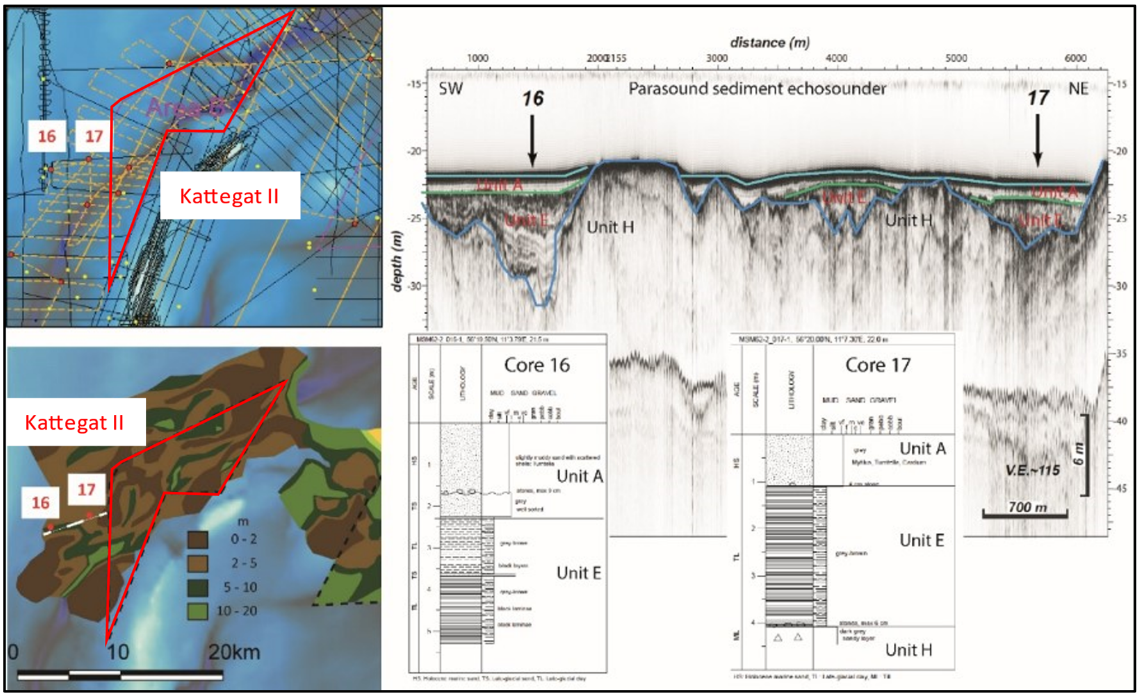

Figure 9.4 Parasound echosounder profile west of the Kattegat II OWF area, with location in relation to the seismic archive data grid (yellow lines are Parasound data). The position of the seismic example and vibrocores 16 and 17 are indicated on the geotechnical soft sediment thickness map and core descriptions with indication of seismic units are shown on the seismic profile.

Also the Parasound examples from the southern part of the Kattegat II OWF area (Figure 9.5) show the Unit H till with chaotic internal seismic reflection pattern and with partly infill of Unit E Late Glacial clay and silt with stratified seismic reflections. The examples show the palaeo-Great Belt channel incision and the channel infill of more than 10 m of Unit A (lower part parallel infill reflectors and upper part structureless to transparent) Holocene sandy clay to mud (core 15 and 18).

