SN2021_015 - Geophysical Survey For Offshore Wind Farms And Energy Island BORNHOLM I

Title	**Geophysical Survey Report BHI - Work Package A**
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4.0	10/03/2023	Last Comments to be addressed on some figures	IMD		MCO
Revision	Date	Description of Revision	Author	Checked	Approved

REVISION HISTORY

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The table on this page should be used to explain the reason for the revision and what has changed since the previous revision.

Rev.	Date	Reason for revision	Changes from previous version
1.0	01/07/2022	First draft	N/A
2.0	07/10/2022	Addition of extension areas and client comments	Addition of extension areas and updated figures and text
2.1	23/11/2022	Formatting corrections	Formatting corrections
3.0	03/01/2023	Client comments	Corrections made to text, figures and formatting
4.0	10/03/2023	Client's comment	Lasts comments on section 8.6 and 8.4 figures to be addressed.

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LISTS OF TABLES AND FIGURES

DEFINITIONS AND ABBREVIATIONS

Throughout this document the abbreviations listed in Table 1 are used. Where abbreviations used in this document are not included in Table 1, it may be assumed that they are either equipment brand names or company names.

Table 1: Abbreviations used in this document

Abbreviation	Definition
2D	Two Dimensional
3D	Three Dimensional
AS	Analytical Signal
BHI	Bornholm I
BHII	Bornholm II
CPT	Cone Penetration Test
dB	Decibel
DGNSS	Differential Global Navigation Satellite System
DTM	Digital Terrain Model
ECR	Export Cable Route
EGN	Empirical Gain Normalisation
EPSG	European Petroleum Survey Group
ETRF2000	European Terrestrial Reference Frame 2000
ETRS89	European Terrestrial Reference System 1989
FMGT	Fledermaus Geocoder Toolbox
GIS	Geographic Information System
GOIV	Geo Ocean IV
GOV	Geo Ocean V
GRS80	Geodetic Reference System 1980
Hz	Hertz
IHO	International Hydrographic Organisation
INS	Inertial Navigation System
IOGP	International Association of Oil and Gas Producers
ITRF	International Terrestrial Reference Frame
ka BP	kilo annum [thousand years] Before Present
km	Kilometres
LAT	Lowest Astronomical Tide
LOA	Length Over All
m	Metres
m/s	Metres /Second
MAG	Magnetometer
MBES	Multibeam Echosounder
mE	Metres East
mN	Metres North
MRU	Motion Reference Unit
MSL	Mean Sea Level

Abbreviation	Definition
NMEA	National Maritime Electronics Association
nT	Nanotesla
QC	Quality Control
RES	Residual Magnetic Field
SBP	Sub Bottom Profiler
SEGY	Society of Exploration Geophysicists Y format
SIMOPS	Simultaneous Operations
SP	Shot Point
SSS	Side Scan Sonar
SVP	Sound Velocity Profile
THU	Total Horizontal Uncertainty
TPU	Total Propagated Uncertainty
TVU	Total Vertical Uncertainty
TWT	Two Way Time
UHR	Ultra-High Resolution
USBL	Ultra-Short Baseline
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance
WPA	Work Package A
WPB	Work Package B
ZDA	NMEA-0813 Date Time Message String (UTC, day, month, year, and local time zone offset)

1.1 PURPOSE OF DOCUMENT

This report details the results, achieved data quality and interpreted data products for the Geophysical Survey for Offshore Wind Farms and Energy Island Bornholm I (LOT 3) project.

2 EXECUTIVE SUMMARY

Geophysical Survey – BHI			
Survey dates	Original Scope	Start	28/07/2021
		End	27/11/2021
	Extended Scope	Start	23/03/2022
		End	17/05/2022
Equipment		Geophysical	Multibeam Echo Sounder (MBES), Side Scan Sonar (SSS), Magnetometer (MAG), Sub-Bottom Profiler (SBP), 2D Ultra-High Resolution seismic (2D UHR)
Coordinate system		Datum	ETRS89 (GRS80)
		Projection	UTM Zone 33 N (EPSG: 25833)
Bathymetry			
Depth		27.76 m to 46.23 m (40.04 m mean)	
Slope angles		Typical: <1°, maximum: >15°	
Site topography		Water depth varies moderately, with a gradual increase in water depth from east to west and from south to north across the Bornholm I site.	
Seabed surface: Geology			
The seabed surface geology is generally characterised by SAND and SILT. Widespread bands of fine to coarse GRAVEL extend east-west while in the eastern section of the site, seabed sediments comprise mainly SAND and SILT. Alternating bands of fine to coarse GRAVEL and SAND and a possible till matrix, extend across from the northern to the eastern section.			
Seabed surface: Morphology			
The north and east areas of the BHI site are heavily trawl scarred. Areas of boulder fields and scattered pitted areas are present along with erosional features that cross the southernmost area of that section. Ripples and mega ripples have been identified intermittently across the site. Erosional features cross the northern part of that section, and the southern area is punctuated with disturbed seabed zones. The southern section (Bornholm I S) is formed of boulder field areas interspersed by ripples in the southern tip. Pitted areas exist in the south-west of the BHI site.			
Seabed surface: Man-made features and site-specific hazards			
Wrecks		Eight wrecks found throughout BHI site	
Cables		Zero cables infrastructure identified. Three debris relate cable items identified One unknown linear object (possible cable)	
Pipelines		Baltic Pipe pipeline crosses NE part of BHI site	

Geophysical Survey – BHI	
Debris	939 total debris items
Related with fishing activity	24 items possibly associated with fishing activity
Seabed disturbance	17 seabed disturbances from jack-up platforms and fishing activities
Sub-seabed soil units	
Unit I	Organic-rich post-glacial marine clay. The unit is widely distributed in the western parts of the BHI area.
Unit II	Post glacial, seismically transparent unit. Likely a post glacial clay, deposited as channel fill.
Unit IIa/b	Laminated channel fill facies found sporadically across the BHI site. Unit IIa is a lacustrine laminated clay; Unit IIb is a marine homogenous clay
Unit III	Consolidated post-glacial lacustrine clays and silts.
Unit IV	Glacial, over-consolidated till comprised of a clay prone diamicton of silt, sand, gravel, cobbles and boulders.
Unit V	Bedrock gently dipping north-west. 10 m to 20 m below seabed.

3 PROJECT INTRODUCTION AND BACKGROUND

3.1 PROJECT OVERVIEW

Energinet Eltransmission A/S (Energinet) is developing two new offshore windfarms in the Baltic Sea with a planned capacity of 3GW. The two windfarms are to be known as Bornholm I (BHI) and Bornholm II (BHII) and will be connected to the Danish electricity grid via subsea cables to the island of Bornholm.

The locations of the Baltic Sea projects are shown in Figure 1.

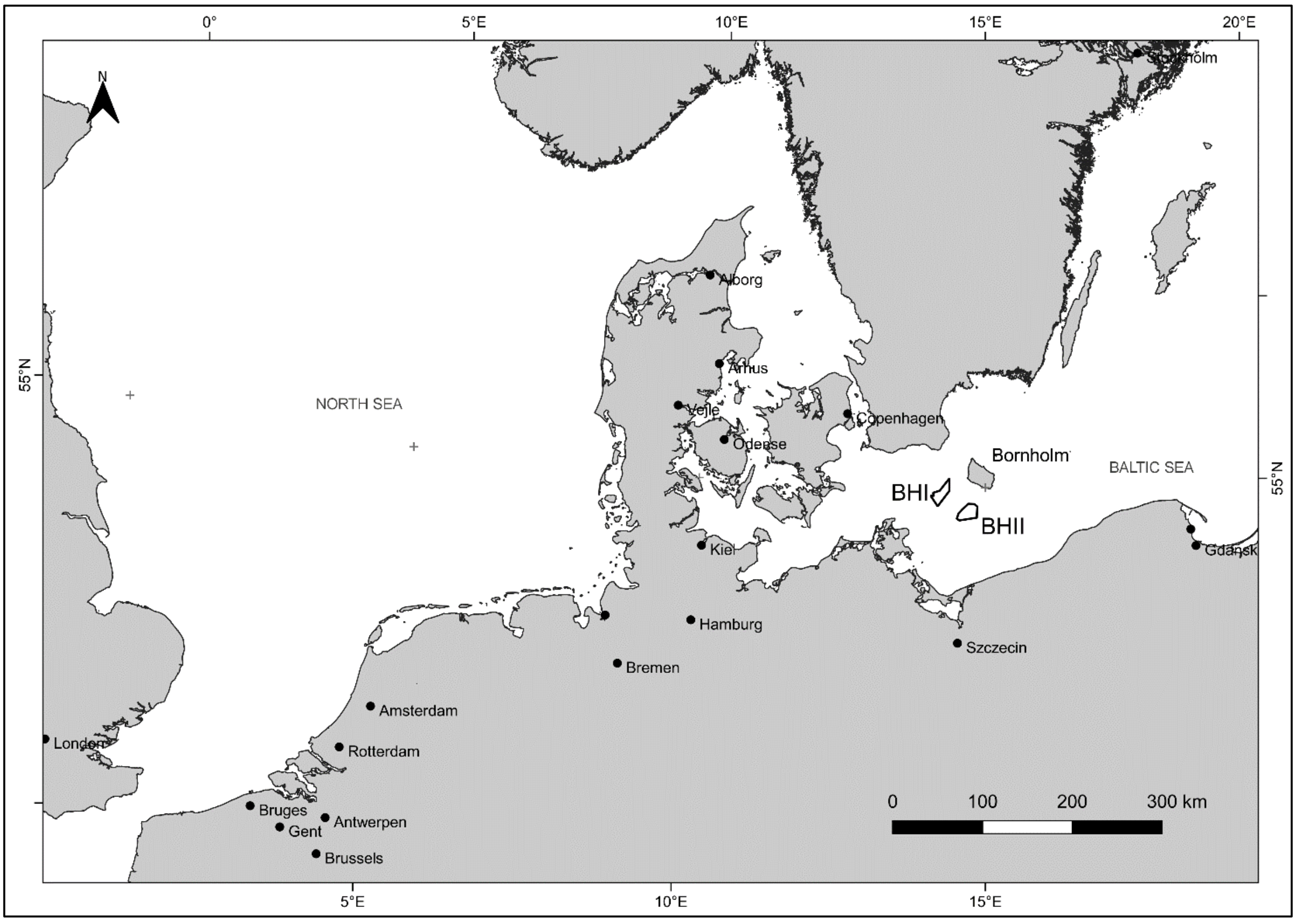


Figure 1: BHI and BHII project locations (Baltic Sea)

The project includes the following main elements:

- Two offshore wind farms, BHI and BHII, with a total of 3 GW including the extension areas surveyed separately in 2022.
- Subsea cables from Bornholm to offshore wind farms.
- Subsea cables from Bornholm to Denmark (Zealand).
- Subsea cables from Bornholm to a neighbouring country.

The Danish Energy Agency instructed Energinet to initiate site investigations, environmental and met-ocean studies for the main project elements. Energinet awarded GEOxyz a contract for the geophysical survey of the Baltic Sea project component. Figure 2 outlines the two proposed wind farm sites: Bornholm I and Bornholm II.

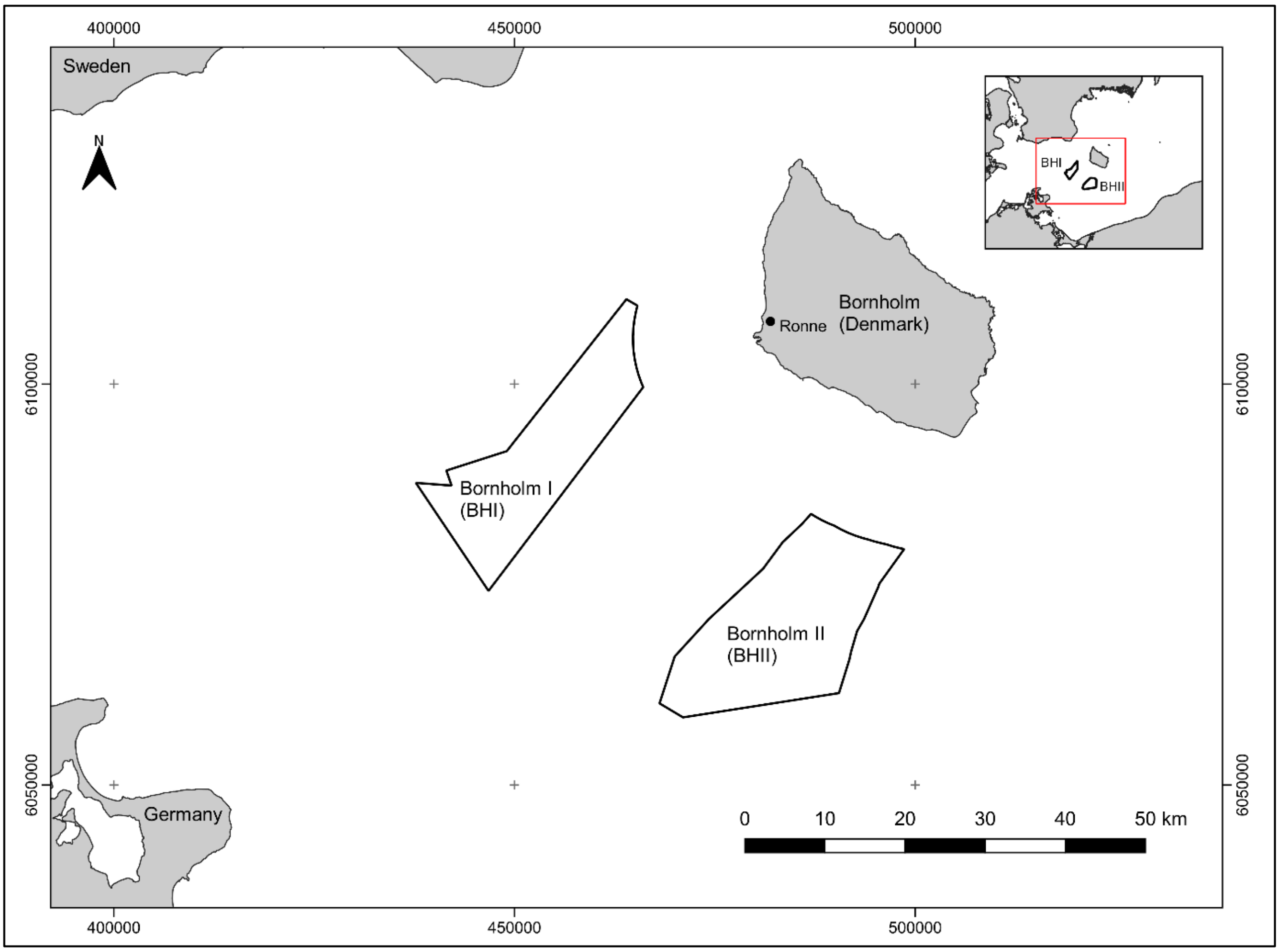


Figure 2: Location of BHI and BHII in the Baltic Sea including the extensions.

This report focusses on the proposed Bornholm I windfarm in the Baltic Sea and includes the additional survey scope. Three extension areas, two in BHI and two in BHII, were additionally surveyed in 2022 in conjunction with the original scope surveyed in 2021.

Two work packages have been executed: Work Package A (WPA- Geophysical Survey) and Work Package B (WPB – Survey for geotechnical clearance). This report details the findings from Work Package A for the Bornholm I site including the extended survey scope areas.

3.1.1 Description of area of investigation

The BHI survey site is located 15 km to the south-west of the Danish Island of Bornholm in the Baltic Sea. The site was extended to include two additional areas to the north and south of the original BHI site to increase the proposed total windfarm capacity for BHI by 1.5 GW. The original scope boundary and extended scope boundary are illustrated in Figure 3. This report details the results from the original survey scope and from the extended scope.

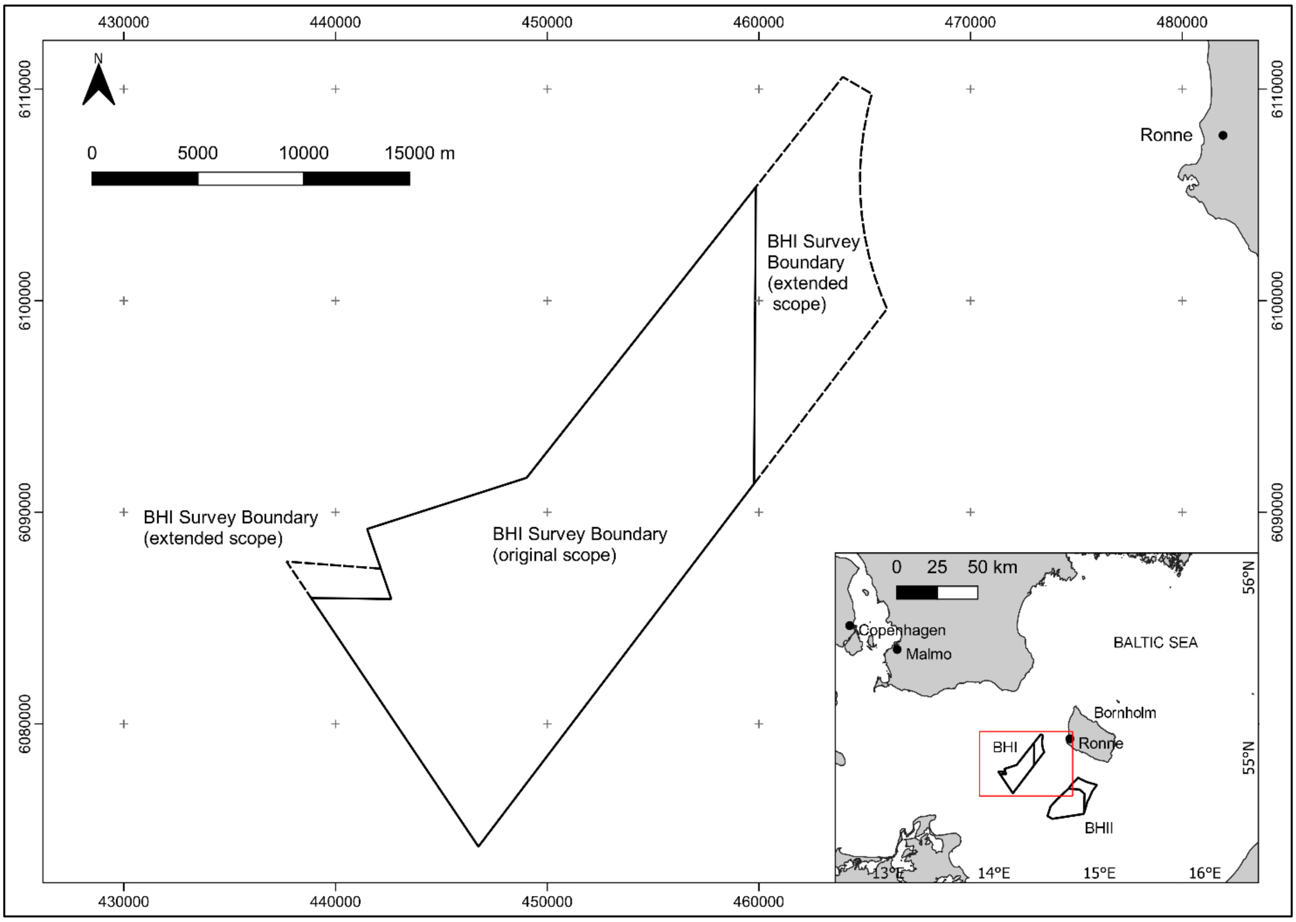


Figure 3: BHI overview with original and extended scope survey boundaries

For charting and reporting purposes, the BHI survey site was split into four tiles: Bornholm I N, Bornholm I E, Bornholm I S and Bornholm I W. These tiles are to clarify the different sections of the survey area and are referred to when necessary. The charting and reporting tiles are depicted in Figure 4.

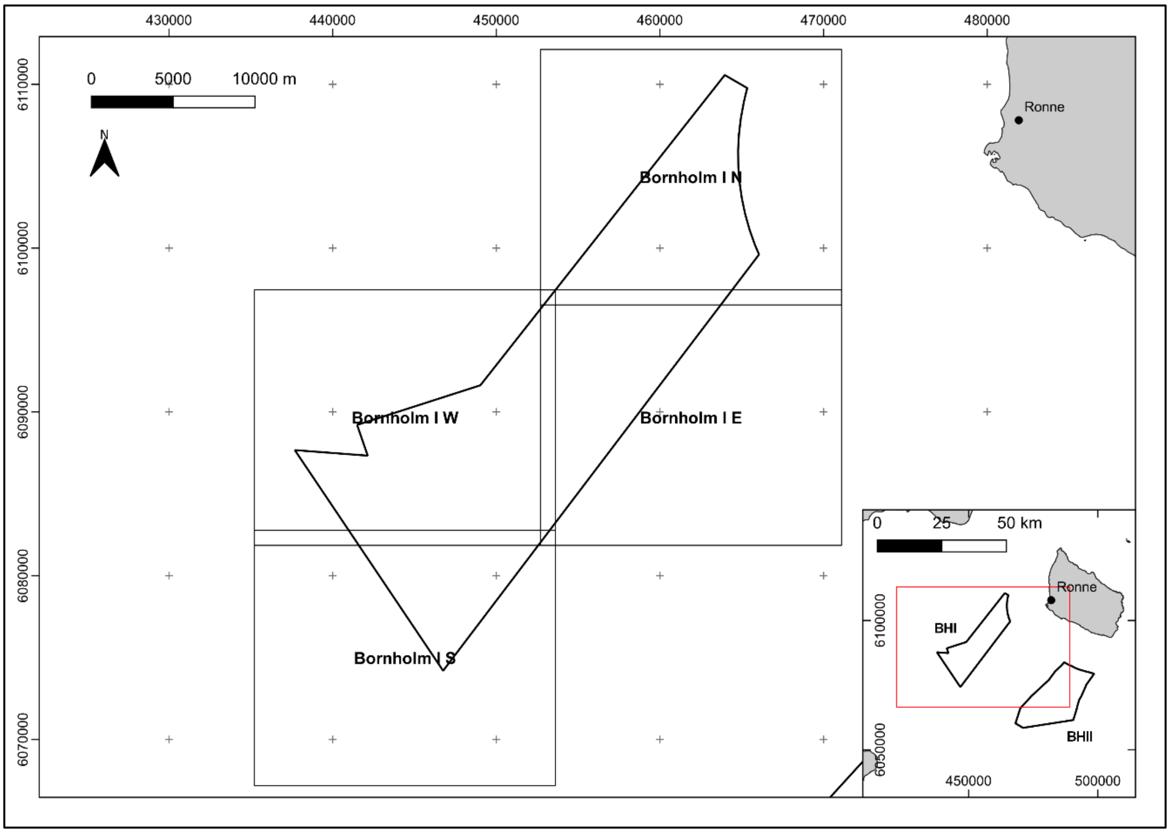


Figure 4: BHI overview with charting and reporting tiles

3.1.2 Existing infrastructure and exclusion areas

The Baltic Pipe pipeline crosses the northern part of the BHI site (Bornholm I N tile).

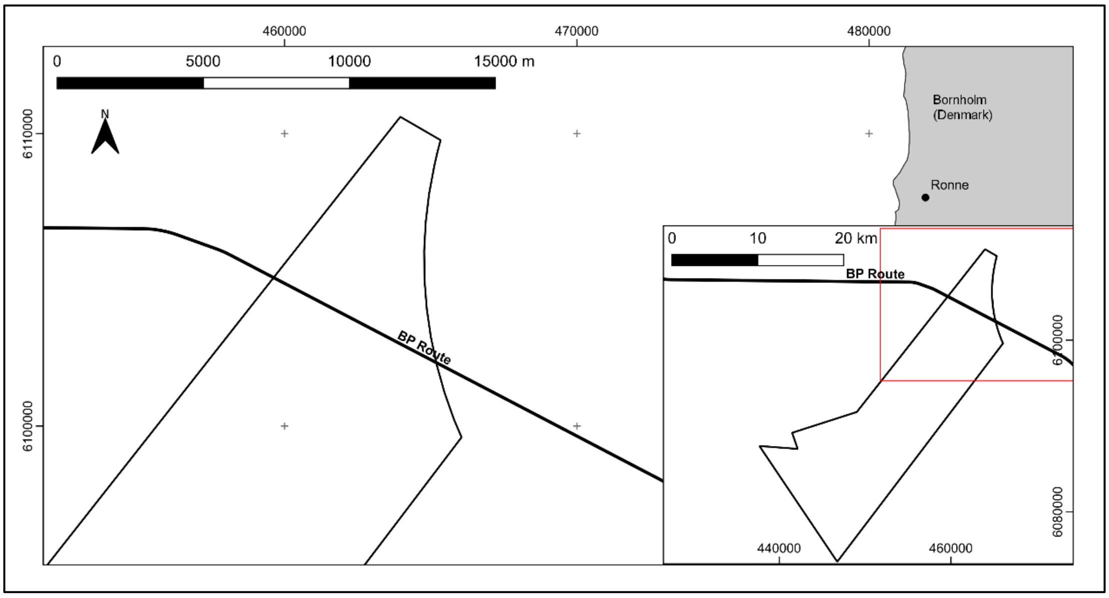


Figure 5: BHI existing infrastructure: Baltic Pipe pipeline crossing site

A number of known cable crossings exist within the BHI site. The cable crossings are outlined in Figure 6. The Baltica fibre optic cable network crosses the BHI site in the south and twice in the north of the BHI site. The Rønne-Rødvig cable crosses the north of the BHI site. A traffic exclusion area and NATO exclusion area crosses the BHI site restricting survey operations (Figure 6).

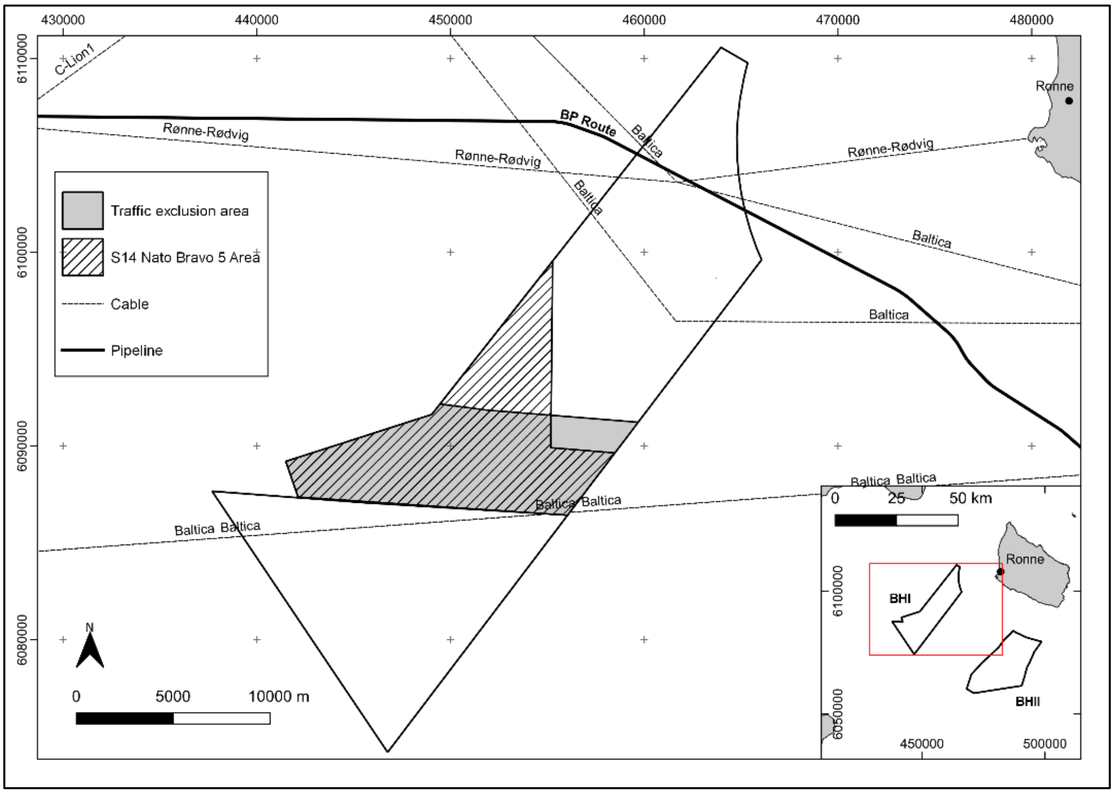


Figure 6: BHI existing infrastructure and exclusion areas

3.2 SCOPE OF WORK AND SURVEY AIMS

A geophysical site survey including 2D UHR seismic survey was performed between 2021 and 2022. The survey achieved full coverage in the area of investigation and mapped the bathymetry, the static and dynamic elements of the seabed surface and the sub-surface geological soil layers to at least 100 m below seabed.

The results of the survey will be used as basis for:

- Initial marine archaeological site assessment.
- Planning of environmental investigations.
- Planning of initial geotechnical investigations.
- Decision of foundation concept and preliminary foundation design.
- Assessment of subsea inter-array cable burial design.
- Assessment of installation conditions for foundations and subsea cables.
- Site information enclosed the tender for the offshore wind farm concession.

To accomplish these aims GEOxyz:

- Acquired high resolution bathymetric data to ascertain water depth and changes in topography across the BHI site using multibeam echosounder (MBES) data.
- Acquired high frequency (600 kHz) side scan sonar (SSS) data to identify seabed objects and features.
- Acquired low frequency (300 kHz) side scan sonar (SSS) data to distinguish seabed sediments.
- Acquired magnetometer data to identify cables, pipelines, potential UXOs and other ferrous objects on and below the seabed.
- Acquired high-resolution sub-bottom profiler (SBP) data to investigate the shallow sub-seabed sediment for possible future cable installation and offshore structure foundations.
- Acquired 2D multichannel ultra-high resolution (2D UHR) seismic data to investigate sub seabed sediment for possible future cable installation and offshore structure foundations.

The client specification and survey overview are detailed in Table 2.

Table 2: Client specifications and survey overview

Equipment	Specification	Survey Requirement
Vessels	Multi-vessel operations	Geo Ocean IV (GEOIV) and Geo Ocean V (GOV)
Line spacing	Main lines / Cross lines	250 m / 1000 m
	Secondary lines	62.5 m
MBES Bathymetry/Backscatter	Data density	16 hits/m^2 at 99% of the site.
	Standard Deviation	0.2 m (reviewed to be 0.25 m – TQ018)
	MBES Mode	Equidistant
	Gridded	0.25 m cell size
	Coverage	100 %
Side Scan Sonar	Resolution sufficient for detecting seabed object/features	1.0 m (Height, width and length)
	Towing altitude	8- 12 % of range (optimised for data quality)
	Positional accuracy	± 2 m (using vessel course-over-ground and USBL)
	Coverage	200 %[1]
Magnetometer	Seabed altitude	≤ 5 m
	Measurement sensitivity	0.01 nT
	Sampling frequency	1-20 Hz (selectable)
	Noise level	≤ 2 nT
Sub-Bottom Profiler	Penetration	10 m
	Vertical resolution	0.3 m
	System	Innomar SES 2000 or similar
	Fundamental frequency	Between 1 and 3 kHz

Equipment	Specification	Survey Requirement
2D Ultra High Resolution Seismic	Vertical resolution	0.3 m at seabed (weather dependant)
	Minimum Penetration	100 m
	Fire rate	2 pulses/second
	Variable energy levels	Between 100 and 1000 Joules
	System	A suitable multi-channel and multi-element hydrophone streamer (e.g., 48 channels @ 3.125 m) with depth control plus depth measurement for continuous monitoring and recording of streamer depth
Notes: [1]SSS coverage adjusted to 100% for nadirs due to thermocline/pycnocline effects. Coverage in some places was accepted to be only 100%. [2] 95% confidence level Standard Deviation was agreed to be increased to 0.25m due to pycnocline affectation on the outer range on the MBES.		

3.3 LINE PLANNING

Survey lines were divided into three categories: Primary lines, Secondary lines and Cross lines. A full survey spread (MBES, SSS, Mag, SBP and 2DUHR) was required on Primary lines and Cross lines. Primary lines were orientated with the long axis of each survey area with 250 m separation, Cross lines run orthogonal to the Primary lines with 1000 m separation. To achieve full seafloor coverage with MBES and SSS, Secondary lines with a separation of 62.5 m were included between the Primary lines. SBP and Mag datasets were also acquired along the Secondary lines. The planned lines allocated to each vessel are summarised in Table 3.

Table 3: Survey line spacing and spread

Survey scope	Survey Line	Line Spacing	Survey Spread	Vessel
Original scope	**Primary Lines**	250 m	MBES, SSS, Mag, SBP, 2D UHR	Geo Ocean V
	Cross Lines	1000 m	MBES, SSS, Mag, SBP, 2D UHR	Geo Ocean V
	Secondary Lines	62.5 m*	MBES, SSS, Mag, SBP	Geo Ocean IV & V
Extension scope	**Primary Lines**	250 m	MBES, SSS, Mag, SBP, 2D UHR	Geo Ocean V
	Cross Lines	1000 m	MBES, SSS, Mag, SBP, 2D UHR	Geo Ocean V
	Secondary Lines	62.5 m*	MBES, SSS, Mag, SBP	Geo Ocean V
Notes	*Provision held to reduce secondary line spacing to 50m if required due to environmental conditions.			

The original scope line plan was split in two parts and consisted of Primary lines and Cross lines, and Secondary lines run by two different vessels in simultaneous operation: Geo Ocean IV (GOIV) and Geo Ocean V (GOV). Primary lines and Crosslines, along with some reruns and infills, were acquired by GOV, whereas Secondary lines and the infills were acquired by GOIV. GOIV utilised a dual SSS approach with two side scan sonar towfish running simultaneously to minimise the effect to the pycnocline over the data on site.

3.3.1 Bornholm I original scope

The Bornholm I original scope area was divided into 9 blocks, to facilitate data coordination during acquisition and processing. Figure 7 shows the sub blocks and the line plan within the Bornholm I area.

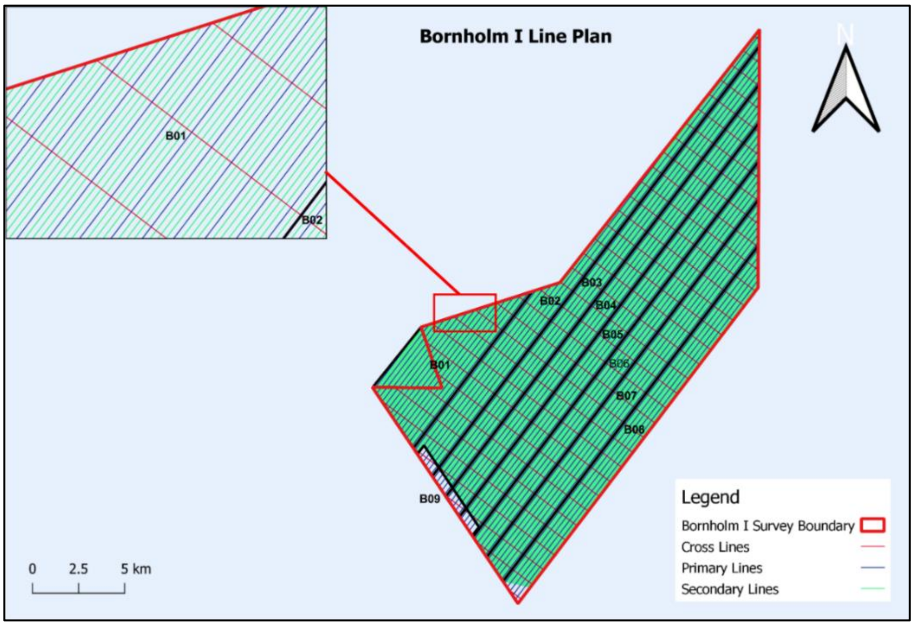


Figure 7: Line plan and work allocation

Due to the proximity of the windfarm areas to the SW of Bornholm I it was necessary to reduce the line length in blocks B02, B03, B04 and B05 in order to allow the vessels a safe turning circle without encroaching on the 3rd party development areas. To ensure full coverage of the survey area was still achieved, block B09 was included with lines reorientated NW-SE.

3.3.2 Bornholm I extended scope

The BHI extended scope areas were split into two areas (Figure 8):

- BHI B – 6.34 km^2 on the western side of BHI.
- BHI C – 72.33 km^2 on north-eastern side of BHI.

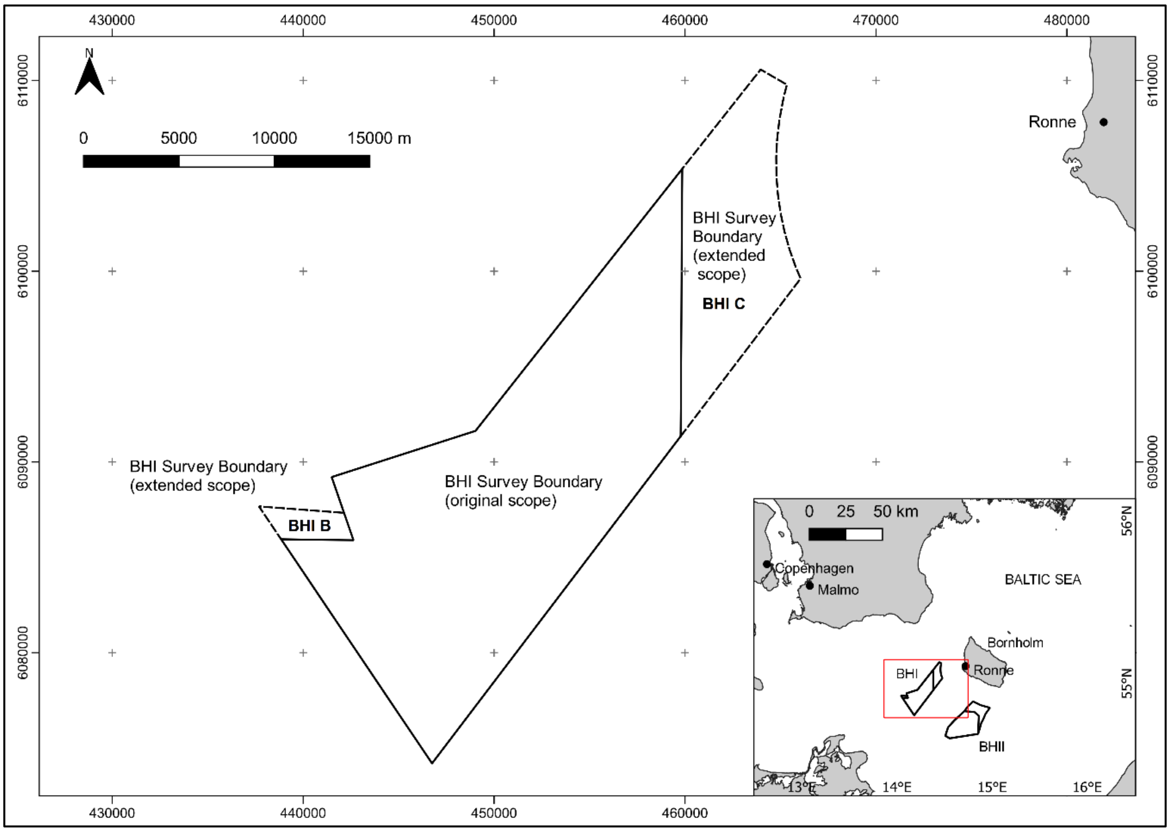


Figure 8: BHI extension areas

Figure 9 shows the line plan for BHI B and Figure 10 shows the line plan for BHI C.

The survey boundaries are shown in red, the main lines in orange, secondary lines in blue and cross lines in green. Original scope areas are denoted by the blue shaded area.

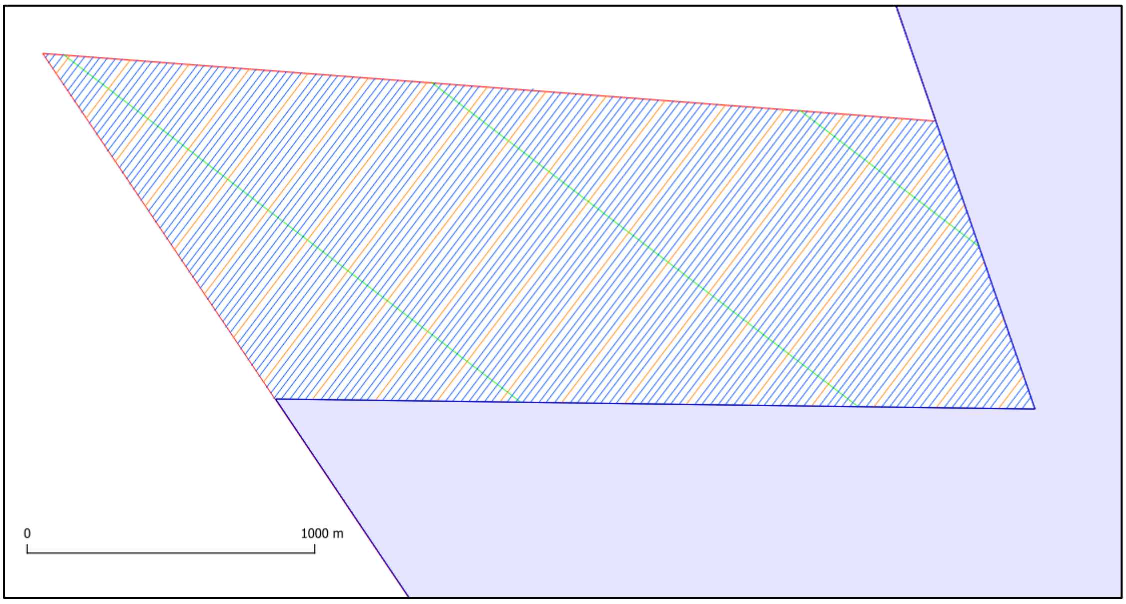


Figure 9: BHI B line plan overview

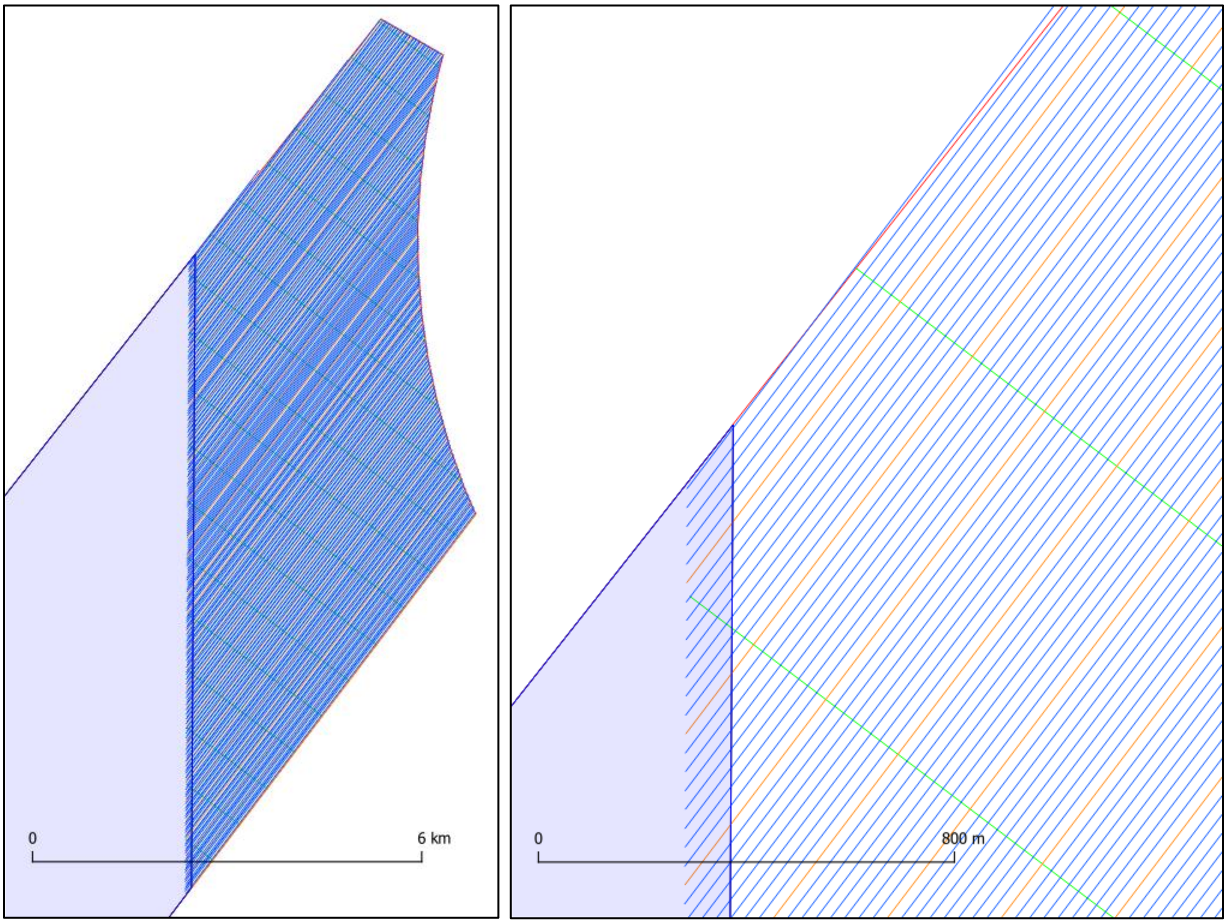


Figure 10: BHI C line plan (overview and zoomed view)

4 DESCRIPTION OF THE APPLIED VERTICAL AND HORIZONTAL REFERENCE SYSTEMS

4.1 HORIZONTAL REFERENCE

The datum parameters for the survey are described in Table 4 and the projection parameters are given in Table 5.

Table 4: Datum parameters

Parameter	Details
Name	European Terrestrial Reference System 1989 (ETRS89)
EPSG Datum Code	6258
EPSG Coordinate Reference System	4258
Spheroid	GRS80
EPSG Ellipsoid Code	7019
Semi-Major Axis	6378137.000
Semi-Minor Axis	6356752.314140
Flattening	1/298.2572221010
Eccentricity Squared	0.00669428002290

Table 5: Projection parameters

Parameter	Zone 33N
EPSG Coordinate Reference Code	25833
EPSG Map Projection Code	16033
Projection	UTM Zone 33 N
Central Meridian	15° East
Latitude of Origin	0°
False Easting	500000.00 m
False Northing	0.00 m
Scale Factor at Central Meridian	0.9996
Units	Metres

4.2 VERTICAL REFERENCE

The vertical datum for the project is Mean Sea Level (MSL) as defined by the Technical University of Denmark geoid model DTU21MSL. Height data was acquired relative to the ellipsoid and reduced to the project vertical datum.

All reported depths in the current report are related to DTU21MSL.

4.3 TIME REFERENCE

The time reference set up for all survey systems onboard the vessel, as well as the reported time in any official form and document, is provided in Coordinated universal time (UTC).

Online displays, overlays and logbooks are annotated in UTC as well as the daily progress report (DPR) and the Daily Processing Progress report (DPPR).

The synchronisation of the survey system was controlled by the ZDA NMEA time and date and the pulse per second (PPS) issued by the primary positioning system.

5 SUMMARY OF THE VESSELS AND INSTRUMENT SPREAD

5.1 SURVEY VESSELS

Two survey vessels were utilised for Work Package A: Geo Ocean IV and Geo Ocean V. The Geo Ocean IV is a 42 m offshore survey vessel (Table 6) and Geo Ocean V is a 54 m offshore survey vessel (Table 7). Geo Ocean IV and Geo Ocean V are equipped to perform a range of subsea services in the offshore renewables and oil and gas industries. Both vessels operate 24 hours a day and can remain at sea for up to four weeks.

Table 6: Geo Ocean IV vessel specifications

Geo Ocean IV	
Owner:	GEOxyz
Flag:	Luxembourg
Length:	41.9 m
Width:	9.1 m
Draught:	5.2 m
Speed:	10 knots (cruising)
Main Propulsion:	High screw CP-propeller
Endurance:	28 days
Accommodation:	22
Positioning:	DGPS, HiPaP352 USBL
A-Frame:	5t Stern
Additional Info: Fully mobilised analogue geophysical spread	

Table 7: Geo Ocean V vessel specifications

Geo Ocean IV	
Owner:	GEOxyz
Flag:	Luxembourg
Length:	53.8 m
Width:	13.0 m
Draught:	4.0 – 4.8 m
Speed:	10 knots (cruising)
Main Propulsion:	Hybrid propulsion CP-propeller
Endurance:	28 days
Accommodation:	24
Positioning:	DGPS, HiPaP351 USBL
A-Frame:	10t Stern
Additional Info: Fully mobilised analogue geophysical spread	

5.2 SURVEY SYSTEMS

Geo Ocean IV and Geo Ocean V were mobilised with the equipment listed in Table 8 and Table 9 respectively.

