DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2022/27**

Investigations of sand resources for the Danish North Sea energy island

Aggregate mapping for the Danish Energy Agency

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

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GEUS

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1. Summary

Pursuant to §2 of Act No. 2379 of 14 December 2021 on the planning and construction of an energy island in the Danish North Sea, the Danish Minister for Climate, Energy and Supply mandated the Geological Survey of Denmark and Greenland (GEUS) to initiate the relevant exploration of sand resources. The execution of the task is coordinated with the Danish Energy Agency (DEA), and survey activities and reporting regarding raw material mapping follow statutory requirements from the Danish Environmental Protection Agency (DEPA).

Following a desk-top study focused on pre-selecting potential areas of sand resources within a limited distance from the planned energy island, three subareas were selected for detailed geophysical studies and sediment coring by GEUS in 2022.

A first vibrocoring campaign in late May 2022 verified the existence of larger potential sand resources in two of the screening areas, Area A and Area B. The areas contain large marine sand bank structures situated immediately to the north-west and to the west of the planned energy island site. In a third Area C, the vibrocores carried out showed relatively thin marine sand deposits on top of late glacial clay-fine sand deposits, not suitable as sand resources. Consequently, a following detailed seismic survey and follow-up vibrocoring campaign in June-August 2022 focused on selected parts of Area A and B only.

For Area A, detailed sand resource mapping confirmed the existence of a large marine sand bank structure with a maximum thickness of up to c. 12 m. In marginal parts of the survey area, sand bank thickness thins to almost zero. The sand bank structure overlies fine-grained late glacial to glacial deposits, with no resource potential. 30 vibrocores with grain size analyses from Area A pinpoint that suitable grain sizes (medium-coarse sand) are found only in the upper 3-5 m of the sand bank unit. Moreover, the thin sand cover of the sand bank margin appears to be dominated by fine-grained sand. A conservative estimate of net sand resource volume in Area A, represented by the upper 3 m of the delimited resource area, gives a total volume of c. 172 million m^3 sand suitable for energy island construction.

For Area B, resource mapping confirmed the existence of a marine sand bank structure with a maximum thickness of up to c. 14 m. In the northern tip of the area, sand bank thickness thins to almost zero. In the southern part, two marine sand units have been identified. The older unit, having a variable internal structure, appears in general to be too fine-grained. The younger unit consists of medium-grained sand forming large clinoform foresets building out towards the north. 13 vibrocores with grain size analyses verify that the upper c. 3 m of the younger sand bank unit constitutes the potential resource in Area B. A conservative estimate of net sand resource volume in Area B, represented by the upper 3 m of the delimited resource area, gives a total volume of c. 80 million m^3 sand suitable for energy island construction.

GEUS' investigations have been able to confirm that suitable sand resources are found close to the planned North Sea Energy Island site. Based on a simple distance relationship, resource Area A is considered to be a potential primary sand extraction area, and resource

Area B is a good alternative area. Due to poor resource quality, Area C disqualify as a potential resource area.

2. Introduction

DEA has asked GEUS to perform investigations of sand resources for energy island construction in three pre-selected areas of the Danish North Sea. The selection of the areas was based on a prior desktop study (GEUS Rep. 2022-4). Survey activities described in this report focus on delimiting, describing, and quantifying potential sand resources. The results will together with a later environmental assessment study, form the decision basis for the selection of one or more dedicated ‘specific purpose construction areas’ (Bygherreområder), from which sand extraction to the planned North Sea Energy Island can take place. The survey activities were approved by DEPA and performed in agreement with applicable requirements in Råstofbekendtgørelsen (BEK no. 1682 of 17/12/2018).

It is intended that this report including survey data and map products shall be included in an upcoming tender regarding the construction of the North Sea Energy Island.

3. Requirement specifications

3.1 Sand quality and amounts

Quality requirements given by the DEA state that the desired material to be identified must be composed of well-graded friction material, and a good resource consists primarily of medium- to coarse-grained sand (0.2-2.0 mm). Parts of the resource can also be coarser gravelly sand (up to 20 mm).

Since the final design of the North Sea Energy Island is currently undecided, the specific amounts of resources needed for construction is unknown. It is stated in the *Framework for the coming draft plan to be used for the strategic environmental assessment*, that the sand/gravel resource consumption will not exceed 45 million m^3. To meet unexpected conditions in future dredging area(s), mapping of significantly larger resources is desired if possible.

One primary extraction area will be identified as the best suitable, and one-two additional areas shall be identified as alternatives.

3.2 Survey and data delivery requirements

In order to fulfil the requirements from DEA and DEPA to survey specifications and final data delivery the following guidelines were followed:
Shallow seismic surveys are performed with methods which can meet the requirements to produce map types listed in the following section. Apart from shallow seismic acquisition, the following survey instruments shall also be included:

a) Side scan sonar with a maximal range of 100 m and acquisition in both high and low frequency mode. At water depths less than 10 m, the maximal line distance shall be 80 m, and at water depths larger than 10 m, the maximal line distance shall be 100 m.
b) Magnetometer

Detailed mapping can include sediment samples up to 50 liters or sediment cores.

The description of the raw material resources shall be illustrated with the following map types:

a) Areal distribution of raw material resource(s)
b) Volumetric distribution of raw material resource(s)
c) Bathymetry map (based on echosounder or multibeam data)
d) Seabed surface sediment distribution
    i) With areal distribution of the identified seabed substrate types (see below)
    ii) With indication of eventual sediment cover above a potential resource unit

iii) With indication of whether the seabed has been influenced by human activity (traces and artefacts) and with documentation of the nature of the influenced seabed surface (typically side scan sonar documentation)

iv) With indication of natural dynamic processes influencing the seabed

e) Results of sediment sample analyses

All results, positions, sailing lines, maps and interpretations are to be delivered to DEA and DEPA as a report with relevant GIS layers and data appendices. In addition, all survey results are to be delivered to GEUS, and side scan sonar data are to be delivered to Strandingsmuseum St. George in Thorsminde, Denmark, responsible for marine archeological data of the respective part of the Danish North Sea.

4. Selection of survey areas

Three survey areas, A, B, and C were chosen on basis of a desktop screening study performed by GEUS (GEUS Rep. 2022-4). The areas are situated north, west, and east of the planned energy island at water depths of 30-40 m (Figure 4.1).

Existing survey data from former raw material and habitat mapping surveys by GEUS and Orbicon/WSP for DEPA (GEUS Rep. 2021-25; Nicolaisen et al., 2010) indicate that survey Area A and B are characterized by large Holocene sand bank structures, with thicknesses in places exceeding 10 m. The Holocene marine deposits are resting on late glacial fine-grained deposits and locally glacial till or meltwater deposits. Area C to the east are characterized by Weichselian meltwater deposits, locally overlain by a few meter thick marine sand cover. As sediment core data from the selected survey areas and nearby areas were very sparse, it was decided that the survey program should be initiated by a vibrocoring campaign on sites selected along existing seismic lines.

After the first vibrocoring survey (phase 1A) was completed ultimo May 2022, two detail survey areas within Area A and B were selected for further phase 1B investigations. The phase 1B seismic survey took place mid-June 2022 and a second vibrocoring campaign, with a denser net of vibrocore sites within the detail survey areas of Area A and B, took place mid-August 2022.

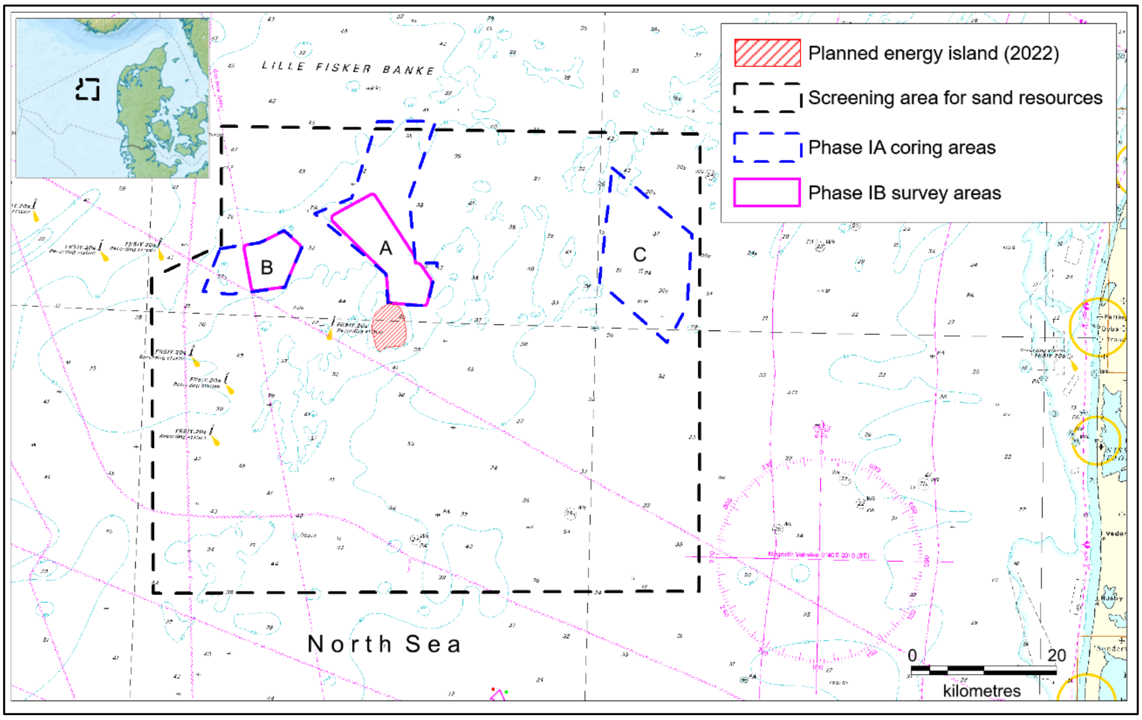

Figure 4.1. Location of planned North Sea Energy Island (primo 2022), screening area, phase IA and IB survey areas in the Danish North Sea.

5. Survey specifications

5.1 Survey completion

The survey vessel *MV Arctic Ocean* was mobilised in Esbjerg 30th of May 2022 for the first vibrocoring campaign. Vibrocoring took place in the period May 31st to June 6th, interrupted by a bad weather period 2-4th of June. Demobilisation of the vibrocoring gear took place in Thyborøn 7th of June. At 18th of June 2022 *MV Arctic Ocean* was mobilised in Esbjerg for seismic survey, and the survey took place without interruptions from 19th-26th of June. At 22nd of August, *MV Arctic Ocean* was mobilised in Esbjerg for the second vibrocoring campaign, and coring took place 23rd –26th August 2022.

For the seismic survey, a single channel sparker system, a parametric subbottom profiler, side scan sonar, multibeam and magnetometer instruments were deployed. Specifications of the instruments are given below. Survey took place along parallel lines with a distance of 100 m. In order to ease turns at end of survey lines and to distribute survey time with respect to changing weather conditions over a larger area, every second line was first sailed, followed by infill of remaining every other line. In total 1358 km lines were surveyed. This includes a few lines or sections of lines that were repeated due to recording failures of single instruments. In order to calibrate the multibeam system, a patch test was completed in the northern part of Area B, and sound velocity probe measurements of the water column were performed daily.

The seismic survey was performed under relatively good and stable weather conditions. Wind speeds were in the range 6-9 m/s from westerly to southerly directions, and wave height and swell were in the range 0.5-1.0 m. During the vibrocoring surveys, more challenging weather conditions were met. During the period 2-4th of June vibrocoring were cancelled due to wave heights exceeding 1.5 m. Likewise, on the 26th of August a strong weather front from the Northwest, prevented further vibrocoring.

5.2 Survey vessel and equipment mounting

The survey vessel *MV Arctic Ocean* chartered from OS Energy through FOGA Aps. was used for the seismic survey and vibrocoring (Figure 5.1). In Figure 5.2 the equipment set-up is shown. GEUS' survey container with acquisition output units, recording computers and monitoring screens was placed close to the stern of the ship. Sparker source and streamer were towed from the starboard side c. 20 meter after the vessel. The distance between sparker and streamer was c. 3 m. The subbottom profiler and combined side scan sonar and multibeam was mounted on a survey pole at the port side, at respectively 440 cm and 400 cm under the water line. The magnetometer was towed ca. 30 meter behind the vessel at the port side. In order to prevent the magnetometer from sinking to the bottom by slow manoeuvring and turns, a buoy was fastened at the magnetometer with a 10 m line.

Figure 5.1. Survey vessel MV Arctic Ocean (www.os-energy.de/fleet/ships).

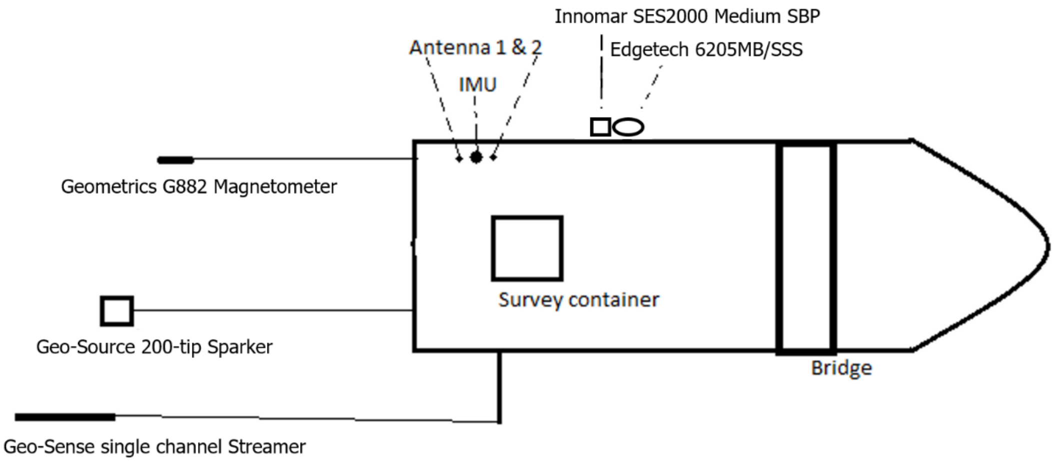

Figure 5.2. Equipment mounting on MV Arctic Ocean.

5.3 Equipment and acquisition software

The equipment used is listed in Table 5-1.

Table 5-1. Equipment used.

Instrumentlist	
Integrated side scan sonar/ multibeam	Edgetech 6205
Subbottom profiler (SBP)	Innomar SES 2000 Medium
Sound velicity profiler (SVP)	AML Minox
Navigation/Motion	Applanix PosMV v.5
Streamer	Geo-Sense 1 channel, 8 elements, High resolution streamer
Sparker	Geo-Source 200
Power supply	Geo-Pulse 1000
Magnetometer	G-882 magnetometer
Vibrocorer	MED-C VC(VKG)-6

Positioning

For positioning, an Applanix PosMv 5 receiver was used. The GPS/GNSS/L receiver uses NTRIP GP corrections, by which a horizontal position accuracy of 0.1 m and a vertical accuracy of 0.3 m are achieved. Depth soundings relative to a reference point thereby becomes tide corrected. As RTK connection was flawed for some periods during the survey, multibeam data was tide corrected based on the Hvide Sande harbour tidal table. The Offset from GPS antenna to the sonar transducer was measured in connection to mobilisation. During survey, antenna positions and corrected navigation data are distributed in a data string to the individual acquisition instruments. GPS heights are calculated on basis of geoid separation (DKGE-OID02).

Bathymetry

For depth measurement an Edgetech 6205 combined multi beam and side scan sonar was used, operating at a 230 kHz frequency for the bathymetry and low-resolution side scan, and with 550 kHz frequency for the high-resolution side scan. Position and altitude data, roll, pitch and heave were compensated by motion sensor and Applanix PosMv 5 receiver. The combination of the two instruments gives an absolute accuracy of 0.3 m. Data collection was in Edgetech Discovery software and the files were registered in Edgetech JSF format. A SVPT/CTD probe was used for daily in-situ water column velocity measurements.

Side scan sonar

The EdgeTech 6205 side scan sonar used has an optimum resolution across the sailing direction of c. 4.5 cm. It is a dual-frequency side scan sonar, which operate simultaneously at 230 and 550 kHz. Data was recorded in Edgetech JSF format with Discovery software. A 100 m range to each side was used.

Seismic aquisition

A Geo-Resources sparker-system and a single-channel 8 element Geo-Sense streamer was used for vertical penetration down to 50-150 ms two-way travel time (TWTT). For acquisition a Mini-Trace 2 system from Geo-Resources was used. The following specifications and settings were used:

Sparker system	Specifications/setting
Power Supply	Geo-Spark 1000
Power output	400 J
Tow frame	Geo-Source 200
Streamer	Geo-Sense 8 element single channel
Firing interval	0,5 seconds
Layback	20 m

For higher resolution of the uppermost seabed layers (down to about 20-50 ms TWTT), an Innomar SES-2000 Medium parametric subbottom profiler was used. The subbottom profiler data are corrected for roll and heave with a SMC motion sensor. The following specifications and settings were used:

Innomar SBP	Specifications/setting
Primary frequency	6 kHz
Recording range	100 m
Firing interval	Triggered from internal trigger

Magnetometer

Data from the Geometrics G-882 magnetometer were recorded in Geometrics MagLog software.