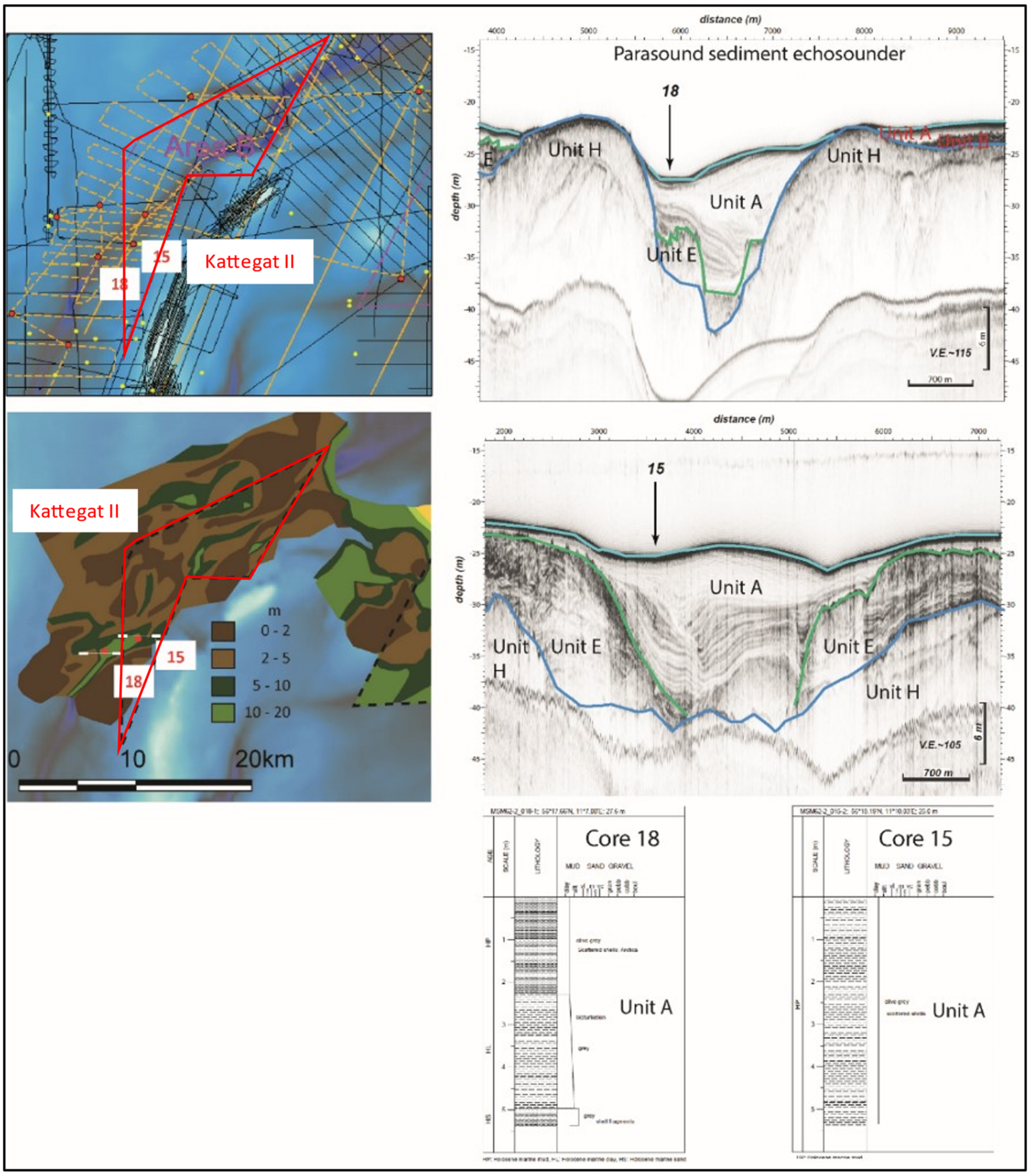

Figure 9.5 Parasound echosounder profiles from the southern part of the Kattegat II OWF area, with location in relation to the seismic archive data grid (yellow lines are Parasound data). The positions of the seismic profiles and vibrocores 18 and 15 are indicated on the geotechnical soft sediment thickness map. Core descriptions with indication of seismic units are shown below the seismic profiles.

9.3 Sparker line interpretation in the cable corridor

The seismic interpretation in the cable corridor is primarily based on new and unpublished sparker lines from investigations for the Danish Energy Agency as part of a geological screening for offshore wind of the Danish Sea area.

The current interpretation suffers from lack of borehole verification and is mainly based on the seismic facies interpretation.

Sparker line AS_SC_02b (Figure 9.6) is located in the northwestern part of the cable corridor and show what is expected to be the Unit H till with a hummocky surface and chaotic internal seismic reflection pattern. To the south sporadic, but strong reflections below Unit H is likely to represent the top of the Unit I bedrock, here probably Danien limestone. To the north, a larger northeast–southwest-oriented incised valley appears, with infill of what is expected to be Unit E Late Glacial, possibly soft, clay up to 20 m thick and with some weak to strong internal stratification. Above Unit E in the incised valley, and to the south, what is expected to be Unit A Holocene soft, muddy and sandy sediments is filling in basins in the Unit E and Unit H surfaces with a thickness up to 5-8 m.