Table 8: Geo Ocean IV survey equipment

System	Manufacturer – Model	Equipment Specifications
GNSS	2x Trimble BX992 (1 x XP2 and 1 x G4 corrections)	RTK: < 0.05 m; DGNSS: <0.10 m
INS (motion, heading)	IXBlue Octans IV IXBlue Phins II	H: 0.1°; R&P: 0.01°; Heave: 5cm H: 0.01°; R&P: 0.01°; Heave: 2.5cm
SVP	Valeport Swift	0.02 m/s
MBES	2x Kongsberg EM2040	Freq: 200 - 400 kHz Focus: 0.4° x 0.7° at 400 kHz
USBL	Kongsberg HiPAP 352	0.02 m range detection accuracy or < 0.3% of slant range
Magnetometer	Geometrics G882	Accuracy: < 2nT throughout range. Freq: up to 40 Hz
SSS	Edgetech 4200 (300/600kHz)	Horizontal beamwidth: 0.5° @ 300 kHz, 0.26° @ 600 kHz Resolution Across Track: 3 cm @ 300 kHz, 1.5 cm @ 600 kHz
SBP	Innomar SES-2000 Medium	3.5-15kHz 1-5cm resolution

Table 9: Geo Ocean V survey equipment

System	Manufacturer – Model	Equipment Specifications
GNSS	Trimble BX992 & BD982 (1 x XP2 and 1 x G4 corrections)	RTK: < 0.05 m; DGNSS: <0.10 m
INS (motion, heading)	IXBlue Octans V Applanix POSMV Oceanmaster	H: 0.1°; R&P: 0.01°; Heave: 5cm H: 0.01°, R&P: 0.01°, Heave: 5cm
SVP	Valeport Swift	0.02 m/s
MBES	2x R2Sonic 2024 (1x TruePix)	Freq: 170 - 450 kHz Focus: 0.45° x 0.9° at 450 kHz
USBL	Kongsberg HiPAP 351P	0.02 m range detection accuracy or < 0.3% of slant range
Magnetometer	Geometrics G882	Accuracy: < 2nT throughout range. Freq: up to 40 Hz
SSS	Edgetech 4200 (300/600kHz)	Horizontal beamwidth: 0.5° @ 300 kHz, 0.26° @ 600 kHz Resolution Across Track: 3 cm @ 300 kHz, 1.5 cm @ 600 kHz
SBP	Innomar SES-2000 Medium	3.5-15kHz 1-5cm resolution

6 TECHNICAL QUERIES AND CHANGES TO SURVEY SCOPE

Geological, oceanographical and technical site limitations resulted in necessary adjustments to the survey scope. These survey scope adjustments were made as Technical Queries (TQs) and were checked and validated by the Client and by GEOxyz. Table 10 outlines the project specific TQs and their implications for the survey.

Table 10: TQ clarifications and outcomes

TQ ID	Subject	Clarification	Outcome
TQ - 001	Vertical reference (DTU21)	Client requested to modify the geodetic system for vertical reference from DTU18MSL to DTU21MSL.	The geodetic system for vertical reference changed from DTU18MSL to DTU21MSL.
TQ - 002	Code list – Geology	Client specified codes and nomenclature to use for geological classification.	Updated codes and nomenclature used for geological interpretation and classification.
TQ - 003	Planning of geotechnical program	Client requirements updated to plan for 20 geotechnical locations (combined borehole and CPT) and 50 CPT locations.	Updated requirements implemented into geotechnical program.
TQ - 005	DEA conditions for geophysical survey	No geophysical and geotechnical investigations can be performed within the Natura 2000 area including soft-start procedure.	All cross lines sailed in NW-SE direction. Additional vessel time formalised in a Variation Order.
TQ - 006 TQ - 007	2D UHR vertical resolution	The 2D UHR vertical resolution of 0.3 m would require a streamer tow depth of 0.5 m. Weather and sea state would make acquiring data with a tow depth of 0.5 m challenging.	Use of a slanted streamer, with the streamer head at 0.5 m depth and tail end at 1.5 m depth to mitigate the effects of weather and sea state was assessed. Due to equipment considerations, the slanted streamer configuration was not possible. Instead, a horizontally towed streamer at 1.0 m depth was utilised, with a small decrease in vertical resolution.
TQ - 008	Data specifications clarifications	Clarification on the SSS deliverables criteria.	SSS deliverable criteria clarified by Client.
TQ - 010	MAG altitude	Some magnetometer data were recorded with an altitude greater than 5 m.	Client agreed to accept magnetometer altitudes between 4.5 m to 6.0 m. Altitudes greater than 6.0 m flagged as potential line re-runs but assessed with offshore Client representative on a case-by-case basis.
TQ - 011	SSS Pycnocline Interference	The SSS was affected by a thermocline effect which severely impacted the data in areas of the sites BH1 and BH 2, reducing usable range for SSS and reducing coverage to under 200%.	The Client confirmed that the requirement for 200 % coverage can be relaxed for the SSS nadirs as long as 100 % coverage is achieved for the SSS nadirs.

TQ ID	Subject	Clarification	Outcome
TQ - 014	Extension of survey area	The OWF area for Bornholm I and Bornholm II increased by approximately 192 km2.	Extension area will be covered by an additional report.
TQ - 018	MBES relaxation	Request made to increase the MBES SD limit to 0.25 on 95% of the site and to modify the hit count specs to the following: A minimum of 99% of site will show a hit count of at least 16 hits/m.	The MBES criteria was relaxed.
TQ - 020	Automatic Boulder Picking Methodology	Automated boulder picking method outlined to Client by GEOxyz.	Method accepted by Client.
TQ - 022	Magnetometer navigation and altitude interpolation threshold	GEOxyz proposed to define a maximum gap for interpolation in the navigation and altimeter data of the magnetometers	Maximum gap determined to be 20 m along track.
TQ - 026	2D UHR feather angle	GEOxyz proposed to limit the feather angle of the 2D UHR streamer to 12 degrees during 95 % of the shots.	The feather angle of the 2D UHR streamer was limited to 12 degrees during 95 % of the shots.

The outcomes of some TQs had implications for the survey, particularly the effect of the pycnocline on the SSS dataset (TQ - 011), which resulted in a reduced usable SSS range. For affected areas, the accepted SSS coverage was reduced from 200 % to 100 %. Figure 11 highlights the effect of the pycnocline on the SSS dataset. To mitigate the effects of the thermocline/pycnocline, the Geo Ocean IV was mobilised with a dual SSS survey spread.

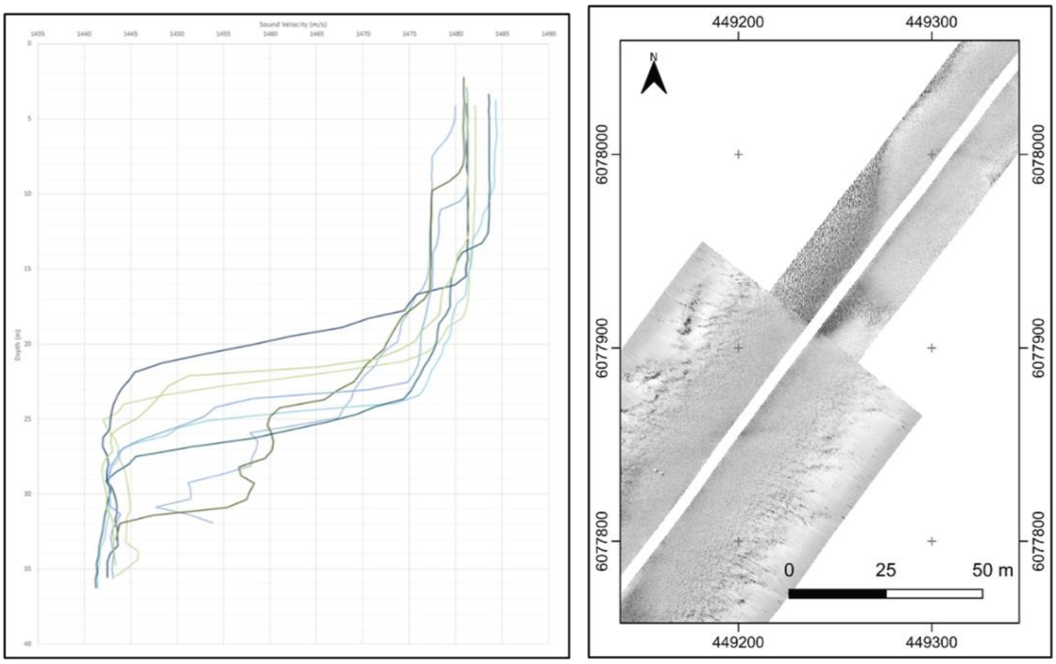


Figure 11: Pycnocline/thermocline and effect on SSS dataset

7 ASSESSMENT OF THE ACHIEVED DATA QUALITY

7.1 MULTIBEAM ECHOSOUNDER

Table 11: Multi-beam Echo Sounder client specification

Item	Specification
Data density	16 hits/m^2
Standard Deviation	0.2 m
MBES Mode	Equi-distant
Grid	0.25 m cell size
Coverage	100 %

It was requested and agreed in TQ 018- MBES to increase the MBES standard deviation limit to 0.25 for 95% of the site and to modify the hit count specifications to the following: A minimum of 99% of the site to have a hit count of at least 16 hits/m.

The processed MBES bathymetry data meets the required client specifications. Checks were made during acquisition to ensure that sounding density conformed to the 16 soundings per 1 m cell criteria and that the 95% confidence was within the final agreed 0.25 m.

A strong pycnocline was present, which affected the MBES dataset quality considerably. Outer ranges were sometimes out of the Standard Deviation specifications and therefore the data had to be trimmed and sometimes heavily cleaned in the outer range areas. This led to a lower density of soundings in some regions and a slightly higher Standard Deviation (around 0.25 m) in some flat areas where the lines and the dual swath overlapped.

A technical query (TQ 018 – MBES relaxation) was raised to the client and a relaxation on the hit count and SD specifications was agreed. The resultant specifications were:

- Hit count: 16 hits/m in at least 99 % of the data
- Standard Deviation: 0.25 % on 95 % of the dataset.

Some data gaps existed in the 0.25 m resolution final exports, but the hit count was achieved in 99% of the site, which was deemed acceptable by the client.

The MBES datasets from GOIV and GOV vessels were initially combined in the GOIV vessel to ensure consistency between vessels with a proper vertical alignment. This procedure also allowed for a sitewide in-field QC of the datasets.

After the first data drop, both vessels' datasets were brought into the office, where the processing continued to final processed surfaces.

The Standard Deviation at 95% confidence interval was checked in order to highlight areas where the vertical spread of soundings within the DTM is higher than expected and checks can be made to determine the cause.

If necessary, further processing was applied to the dataset to bring the soundings into closer alignment. Regions that have high standard deviations can occur where there are sound velocity errors (pycnocline effect), errors in the post-processed navigation, GNSS failures, poor weather affectation and where there are steep slopes such as boulder fields or presence of features such as wrecks, pipelines or the crests of some bedforms (sand waves).

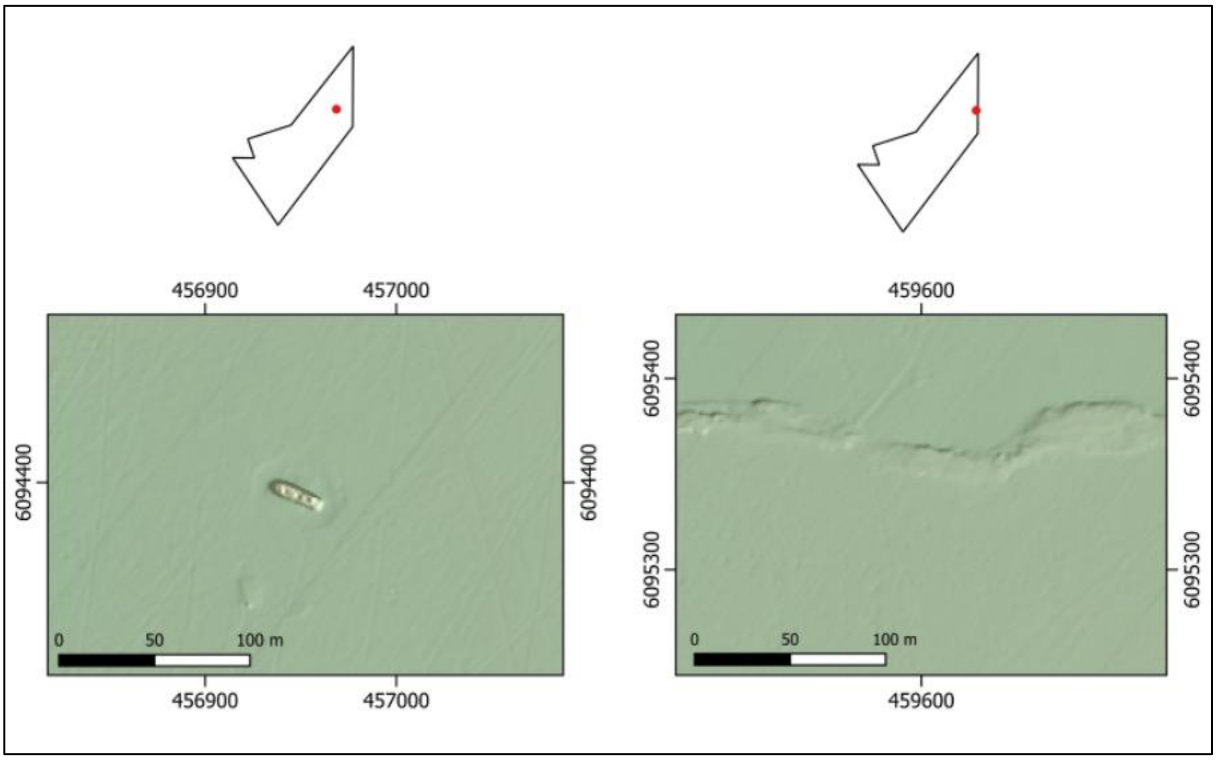


Figure 12: General examples of the mean DTM surfaces.

In the case of Bornholm area, the major variable, as described above, affecting the Standard Deviation values was the pycnocline which was filtered and corrected as much as possible, ensuring that the resulting data realistically represented the bathymetry.

Regions with boulders present or with till outcrops, had a high vertical spread but they cannot be considered as areas of poor data.

Some lines present a trending strips of higher Standard deviation values. These corresponded to survey lines that were acquired during poor weather, but still within the 0.25 m agreed after the TQ acceptance.

Data density was also monitored during acquisition and on final processing stage in the office. The dual head systems provided enough density in the raw data. However, the pycnocline forced the data to be trimmed and cleaned, which generated gaps and areas of lower density. This forced the vessels to infill some of the overlapping areas.

A technical issue with one of the heads onboard the GOV during the Bornholm I original scope survey, provided some lines with lower data density, which had to be infilled at a later stage.

The time gap between the virgin lines and the infill ones did not affect the Standard deviation on the MBES due to any potential seabed dynamic movement and the seabed features were not affected.

A summary of the statistics for each survey area and MBES processed block are shown in the tables below:

Table 12: BH1 original scope hit count and SD Statical parameters.

Block	Mean of Hit Count	% Of Cells with Hit Count of at least 16	Mean of Standard Deviation
01	50	99.82	0.05
02	57	100.00	0.06
03	57	99.98	0.05
04	60	99.99	0.05
05	72	100.00	0.05
06	50	100.00	0.04
07	57	100.00	0.05
08	67	100.00	0.05
09	65	99.07	0.04

7.2 BACKSCATTER

The quality of the final processed backscatter dataset was assessed in GIS (QGIS and Global Mapper) after combining all processed blocks into one gridded surface (1 m resolution backscatter mosaic). The processed backscatter image is shown in Figure 13.

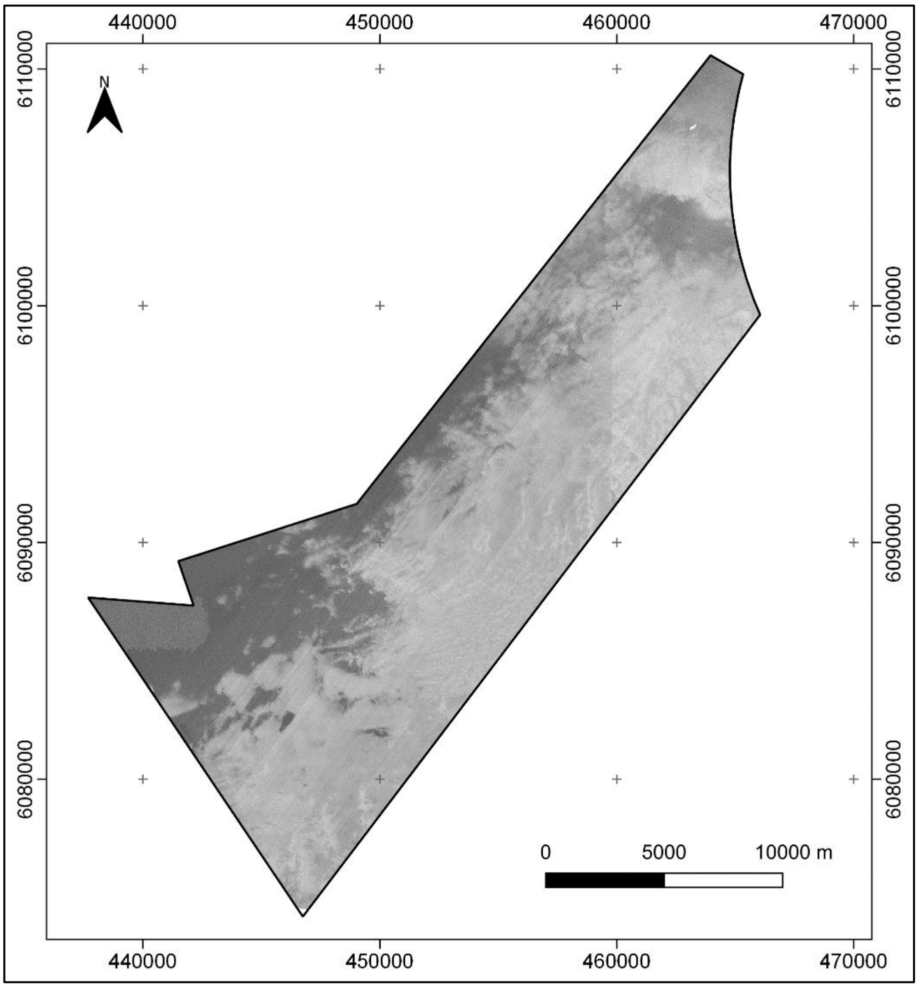


Figure 13: Backscatter image Bornholm I

The processing of the backscatter was done to try to achieve a homogeneous colour scale between blocks. The colour scale was then normalised between blocks. This step is necessary because it is not possible to process the entire survey area into a single mosaic due to the size of the dataset and the resolution specifications.

The backscatter Mosaic assessment indicated that the boundaries between different sediment types were differentiated and therefore the results were fit for purpose.

Some artefacts are present and mostly manifest as stripes aligned with the survey line direction with a clear difference when the lines come from different vessels.

Both GOIV and GOV were fitted with different MBES systems, which made it more difficult to mitigate differences observed between the two datasets due to different acquisition settings. These artefacts also appear to be exacerbated during periods of poor weather. The MBES acquisition setup was preferential over the backscatter acquisition.

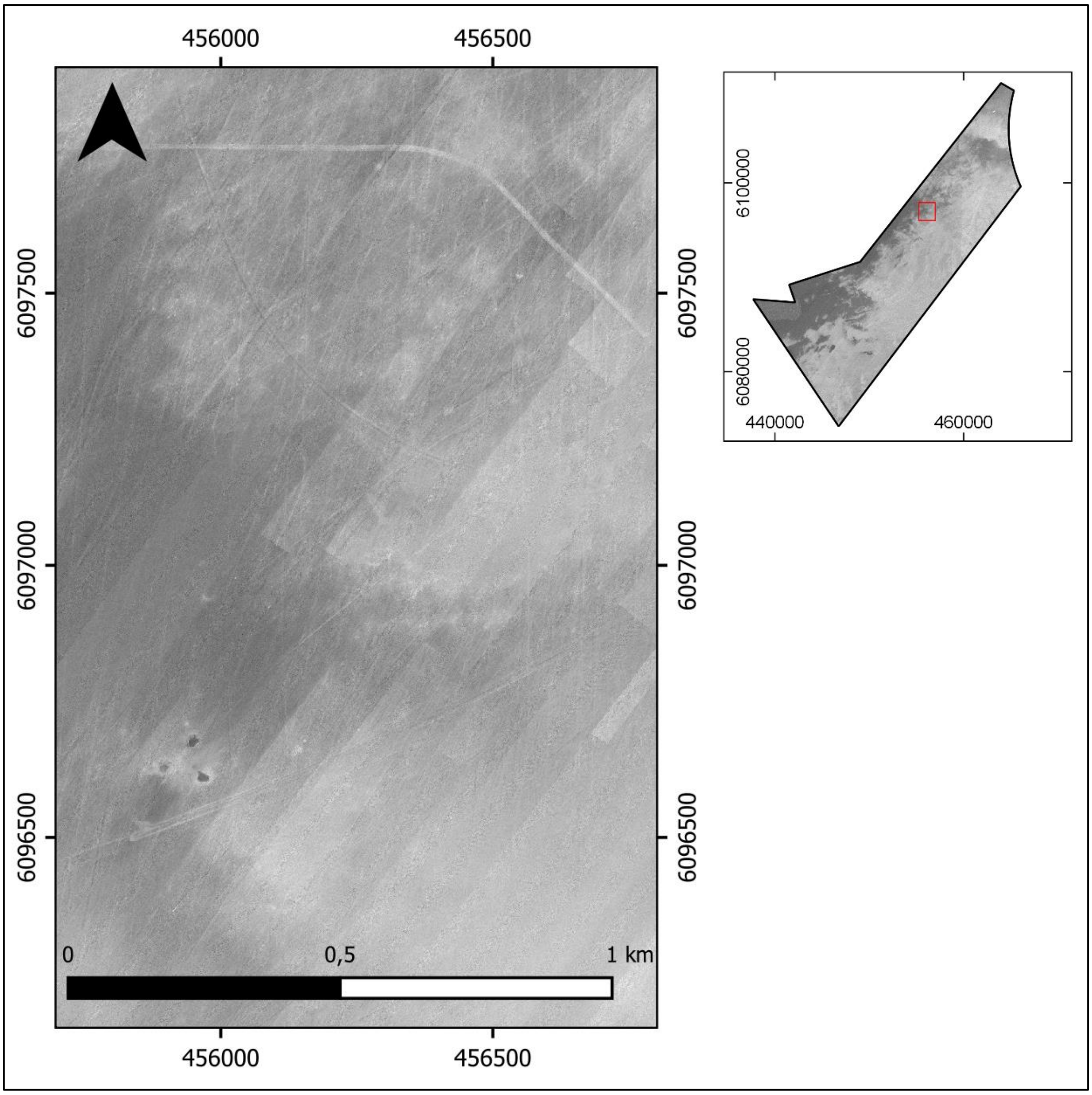


Figure 14: Example of stripe effect on the backscatter mosaic in Bornholm I

Despite the presence of these artefacts and differences in the dataset, the backscatter data is of sufficient quality to derive sediment boundaries and assist to the interpretation as additional help to the SSS dataset.

7.3 SIDE SCAN SONAR

The side scan sonar dataset achieved the client specifications outlined in Table 13 with good data quality throughout the BHI survey area.

Table 13: Side scan sonar specifications

Item	Specification	Achieved by survey
Resolution sufficient for detecting seabed object/features	1.0 m (Height, width and length)	< 0.5 m (Height, width and length)
Towing altitude	8- 12 % of range (optimised for data quality)	10 % of range
Positional accuracy	± 2 m (using vessel course-over-ground and USBL)	± 2 m (using vessel course-over-ground and USBL)
Coverage	200 %	> 200 %

Figure 15 is an example of the side scan sonar data quality achieved across the survey site and shows side scan sonar contact BHI_SSS_110649, identified as a wreck at 40 m depth. Individual seabed objects surrounding the wreck are clearly delineated with the acoustic dataset.

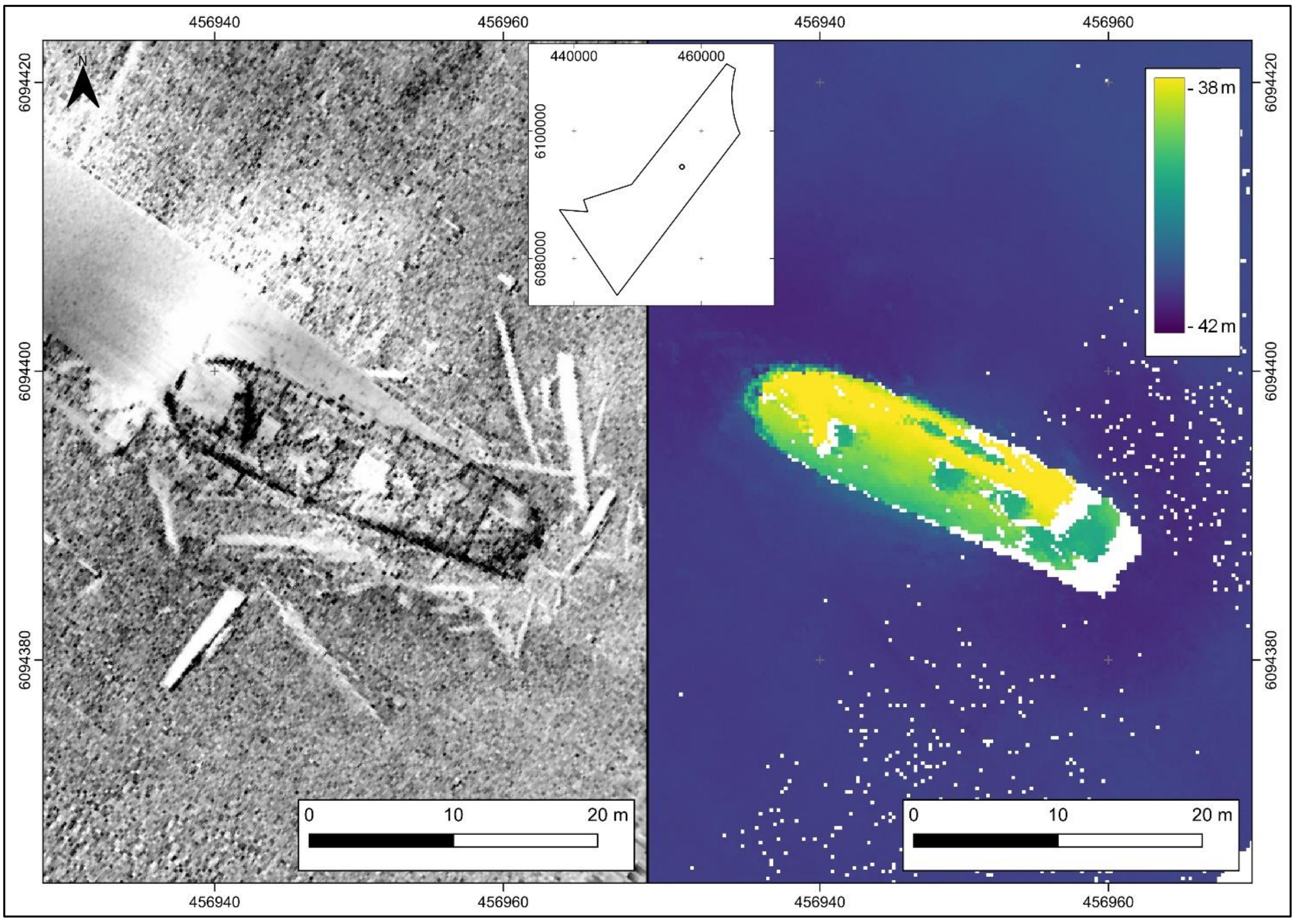


Figure 15: Side scan sonar dataset example with MBES imagery (BHI_SSS_110649)

7.4 MAGNETOMETER

The magnetometer dataset achieved the client specifications outlined in Table 14 with good data quality throughout the BHI survey area.

Table 14: Magnetometer client specification and achieved by survey.

Item	Client Specification	Achieved by survey
Seabed altitude	≤ 5 m	≤ 5 m
Measurement sensitivity	0.01 nT	0.01 nT
Sampling frequency	1-20 Hz (selectable)	10 Hz
Noise level	≤ 2 nT	≤ 2 nT

7.4.1 Magnetometer dataset profile example

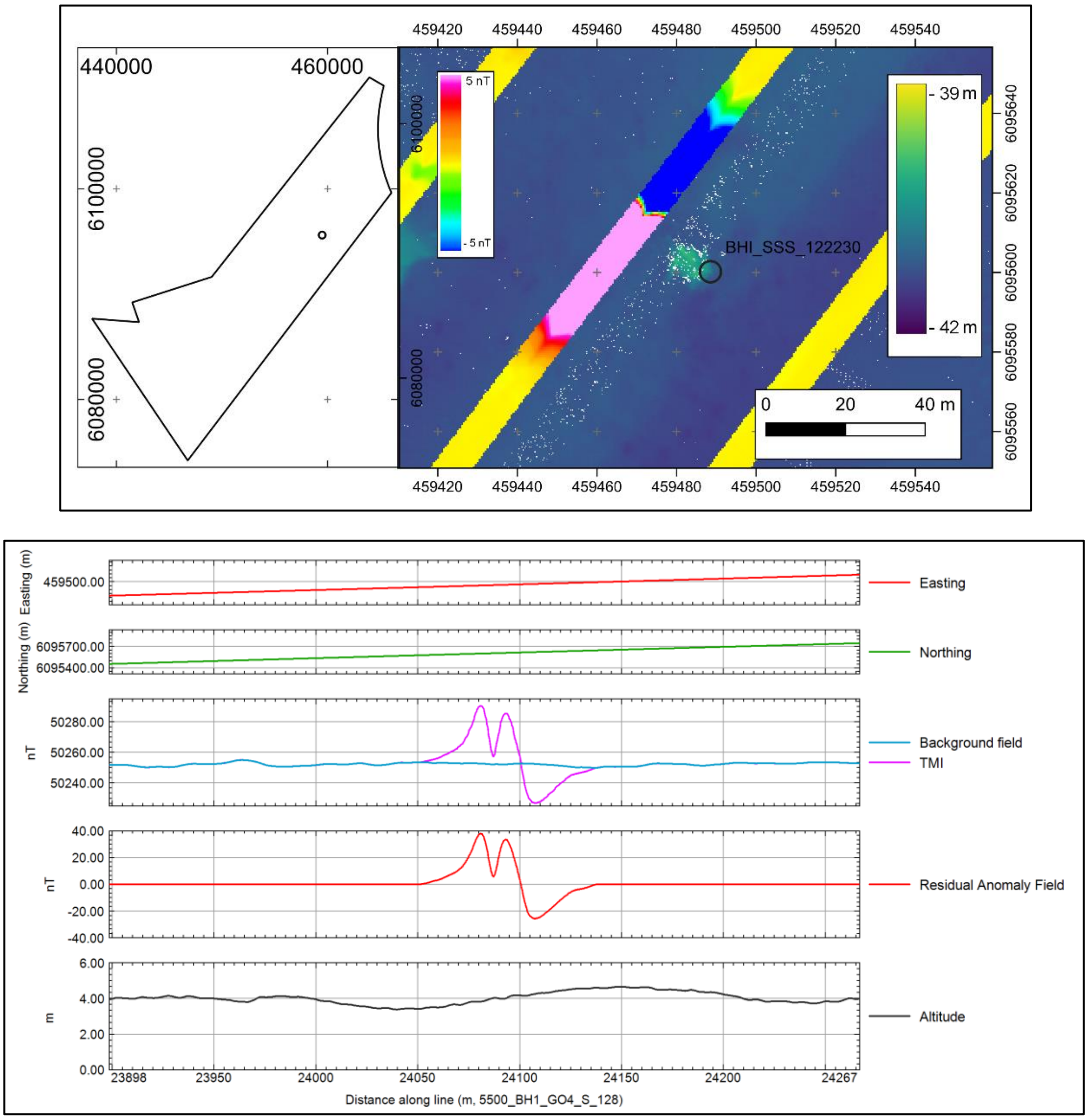


Figure 16: Magnetometer dataset profile example with MBES dataset (Line 5500_BH1_GO4_S_128)

Figure 16 shows a typical magnetometer dataset profile example of a wreck contact (BHI_SSS_122230, BHI_MAG_0111). The Residual Anomaly Field shows good discrimination between anomalies and the background magnetic field.

7.4.2 Magnetic residual anomaly grid

The BHI magnetic residual anomaly grid with an example of typical data quality is shown in Figure 17. The BHI magnetic residual anomaly grid was processed and gridded as a single magnetometer. The magnetic residual anomaly data exhibits little background or geological influence, with magnetic anomalies clearly distinguishable.

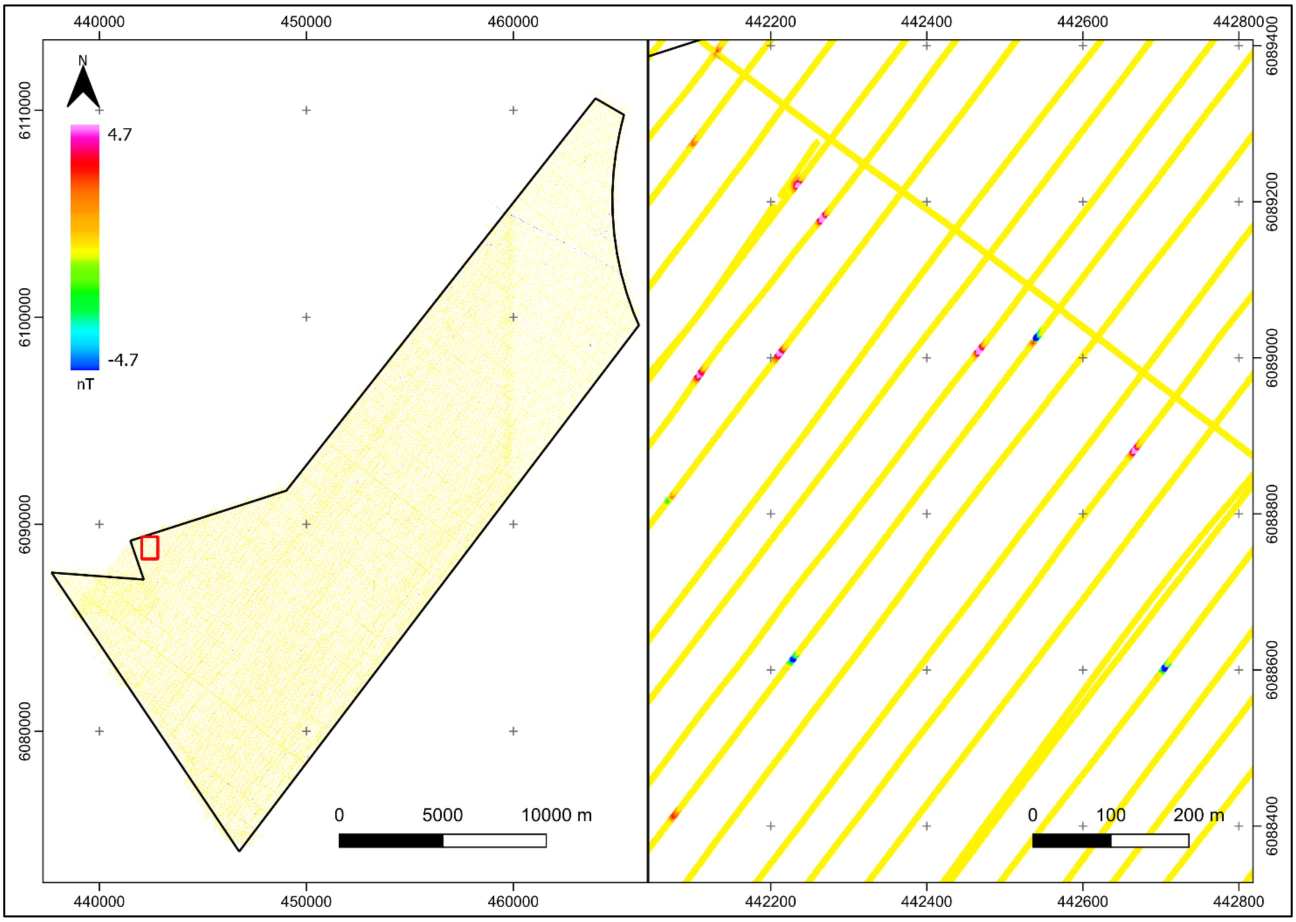


Figure 17: Magnetic residual anomaly grid overview with inset data example

7.4.3 Magnetic analytic signal grid

The BHI magnetic analytic signal grid with an example of typical data quality is shown in Figure 18. The BHI magnetic analytic signal grid was processed and gridded as a single magnetometer. The magnetic analytic signal exhibits little background or geological influence, with magnetic anomalies clearly distinguishable in the analytic signal grid. The analytic signal grid was used to aid magnetic anomaly identification.

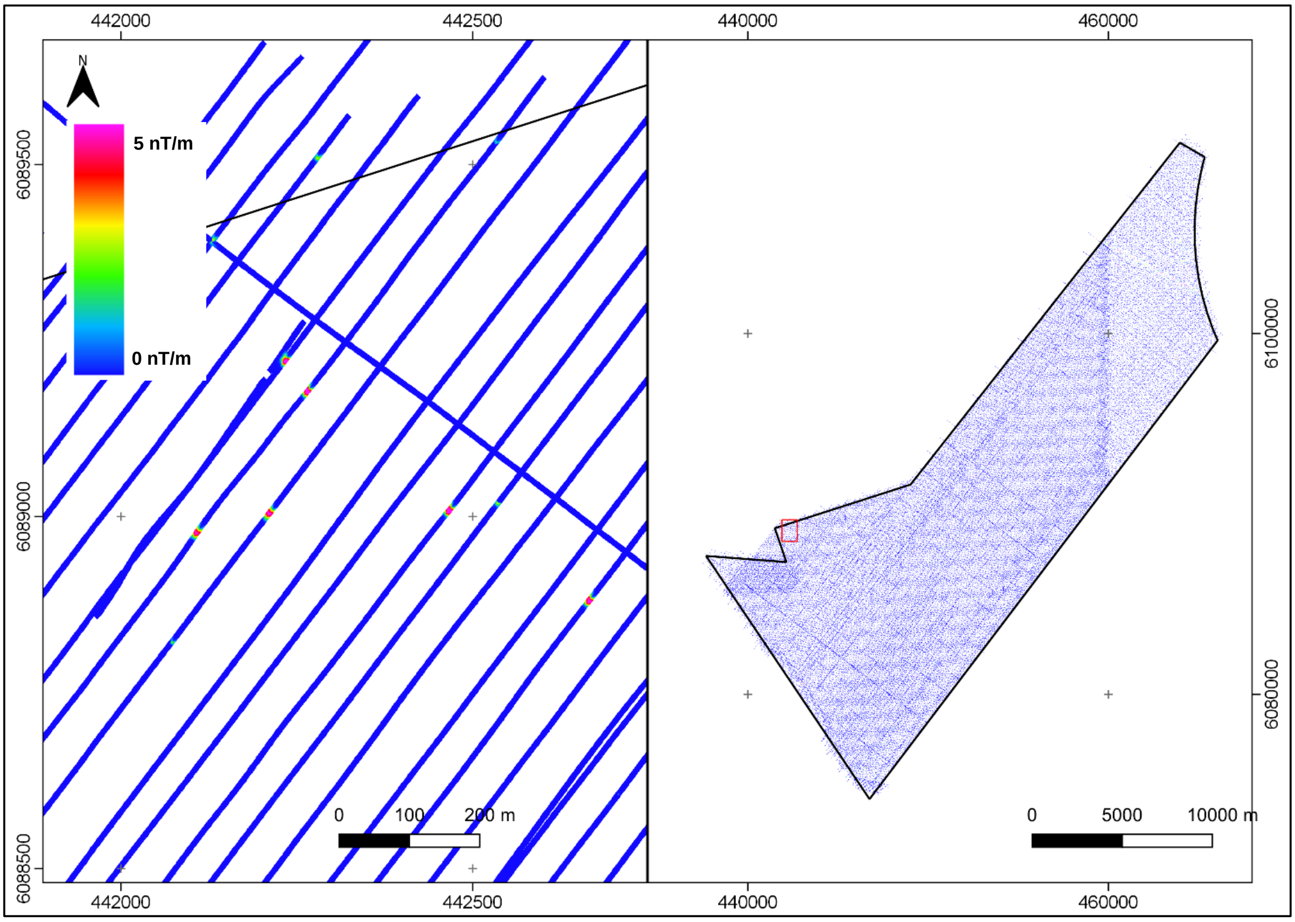


Figure 18: Magnetic analytic signal grid overview with inset data example

7.5 SUB-BOTTOM PROFILER

The sub-bottom profiler dataset achieved the client specifications outlined in Table 15 with good data quality and penetration throughout the BHI survey area. Figure 15 shows line X_07, which is an example SBP profile with typical penetration of > 10 m. For reference, interpreted units and horizons are outlined in Table 16.

Table 15: SBP acquisition specifications

Item	Specification	Achieved by survey
Penetration	10 m	> 10 m
Vertical resolution	0.3 m	< 0.3 m
System	Innomar SES 2000 or similar	Innomar SES 2000

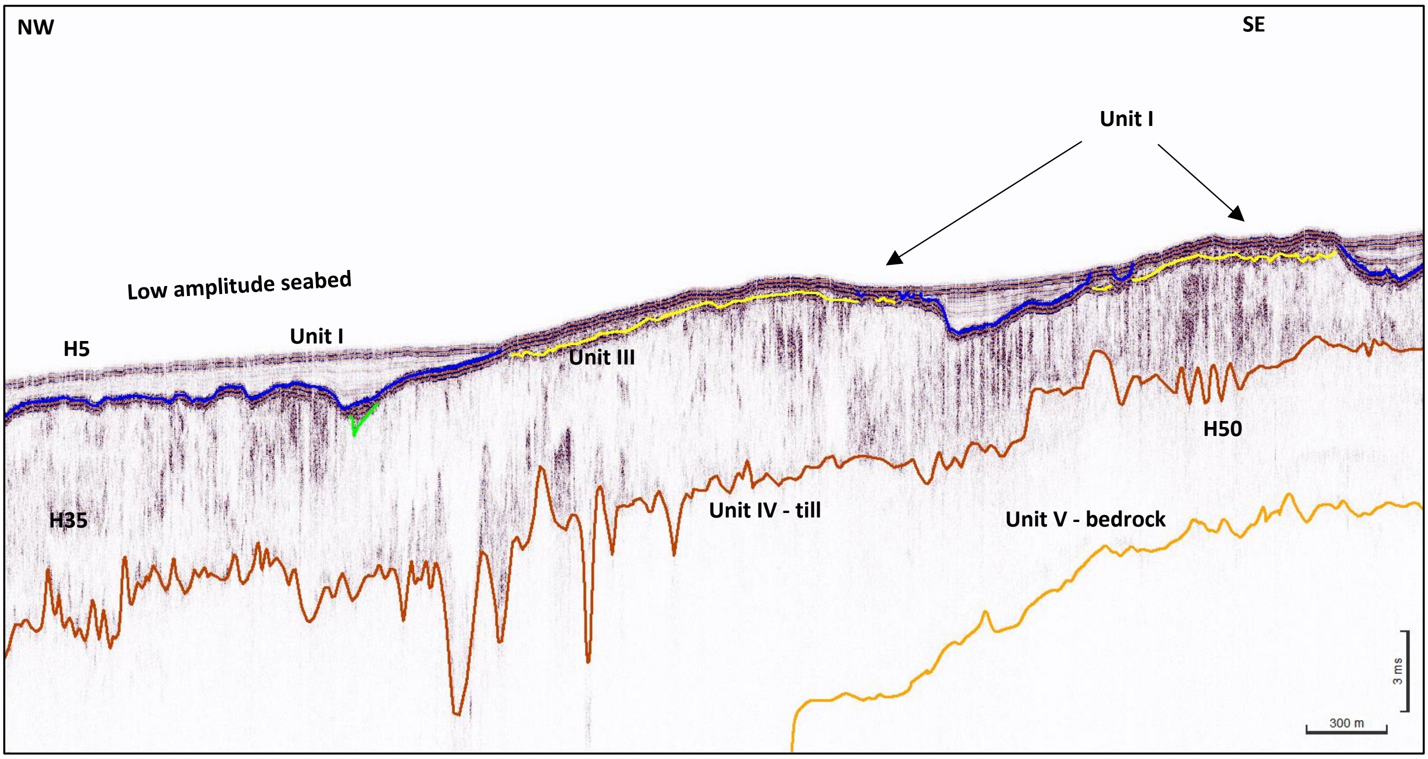


Figure 19: SBP data example (line X_07)

Table 16: Shallow Geological Units

Unit	Upper surface	Lower surface	Main Soil Description	Depositional Environment
I	Seabed	H5	Organic-rich CLAY	Post-glacial marine
II mounded facies	Seabed/H5	H15	SILT/fine SAND	Post-glacial (drowned beach?)
IIa/b channel-fill facies	H5/H15	H20	CLAY, laminated towards top	Post-glacial transitional (lake)
III	H5/H15/H20	H35	CLAY, locally silty	Post-glacial estuarine/lacustrine (Holocene)
IV	H35/seabed	H50	CLAY prone diamicton	Ice contact till (upper parts)
V	H50	Not imaged >70m BSB	LIMESTONE bedrock	Ancient shallow marine

Processed SBP data were loaded into an IHS Kingdom project for interpretation.

The picked horizons were gridded to 5 m lateral resolution using the IHS Kingdom Flex Gridding algorithm default settings. The seabed datum depth grids were created from sub-seabed thickness horizons. This removes the effect of any pinger static miss-ties and provides the best gridded surface possible. Sub-bottom data were thickness converted using a velocity of 1600m/s for the normally consolidated Units I – III, 1850m/s was applied to Unit IV, as this unit is interpreted to be over-consolidated.

The depth grids show some minor artefacts (approximately 0.2 m) related to imaging variations between lines and the ambiguous characteristics of some of the interfaces.

The SBP data are of good quality and allow separate imaging and mapping of interfaces with vertical spacing as close as 0.15 m. There is minor cavitation noise contamination of some of the records which has no effect on the generation of map products. The data locally offer good imaging to around 10m below seabed (Figure 20). Penetration does vary across the survey area related to differences in the geology.