Vibrocoring

GEUS' 6 m VKG Vibrocorer was used for coring. The vibrocorer can penetrate unconsolidated and consolidated sediments such as sand, mud, clay, till and loosely lithified sediments. The 6 m core barrel is made of stainless steel and contains a PVC liner of 106 mm inner diameter. During coring, penetration depth and performance of the vibrator (ampere values) were monitored via a control unit. After recovery of each core, the sediment-filled core liner was divided in 1 m core sections, and notes of grain size, shell content etc. as observed at divisions were done. Hereafter the core sections were labelled and packed for further description and analyses at the home laboratory.

6. Data processing

The geophysical data have been processed for further interpretation and mapping in different software packages and GIS-based final maps. Table 6-1 gives an overview of data formats, interpretation software and end products.

Table 6-1. Data format, software used and end products.

Data type	Data format	Data- and interpretation software	End product
Positioning	ASCII text	Hypack, MapInfo	Survey line map
Bathymetry	ASCII text	Edgetech Discovery, SonarWiz 7 MapInfo Vertical Mapper	Bathymetry
Side scan	Jsf converted to geotiff	SonarWiz 7, Mapinfo	Seabed substrate map Human impact structures
Sparker	SEGY	Minitrace 2, Geosuite Allworks, IHS Kingdom, MapInfo	Seismic stratigraphy, Resource thickness
Innomar	SES, RAW	SES Convert 64, Geosuite Allworks, IHS Kingdom, MapInfo	High resolution seismic stratigraphy

6.1 Multibeam data

Multibeam JSF files were processed daily in order to check data quality. Tide level, heave and sound velocity profiles were imported to SonarWiz to correct raw data. The multibeam dataset was cleaned for 'outliers' and data were limited to a 140° beam interval to exclude lower accuracy data from the outer beams. As RTK connection was flawed for some periods during the survey, data was tide corrected based on the Hvide Sande harbour tidal table. The cleaned dataset was exported as Geotiff files to create an overview picture. Moreover, an ESRI grid with 5 m grid points was created for further analysis and presentation in GIS software.

6.2 Side scan sonar data

Side scan sonar JSF files (230 kHz data set) were imported in SonarWiz 7 for processing of gain and sea bottom tracking. Geotiff tiles were generated for GIS import and construction of a side scan sonar mosaic of each survey area. Individual side scan sonar files were studied for close-up view and mapping of seabed substrate features, bed forms, and man-made features such as trawl traces.

6.3 Sparker seismic data

Sparker data recorded in SEGY format were processed with Geosuite Allworks software comprising the following steps/parameters:

- Infinite Impulse Response (Bandpass) filter, low cut-off at 200 Hz, high cut-off 2000 Hz
- Median Filter
- Constant gain of 4 dB
- Trace equalisation from detected seabed with Root Mean Squared (RMS) scaling
- Normalisation
- Automatic Gain Control (AGC)
- Trace mixing of adjacent traces with weighting on 50, 100, 50 for previous, current and following trace
- Detection of seabed reflector
- Muting of water column
- Time Variant Gain (TVG) from seabed, with 0 dB at seabed and 10 dB at end of trace (150 ms TWTT)
- Swell filter over 15 traces

After processing, sparker data were exported in SEGY format and imported in IHS Kingdom seismic interpretation software for stratigraphic analysis. The time (depth)-axis on the seismic profiles is shown in two-way travel time (TWTT). Based on an estimated sound velocity of 1600 m/s in the dominantly sandy upper seabed, 10 ms corresponds to c. 8 m depth.

6.4 Innomar subbottom profiler data

Innomar data in raw format were converted to SEGY format with Innomar SESConvert64 software. SEGY data were imported to Geosuite Allworks and processed with the following steps/parameters:

- Median Filter
- Constant gain of 5 dB
- Detection of seabed reflector
- Trace equalisation from seabed with Root Mean Squared (RMS) scaling base
- Muting of water column
- Time Variant Gain (TVG) from seabed, with 0 dB at seabed and 10 dB at end of trace (75 ms TWTT)
- Swell filter over 15 traces
- Swell filter over 100 traces

After processing, Innomar data were exported in SEGY format and imported in IHS Kingdom seismic interpretation software for stratigraphic analysis. The time (depth)-axis on the seismic profiles is shown in two-way travel time (TWTT). Based on an estimated sound velocity of 1600 m/s in the dominantly sandy upper seabed, 10 ms corresponds to c. 8 m depth.

7. Area A - survey results

7.1 Survey lines

The geophysical survey in Area A was conducted along 82 NW-SE orientated survey lines with 100 m spacing (Figure 7.1, Appendix A1). Hereby full-coverage side scan sonar and multibeam depth mapping of the seabed could be carried out.

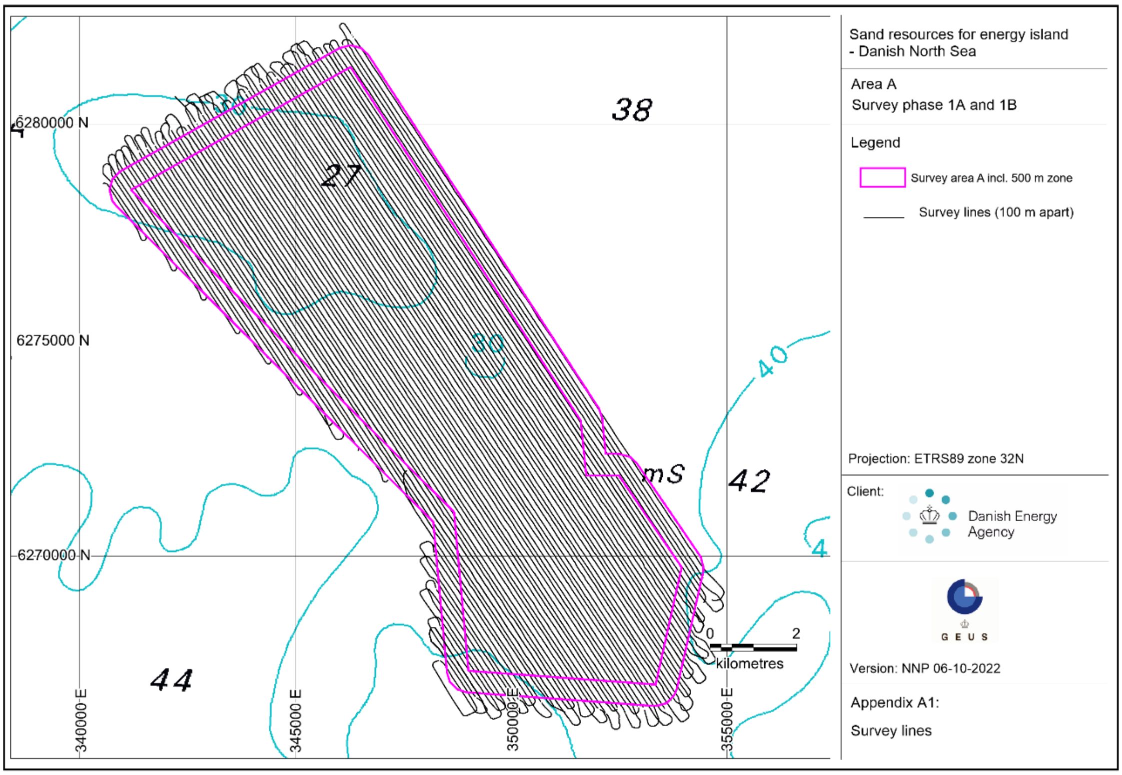

Figure 7.1. Surveyed lines in Area A. See larger version in Appendix A1.

7.2 Bathymetry

On basis of multibeam data, a full-coverage 5 m grid bathymetric map of Area A was constructed and presented in GIS (Figure 7.2, Appendix A2). Depths are in the range 27-41 m (DVR90). In general, the survey area is seen to frame very well the depth contour of the large sand bank structure contained in Area A. The shallowest depths of 27-28 m are seen in the north-westerly central parts of the survey area. The deepest parts of 40-41 m are found along the outer margin in the south-westerly and south-easterly parts of the area.

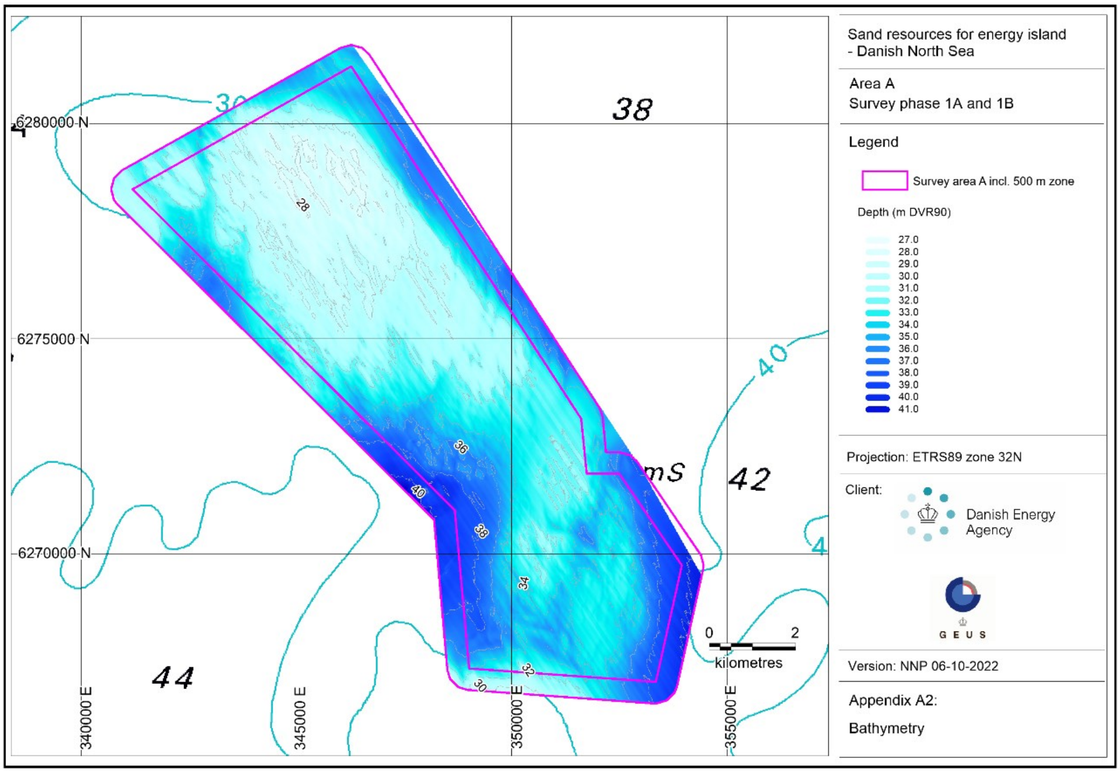

Figure 7.2. Mapped bathymetry in Area A. See larger version in Appendix A2.

7.3 Side scan sonar mosaic

The side scan sonar mosaic map shows dominantly low reflective (light colour) sandy seabed (Figure 7.3, Appendix A3). High reflective parts are however seen in the central westerly and in the north-westerly parts of the area, where the sand bank appears to be thin or absent. Based on core top description of vibrocores located in the high reflective areas, the seabed substrate type here appears to be characterised by gravelly sand, corresponding to lag sediments on top of the late glacial clay/silt/sand layered sequence.

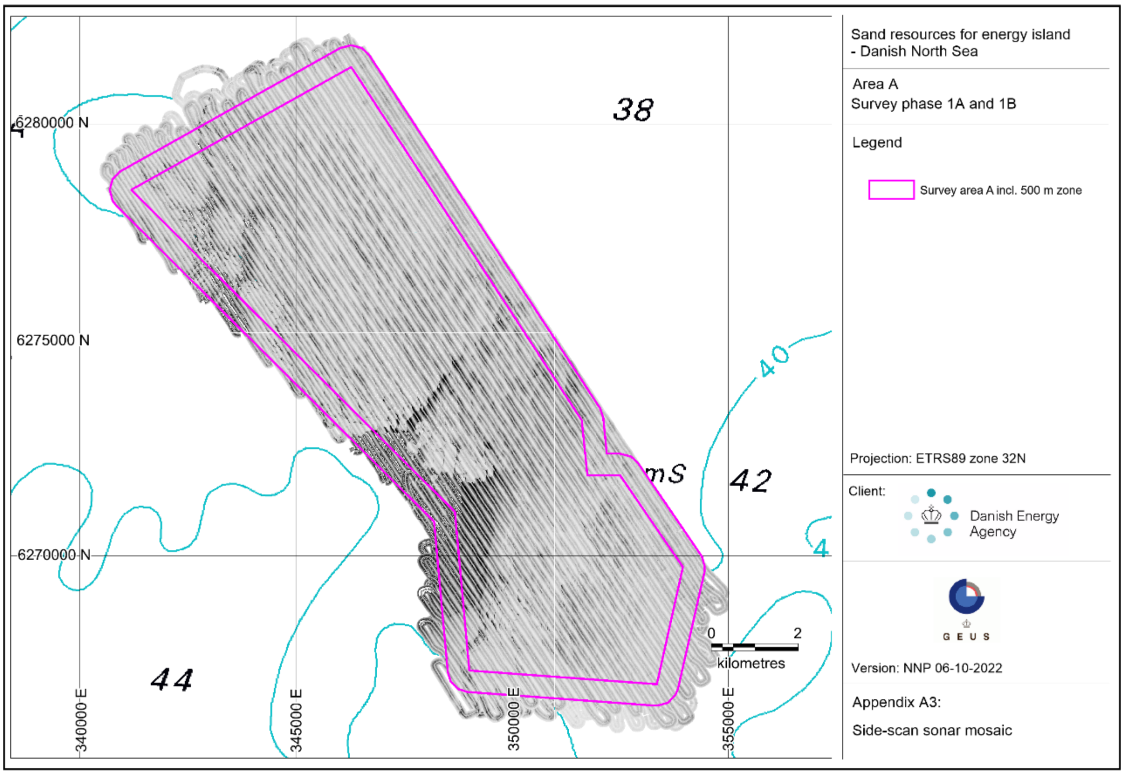

Figure 7.3. Side scan sonar mosaic of Area A. See larger version in Appendix A3.

7.4 Substrate types

The seabed substrate types were mapped out based on side scan sonar data and ground truth verification through vibrocore top samples as well as archive data from 2019 habitat mapping of the area (GEUS Rep. 2021-25). The division into the following four substrate classes is according to DEPA requirements:

- **Substrate type 1** consists of fine-grained soft seabed (**type 1a**) or firmer sandy seabed with a variable content of shells and gravel and often with dynamic bedforms **(type 1b)**.
- **Substrate type 2** consists of a mixture of sand and gravel with small stones up to c. 10 cm in diameter. The substrate type can also be characterized by scattered larger stones, covering up to 10% of the seabed.
- **Substrate type 3** consists of sand, gravel and small stones, as well as larger stones (>10 cm diameter) covering 10-25% of the seabed.
- **Substrate type 4** consists of a stony seabed, with larger stones (>10 cm diameter) covering >25%. Sand, gravel and small stones occur as well.

Area A is dominated by sandy substrate type 1b, with subordinate substrate type 2 (sand and gravel) observed in the central western part of the area, as well as in elongated zones in the northwestern tip of the area (Figure 7.4, Appendix A4).

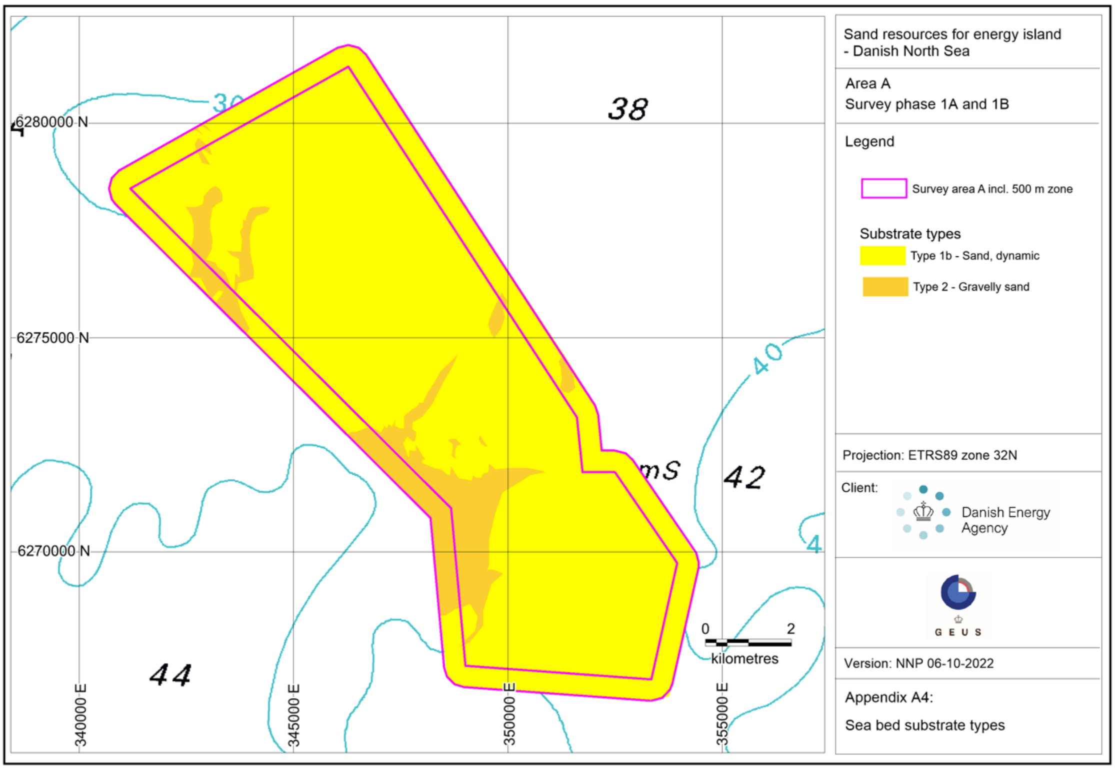

Figure 7.4. Substrate types in Area A. See larger version in Appendix A4.