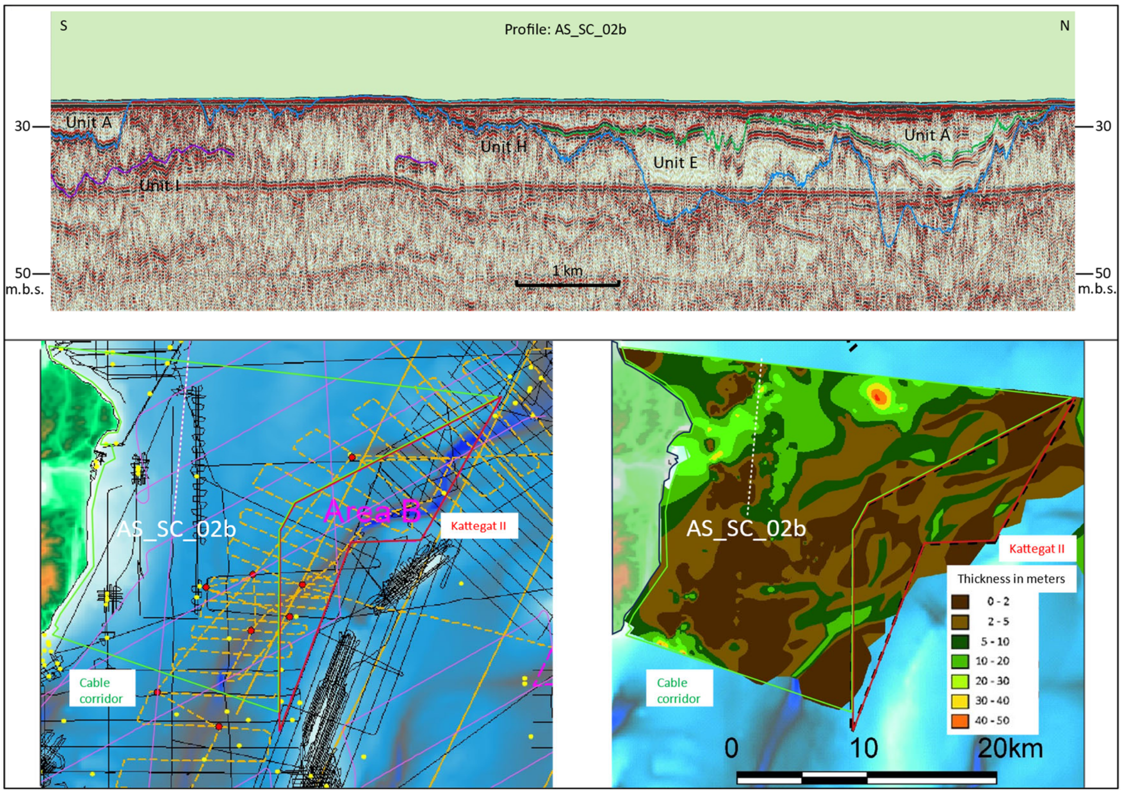

Figure 9.6 South to north Sparker profile AS_SC_02b with location in relation to the Sparker seismic archive data (black lines are archive Sparker data, yellow lines Parasound data and purple lines are new Sparker data) and the geotechnical soft sediment thickness map.

Sparker line AS_SC_17 (Figure 9.7) is located in the northern part of the cable corridor on the southern flank of the incised valley described above and to the northeast into the central part of the valley. The top of the expected Unit H till is less hummocky and relatively shallow to the southwest and deeper in the central part of the valley to the northeast. In the central part of the valley, the expected Unit E valley fill is up to 40-50 m in thickness and generally less than 10 m to the southwest.

The deep part of the incised valley is a conservative interpretation and is uncertain. Hence, the top of the expected Unit H till may be situated shallower and Unit E be considerably thinner on the northeastern part of AS_SC_17.

To the southwest, Unit E is covered by around 10 m of the expected Unit A. To the northeast, a minor basin in the Unit E surface is filled with 5-15 m of sediments also expected to be Unit A.