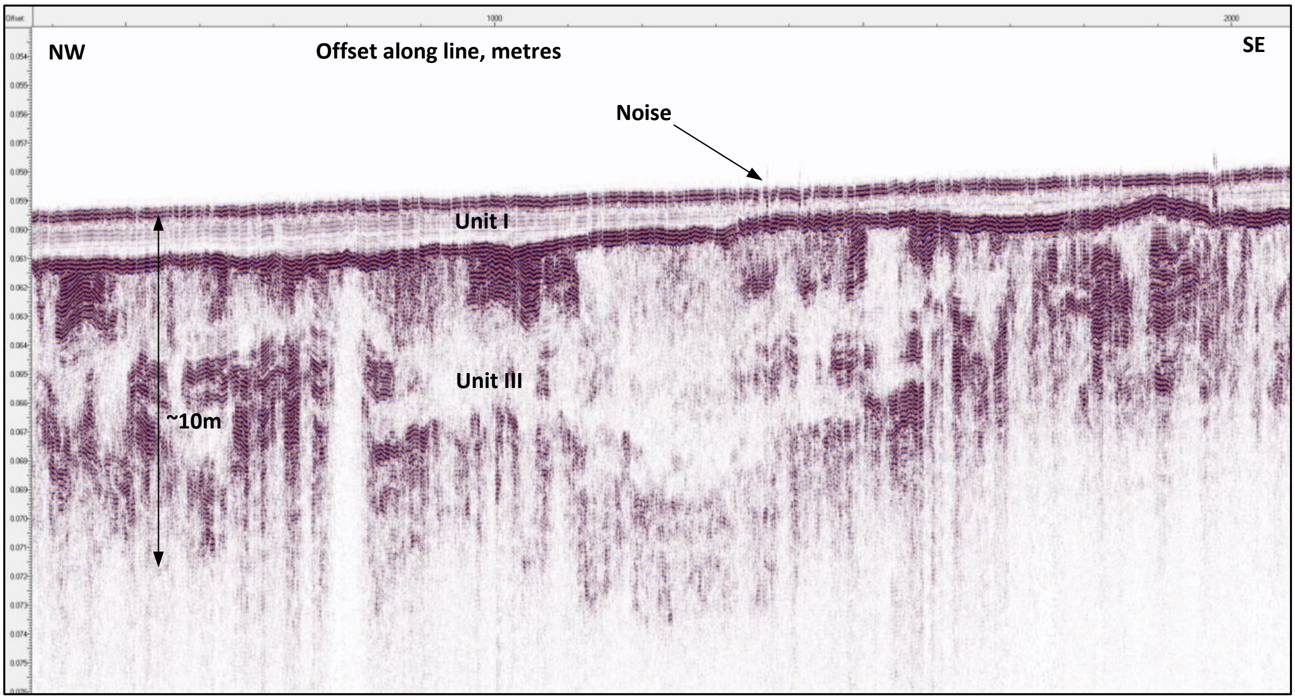


Figure 20: SBP data example, line X006, typical SBP line

The data are omni-directional. This means that energy reflected from off the plane of the survey line may be recorded. This most affects the certainty of depth and position extreme features such as the top of till ridges. These are mapped in terms of their apparent position – features in the data are assumed to have been generated by interfaces directly under the survey line and at their apparent time below seabed. In reality, many of these returns will originate off the plane (either side) of the line and be slightly closer to seabed.

7.6 2D UHR SEISMIC

These data are of good quality with generally low noise levels. There are localised parts of some lines which show a reduction in dominant frequency and some phase distortion. This is due to the receiving streamer being at too great a depth and/or weather noise. These degraded areas have a negligible effect on the overall interpretation of the data.

The data offer good imaging to at least 70 m below seabed (Figure 21).

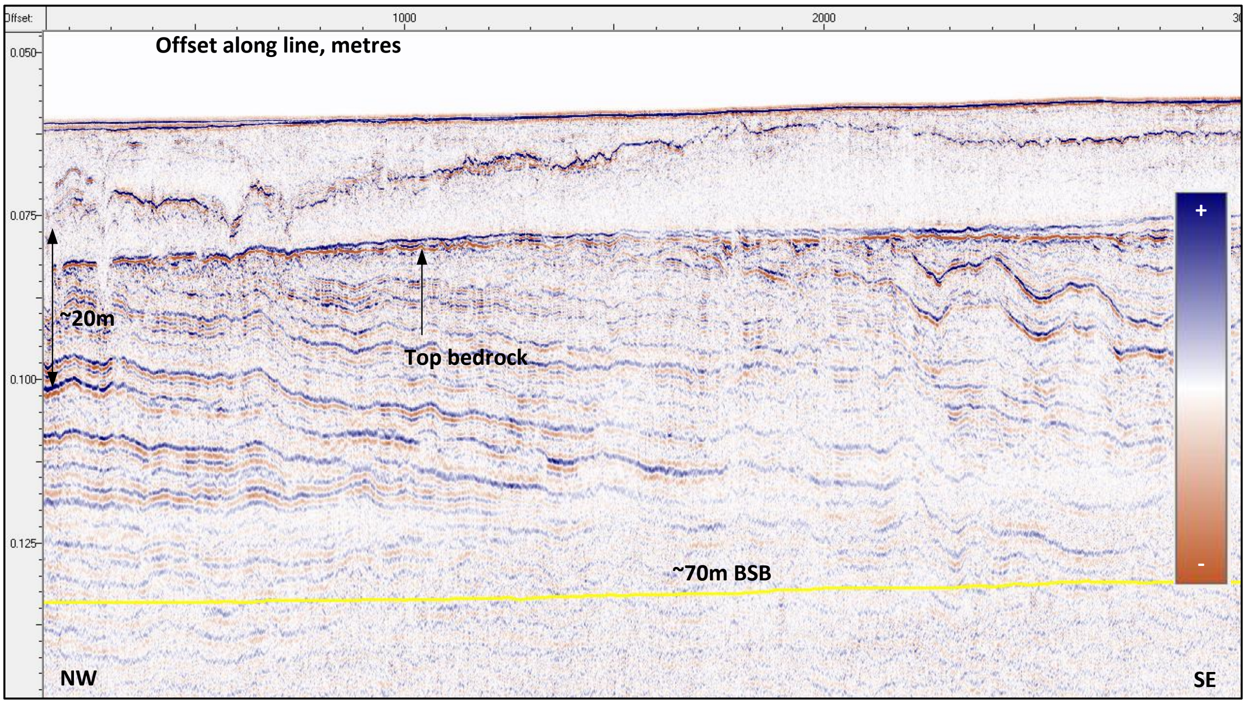


Figure 21: 2D UHR seismic data example, line X18, typical UHR line

The dominant frequency of the data is in the order of 700 Hz. This corresponds to a 1.4 ms wave period and a wavelength of around 2.3 m (1600 m/s, 700 Hz). The data make it possible to map separate events or reflections as vertically close as ~1 m apart. Along-line lateral resolution of these data is reduced to around 2 m by migration. Perpendicular to the line, where data are unmigrated, the imaging may come from a zone with an 8 m radius (70 ms TWTT, 700 Hz and a 1600 m/s velocity).

The data have been converted to zero phase with statics applied to place the centre peak of the water bottom signal at the position of the time version of the MBES data seabed model (Figure 22).

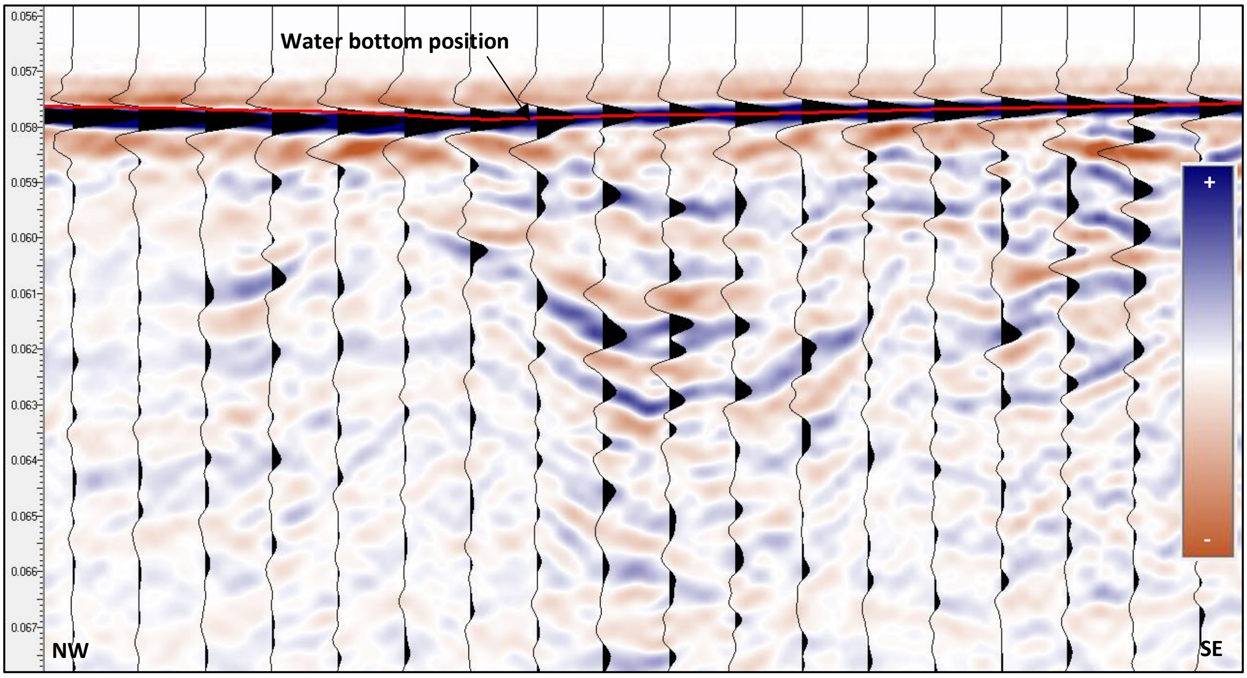


Figure 22: 2D UHR seismic data example, line X14, centre peak corrected to seabed time

7.7 DATA GAP DUE TO BUOY

A buoy located at 463237.23 mE, 6107505.95 mN resulted in a data gap due to safe vessel navigation preventing complete seabed coverage. To mitigate the size of the data gap, additional infill lines were run perpendicular to the main lines. The resultant data gap is approximately 260 m by 80 m in size (Figure 23).

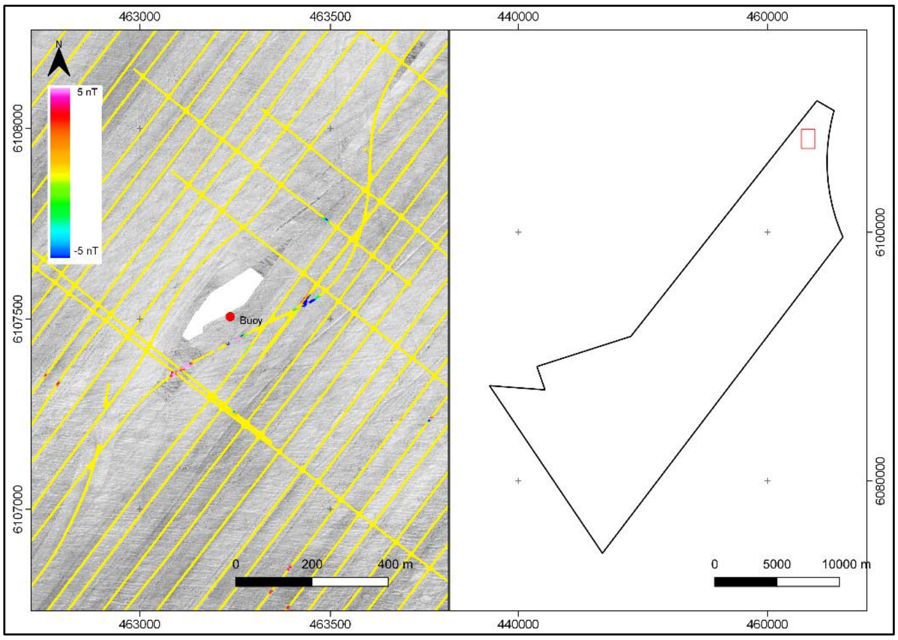


Figure 23: Data gap due to buoy: Residual magnetic anomaly grid overlaid SSS data

8 SURVEY RESULTS FOR THE SEABED SURFACE

8.1 CLASSIFICATION CRITERIA

8.1.1 SLOPE CLASSIFICATION CRITERIA

Seabed gradient has been classified as per the table below:

Table 17: Slope classification

Classification	Slope
Very Gentle	< 1°
Gentle	1° - 5°
Moderate	5° - 10°
Steep	10° - 15°
Very Steep	>15°

8.1.2 SEABED SURFACE GEOLOGY CLASSIFICATION CRITERIA

The interpretation criteria for the survey were informed from the GEUS Desk Study (Jenson et al., 2021) and Technical Query TQ-002. Terminology and classifications were preserved from the Desk Study where possible to maintain consistency between reports. Table 18 provides the list based on the TSG GIS classification applied to the geology assessment.

Table 18: TSG Geology classification used.

TSG Geology Classification
Mud and sandy mud
Muddy sand
Sand
Gravel and coarse sand
Till/diamicton
Quaternary clay and silt
Sedimentary rock
Unknown
Other

8.1.3 SEABED SURFACE MORPHOLOGY CLASSIFICATION CRITERIA

The interpretation criteria for the survey were informed from the GEUS Desk Study (Jenson et al., 2021) and Technical Query TQ-017. Table 19 provide a summary of the criteria used for bedform classification.

Table 19: TSG Bedform classification used.

SEABED FEATURE	CRITERIA
Ripples	Wavelength < 5 m Height < 0.01 m – 0.1 m
Large Ripples	Wavelength 5 m – 15 m Height < 0.1 m – 1 m
Mega Ripples	Wavelength 15 m – 50 m Height 1 m – 3 m
Sand Waves	Wavelength 50 m – 200 m Height 3 m – 5 m

8.1.4 BOULDER FIELD IDENTIFICATION CRITERIA

The boulder field identification criteria for BHI were outlined in Technical Queries TQ-004 and TQ-020. Seabed objects, including boulders, greater than 0.5 m in any direction were interpreted and classified. Areas with high boulder densities were analysed using an automatic boulder picking algorithm. The automatic boulder picking algorithm picked individual boulders within a boulder field, resulting in improved picking accuracies. The boulder zone type was automatically classified by the boulder picking algorithm (Table 20). Debris objects were isolated from the auto-picked boulder fields using correlation between sensor datasets.

Table 20: TQ-004 Boulder field identification criteria

Boulder density	Boulder zone type	Description
< 40 boulders	N/A	Not a boulder zone
40 – 80 boulders	Boulder zone Type 1	Intermediate boulder density
> 80 boulders	Boulder zone Type 2	High boulder density

The effectiveness of the algorithm is shown in Figure 24.

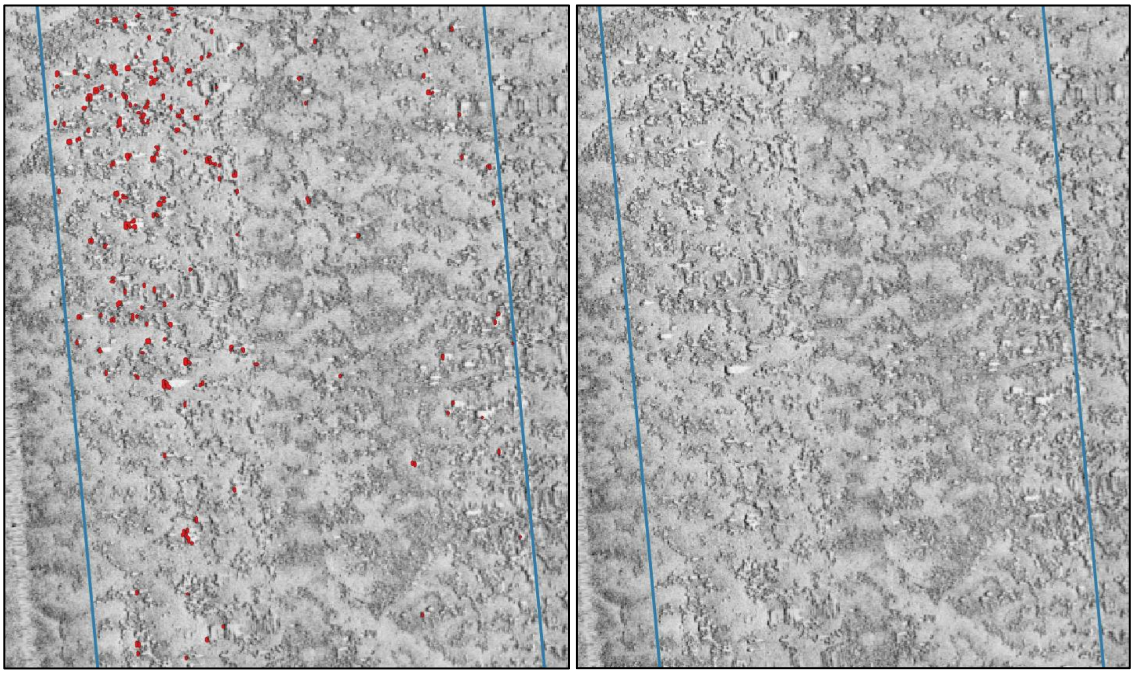


Figure 24: 2D Auto-picking result: Picked boulders (left, red) and the original dataset on right.

8.1.5 SEABED SURFACE SUBSTRATE CLASSIFICATION CRITERIA

Substrate classification has been based in the TSG substrate list and following the indications also provided in TQ – 016. The classifications refer to the Danish Rastofbekendtgorelsen (BEK no. 1680 of 17/12/2018).

Four main substrate classes have been used in the mapping classification which are summarised in Table 21:

Table 21: Substrate classification.

SUBTRATE TYPE	CRITERIA
1a	Sand, silty, soft bottom
1b	Sand, solid sandy bottom
1c	Clay bottom
2a	Sand, gravel and pebbles – few larger stones
2b	Sand, gravel and pebbles – seabed cover of larger stones 1% to 10%
3	Sand, gravel and pebbles – seabed cover of larger stones 10% to 25%
4	Stony areas and stone reefs – seabed cover of larger stones 25% to 100%

8.2 BATHYMETRY

The water depth varies moderately across Bornholm I. The minimum surveyed depth is 27.83 m at 447296 m E, 6075327 m N located in the southern part of the survey (Bornholm I S). The maximum surveyed depth is 47.32 m at 462945 m E, 6106756 m N in the northern extended scope (Bornholm I N). The mean depth across the site is 40.63 m. Figure 25 shows an overview of the bathymetry within Bornholm I.

The terrain profiles are presented running from west to east across site. A longitudinal profile is also show from south to north. These are derived from the following geophysical survey lines:

- BH1C_GO5_X_016 (northernmost)
- BH1C_GO5_X_011
- BH1_GO5_X20
- BH1B_GO5_X_003 + BH1_GO5_X06 (southernmost)
- BH1_GO5_P_027 + BH1C_GO5_P_028 (longitudinal)

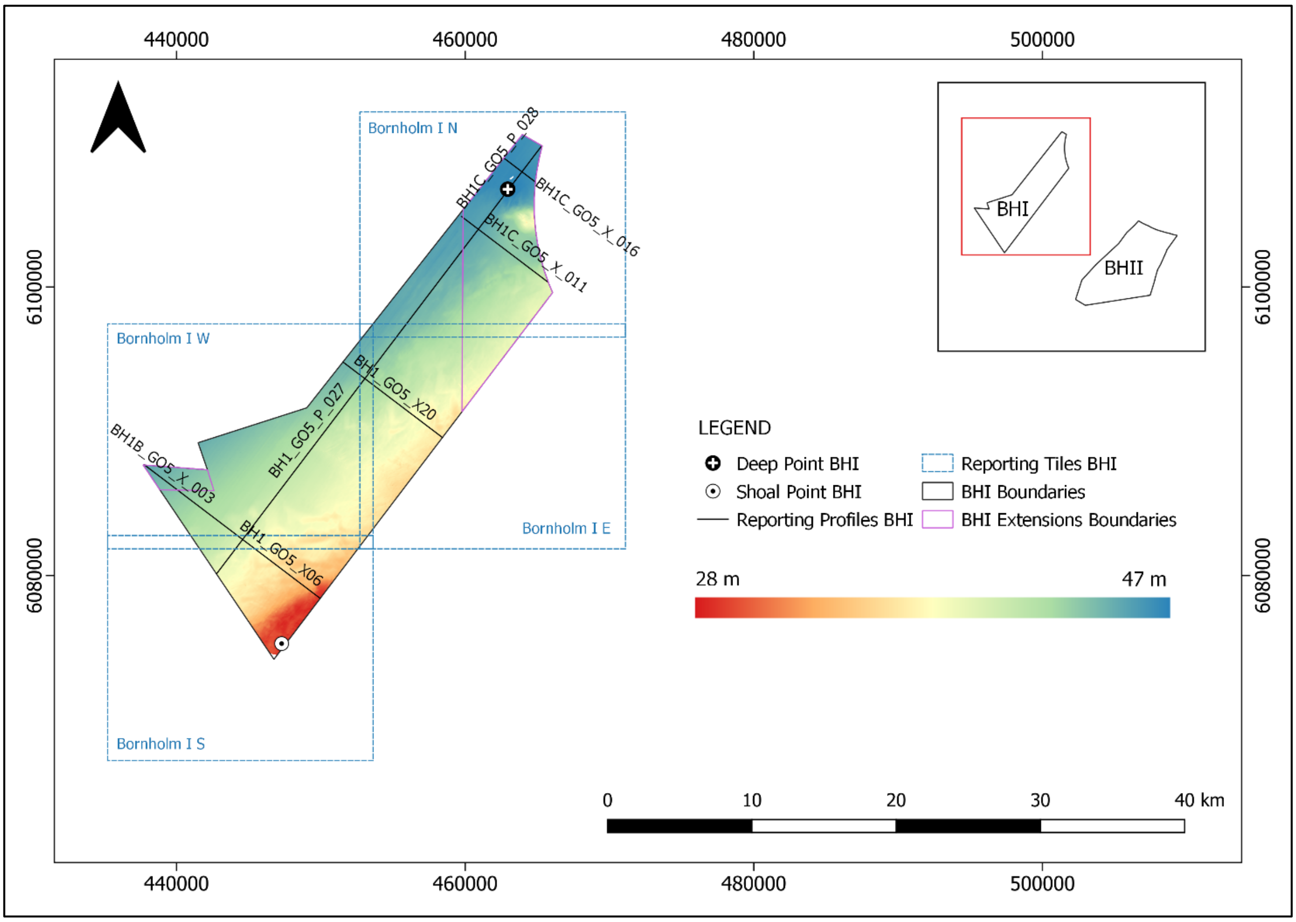


Figure 25: Overview of the bathymetry

Profiles obtained from the bathymetry files are shown in Figure 26 and Figure 27, showing water depth relative to DTU21 MSL. Profiles have been matched to the position of the southernmost lines (BH1B_GO5_X_003 and BH1_GO5_X06). This has been conducted so that the relative positions of the profiles obtained from cross lines are normalised and allows any feature which may extend between the profiles to be visually aligned.

The profiles are used to provide the bathymetry results over the Bornholm I survey area and a specific sub-section of the report for each profile is presented, where features of interest are discussed. The profiles generally show that the water depth increases gradually from east to west, and from south to north across Bornholm I site.

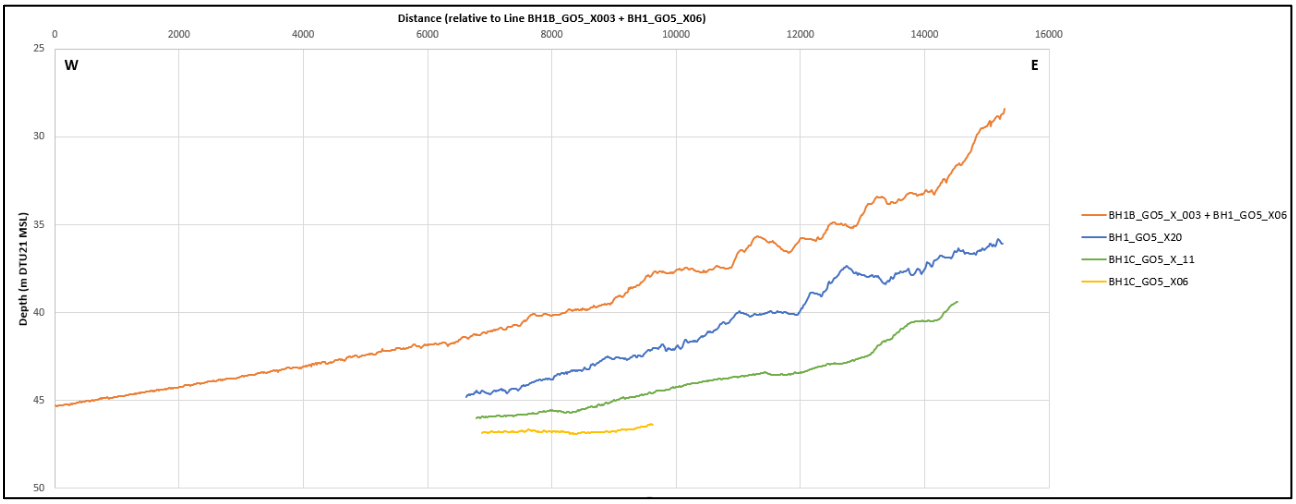


Figure 26: Profiles across BHI showing depth relative to DTU21 MSL. Profiles have been matched to the position of survey lines BH1B_GO5_X_003 + BH1_GO5_X06

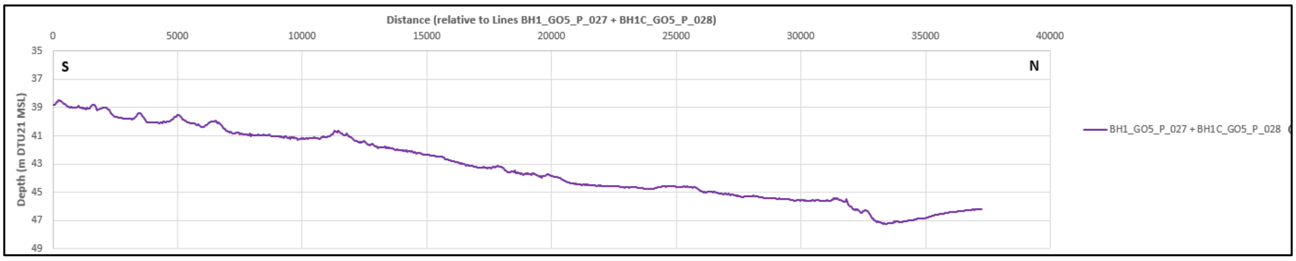


Figure 27: Longitudinal profile across BHI showing depth relative to DTU21 MSL

8.2.1 Profile BH1C_GO5_X016

Profile BH1C_GO5_X016 (Figure 28) is located 2.1 km south of the northern corner of the survey area and spans 2.8 km across the site. The depth variation is 0.53 m from a minimum depth of 46.35 m at 464865 m E, 6107282 m N to a maximum depth of 46.88 m at 463016 m E, 6108683 m N.

The profile reveals that the deepest seabed in the northern zone of the survey, with no significant change in depth in this area. Maximum depth variation for the BHI site is in this profile.

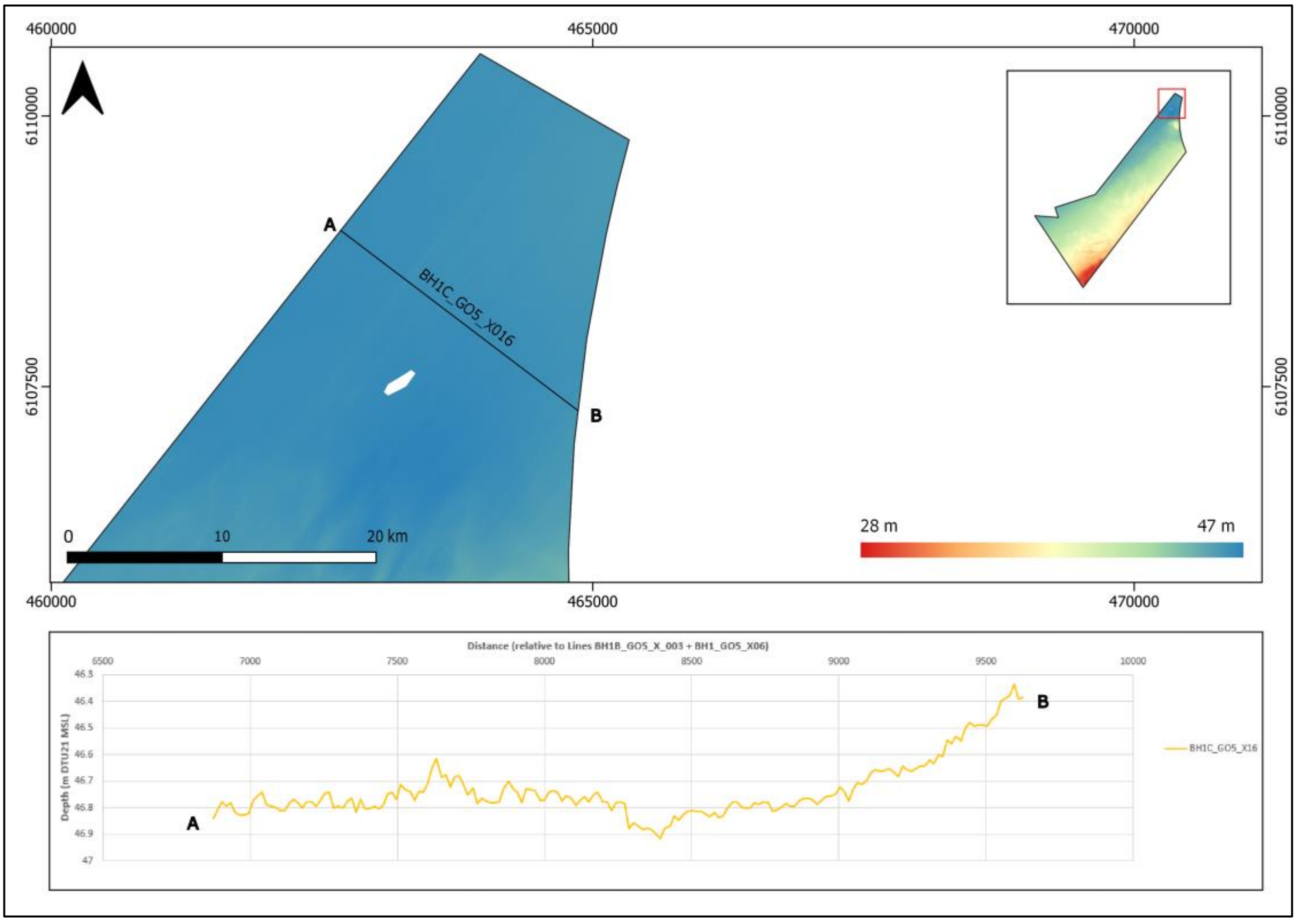


Figure 28: Profile BH1C_GO5_X016 location overview

8.2.2 Profile BH1C_GO5_X_011

Profile BH1C_GO5_X_011 (Figure 29) is located 7.1 km south of the northern corner of the survey area and spans 7.5 km across the site. The depth variation is 6.65 m from a minimum depth of 39.31 m at 465763 m E, 6100318 m N to a maximum depth of 45.96 m at 459737 m E, 6104894 m N.

Showing the same tendency as in the previous case, this profile also reveals that the deepest seabed is in the northern zone of the scope. Depth increment to the west is evident, with a smoothing of the slope in the same direction.

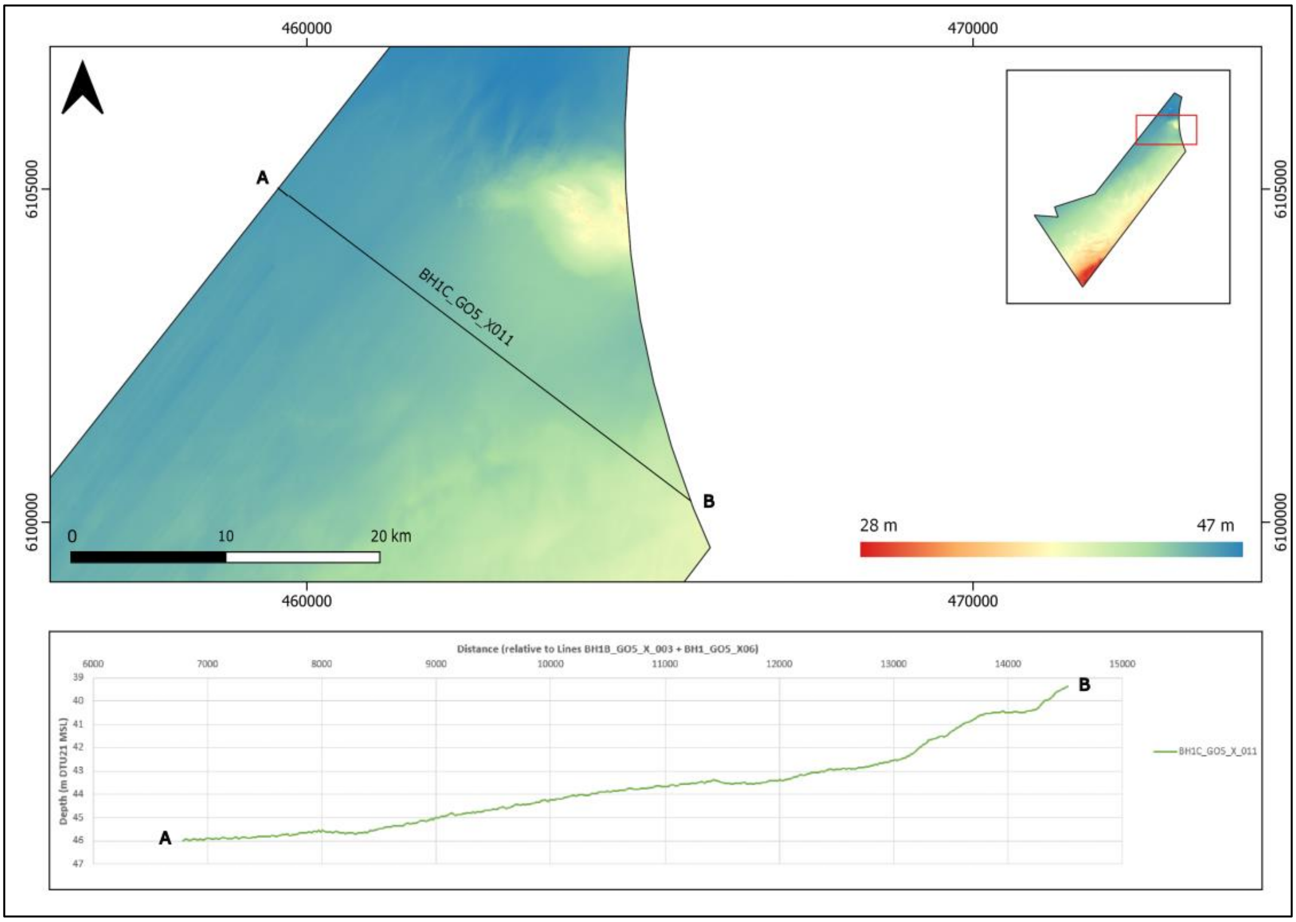


Figure 29: Profile BH1C_GO5_X_011 location overview

8.2.3 Profile BH1_GO5_X20

Profile BH1_GO5_X20 (Figure 30) is located 19.3 km from the southern corner of the site and spans 15.2 km of the survey area. The depth variation along this profile is 8.73 m from a minimum depth of 36.01 m at 458370 m E, 6089631 m N to a maximum depth of 44.74 m at 451528 m E, 6094805 m N.

Depth increments gradually to the west, but a presence of slight ridges associated with boulder field (top of till) areas can be observed. These areas have some variation in the bathymetry that interrupts the smoother trend of the profile in some discrete areas east of the profile.

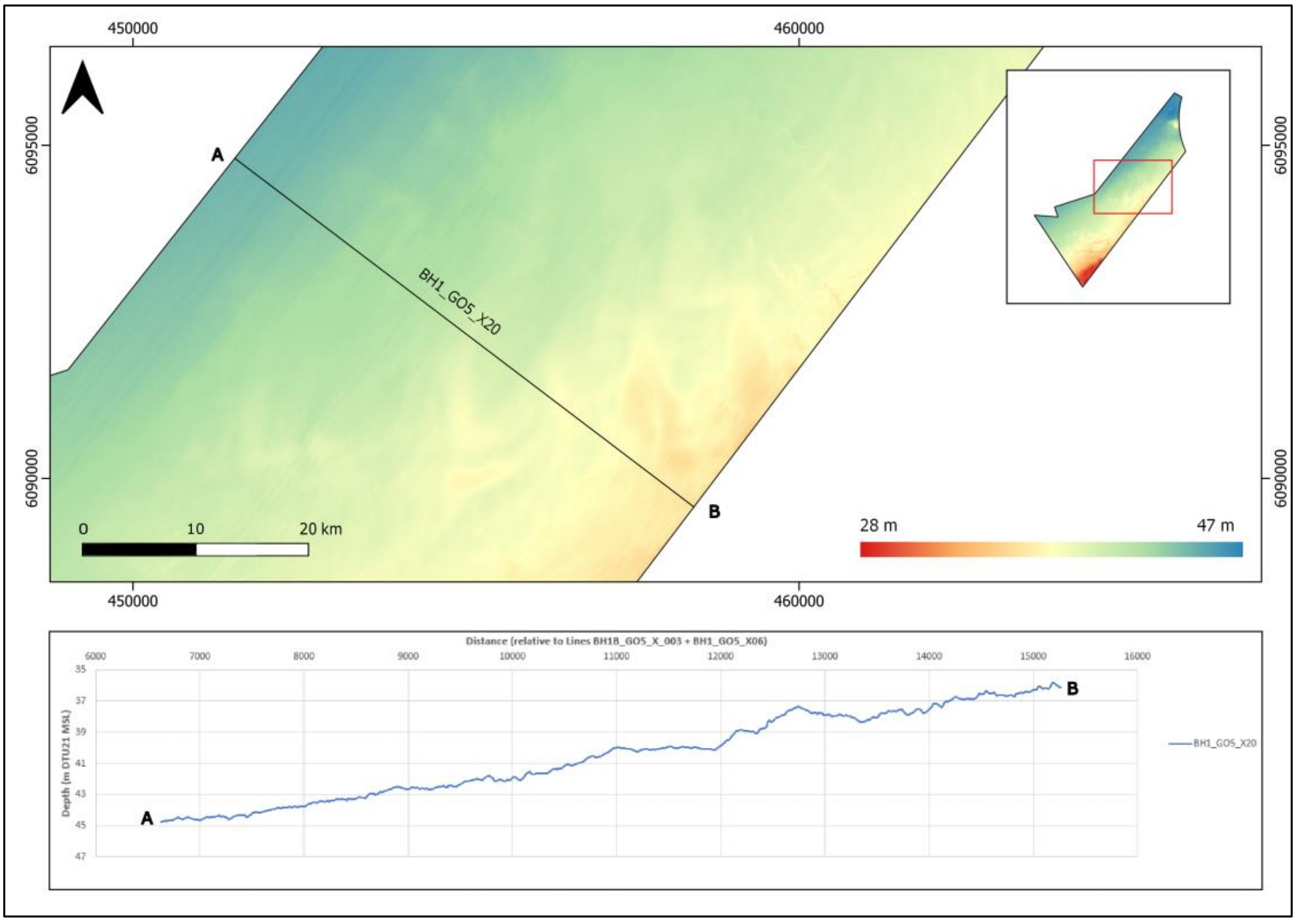


Figure 30: Profile BH1_GO5_X20 location overview

8.2.4 Profile BH1B_GO5_X_03 + BH1_GO5_X06

Profile BHI_GO5_X06 (Figure 31) is located at the southern zone of the survey, 5.3 km from the southern corner, and spans 15.2 km across the site. The depth variation along this profile is 13.89 m from a minimum depth of 28.38 m at 437790 m E, 6087664 m N to a maximum depth of 42.27 m at 449965 m E, 6078412 m N.

The depth increases towards the west and in the shallowest area, to the east of the profile, there is a steep slope and rough bathymetry that coincides with ripple areas (wavelength 0.5 – 2 m). It is in this profile where the minimum depth variation for the BHI site exists.

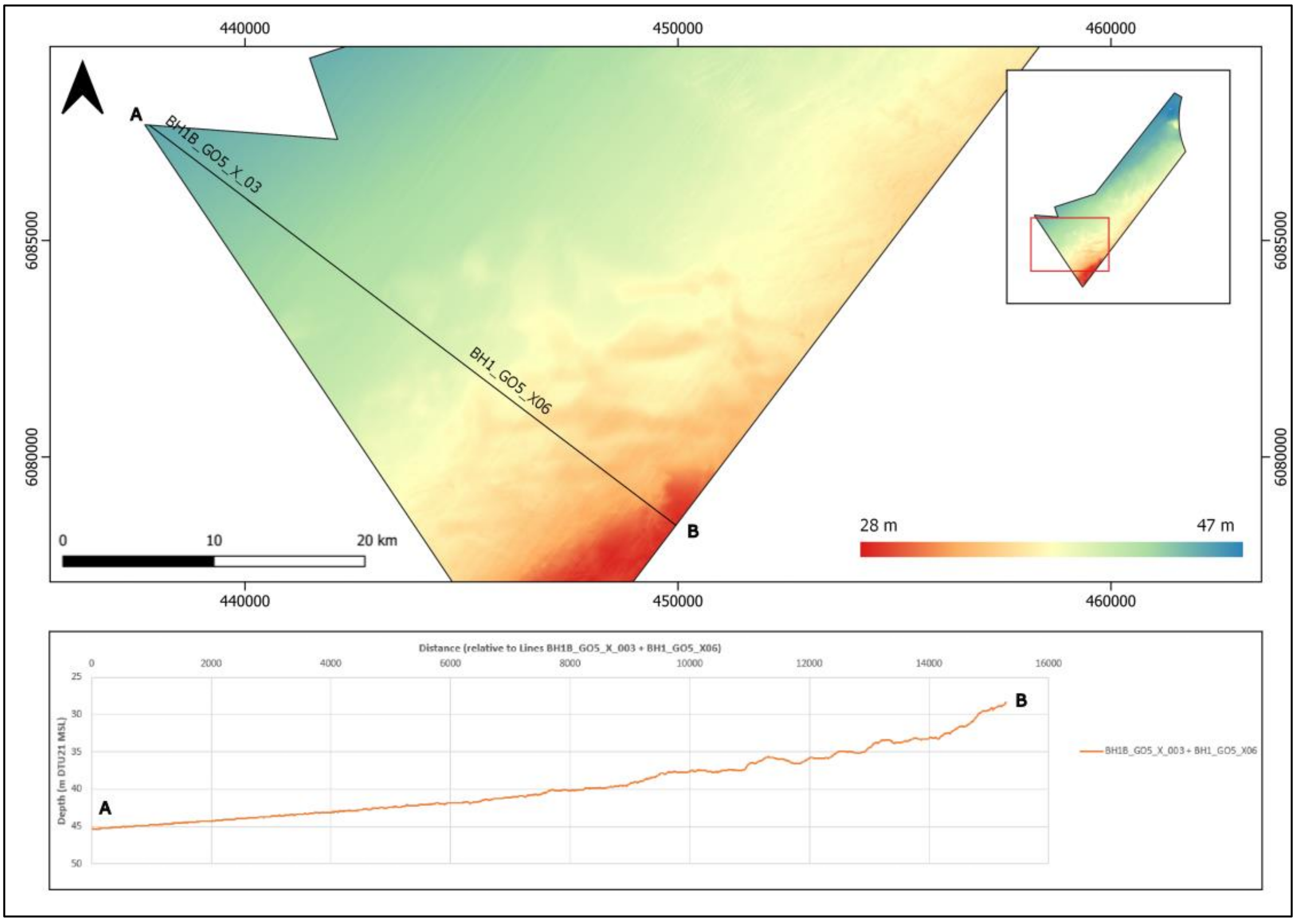


Figure 31: Profiles BH1B_GO5_X_03 + BH1_GO5_X06 location overview

8.2.5 Profile BH1_GO5_P_027 + BH1C_GO5_P_028

Profile BH1C_GO5_P_027 + BH1C_GO5_P_028 (Figure 32) crosses the survey area from south to north, and spans 37 km. The depth variation along this longitudinal profile is 7.37 m from a minimum depth of 38.79 m at 463246 m E, 6106820 m N to a maximum depth of 46.16 m at 443988 m E, 6081489 m N.

The depth increases from south to north. This profile crosses the deepest point of the entire scope in the northern part, after an abrupt depth change. In the shallow zone (south) the bathymetry is rougher and with more abrupt changes than in the deeper zone (north).

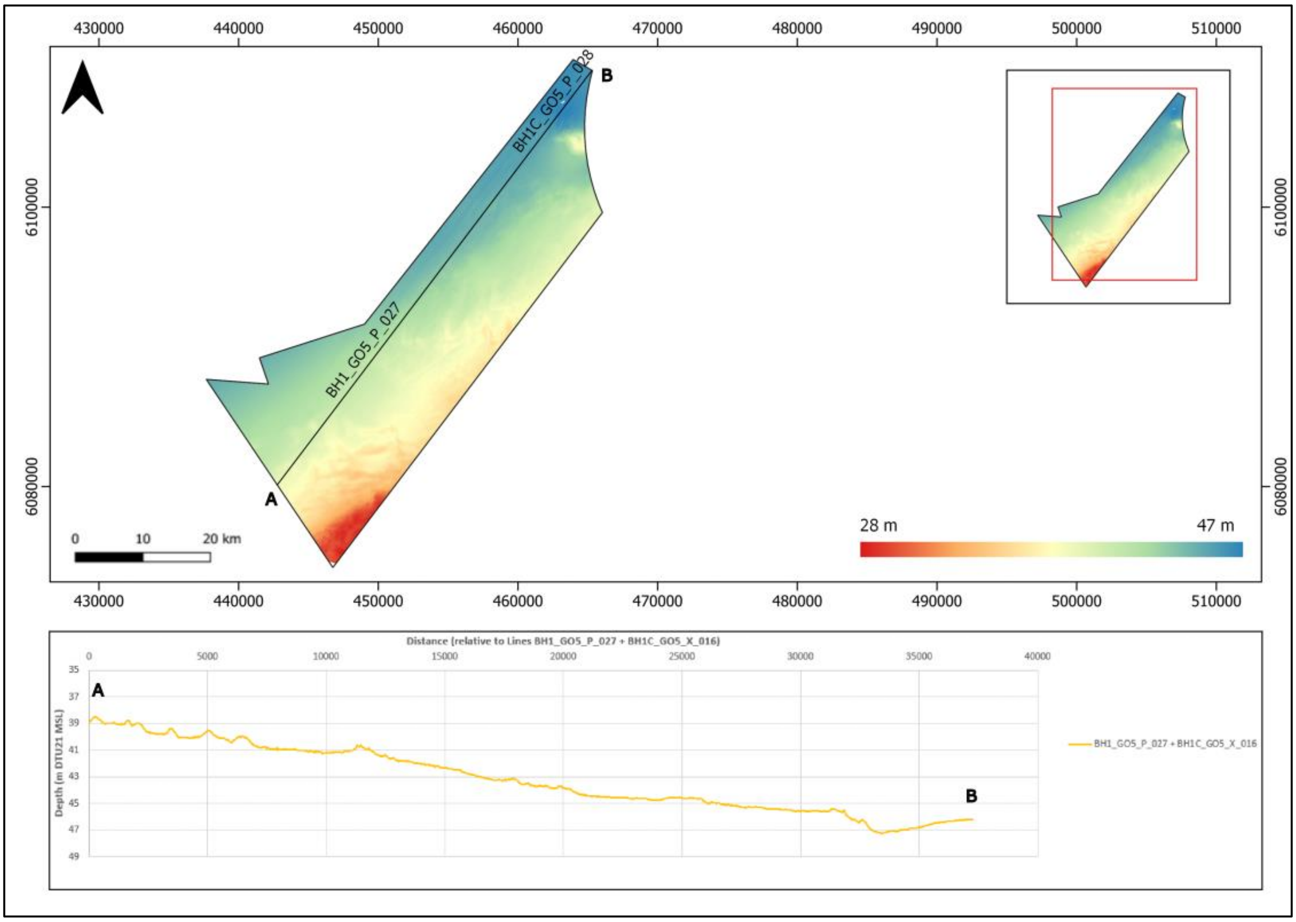


Figure 32: Profile BH1_GO5_P_027 + BH1C_GO5_P_028 location overview

8.2.6 Slope analysis

Slope angles were derived from 1 m resolution bathymetry data in QGIS. This data has been used as the basis for assessing gradients across Bornholm I.

Slope angles across the site are typically very gentle (<1º) and gentle (1º - 5º). The maximum slope in the survey area is 53.08º distributed on several features. The most remarkable feature associated with maximum slope is centred on the northern part of the survey, at 456952 m E, 6094394 m N. This corresponds to a wreck, which has not been correlated with any known wrecks, located at an approximate depth of 37 m and which dimensions are 31 m length and 10 m width. This feature is presented in Figure 33.

