SN2021_016 - Geophysical Survey For Offshore Wind Farms And Energy Island BORNHOLM II

Title	**Geophysical Survey Report BHII - Work Package A**
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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 extended scope	Addition of extended scope and client comments revision
3.0	23/12/2022	Client comments	Text and figure amendments
4.0	10/03/2023	Client Comments	Last client comments on two figures

TABLE OF CONTENTS

LISTS OF TABLES AND FIGURES

DEFINITIONS AND ABBREVIATIONS

Throughout this document the abbreviations listed in Table 1 is 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
mBSB	Metres Below Seabed
mE	Metres East
mN	Metres North
MRU	Motion Reference Unit
MSL	Mean Sea Level
NMEA	National Maritime Electronics Association

Abbreviation	Definition
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 – BHII			
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	15.04 m to 57.30 m (46.41 m mean)		
Slope angles	Typical: <1°, maximum: >15°		
Site topography	Water depth varies moderately, with a gradual increase in water depth from west to east and from south to north across the Bornholm II site.		
Seabed surface: Geology			
The seabed surface geology is characterised by clayey SAND and SILT. Bands of clayey and silty SAND with some areas of gravel are found in the north-eastern section of the site. The south of the site is dominated by SAND and SILT areas. An area of outcrop is found in the north-west of the site with some areas of clayey, silty SAND with gravel.			
Seabed surface: Morphology			
The east of the BHII site is heavily trawl scarred with some pitted areas present. Disturbed sediment areas due to the construction of the Nordstream 1 and Nordstream 2 pipelines are also present. The west of the BHII site has erosional features, boulder fields and sand ripples present.			
Seabed surface: Man-made features and site-specific hazards			
Wrecks	8 wrecks or suspected wrecks were identified throughout the BHII survey site		
Cables	0 cables identified		
Pipelines	3 Pipelines (Nordstream Pipelines, Baltic Pipe) [+ Nordstream 2 Denmark Route to the south of BHII site]		
Debris	1313 debris items were identified.		
Items related to fishing activity	147 items relating to fishing activity were identified.		
Seabed disturbances	37 Seabed disturbances from jack-up platforms and fishing activities		
Sub-seabed soil units			
Unit I	Unit I is a thin package of organic-rich post-glacial marine CLAY. Unit I is interpreted to be less than 1 m in thickness with areas of thicknesses greater than 2 m in the east of the BHII site.		
Unit IIa	Unit IIa is a laminated post-glacial CLAY with a maximum thickness of 5 m in the southeast of the site.		

Geophysical Survey – BHII	
Unit IIb	Unit IIb is a marine homogenous clay with an irregular internal seismic appearance. The interface between Unit IIa and Unit IIb can be indistinct where the two units are acoustically transparent.
Unit III	Unit III is formed of consolidated post-glacial lacustrine clays and silts.
Unit IV	Unit IV is a glacial, over-consolidated till comprised of a clay prone diamicton of silt, sand, gravel, cobbles and boulders.
Unit V	Bedrock comprising of late Cretaceous or Paleogene limestones and Jurassic clastics. Identified up to 70 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.

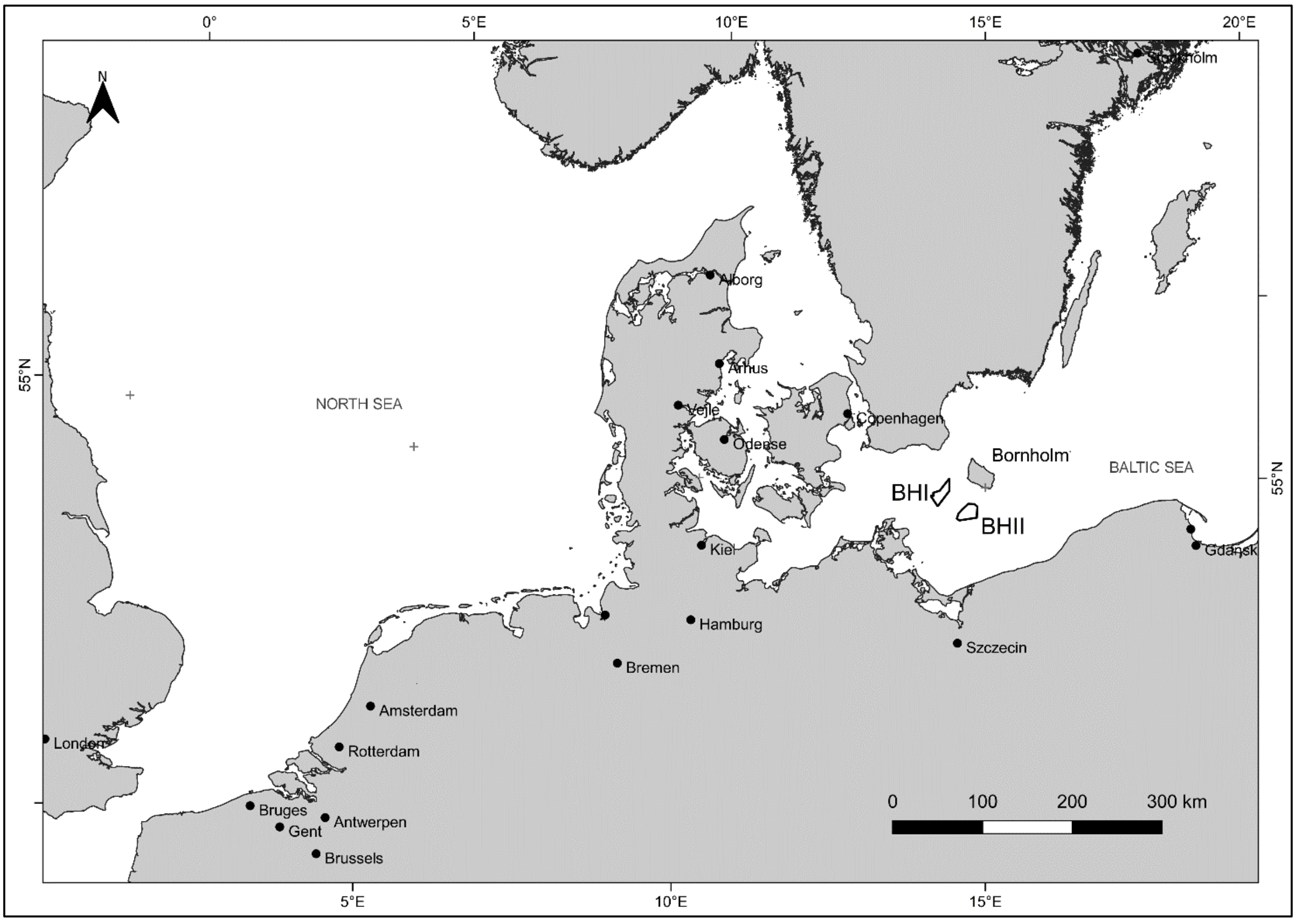


Figure 1: BHI and BHII project locations (Baltic Sea)

The project includes the following main elements:

- Two offshore wind farms, BHI and BHII, with a total of 3 GW including extensions areas.
- 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.

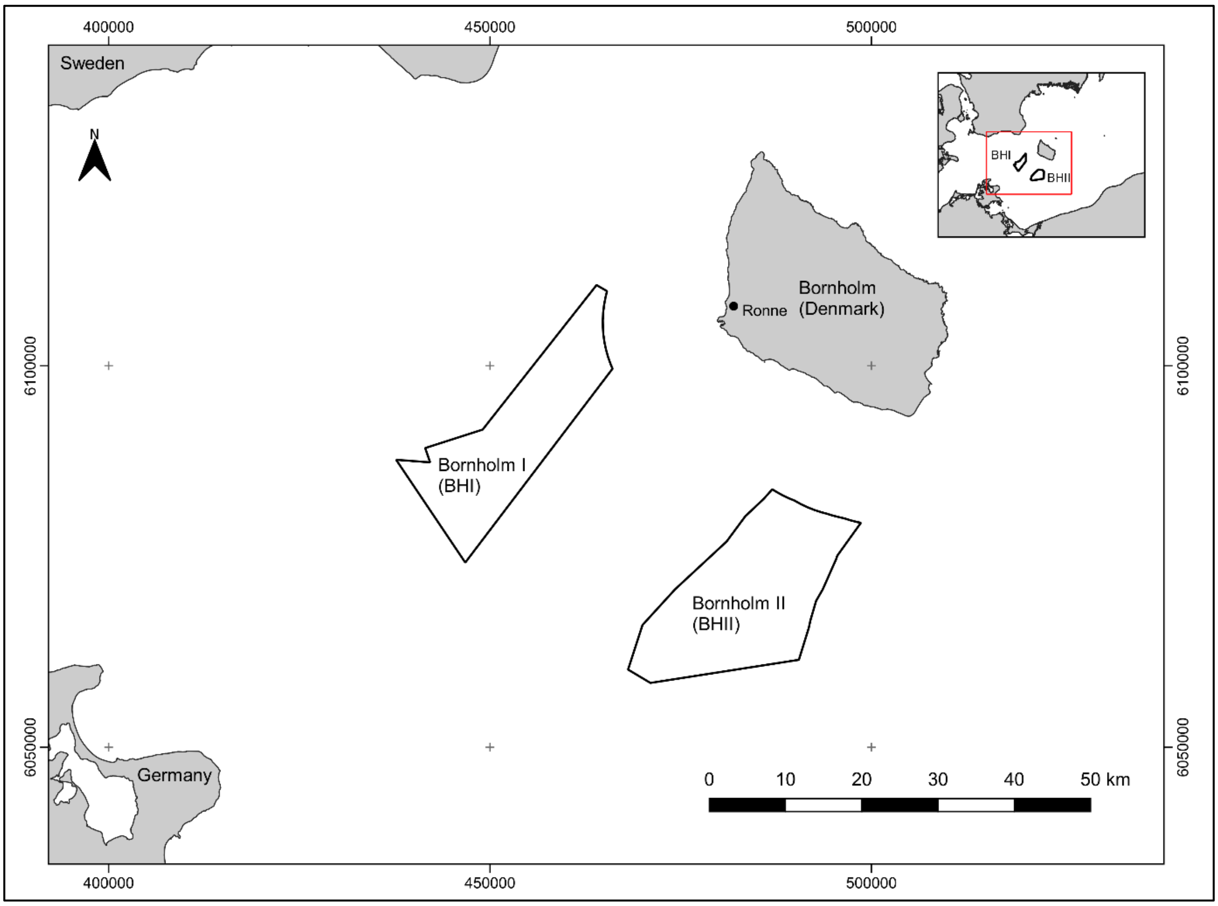


Figure 2: Location of BHI and BHII in the Baltic Sea

Two work packages were implemented: Work Package A (WPA) and Work Package B (WPB). This report details the findings from Work Package A for the Bornholm II site and includes the extended survey scope (Figure 3).

3.1.1 Description of area of investigation

The BHII survey site is located 15 km to the south-west of the Danish Island of Bornholm in the Baltic Sea. The BHII site was extended to include an additional area to the north and east of the original BHII site. The original scope boundary and extended scope boundary are illustrated in Figure 3.

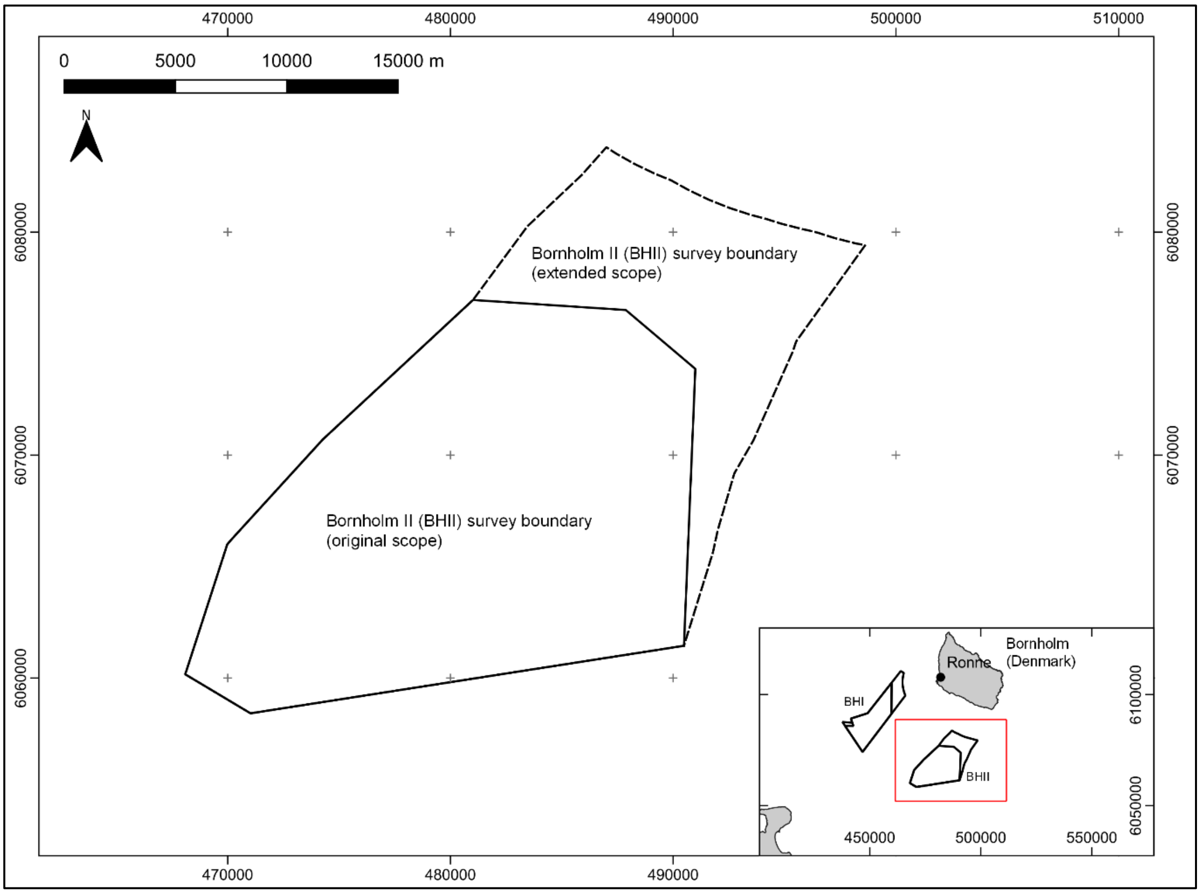


Figure 3: BHII overview with original and extended scope survey boundaries

For charting and reporting purposes, the BHII survey site was split into four tiles: Bornholm 2 NE, Bornholm 2 SE, Bornholm 2 SW and Bornholm 2 NW. 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.

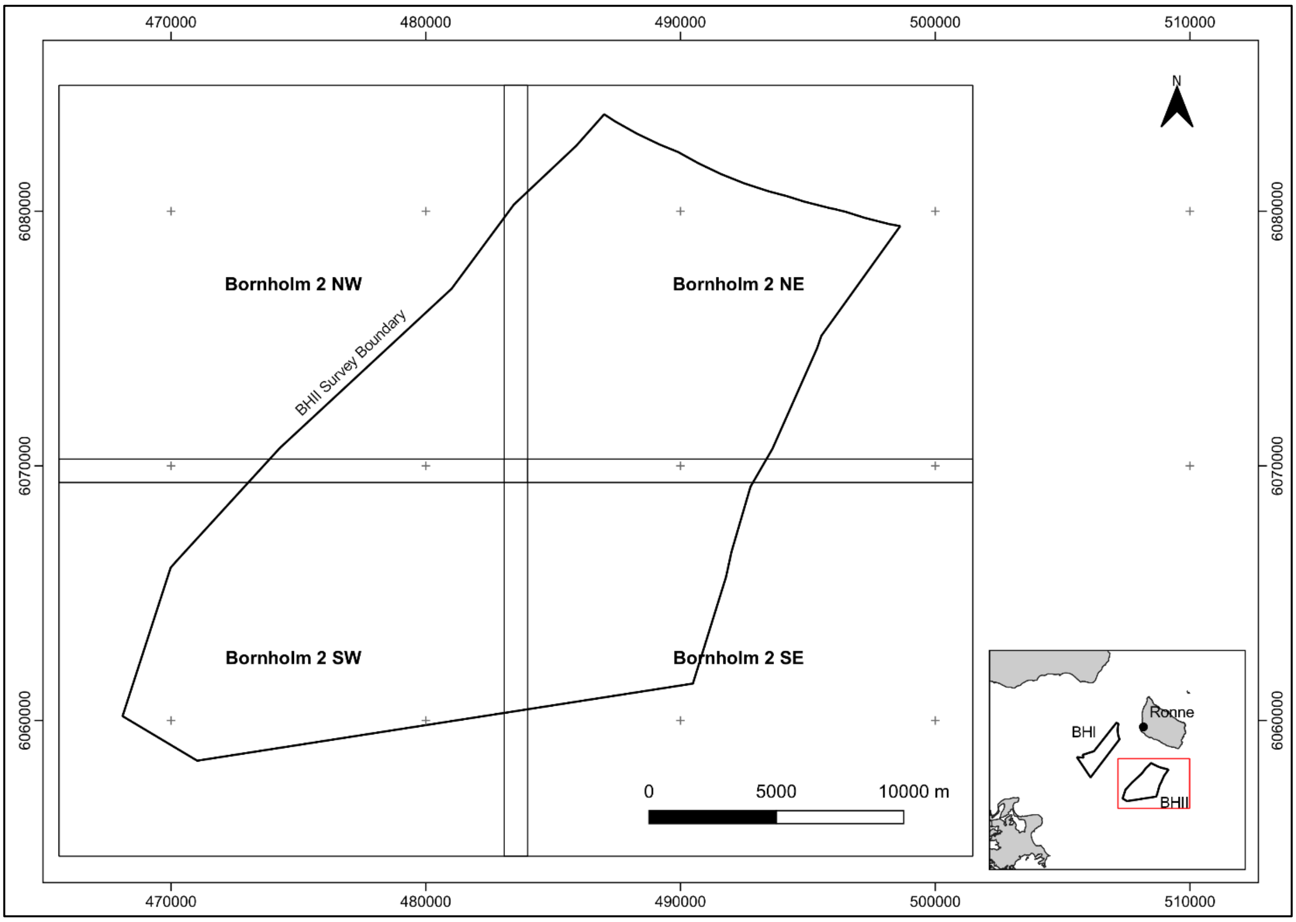


Figure 4: BHII overview with reporting tiles

3.1.2 Existing infrastructure

Nordstream I, formed of two parallel pipelines, runs through the centre of the Bornholm II survey area in a SW-NE direction. The Baltic Pipe runs through the east of the Bornholm II site before turning to the northwest and crossing the north of Bornholm I. The Nordstream II pipelines run to the south of Bornholm II outside the survey area. Construction activities for Nordstream II are ongoing. The location of the pipelines in relation to the survey areas are shown in Figure 5. Zero cable infrastructure is known to exist within the BHII site.