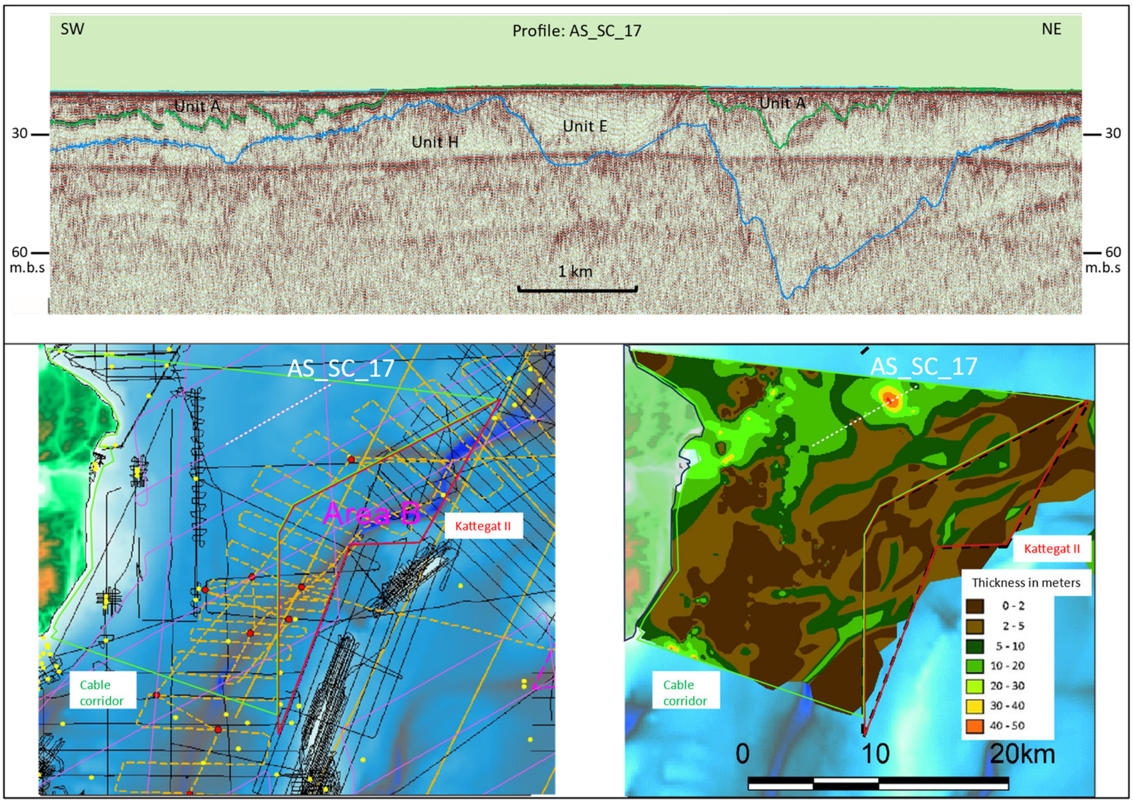

Figure 9.7 Southwest to northeast Sparker profile AS_SC_17 with location in relation to the Sparker seismic archive data (black lines are archive Sparker data, yellow lines Parasound data and purple lines are new Sparker data) and the geotechnical soft sediment thickness map.

Sparker line AS_SC_15 (Figure 9.8) is located in the southern part of the cable corridor on a plateau of shallow bedrock (Unit I), probably Danien Limestone. The interpretation of Unit I is, however, tentative, and thus relatively uncertain. Above the interpreted top of Unit I, the expected Unit H till appears from the seabed with a thickness of around 10 m or more, except to the southwest where an incised valley is filled with up to 45 m of the expected Unit E. The uppermost part of the valley fill is a small basin filled with around 5 m of the expected Unit A.

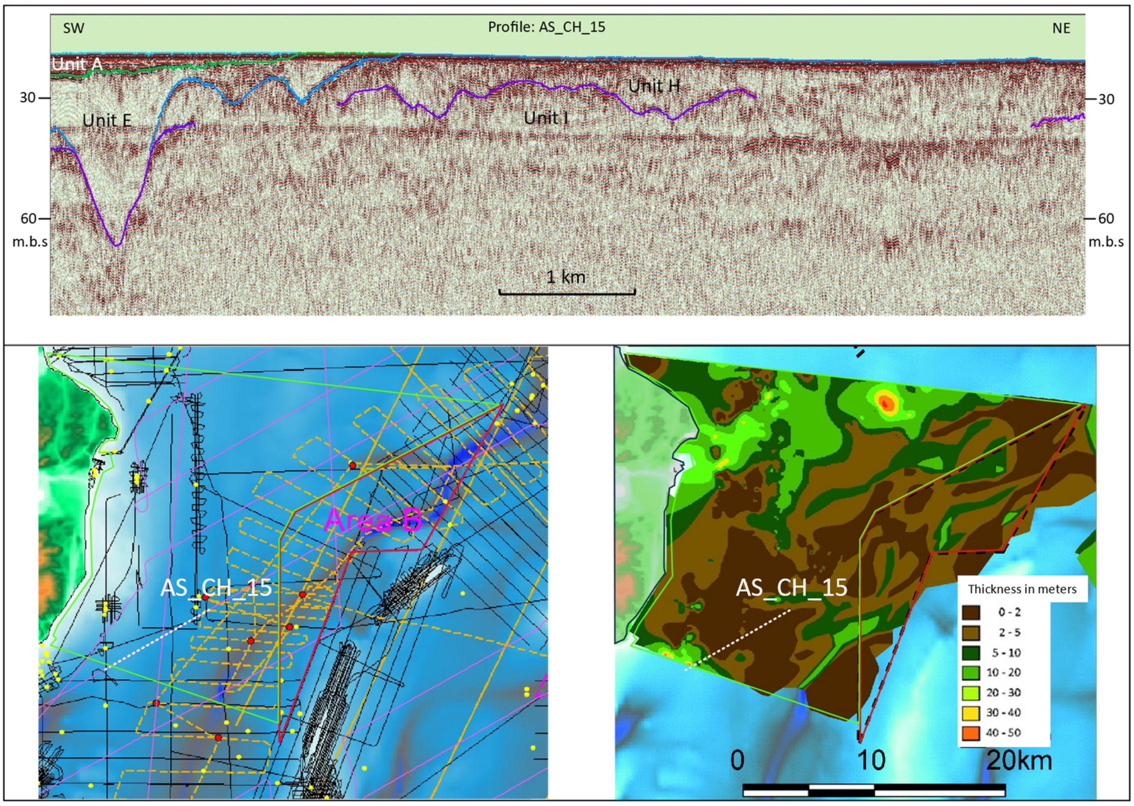

Figure 9.8 Southwest to northeast Sparker profile AS_SC_15 with location in relation to the Sparker seismic archive data (black lines are archive Sparker data, yellow lines Parasound data and purple lines are new Sparker data) and the geotechnical soft sediment thickness map.

9.4 Thickness map of geotechnical soft sediments

Based on the described stratigraphy, all available seismic lines have been interpreted and a general thickness map of geotechnical soft sediments in the current Kattegat II OWF area and cable corridor has been produced and compared with the detailed mapping of the previous Hesselø OWF area.