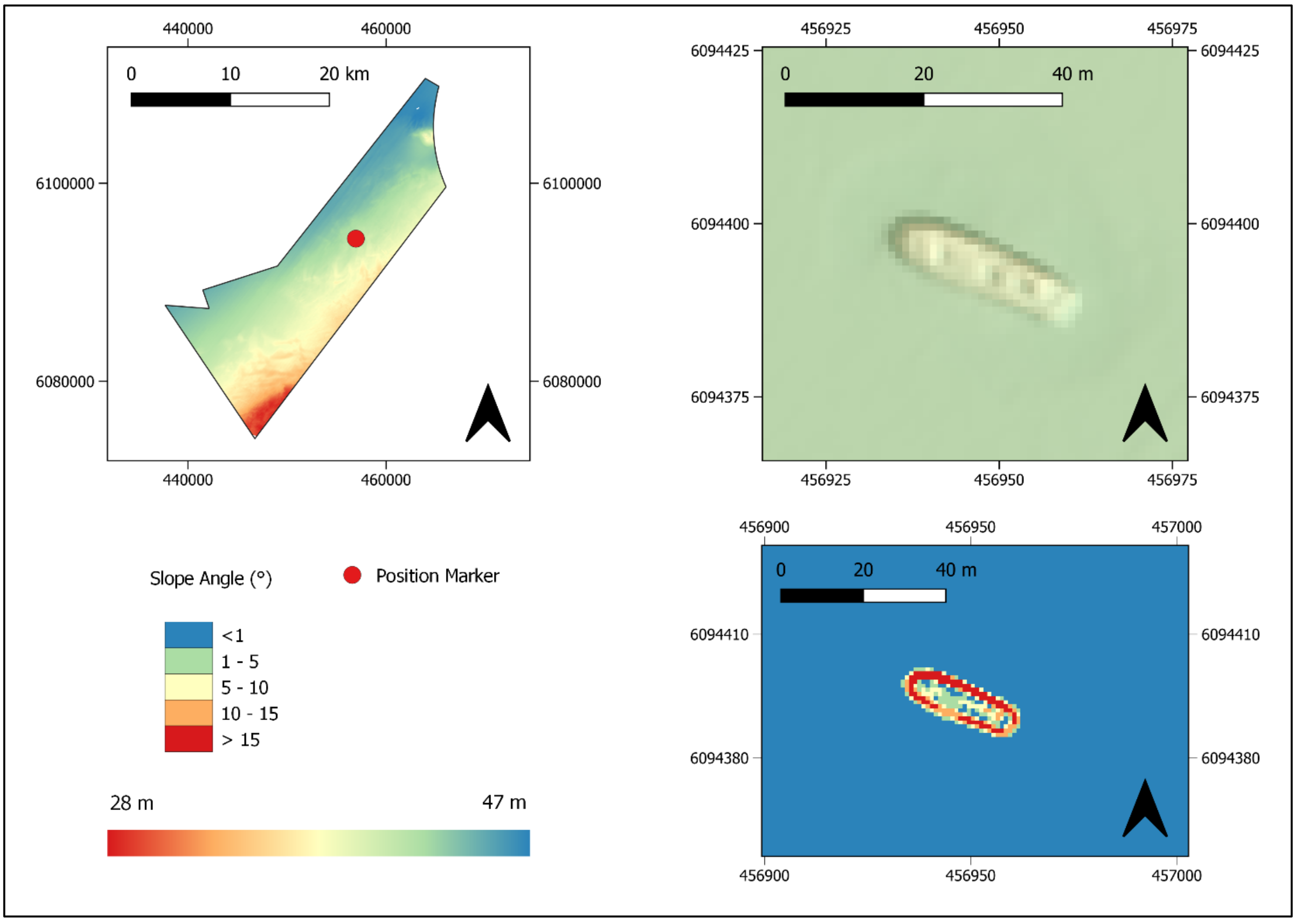


Figure 33: Wreck contact with >15º slope angle in northern zone of Bornholm I

In the extended scope Bornholm 1C, maximum slope values are associated with a wreck. It is located at 463726 m E, 6098644 m N, at an approximate depth of 40 m and which dimensions are 57 m length, 10 m width. The slope information of this wreck is presented in Figure 34.

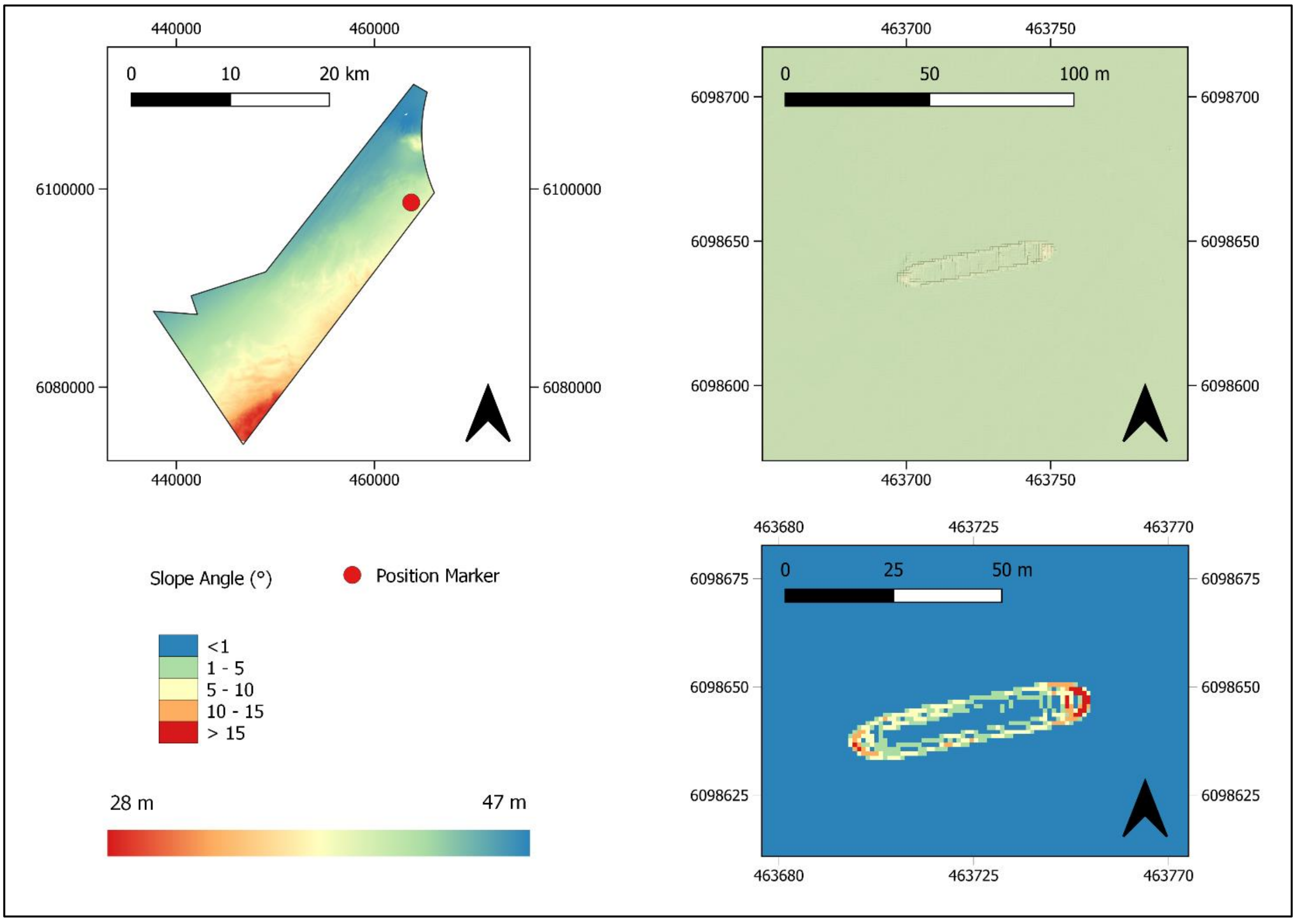


Figure 34: Wreck contact with > 15º slope angle in the extended scope Bornholm 1C

Changes in the slope exist in the northern part of the site at 155949 m E, 6096656 m N. These changes are related to jack-up vessel footprints and seabed disruption, located at a depth of 46 m. The area is about 7 km^2, with 22 m diameter for each jack-up footprint (Figure 35).

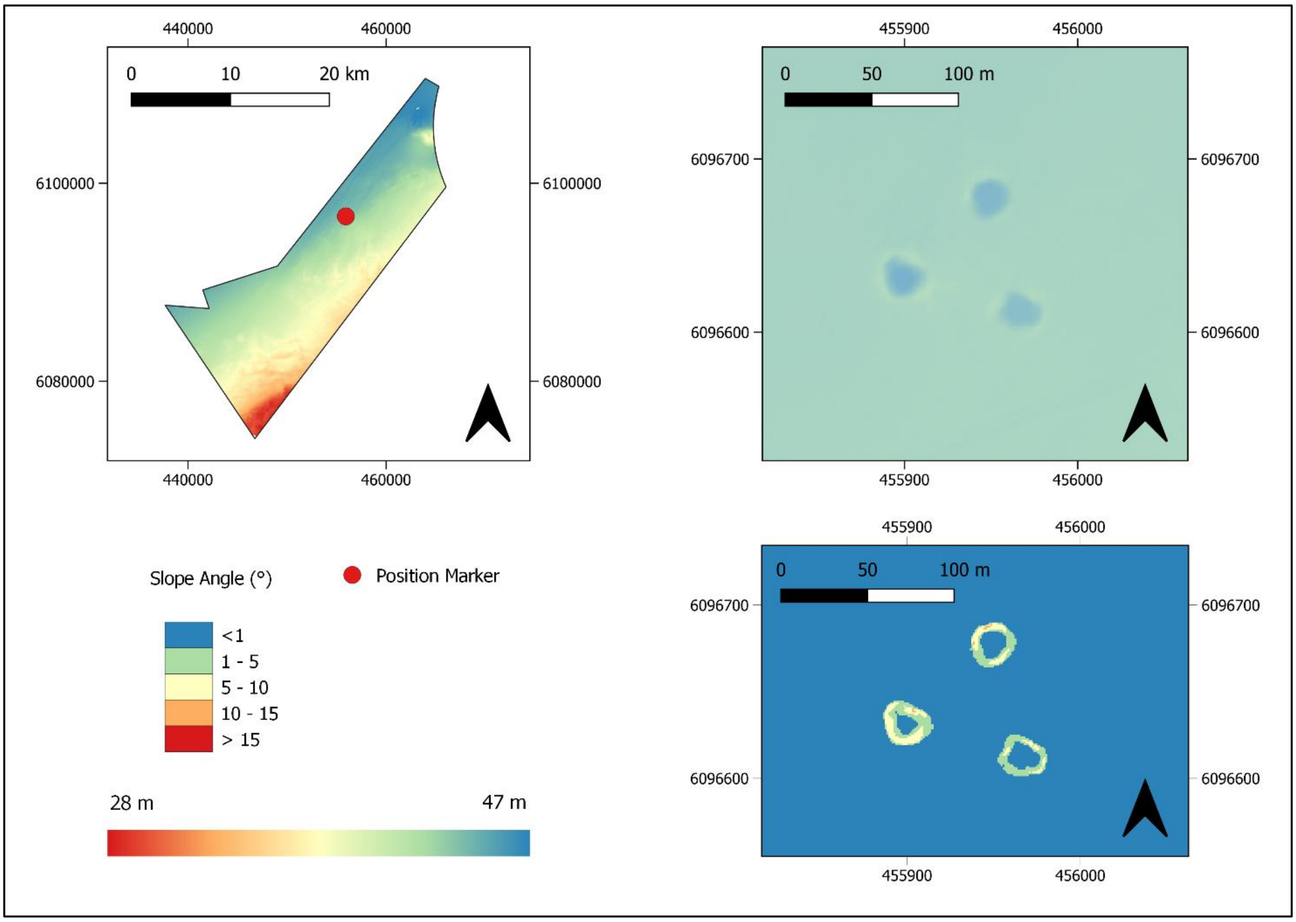


Figure 35: Jack-up vessel footprint and seabed disruption with >15º slope angle in the northern zone of Bornholm I

South of Bornholm I, a moderate-steep slope (5º - 10º) is related to a 4 km^2 disturbed raised seabed. It is unknown if this feature is man-made or natural. It is located at 441461 m E, 6082342 m N, and at a depth of 41 m. This feature is presented in Figure 36.

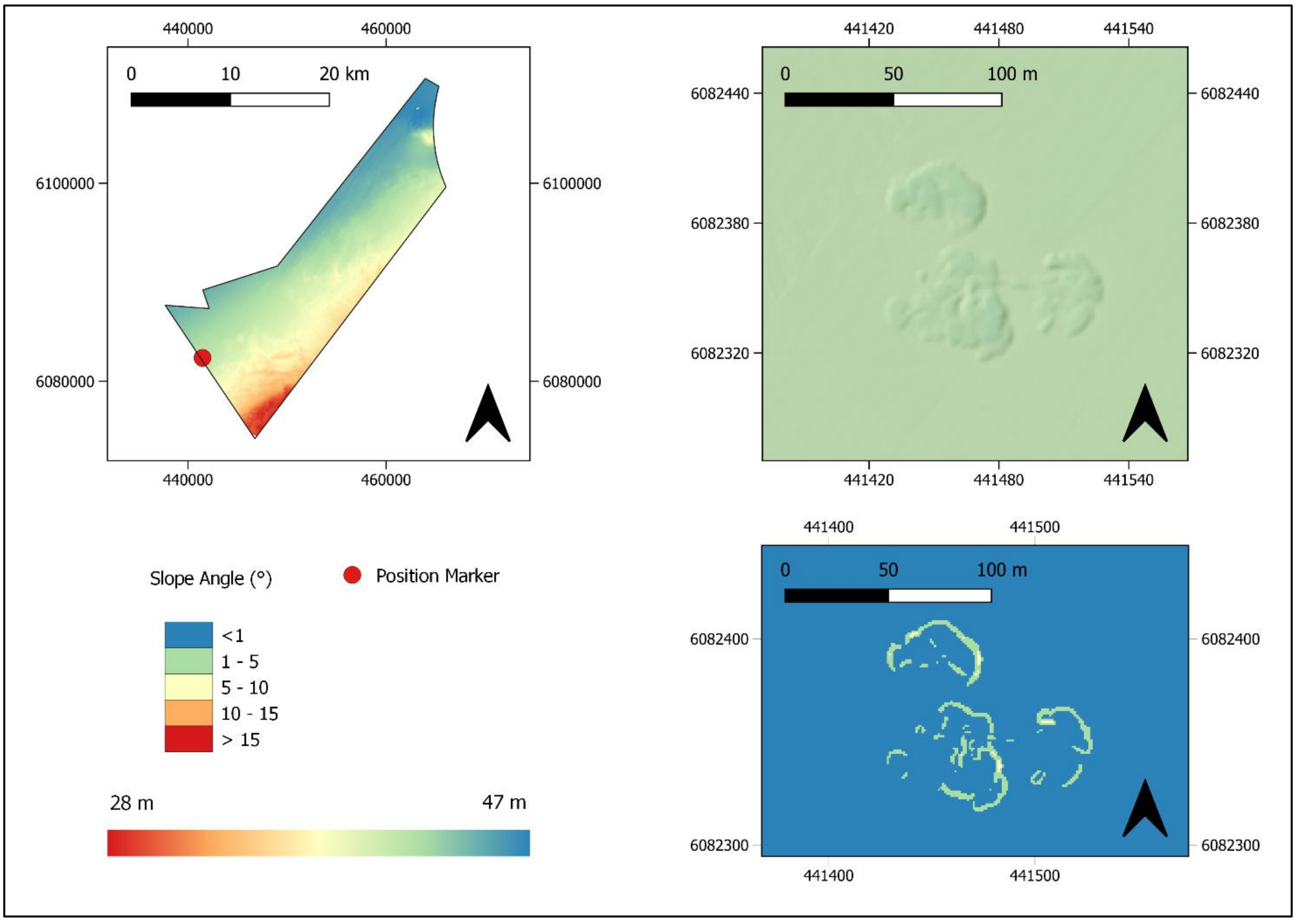


Figure 36: Disturbed raised seabed (unknown if man made or natural) with generally moderate – steep (5º - 10º) slope angle in southern zone of Bornholm I

In the northernmost part of the scope there is a larger area with a moderate-steep slope (5º - 10º), matching with elongated depressions easily recognisable by their shape both in the bathymetry and slope maps. These depressions are presented in Figure 36.

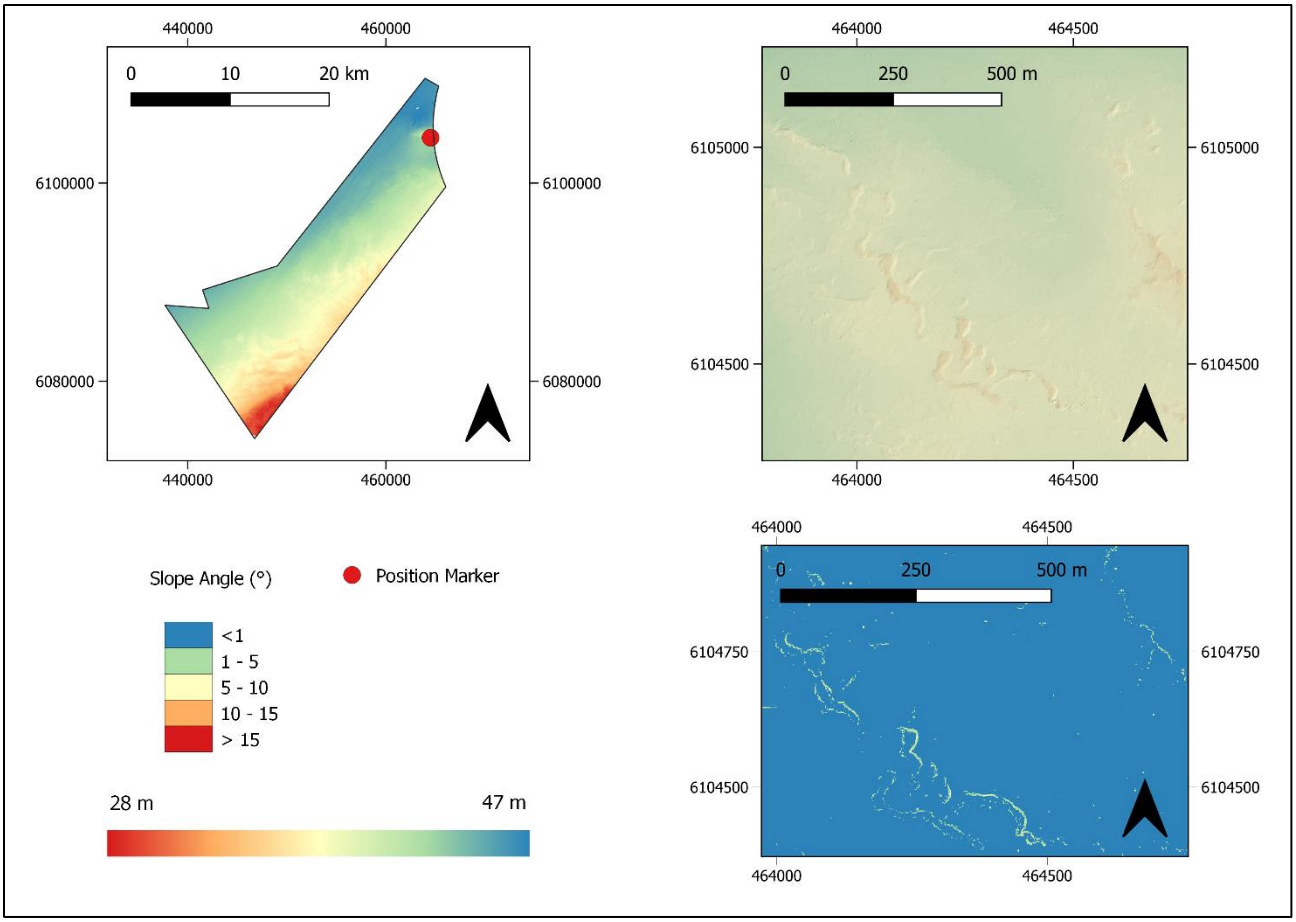


Figure 37: Elongated depressions with moderate – steep slope (5º - 10º) slope in northern Bornholm I

The highest slope angles associated with seabed features is moderate (5º - 10º). In the central-west part of the scope, the seabed has a slight rough texture and is directly associated with erosional features, possibly seabed gullies, oriented NNE-SWW. This area is presented in Figure 38. High slope angles related to linear seabed features occur in the central part of Bornholm I, consisting of erosional trenches created by the presence of clay. This is presented in Figure 39. Other seabed features consist of an erosional depression located at the southern area of the site, at 444807 m E, 6079340 m N. It is about an area of 0.49 ha at 34 m depth. Another location corresponds to an area close to a boulder field. It is located northeast of the site, (458397 m E, 6092107 m N) at an approximate depth of 38 m. It consists of a rounded, unknown feature of 9 m in diameter located at 33 m from a boulder field, likely a large boulder.

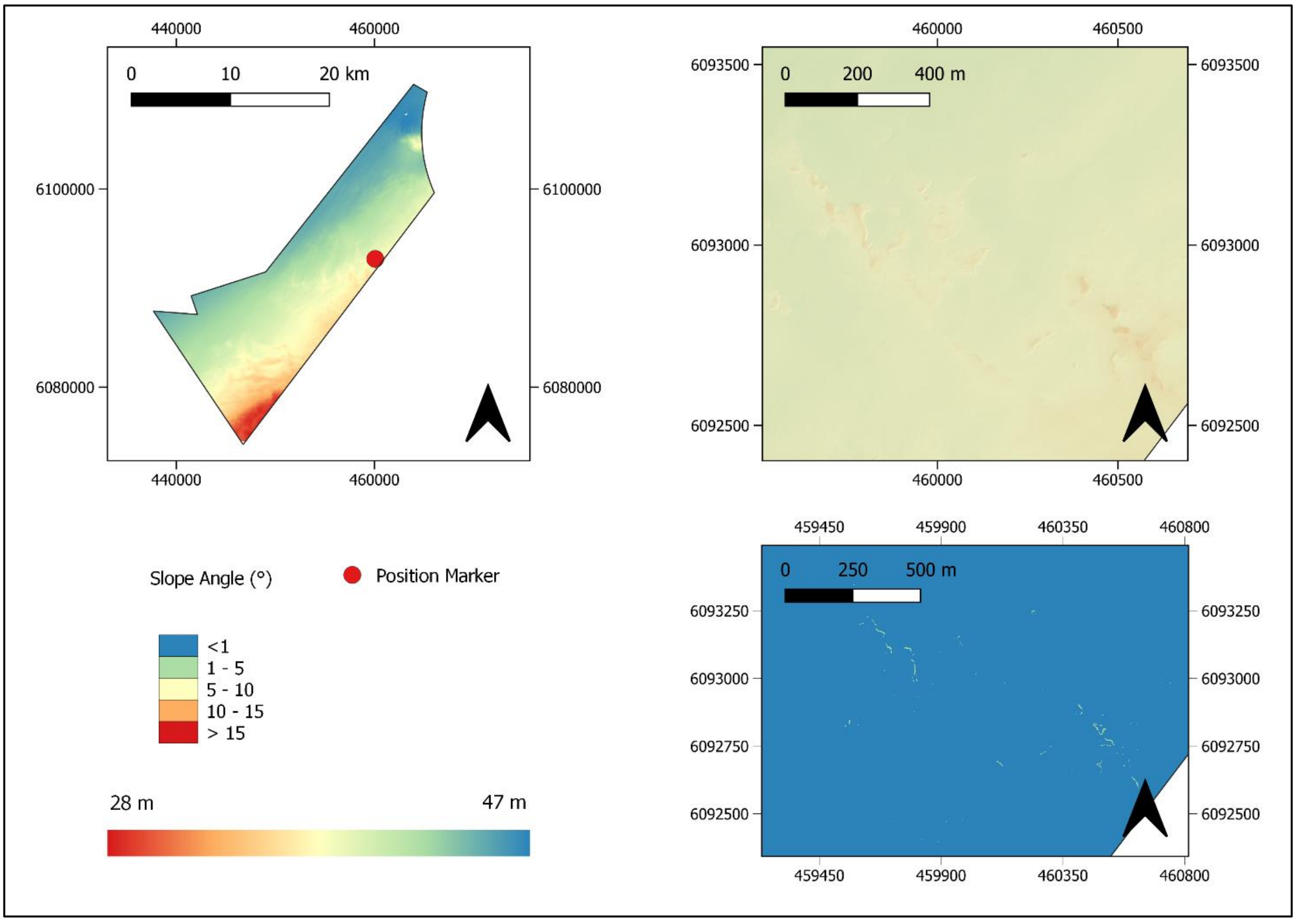


Figure 38: Erosional features, possibly seabed gullies, oriented NNE-SWW, with gentle-moderate (1º - 10º) slope angle in south-west zone of Bornholm I.

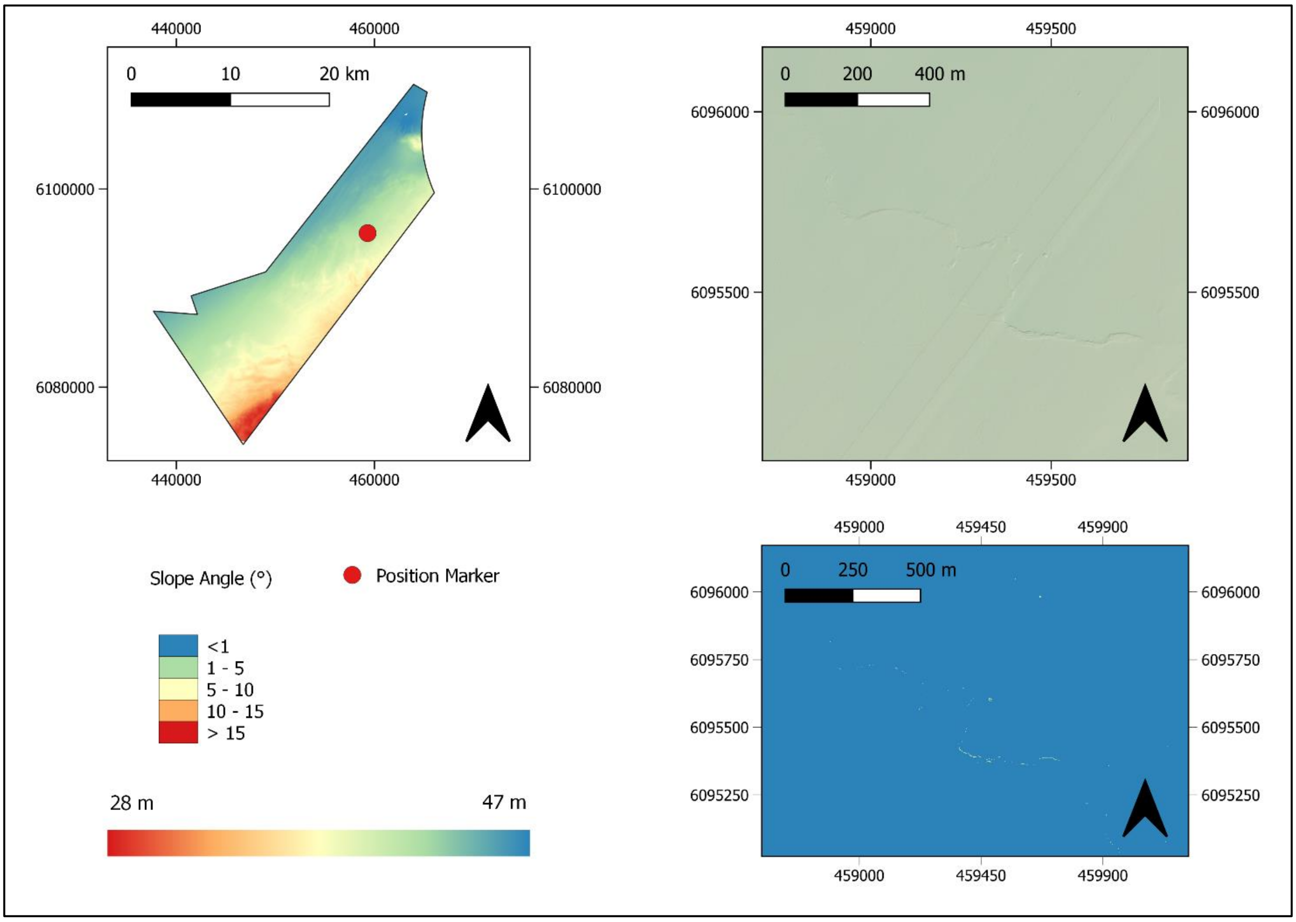


Figure 39: Erosional trenches created by the presence of clay with moderate-steep (1° - 10°) slope angle in northern zone of Bornholm I.

Other locations where moderate-steep slopes can be found are scattered widely across the survey area and are generally associated with anchor seabed or anchor scars, probably related to fishing or dragging activities. Example of these areas are presented at:

- 454302 m E, 6097403 m N
- 458891 m E, 6097418 m N
- 454516 m E, 6097418 m N
- 444017 m E, 6080879 m N

8.3 SEABED SURFACE CLASSIFICATION: GEOLOGY

The seabed geology for BHI, BHIB and BHIC was evaluated from the interpretation of the low frequency SSS data and backscatter datasets. The resultant seabed surface geology interpretation is highlighted in Figure 40.

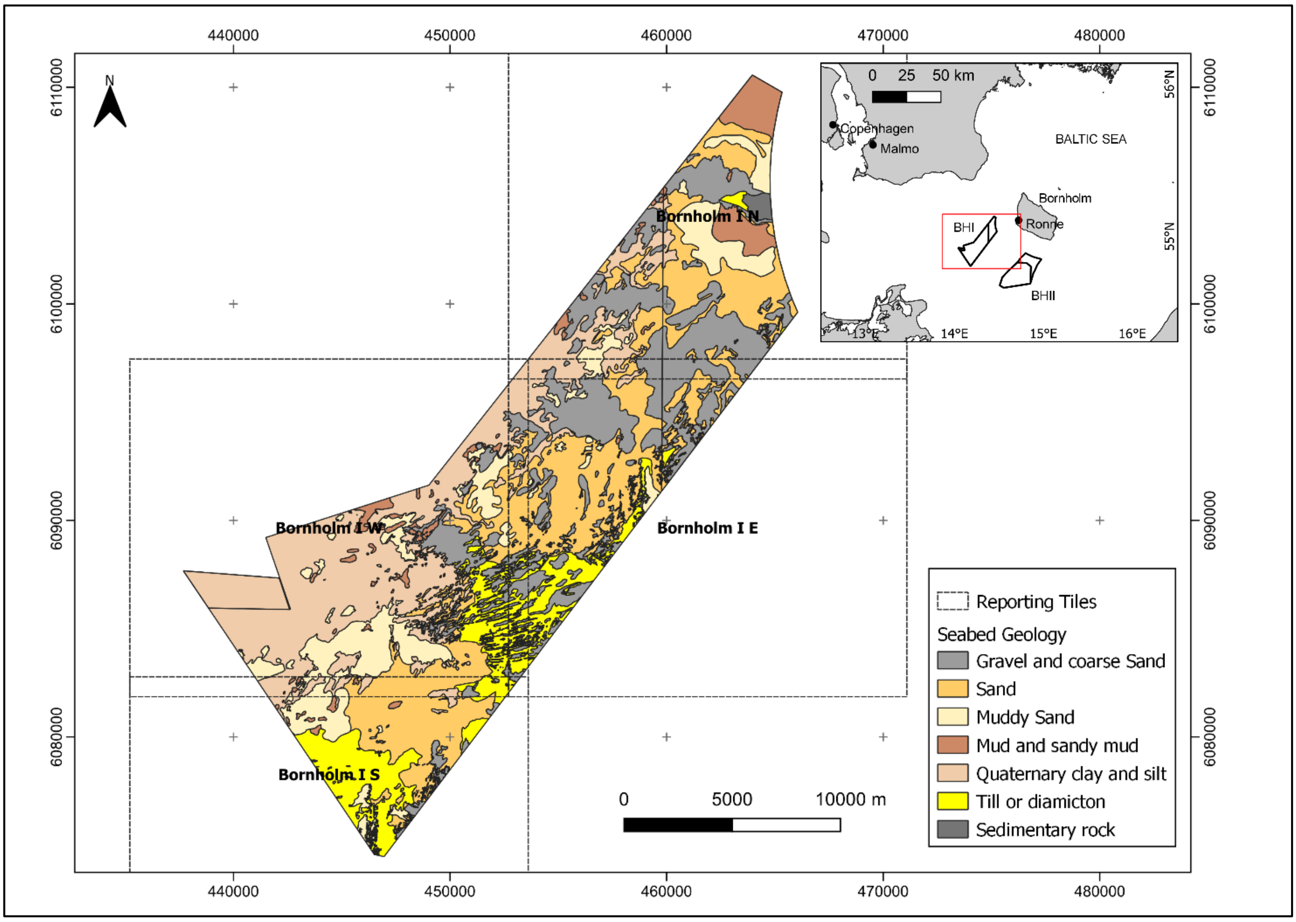
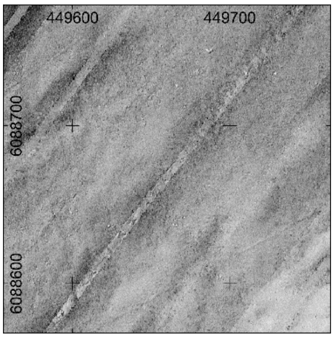
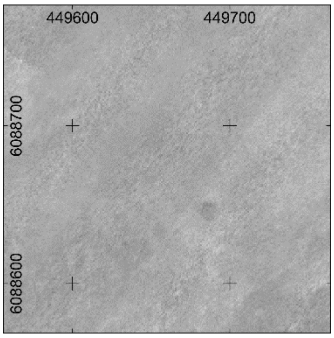
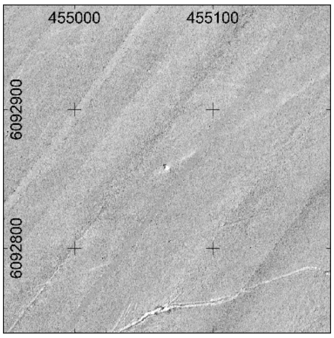
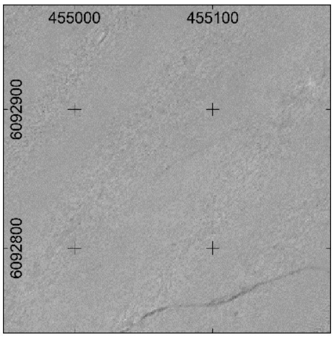
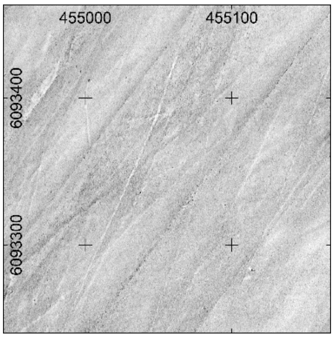
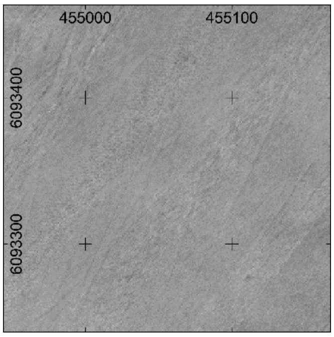
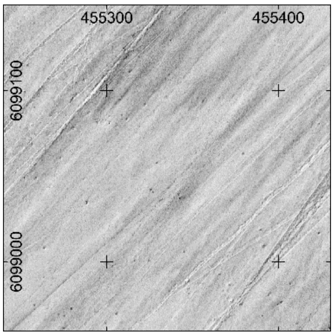
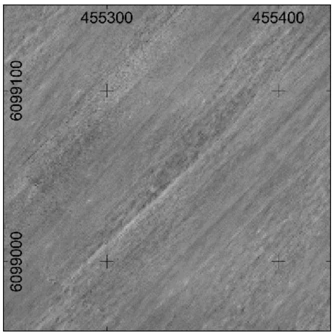
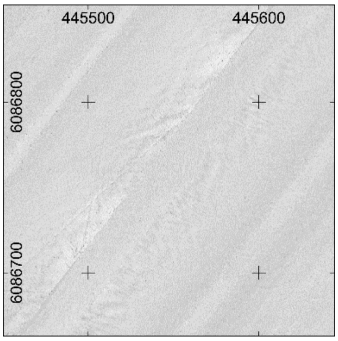
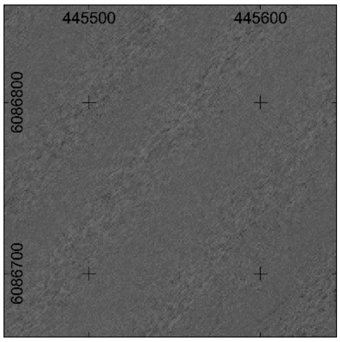
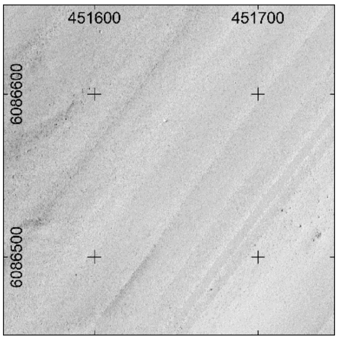
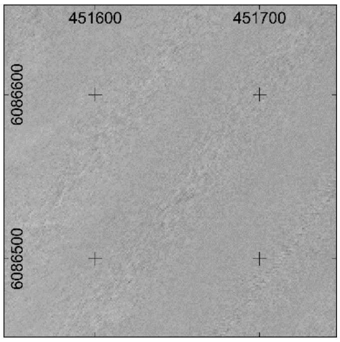
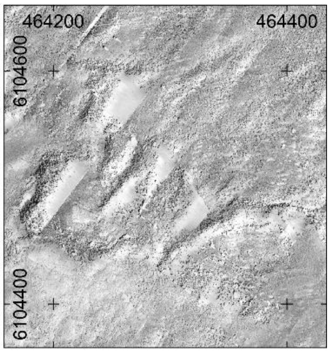
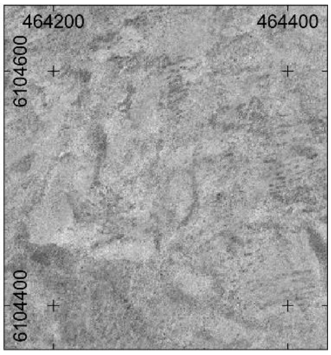


Figure 40: BHI seabed surface geology classification

Table 22 highlights the seabed geology classification interpreted across the BHI, BHIB and BHIC sites. Geological interpretation using geophysical data was guided by the grab sampling campaign.

Table 22: Geological interpretation

<table>
<tr><th>Geological Interpretation</th><th>Colour</th><th>Acoustic description</th><th>SSS LF image</th><th>Backscatter image</th></tr>
<tr><td>Gravel and coarse Sand</td><td></td><td>Medium to high reflectivity</td><td>
</td><td>
</td></tr>
<tr><td>Sand</td><td></td><td>Medium reflectivity</td><td>
</td><td>
</td></tr>
<tr><td>Muddy Sand</td><td></td><td>Low to medium reflectivity</td><td>
</td><td>
</td></tr>
<tr><td>Mud and sandy mud</td><td></td><td>Low to medium reflectivity</td><td>
</td><td>
</td></tr>
</table>

Geological Interpretation	Colour	Acoustic description	SSS LF image	Backscatter image
Quaternary clay and silt		Low to Medium reflectivity		
Till or diamicton		Medium reflectivity		
Sedimentary rock		High reflectivity		

8.3.1 Seabed surface classification: Geology BHI north (Bornholm I N)

The seabed surface geology for the northern section of the site (Bornholm I N), is classified predominately as Sand. Areas of Silt and Clay occur mainly in the eastern part of Bornholm I N and extended zones of Gravel and coarse Sand are in the southern, western and northern parts (Figure 41). Muddy Sand areas occur in the central and northern parts, whereas finer sediments of Mud and Sandy Mud exist mainly in the eastern and northern parts of Bornholm I N. An area of Till and a sedimentary rock outcrop are in the north-eastern part of the region and a limited area of till in the south-eastern part (Figure 41).

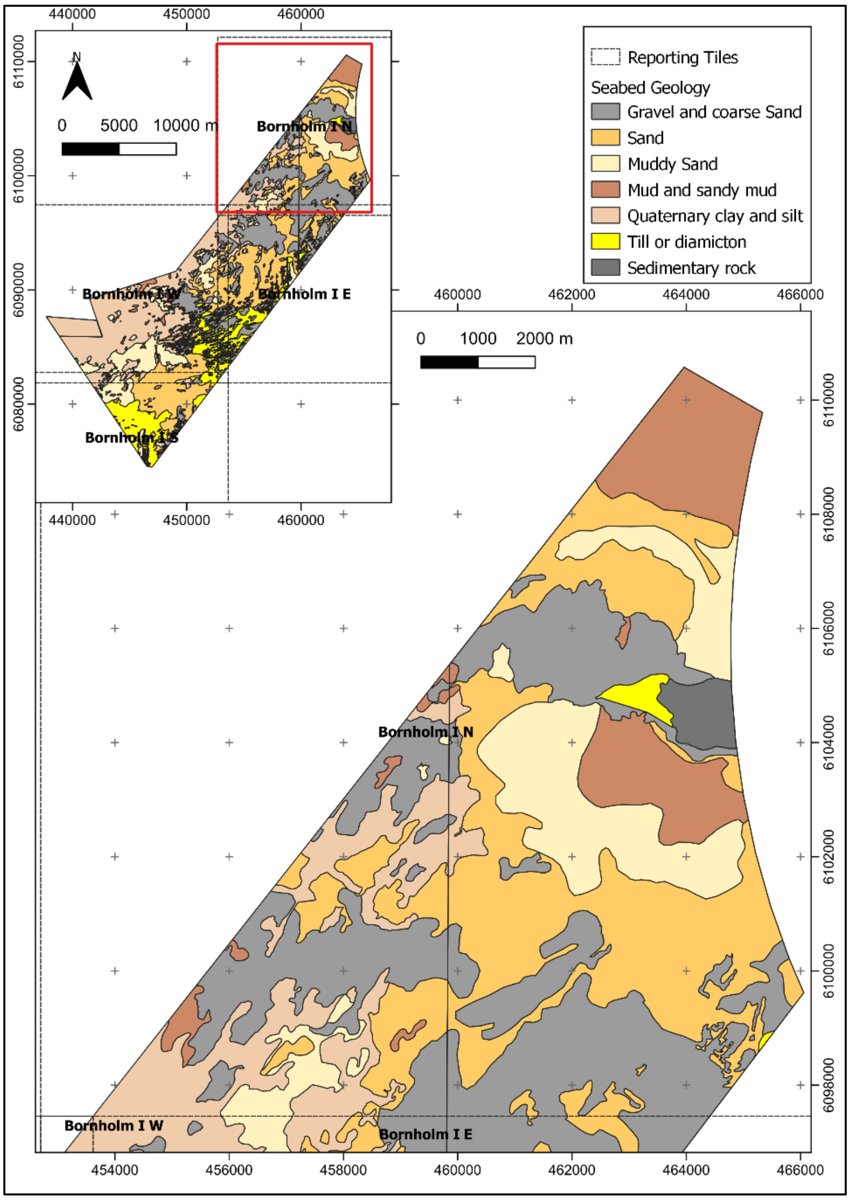


Figure 41: Seabed surface classification: Geology BHI north (Bornholm I N)

8.3.2 Seabed surface classification: Geology BHI east (Bornholm I E)

The seabed surface geology for the eastern section of the site (Bornholm I E), is classified as predominately Sand (Figure 42). Finer grain sediments comprising mainly Clay and Silt as well as Muddy Sand, Mud and Sandy Mud are delineated in the in the north-eastern part of Bornholm I E. Extended Gravel and coarse Sand areas are in the central and in the north-eastern part of Bornholm I E. Alternating bands of Gravel and coarse Sand with till cover the south-west of the Bornholm I E tile.

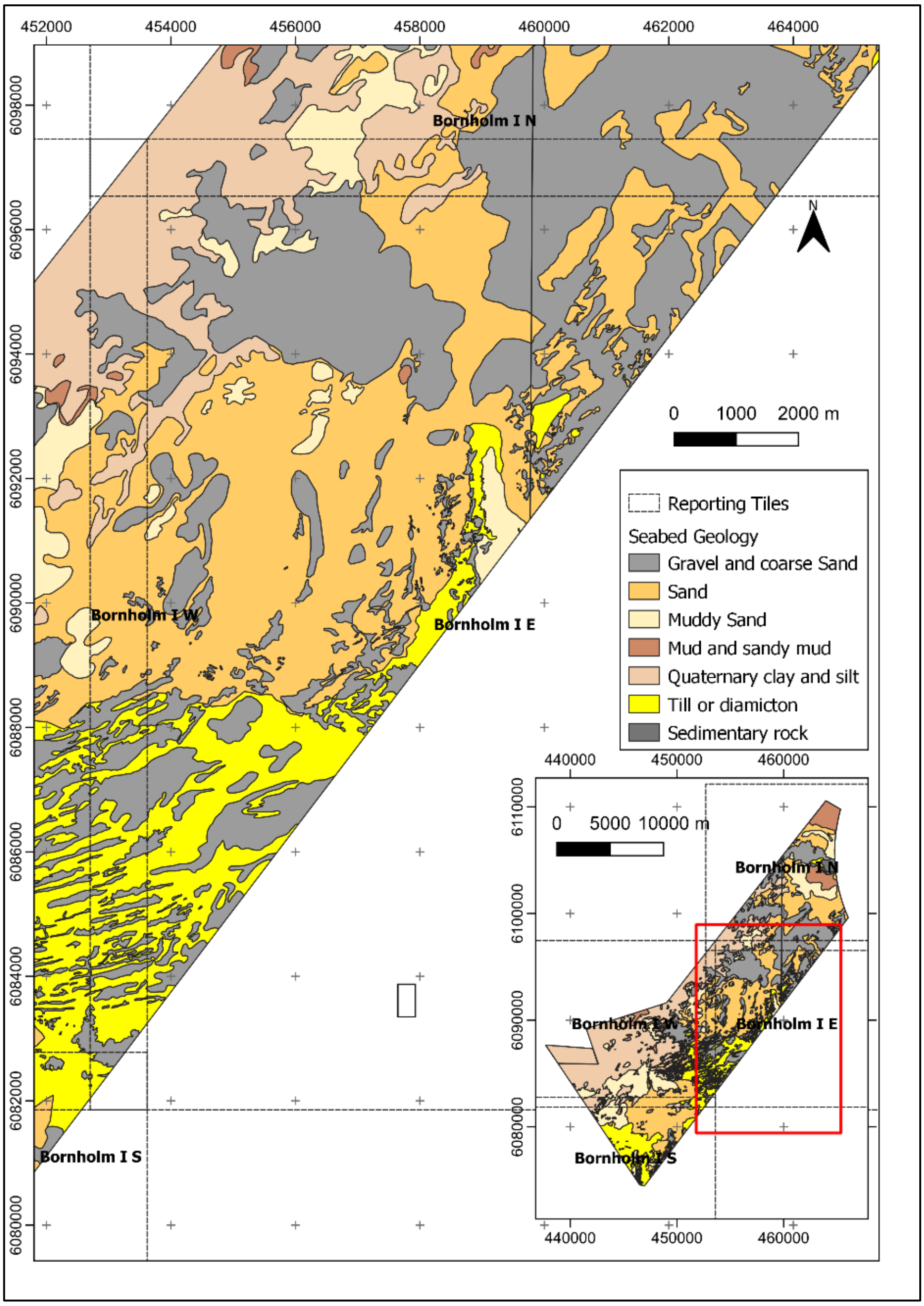


Figure 42: Seabed surface classification: Geology BHI east (Bornholm I E)

8.3.3 Seabed surface classification: Geology BHI south (Bornholm I S)

The seabed surface geology for the southern section of the site (Bornholm I S), is predominately Sand with fine grain sediments, mainly Muddy Sand and Clay and Silt, covering the north-east part of Bornholm I S (Figure 43). The southern part of Bornholm I S is predominantly till with patches of Gravel, Sand, Muddy Sand and Sandy Mud.