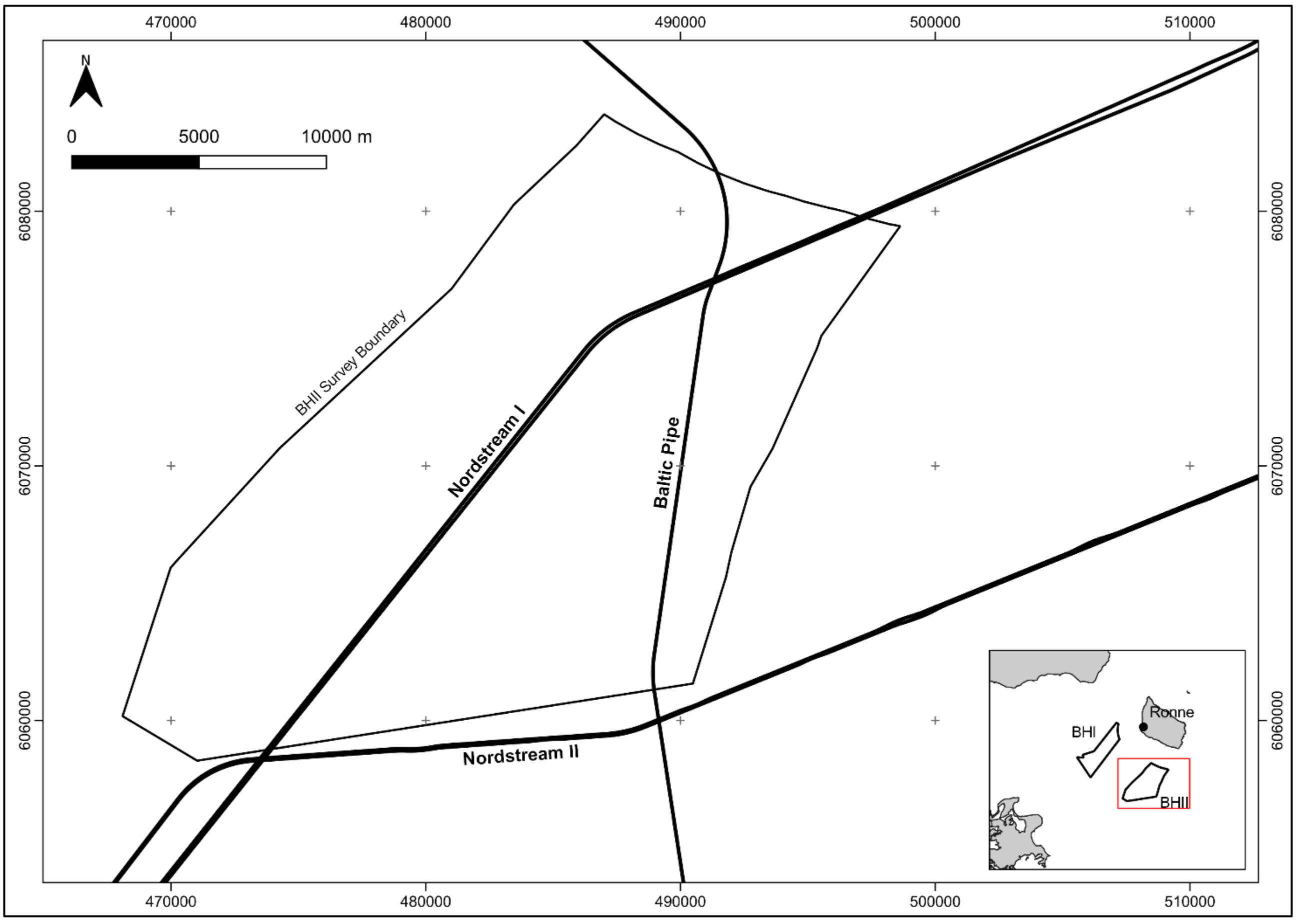


Figure 5. BHII existing pipeline infrastructure

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 BHII 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 specifications and survey overview information are detailed in Table 2.

Table 2: Client specifications and survey overview

Equipment	Specification	Survey Requirement
Vessels	Multi-vessel operations	Geo Ocean IV and Geo Ocean V
Line spacing	Main 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 %
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
2D Ultra High Resolution Seismic	Fundamental frequency	Between 1 and 3 kHz
	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

Equipment	Specification	Survey Requirement
		for continuous monitoring and recording of streamer depth
Notes: [1]SSS coverage adjusted to 100% for nadirs due to thermocline/pycnocline effects.		

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

The line plan was split in two phases and consists of Primary lines and Cross Lines, and Secondary Lines to be run by two different vessels. In Bornholm II, Primary lines and Crosslines, along with some reruns and infills, have been acquired by GOV, whereas Secondary lines and the infills have been acquired by GOIV. Onboard GOIV, a dual SSS approach was setup with two side scan sonar sensors running concurrently to minimise the effect of the pycnocline on the dataset.

3.3.1 BHII original scope survey Blocks

The original scope survey area was divided into 11 blocks to improve data coordination during acquisition and processing. The sub blocks and the line plan within the Bornholm II area are shown in Figure 6.

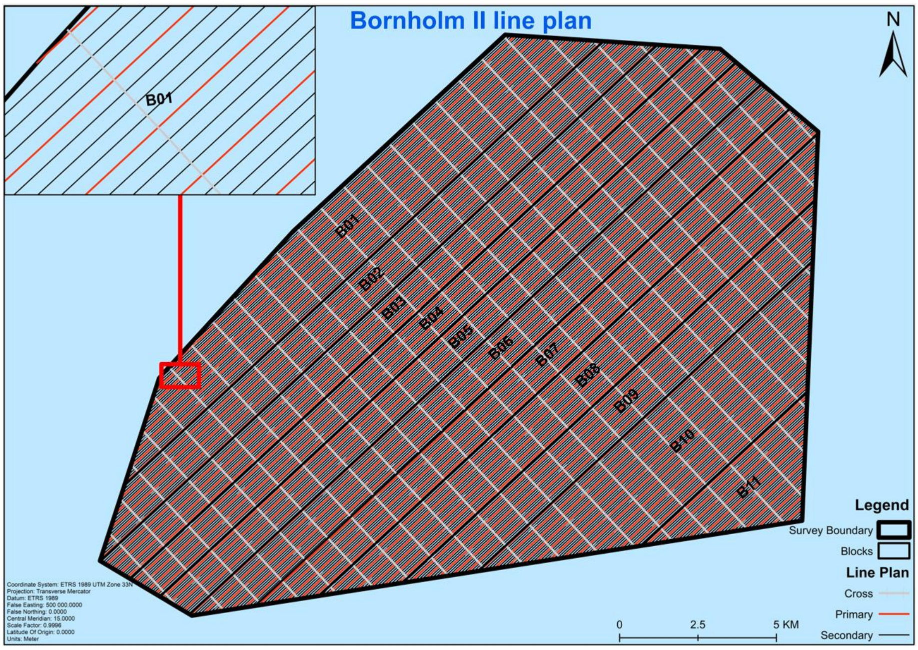


Figure 6: Line plan and work allocation, Bornholm II original scope

3.3.2 BHII extended scope

The BHII extended scope (BHII B) is outlined in Figure 7, encompassing an area to the north and east of the original scope.

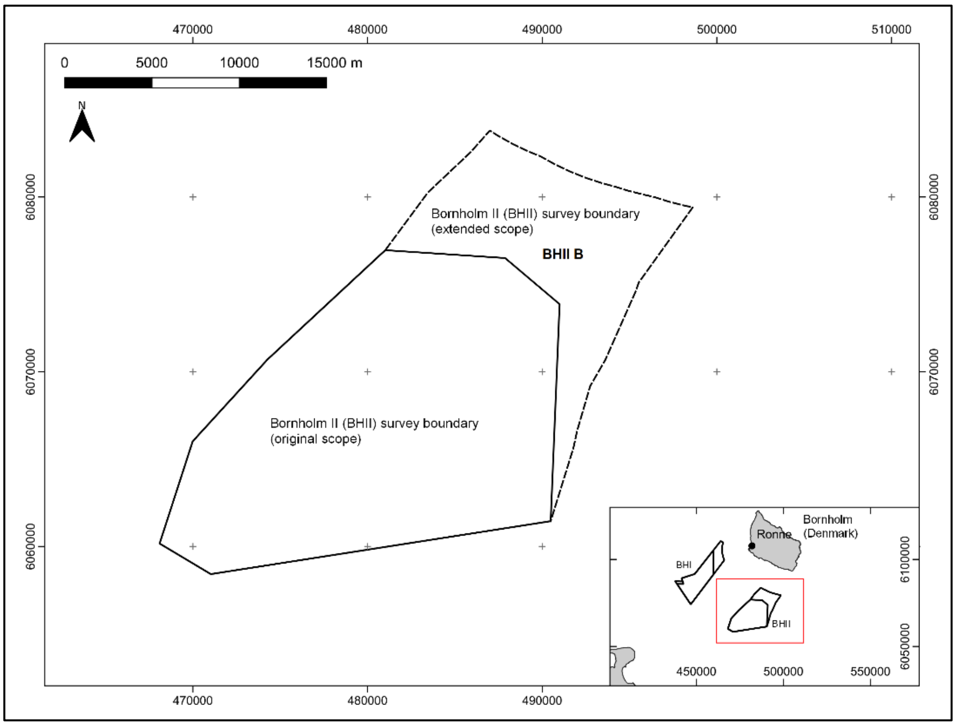


Figure 7: Bornholm II site with original scope and extension scope

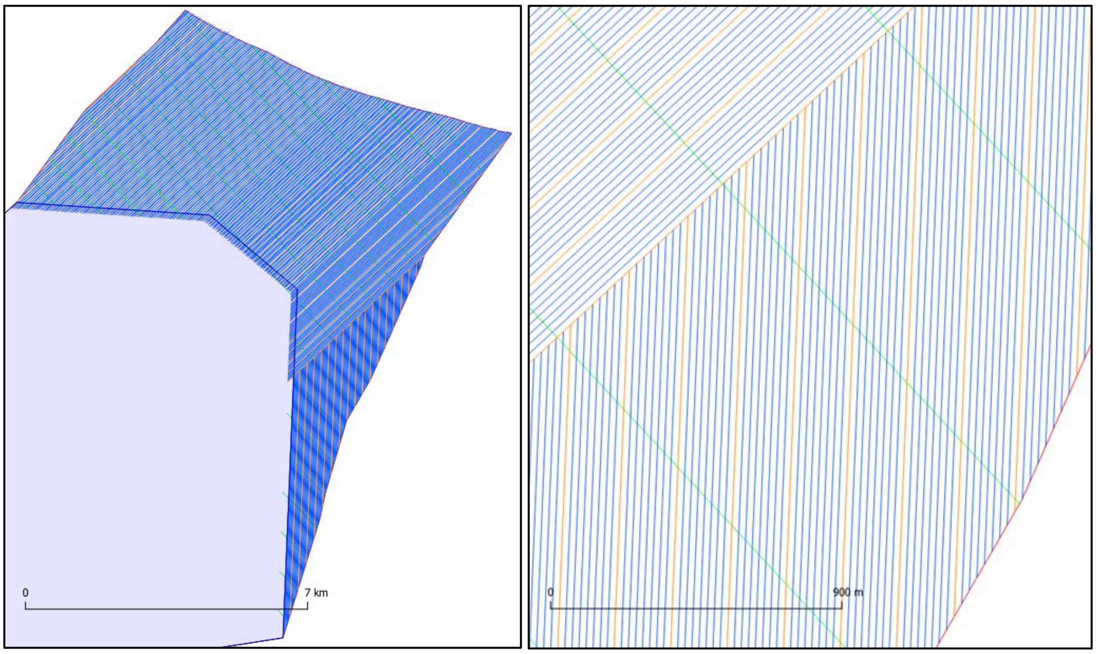


Figure 8: Bornholm II BHII B line plan

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 depths reported are relative 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 %. The effect of the pycnocline on the SSS dataset is highlighted in Figure 9.

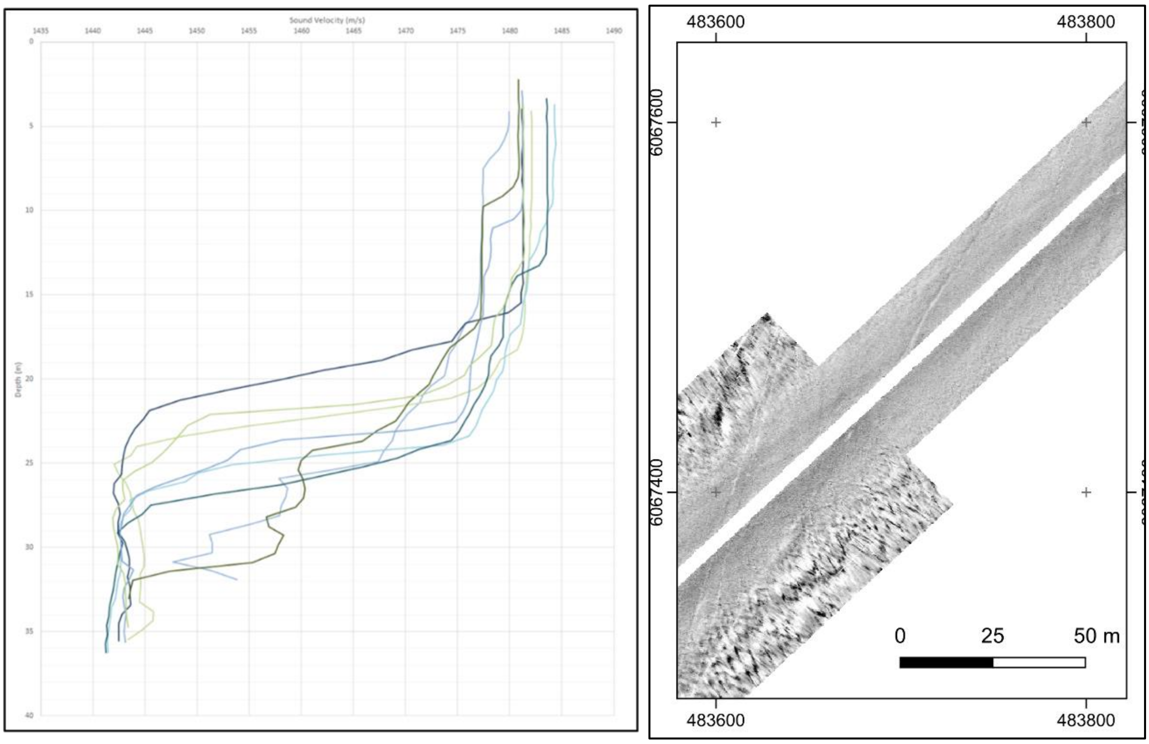


Figure 9: Pycnocline and effect on SSS dataset

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 %

In TQ 018- MBES, it was requested and subsequently agreed to increase the MBES SD limit to 0.25 on 95% of the site and to modify the hit count specifications to the following: A minimum of 99% of site will 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, present along and across both sites, affected the MBES dataset quality considerably. Outer ranges were sometimes out of the Standard Deviation specifications. The data therefore 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 with the client and a relaxation on the hit count and SD specifications was agreed:

- 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 were combined onboard GOIV to ensure consistency vertical alignment between vessels and to avoid the dataset reaching the office without a proper QC performed in the field.

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 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 used to bring the soundings into closer alignment. Regions that have high standard deviations can occur where there are sound velocity errors (pycnocline effect). Other possible errors include 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).

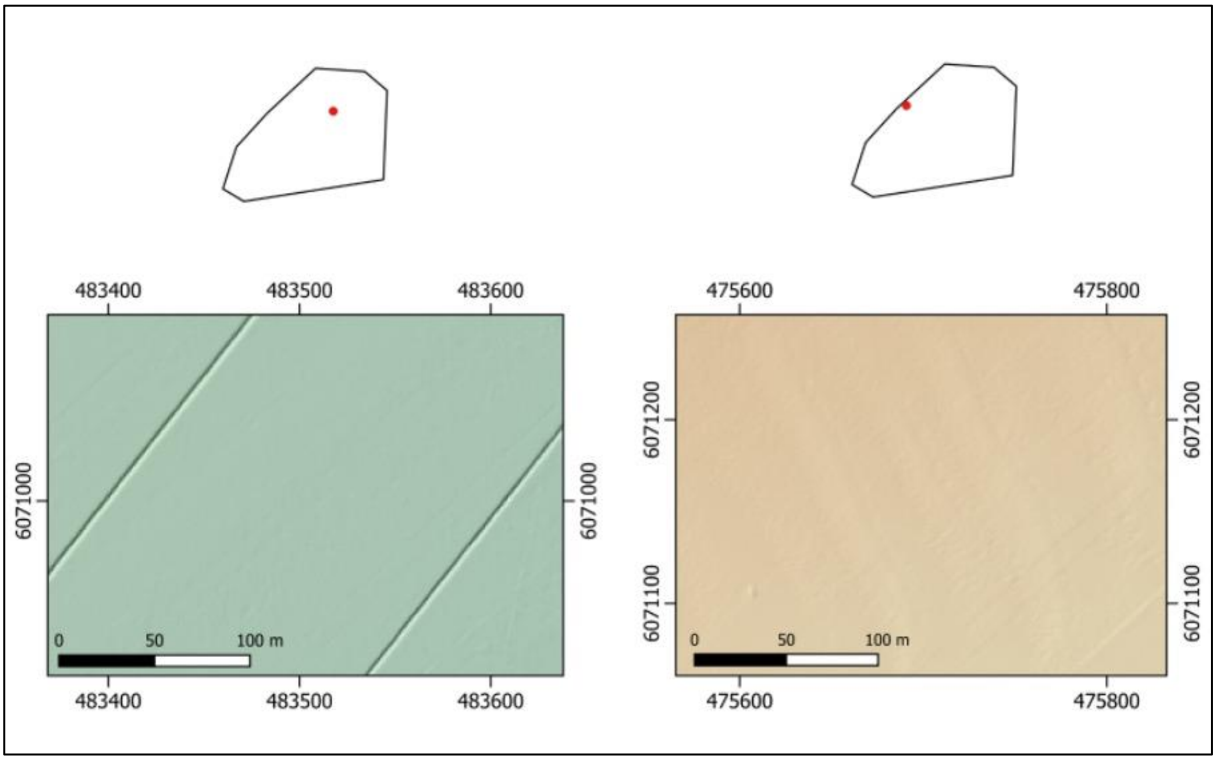


Figure 10: General examples of the mean DTM surfaces.