In the Kattegat II OWF area and most of the cable corridor, a hummocky till surface with northeast–southwest-oriented depressions have infill of what is expected to be Unit E Late Glacial, possibly soft, clay up to 10 m thick. Through the Kattegat II OWF area runs a palaeo-Great Belt Channel with infill of Holocene soft, muddy, and sandy sediments in delimited areas and up to 10 m thick, locally even more. Through the north-western part of the cable corridor runs a larger northeast–southwest-oriented incised valley, with infill of what is expected to be Unit E Late Glacial, possibly soft, clay, in general up to 20 m thick and locally up to 40-50 m in thickness. The deep part of the incised valley is, however, a conservative interpretation and the area with 40-50 m thickness is uncertain. Above Unit E, what is expected to be Unit A Holocene soft, muddy and sandy sediments is filling in basins in the Unit E and Unit H surfaces with a thickness up to 5-8 m.

The combined thickness of geotechnical soft sediment is shown in Figure 9.9. The general impression is that the soft sediments are thinner than in the previous Hesselø OWF area. In most of the Kattegat II OWF area and cable corridor, the thickness of soft sediment is between 2 and 5 m. In the northeast to southwest elongated depressions are found with 5–10 m of soft sediment and locally 10–20 m. In the larger incised valley up to 20-30 m of soft sediments, and locally even up to 40-50 m are seen.

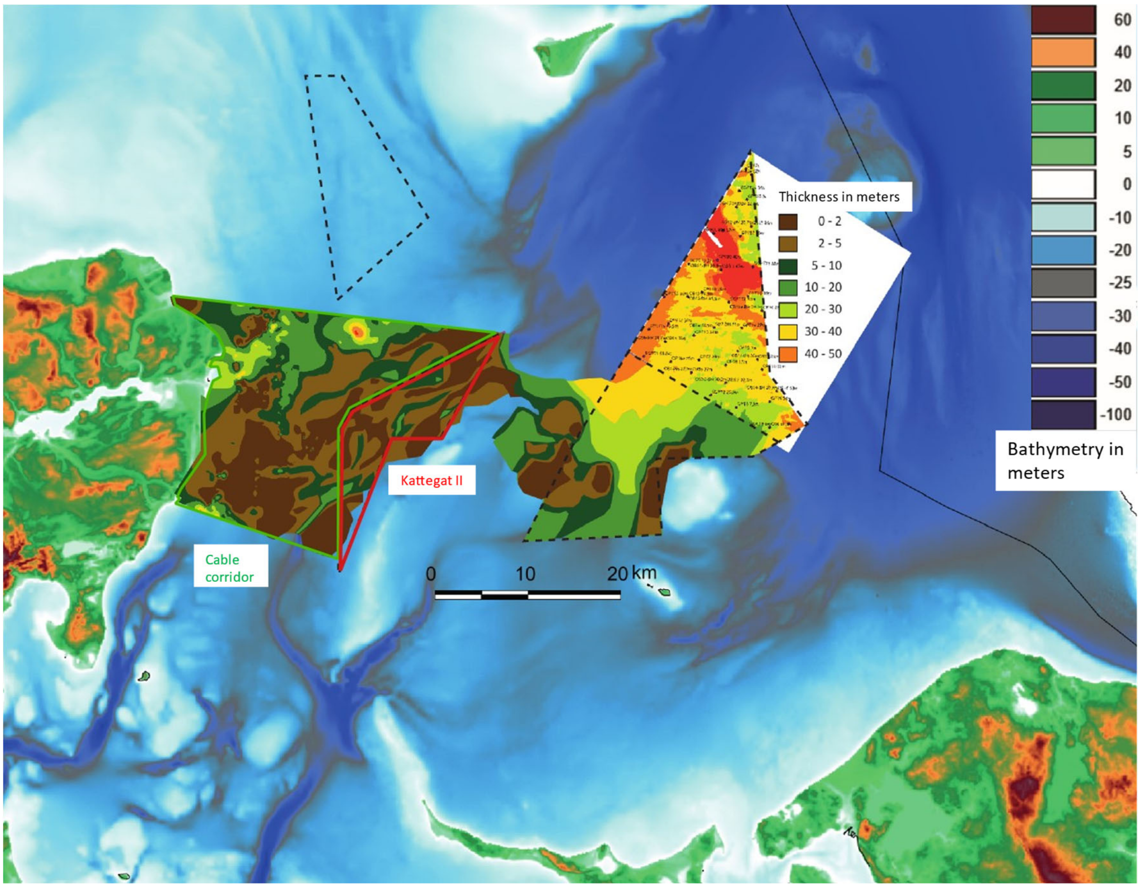

Figure 9.9 General thickness of geotechnical soft sediments (combined thickness of seismic Units A–E/F) in the current Kattegat II OWF area compared with the detailed mapping of the previous Hesselø OWF area. The Kattegat II OWF area and cable route is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines).