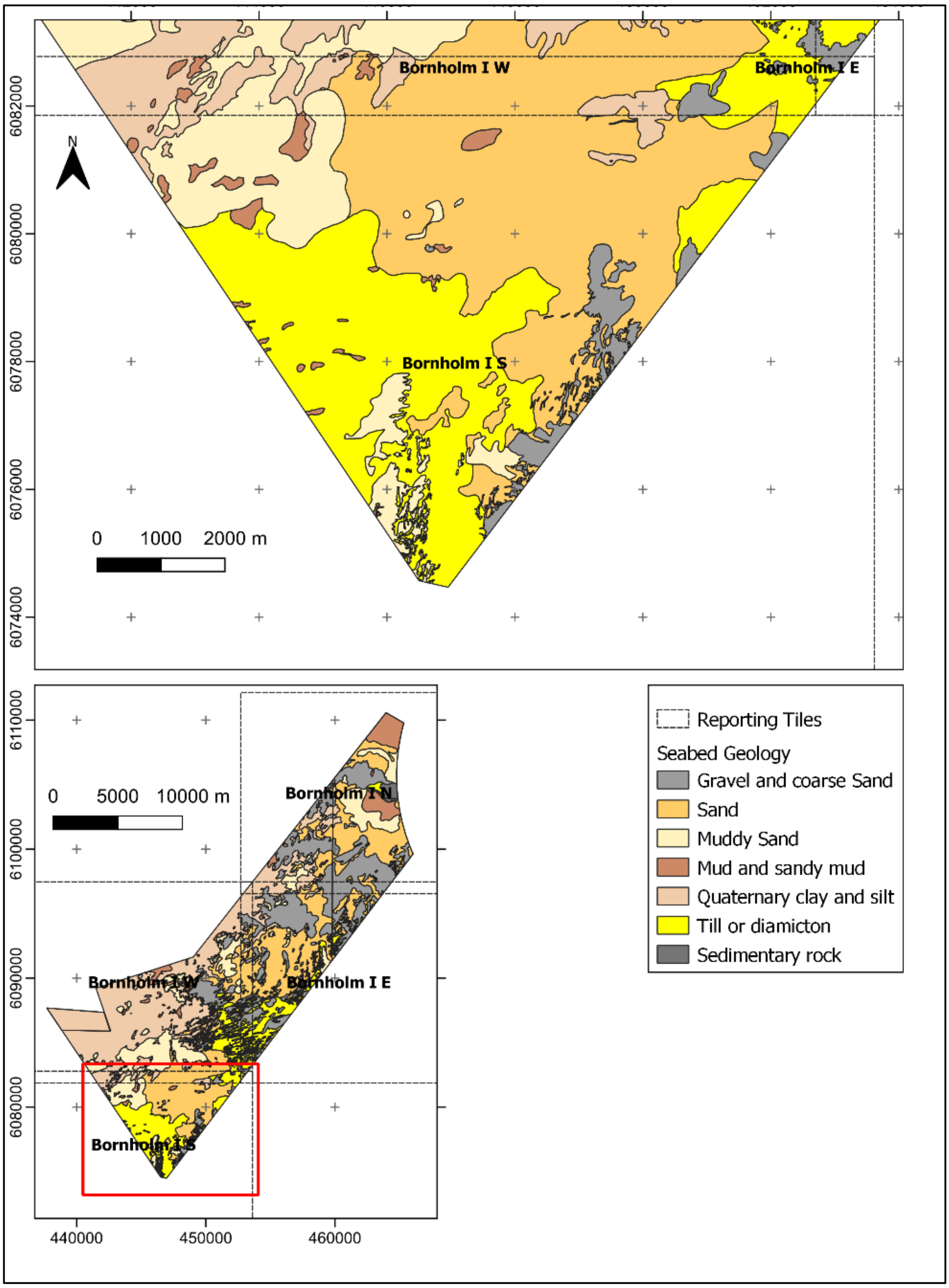


Figure 43: Seabed surface classification: Geology BHI south (Bornholm I S)

8.3.4 Seabed surface classification: Geology BHI west (Bornholm I W)

The seabed surface geology for the western section of the site (Bornholm I W) is predominately fine grain sediments consisting mainly of Clay and Silt along the northern part of the region (Figure 44). Mud and Sandy Mud, and Muddy Sand areas are widespread in the region. Sand dominates the south-eastern part and alternating bands of Till with Gravel and Sand ribbons are in the eastern part of Bornholm I W.

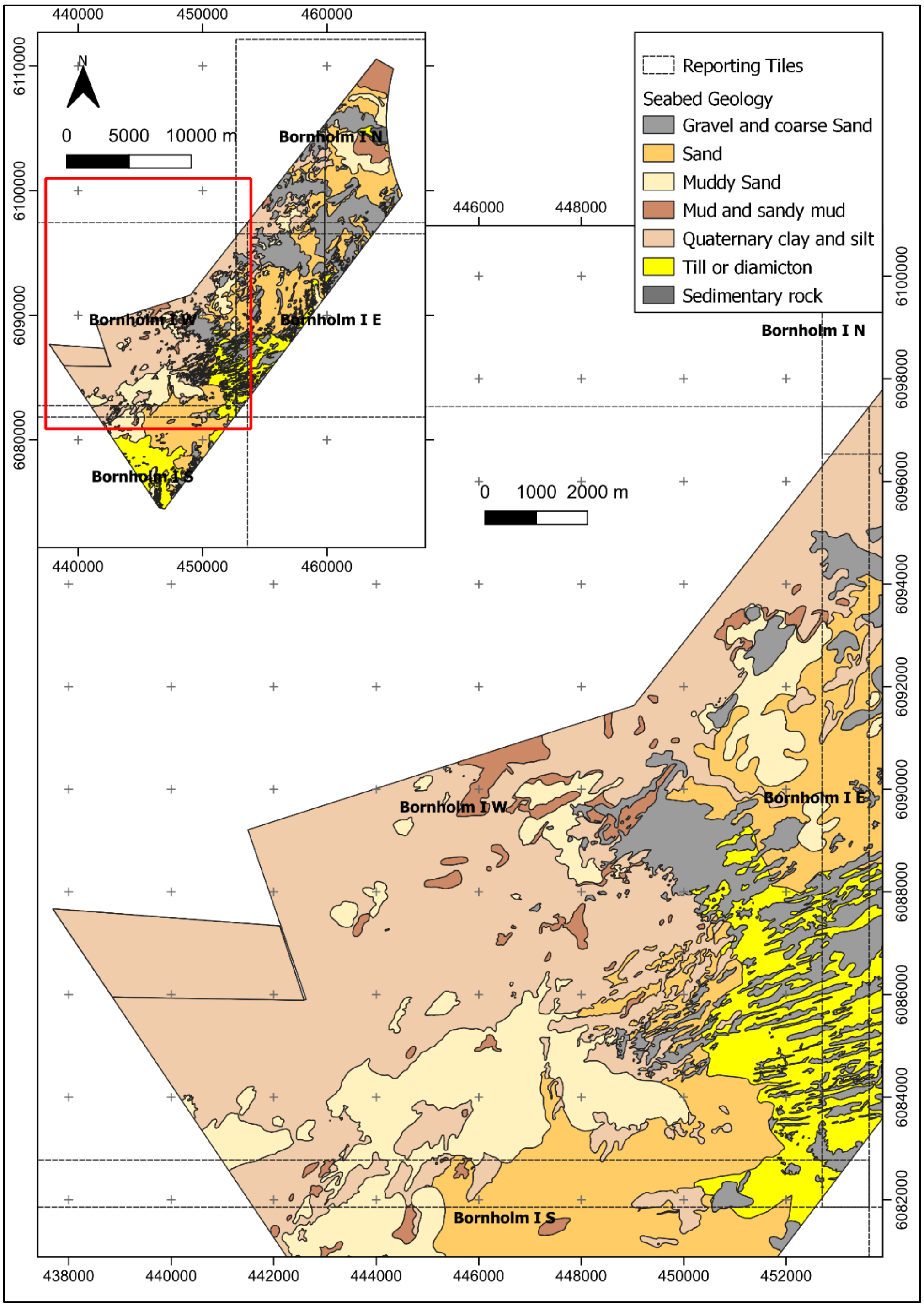


Figure 44: Seabed surface classification: Geology BHI west (Bornholm I W)

8.4 SEABED SURFACE CLASSIFICATION: MORPHOLOGY

The seabed morphology for BHI was evaluated from interpretation of the low frequency SSS data and backscatter imagery. The resultant seabed surface morphology interpretation is described in Figure 45.

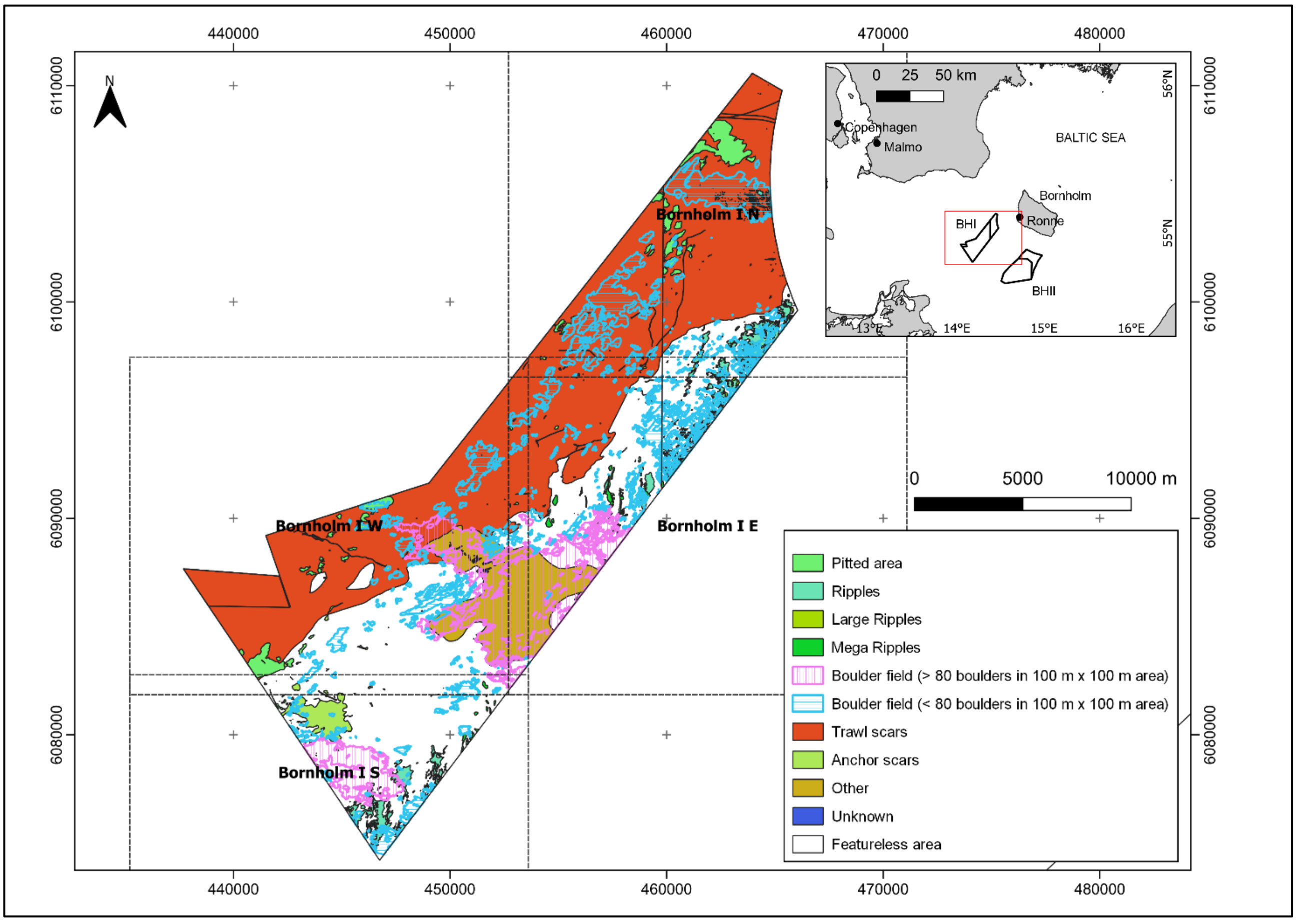
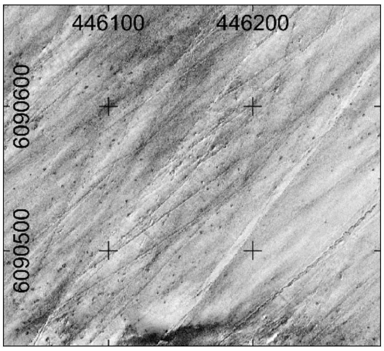
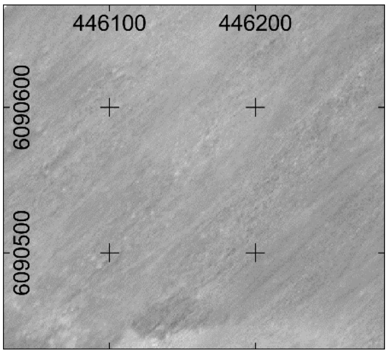
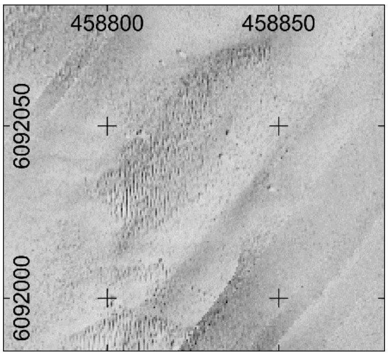
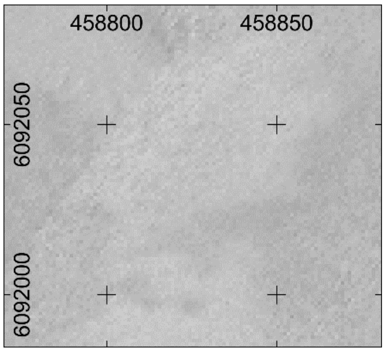
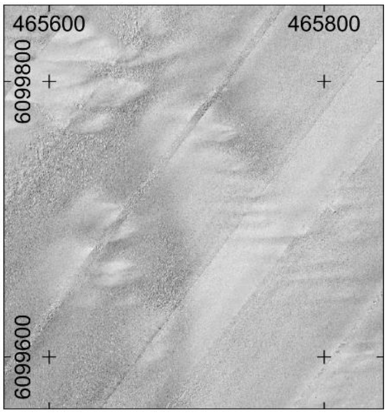
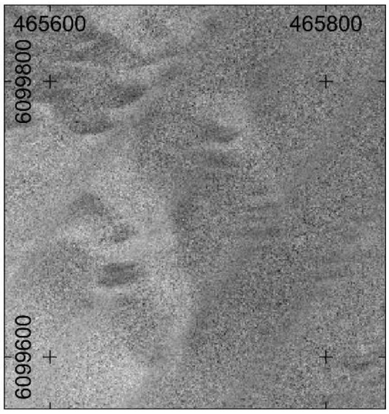
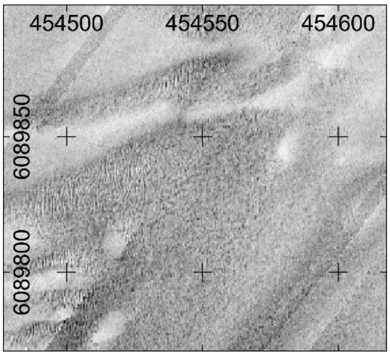
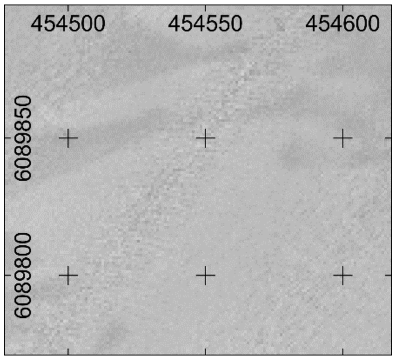
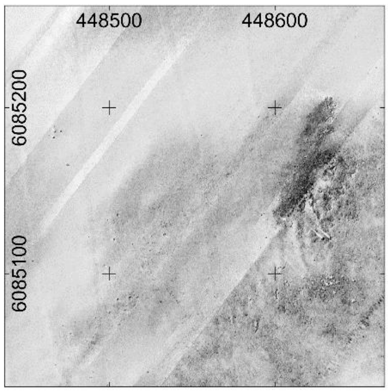
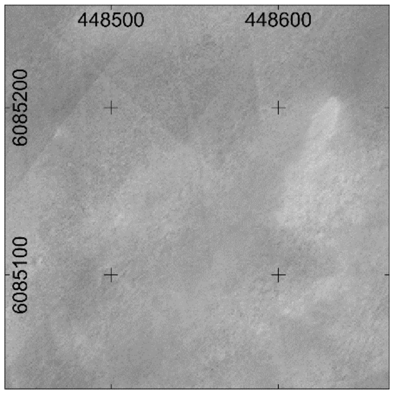
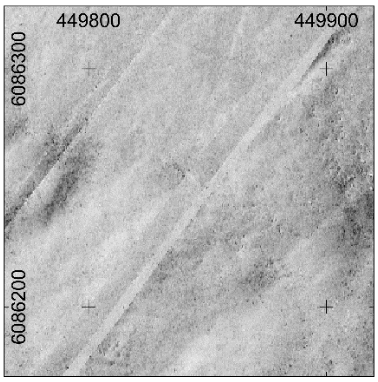
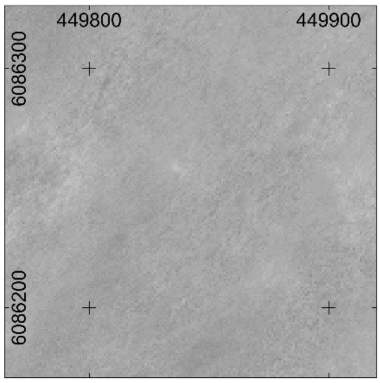


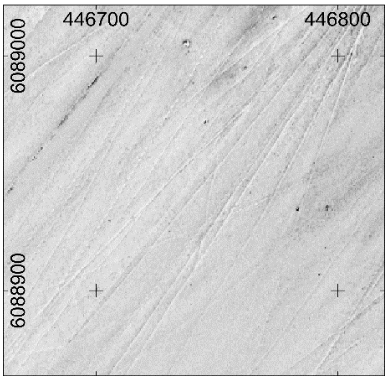
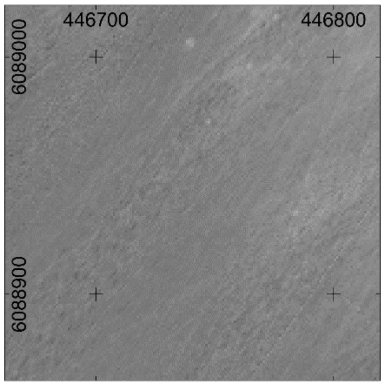
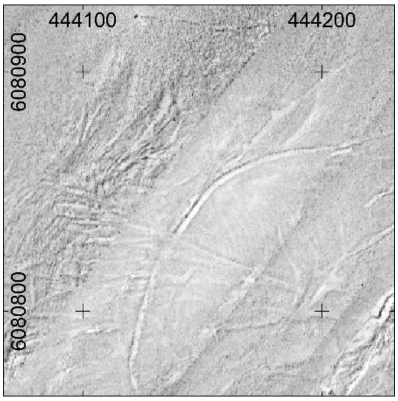
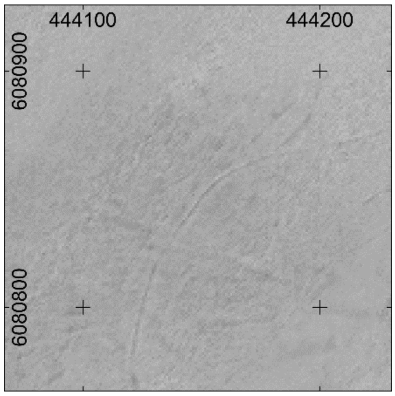
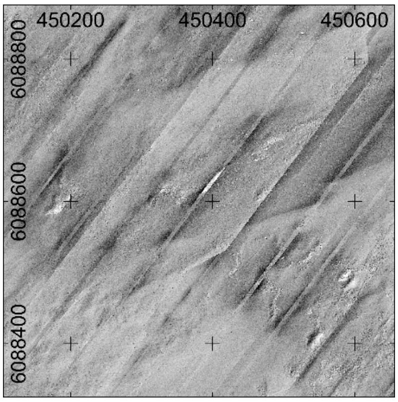
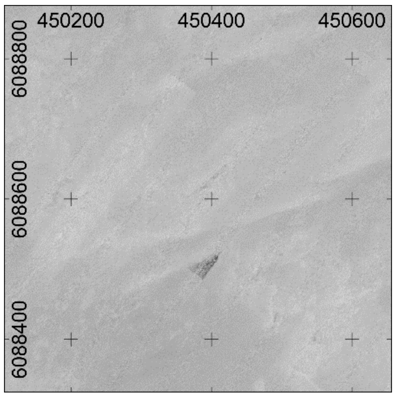
Figure 45: BHI seabed surface morphology classification (in the presented map scale some narrow polygon features are presented as black lines)

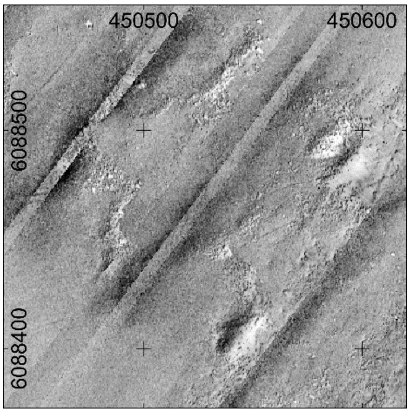
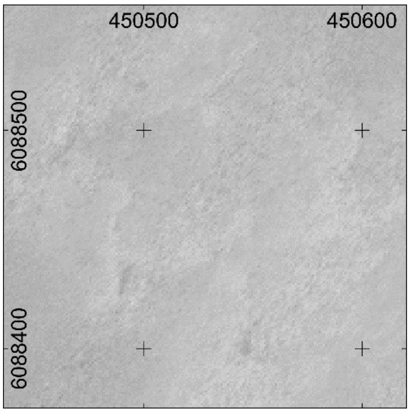
Table 23 details the seabed morphology classification interpreted across the BHI site. Geological interpretation using geophysical data was guided by the grab sampling campaign.

Table 23: Morphological interpretation

Morphology interpretation	Colour	Description	SSS LF image	Backscatter image
Pitted area		Area dominated by pit marks (0.5 – 1.0 m). No gas detected in underlying sediments. Likely cause to be changes in current regime		
Ripples		Ripple bedform areas (0.5 – 2.0 m wavelength)		
Large Ripples		Large Ripple bedform areas (5 – 15 m wavelength)		

Morphology interpretation	Colour	Description	SSS LF image	Backscatter image
Mega-ripples	(green)	Mega-ripple bedform areas (10 m – 20 m wavelength)		
Boulder field (> 80 boulders in 100 m x 100 m area)	(pink)	High density boulder field with more than 80 boulders per 100 m x 100 m area.		
Boulder field (< 80 boulders in 100 m x 100 m area)	(light blue)	Intermediate density boulder field with less than 80 boulders per 100 m x 100 m area. Boulders less than 1.0 m in size.		

Morphology interpretation	Colour	Description	SSS LF image	Backscatter image
Trawl scars		Seabed scarring from fishing trawling		
Anchor scars		Seabed areas affected by anchor scarring		
Other		Disturbed seabed (Wrecks, debris, jack-up depressions, pipelines)		

Morphology interpretation	**Colour**	**Description**	**SSS LF image**	**Backscatter image**
Unknown	(blue)	Erosional features (gravel ridges, trenching artifacts)		

8.4.1 Seabed surface classification: Morphology BHI north (Bornholm I N)

Bornholm I N is heavily trawl scarred (Figure 46). Areas of intermediate density boulder fields are widespread over the area and pitted areas exist mainly in the north-western region. Areas of primarily NW-SE ripples, as well as NE-SW to E-W large ripples and mega ripples, are extended over the southern and south-eastern part of the region. The Bornholm I N area is heavily anchor-scarred, and seabed scars are also present in the southern and the northern areas. The north-eastern part of Bornholm I N has some depression areas.

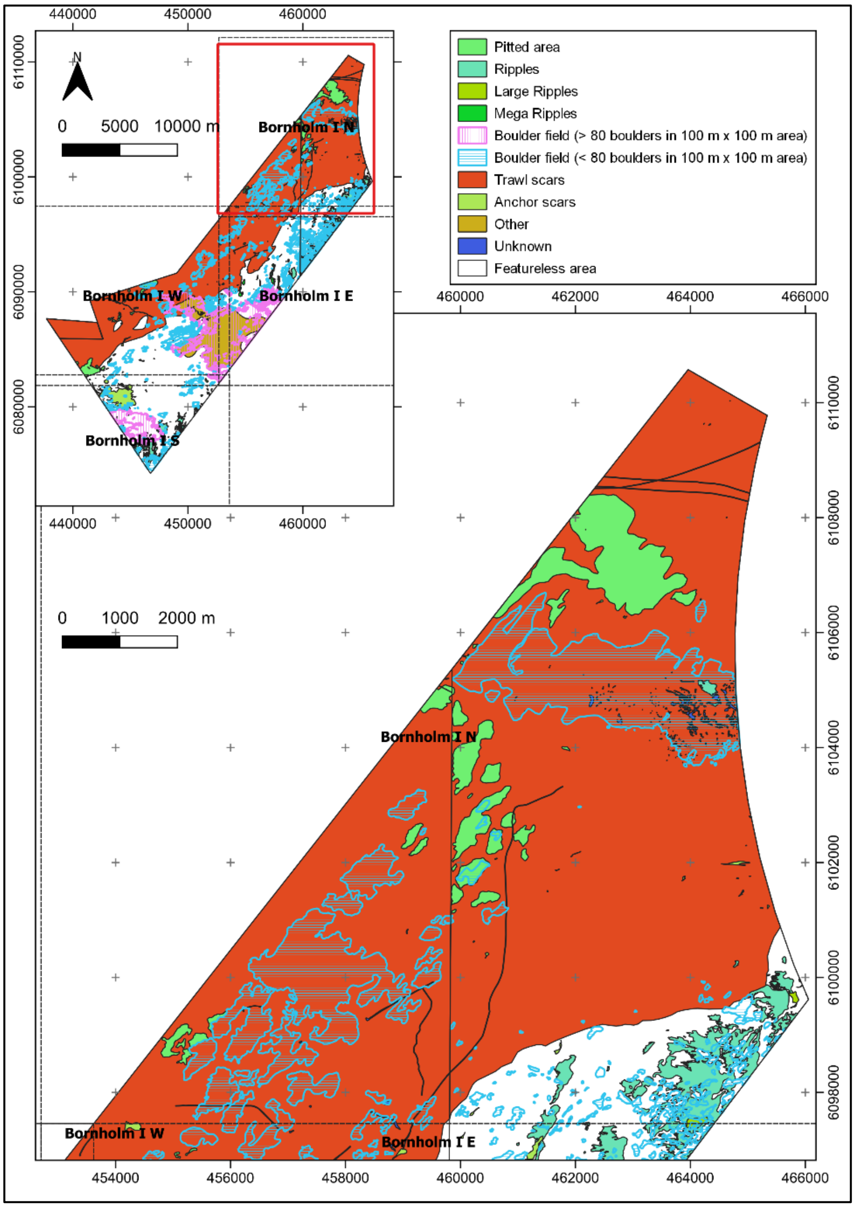


Figure 46: BHI seabed surface morphology classification (Bornholm I N) (in the presented map scale some narrow polygon features are presented as black lines)

8.4.2 Seabed surface classification: Morphology BHI east (Bornholm I E)

Bornholm I E is extensively trawl scarred to the northwest (Figure 47). High density boulder fields occupy the southern part and intermediate density boulder fields occur over the whole area. Areas of generally NW-SE oriented ripples and NE-SW to E-W oriented large ripples and mega ripples occur mainly along the southwestern parts. Seabed scars cross the northern area, while in the southern area erosional features, oriented NEE-SWW, are extended over a large part along with punctuated disturbed seabed areas.

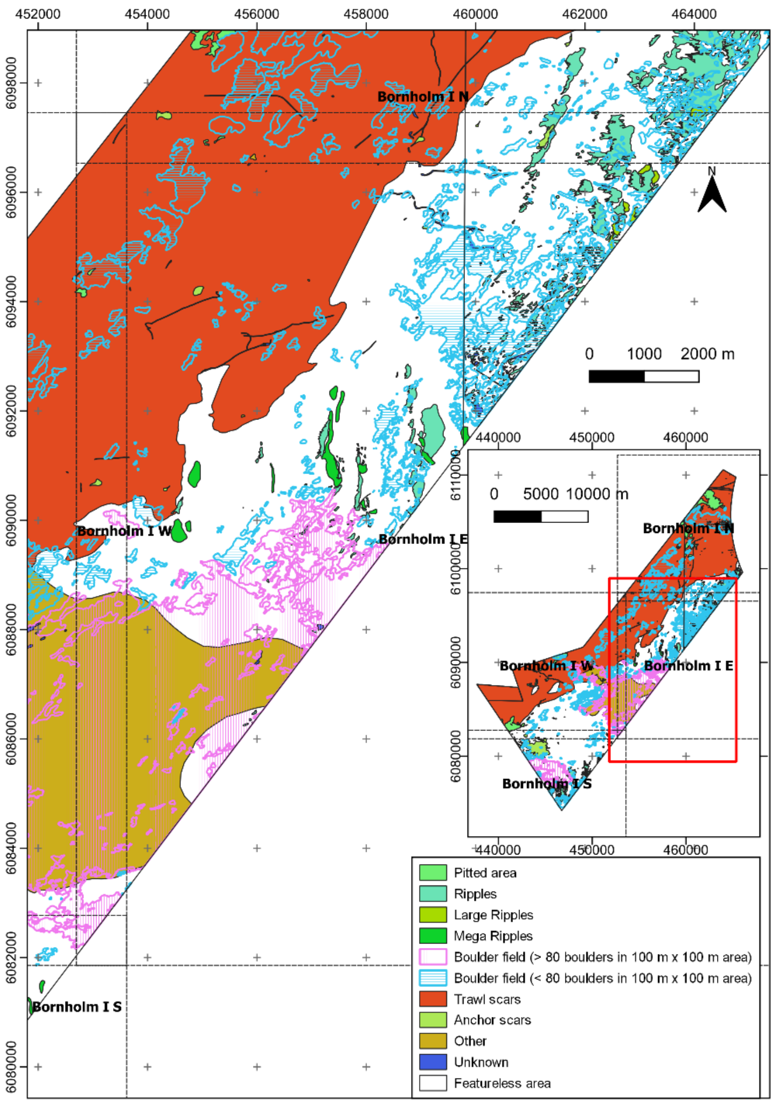


Figure 47: BHI seabed surface morphology classification (Bornholm I E) (in the presented map scale some narrow polygon features are presented as black lines)

8.4.3 Seabed surface classification: Morphology BHI south (Bornholm I S)

Bornholm I S is formed of high and intermediate density boulder field areas interspersed by ripples of general NW-SE direction in the southern tip. Smaller areas of generally E-W oriented mega ripples, limited pitted areas and an extended anchor scarring zone occur in the north-west of the Bornholm I S region.

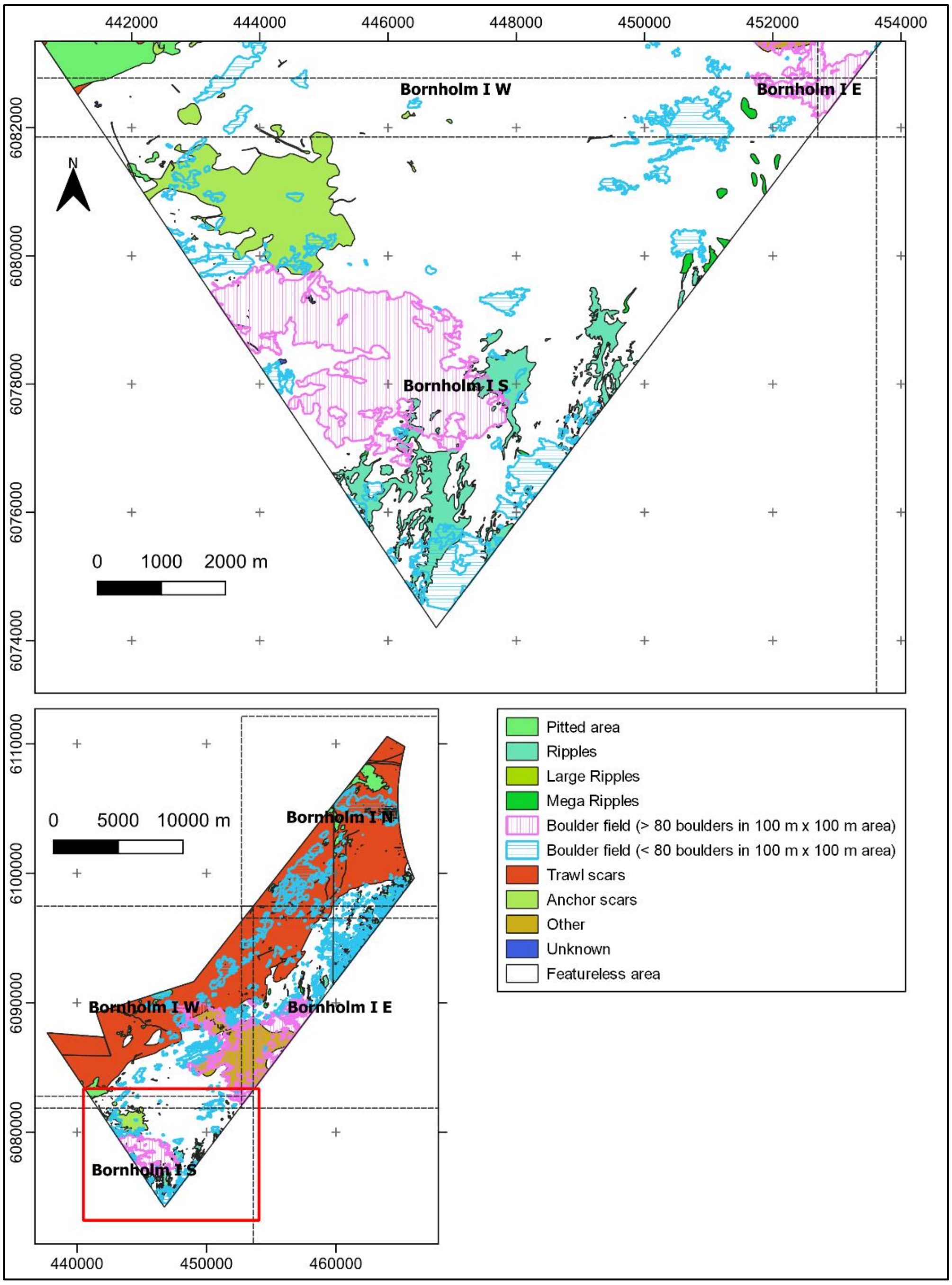


Figure 48: BHI seabed surface morphology classification (Bornholm I S). In the presented map scale some narrow polygon features are presented as black lines.

8.4.4 Seabed surface classification: Morphology BHI west (Bornholm I W)

The northern part of the Bornholm I W (Figure 49) area is heavily trawl scarred with extended areas of high-density boulder fields to the west and some areas of intermediate boulder fields. The northern part is interspersed with pitted areas and to the west erosional features oriented NEE-SWW are extended over a large portion of the region

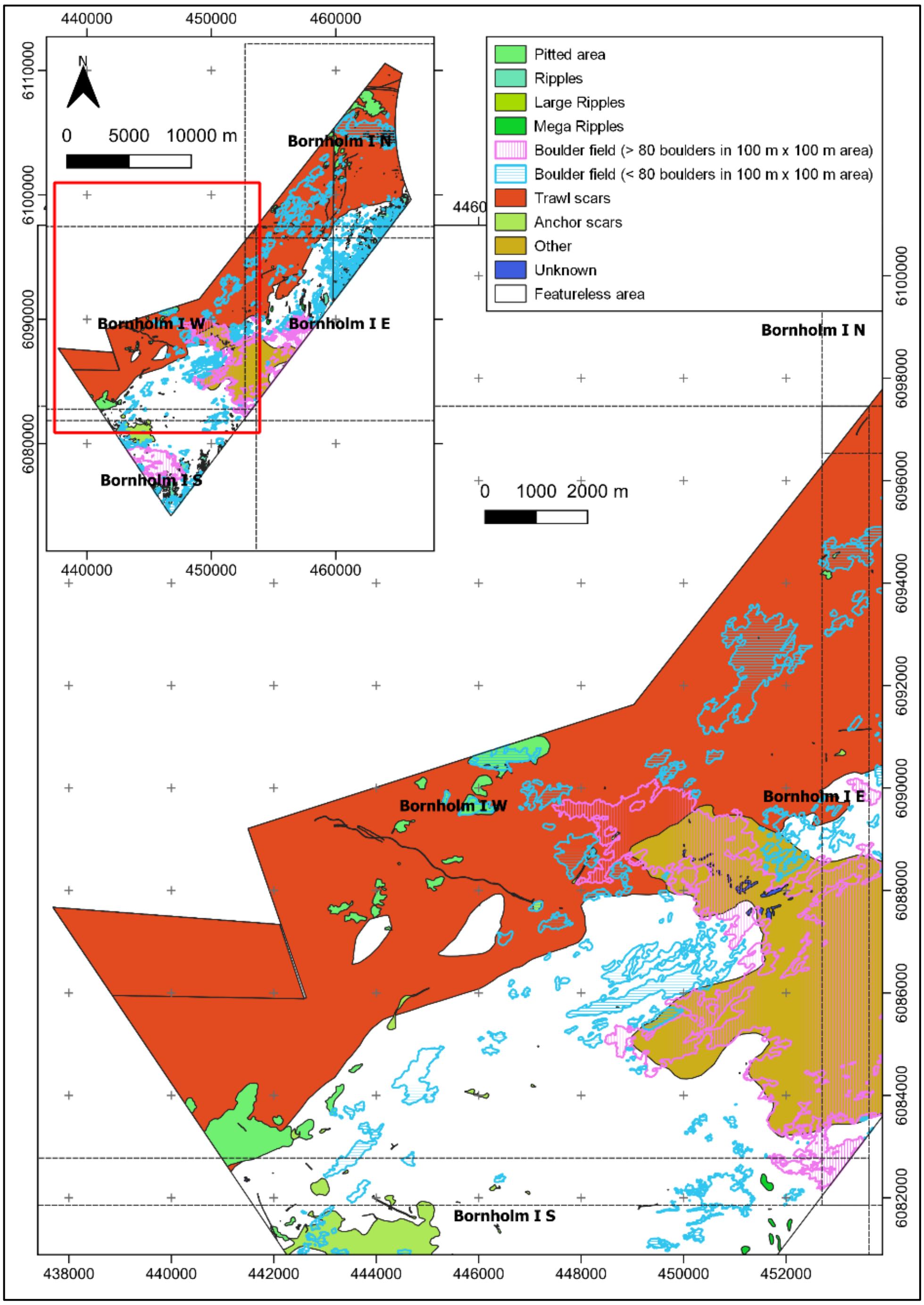


Figure 49: BHI seabed surface morphology classification (Bornholm I W) (in the presented map scale some narrow polygon features are presented as black lines)

8.5 SEABED SURFACE CLASSIFICATION: MAN-MADE FEATURES

Seabed surface objects that were determined to be of a man-made origin (MMO) are outlined in Table 24. A total of 8 wrecks, 951 point objects and 17 seabed disturbances were identified through the interpretation of the MBES, SSS and magnetometer datasets with reference to the desk study.

Table 24: Identified man-made features

Feature type	Count	Comment
Wrecks	8 Wrecks (12 constituent MMOs)	8 wrecks found throughout BHI site in varying states of completeness.
Cables	0 (infrastructure) 1 (unknown) 3 (debris related)	Zero cables infrastructure identified. One unknown linear feature (possible cable) 3 debris relate cable items identified
Pipelines	1	Baltic Pipeline crosses NE part of BHI site
Debris	939	939 total debris items
Items related to fishing activity	24	24 items possibly associated with fishing activity
Seabed disturbances	17	17 seabed disturbances from jack-up platforms and fishing activities

8.5.1 Wrecks

Eight wrecks or suspected wrecks were identified throughout the BHI survey site. The locations of the identified wrecks are shown in Figure 50 and outlined in Table 25.

Wrecks or suspected wrecks are in differing states of preservation on the seabed; some wrecks are well preserved, and others are concentrated debris areas.

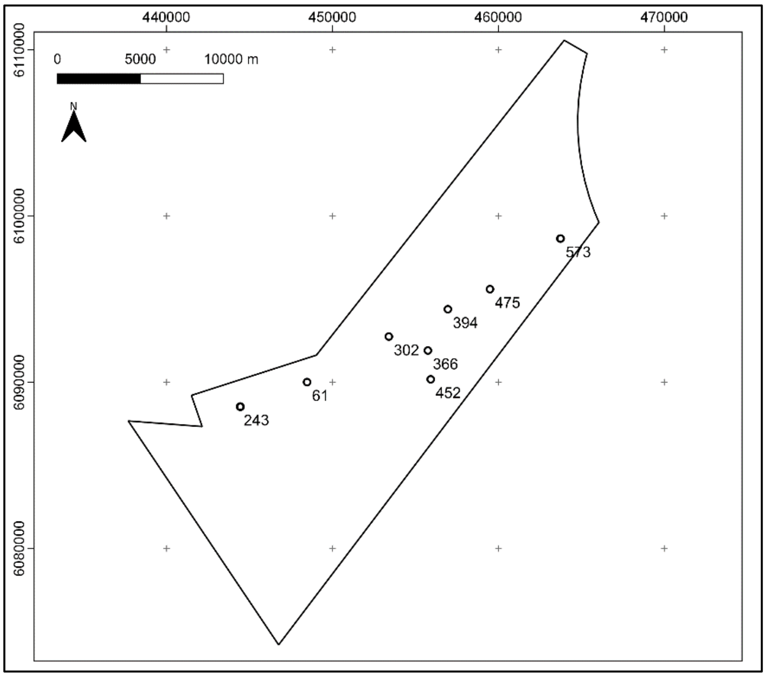
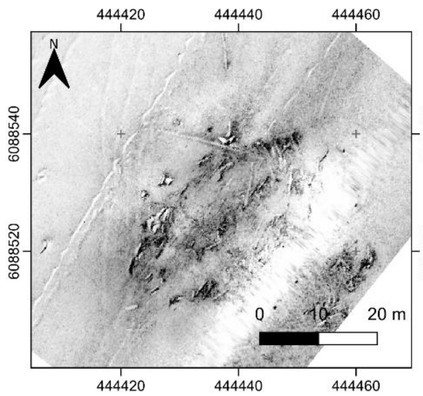
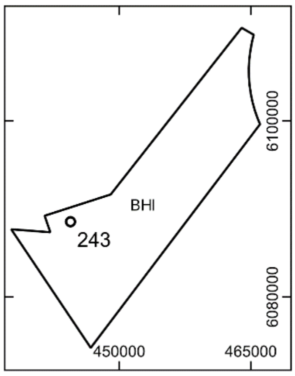
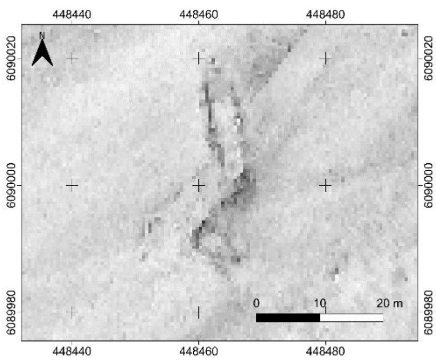
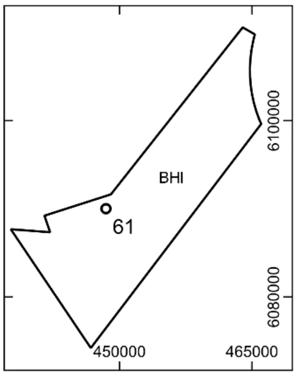
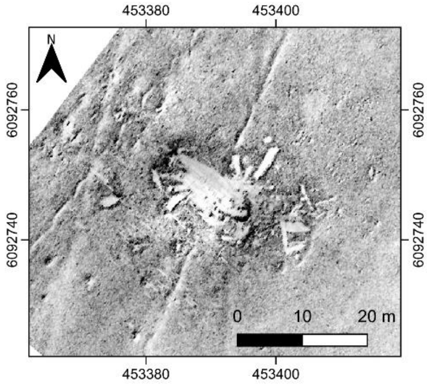
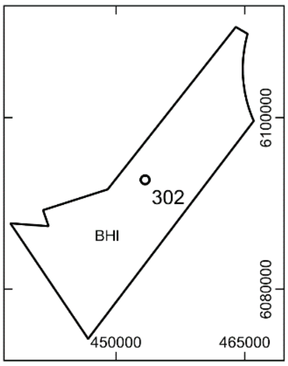
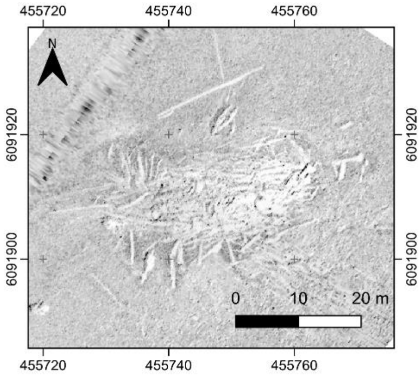
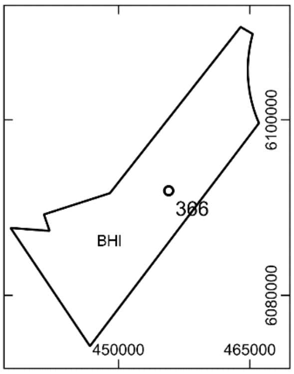
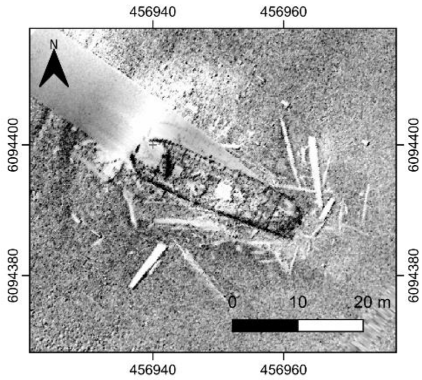
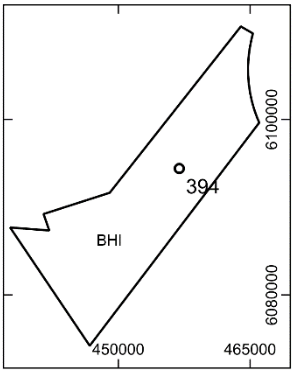
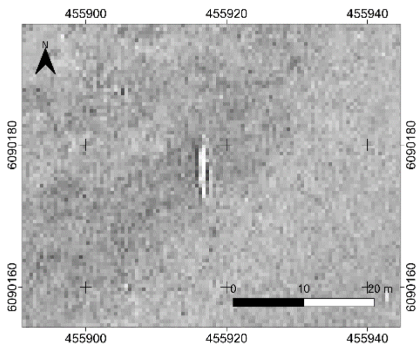
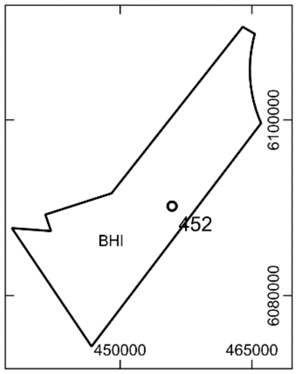
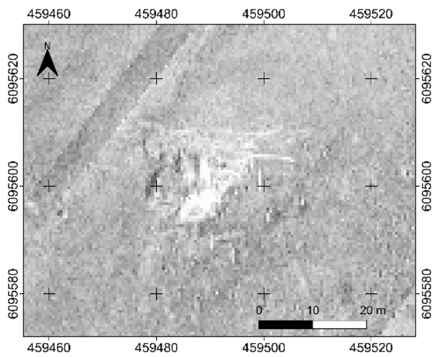
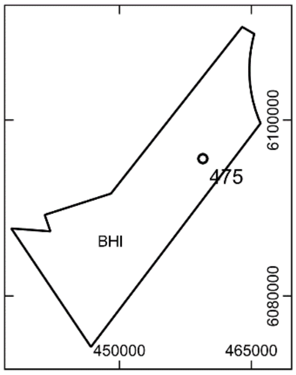
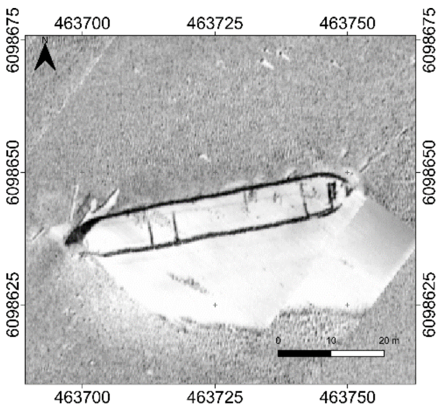
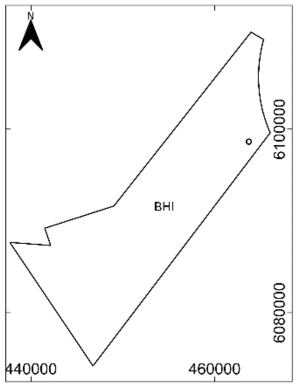


Figure 50: BHI wreck locations with MMO Target IDs

Table 25: Identified wrecks

MMO ID	Dimensions	Description	SSS image	Location
243	L: 41 m W: 15 m H:	Wreck with debris spread over large surrounding area > 40 m radius		
61	L: 32 m W: 9 m	Possible wreck		

MMO ID	Dimensions	Description	SSS image	Location
302	L: 28 m W: 18 m	Large object surrounded by debris - possible wreck BHI_MAG_0073 BHI_SSS_106242		
366	L:33 m W: 17 m	Possible wreck with large debris area		
394	L: 29 m W: 8 m	Well preserved wreck BHI_SSS_110649		

MMO ID	Dimensions	Description	SSS image	Location
452	L: 10 m W: 3 m	Associated with known wreck		
475	L: 30 m W: 22 m	BHI_MAG_0111 BHI_SSS_122230		
BH1C 569	L: 56 m W: 9 m	Well preserved wreck not previously known. SSS: BH1C_B06_2694 BH1C_B06_2712 MAG: BH1C_MAG_0435		

8.5.2 Cables

In the north of the BHI site, an unknown linear object, trends east-northeast to west-southwest across the BHI site. The object was resolved in the SSS and magnetometry datasets. The linear object linear object runs 0.5 km parallel to the Rønne-Rødvig cable as-laid position. The Rønne-Rødvig and Baltica cable networks were not resolved in the dataset.