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 where there were numerous boulders or where the till could be seen outcropping, did show a high vertical spread but they cannot be considered as areas of poor data.

Also, there are some higher Standard Deviation values on top of the pipelines crossing Bornholm II.

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 to trim and clean the data which generated gaps and areas of lower density. This forced the vessels to infill some of the overlapping areas.

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 or 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: BH2 Hit count and SD Statistical parameters.

Block	Mean of Hit Count	% of Cells With Hit Count of at least 16	Mean of Standard Deviation
01	45	99.95	0.07
02	75	99.99	0.05
03	81	99.99	0.05
04	74	99.97	0.05
05	83	99.97	0.05
06	68	99.97	0.05
07	76	99.99	0.05
08	79	99.87	0.05
09	79	99.84	0.06
10	94	99.97	0.06
11	40	99.79	0.04

7.2 BACKSCATTER

The quality of the final processed backscatter was assessed in GIS software (QGIS and Global Mapper) after combining all processed blocks in one gridded surface as 1 m resolution backscatter mosaic (Figure 11).

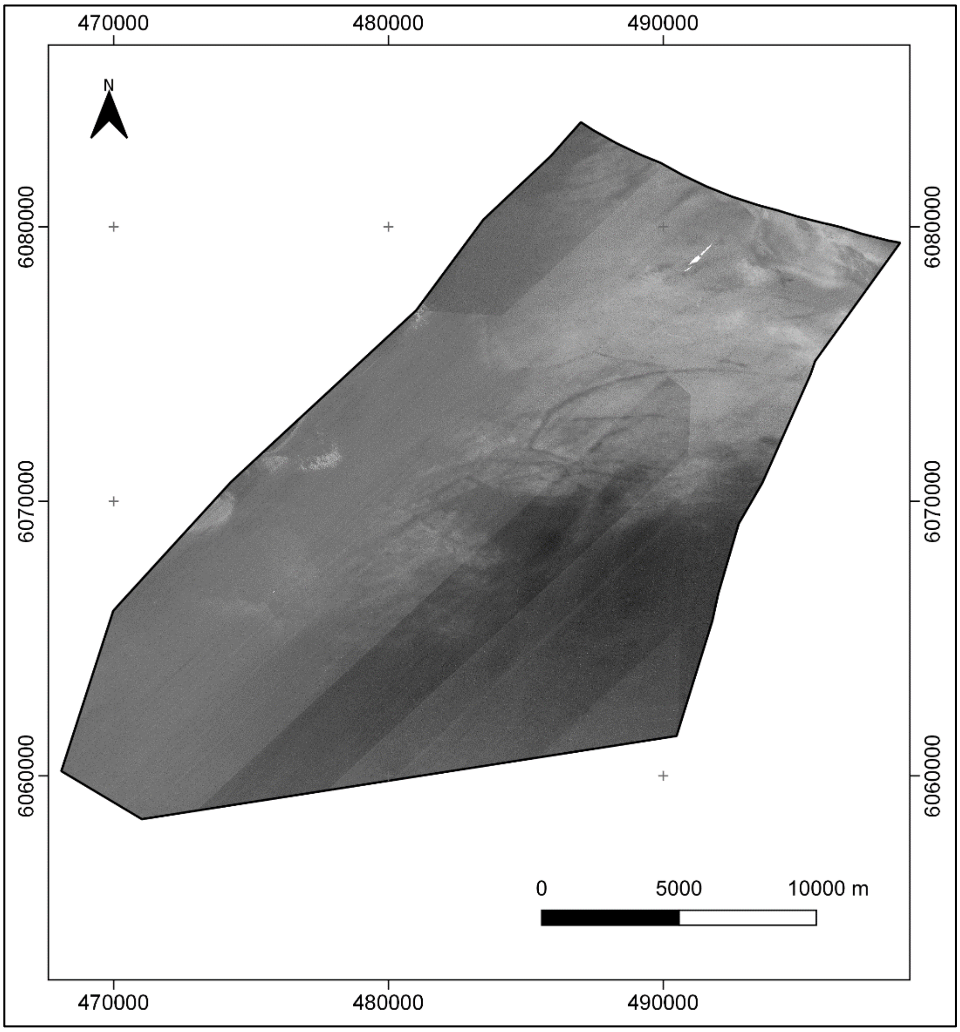


Figure 11: Backscatter data: Bornholm II

The processing of the backscatter was done to try to achieve a homogeneous colour scale between blocks. The colour scale was normalised between blocks. This step is necessary, as 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 an evident 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 to the backscatter one.

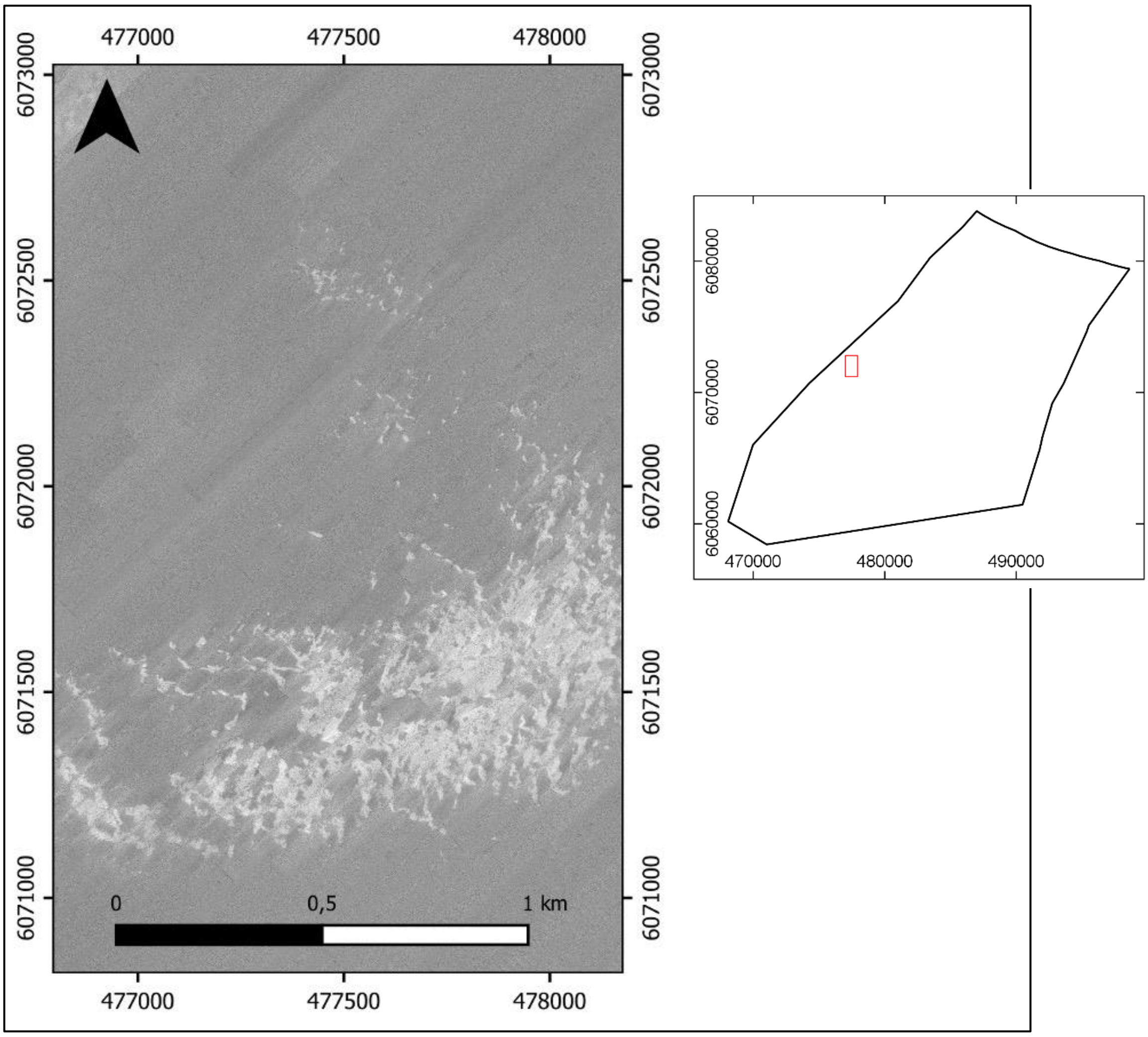


Figure 12: Example of stripe effect on the backscatter mosaic in Bornholm II

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 BHII survey area. SSS coverage was reduced from 200% coverage to 100% coverage due to thermocline and pycnocline effects.

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 %	> 100 %

Figure 13 is an example of the side scan sonar data quality achieved across the survey site and shows side scan sonar contact BHII_SSS_6522 (MMO 616), identified as a wreck. Individual seabed objects surrounding the wreck are clearly delineated, with good image definition throughout.

Figure 13: Side scan sonar dataset example with MBES imagery (BHII_SSS_6522, MMO 616)

7.4 MAGNETOMETER

The magnetometer dataset achieved the client specifications outlined in Table 14 with good data quality throughout the BHII 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 14 shows a typical magnetometer dataset profile example of a wreck contact (BHII_SSS_6522, BHII_MAG_0439, MMO 616). The Residual Anomaly Field shows good discrimination between anomalies and the background magnetic field.

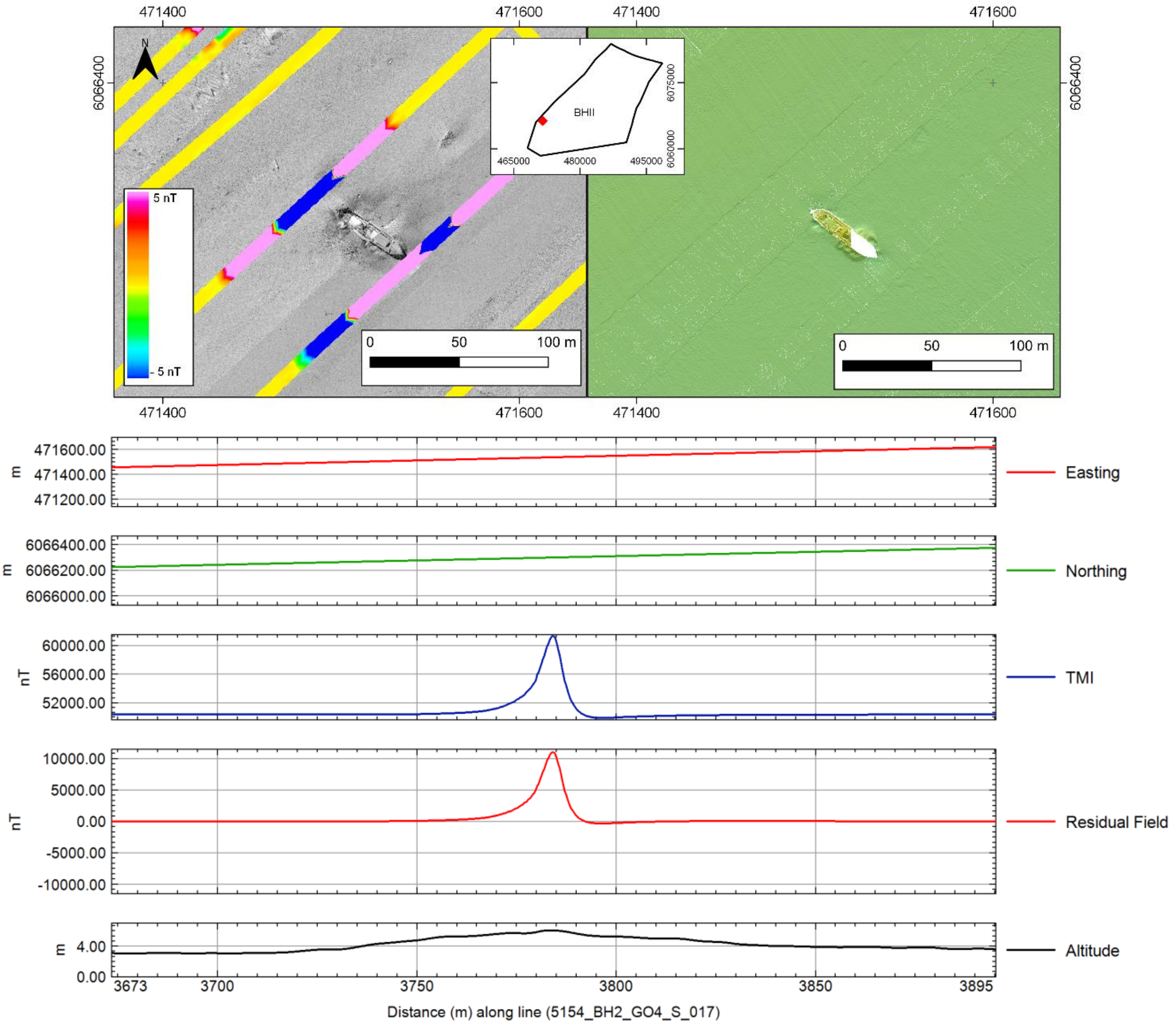


Figure 14: Magnetometer dataset profile example with MBES dataset (Line 5154_BH2_GO4_S_017)

7.4.2 Magnetic residual anomaly grid

The BHII magnetic residual anomaly grid with an example of typical data quality is shown in Figure 15. The BHII magnetic residual anomaly grid was processed and gridded as a single magnetometer dataset. The magnetic residual anomaly data exhibits little background or geological influence, with magnetic anomalies clearly distinguishable.

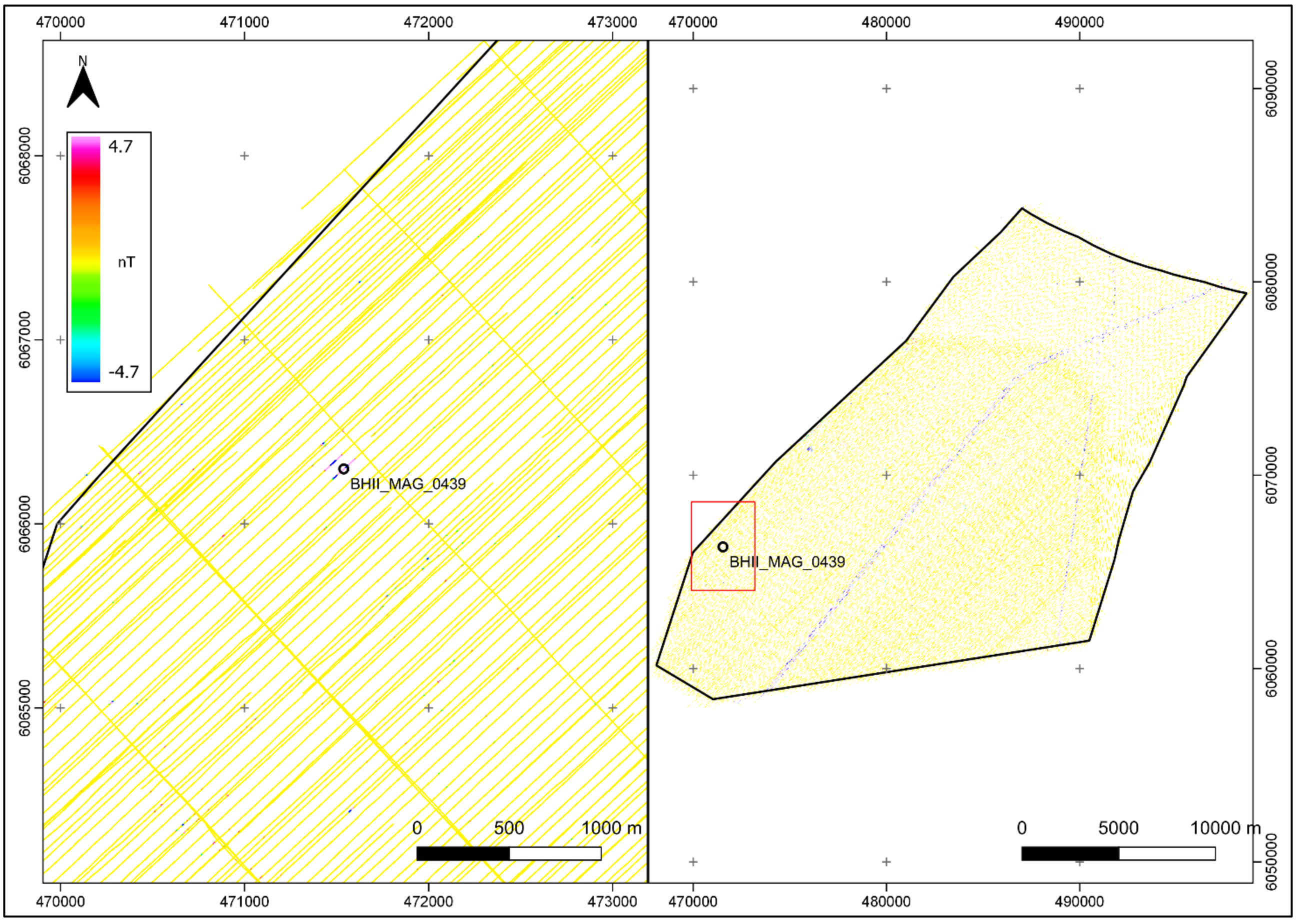


Figure 15: Magnetic residual anomaly grid overview with inset data example

7.4.3 Magnetic analytic signal grid

The BHII magnetic analytic signal grid with an example of typical data quality is shown in Figure 16. The BHII magnetic analytic signal grid was processed and gridded as a single magnetometer dataset. The magnetic analytic signal exhibits little background or geological influence, with magnetic anomalies clearly distinguishable in the analytic signal grid.