10. Anholt OWF as an analog for the Kattegat II OWF area and cable corridor

Whereas the current Kattegat II OWF area is in the screening phase, the Anholt OWF is in function and all geological basis information is available and of great importance for the geotechnical evaluation of this part of the Kattegat.

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 the Kattegat II OWF area and cable corridor with the same seismic units as described in Table 1.

A schematic geological profile of the Anholt OWF and a general map of the thickness of geotechnical soft sediments (Figure 10.1) shows an area comparable to the Kattegat II OWF area 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.

Especially the northern Anholt OWF area is dominated by 10–30 m soft sediments above till, corresponding to the north-western part of the cable corridor.

The southern Anholt OWF area is dominated by 0–5 m soft sediments above till and as such comparable to the south-eastern part of the cable corridor and the Kattegat II OWF area.

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 10.1). The windmills show an overall north-western pointed shape, but with obvious considerations to soft bottom, with missing windmills in the areas with the thickest layers of soft sediments.

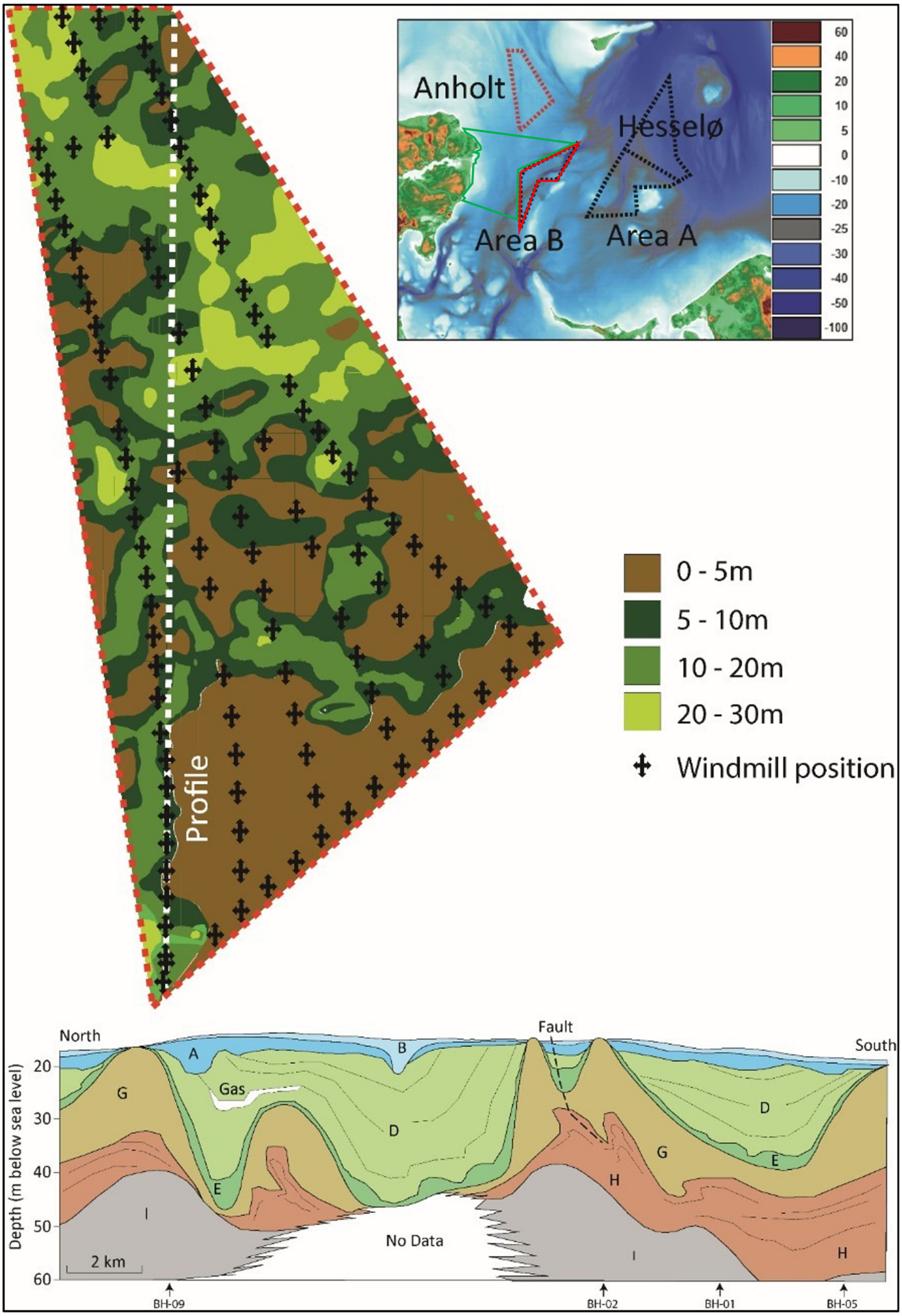

Figure 10.1 Anholt OWF general map of thickness of geotechnical soft sediment, with indication of location of schematic profile and windmill positions. Details of seismic units A–I in the schematic profile are provided in Table 1.