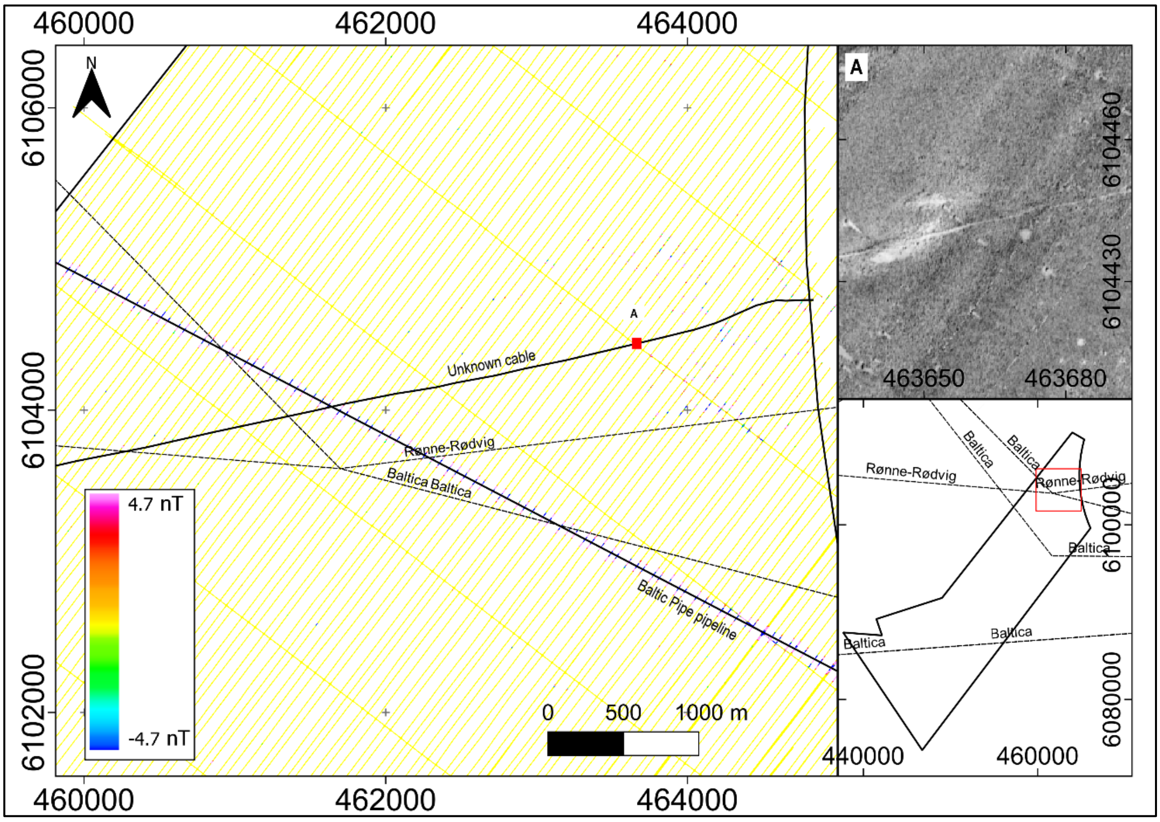


Figure 51: Unknown linear object or cable in north of BHI site

The BHI site has three cables with a debris related origin. Two of the three debris related origin cables are highlighted in Figure 52 (MMO 356 and MMO 357).

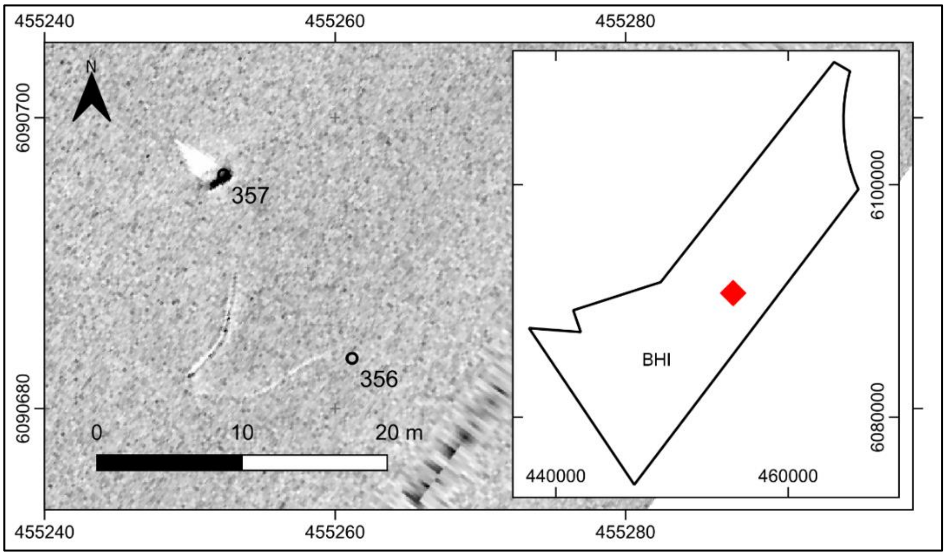


Figure 52: BHI cable examples (SSS image with MMO Target IDs)

8.5.3 Pipelines

The Baltic Pipe pipeline crosses the northern section of the BHI site. The extent of the Baltic Pipe pipeline through the BHI site, as detected in the magnetometer dataset, is shown in Figure 53. No other pipelines were identified.

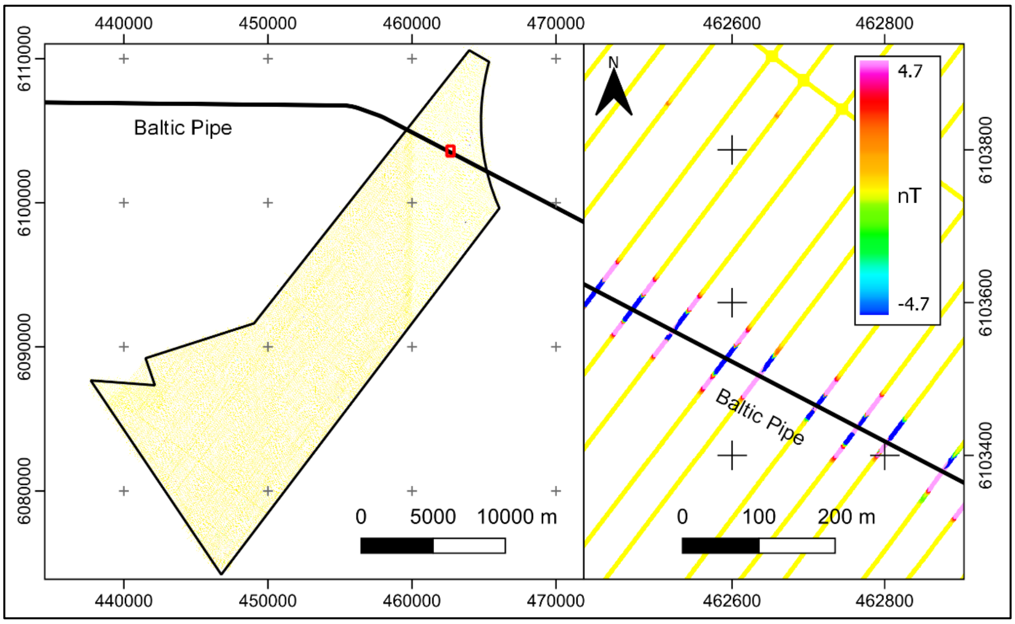


Figure 53: Baltic Pipe pipeline extent through the BHI site with magnetometer data

8.5.4 Debris

The BHI site has 439 debris items. Debris objects were identified from interpretation or the MBES, SSS and magnetometer datasets. An example of a debris item, as seen in SSS HF imagery (MMO 168), is shown in Figure 54.

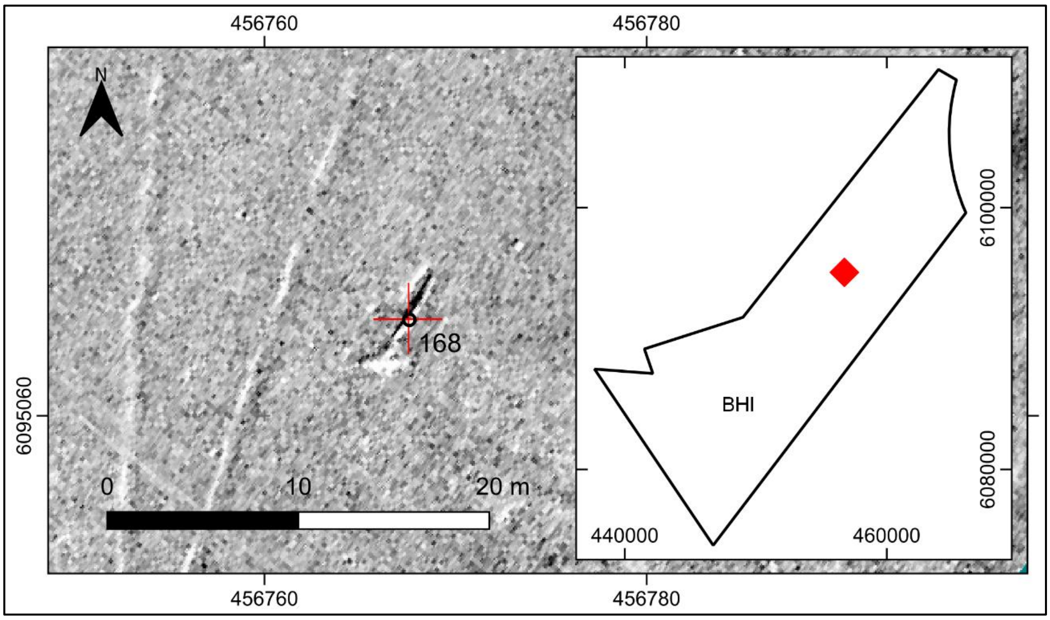


Figure 54: Debris object example as seen in SSS HF imagery (MMO 168)

8.5.5 Items related to fishing activity

The BHI site has 24 items possibly relating to fishing activity. These are objects with a rope connected to other debris objects as shown in Figure 55. These objects are believed to be fish traps or other discarded fishing gear. There was no discernible magnetic response from these items suggesting a non-ferrous construction.

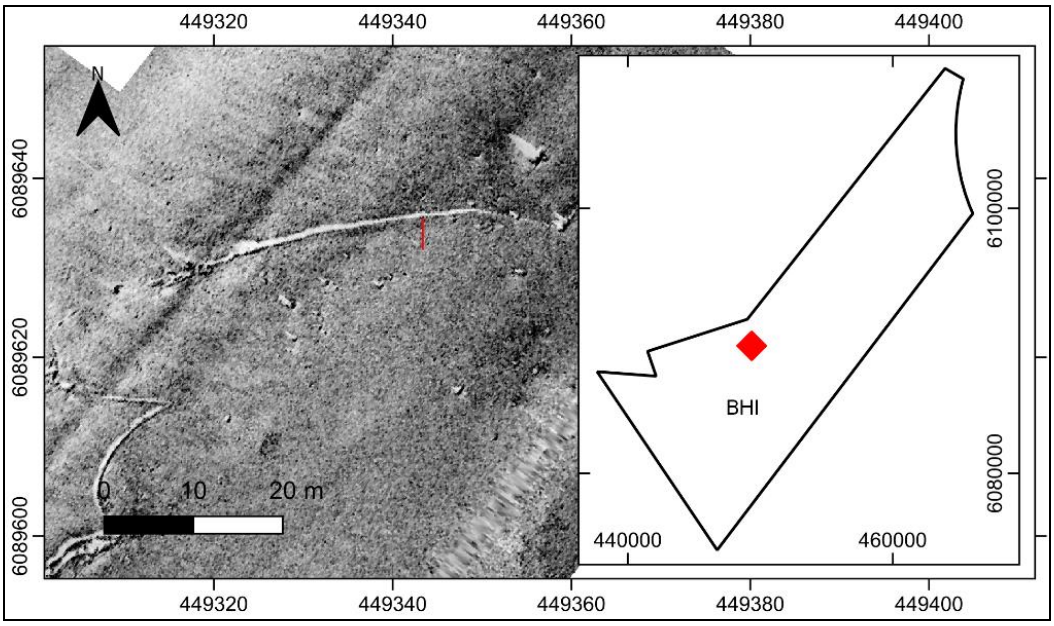


Figure 55: Fishing activity related item as seen in SSS HF imagery (MMO 109)

8.5.6 Seabed disturbances

Seabed disturbances due to natural, human and unknown seabed interference, were identified throughout the BHI site. The locations of these seabed disturbances are highlighted in Figure 56 in addition to areas of trawl and anchor scarring. The seabed disturbances in the south-west of the site are likely related to the Figure 57 shows an example of a seabed disturbance, which has an unknown origin (MMO_431).

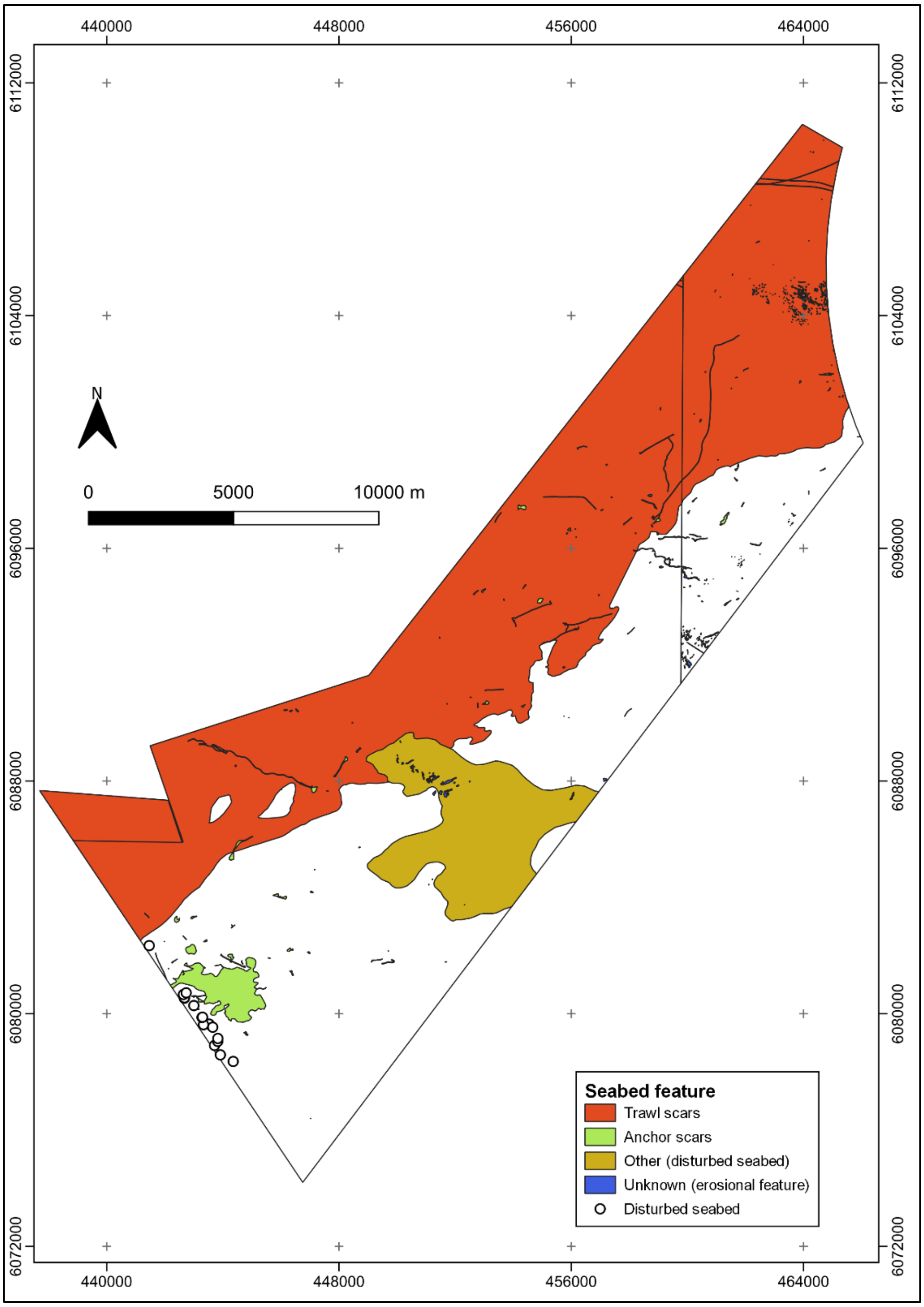


Figure 56: Seabed disturbances (BHI)

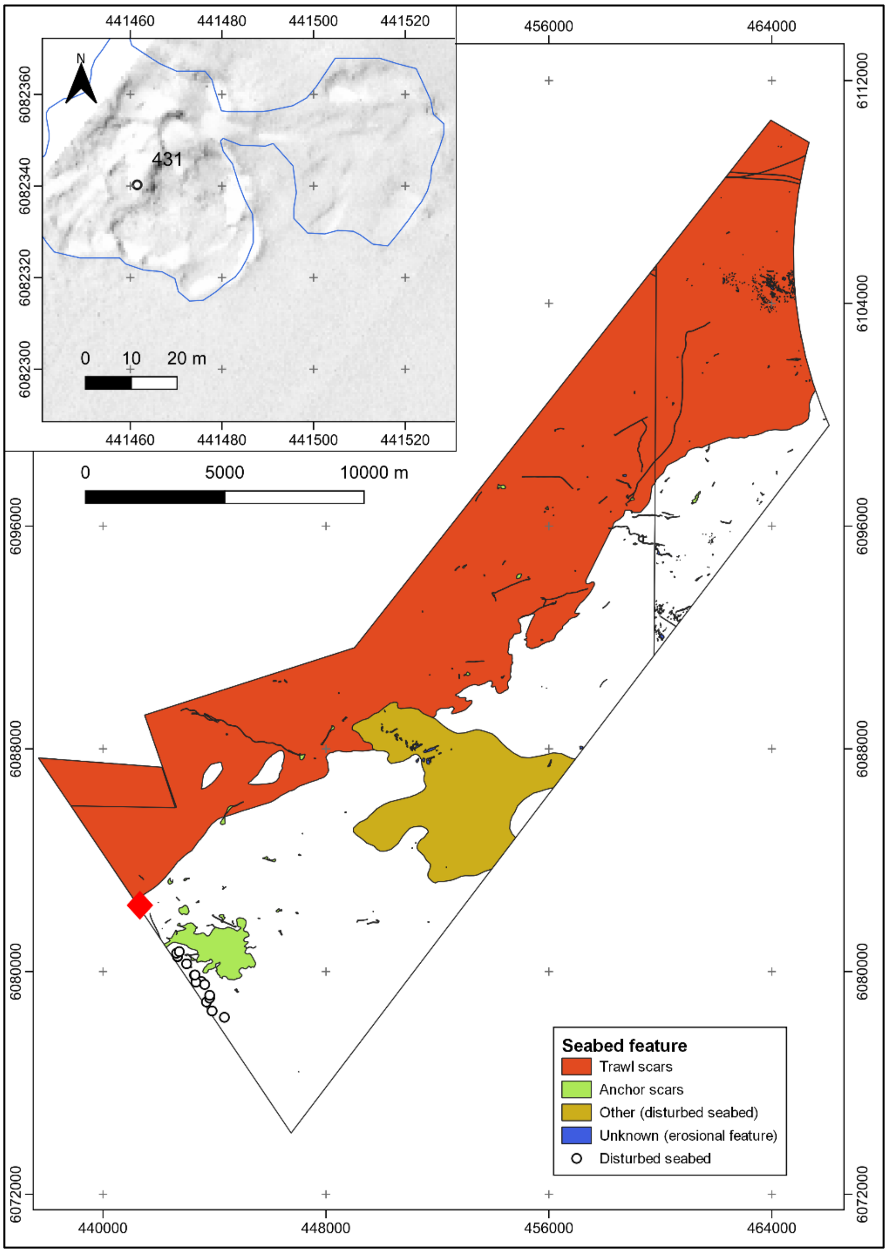


Figure 57: Unknown seabed disturbance. Possible spud-can depressions (MMO_431)

8.6 SEABED SURFACE CLASSIFICATION: SUBSTRATE TYPE

The seabed substrate for BHI was evaluated from interpretation of the low frequency SSS data and backscatter imagery. The surficial geology was considered, and the resultant seabed surface substrate interpretation is highlighted into particular particle size subdivisions in Figure 58. Western areas of the BHI site are predominately clay bottom with extended stone areas to the south, east and north. Central areas are mainly sand with some gravel areas, whereas in the north gravel areas are more prominent.

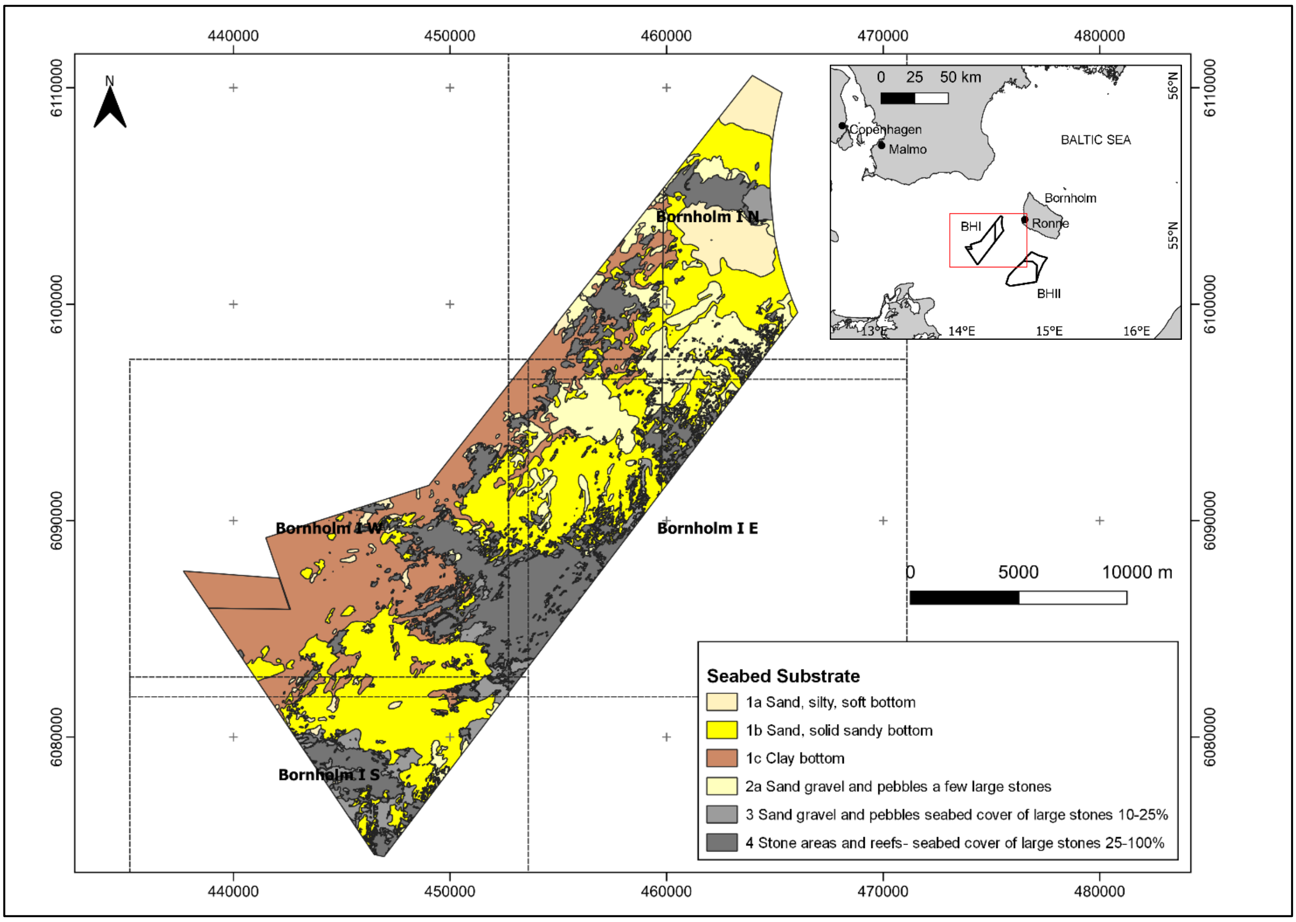
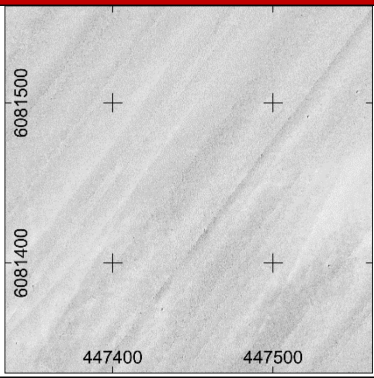
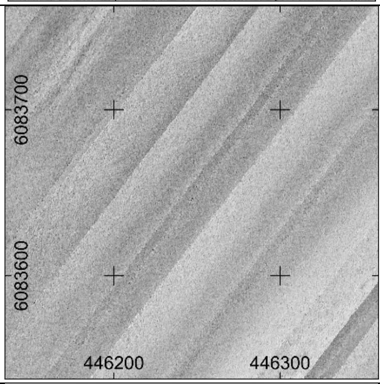
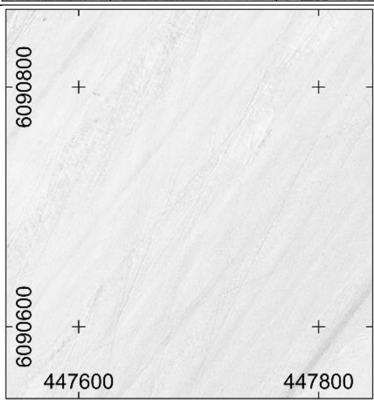
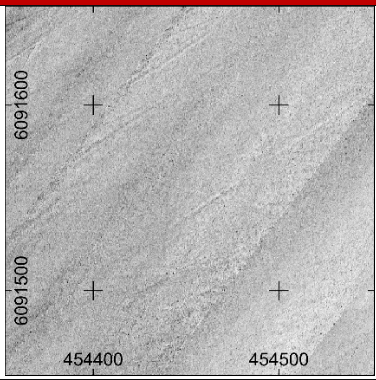
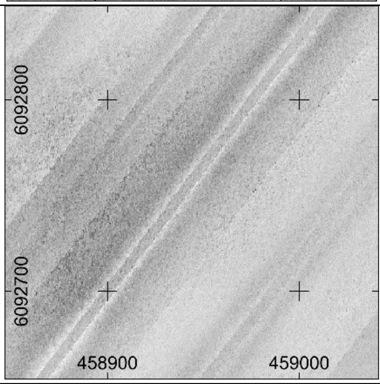
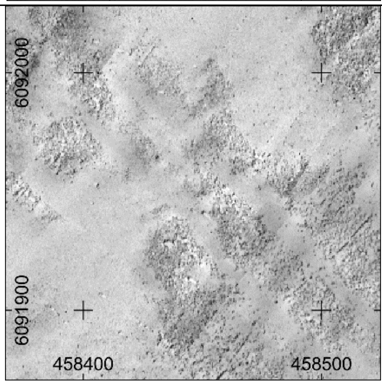


Figure 58: BHI seabed surface substrate classification

Examples of substrate classification from the SSS dataset are described in Table 26.

Table 26: Substrate interpretation from SSS data

<table>
<tr><th>Description of Substrate Class</th><th>Colour</th><th>Code</th><th>SSS Example</th><th>Rationale</th></tr>
<tr><td>Sand, silty, soft bottom</td><td></td><td>1a</td><td>
</td><td>Low reflectivity represents fine sediments on the seabed.</td></tr>
<tr><td>Sand, solid sandy bottom</td><td></td><td>1b</td><td>
</td><td>Low - Medium reflectivity indicates coarser sediments.</td></tr>
<tr><td>Clay bottom</td><td></td><td>1c</td><td>
</td><td>Very Low reflectivity represents fine sediments.</td></tr>
</table>

Description of Substrate Class	Colour	Code	SSS Example	Rationale
Sand, gravel and pebbles - few larger stones		2a		Darker grey representing a more reflective seabed surface, which is slightly textured, indicates the presence of gravel.
Sand, gravel and pebbles, seabed cover of larger stones 10% to 25%		3		A textured seabed represents coarser grain sediments and presence of larger stones on the seabed.
Stony areas and stone reefs - seabed cover of larger stones 25% to 100%		4		Textured seabed indicating areas dominated by stones and/or outcropping rock.

8.6.1 Seabed surface classification: Substrate BHI north (Bornholm I N)

In the northern part of the BHI site (Bornholm I N), Sand and Gravel are predominant (Figure 59). Clay bottom covers the western part of the region along with extended stony areas whereas patches of stony areas in the west and an E-W stony zone exist in the north (Figure 59).

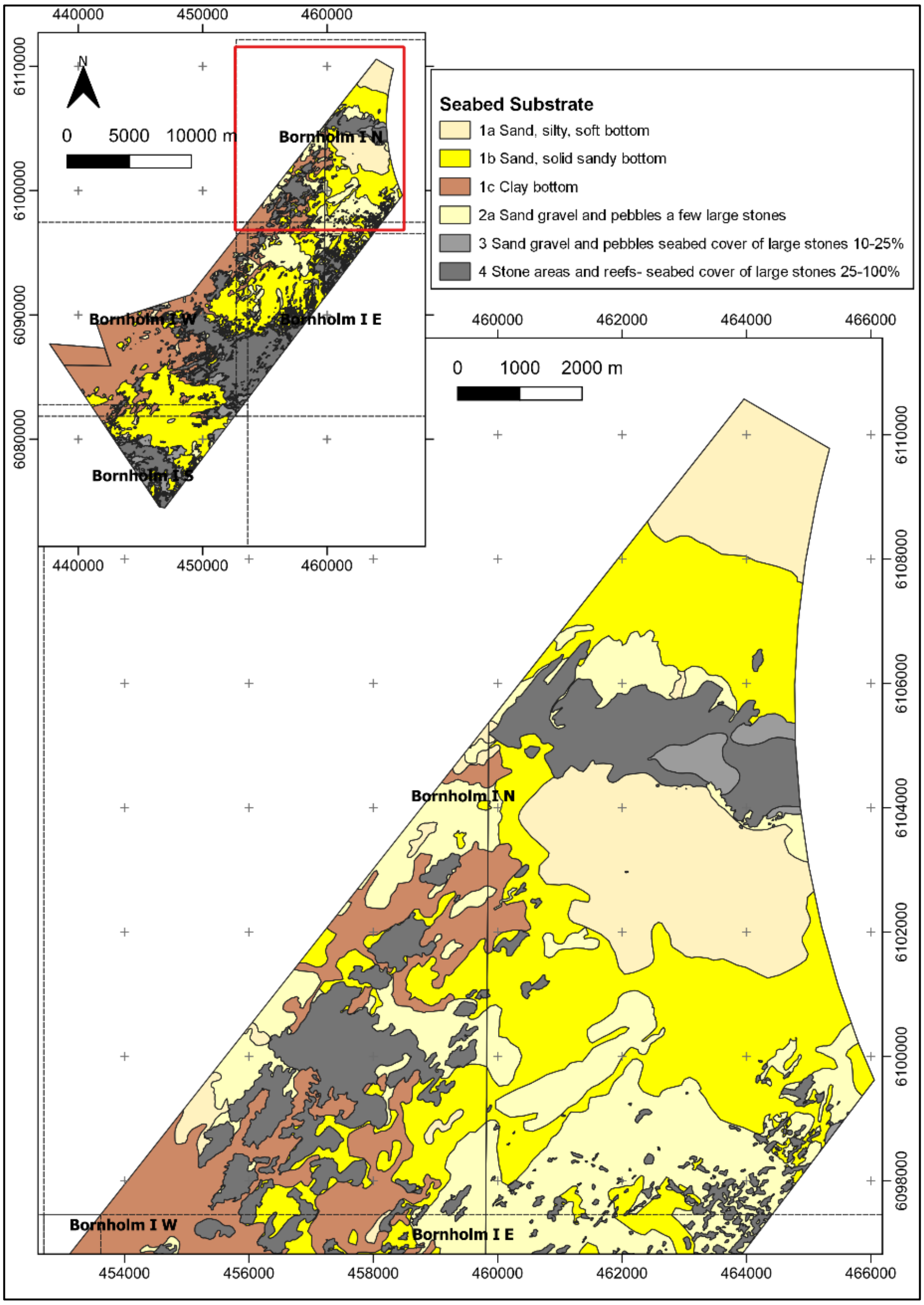


Figure 59: BHI seabed surface substrate classification (Bornholm I N)

8.6.2 Seabed surface classification: Substrate BHI east (Bornholm I E)

The eastern part of the BHI site (Bornholm I E) is mainly Sand. Clay is predominant in the north-eastern part of the region and some Gravel in the western, central and north-eastern part (Figure 60). Patches of stone areas are widespread over the western and the northern part, whereas areas of large stones (25% to 100%) are more extended in the eastern area. The southern section is a stone area with a seabed cover of large stones (25% to 100%).

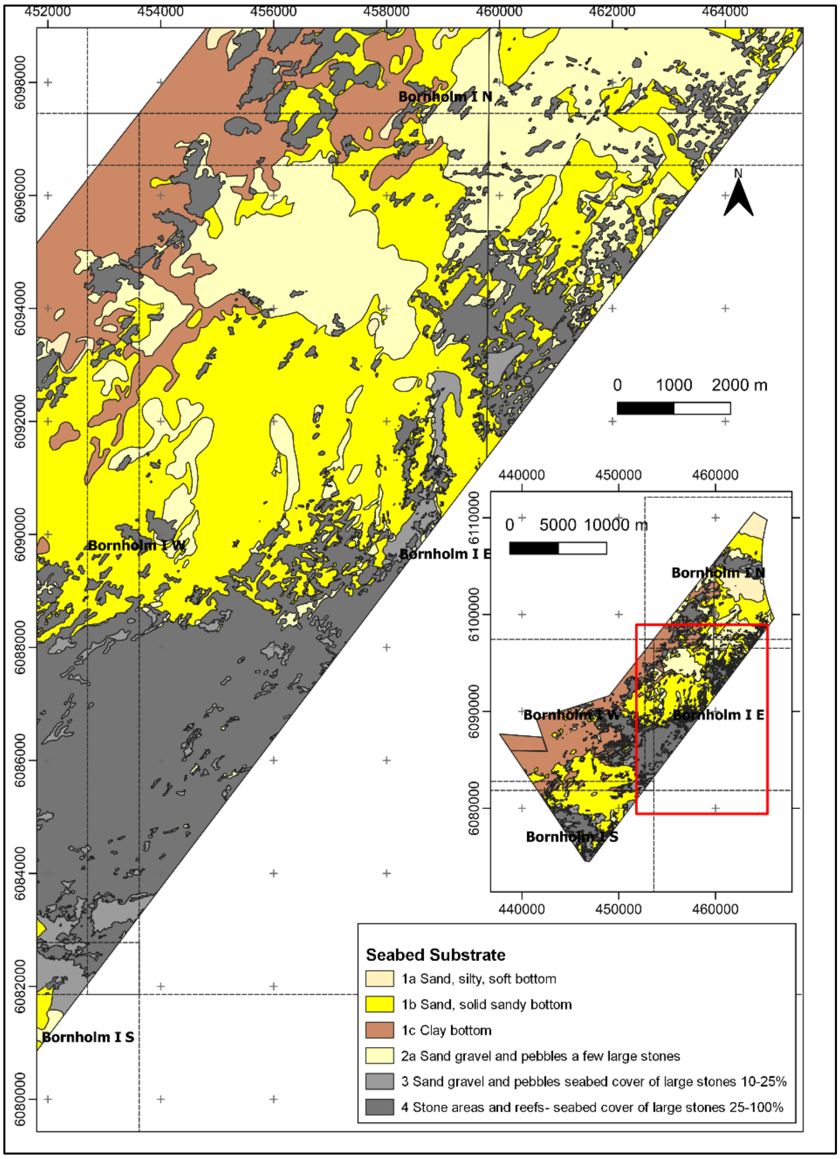


Figure 60: BHI seabed surface substrate classification (Bornholm I E)

8.6.3 Seabed surface classification: Substrate BHI south (Bornholm I S)

The southern part of the BHI site (Bornholm I S) is primarily Sand with some Clay areas mainly in the northern section and some patches of Gravel areas (Figure 61). Stone areas occur in the eastern region and predominate the southern tip of Bornholm I S.

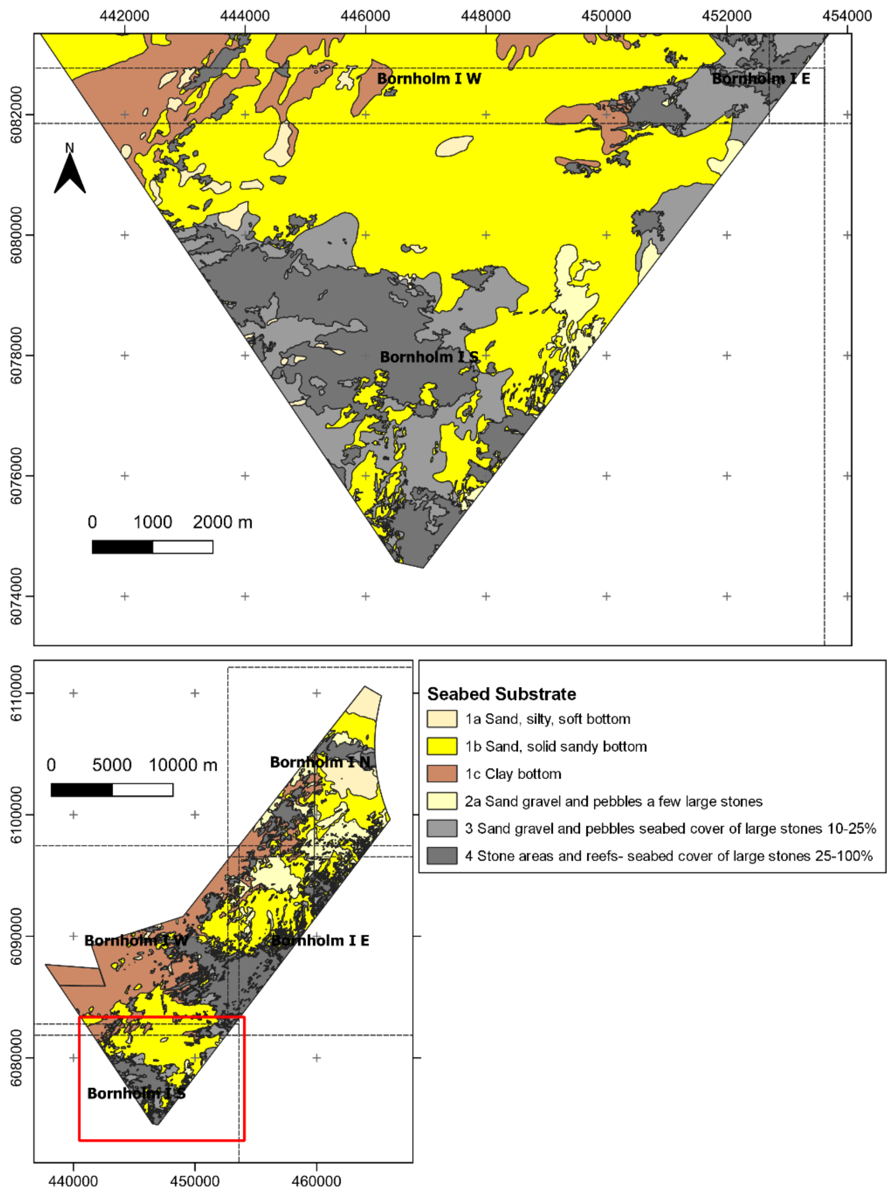


Figure 61: BHI seabed surface substrate classification (Bornholm I S)

8.6.4 Seabed surface classification: Substrate BHI west (Bornholm I W)

The northern and north-western parts Bornholm I W region are mostly Clay (Figure 62). Sand is dominant in the southern part and widespread Sand and Stone areas prevail in the eastern section of Bornholm I W.

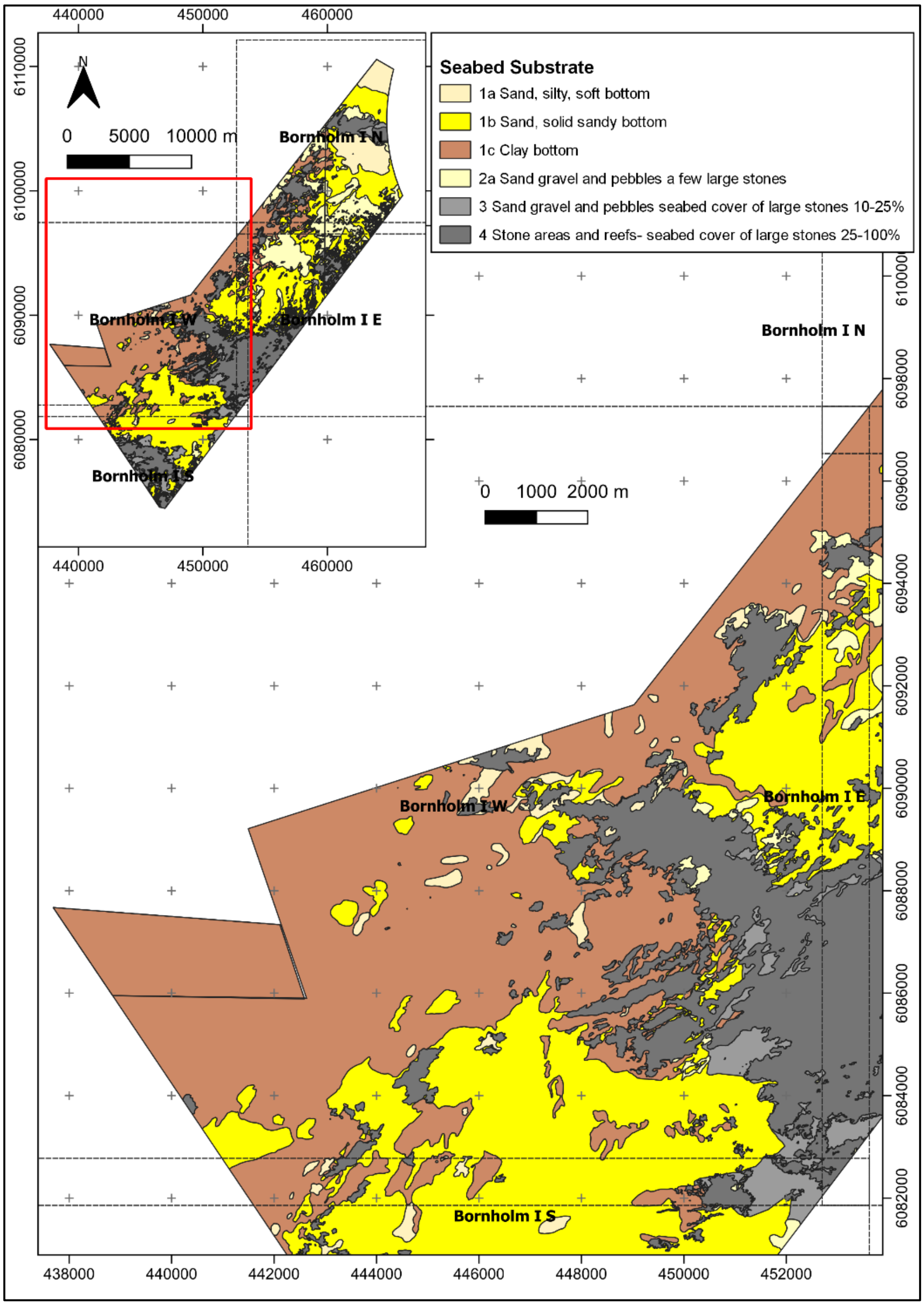


Figure 62: BHI seabed surface substrate classification (Bornholm I W)

9 SUB-SURFACE GEOLOGY

9.1 REGIONAL GEOLOGICAL HISTORY

The geological foundation zone extends to 70 m below seabed. The rocks and sediments within this interval have been interpreted with reference to the supplied GEUS desk study (Jensen et al., 2021). This desk study applies a stratigraphic model developed by Jensen et al (2017) in conjunction with archive seismic data and limited ground truth information.

In overview, the area has a glacial to post-glacial sequence of younger sediments over much older carbonate bedrock. The recent sediments are generally 10-20 m thick, although in small areas these recent sediments are interpreted to be much thicker.

There is a very good correspondence between shallow geology imaged in this project's sub-seabed data and the desk study. The unit names for this project are aligned with those in the GEUS desk study.

9.2 STRATIGRAPHIC UNIT INTERPRETATION

Figure 65 shows the arrangement of units within Bornholm I and Table 26 shows the basic characteristics of the stratigraphic units.