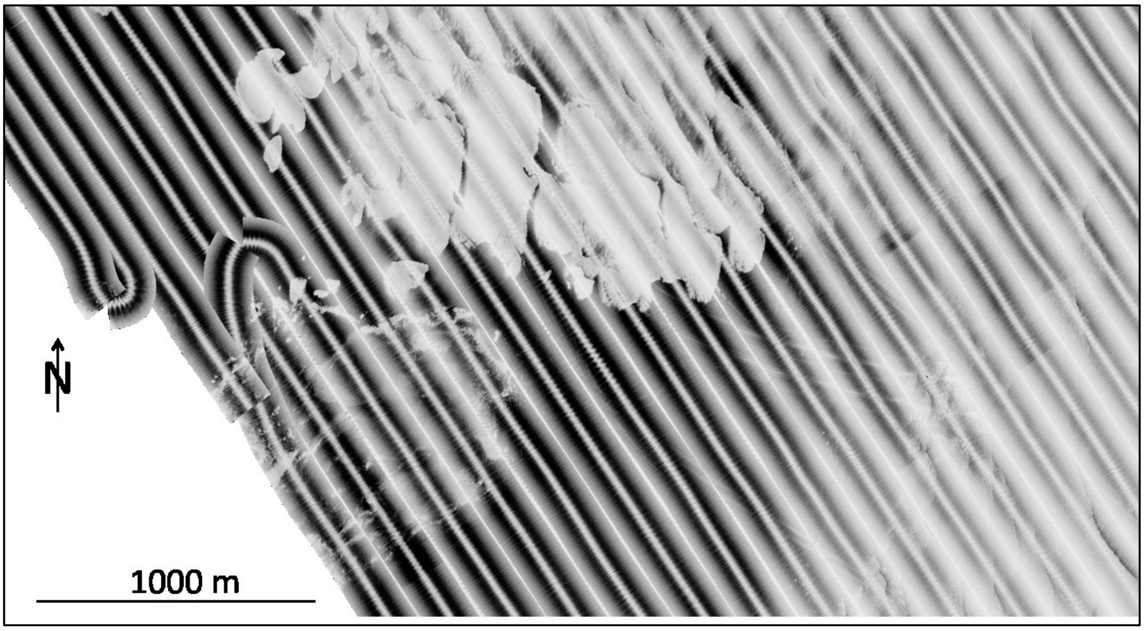

Figure 7.5. Side scan sonar mosaic of the central western area characterised by substrate type 2 (dark colour: gravelly sand) and substrate type 1b (light colour: closely spaced sandbars).

7.5 Dynamic bed forms and traces of human activity

Sand wave bedforms occur over almost all parts of Area A, characterized by sandy substrate type 1b (Figure 7.6, Figure 7.7, Appendix A5). The bedforms show wave lengths of up to c. 500 m and heights of c. 1-2 m. The sand wave crests are undulating and in general orientated NNE-SSW.

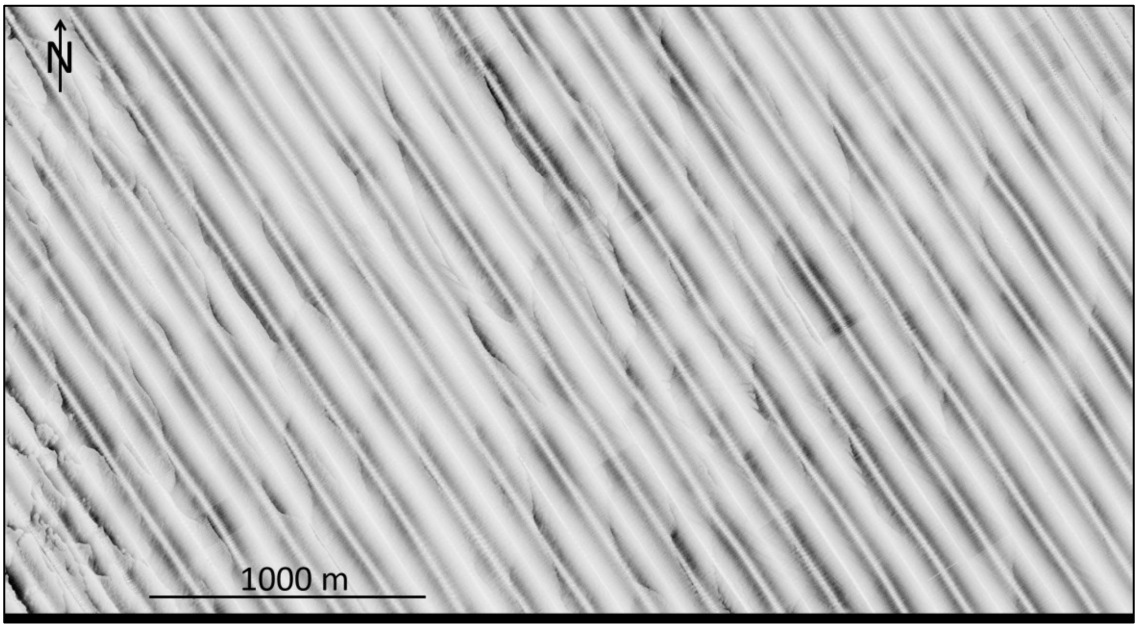

Figure 7.6. Side scan sonar mosaic from the northern central part of Area A, showing large sand waves with light undulating crests.

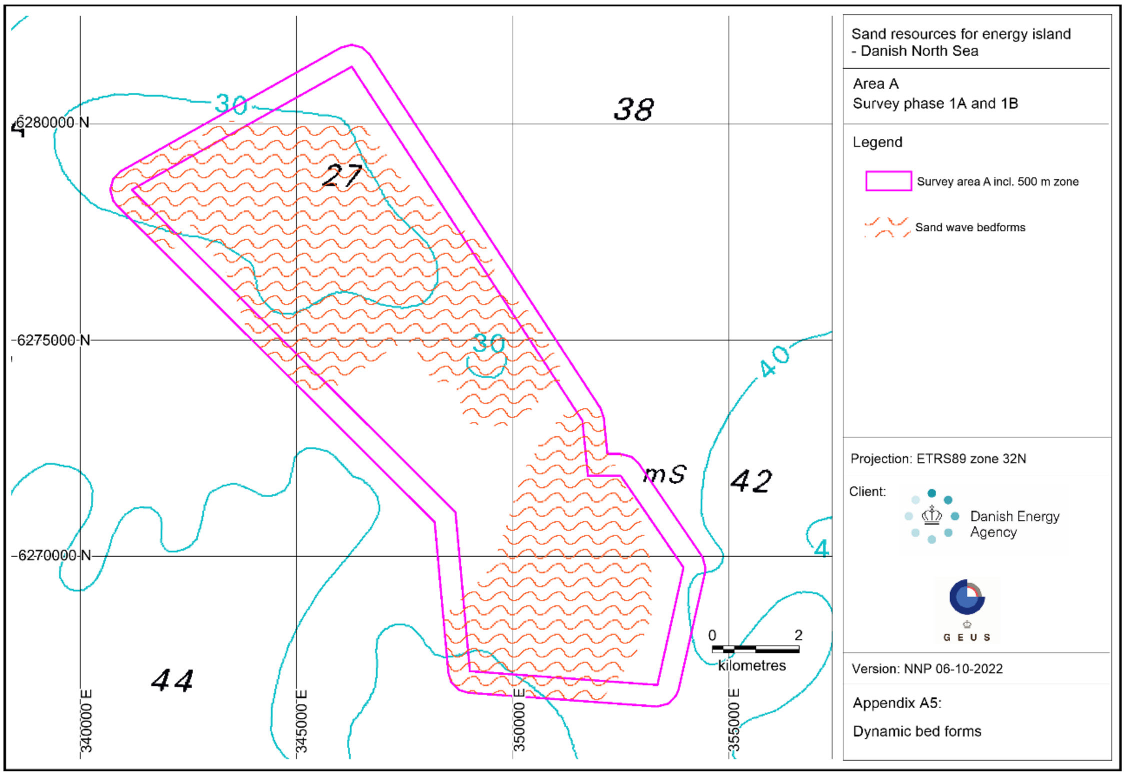

Figure 7.7. Distribution of large sand wave bedforms in Area A. In addition, trawl traces are found over the whole area. See larger version in Appendix A5.

All parts of Area A are characterized by trawl traces. The traces vary between distinct features (relatively newly formed) and others who appear to be more blurred (of older age) (Figure 7.8).

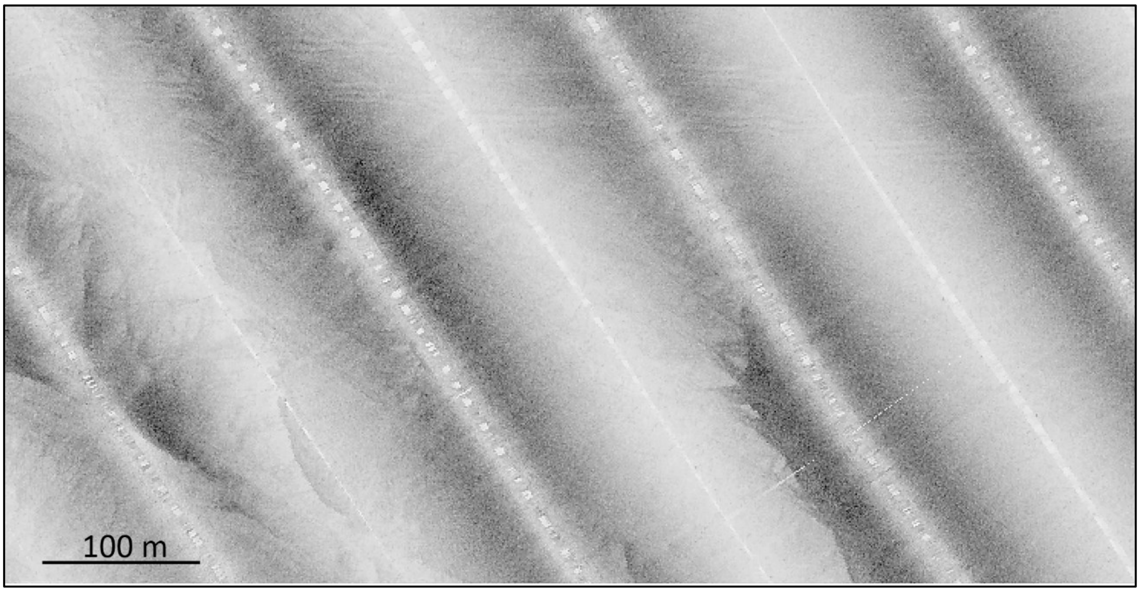

Figure 7.8. Side scan sonar example of trawl traces criss-crossing Area A.

7.6 Seismic profiles

In general, the southeast-northwest orientated seismic profiles show very similar seismic units. Examples of Sparker and Innomar profiles are given in Figure 7.9 and Figure 7.10, and in Appendix A10 representative Sparker and Innomar profiles with interpretation of the base of the Holocene marine sand bar unit (potential resource) are shown.

The seismic profiles reveal a strong and near to horizontal reflector 0-12 m below seabed corresponding to the base of the marine sand bar unit (potential sand resource) characterising the area. Below this, in the south-eastern half of Area A, a markedly stratified unit with embedded erosive channel elements (possibly of late glacial origin) is found. In the north-western half, a high of possibly glacial or prequaternary (Miocene) sediments is found below the sand bar unit. The division line or surface between the different sub-sand geological units is relatively steep and runs east-west through the central part of Area A. It is likely that the south-easterly dipping surface represents the northern margin of a buried glacial valley.

Tracing the reflector marking the base of the marine sand bar unit as well as the seabed reflector on all sparker profiles allows a 3D mapping of the extension of the potential sand resource unit. The base sand reflector can also be identified on the higher resolution Innomar subbottom profiles, but only where the sand bar unit thickness does not exceed more than c. 5-6 m. At larger thicknesses, the high-frequency Innomar reflection signal becomes attenuated or absent. Results of the vibrocore campaigns were used to confirm the seismic interpretation with respect to verifying the base of the main sand bar unit, and to characterise sediment composition of sub-sand units.

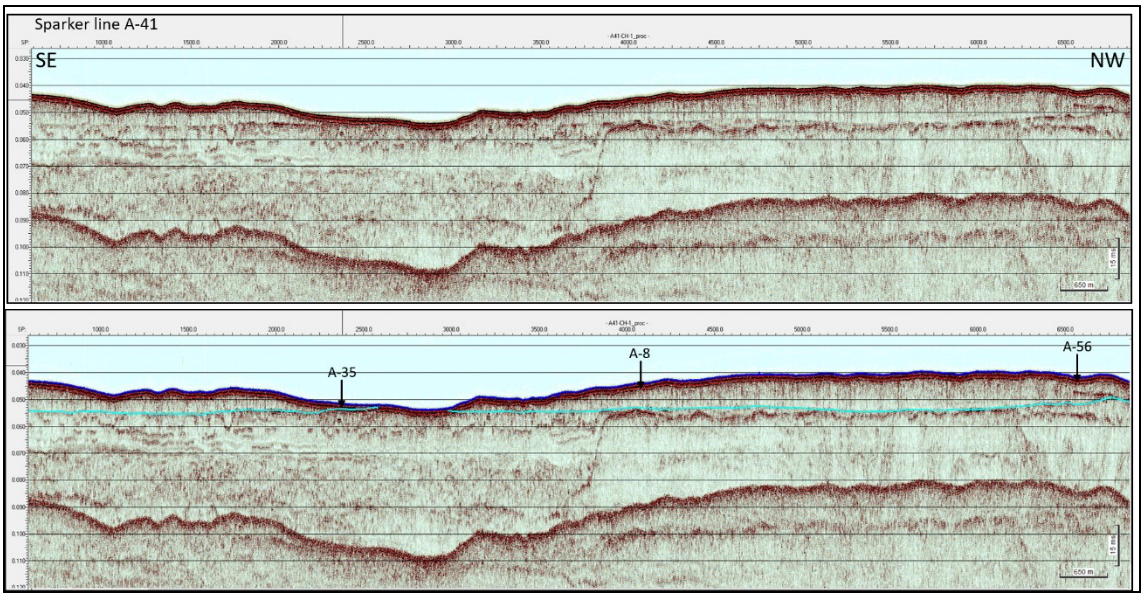

Figure 7.9. Example of sparker seismic profile (line A-41) from SE to NW in Area A, shown without interpretation (top) and with interpretation of base of sand bar unit (blue line on bottom section). Position of vibrocores A-35, A-8 and A-56 are indicated. Vertical scale is given by horizontal lines with 10 ms spacing corresponding to c. 8 m. The profile is shown in larger scale in Appendix A10.

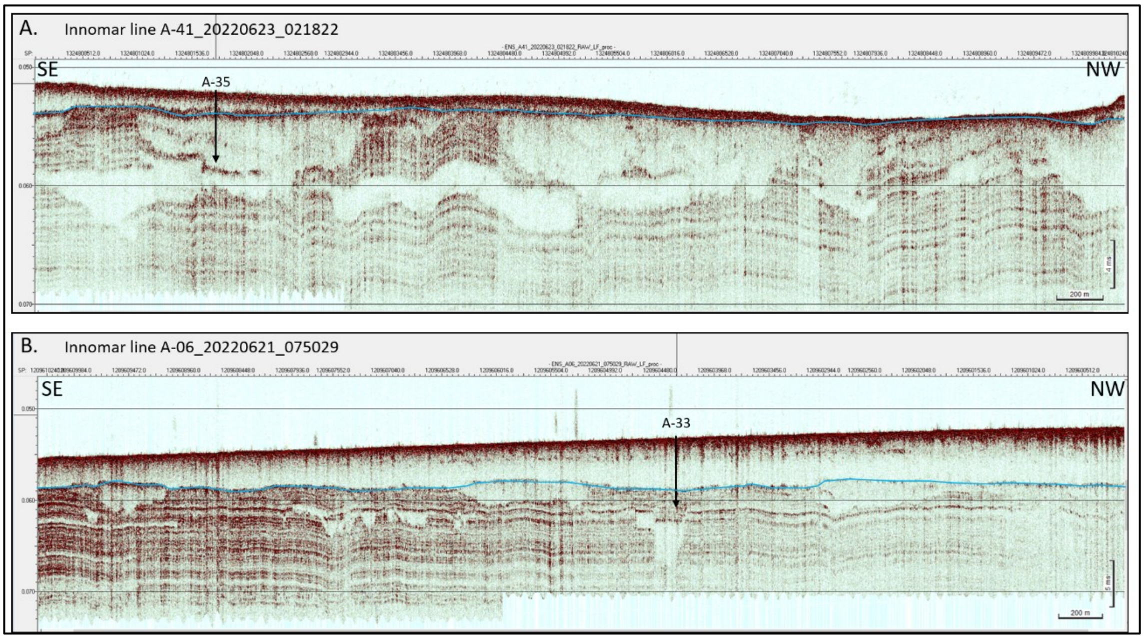

Figure 7.10. Example of two Innomar subbottom profiles showing a conspicuous layered unit with embedded channel elements (possibly late glacial) below the almost structureless sand bar unit (Holocene). Blue line indicates interpreted base of sand bar unit. Penetration depth of vibrocores A-35, A-33 are indicated. Vertical scale is given by horizontal lines with 10 ms spacing corresponding to c. 8 m. The profiles are shown in larger scale in Appendix A10.