11. Archaeological interests

The distribution of land and sea after the last deglaciation is not only important for establishing a geological model for the area and for the subsequent planning of detailed geotechnical investigations, but also of great interest for an archaeological screening.

As described in Chapter 5.4, highstand sea-level characterised the initial period after the deglaciation of central and southern Kattegat. Around 18 cal. ka BP Kattegat was deglaciated and the Kattegat II OWF area and the cable corridor were covered by the glaciomarine Younger Yoldia Sea (Figure 11.1). This corresponds in part 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 the Kattegat II OWF area and cable corridor emerged from the sea (Figure 11.1) in the time period of the Ahrensburg culture or Ahrensburgian (12.9 to 11.7 ka BP) – a late Upper Palaeolithic nomadic hunter culture.

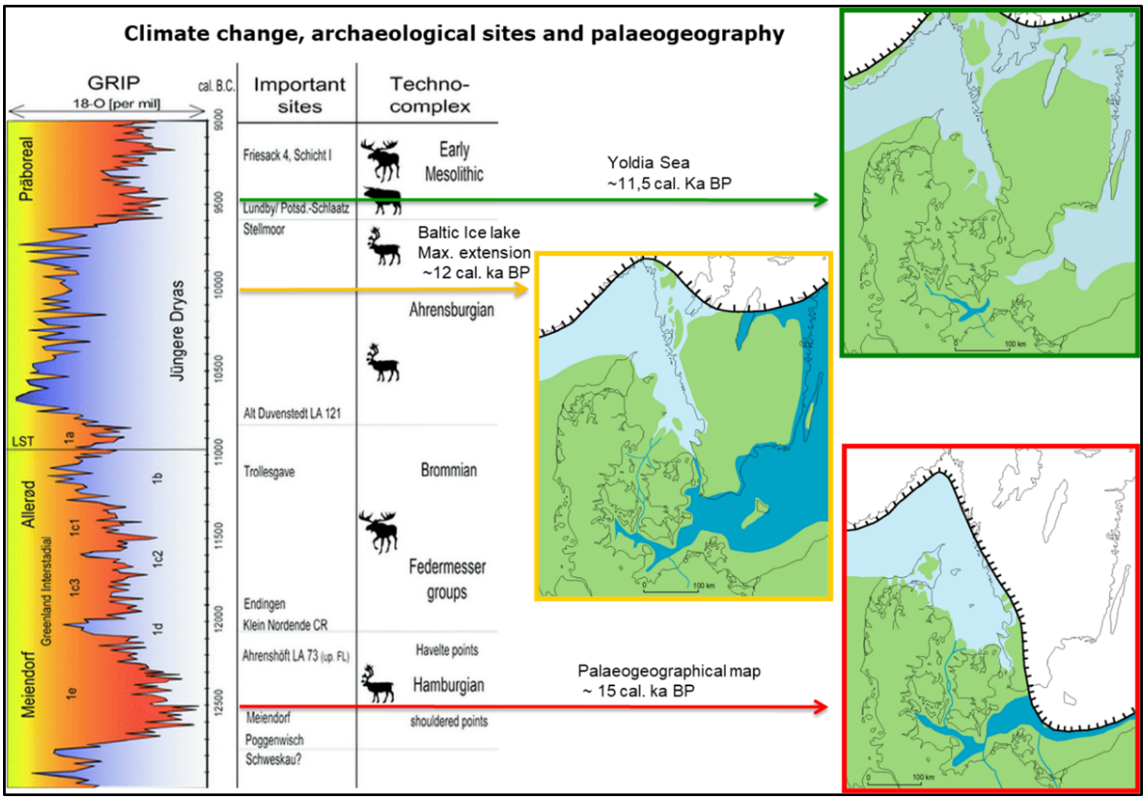

Figure 11.1. Late Glacial and Holocene general palaeogeography in Kattegat and related archaeological cultures (from Jensen et al. 2003).

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 11.1). Large parts of the Kattegat II OWF area and cable corridor was land but with N–S/NE–SW-oriented channels, e.g. the palaeo-Great Belt channel. The northern part of the Kattegat II OWF area crosses the mouth of a possible fjord system (Figure 6.4). 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 Ancylus Lake in the Baltic Basin (Figure 6.4). 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 5.9) shows that the spit/ barrier/estuary has to a large degree been preserved, with only minor modification during the continued Holocene transgression. This leads to the conclusion that the following rapid 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 are not represented in the Kattegat II OWF area and will only be of relevance close to the present coastline in the cable corridor.

12. Conclusions

In this screening study, a combination of published papers and reports, new and archive seismic and archive sediment core data have been used to assess the general geological development of the southern Kattegat and the Kattegat II OWF area and cable corridor.

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

As part of the geological desk study, a relative Late Glacial and Holocene sea-level curve for the area has been presented and the geological development with respect to archaeological interests has been described.

The previous 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 the current Kattegat II OWF area and cable corridor.