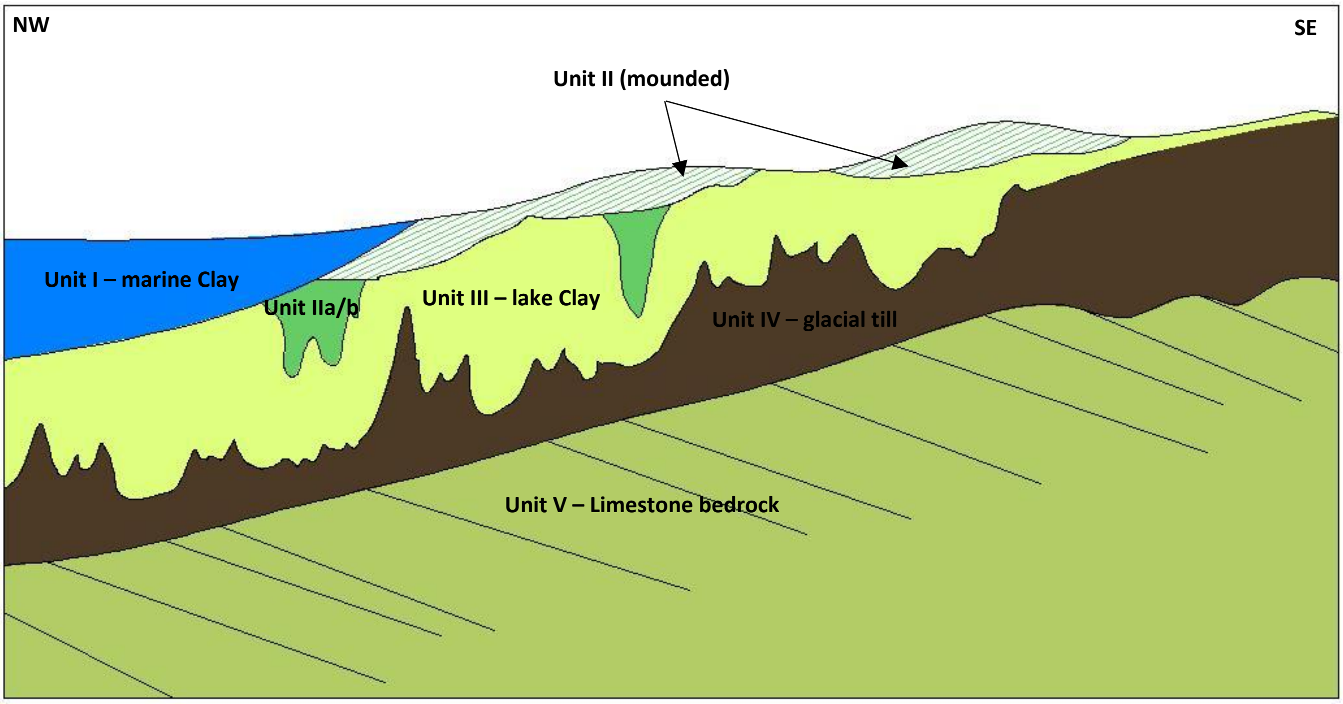


Figure 63: Geological Schematic, general arrangement of units

Table 27: Shallow Geological Units

Unit	Upper surface	Lower surface	Main Soil Description	Depositional Environment
I	Seabed	H5	Organic-rich CLAY	Post-glacial marine
II mounded facies	Seabed/H5	H15	SILT/fine SAND	Post-glacial (drowned beach?)
IIa/b channel-fill facies	H5/H15	H20	CLAY, laminated towards top	Post-glacial transitional (lake)
III	H5/H15/H20	H35	CLAY, locally silty	Post-glacial estuarine/lacustrine (Holocene)
IV	H35/seabed	H50	CLAY prone diamicton	Ice contact till (upper parts)
V	H50	Not imaged >70m BSB	LIMESTONE bedrock	Ancient shallow marine

The stratigraphic model from Jensen et al. (2017) and the correlation of the stratigraphic model to the BHI project is illustrated in Figure 64. Key surfaces are the top of Unit IV (H35/seabed), which is the top of over-consolidated deposits, and H50, the top of the bedrock.

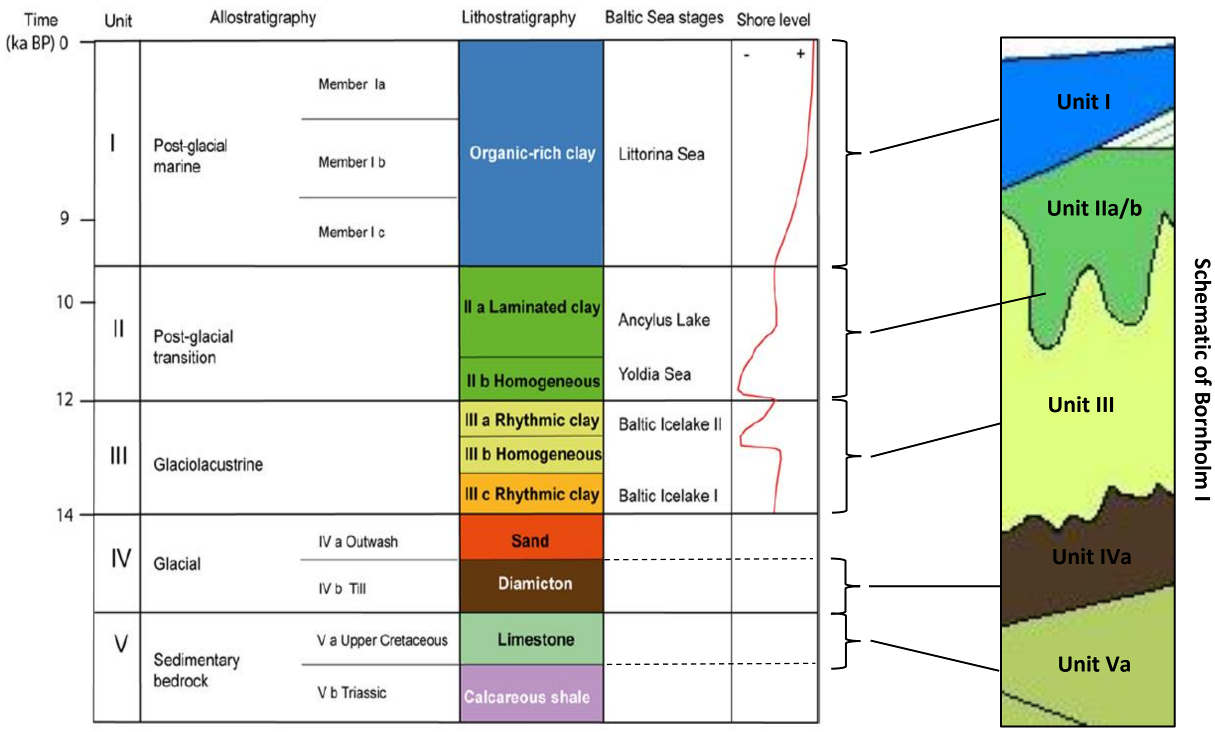


Figure 64: Stratigraphic model (after Jensen et al, 2017) with correlation to Bornholm I

9.2.1 Quaternary Deglaciation History

Table 27 links the interpreted stratigraphic units to changing paleoenvironments.

Table 28: Quaternary deglaciation history

Time (ka BP)	History	Unit	Depositional environment	Comments
> 22 - 15	The Scandinavian Ice Sheet reached its maximum extent about 22000 years BP followed by retreat with evidence for short-lived advances.	**Unit IV**	Glacial	**Unit IV** was laid down by the Scandinavian Ice Sheet.
15 – 11.5	The survey area became ice free by around 15000 years BP at which point the area was an ice-dammed lake. This lake filled and drained twice; the ancient lake was at its maximum around 12000 years BP.	**Unit III**	Lacustrine	**Unit III** was laid down in these ancient lakes.
11.5 – 10.2	About 11500 years BP a strait developed to the North Sea transforming the Baltic Basin into a marine environment named the Yoldia Sea.	**Unit IIb**	Marine	**Unit IIb** was deposited in Yoldia Sea marine environment.
10.2 – 9.4	Glacio-isostatic uplift then closed the strait forming the last Baltic Lake phase, the Ancylus Lake which reached a maximum level about 10200 years ago.	**Unit IIa**	Lacustrine	**Unit IIa** was deposited in the Ancylus Lake.
9.4 - 0	The Ancylus Lake was gradually encroached by marine transgression becoming brackish by 9400 years BP, by 7000 years BP the study area was fully marine.	**Unit I**	Marine	**Unit I** was laid down in this marine environment.

9.2.2 Sub-surface acoustic velocity model

The depth and thickness grids were converted from time to depth or thickness using an interval acoustic velocity of 1600 m/s for Units I, II and III as these units are normally consolidated. An acoustic velocity of 1850 m/s is applied to Unit IV because this unit has been over-consolidated by ice contact. The below seabed depth of the top of the bedrock is based on a sum of Unit I to III thickness and Unit IV thickness: this depth is calculated using both interval velocities (Table 29).

Table 29: Shallow geological units acoustic velocity model

Unit	Upper surface	Lower surface	Main Soil Description	Velocity (m/s)
I	Seabed	H5	Organic-rich CLAY	1600
II mounded facies	Seabed/H5	H15	SILT/fine SAND	1600
IIa/b channel-fill facies	H5/H15	H20	CLAY, laminated towards top	1600
III	H5/H15/H20	H35	CLAY, locally silty	1600
IV	H35/seabed	H50	CLAY prone diamicton	1850
V	H50	Not imaged >70m BSB	LIMESTONE bedrock	N/A

9.2.3 Unit I

Unit I is a thin package of organic-rich post-glacial marine CLAY. It is widely distributed in the western parts of the study area. In the southern and central parts of the area the unit occurs in water depths greater than ~40 m whereas in the northern parts of the area it occurs in water depths greater than ~45 m.

Unit I is thin, it is typically less than 1 m thick, exceptionally reaching a thickness of 2 m in westernmost parts of the area (Figure 65).

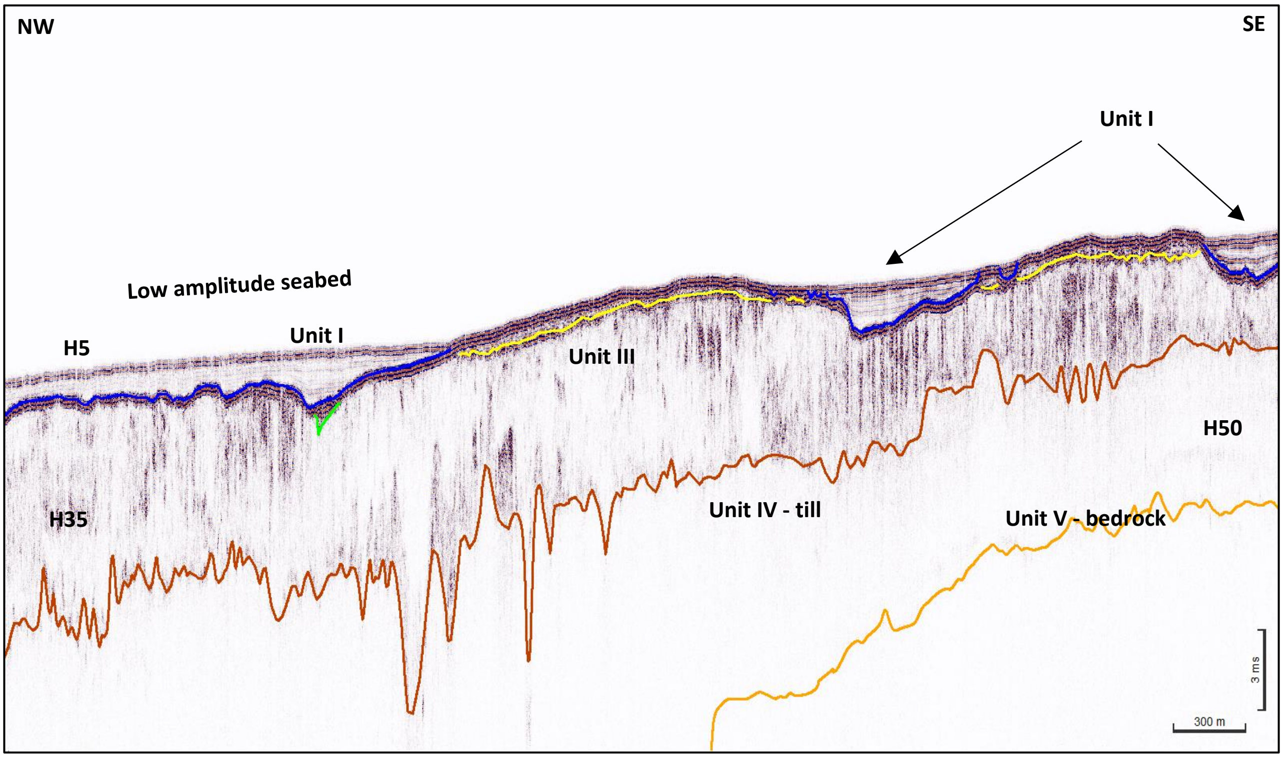


Figure 65: SBP data example, line X_07, Unit I ponded within lows, lower to middle slope

Where it is thick enough for such features to be resolved, Unit I shows seismic evidence of internal laminations (Figure 66). Unit I tends to infill relative lows; its thickness variation is related to the morphology of its basal surface rather than its upper surface. Unit I has a tendency to infill relative lows around the mounds formed by Unit II, there is an element of mutual exclusivity in the distribution of these two units.

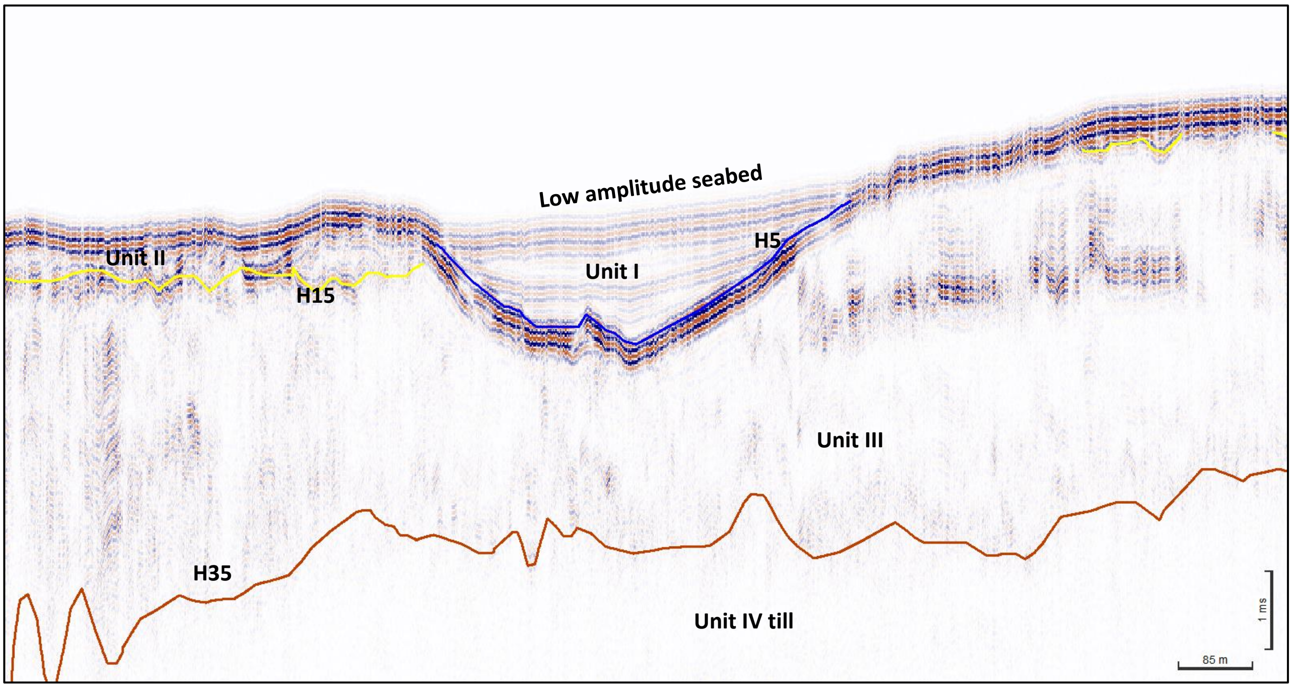


Figure 66: SBP data example, line X_07, Unit I ponded within low

The desk study mentions complex patterns of asymmetrical on-lap within Unit I deposits, indicative of syn-sedimentary tectonic activity. There is no evidence for such activity in Bornholm I; the unit appears to be a passive drape.

Unit I has seismic characteristics which indicate that it is extremely soft/weak. Where Unit I occurs, the seabed is of very low reflection amplitude and the base, at the transition to sub cropping sediments, is of much higher amplitude, an amplitude similar to that of the seabed outside the distribution of Unit I. These seismic characteristics indicate that Unit I has an acoustic impedance which is closer to that of the seawater than the other shallow geological units. On the basis of these seismic observations an ad-hoc sample was taken during geophysical acquisition. This confirmed that these sediments are extremely soft/weak CLAY. The thickness and distribution of Unit I across the BHI site is shown in Figure 67.

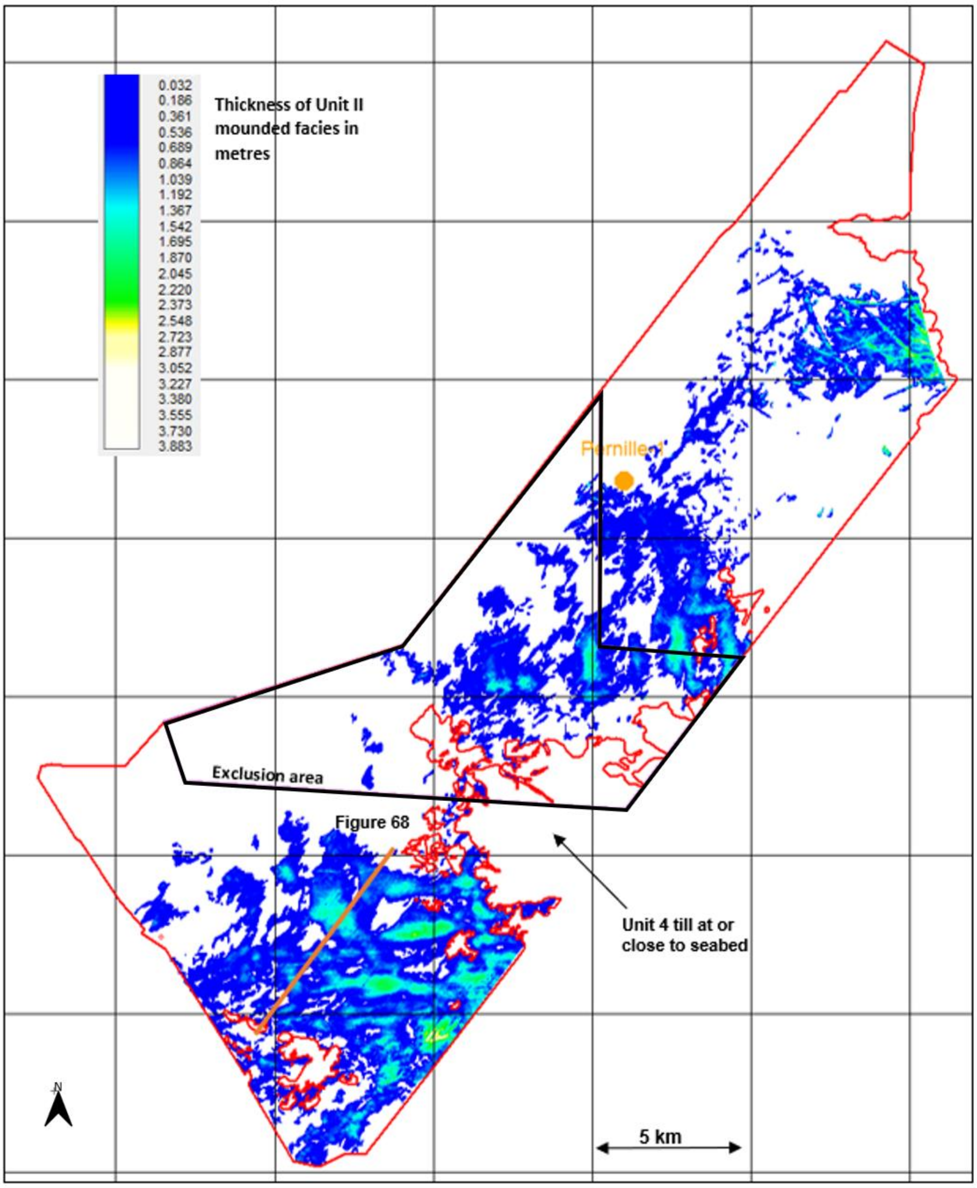


Figure 67: Thickness and distribution of Unit I

9.2.4 Unit II

This post-glacial unit is not specifically defined in Jensen et al. (2017)'s stratigraphic model. The desk study's schematic sections group this interval within Unit I (Fig.11.4 in Jensen et al. (2017)). However, this interval may be more directly equivalent to the proximal Unit II facies in Bornholm II and is seen to pre-date Unit I deposits.

The unit has a distinctive mounded form (Figure 68), its thickness variation is largely due to this relief at its upper surface rather than at its base. The unit is generally less than 2 m thick (Figure 69).

Distribution is widespread but patchy over the central to upper slope areas. The seismic appearance is ambiguous/transparent. The subtle mounds of this package have some influence over the position of the eastern limit of Unit I.

The mounded forms are not consistent with what might be expected of post-glacial clays, which tend to be laid down in lows or as channel fill.

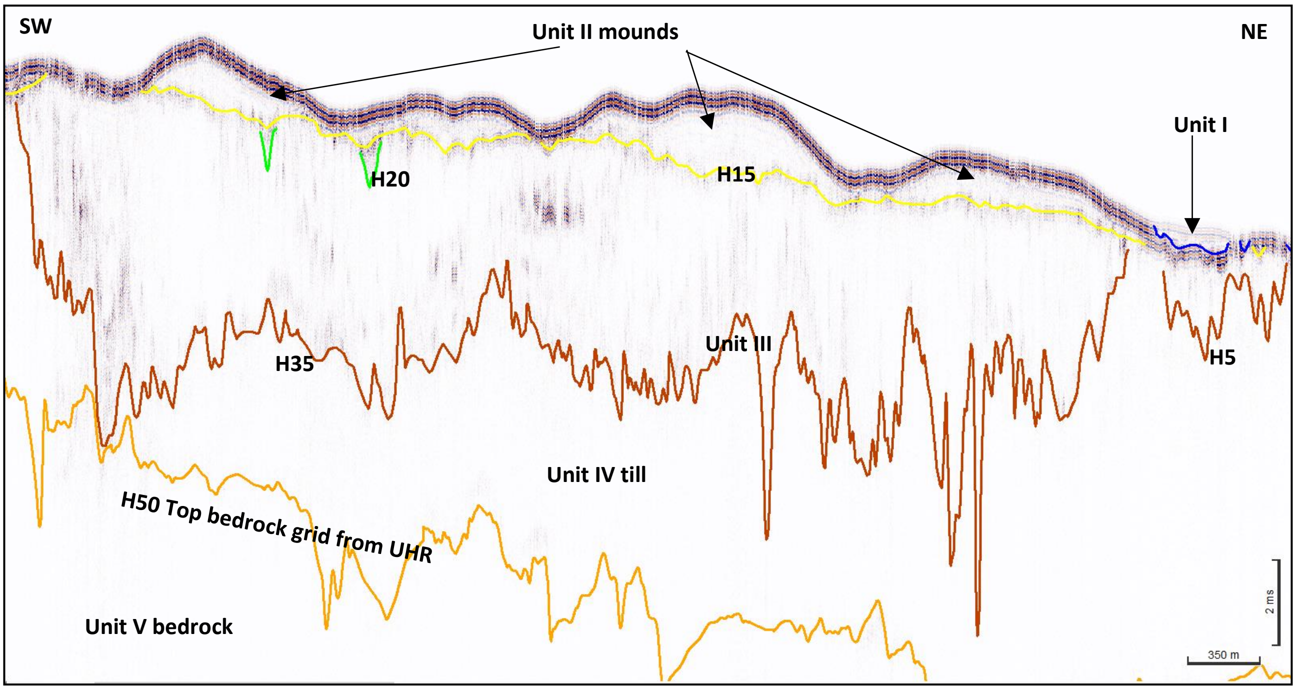


Figure 68: SBP data example, line P_034, mounded Unit II, middle-upper slope

The unit is definitively post-glacial as it occurs above the ancient lake deposits of Unit III - therefore it is not a till. This unit is tentatively interpreted to comprise drowned beach deposits of silt and fine sand which may have been partially reworked during marine transgression.

The desk study includes a chain of shallow samples across the study area (Fig.11.4 in Jensen et al. (2017)) but this appears to be in an area where Unit II is virtually absent.

In the extreme north of the area there is an accumulation of Unit II immediately south of a bedrock high. In this area the unit appears to infill some ice plough marks caused by floating ice rather than ice sheets or streams.

The age relationship of Unit I and Unit II is not so clear cut as it might be as there is very limited overlap in the distribution of these packages. Unit I does appear to be ponded around the mounds of Unit II and, in places, the base of Unit II does appear to slightly extend under Unit I. In places the base of Unit I appears to be a continuation of the surface which is the top of Unit II elsewhere. The combination of these observations points towards Unit II generally pre-dating Unit I. The thickness of Unit II across the BHI site is shown in Figure 69.

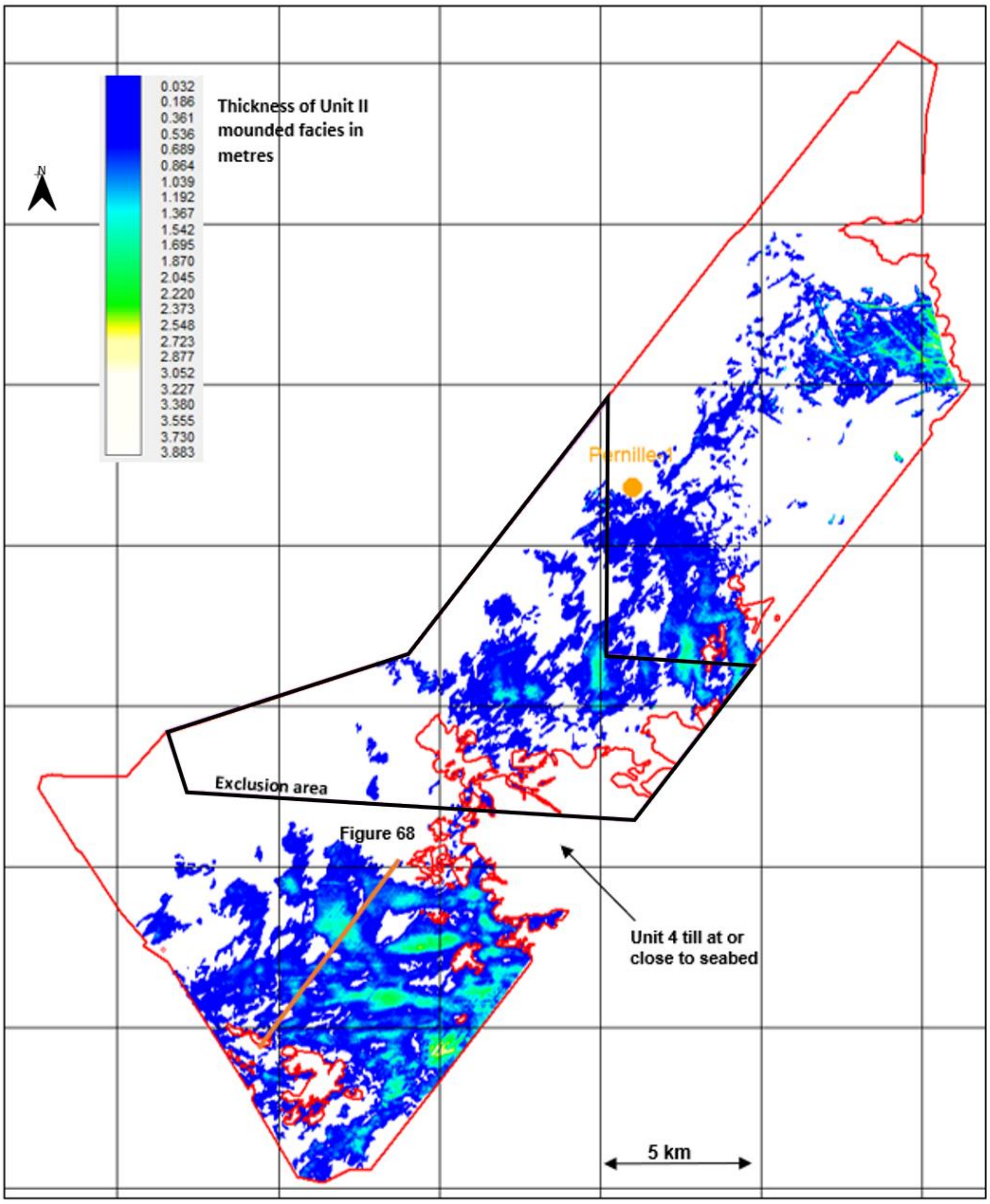


Figure 69: SBP Thickness and distribution of Unit II mounded facies

9.2.5 Unit IIa/b channel fill facies

Within Bornholm I, Unit IIa/b is generally restricted to small pockets and the infill of ~120 m wide, east-west trending channels (Figure 70 and Figure 71). These channels may be keel scours cut by ice bergs. In northernmost 4 km of the survey area the interval is far more continuous and appears similar to the appearance of Unit II in Bornholm 2 where Unit II deposits form a near continuous blanket (Figure 71). The desk study indicates that this package is generally a more extensive basin-wide drape.

Unit IIa/b shows internal reflectors, indicating that the sediments were laid down as a conformable drape, and tends to be quite thin (<2 m thick) except for the area in the far north, where the interval is over 5 m thick. It has not been possible to sub divide these laminated Unit II deposits within Bornholm I. Jensen et al.'s stratigraphic model splits the interval into sub-units a (Ancylus Lake, laminated clay) and b (Yoldia Sea, homogenous clay).

Unit IIa/b is interpreted to comprise normally consolidated CLAY, possibly with iron sulphide-rich laminations in upper parts.

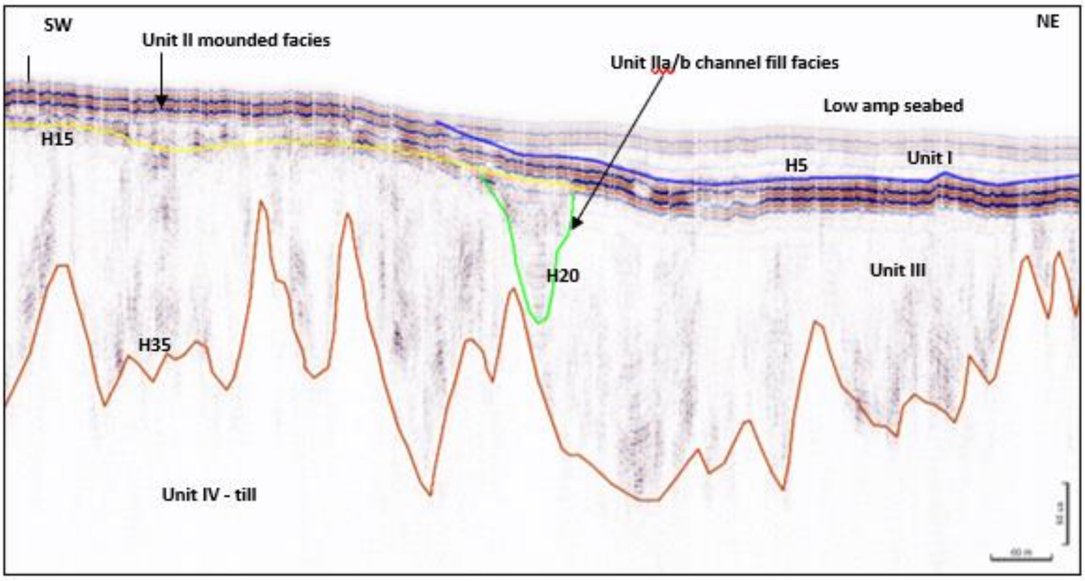


Figure 70: SBP data example, line P_024, channelized Unit IIa/b, middle slope

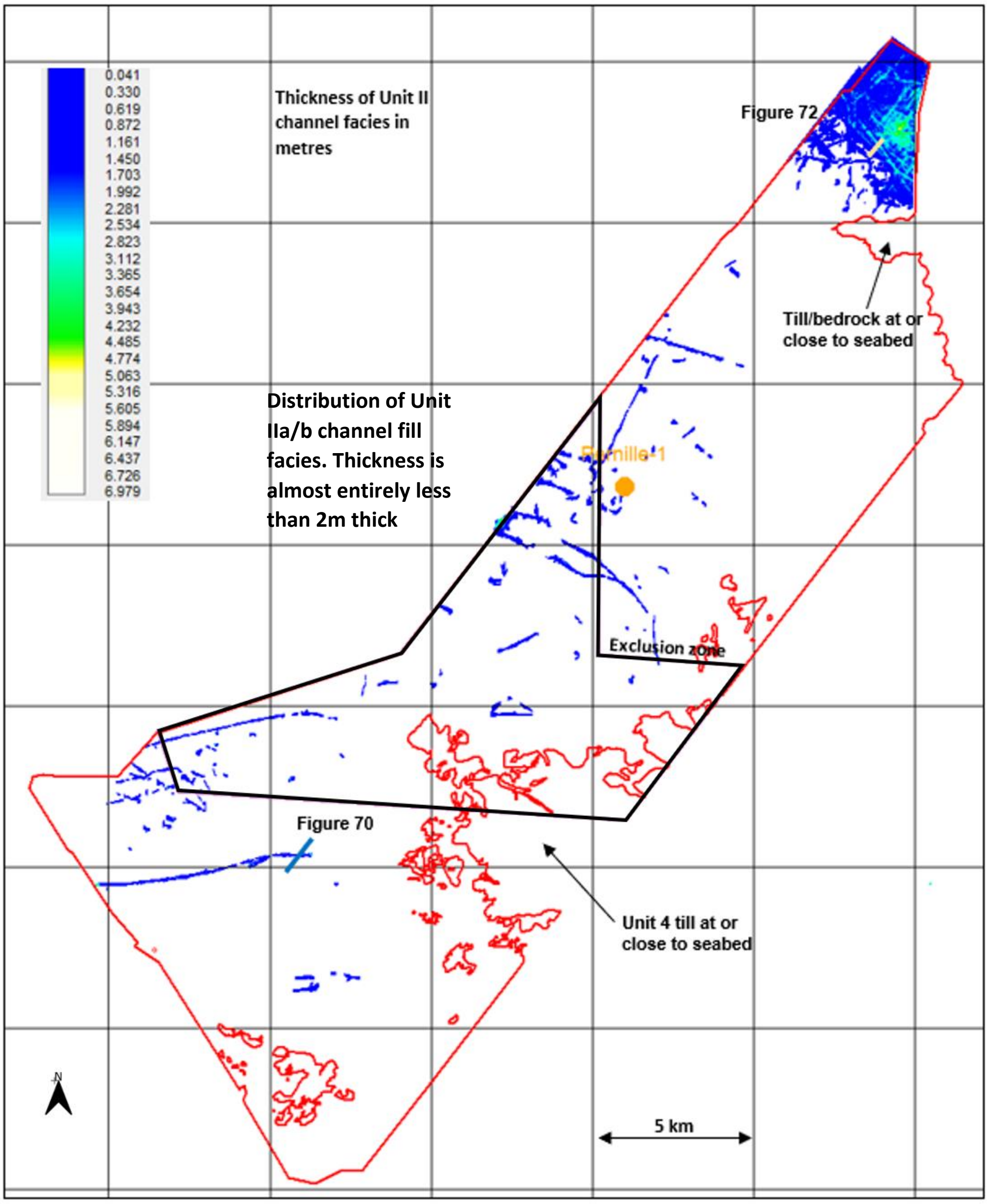


Figure 71: Distribution of Unit IIa/b channel fill facies

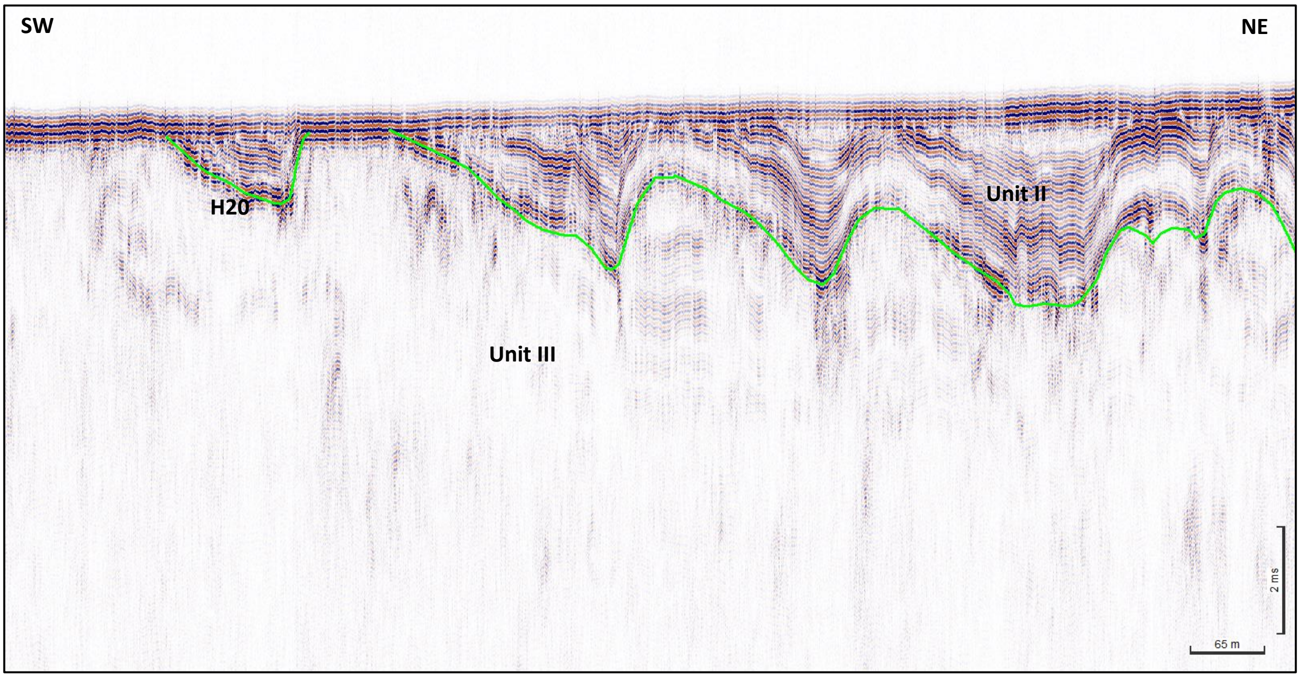


Figure 72: SBP data example, line 1C_S_080, more continuous Unit IIa/b, far north

9.2.6 Unit III

Unit III sediments were laid down in ice dammed lakes and conformably drape the irregular top till basal surface. Unit III is generally ~5-7 m thick within Bornholm I and extends over most of the area, pinching out against the top of the Unit IV till along the eastern margin of the site and against bedrock/till in the far north-east where till/bedrock is at or close to seabed (Figure 73). Unit III thickens in the northern extreme of the area to 30 m (Figure 74).

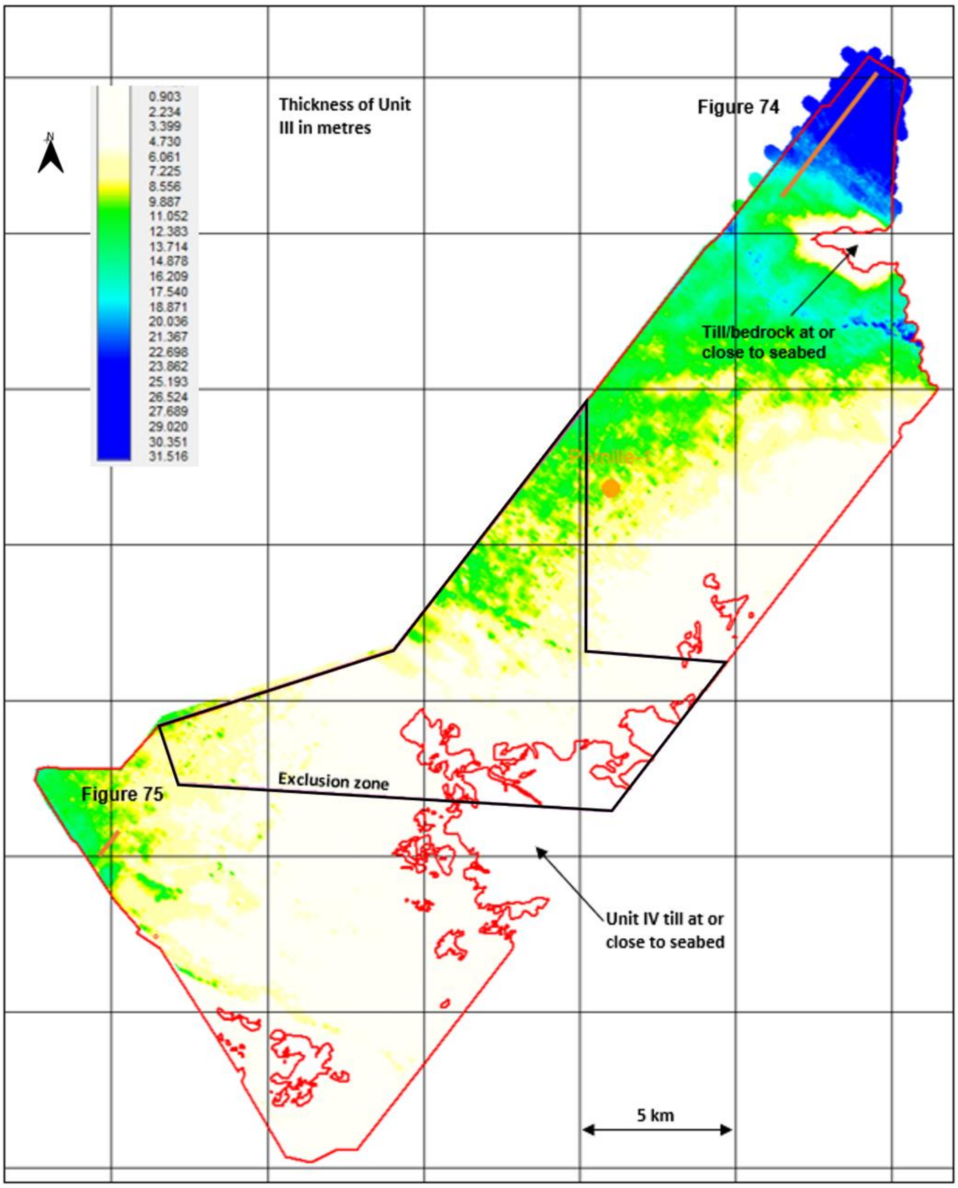


Figure 73: Thickness and distribution of Unit III

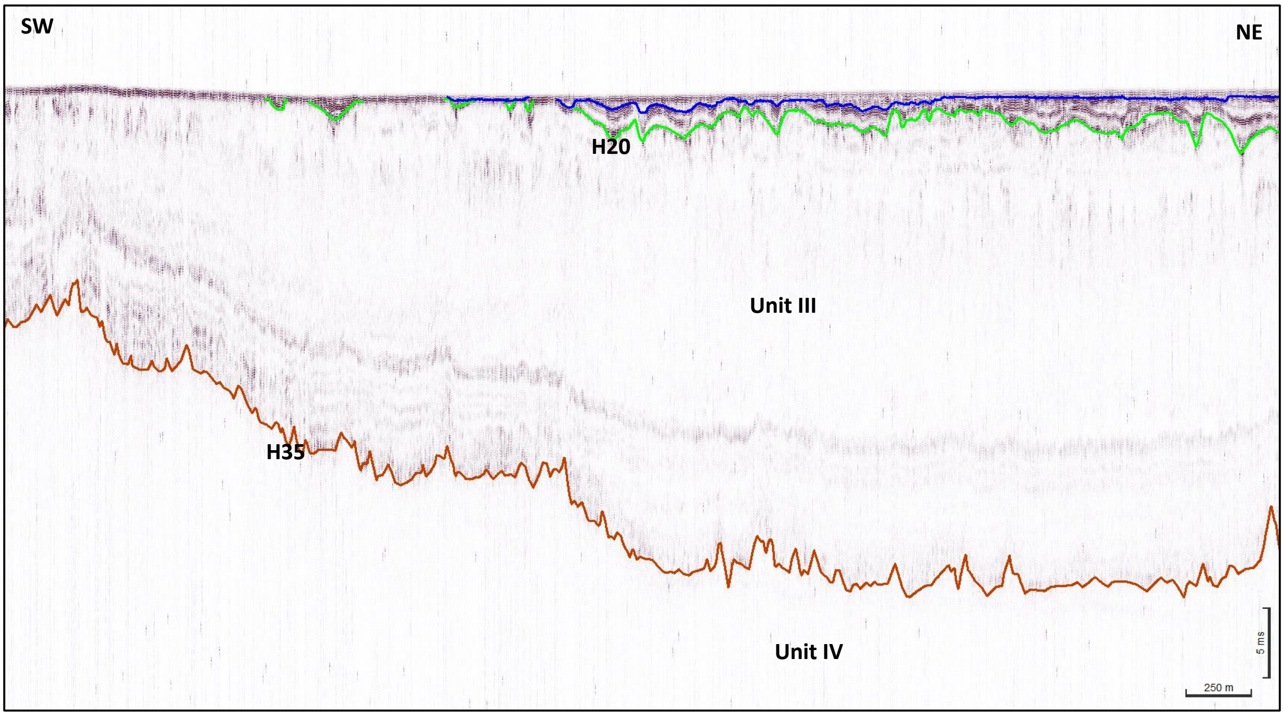


Figure 74: SBP data example, line 1C_P_031, Unit III, thick in far north

In detail, there is significant thickness variation of this unit over short distances because the underlying till is very irregular and forms steep sided ridges and gullies.

The stratigraphic model separates Unit III into three sub-units, though this has not been done during this phase of mapping. Locally, laminated intervals are imaged at the top and bottom of Unit III, sub-units a and c (Figure 75). These are the deposits of Baltic Ice Lake I and II, which sandwich the homogenous lowstand clays of sub-unit b. More usually the interval has a complicated internal structure with laminated intervals abruptly giving way to acoustically transparent zones. A proportion of the complexity is related to the rough texture of the draped basal surface. Additionally, a certain amount of reworking may have occurred during the drainage and refill of the ancient ice lakes.

The entire interval is clay-prone, though the upper part of the unit may be silty. The Pernille borehole proved silty clay at this interval (Figure 85). As post-glacial deposits these sediments will be normally consolidated.

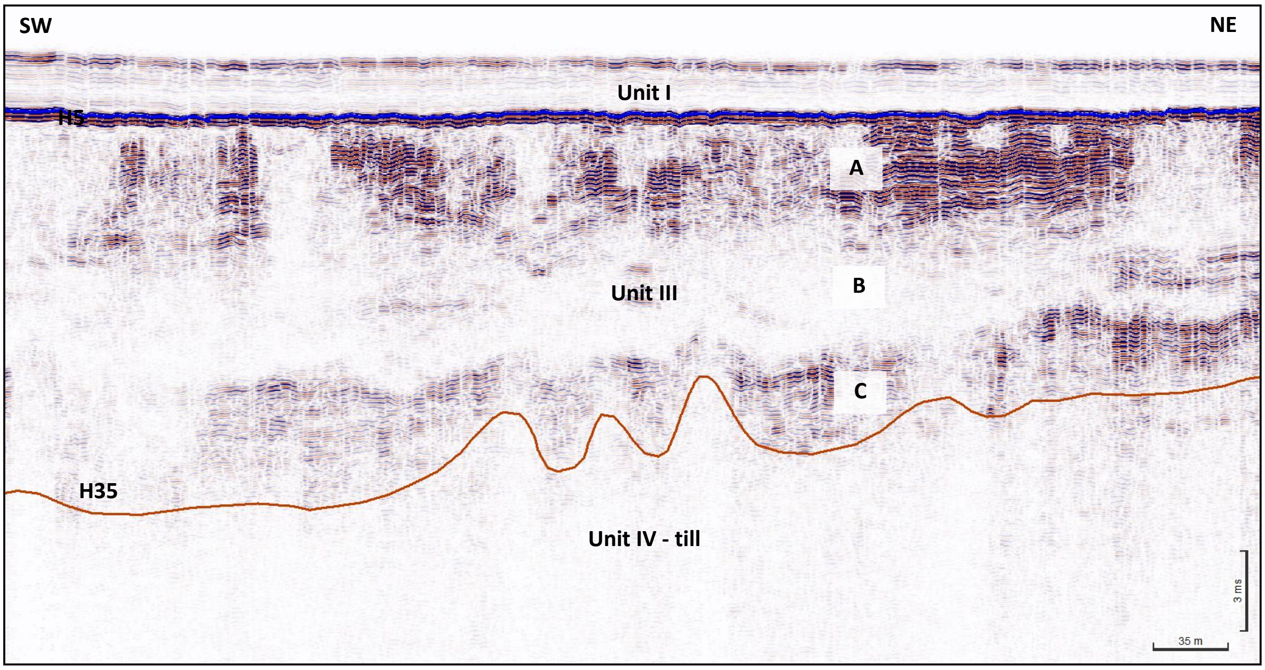


Figure 75: SBP data example, line P_004, Unit III, lower slope

9.2.7 Unit IV

The upper part of Unit IV is a glacial till which has been subjected to ice contact. It comprises a clay-prone diamicton which is likely to contain subordinate silt, sand, gravel, cobbles and boulders. The Pernille borehole proved silty, sandy clay with gravel over this interval (Figure 85). Unit IV will be over-consolidated. Consolidation levels may significantly vary over short distances.