7.7 Vibrocores

In total 30 vibrocores were retrieved from Area A (Figure 7.11, Appendix A6, D1), with 11 cores taken during the first phase IA survey and 19 cores taken during the later phase IB survey, following the detailed seismic survey of the area. The core lengths (recovery) are varying between 3.7 m and 6.0 m. Core descriptions and photos are shown in Appendices D2 and D3, and results of the grain size analyses performed are shown in Appendix D4.

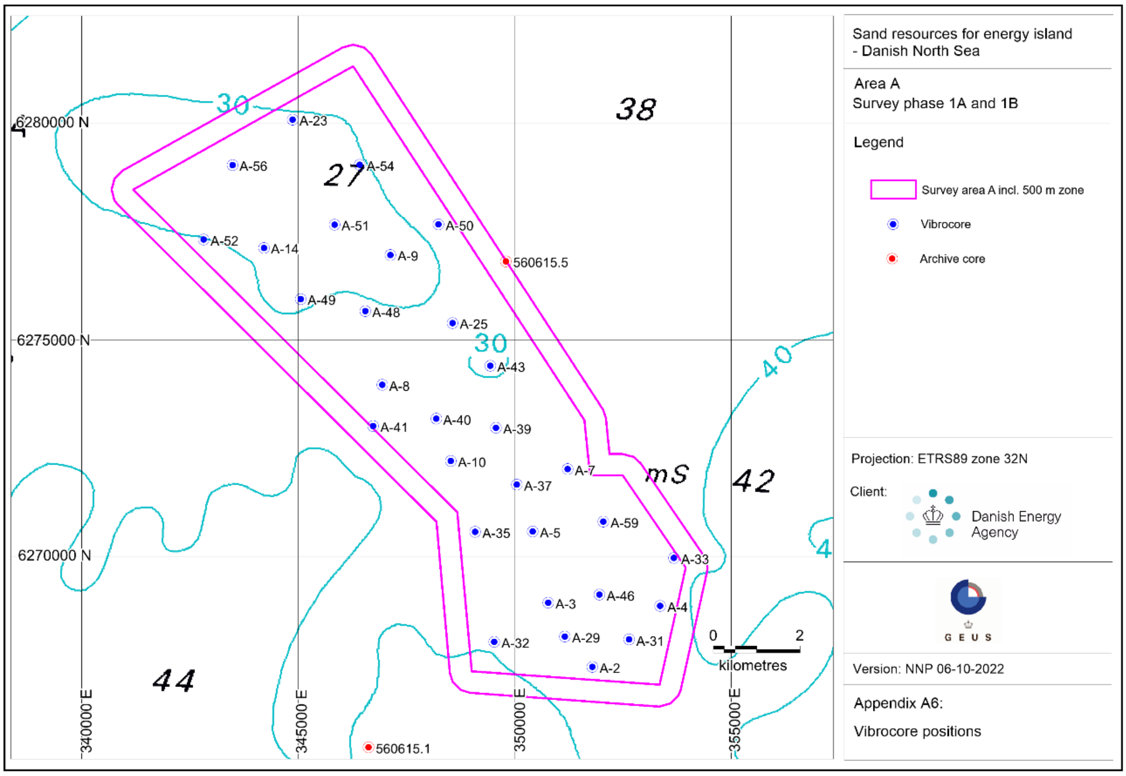

Figure 7.11. Vibrocore sites in survey Area A. See larger version in Appendix A6.

Core descriptions based on visual inspection of opened core sections confirm that the geophysically mapped large sand bars almost exclusively consist of marine sand, ranging from fine to coarse-grained (Figure 7.12, Appendix D2). However, single few cm thick black clay layers were observed in some of the cores. The base of the sand bar unit has often a gravelly character, possibly related to an origin as a transgression lag formed during the early to mid-Holocene period. This interpretation is corroborated by five bivalve shell radiocarbon dates from Area A and B (Table 7-1). Core sections penetrating the base of the sand bank unit, typically show fine layered clay-silt-very fine sand, representing late glacial lacustrine or shallow marine sediments. Channel units within this sequence typically shows a gravelly-sandy base fining upward to laminated clay-silt (cf. vibrocores A-35, A-32).

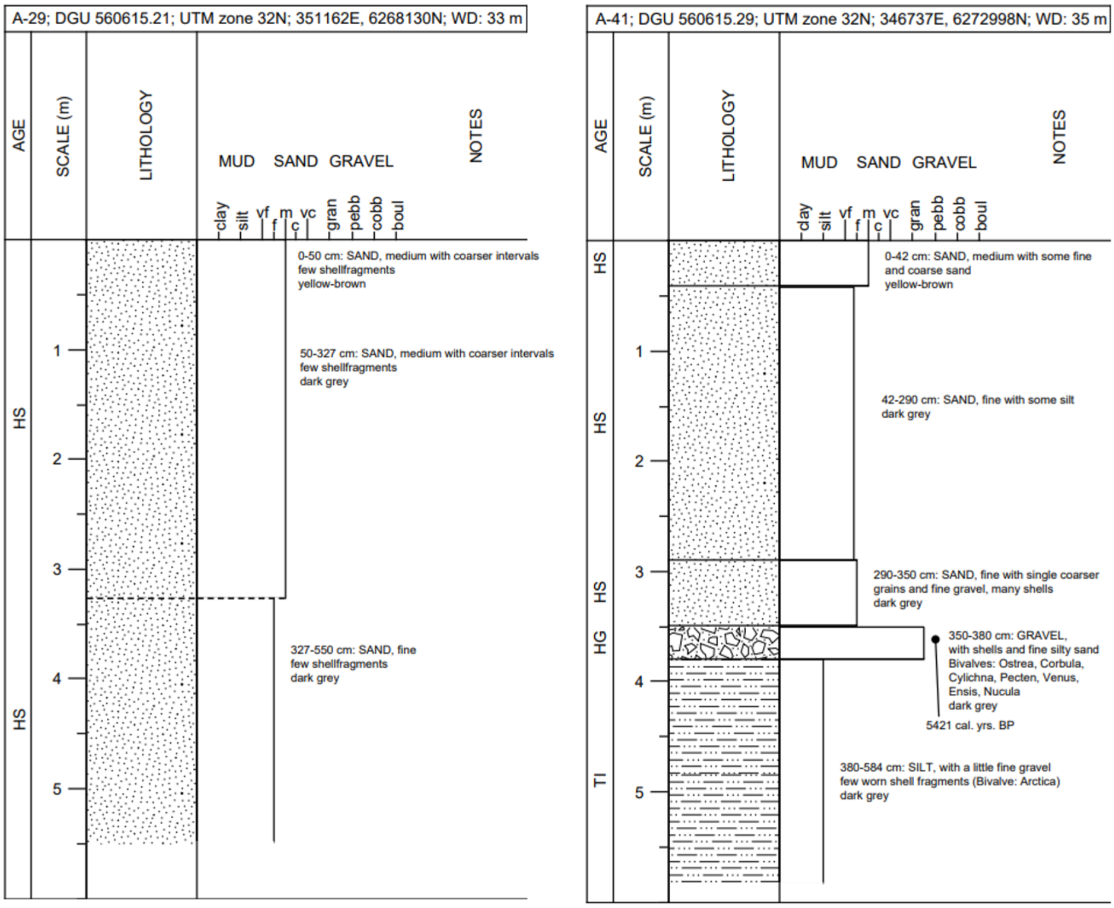

Figure 7.12. Examples of core logs of vibrocore A-29 (southern central sand bar) and A-41 (marginal western part of sand bar) from Area A (see Appendix D2 for log legend).

Table 7-1. Radiocarbon dating results on shell material from base of sand bar unit, Area A and B.

Core no.	X (UTM 32N)	Y (UTM 32N)	Lab. No.	Species	Depth below core top (m)	Age (14-years BP)[1]	Cal. Age (years BP)[2]
A-40	348191	6273164	Beta-639827	*Littorina littorea*	4.7	8920 ± 30	9586
A-41	346737	6272998	Beta-639828	*Acanthocardium echinatum*	3.6	5100 ± 30	5421
A-50	348247	6277660	Beta-639829	*Ostrea edulis*	3.9	4330 ± 30	4467
B-11	334006	6275959	Beta-639825	*Spisula subtruncata*	3.2	4130 ± 30	4205
B-16	335874	6274506	Beta-639826	*Aporrhais pespelicani*	5.0	6840 ± 30	7307

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

7.8 Grain size analysis results

Results of grain size analysis are shown in Appendix D4, with sieve analysis size fractions, size classes, moment measures (Folk and Wards), moment statistics, and grain size distribution histograms and cumulative curve given for each sample. Figure 7.13 shows summary plots of derived grain size statistics (sorting, uniformity coefficient, skewness) for all samples in Area A (n=117).

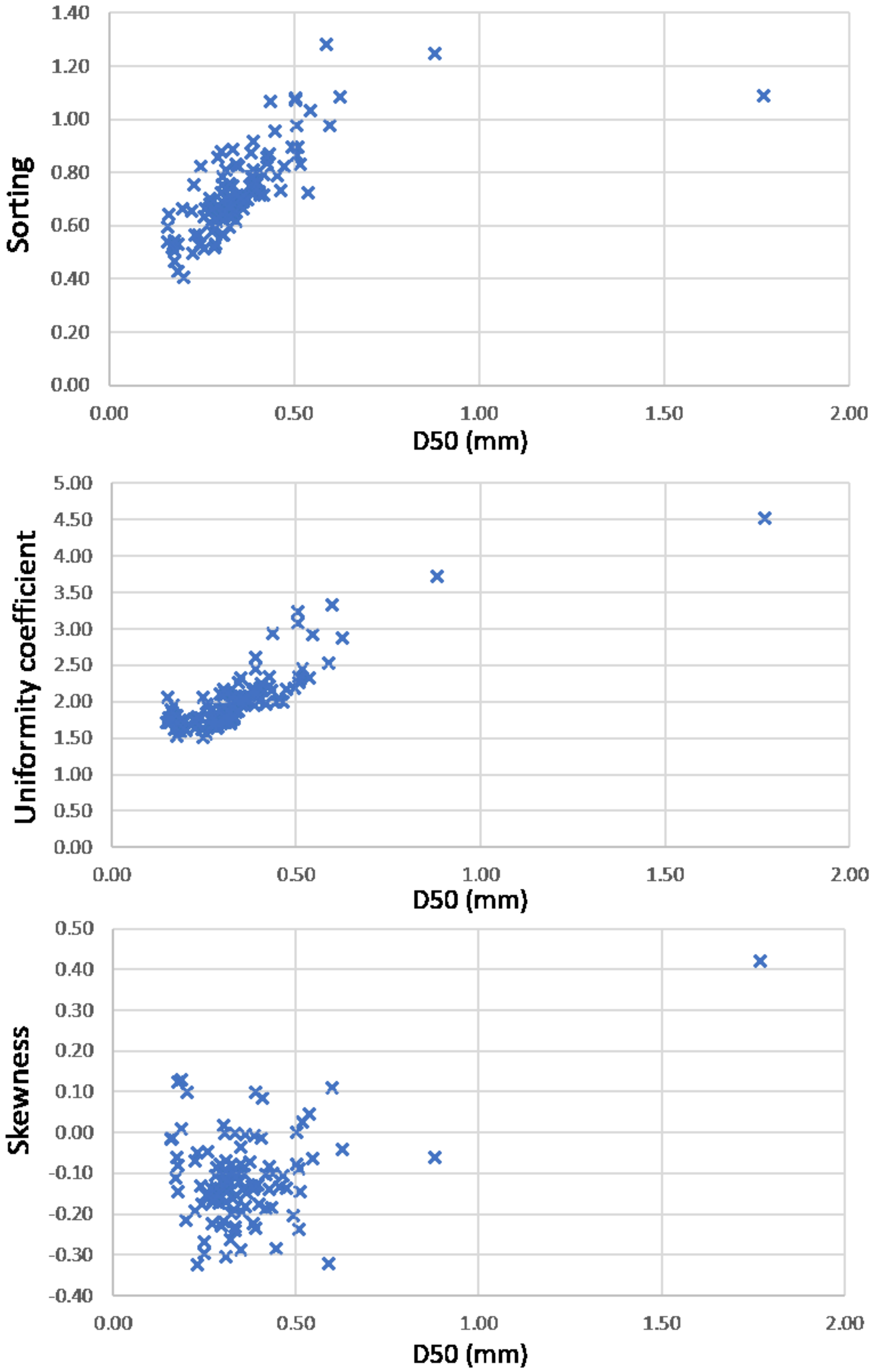

Figure 7.13. Plots of sorting, uniformity coefficient and skewness versus grain size median (D50) for samples in Area A (n=117).

The statistical value D50 representing the sieve size (in mm) allowing 50% of the sample to pass through, has been used as a general measure of the average grain size determined for each sample. Sorting is an expression of the standard deviation of grain size distribution for each sample (measured in ϕ), and the Uniformity coefficient is a measure of the degree of grain size uniformity. Skewness describes the asymmetry of the frequency curve.

Grain size medians (D50) are generally in the range 0.2-0.5 mm, but samples from marginal parts of Area A, and from deeper levels of the sand bank, appear to be more fine-grained. Sorting is mostly in the range 0.4-1.0, corresponding to moderately well sorted material. Uniformity coefficients are mostly in the range 1.5-3.0 corresponding to a relatively uniformly graded composition. Skewness is typically in the range -0.4-0.2, indicating mostly coarsely skewed material.

A consistent grain size trend is observed with typically medium-grained sand (D50 = 0.2-0.6 mm) found in the uppermost 3-5 m of the cores, and with more fine-grained sand (D50 = 0.2 -0.063 mm) found at deeper levels. This is shown in Figure 7.14, where the subbottom transition depth (down core) from medium to fine-grained sand, based on comparison with sediment core log description and grain size analyses, has been plotted for each core site. The transition from medium to more fine-grained sand appears to take place at about 325-400 cm core depth in the southern part of Area A and at about 400-600 cm in the northern part of Area A. Cores taken at marginal sites of the sand bank in Area A with only a thin uppermost sand layer (0-2 m), are typically dominated by fine-grained sand with D50 < 0.2.

Apart from the general down-core trend in grain size, grain sizes at many core sites are observed to vary in few dm thick intervals, probably representing deposition from migrating sand waves superimposed on the large sand bank structures, as observed on the present seabed surface.

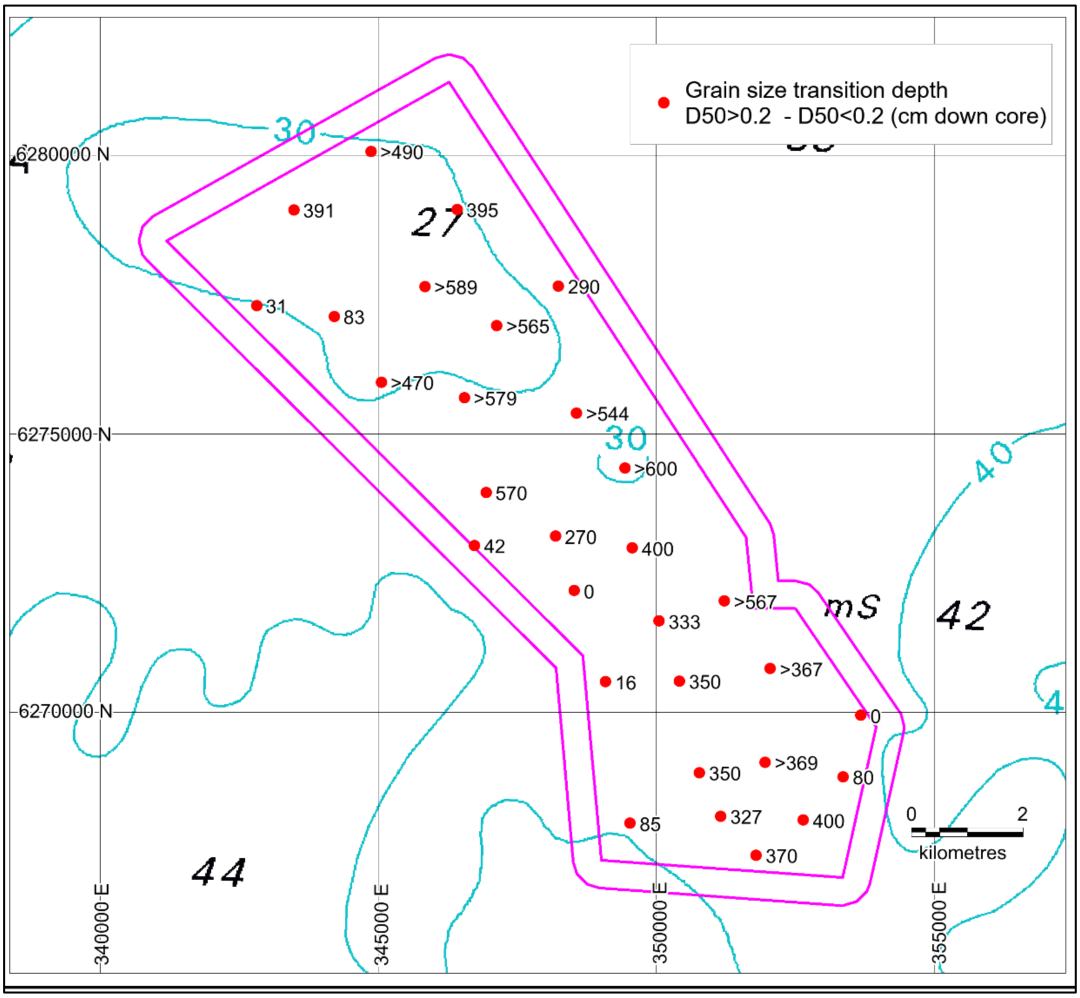

Figure 7.14. Grain size transition subbottom depth (in cm from core top) from a more coarse-grained upper part (D50>0.2), to a more fine-grained lower part (D50<0.2) as observed in vibrocores.