The results of the mapping are presented as seismic examples. A map showing the general thickness of geotechnical soft sediments in the current Kattegat II OWF area and corridor as well as in the existing Anholt OWF and OWF areas covered in previous screening reports is presented in Figure 12.1.

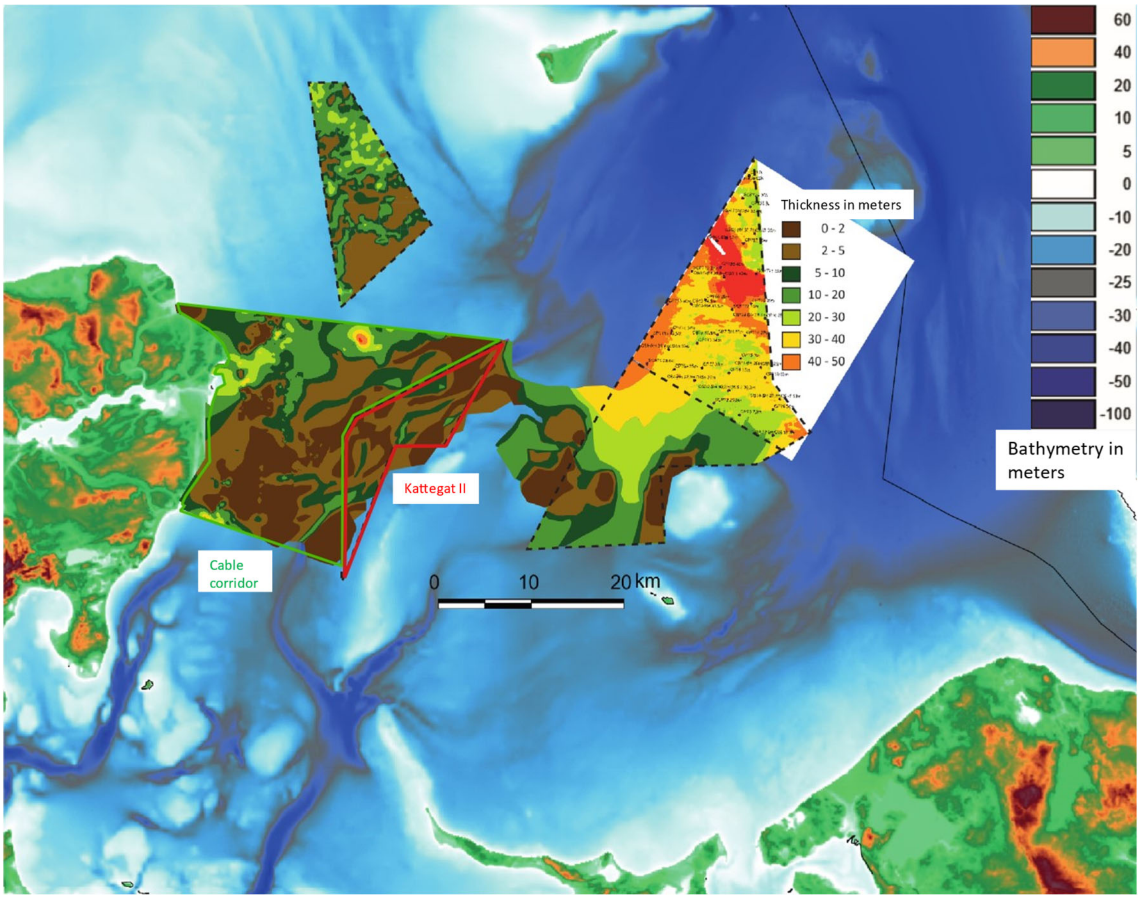

Figure 12.1 Thickness of geotechnical soft sediments in the southern Kattegat. The Kattegat II OWF area and cable corridor is shown in red and green together with the existing Anholt OWF and OWF areas covered in previous screening reports (black hatched lines).

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.

- In the Kattegat II OWF area and cable corridor, the general thickness of soft sediments is between 2 and 5 m. In the northeast to southwest elongated depressions are found with 5–10 m of soft sediment and locally 10–20 m. In the larger incised valley up to 20-30 m of soft sediments, and locally even up to 40-50 m are seen. The latter values are considered a conservative estimate.

- The Anholt OWF is a relevant analogue for the Kattegat II OWF area and cable corridor with obvious similarities in relation to geotechnical considerations concerning the thickness of geotechnical soft sediments.

- The Late Glacial and Early Holocene coastal zone development of the southern Kattegat 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 the Kattegat II OWF area, in contrast to the relatively flat seabed in most of the cable corridor.

An overall conclusion is that in the Kattegat II OWF area, similar soil conditions as in the southern part of the Anholt OWF can be expected. This means, from a geological point of view, it is most likely possible to establish an OWF in the Kattegat II OWF area.

Also, most of the cable corridor is similar to the southern part of the Anholt OWF, except for a larger southwest–northeast-oriented incised valley with infill of soft sediments up to 20-30 m in thickness and locally up to 40-50 m.

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