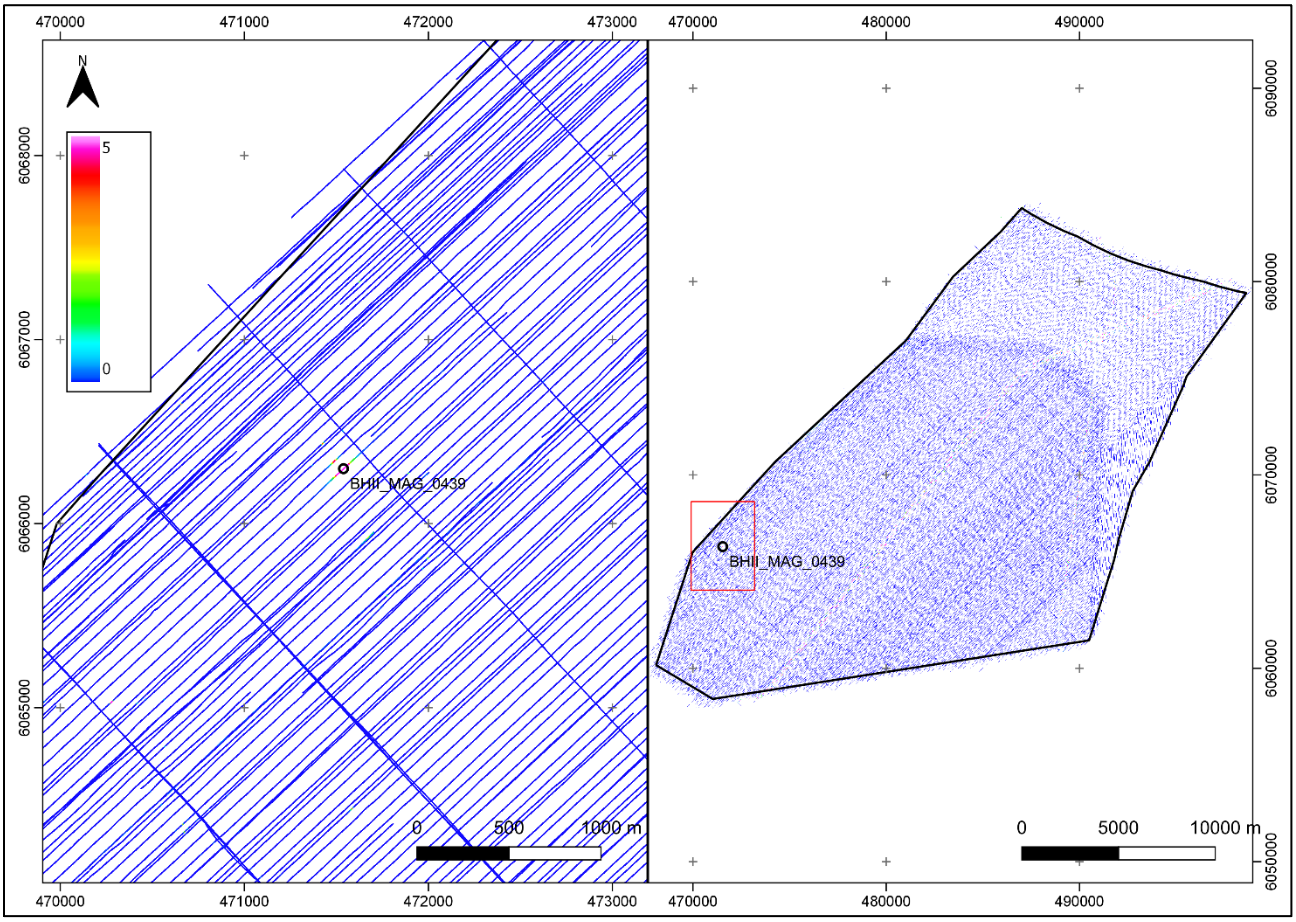


Figure 16: Magnetic analytic signal grid overview with inset data example

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 BHII survey area.

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 17 shows line X_07, which is an example SBP profile with typical penetration of > 10 m.

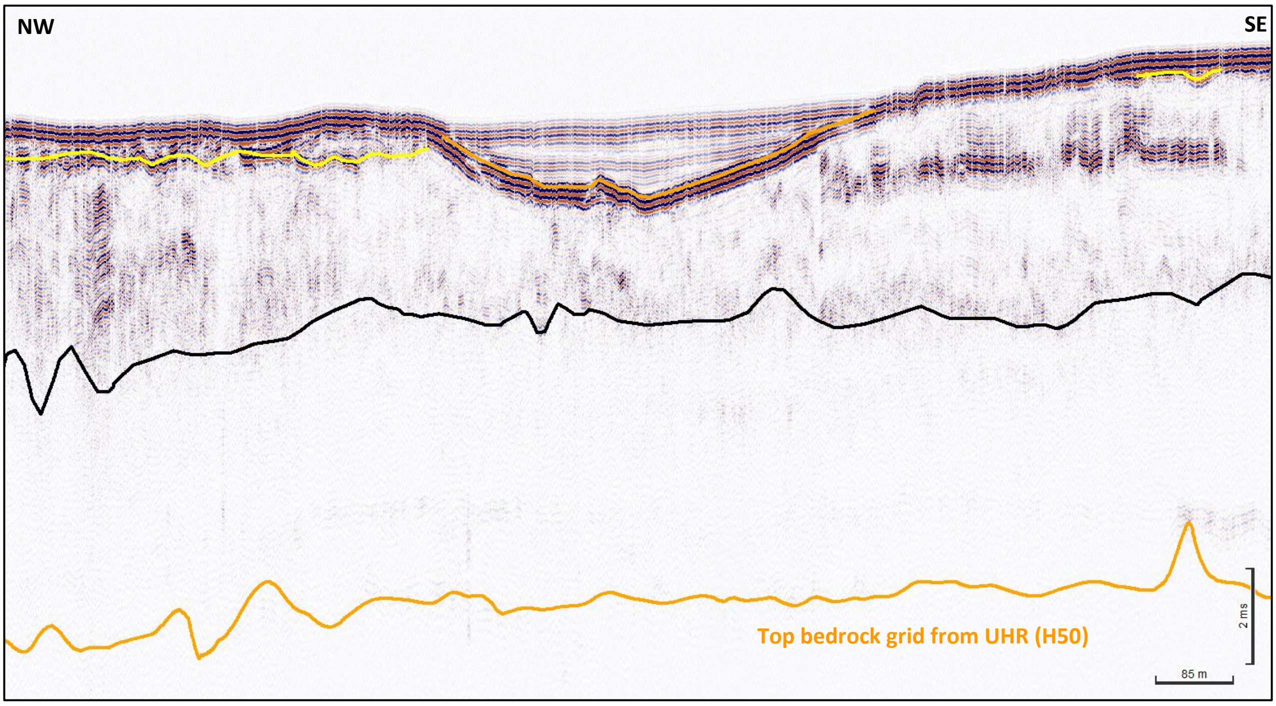


Figure 17 SBP data example (line X_07)

Once processed, the 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 II – 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 0.15m. 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 18). Penetration does vary across the survey area related to differences in the geology.

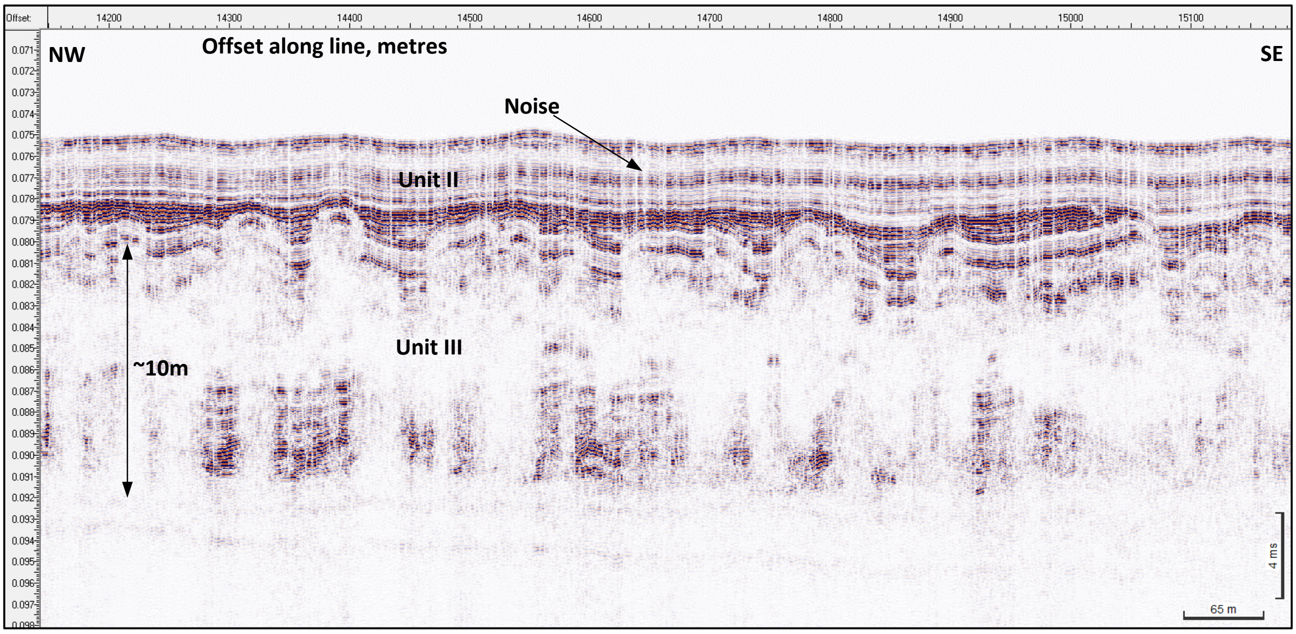


Figure 18 SBP data example, line X018, typical SBP line

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 70m below seabed (Figure 19).

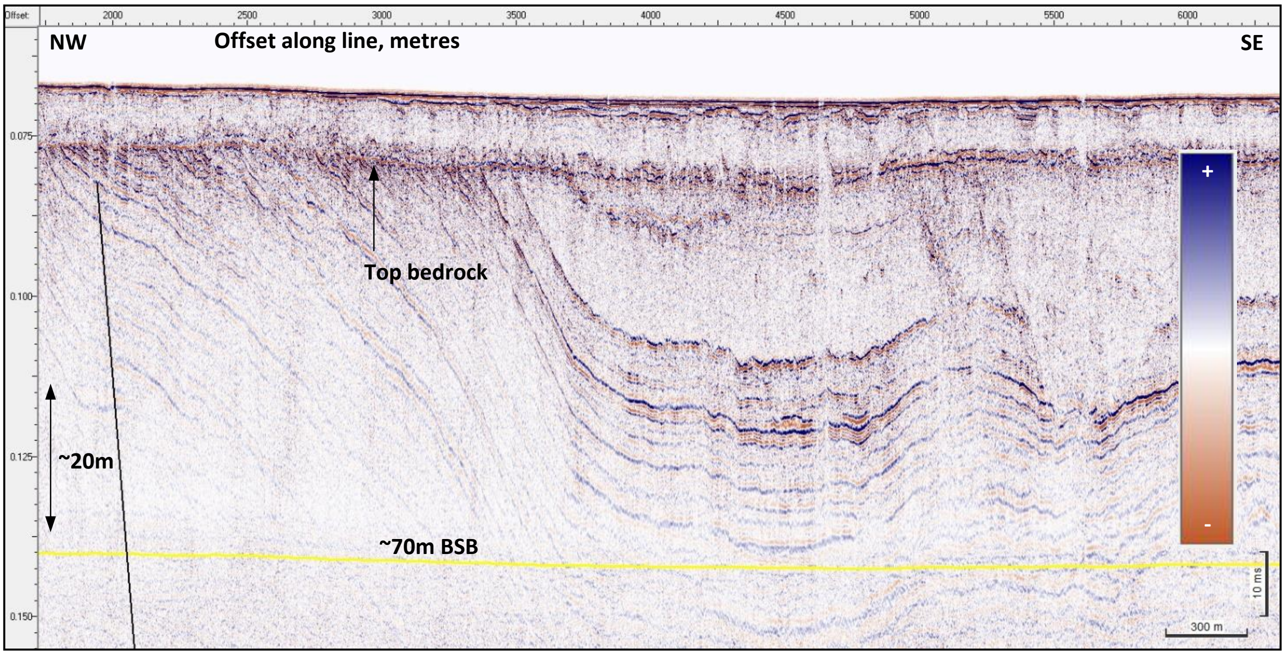


Figure 19 UHR data example, line P29, typical UHR line

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 (1600/700). The data make it possible to map separate events/reflections as vertically close as ~1m apart. Along-line lateral resolution of these data is reduced to around 2m 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 an 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 20).

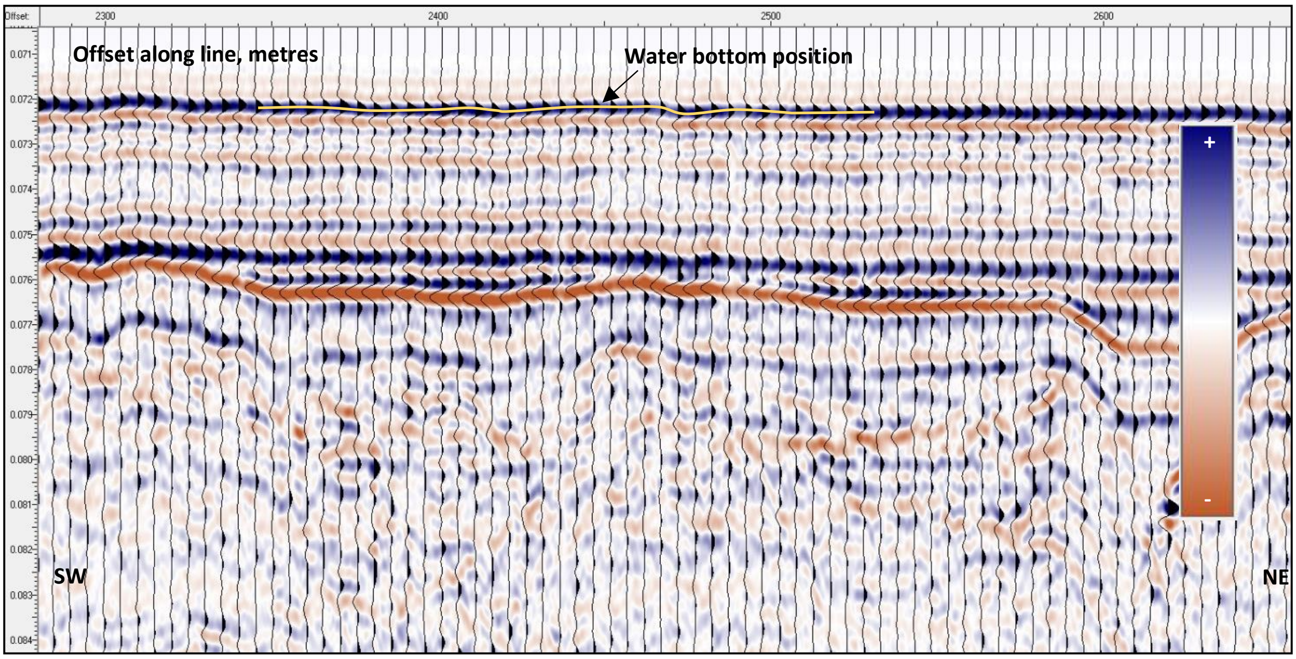


Figure 20 UHR data example, line P53, centre peak corresponds to water bottom

7.7 DATA GAP DUE TO BUOY

A data gap exists in the north of the site due to a buoy located at 491029 m E, 6078701 m N, preventing safe vessel navigation and acquisition nearby. Survey lines were re-routed and perpendicular infill line were run to migrate the size of the data gap. Figure 21 details to the extent of the gap and shows magnetometry data overlaid the backscatter dataset. The resultant data gap is approximately 1200 m by 150 m in size.

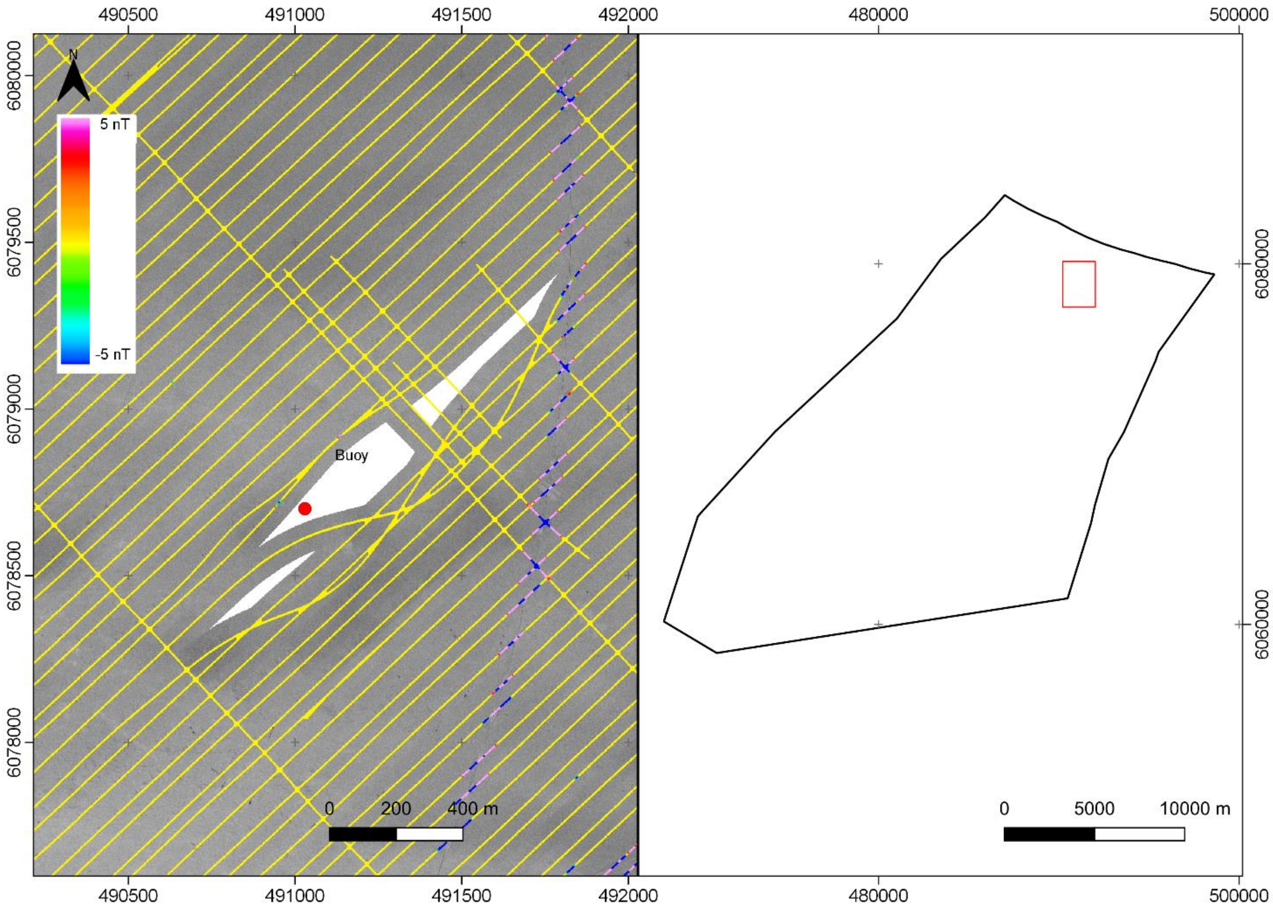


Figure 21: Data gap due to buoy in north of BHII. The Baltic Pipe pipeline is also shown.