8. Area A resource mapping

The sand resource volume has been mapped by a combination of seismic data interpretation and information on sand resource composition from vibrocores.

The resource maximum thickness distribution was mapped by seismic interpretation (tracing) of the base of the sand bar and the seabed reflector, recording the two-way travel time (TWTT) to the respective surfaces. Assuming a constant sound velocity of 1600 m/s of the sand bank unit, the total sand bank thickness was calculated along each seismic line as:

Thickness (Z) = $(TWTT_{base\ sand} - TWTT_{seabed}) * Vs/2$ (with sound velocity Vs = 1600 m/s)

The sand bank thickness (z) data was exported as x,y,z values and gridded in Mapinfo Vertical Mapper with Natural Neighbor interpolation. The gridded data were plotted in GIS with colour scale and contour lines showing the mapped thickness distribution (Figure 8.1, Appendix A7).

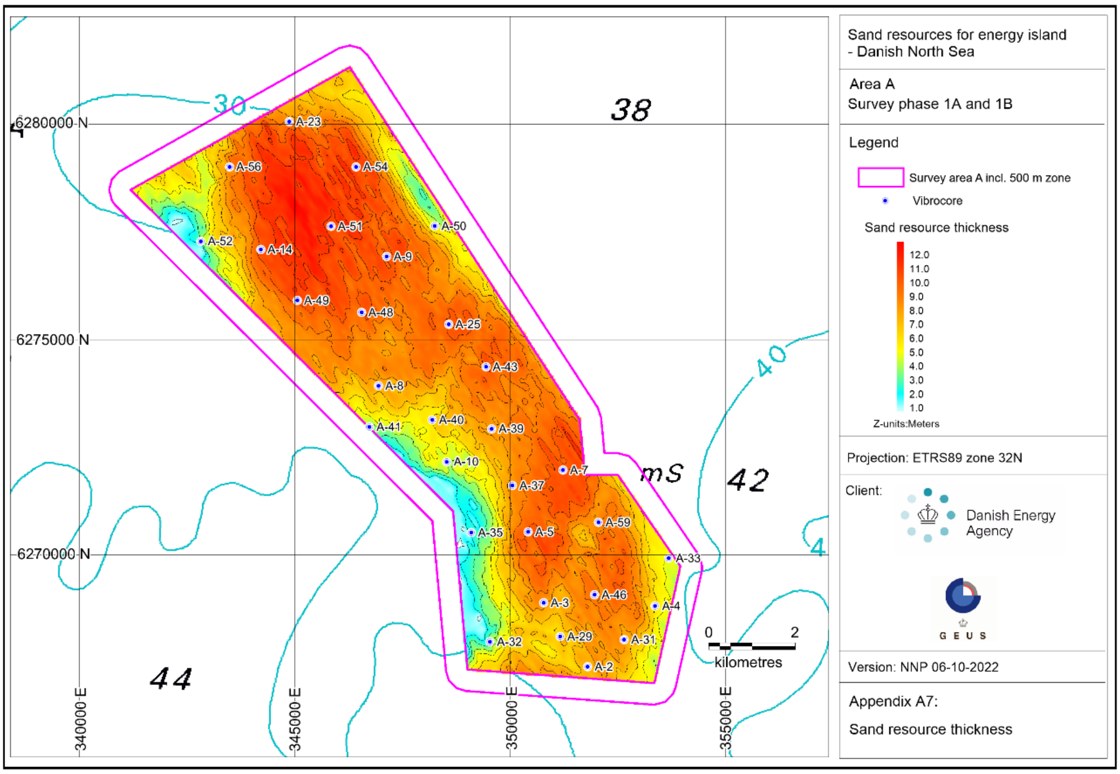

Figure 8.1. Mapped maximum resource thickness based on seismic mapping of the base of the sand bank unit. See larger version in Appendix A7.

Vibrocore description and grain size analyses verify that it is only the upper 3-5 m of the sandbank that contain sand of the desired grain size composition. Moreover, vibrocore data also pinpoint that the marginal parts of the sandbank, with thinner sand thickness, contain only fine-grained sand, typically with D50<0.2 mm. Based on this information, the areal extent of the Net sand resource in Area A was delineated (Figure 8.2, Appendix A8) and the total net resource volume was calculated (Table 8-1), taking the conservative assumption that about 3 m of sand within Area A can be used for sand dredging.

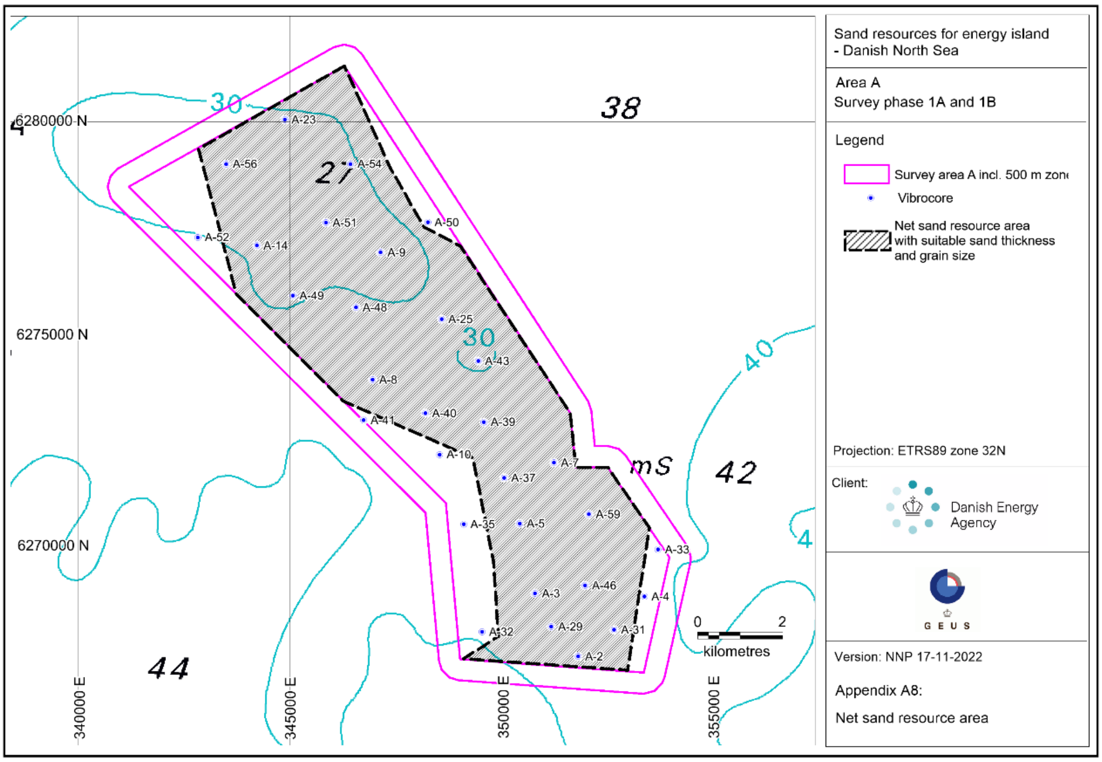

Figure 8.2. Extent of Net sand resource area within survey Area A. See larger version in Appendix A8.

Table 8-1. Estimated volumes of total sand amount and Net resource sand.

Area A	Area (km2)	Thickness (m)	Volume (million m3)
Total sand amount	69.4	0-12	450
Net sand resource	57.4	3	172

9. Area B - survey results

9.1 Survey lines

The geophysical survey in Area B was conducted along 77 NNW-SSE orientated survey lines with 100 m spacing (Figure 9.1, Appendix B1). Hereby full-coverage side scan sonar and multibeam depth mapping of the seabed surface were achieved.

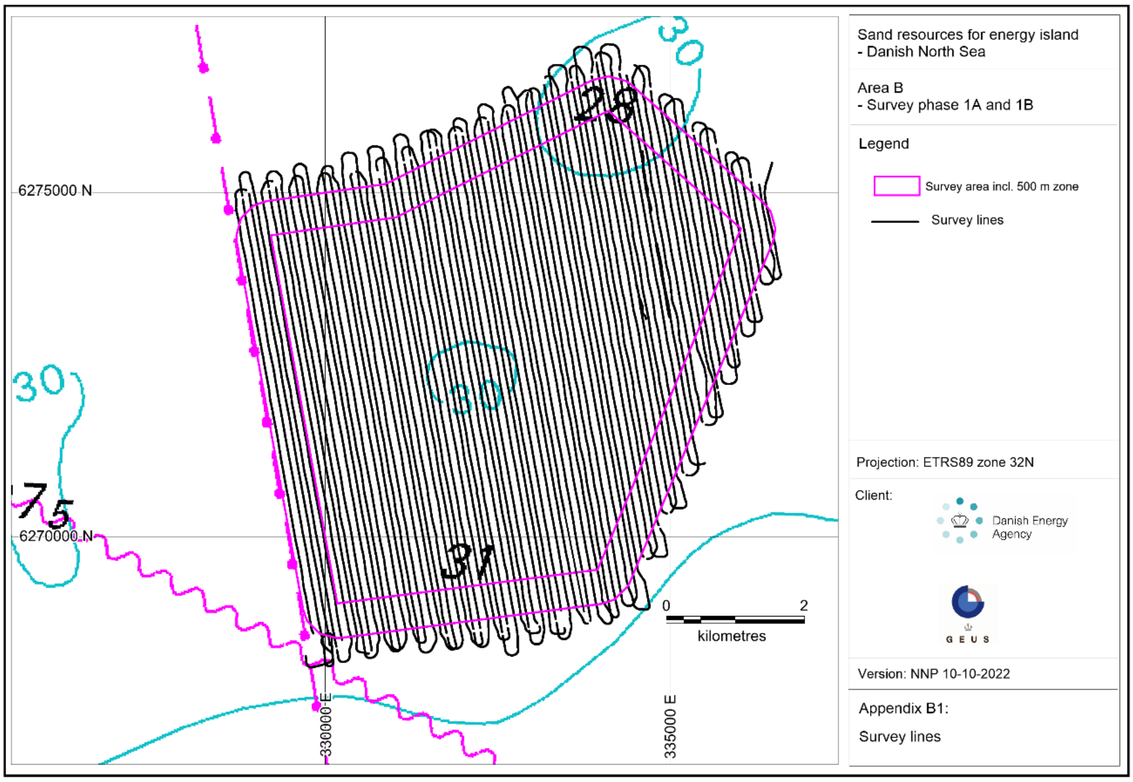

Figure 9.1. Surveyed lines in Area B. See larger version in Appendix B1.

9.2 Bathymetry

On basis of multibeam data, a full-coverage 5 m grid bathymetric map of Area B was constructed and presented in GIS (Figure 9.2, Appendix B2). Depths are in the range 30-43 m (DVR90). The shallowest depths of c. 30 m are seen in the central part of the survey area and the deepest of 42-43 m are found along the northern margin.

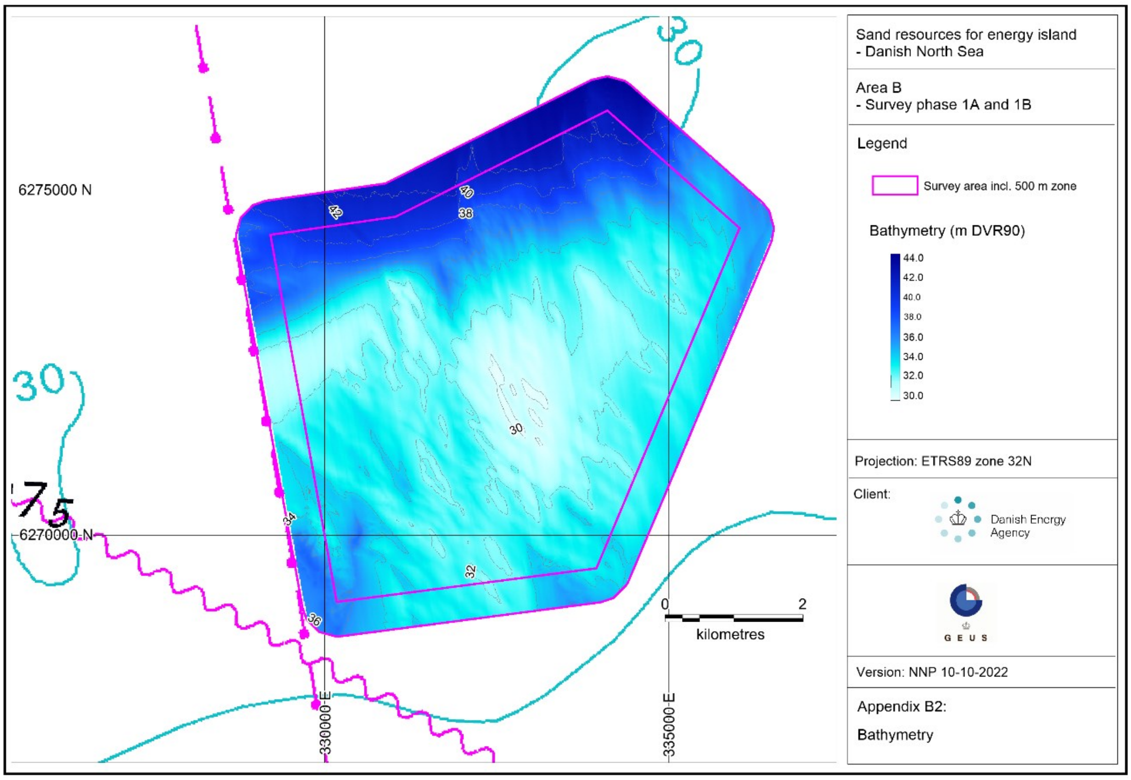

Figure 9.2. Mapped bathymetry in Area B. See larger version in Appendix B2.

9.3 Side scan sonar mosaic

The side scan sonar mosaic map shows dominantly low reflective (light colour) sandy seabed (Figure 9.3, Appendix B3Figure 7.3). High reflective areas are however seen in the south-western part, as well as smaller areas in the southern part where the sand bank appears to be thin or absent. Based on core top description of vibrocores located in the high reflective areas, the seabed substrate type appears to be gravelly sand. Based on seismic data interpretation, it is likely that late glacial fine-grained deposits are exposed at the seabed in the southwestern corner of the area.

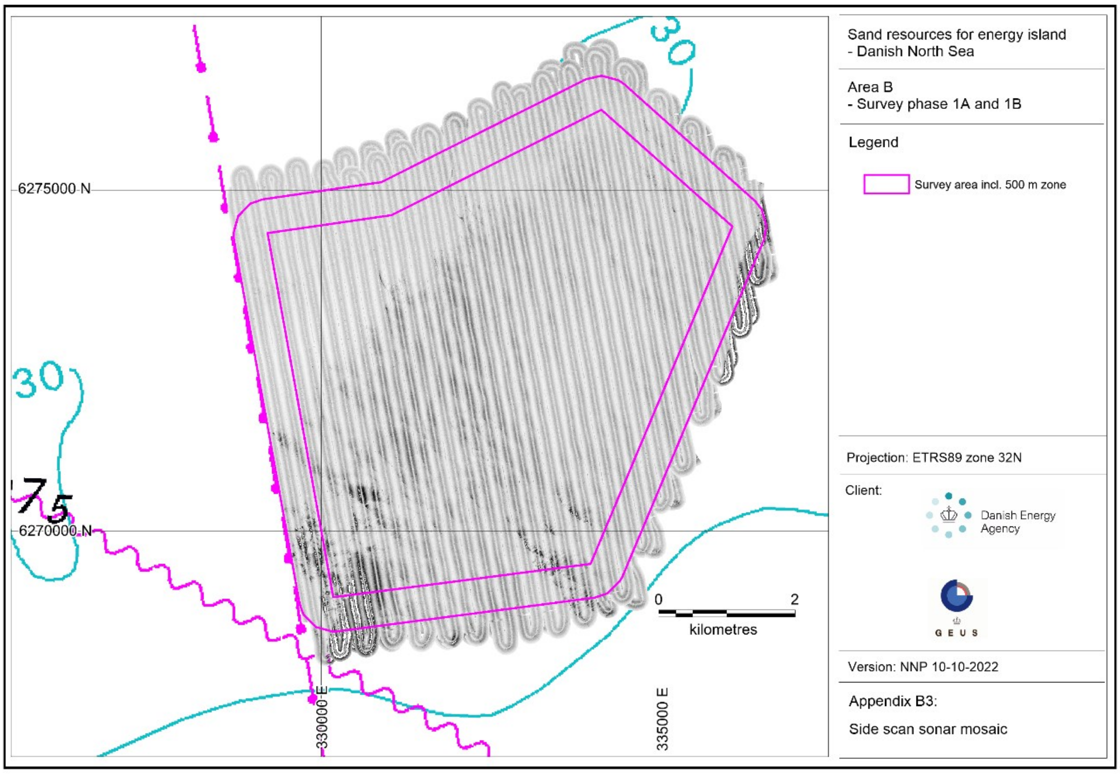

Figure 9.3. Side scan sonar mosaic of Area B. See larger version in Appendix B3.