Unit IV occurs throughout Bornholm I and is at or close to outcrop over eastern areas and in the far north-east (Figure 76).

The upper surface of the till appears to be arranged into a series of ridges, though it is difficult to be certain of this in a 2D data grid, the upper surface is certainly irregular. The unit is occasionally just 1-2 m thick over the bedrock unconformity. The till is only clearly absent in the extreme north-east where bedrock is at or close to seabed.

The stratigraphic model includes sub-unit IVa, an outwash deposit. This is not clearly imaged in either of the Bornholm areas. Unit IV is equivalent to Unit IVb in the stratigraphic model, where it is described as a diamicton.

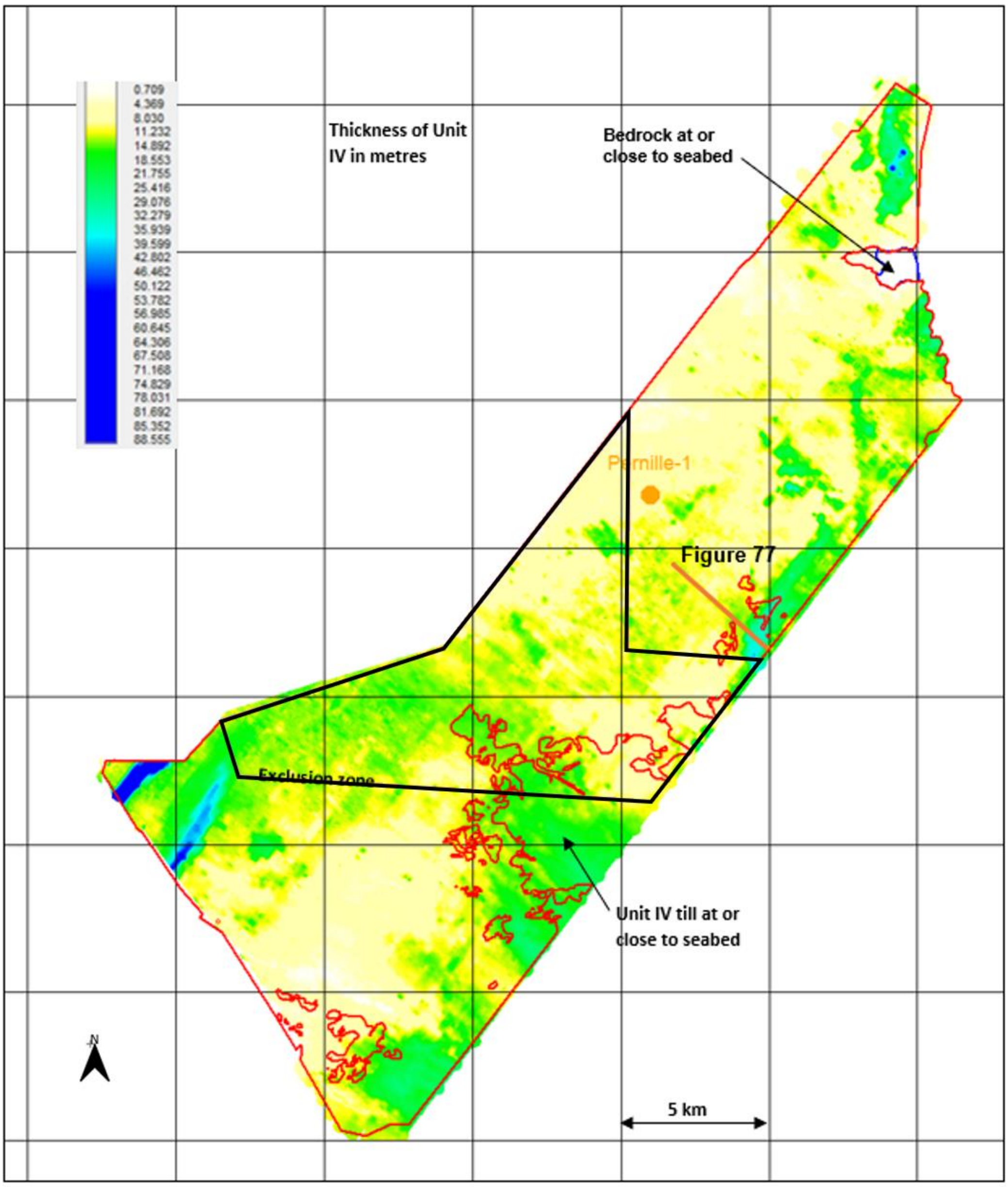


Figure 76: Thickness and distribution of Unit IV

Unit IV thickens in proximal areas and in restricted areas farther west, where the top bedrock is interpreted to be eroded beneath the level of the truncation surface. While the upper parts of Unit IV are confidently interpreted as an ice-contact till, the nature of the deeper parts of Unit IV is less clear.

In eastern proximal areas some structure is imaged within these deeper parts of Unit IV. These sediments may be outwash deposits sourced from the east which were then buried by tills of a subsequent ice advance (Figure 77). If this is the case, then these sediments may be sandy.

The infill of the deeply eroded areas further west is probably older tills (as glacial activity is the most likely cause of the deep erosion) but may be neo-tectonic sediments, laid down at some time between the

Paleogene carbonates of the bedrock and onset of Quaternary glacial activity. This is one of the uncertainties which should be reduced by geotechnical acquisition.

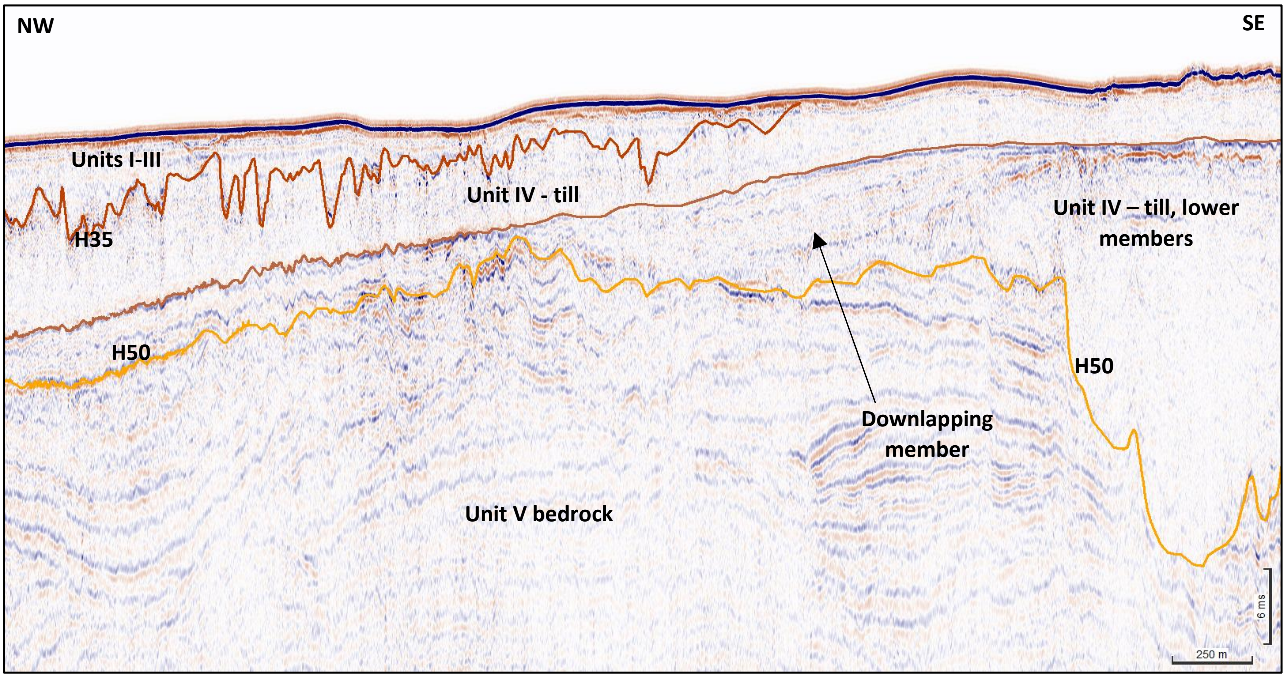


Figure 77: UHR data example, line X_023, Unit IV

9.2.8 Unit V Bedrock

Within Bornholm I the bedrock comprises limestone of late Cretaceous or Paleogene age. This is confirmed by the Pernille well and borehole, towards the north of the area.

The upper surface of the bedrock is a generally a gently north-west dipping truncation surface with an angular unconformity between the limestones and their much younger overburden. The bedrock is generally between 10 m and 20 m below seabed.

The depth of the bedrock below seabed is shown in Figure 78.

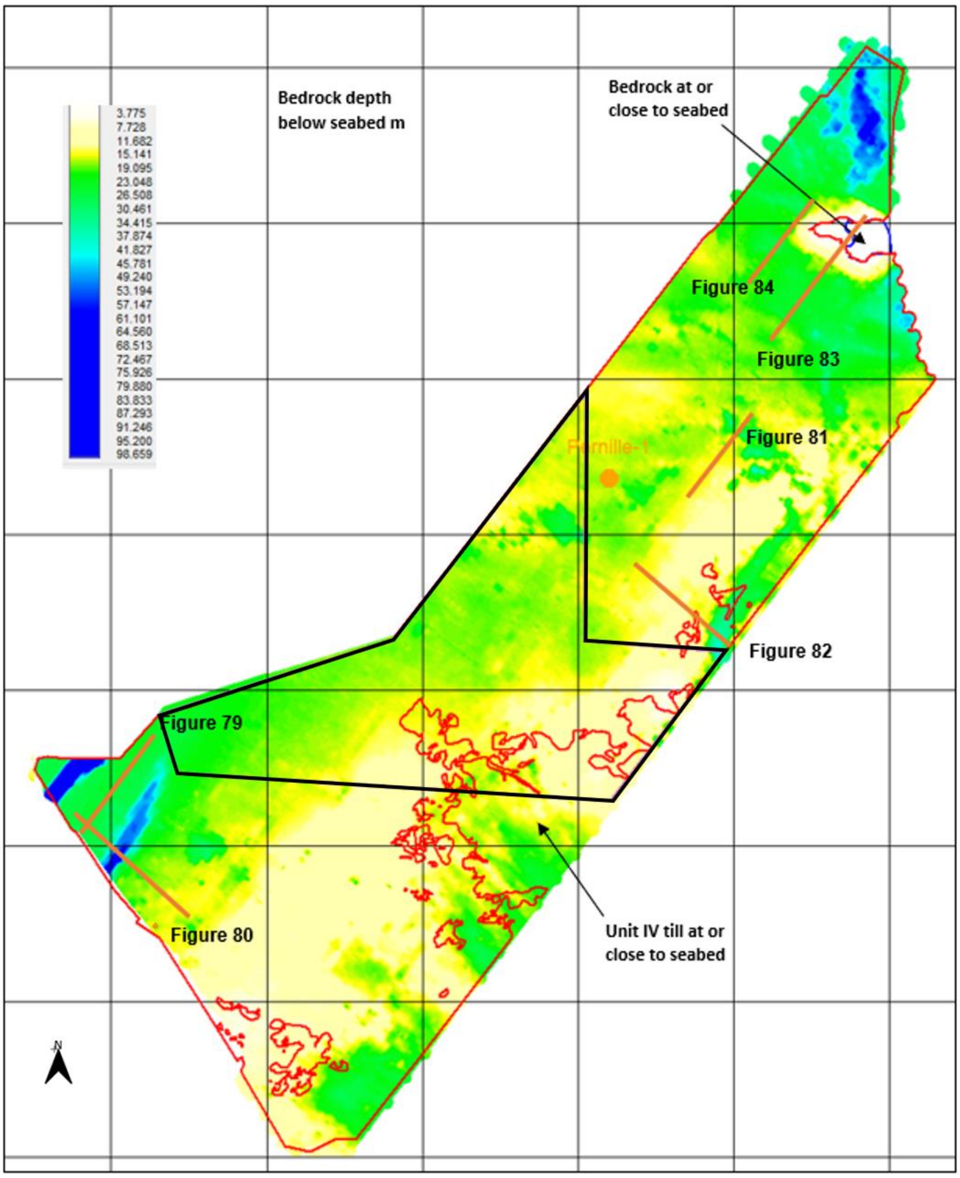


Figure 78: Depth BSB to H50 (Bedrock)

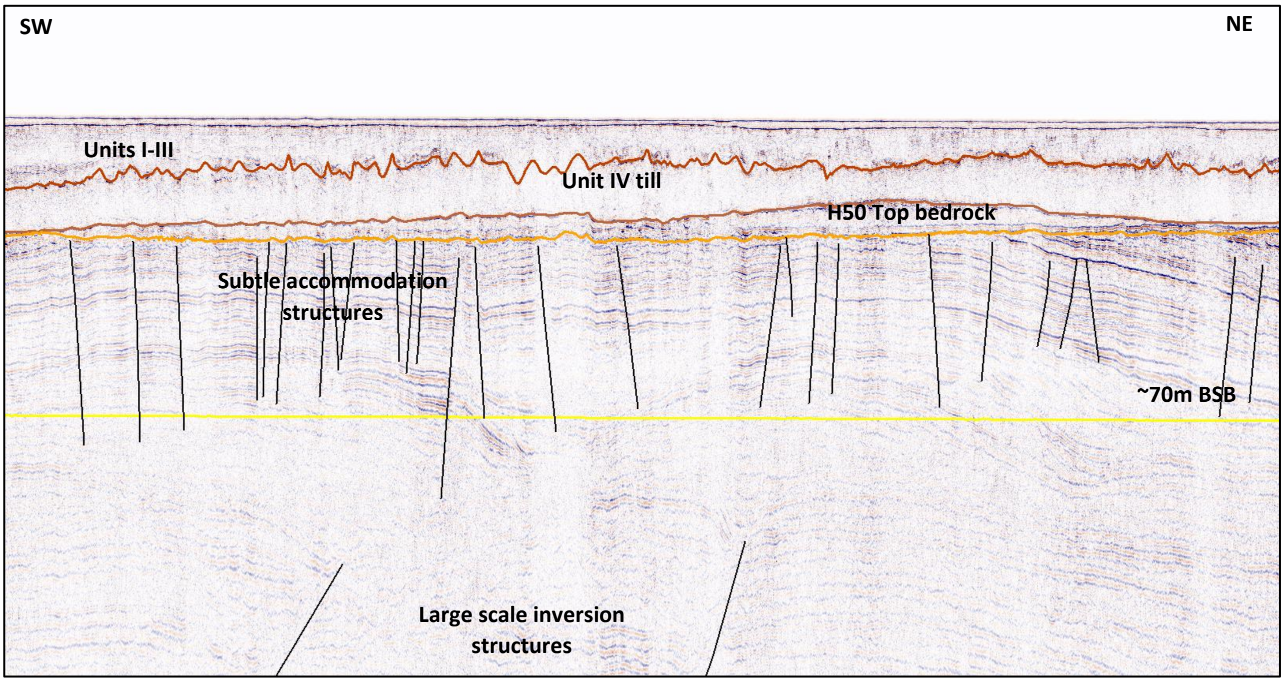


Figure 79: UHR data example, line P_003, Unit V, south of area

The folds and faults imaged within 70 m of the seabed are interpreted to be related to the late Cretaceous/early Paleogene inversion episode caused by compressional strike slip movements. Low displacement (~2 m) normal faults and gentle folds are imaged over the southern and central parts of the area (Figure 79). These are interpreted to be accommodation structures in the limestone deposited in the closing phases of inversion or immediately afterwards. Greater structuration is imaged in the northernmost 15 km of the area (Figure 81 and Figure 84). This area is interpreted to have been more directly influenced by the inversion episode.

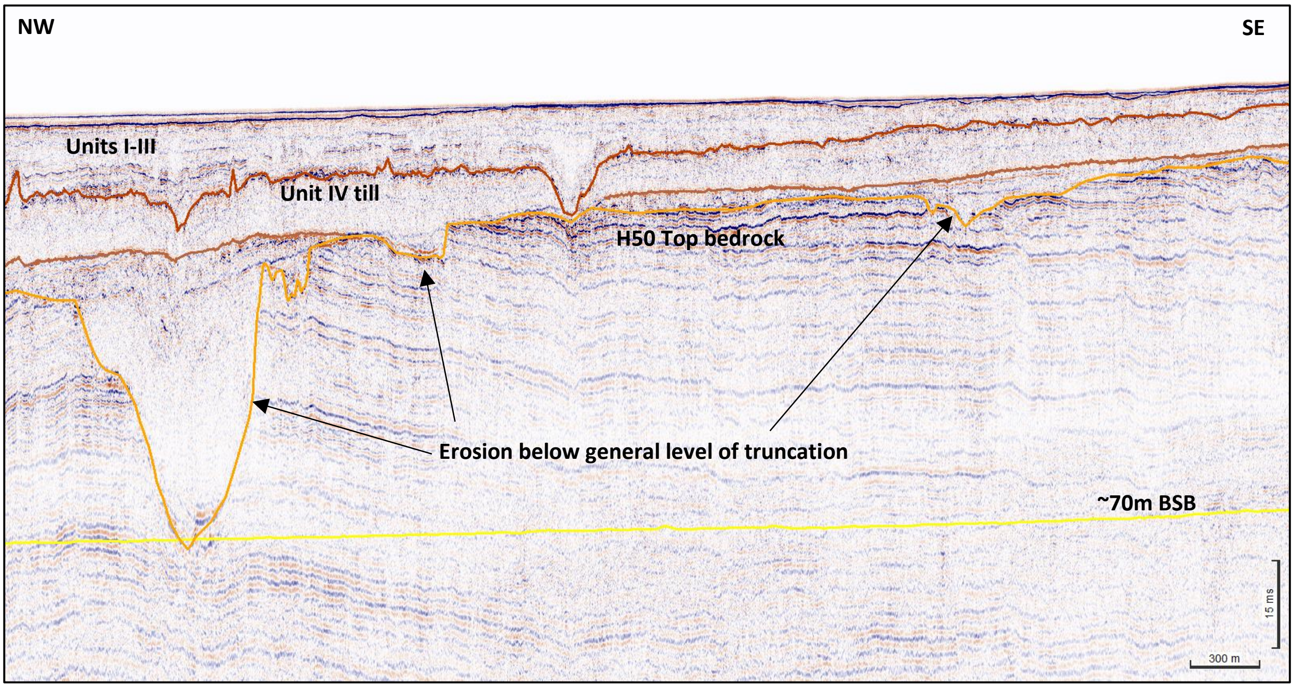


Figure 80: UHR data example, line X_005, Unit V, deeper erosion, south of area

The upper truncation surface was initially eroded off in response to this uplift, but the bedrock may have been subjected to further phases of erosion during early glaciations. There are areas of deeper erosion in the south-west of the area and along the eastern margin of the area (Figure 78). In the south-west this erosion extends to approximately 70 m below seabed – the entire foundation zone (Figure 80). It may be that the planar truncation surface was cut following the Late Cretaceous inversion episode and the localised deeper erosion may be the result of early glacial activity.

In the extreme north-east, there is an exceptional area where the bedrock forms a 2.8 km wide dome, which at its apex, crops out over a 1 km by 1 km area. The unconformity, which elsewhere marks the top of the bedrock, appears to pass under the bedrock dome (named H52), which is interpreted to comprise younger, disturbed bedrock (Figure 83 and Figure 84).

The younger glacial and post glacial units pinch out over this feature.

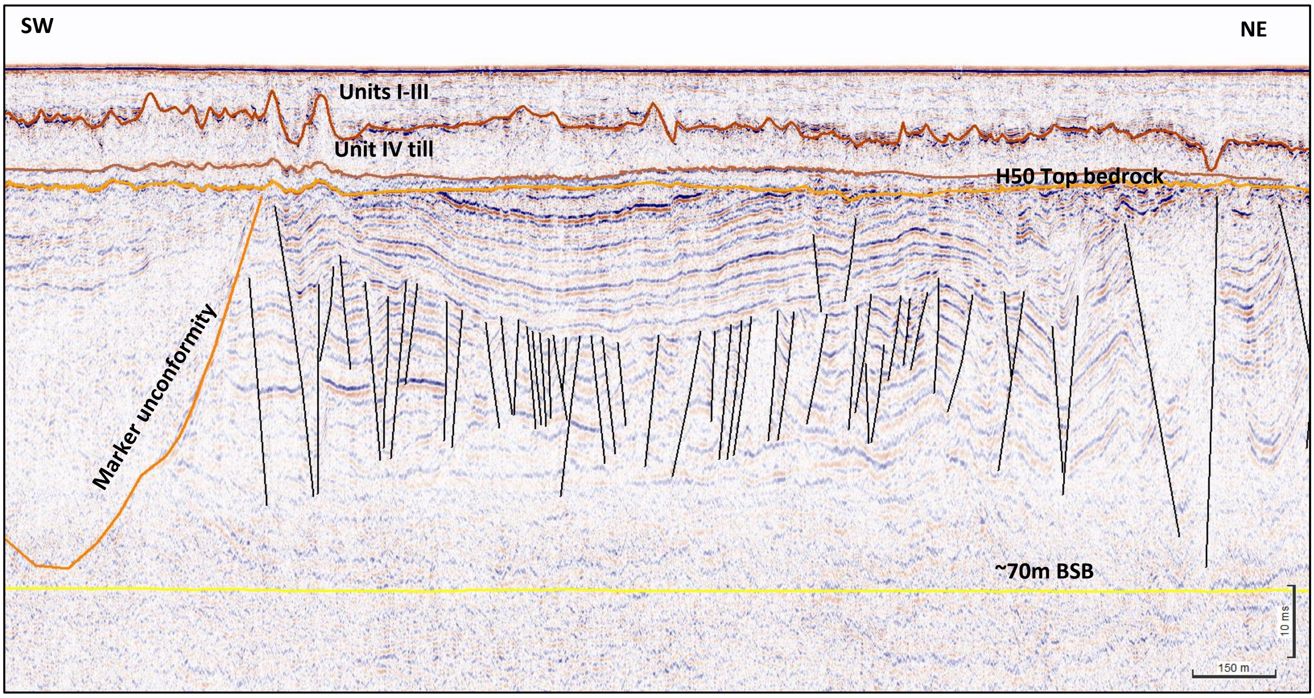


Figure 81: UHR data example, line P_038, Unit V, structure, north of area

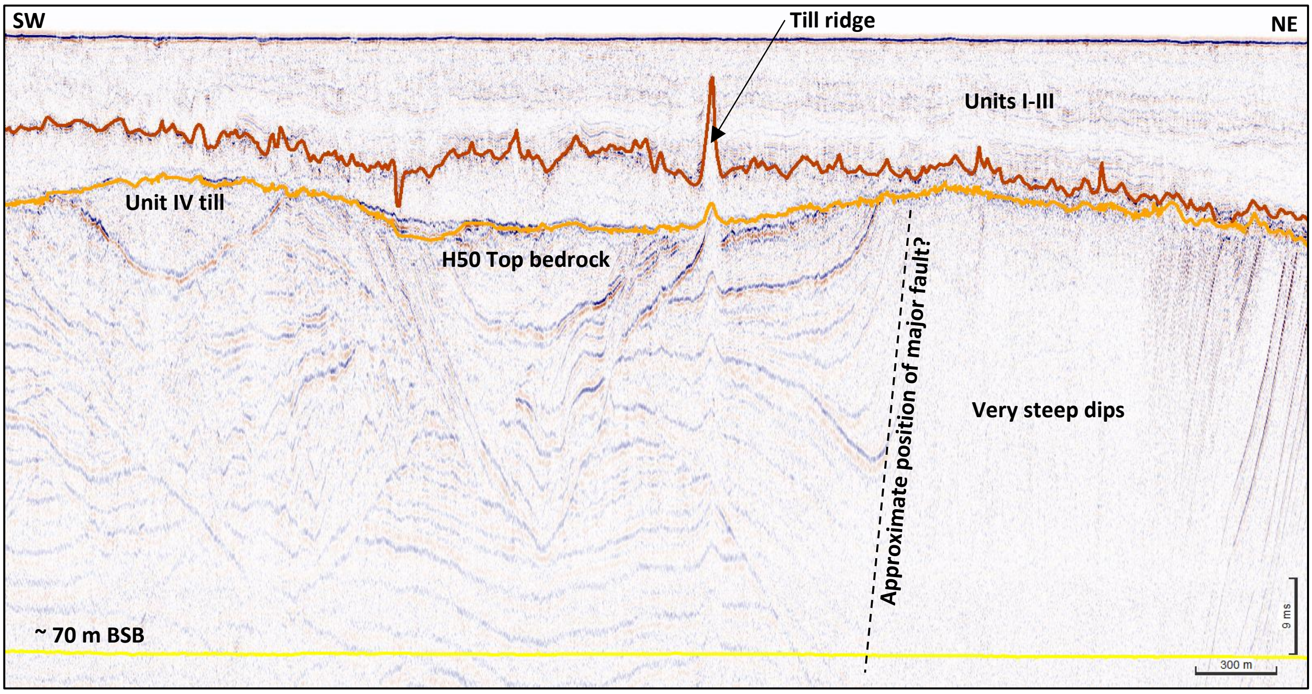


Figure 82: UHR data example, line P_022, Unit V, structure, north of area

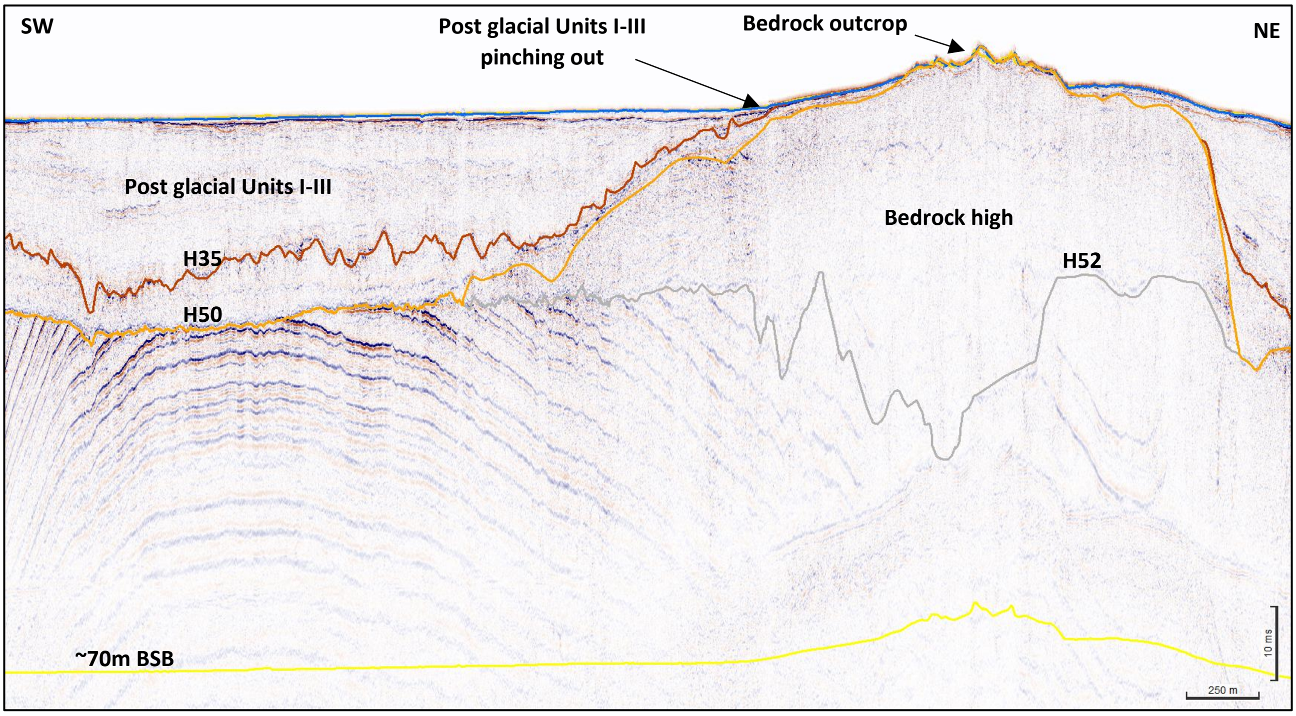


Figure 83: UHR data example, line 1C P_020, bedrock high, extreme north of area

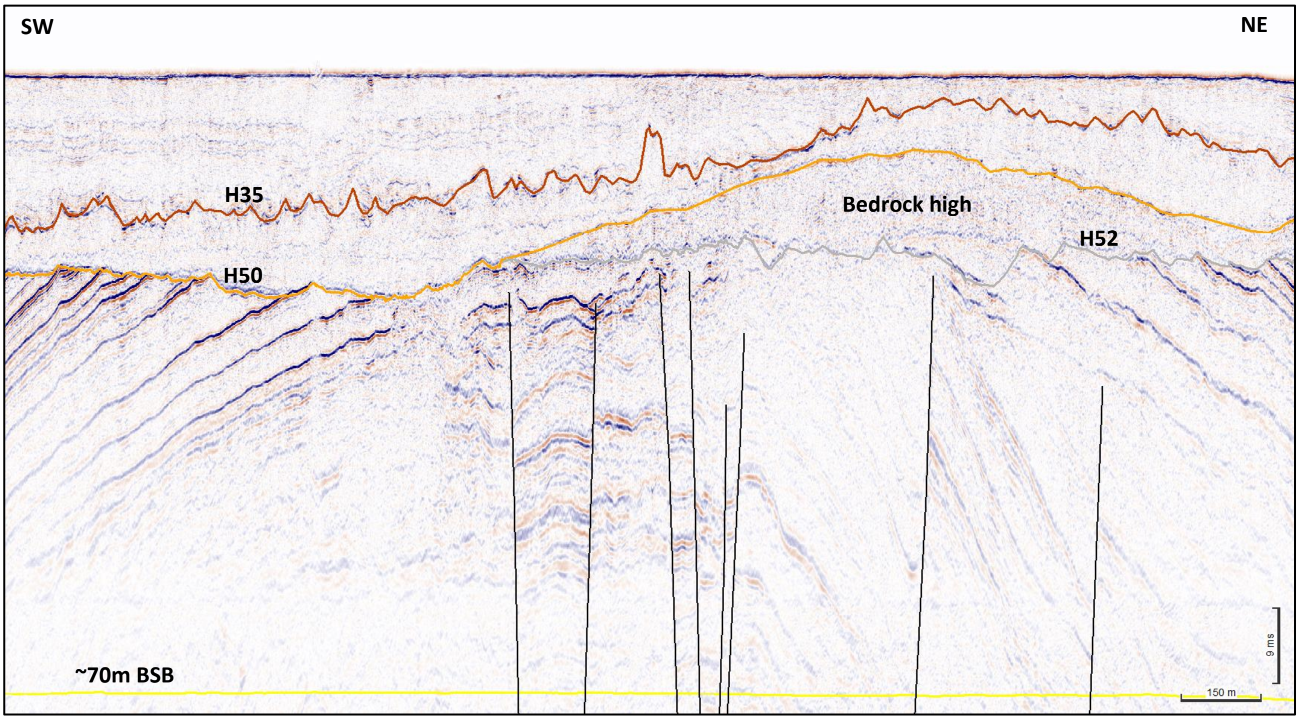


Figure 84: UHR data example, line 1C P_026, bedrock high, and faults

A major north-west to south-east striking fault is inferred approximately 5 km from the northern extremity of the study area (Figure 86). North of this fault bedrock dips are very steep, and the bedrock may potentially comprise Lower Cretaceous clastics.

9.2.9 Existing Ground Truth

The Pernille-1 exploration well is located in the north of the study area. The desk study contains information on the well and a borehole acquired at the same location (Figure 7.1 in the desk study, Jenson et al, 2017).

The tophole geology was logged in the well. The most important matter shown at this location is that the carbonates of the Chalk Group extend to a depth of 908 m MSL – the part of the foundation zone below the top bedrock is likely to comprise limestone/chalk to well beyond 70 m below seabed.

The borehole log shows 16 m of clastics over the limestone bedrock. Figure 85 shows a correlation between the profiler seismic data and the interfaces at the borehole. The borehole depths are time converted using the velocities shown on the figure, horizon depths are calculated using the same velocities.

The correlation is generally very good. There are slight differences at the surfaces with significant relief – this can be explained as the result of small positioning errors. The tie is excellent at the top bedrock surface.

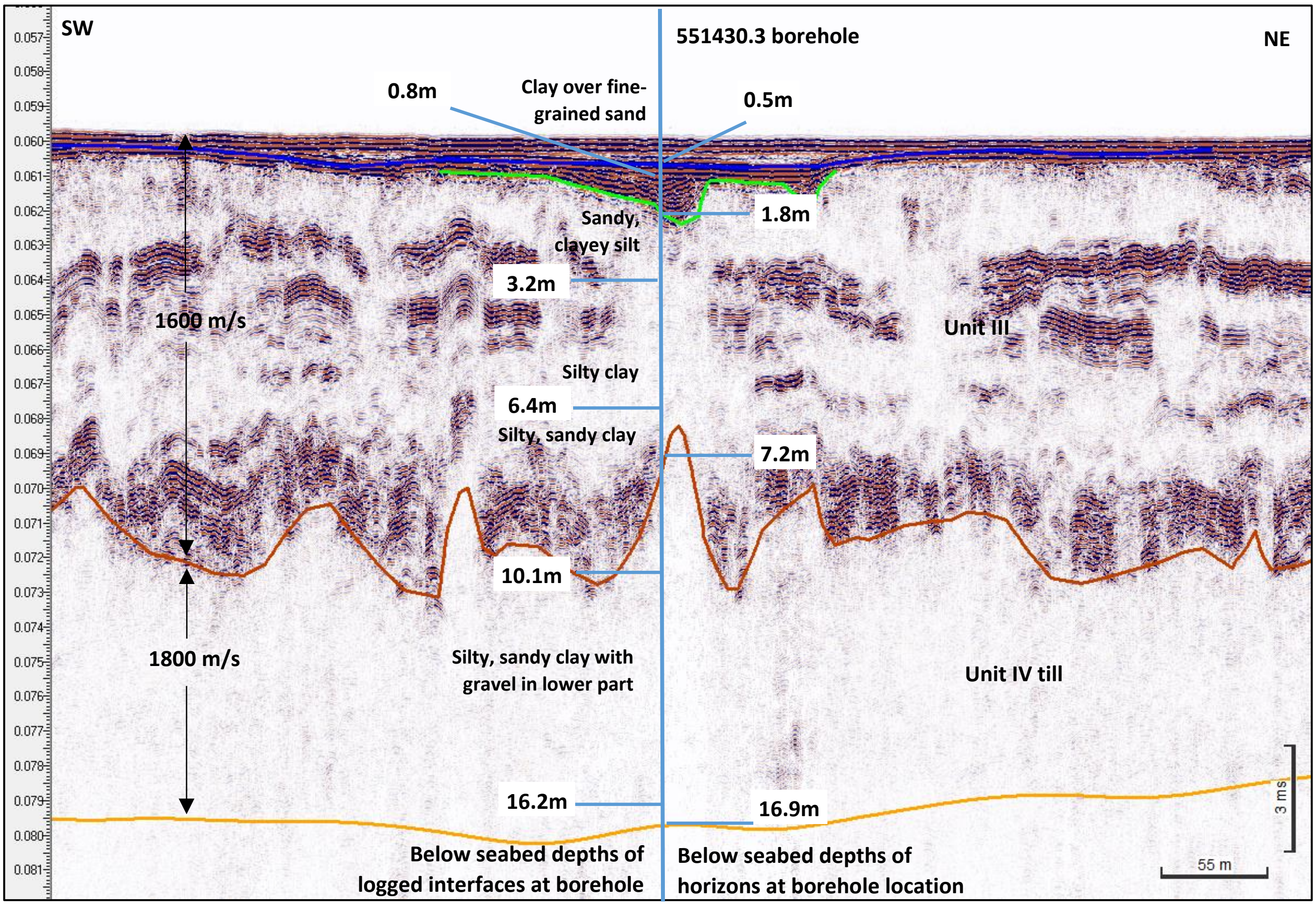


Figure 85: SBP data example, line S_086, Pernille borehole location, north of area

9.2.10 Shallow Geological installation constraints

- Unit I sediments are very weak/soft. Their bearing capacity will be negligible and could cause retrieval difficulties related to settlement of seabed frames.
- Unit IV may have variable levels of over-consolidation.
- Unit IV may contain cobbles and boulders.
- Unit V may have strength variations.
- Unit V may be weathered at the upper truncation surface.
- Unit V may locally be weakened by faulting and micro fractures.

There is no clear evidence of shallow gas within 70 m of the seabed.

9.2.11 Shallow Geological comparison of BHI and BHII

There is a good correspondence between the shallow geology of the Bornholm I and Bornholm II sites. These two development areas are arranged north-west (BHI) and south-east (BHII) of a structural high. To a large degree the two sites are like the wings of a butterfly: mirror images of each other. Geology dips away to the north-west in BH I and to the south-east in BH II.

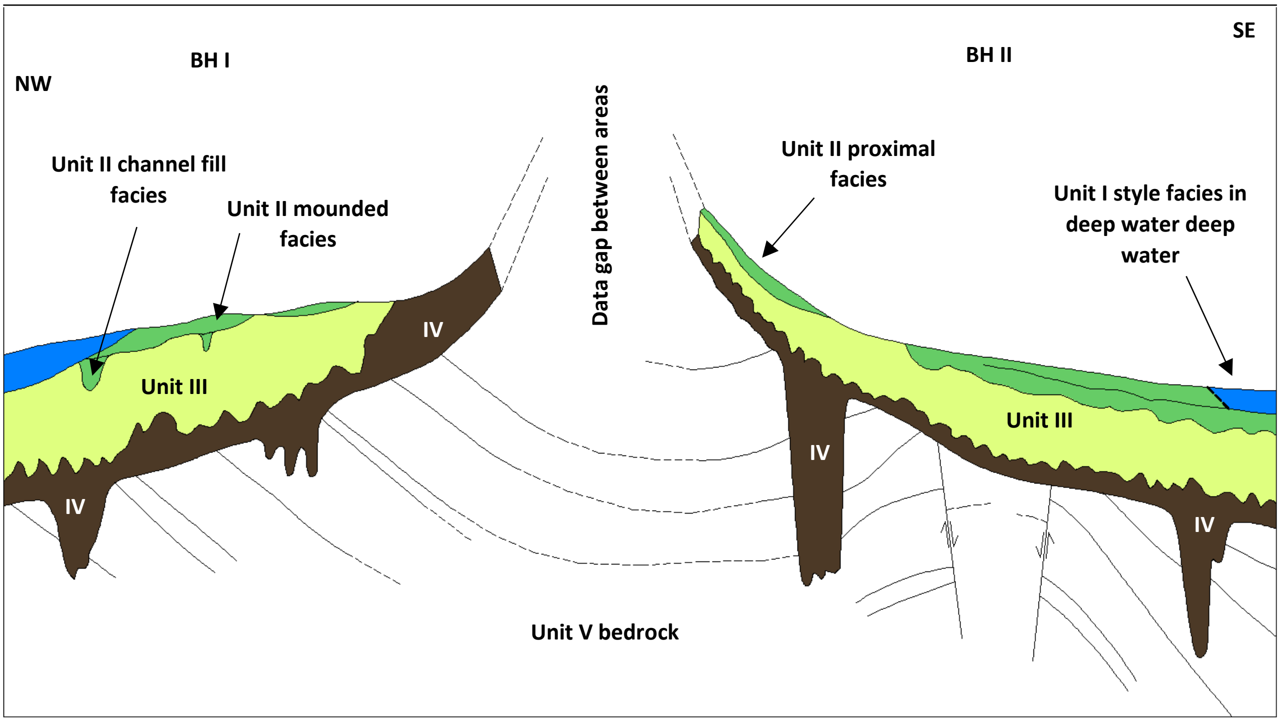


Figure 86: Schematic comparison of BHI and BHII

In detail there are differences between the areas:

- Unit I is a distinct unit in BHI with H05 at its base. In BHII the shallowest sediments appear to take on similar characteristics but as a deep-water variation of Unit IIa.
- Unit II is divided into a younger mounded facies and older channel-fill facies in BHI. In BHII Unit II is spilt into a proximal facies and a distal, laminated facies. The proximal facies of BHII is considered equivalent to the mounded BHI facies and the distal facies of BH II is considered equivalent to the channel-fill facies of BHI.
- Unit III is very similar in the two sites.
- Unit IV is very similar in the two sites.
- The bedrock in BHII is generally more heavily structured than in BHI and may show greater diversity, there are interpreted to be areas of Jurassic clastic outcrop in BHII, BHI may have carbonate sub-crop throughout.

10 SEABED SURFACE CLASSIFICATION AND SUB-SURFACE GEOLOGY COMPARISON

Seabed geology was interpreted from side scan sonar imagery and bathymetry data. There is a good correlation between outcrops mapped in the seabed data (Figure 40) and the distribution and outcrop boundaries generated in the interpretation of the SBP and UHR data (Figure 76)

In the east of the area there is a good correspondence between the areas where the UHR data indicate that the till of Unit IV is at or close to seabed (Figure 76), and the areas classified as Till in the seabed surface geology interpretation (Figure 40).

In the extreme north-east (Figure 76), profiler data indicate that till and bedrock crop out over a 2.5 by 1.3 km area, and the area is Till and Sedimentary rock in the seabed geology classification (Figure 41).

11 CONCLUSIONS

The bathymetric survey results show that the water depth varies moderately across the Bornholm I site, ranging between 27.83 m at the southern part of the survey site (Bornholm I S) and 47.32 m at the northern extended scope (Bornholm I N). The mean depth across the site is 40.63 m. Terrain profiles show a gradual increase in water depth from east to west and from south to north across Bornholm I site. In the northern region there are no prominent slopes and southward the increase in depth to the west is becoming more evident with slopes increments. In the central region, the western part is showing a rough topography associated with boulder field areas. In the southern region of the site, depth increases westward whereas higher slope values are detected eastwards outlining the shallowest zone of the site and matching with ripples areas.

Slope angles across the site are typically and very gentle (<1°) and gentle (1°-5°). Very high slope values (15>°) are outlining specific features such as wrecks, jack-up vessel footprints, large boulders and disturbed raised seabed. Moderate to high slope values (5>°) indicate anchor scars and seabed disruption, bedform features, possible seabed gullies and erosional trenches, as well as fishing or dragging activities.

The seabed surface geology is generally characterised by Sand and Silt. In the northern section of the site (Bornholm I N), Sand, and Clay and Silt areas are dominant, whereas widespread regions of Sand and Gravel extend over the area. In the north-easternmost part Till and Sedimentary rock outcrops are outlined. In the eastern section of the site (Bornholm I E), seabed sediments comprise mainly Sand, and Clay and Silt. Alternating bands Gravel and Sand and a possible till matrix, extend across from the northern to the eastern section. The southern section of the site (Bornholm I S) is classified as Sand with some Clay and Silt areas and its southernmost region is predominantly Till. The western section of the site (Bornholm I W) is predominately Clay and Silt with extended Sand areas, a likely till matrix and Gravel and Sand bands eastwards.

The northern section (Bornholm I N) is heavily trawl scarred. Extended areas of boulder fields and scattered pitted areas are present along with ripples, large ripples and mega ripples. The eastern section (Bornholm I E) is extensively trawl scarred northwards and extended boulder field areas are outlined southwards. Ripples and mega ripples occur mainly at the south-west. Erosional features cross the northern part of that section, and the southern area is punctuated with disturbed seabed zones. The southern section (Bornholm I S) is formed of boulder field areas interspersed by ripples in the southern tip. Anchor scarring is outlined northwards. In the western section (Bornholm I W), the northern part is heavily trawl scarred and boulder fields occur eastwards. The westward part of that section is interspersed with pitted areas whereas disturbed seabed areas are outlined eastwards.

A total of 121804 seabed surface objects (including auto picked boulders) were detected in Bornholm I site, some of them are determined to be of man-made origin and include: 8 wrecks or suspected wrecks, 1 unknown linear feature/possible cable, 3 debris related cable items, 1 pipeline (Baltic Pipeline) that crosses the NE part of the site, 439 debris items, 24 items possibly related to fishing activity and 17 seabed disturbances from jack-up platforms and fishing activity.

The geological foundation zone extends to 70 m below seabed. The rocks and sediments within this interval have been interpreted, with reference to the stratigraphic model from the GEUS desk study (Jensen et al., 2021), and five units were identified from the sub-surface dataset. Key surfaces are the top of Unit IV (H35/seabed), which is the top of over-consolidated deposits and H50, the top of the bedrock.

Unit I is a thin package, typically less than 1 m and exceptionally reaching a thickness of 2 m, of organic-rich post-glacial marine CLAY that is widely distributed in the western parts of the site. It tends to infill relative lows and its thickness varies in relation to the morphology of its basal surface. Unit II is generally less than 2 m thick and has a distinctive mounded form. Its thickness variation is largely due to this relief at its upper surface, and it is widespread but patchy over the central to upper slope areas. The unit is post-glacial, and it occurs above the ancient lake deposits of Unit III. It is tentatively interpreted to comprise drowned beach deposits of silt and fine sand which may have been partially reworked during marine transgression. The age relationship of Unit I and Unit II is not so clear as there is very limited overlap in the distribution of these packages it is determined that Unit II generally pre-dating Unit I.

Unit IIa/b is interpreted to comprise post glacial – transitional normally consolidated CLAY, possibly with iron sulphide-rich laminations in upper parts. It is restricted to small pockets and the infill of ~120 m wide, east-west trending channels. Unit III is generally ~5-7 m thick within and extends over most of the area, pinching out against the top of the Unit IV till along the eastern margin of the site. It thickens in the northern extreme of the area and shows significant thickness variation over short distances. Unit III sediments were laid down in ice dammed lakes and conformably drape the irregular top till basal surface. The entire interval is clay-prone, though the upper part of the unit may be silty. As post-glacial deposits these sediments will be normally consolidated.

Unit IV occurs throughout Bornholm I and is at or close to outcrop over eastern areas. The upper part of Unit IV is a glacial till which has been subjected to ice contact. It comprises a clay-prone diamicton which is likely to contain subordinate silt, sand, gravel, cobbles and boulders. It will be over-consolidated and consolidation levels may significantly vary over short distances. The upper surface of the till appears to be arranged into a series of ridges, its upper surface is certainly irregular, and the unit is occasionally just 1-2 m thick over the bedrock unconformity. While the upper parts of Unit IV are confidently interpreted as an ice-contact till, the nature of the deeper parts of Unit IV is less clear. The infill of the deeply eroded areas further west is probably older tills (as glacial activity is the most likely cause of the deep erosion) but may be neo-tectonic sediments, laid down at some time between the Paleogene carbonates of the bedrock and onset of Quaternary glacial activity.

Unit V – Bedrock comprises limestone of late Cretaceous or Paleogene age, generally between 10 m and 20 m below seabed. Its upper surface is a gently north-west dipping truncation surface with an angular unconformity between the limestones and their much younger overburden. In the north-east of the site, the bedrock forms a 2.8 km wide dome, which outcrops over a 1 km by 1 km area. An unconformity passes under the bedrock dome.

The folds and faults imaged within 70 m from the seabed are interpreted to be related to the late Cretaceous/early Paleogene inversion episode caused by compressional strike slip movements. Low displacement (~2 m) normal faults and gentle folds are imaged over the southern and central parts of the area. Greater structuration is imaged in the northernmost 11 km of the area and is interpreted to have been more directly influenced by the inversion episode. A major north-west to south-east striking fault is inferred approximately 5 km from the northern extremity of the study area. North of this fault, bedrock dips are very steep, and the bedrock may potentially comprise Lower Cretaceous clastics.

11.1 ARCHAEOLOGICAL CONSIDERATIONS

Considering that Quaternary sea level fluctuations have affected the area and the formation of the paleo shorelines, the likelihood of paleo landscapes that could have been occupied by early human, a full archaeological assessment and investigation from the current dataset will be performed by Vikingeskibsmuseet.

12 REFERENCES

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