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 16: 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 Desk Study (Jenson et., 2017) and Technical Query TQ-002. Terminology and classifications were preserved from the Desk Study where possible to maintain consistency between reports. Table 17 provide the list based on the TSG GIS classification to be applied to the geology classification assessment.

Table 17: 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 Desk Study (Jenson et., 2017) and Technical Query TQ-017. Table 18 provide a summary of the criteria used for bedform classification.

Table 18: TSG Bedform classification used.

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

8.1.4 BOULDER FIELD IDENTIFICATION CRITERIA

The boulder field identification criteria for BHII 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 (). Debris objects were isolated from the auto-picked boulder fields using correlation between sensor datasets.

Table 19: 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 22.

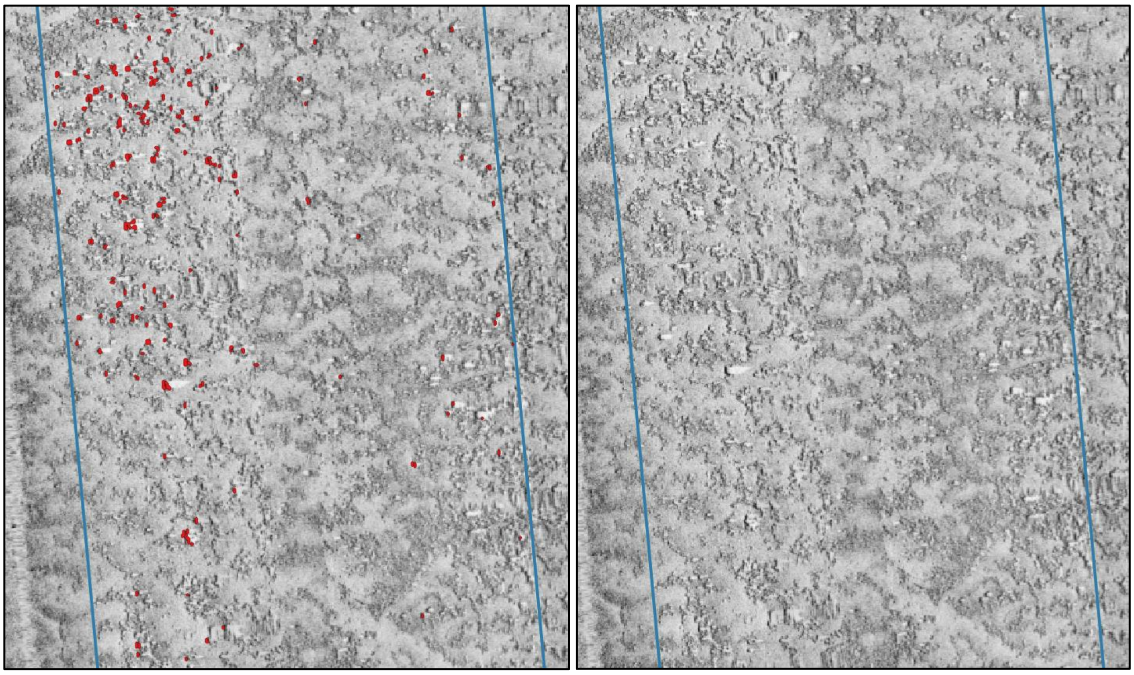


Figure 22: 2D Auto-picking result: Picked boulders (left, red) and the original dataset on right.

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 20:

Table 20: 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 depth varies moderately across Bornholm II, except in the central-west area of the site. The minimum surveyed depth is 15.04 m at 476326 m E, 6072604 m N in the western part of the survey (Bornholm 2 NW). The maximum surveyed depth is 57.30 m at 493100 m E, 6070045 m N in the northern area (Bornholm 2 SE). The mean depth across the site is 46.41 m. An overview of the bathymetry within Bornholm II is shown in Figure 23.

Three terrain profile lines are shown running from west to east across site. A longitudinal profile has also been assessed from south to north. They are derived from the following geophysical survey lines:

- BH2B_GO5_X_012 (northernmost)
- BH2_GO5_C18
- BH2_GO5_C08 (southernmost)
- BH2_GO5_M_021 + BH2B_GO5_P_024 (longitudinal)

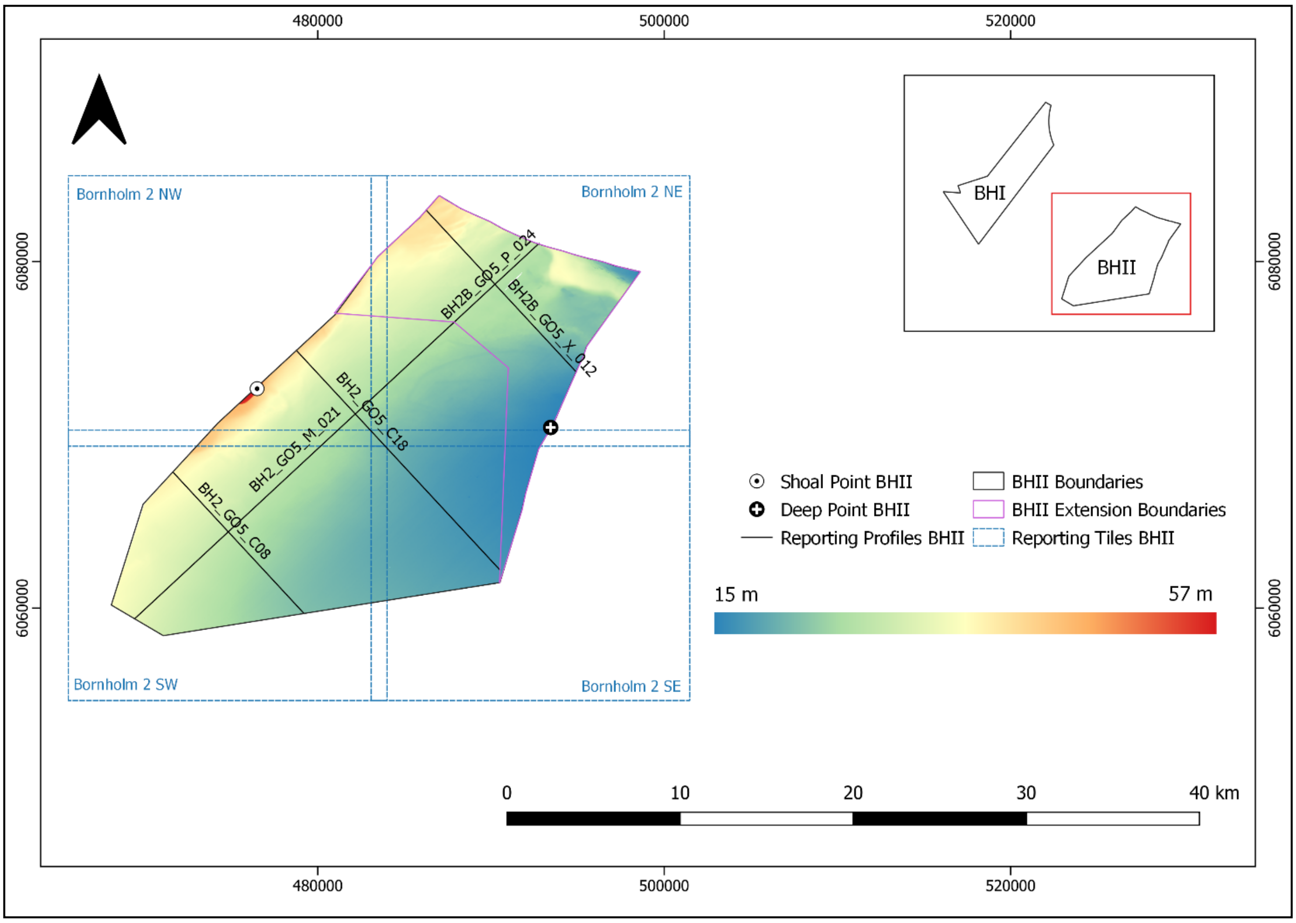


Figure 23: Overview of the bathymetry data

The profile data obtained from these profiles are shown in Figure 23 and Figure 25. The horizontal position of the profiles derived from cross lines have been shifted to match the position of the central line (BH2_GO5_C18). 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.

There is an increase in the depth from west to east with an additional increase in depth from south to north.

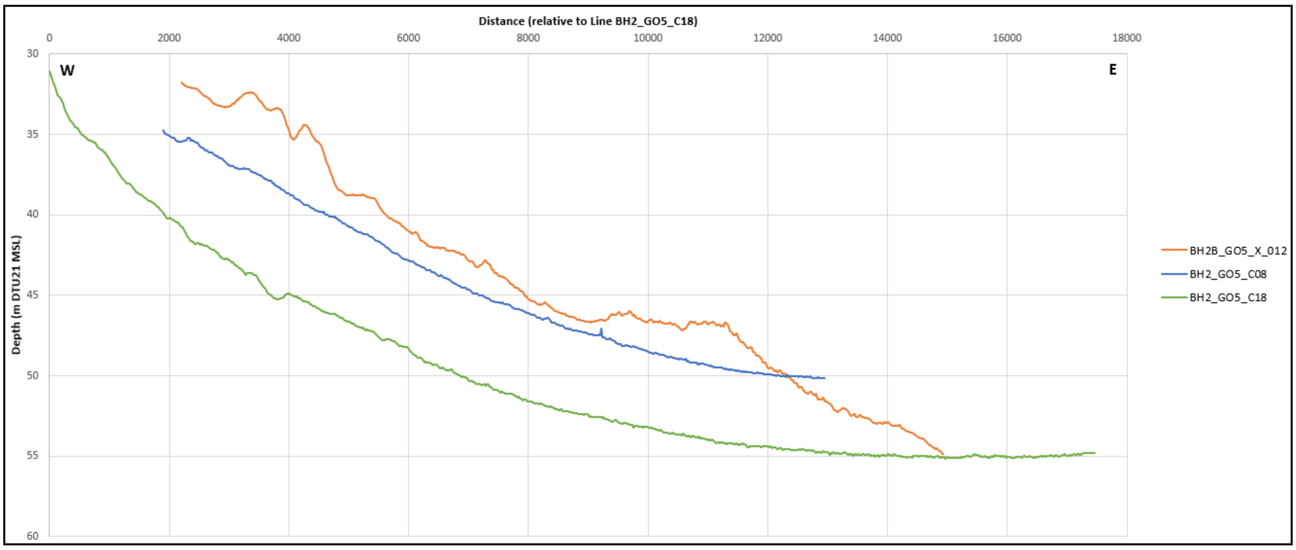


Figure 24: Profiles across Bornholm II showing depth relative to DTU21 MSL. Profiles have been shifted to match the position of survey line BH2_GO5_C18

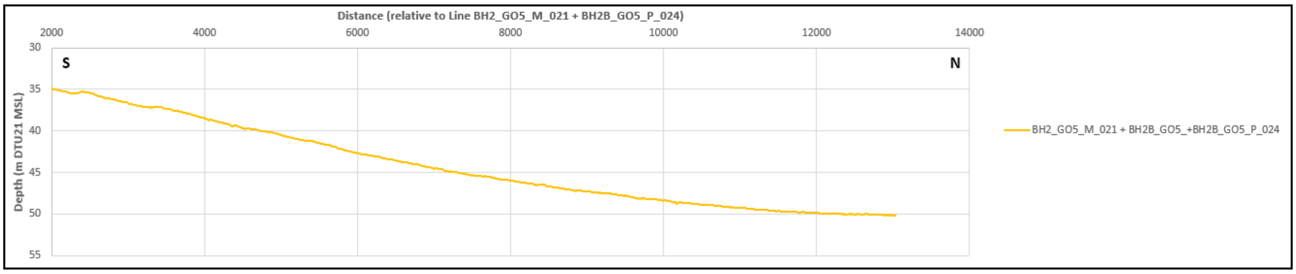


Figure 25: Longitudinal profile across Bornholm II showing depth relative to DTU21 MSL

8.2.1 Profile BH2B_GO5_X_012

The profile BH2B_GO5_X_012 (Figure 26) is located 6.6 km from the northern corner of the site and spans 12.7 km of the survey area. The depth variation along this profile is 23.12 m from a minimum depth of 31.77 m at 487045 m E, 6073626 m N to a maximum depth of 54.89 m at 494921 m E, 6073626 m N.

The depth increments from west to east. Most drastic changes in bathymetry are at both ends of the profile. A rugged topography exists in the western zone, matching a shallower area of bedforms (wavelength 50 – 400 m). This profile achieves the shallowest point compared to the other profiles derived from cross survey lines.

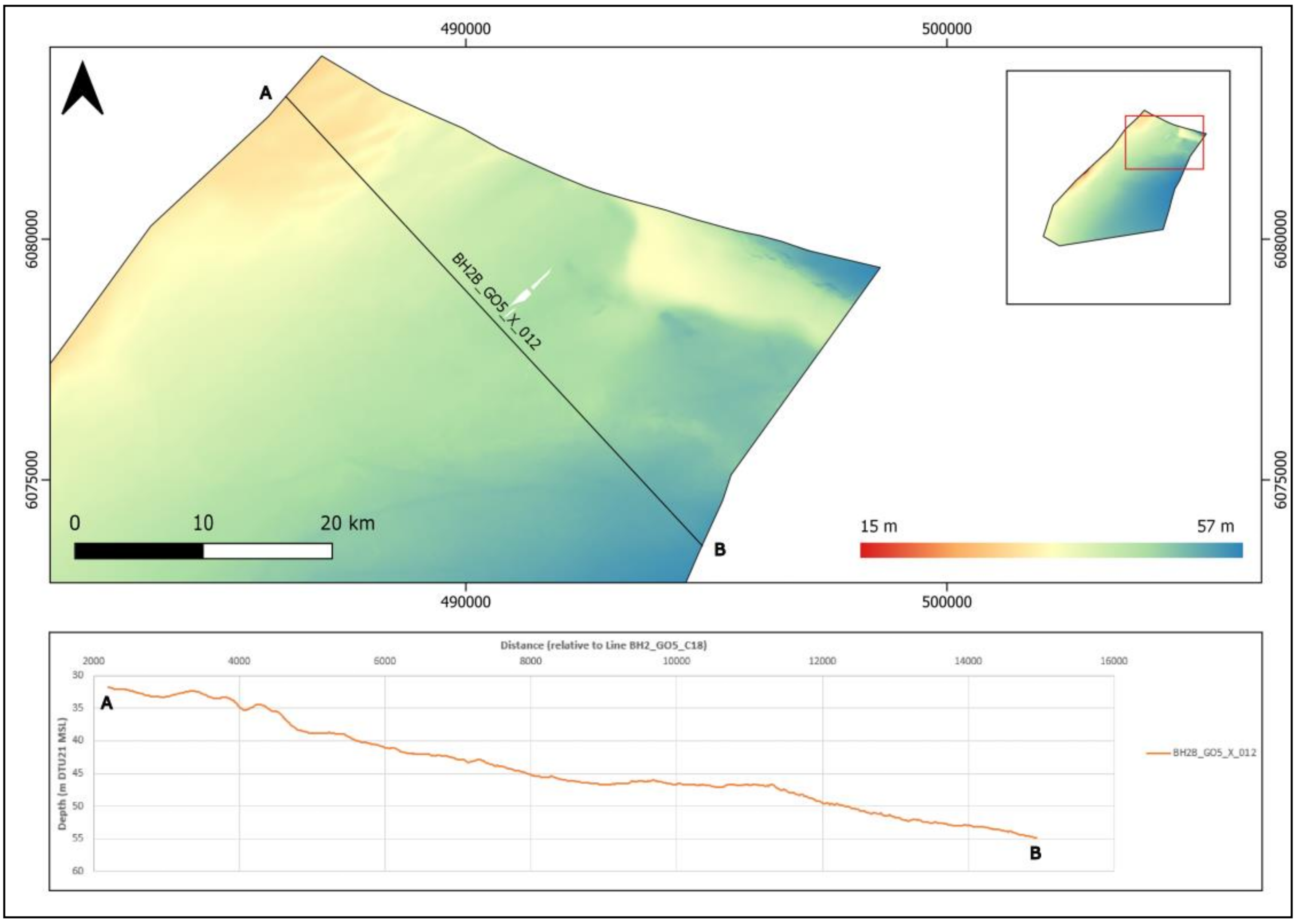


Figure 26: Profile BH2B_GO5_X_012 location overview

8.2.2 Profile BH2_GO5_C18

The profile BH2_GO5_C18 (Figure 27) has been run in the central part of the survey, about 17.9 km from the northern corner, and spans 17.7 km across the site. The depth variation along this profile is 24.38 m from a minimum depth of 30.51 m at 478763 m E, 6074871 m N to a maximum depth of 54.95 m at 490820 m E, 6061875 m N. In this profile it is also possible to observe the depth increment eastward, which occurs abruptly at the western end, i.e., in the shallowest zone. In the deepest zone, the seabed is flat.

This profile achieves the deepest point compared to the other profiles derived from cross survey lines.