9.4 Substrate types

The seabed substrate types have been mapped out, based on side scan sonar data and ground truth verification through vibrocore top samples as well as archive data from 2019 habitat mapping over the area (GEUS Rep. 2021-25). The division follows the substrate classes according to DEPA requirements (see Section 7.4).

Area B is dominated by sandy substrate type 1b, with subordinate substrate type 2 (sand and gravel) observed mainly in the southwestern corner of the area (Figure 9.4, Appendix B4). Sand waves and trawl traces are seen over most of the area.

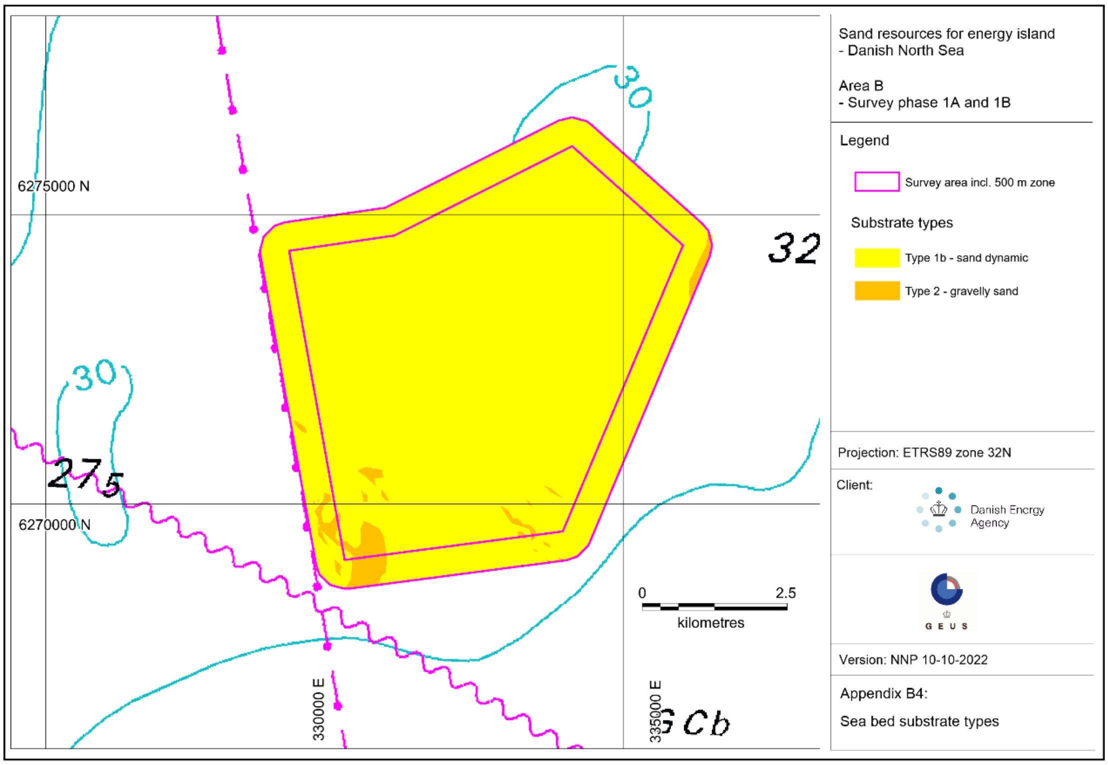

Figure 9.4. Substrate types in Area B. See larger version in Appendix B4.

9.5 Dynamic bed forms and traces of human activity

Sand wave bedforms occur over almost all parts of Area B, apart from the deeper lower flank of the sand bank structure in the northwestern part of the area (Figure 9.5, Figure 9.6, Appendix B5). The sand wave crests are undulating and in general orientated NW-SE. The sand waves appear to be up to a few meters high and distances between crests are c. 50-100 m.

Trawl traces are evident almost all over the sand bank structure (Figure 9.7), but in general they appear to be less frequent over the northwestern deeper part. The traces vary between distinct features (relatively newly formed) and others who appear to be more blurred (of older age).

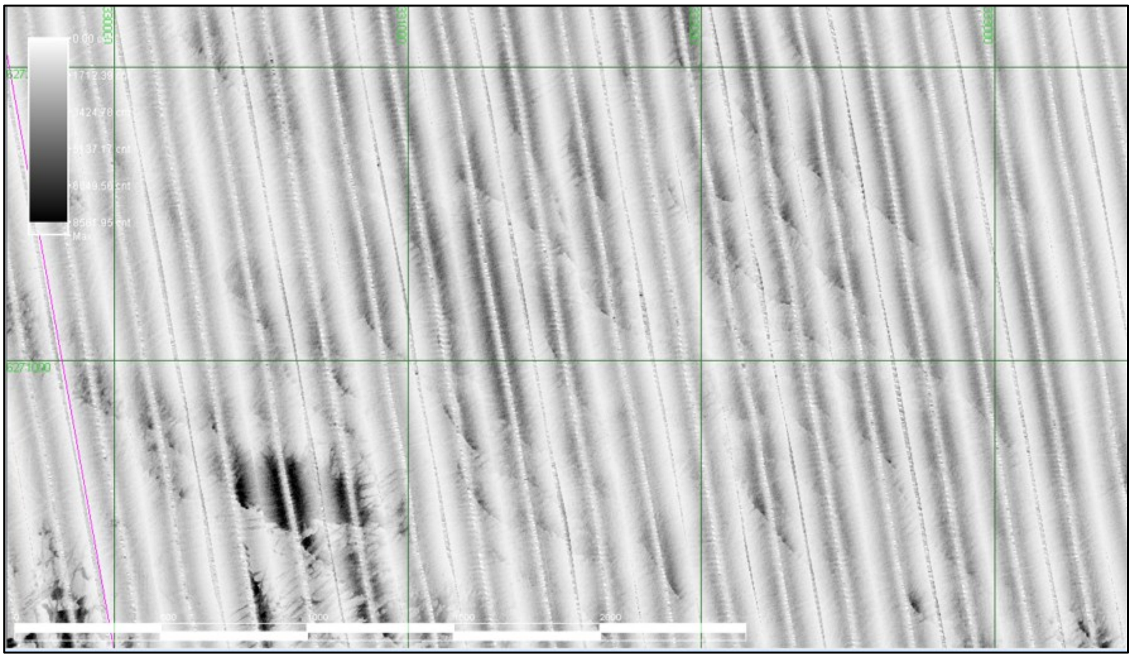

Figure 9.5. Side scan sonar mosaic of the southwestern part of Area B, characterised by substrate type 1b (light colour: sand waves) with smaller areas of by substrate type 2 (dark colour: gravelly sand). Divisions on scale bar is 100 m.

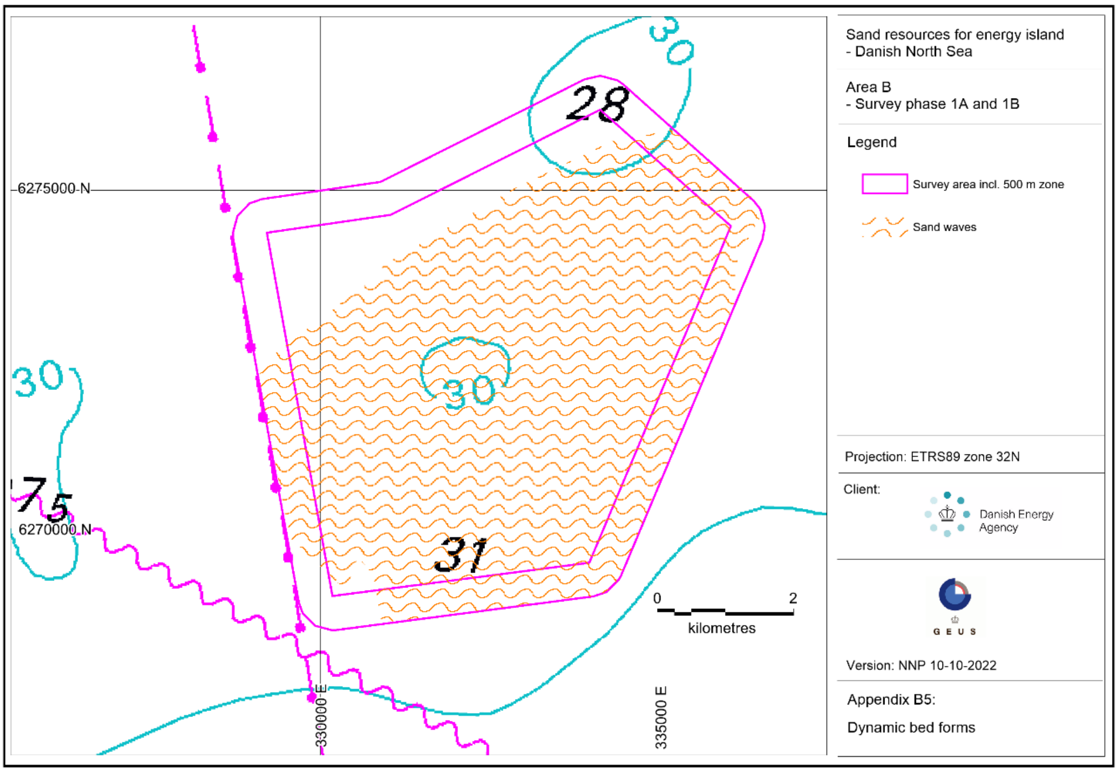

Figure 9.6. Sand wave dynamic bed forms in Area B. See larger version in Appendix B5.

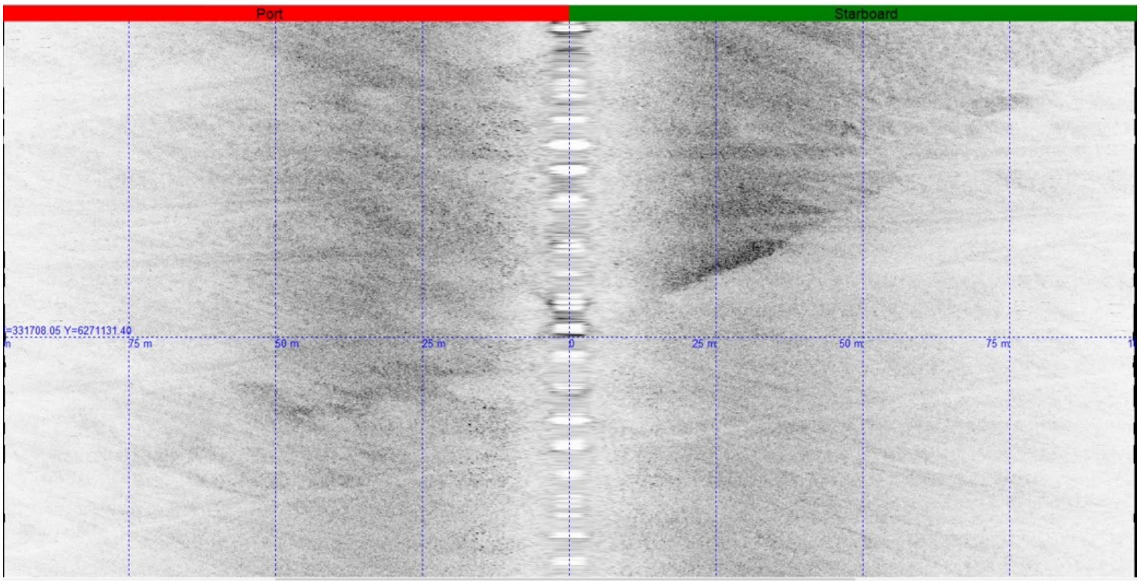

Figure 9.7. Side scan sonar single trace (200 m width) showing multiple trawl traces crossing a sand wave crest.

9.6 Seismic profiles

In general, the south-north orientated seismic profiles show quite similar seismic units. Examples of interpreted Sparker and Innomar profiles are given in Figure 9.8 and Figure 9.9, and Appendix B10 shows six representative Sparker and Innomar profiles with interpretation of the base of the sand bar unit (potential resource).

The seismic profiling reveals a strong slightly northward inclined reflector 0-14 m below seabed corresponding to the base of the Holocene marine sand bar unit. The Holocene unit appears to be divided into two subunits consisting of an older unit occurring in the southern half of the area, and a younger unit, superimposed on the older one and forming the main sand bank unit building out towards the north. The internal structure of the main sand bar unit is dominated by northward inclined stratification, representing clinoforms of the northward migration of the sand bar. A fine parallel stratified unit occurs below the base of the Holocene marine unit in the central to northern part of the area. This unit is tentatively assigned a late glacial origin. The base of the late glacial unit is marked by a strong reflector forming the boundary to underlying more crudely stratified units. These may represent in-fill of an older glacial valley.

Results of the vibrocore campaigns were used to confirm the seismic interpretation with respect to verifying the base of the sand bar unit, and to characterise sediment composition of sub-sand units.

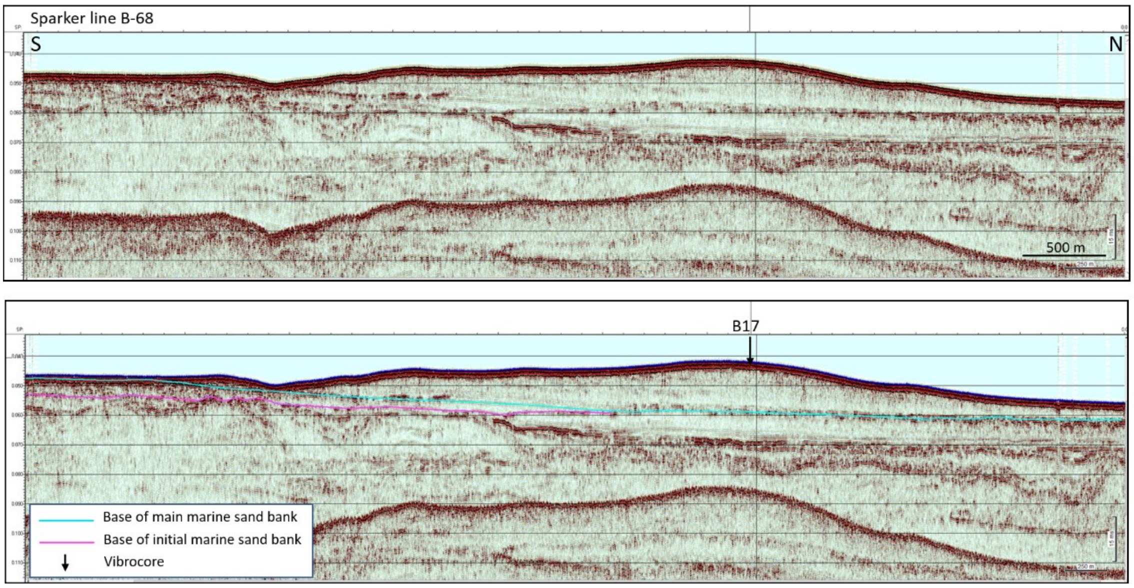

Figure 9.8. Example of sparker seismic profile (line B-68) from S to N, shown without interpretation (top) and with interpretation. Blue line marks base of the main sand bar unit (resource). Vertical scale is given by horizontal lines with 10 ms spacing corresponding to c. 8 m. Position of vibrocore B-17 is shown and the profile are shown in larger scale in Appendix B10.

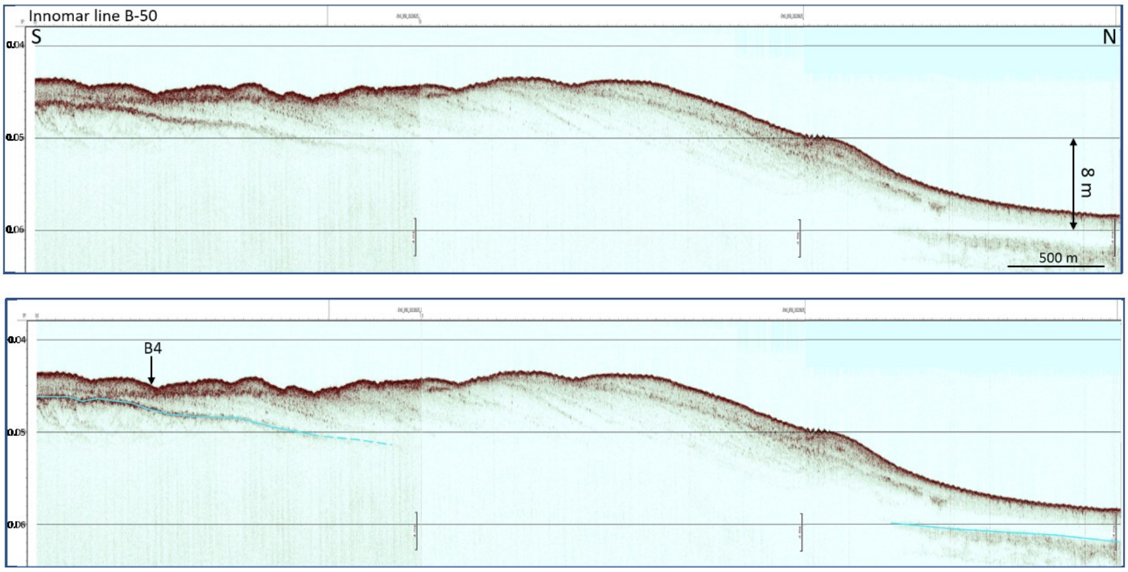

Figure 9.9. Innomar subbottom profile (line B-50) showing internal foreset structures in the main sand bank unit. Blue line indicates interpreted base of the main sand bar unit. Vertical scale is given by horizontal lines with 10 ms spacing corresponding to c. 8 m. Position of vibrocore B-4 is shown and the profile is shown in larger scale in Appendix B10.

9.7 Vibrocores

In total 15 vibrocores were retrieved within or immediately west of Area B (Figure 9.10Figure 7.11), with 4 cores taken during the first phase IA survey and 11 cores taken during the later phase IB survey, following the detailed seismic survey of the area . The core lengths (recovery) are varying between 3.5 m and 6.0 m (Appendix D1). Core descriptions and photos are shown in Appendix D2 and D3, and results of the grain size analyses performed are shown in Appendix D4.

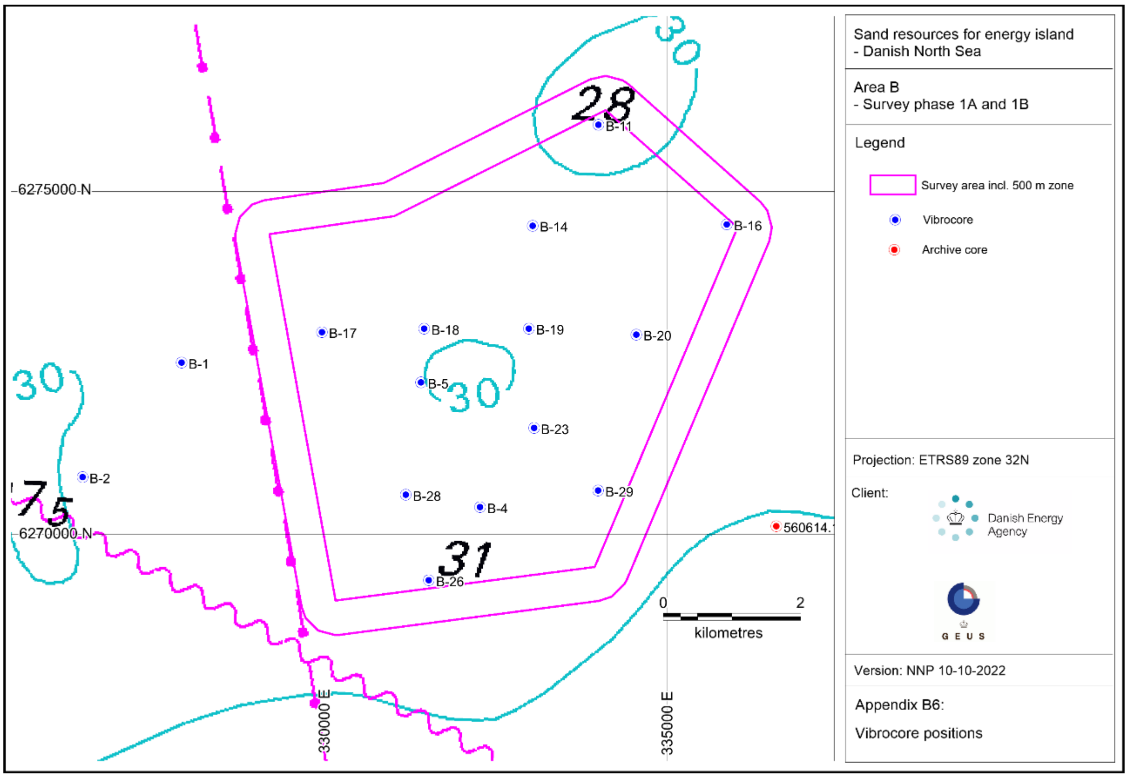

Figure 9.10. Vibrocore sites in survey Area B. See larger version in Appendix B6.

Core descriptions based on visual inspection of opened core sections confirm that the geophysically mapped main sand bar unit almost exclusively consist of marine sand, ranging from fine to coarse-grained. The upper 3-5 m appears to be dominated by medium grained sand, but below this level, more fine-grained sand is observed in several of the cores (B-18, B20, B-23). Single few cm thick black clay layers were observed in some cores (B-11, B-16, B-17, B18, B-20), and the base of the main sand bar unit has often a gravelly character (cores B-4, B-11, B-16, B-26, B-28, B-29). The older Holocene sand unit found in the southern part of the area, is in general dominated by fine-grained sand, but medium sand and thin gravelly sand layers also occur (cf. lower part of B-26). Fine stratified sand found in the lower part of northernmost core B-11, are possibly of late glacial age.

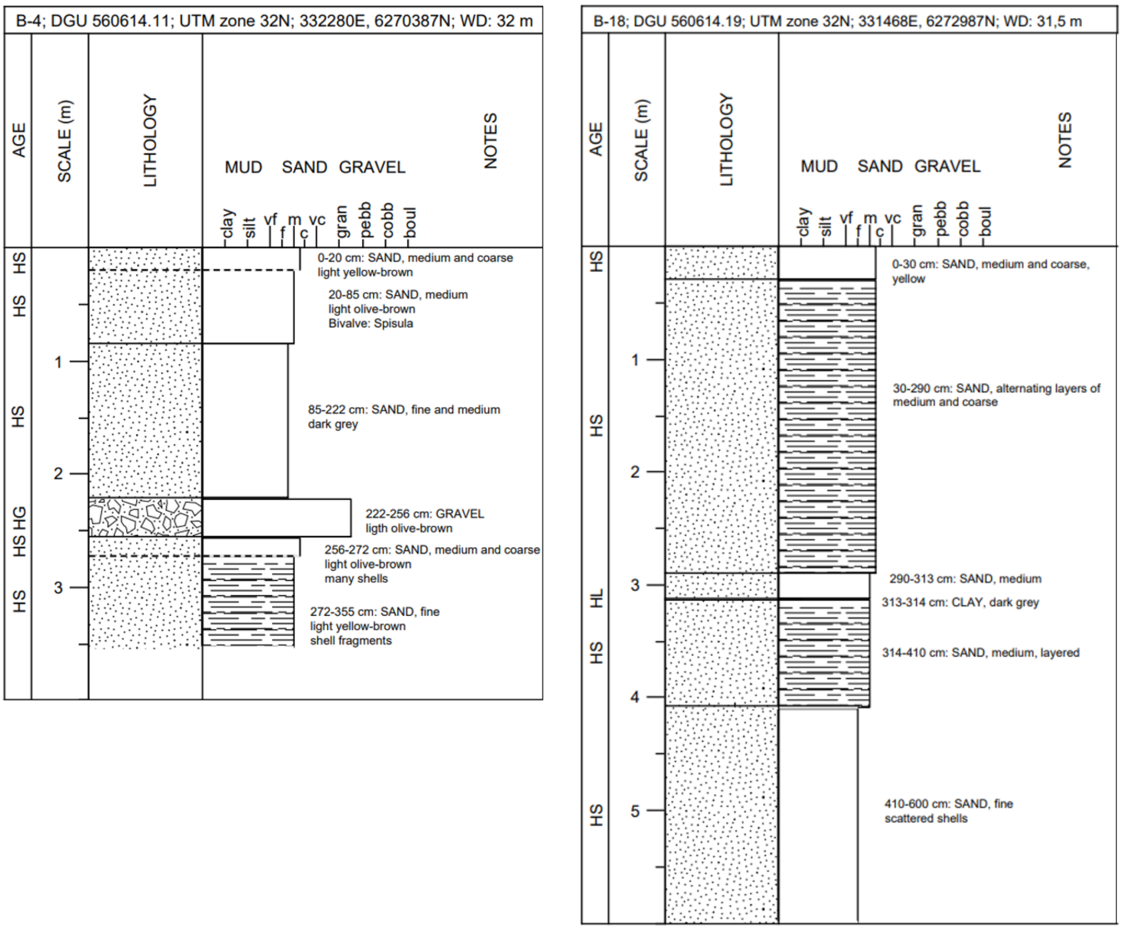

Figure 9.11. Example of vibrocore logs, Core B-4 and B-18, Area B (see Appendix D2 for log legend).

9.8 Grain size analysis results

Results of grain size analysis are shown in Appendix D4, with sieve analysis size fractions, size classes, moment measures, moment statistics, grain size distribution histograms and cumulative curve given for each sample (Folk and Ward, 1957). Figure 9.12 shows summary plots of derived grain size statistics (sorting, uniformity coefficient, skewness) for all samples in Area B (n=62).

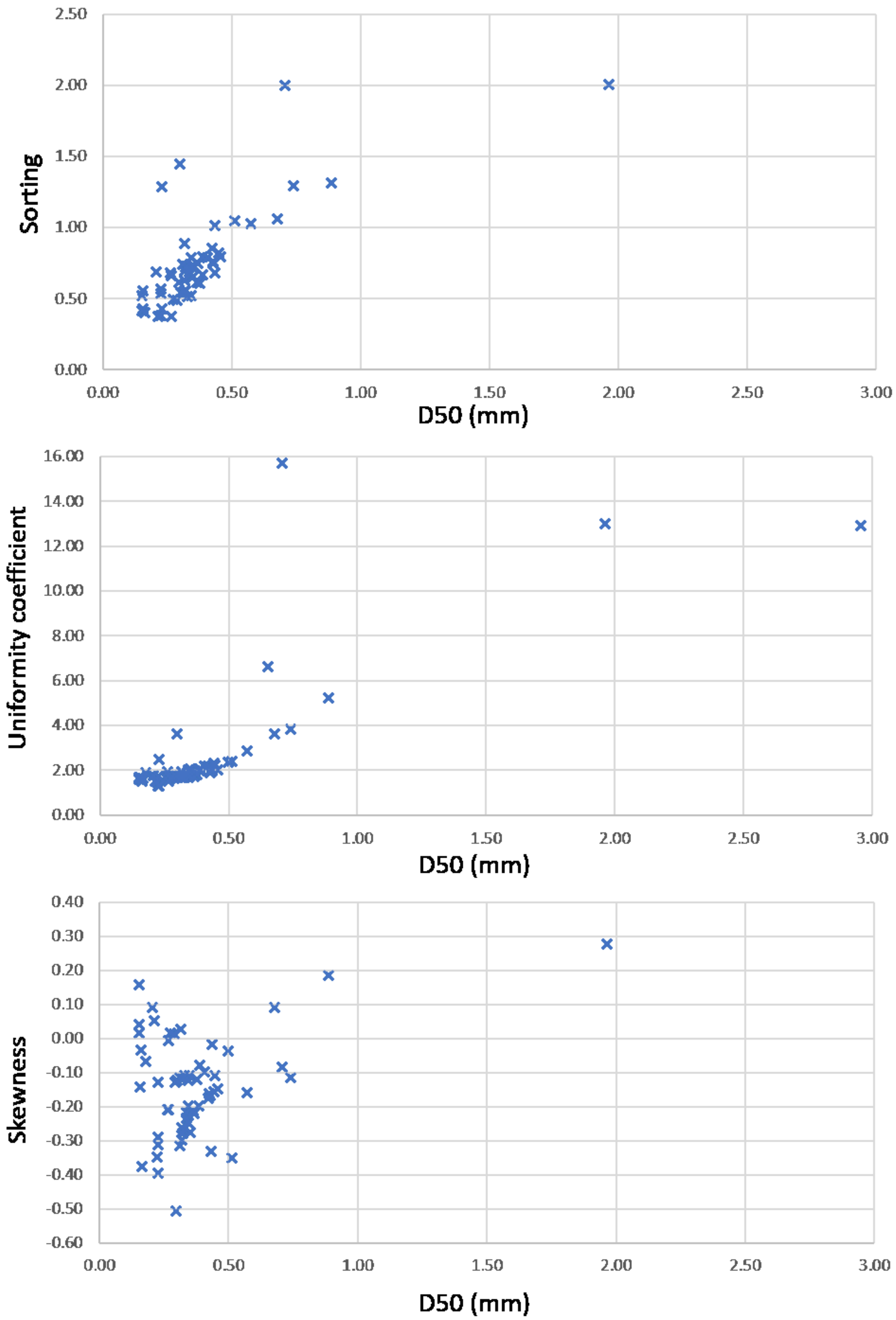

Figure 9.12. Plots of sorting, uniformity coefficient and skewness versus grain size median D50 for all samples in Area B (n=62).

The statistical value D50 representing the sieve size (in mm) allowing 50% of the sample to pass through, has been used as a general measure of the sample average grain size.

Grain size medians (D50) are generally in the range 0.2-0.5 mm, but samples from marginal parts of the area, or deeper levels of the sand bank, appear to be more fine-grained. Sorting (measured in ϕ), is mostly in the range 0.4-0.9, corresponding to moderately well sorted material. Uniformity coefficients are mostly in the range 1.5-3.0 corresponding to a relatively uniformly graded composition. Skewness is typically in the range -0.4-0.2, indicating mostly coarsely skewed material.

A consistent grain size trend is observed with typically medium-grained sand (D50 = 0.2-0.6 mm) found in the uppermost 3-5 m of the cores, and with more fine-grained sand (D50 = 0.2 -0.063 mm) found at deeper levels. This is shown in Figure 9.13, where the subbottom transition depth from medium to more fine-grained sand has been plotted for each core site. The transition from medium to more fine-grained sand appears to take place at > 400 cm core depth in the central part of the Area and at about 200-300 cm in the southern part of the area, where the thickness of the main sand bar unit thins.

Apart from the general down-core trend in grain size, grain sizes at many core sites are observed to vary in few dm thick intervals, probably representing deposition from migrating sand waves superimposed on the large sand bank structure, as observed on the present seabed surface.

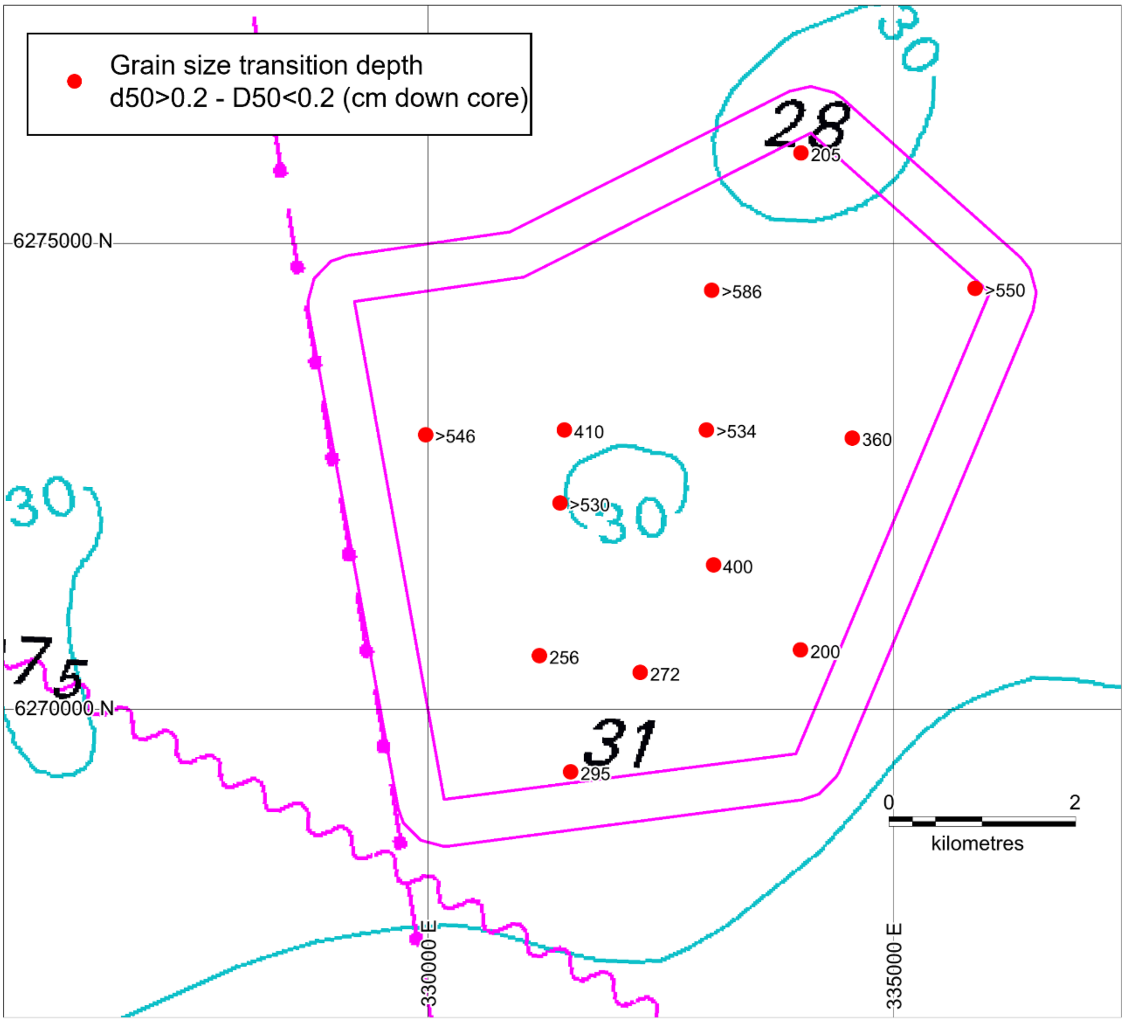

Figure 9.13. Grain size transition subbottom depth (in cm) from a more coarse-grained upper part (D50>0.2) to a more fine-grained lower part (D50<0.2) as observed in vibrocores.