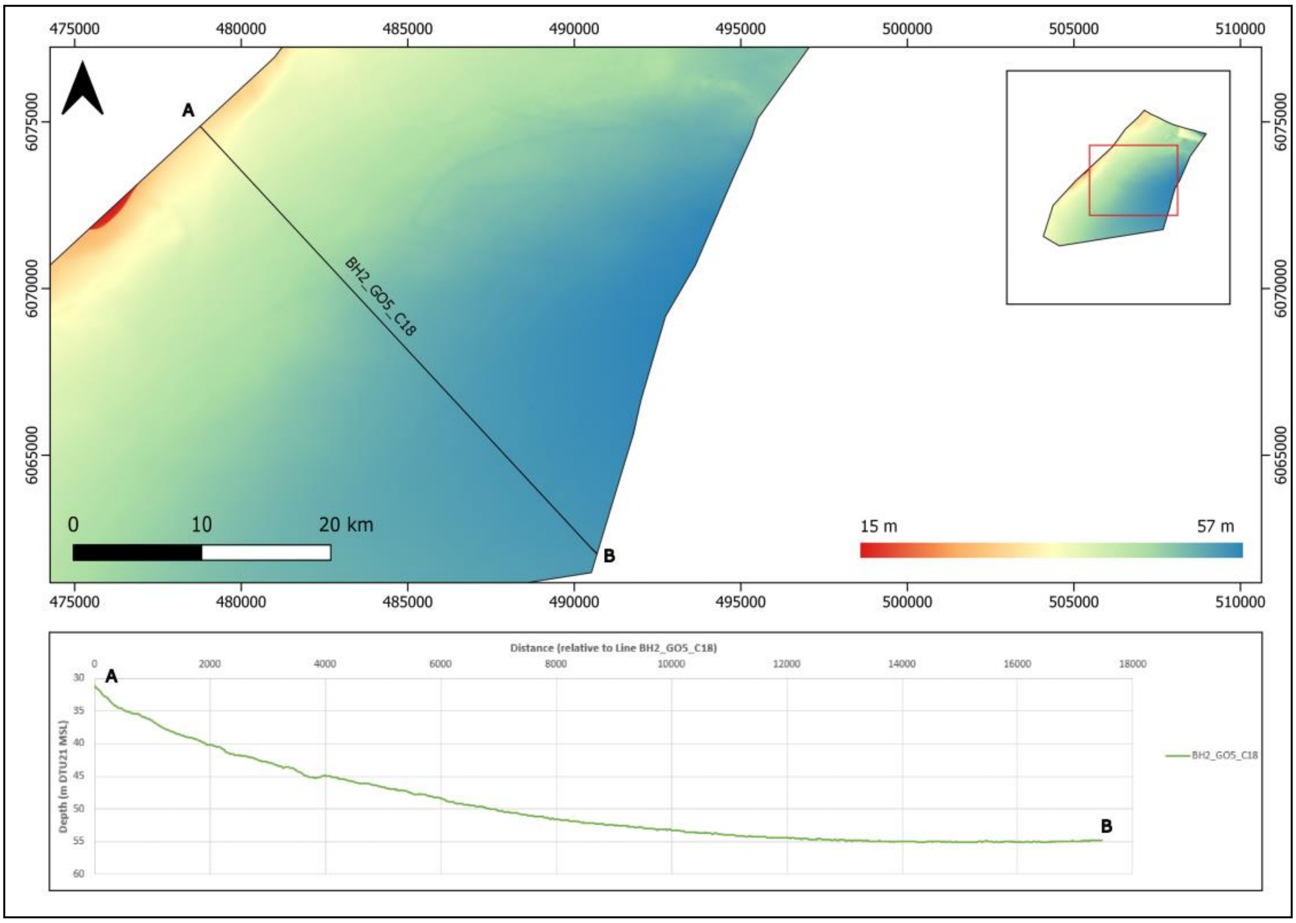


Figure 27: Profile BH2_GO5_C18 location overview

8.2.3 Profile BH2_GO5_C08

The profile BH2_GO5_C08 (Figure 28) is located about 6.9 km of the southern part of the surveyed area and spans 11.20 km across the site. The depth variation across the line is 15.28 m from a minimum depth of 34.88 m at 471649 m E, 6067836 m N to a maximum depth of 50.16 m at 479278 m E, 6059614 m N.

The depth increments from west to east along the site. In this case, the bathymetry varies smoothly along the entire profile.

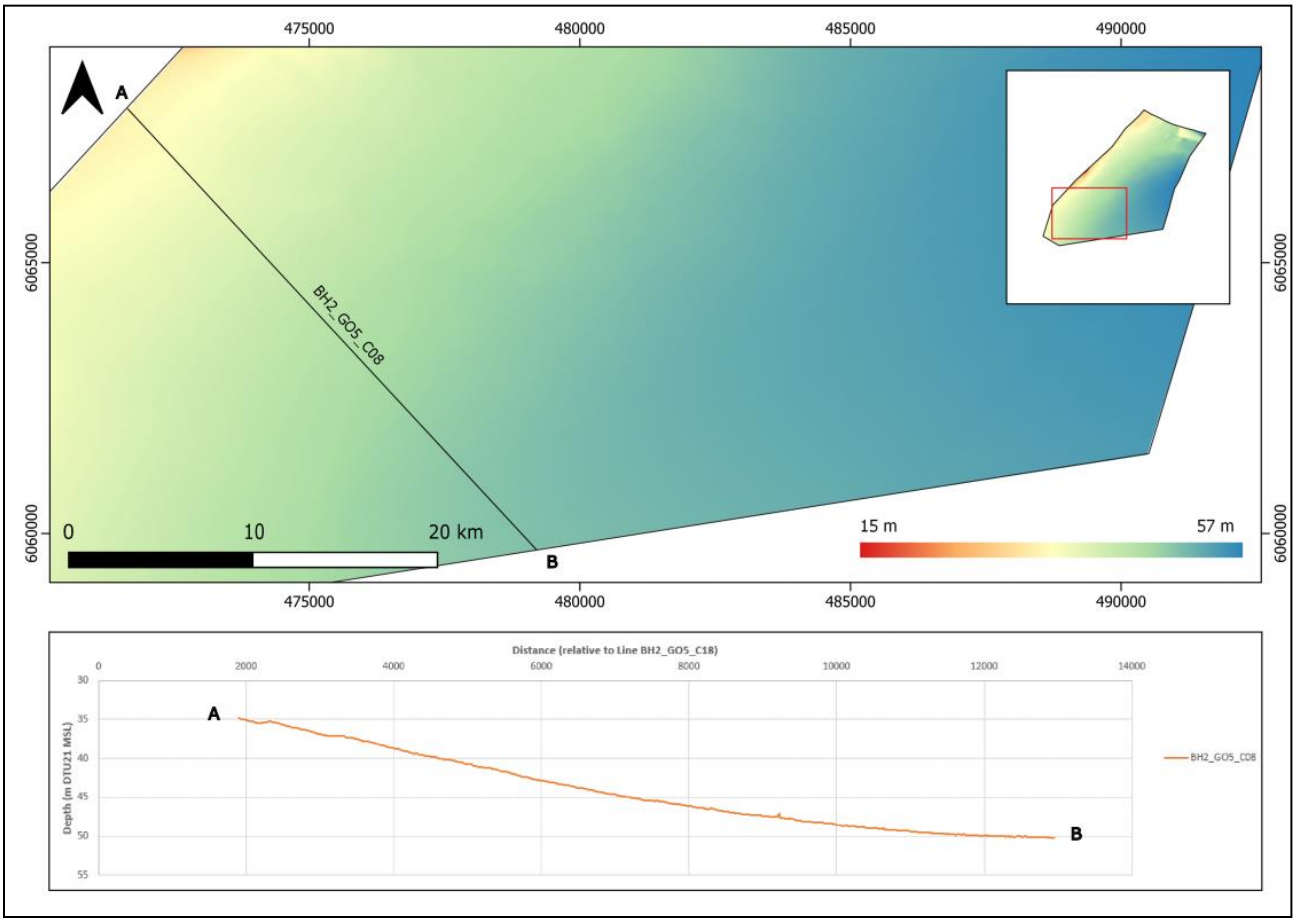


Figure 28: Profile BH2_GO5_C08 location overview

8.2.4 Profile BH2_GO5_M_021 + BH2B_GO5_P_024

Profile BH2_GO5_M_021 + BH2B_GO5_P_024 (Figure 29) crosses the entire area from south to north, and spans about 31.8 km. The depth variation along this longitudinal profile is 7.88 m from a minimum depth of 38.8 m at 469416 m E, 6059380 m N to a maximum depth of 46.68 m at 482630 m E, 60716631 m N.

This longitudinal profile has a depth increment from south to north. In the northern part of the profile the topography is irregular and deep, which could be correlated with areas of high concentration of trawl marks and seabed scars, likely related to the construction of the Nord Stream Pipeline.

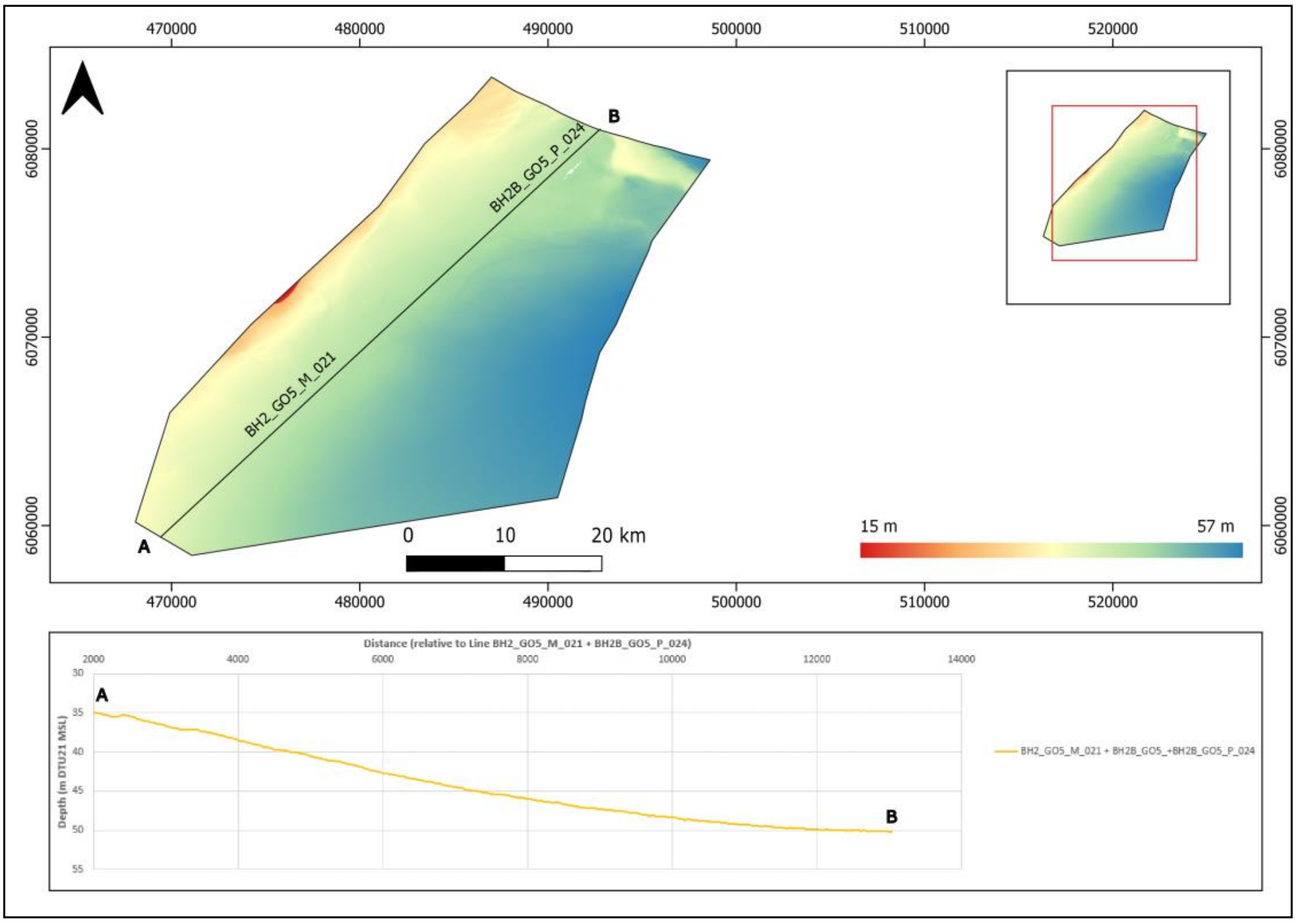


Figure 29: Profile BH2_GO5_M_021 + BH2B_GO5_P_024

8.2.5 Slope analysis

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

Slope angles across the site are typically very gentle (<1º) and gentle (1º - 5º). The maximum slope in the survey area is 41.10 º but only exists in localised areas.

Some representative examples are presented:

- Wreck: 15 m length, 5 m width in the east of Bornholm II (Figure 30).
- Wreck: 26 m length, 8 m width in the east of Bornholm II (Figure 31).
- Wreck: 22 m length, 4 m width in the central-west of Bornholm I (Figure 32).
- Wreck: 44 m length, 7 m width in the south-west of Bornholm II (Figure 33).
- Seabed escarpment: 2 km in length in the northwest of Bornholm II (Figure 34).

A wreck located on the eastern of Bornholm II, at 489195 m E, 6067565 m N, at an approximated depth of 54 m is shown in Figure 30. This wreck is surrounded by a debris field, in an area of 4527 m^2, 93 m length, 56 m width.

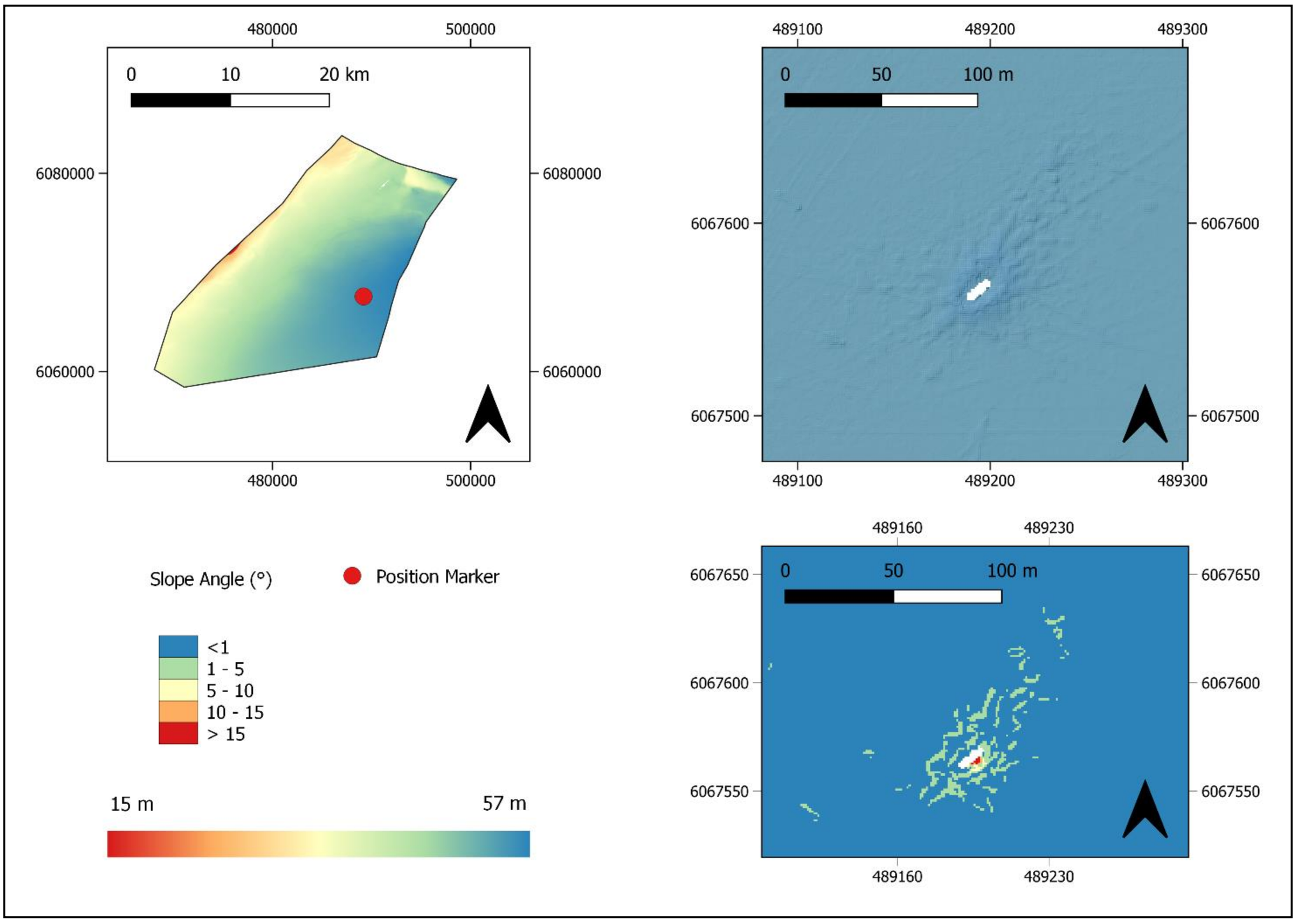


Figure 30: Wreck contact with general slope angle between 1º and 5º and maximum slope angle (>15º) in the centre.

Figure 31 shows a wreck located 1.30 km southwest from the previous example, at 488718 m E, 6066416 m N. It is also associated with a debris field but in a larger area (2.67 ha, 250 m length, 187 m width). It is also located at an approximate depth of 54 m.

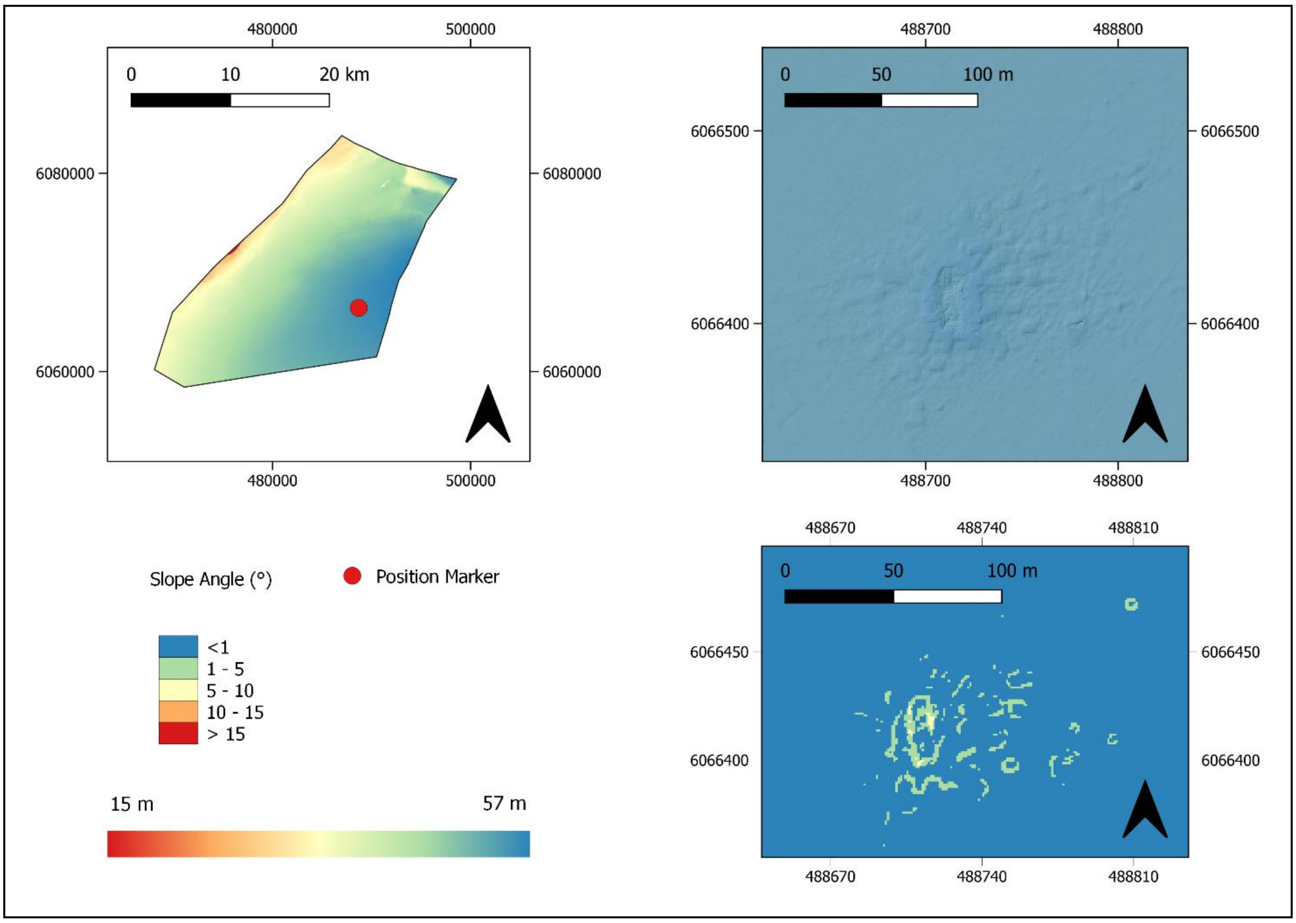


Figure 31: Wreck contact with general slope angle between 1º - 10º.