10. Area B resource mapping

The resource volume has been mapped by a combination of seismic data interpretation and information on resource composition from vibrocores.

The resource maximum thickness distribution was mapped by seismic interpretation (tracing) of the base of the main sand bar unit and the seabed reflector, recording the two-way travel time (TWTT) to the respective surfaces. Assuming a constant sound velocity of 1600 m/s of the sand bank unit, the total resource thickness was calculated along each seismic line as:

Thickness (Z) = ($TWTT_{base\ sand} - TWTT_{seabed}$) * Vs/2 (with sound velocity Vs = 1600 m/s)

The resource thickness (z) data was exported as x,y,z values and gridded in Mapinfo Vertical Mapper with Natural Neighbor interpolation. The gridded data was plotted in GIS with colour scale and contour lines showing the mapped thickness distribution (Figure 10.1).

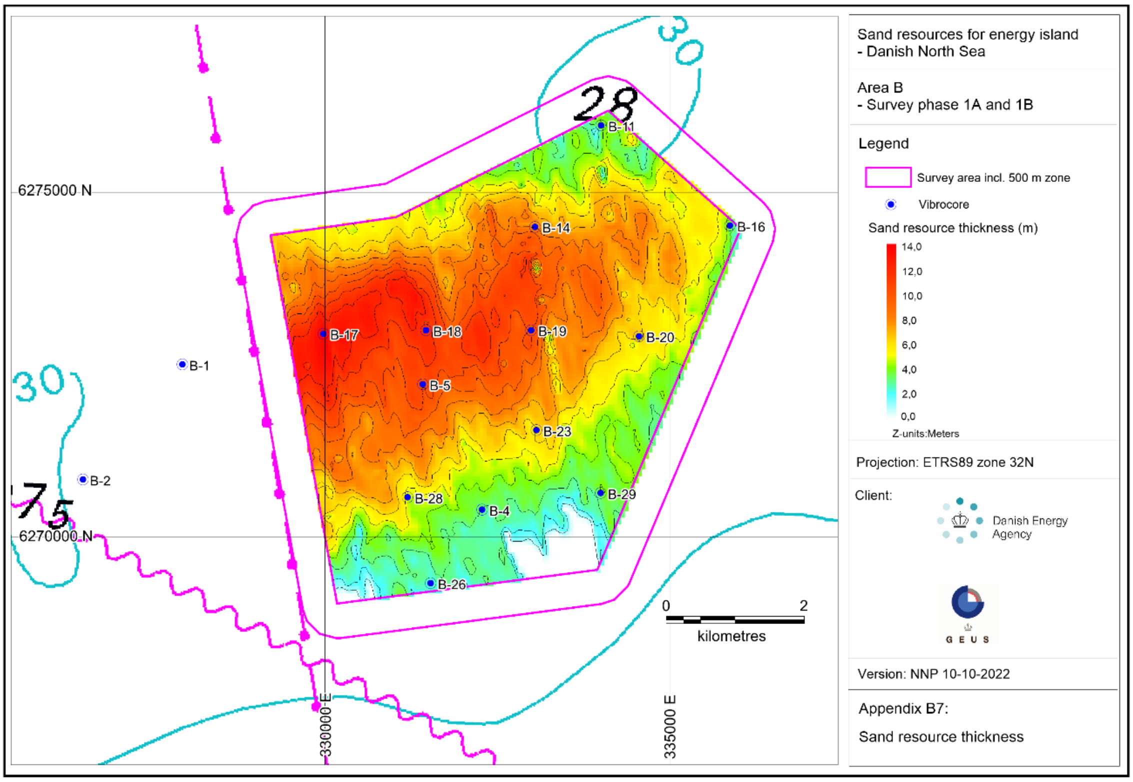

Figure 10.1. Mapped maximum resource thickness based on seismic mapping of the base of the main sand bank unit. See larger version in Appendix B7.

Vibrocore description and grain size analyses verify that the upper 3-5 m of the main sandbank contain sand of the desired grain size composition. The thinner part of the sandbank appears to contain medium grained sand to a subbottom depth of about 2-3 m. Based on the seismic mapping and vibrocore grain size data, the areal extent of the Net sand resource in Area A was delineated (Figure 10.2) and the total net resource volume have been calculated

(Table 10-1) taking the conservative assumption that about 3 m of sand within the area can be used for sand dredging.

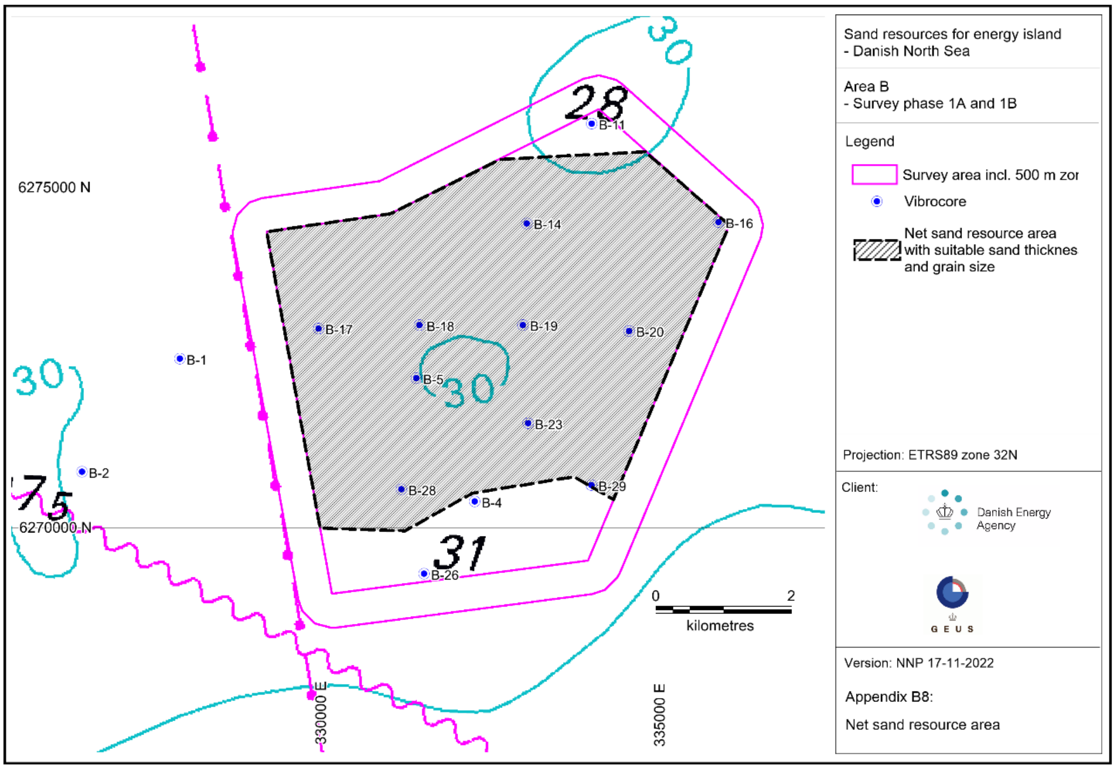

Figure 10.2. Extent of Net sand resource area within survey Area B. See larger version in Appendix B8.

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Table 10-1. Estimated volumes of total sand amount and Net sand resource.

Area B	Area (km2)	Thickness (m)	Volume (million m3)
Total sand amount	31.9	0-14	190
Net sand resource	26.8	3	80

11. Area C - survey results

11 vibrocores were retrieved from Area C during the phase IA vibrocoring campaign (Figure 11.1). The core sites were chosen based on seismic interpretation of archive seismic lines during the initial project screening phase (GEUS Rep. 2022-4). A seismic section example is shown in Figure 11.2. The aim of the coring was mainly to investigate the grain size composition of the glacial-late glacial units occurring closely below the seabed in the area. Focus was primarily on locating potential gravelly resources.

The vibrocoring campaign in general confirmed the occurrence of relatively thin (0.1-3.0 m) marine Holocene deposits dominated by fine-medium grained sand. A few cm thick gravelly lag deposit separates the top Holocene unit from underlying late glacial clay, silt and fine sand deposits, at places containing abundant plant fragments and reworked interglacial shell fragments (Figure 11.3).

As coring results from Area C were not able to locate suitable sand or gravel deposits for energy island construction, the decision was taken not to proceed with further survey investigations of Area C in the following phase IB campaign.

Coring positions, logs, photos, and grain size analysis results are shown Appendix D1-D4.

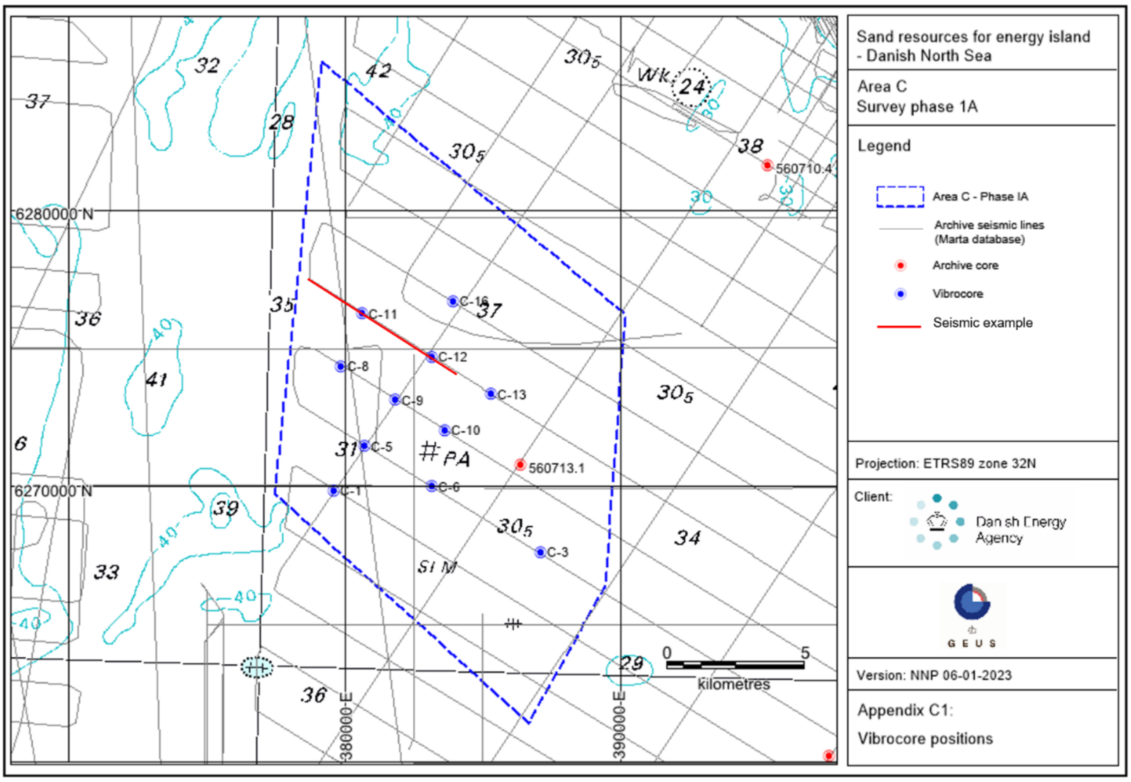

Figure 11.1. Survey Area C with position of vibrocores, archive seismic lines and cores, and line extent of seismic example. See larger version in Appendix C1.

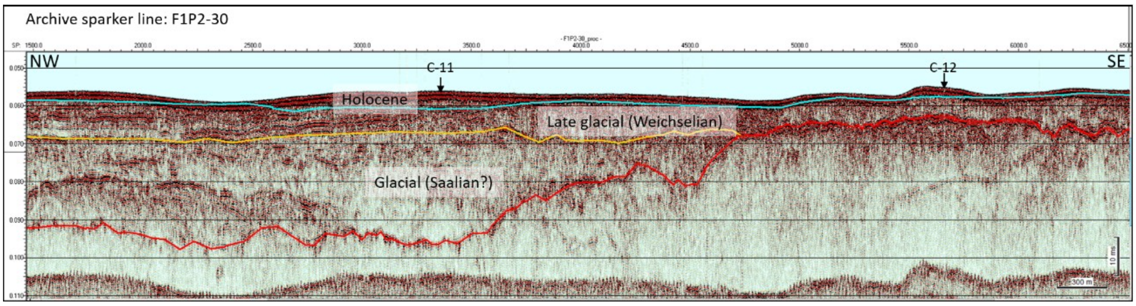

Figure 11.2. Example of sparker seismic line with interpretation of main stratigraphic units: Glacial, Late glacial, and Holocene. Position of cores C-11 and C-12 are marked, and the extension of the profile is shown in Figure 11.1.

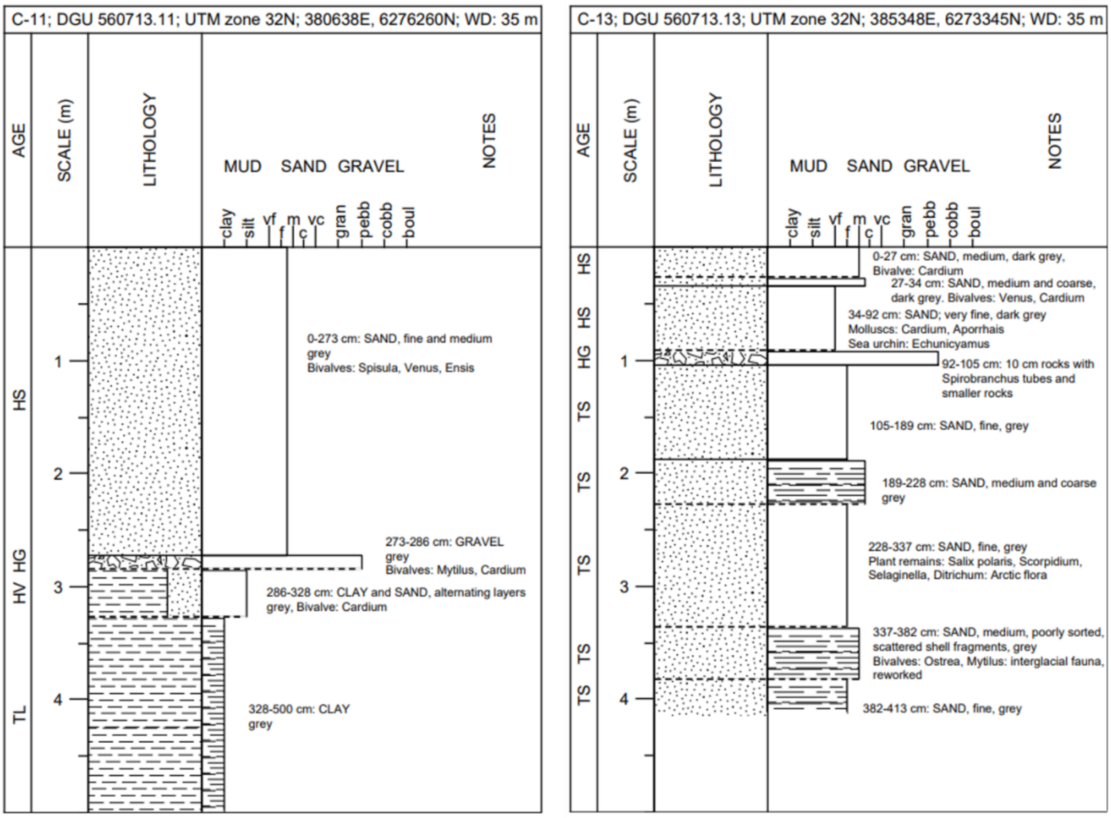

Figure 11.3. Example of vibrocore logs (cores C-11 and C-13) confirming a thin Holocene fine-medium grained sand unit (HS) with a thin gravel layer (HG) at the base superimposed on late glacial clay (TL) and fine sand (TS).

12. Total sand resources

Large sand resources which meet the given sand quality requirement specification have been mapped out in the main parts of detail survey Area A and Area B. In both areas, medium to coarse-grained sand of suitable composition is found in the upper c. 3 meters of the sand bank units. The total resources represented by the upper 3 m sand cover in Area A and Area B are estimated to about 252 million m^3 (Table 12-1). This figure is more than 5 times larger than the estimated maximum sand/gravel resource consumption of 45 million m^3 for the North Sea Energy Island construction.

The investigations have been able to confirm that suitable sand resources are found close to the planned North Sea Energy Island site. Based on a simple distance relationship, resource Area A is considered to be a potential primary sand extraction area, and resource Area B a good alternative area. Due to poor resource quality, Area C disqualify as a potential resource area.

Table 12-1. Summary of Net sand resource inventory of survey Area A and Area B.

	Area (km2)	Distance from centre of planned energy island	Net sand res-source volume (million m3)
Area A	57,4	4-18 km	172
Area B	26,8	16-22 km	80
Total	84,2		252

13. References

Folk, R.L. and Ward, W.C. 1957. A Study in the Significance of Grain-Size Parameters. Journal of Sedimentary Petrology, 27, 3-26.

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GEUS Rep. 2021-25. Marin habitatkortlægning I Nordsøen 2019-2020 – Østlige Nordsøen og Doggerbanke Tail End. Udført for Miljøstyrelsen.

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