Figure 32 provides information of the wreck located in the central-west area of Bornholm II, at 477466 m E, 6067405 m N, at an average depth of 42 m. The area in which this wreck is visible is about 3511 m^2, 110 m in length, 49 m in width.

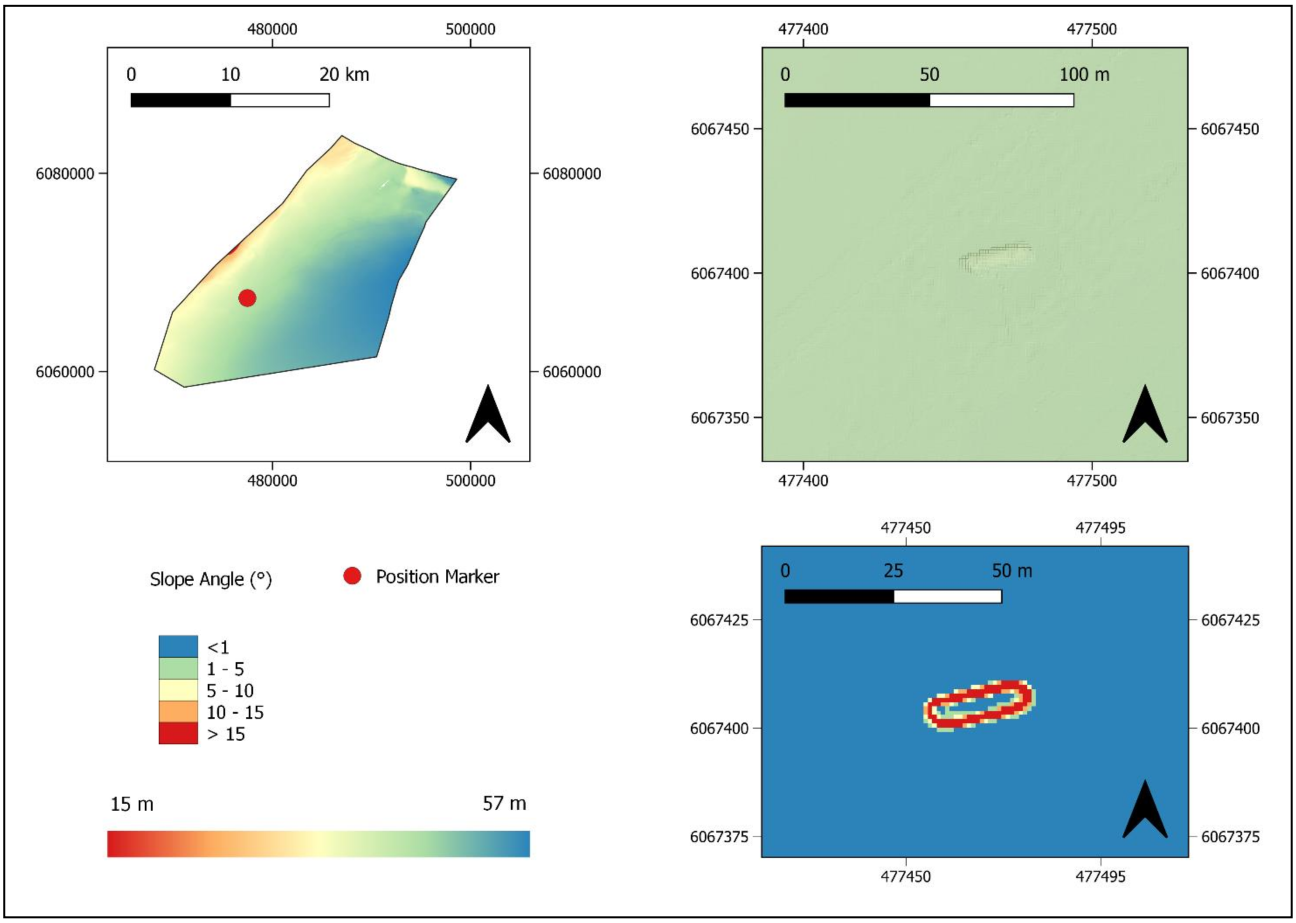


Figure 32: Wreck contact with general slope angle between 1º - 10º.

Figure 33 describes another wreck located southwest of the survey area, at 471516 m E, 6066316 m N. It is a bathymetric anomaly with a variation in the values of 4 m relative to general depth of 35 m. This could be associated with known wreck 262, covering an area about 2422 km^2, 64 m length, 53 m width.

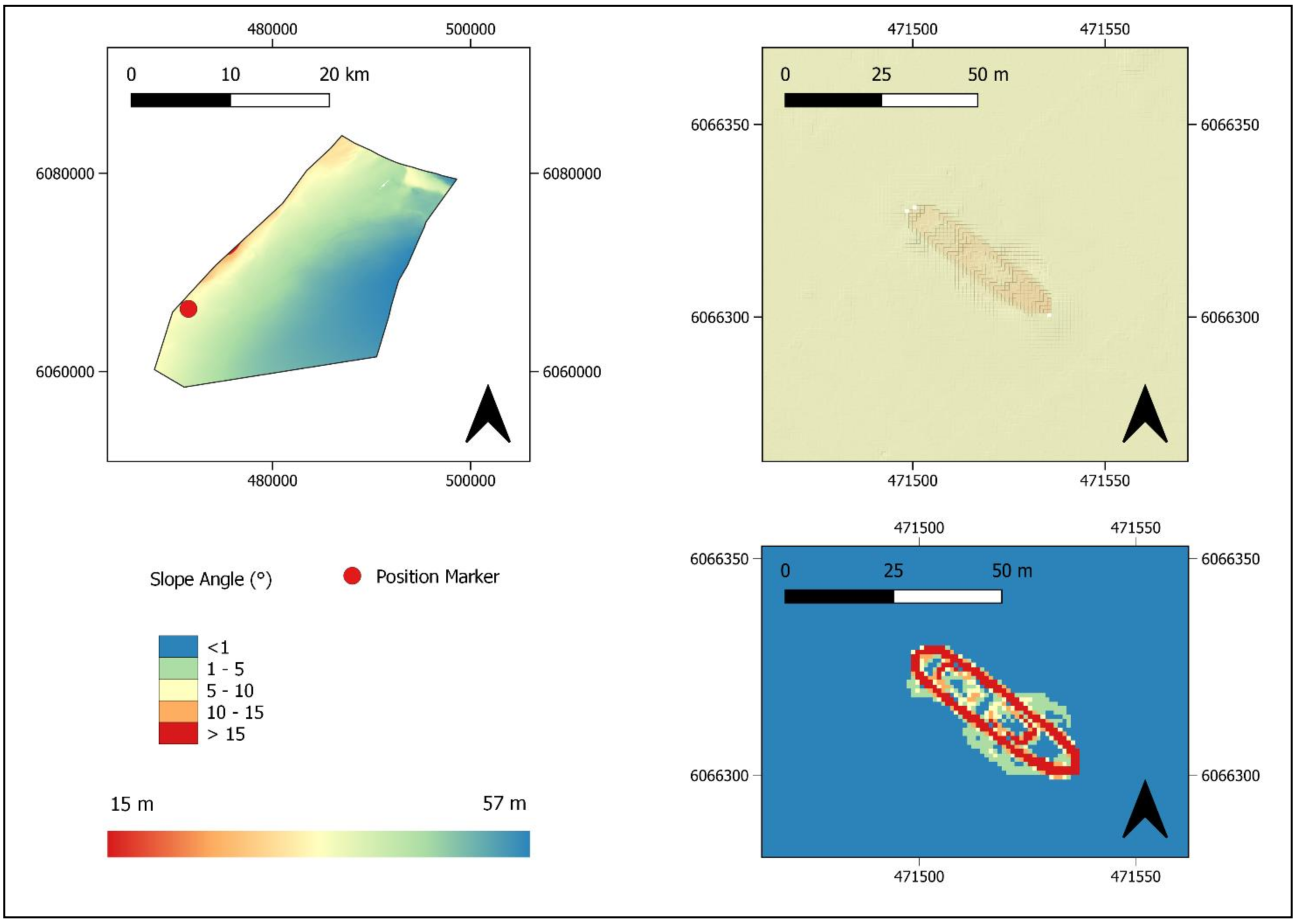
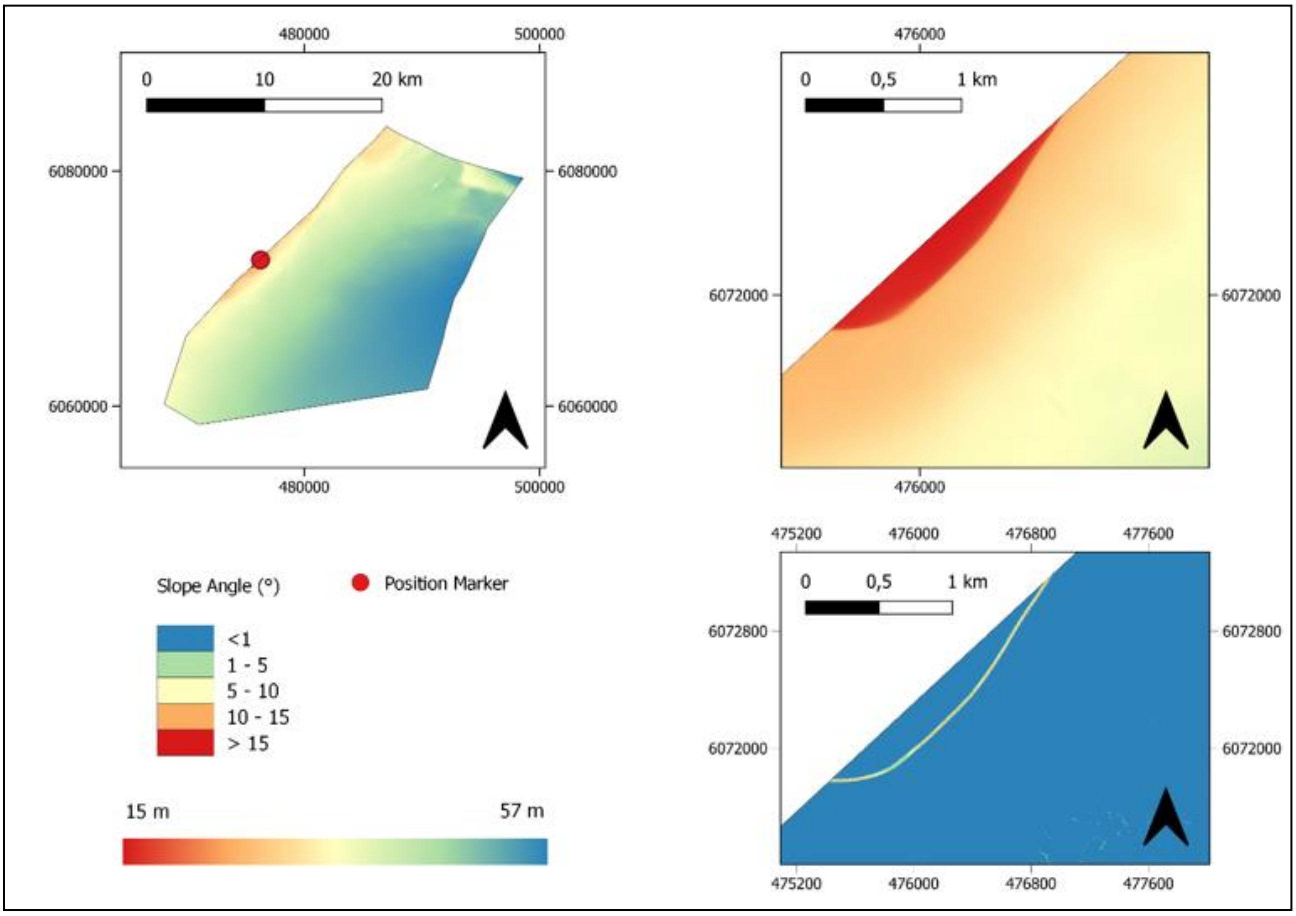


Figure 33: Wreck contact with maximum slope angle (> 15º) west of Bornholm II

The highest slope angle associated with seabed features (> 15º) is located at 476152 m E, 6072340 m N (Figure 34). This feature is formed on the western side of the survey area. High slope values occur, along with a transition od depth from 15 m to 35 m. This corresponds to a seabed escarpment (2 km in length).


480000
500000
0
10
20 km
6080000
6060000
0
0,5
1 km
476000
6072000
475200
476800
477600
6072800
Slope Angle (°)
Position Marker
<1
1 - 5
5 - 10
10 - 15
> 15
15 m
57 m

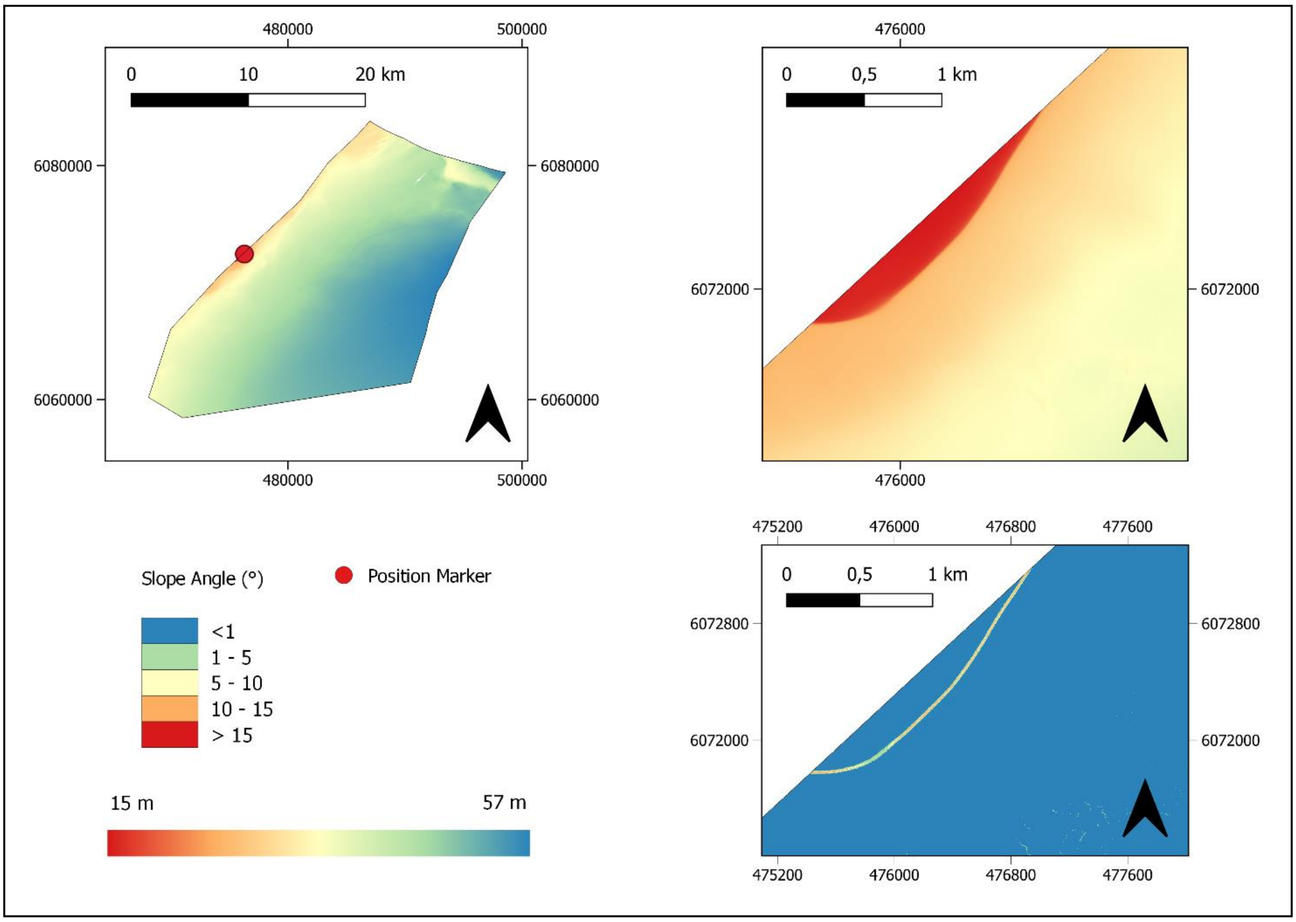


Figure 34: Seabed escarpment with 32º slope angle in western zone of Bornholm II

As expected, the steepest slope values are related to the Nord Stream 2 and Baltic Pipelines (Figure 35)

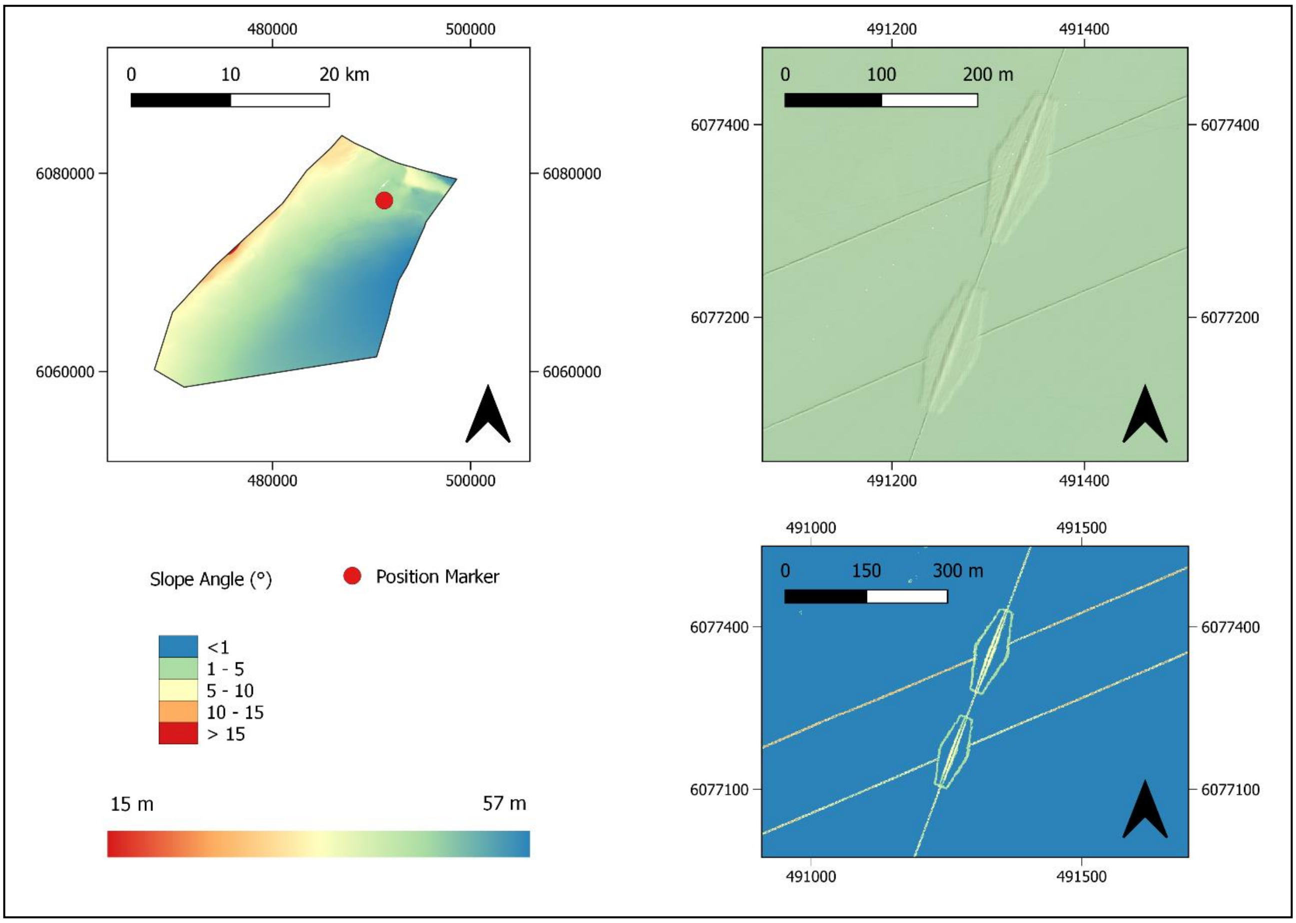


Figure 35: Pipeline Mattress slope contact reaching maximum values north of Bornholm II.

Additional areas where slope angles are classified as very steep (> 15º) are scattered widely across Bornholm II. Such angles are associated with high concentrations of trawl scars from fishing activities (western half of the survey area), seabed scars related to the construction of the North Stream pipeline and boulder fields. Examples of such areas can be found at:

- Related to trawl marks: 49896 m E, 60615226 m N
- Related to Nord Stream construction: 474792 m E, 6059525 m N (Figure 36)
- Related to boulder fields: 477782 m E, 6071510 m N

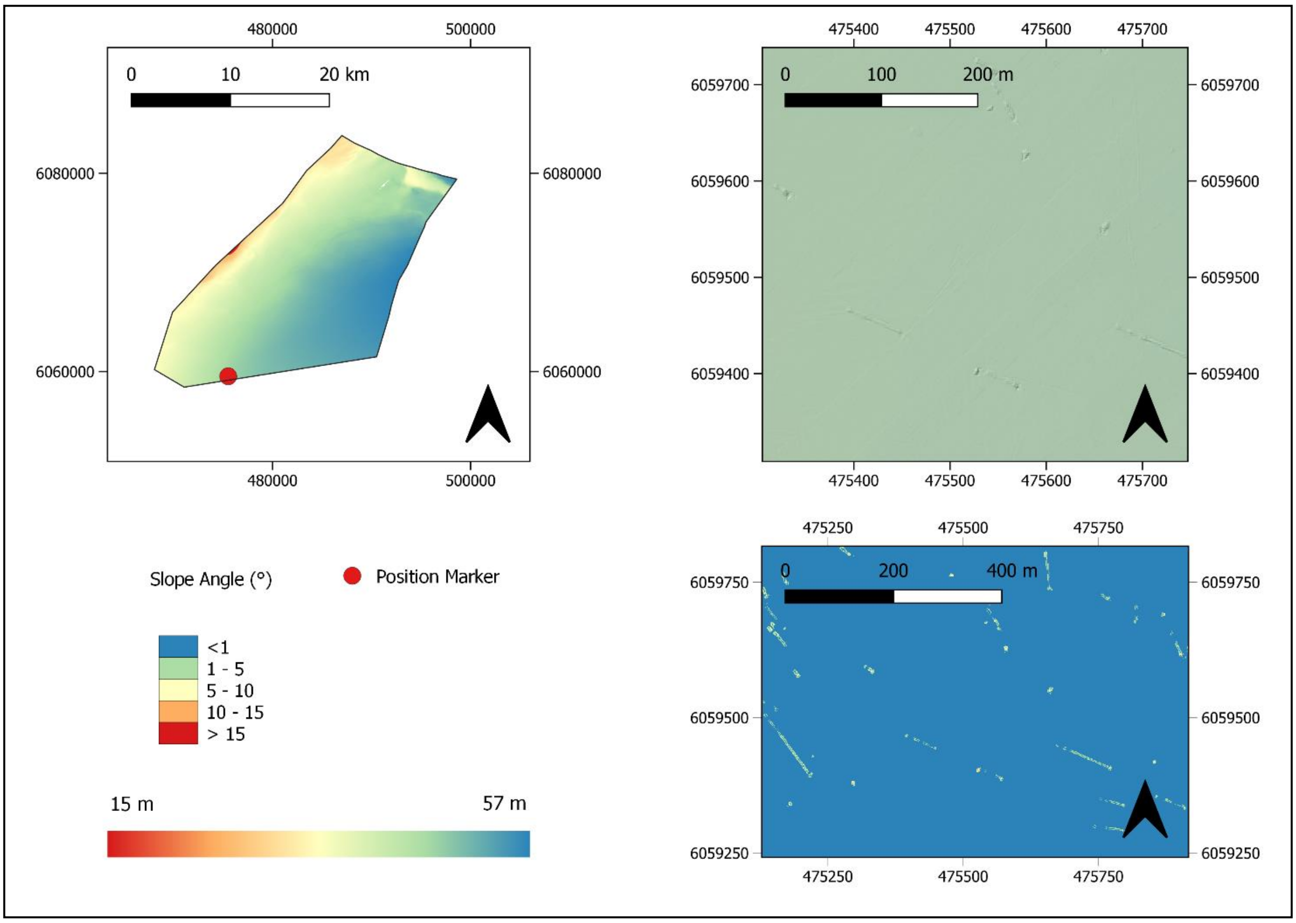


Figure 36: Seabed scar slopes south of Bornholm II

8.3 SEABED SURFACE CLASSIFICATION: GEOLOGY

The seabed geology for BHII and BHII B was evaluated from the interpretation of the low frequency SSS data and backscatter imagery. The resultant seabed surface geology interpretation is highlighted in Figure 37.

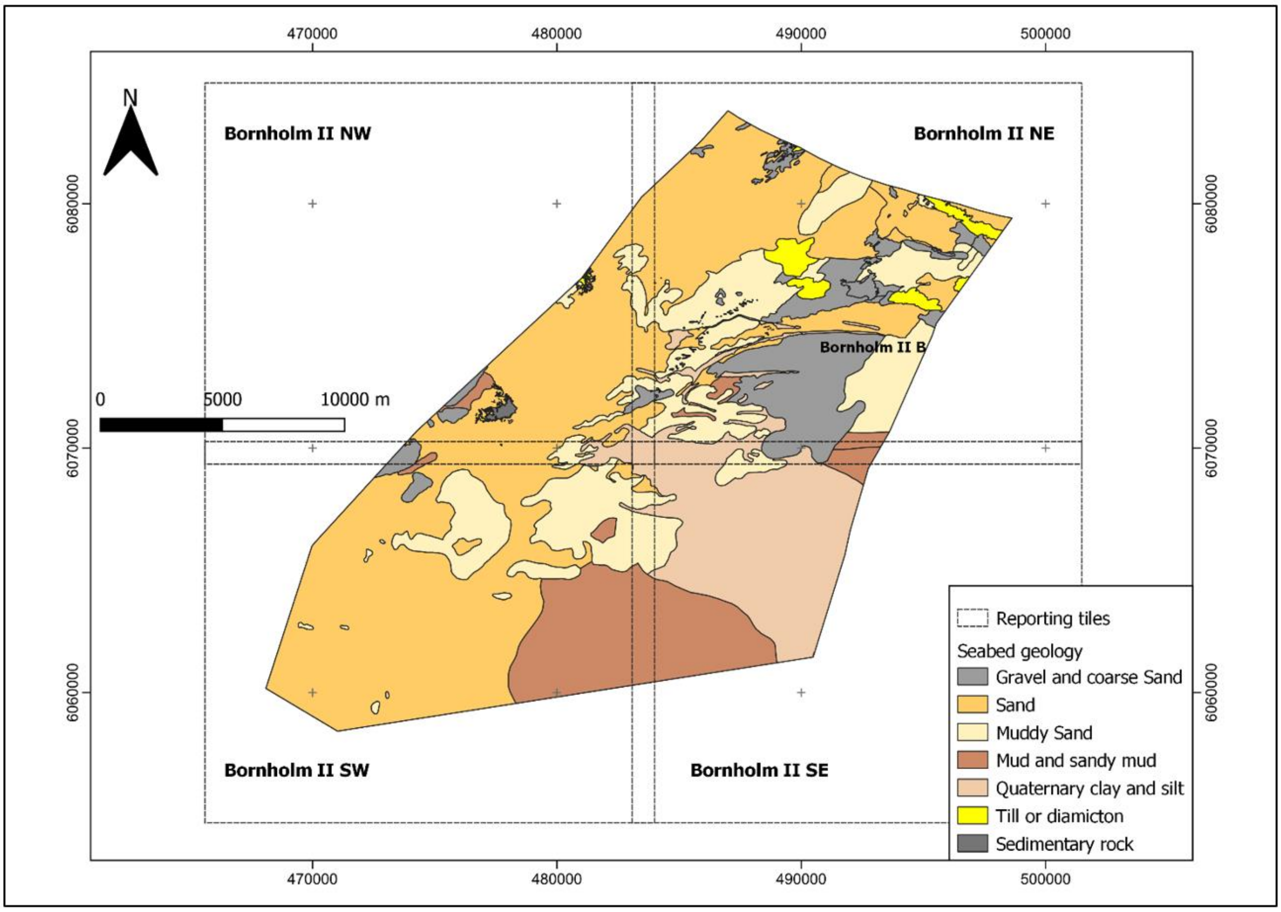
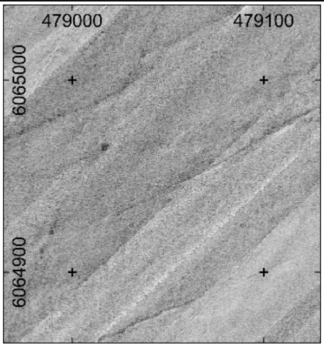
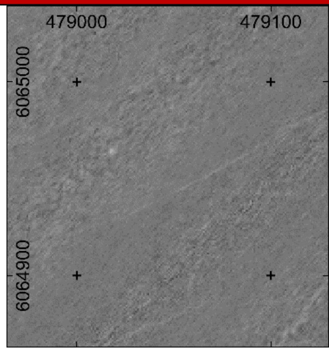
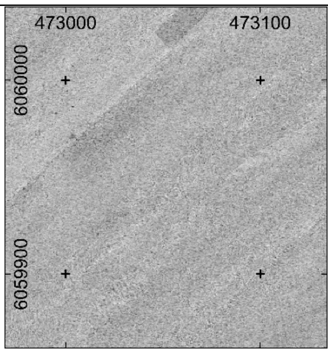
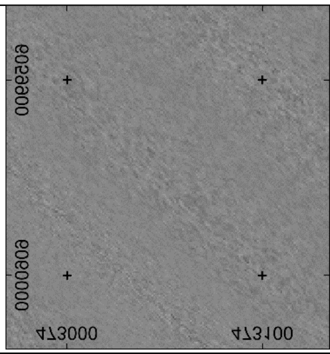
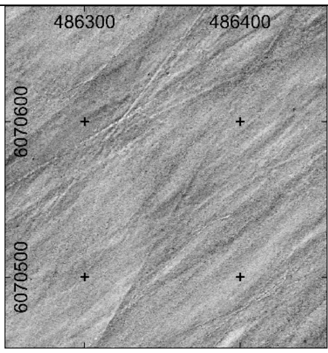
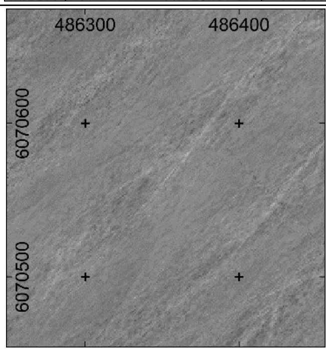
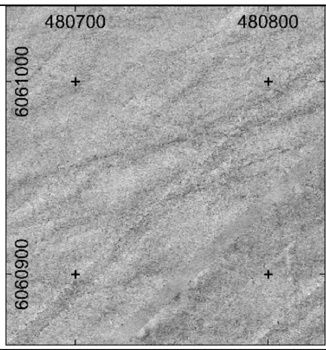
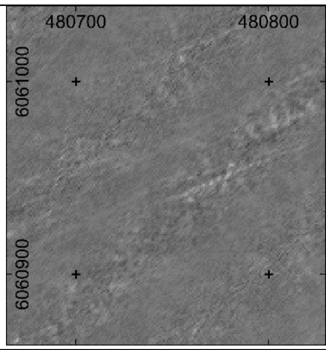
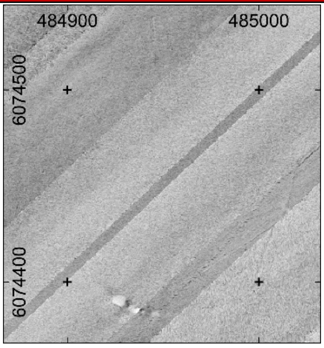
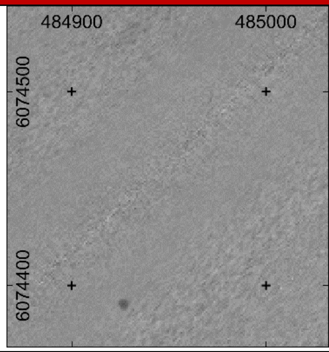
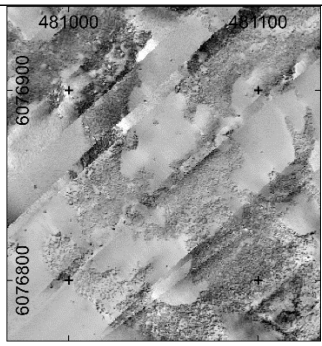
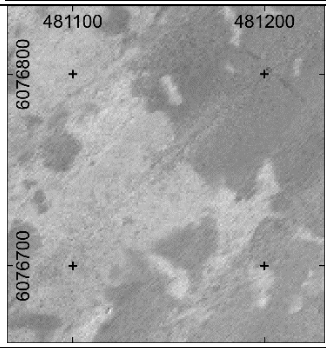
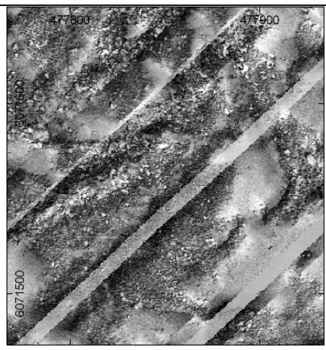
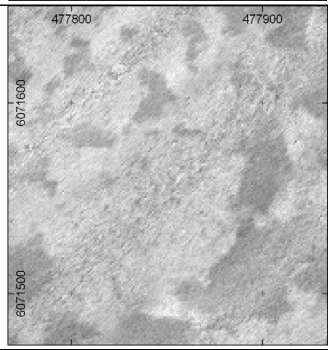


Figure 37: Seabed geology classification

Table 21 Describes examples of identified seabed surface geology types classified within the BHII and BHII B site. Geological interpretation using geophysical data was guided by the grab sampling campaign.

Table 21: Geological interpretation

Geological interpretation	Grab sample description	Colour	Acoustic description	SSS LF image	Backscatter image
Gravel and coarse Sand	Clayey silty Sand with some fine to coarse gravel		Medium to high reflectivity		
Sand	Sand; < 10% clay and silt content		Medium reflectivity		
Muddy Sand	Clayey silty sand		Low to medium reflectivity		
Mud and sandy mud	Clayey very sandy silt		Low to medium reflectivity		

Geological interpretation	Grab sample description	Colour	Acoustic description	SSS LF image	Backscatter image
Quaternary clay and silt	Dark grey clayey sandy SILT		Low to medium reflectivity		
Till or diamicton	Dark grey/brown slightly clayey SAND (till matrix)		Medium reflectivity		
Sedimentary rock	Outcrop		High reflectivity		

8.3.1 Seabed surface classification: Geology BHII northeast (Bornholm 2 NE)

The seabed surface sediment of the north-eastern section of the site (Bornholm 2 NE) is predominantly Sand (Figure 38). Muddy Sand extends at the central, south and south-eastern areas whereas mud and sandy mud areas occur to the southeast of the region. Limited areas of Silt and Clay are found to the south west, some of which are ribbon shaped. Gravel and Coarse sand areas occupy the larger portion of the south eastern and eastern Bornholm 2 NE and Till is reported in the central and north eastern parts of the region. The geology classification for Bornholm 2 NE is presented in Figure 38.

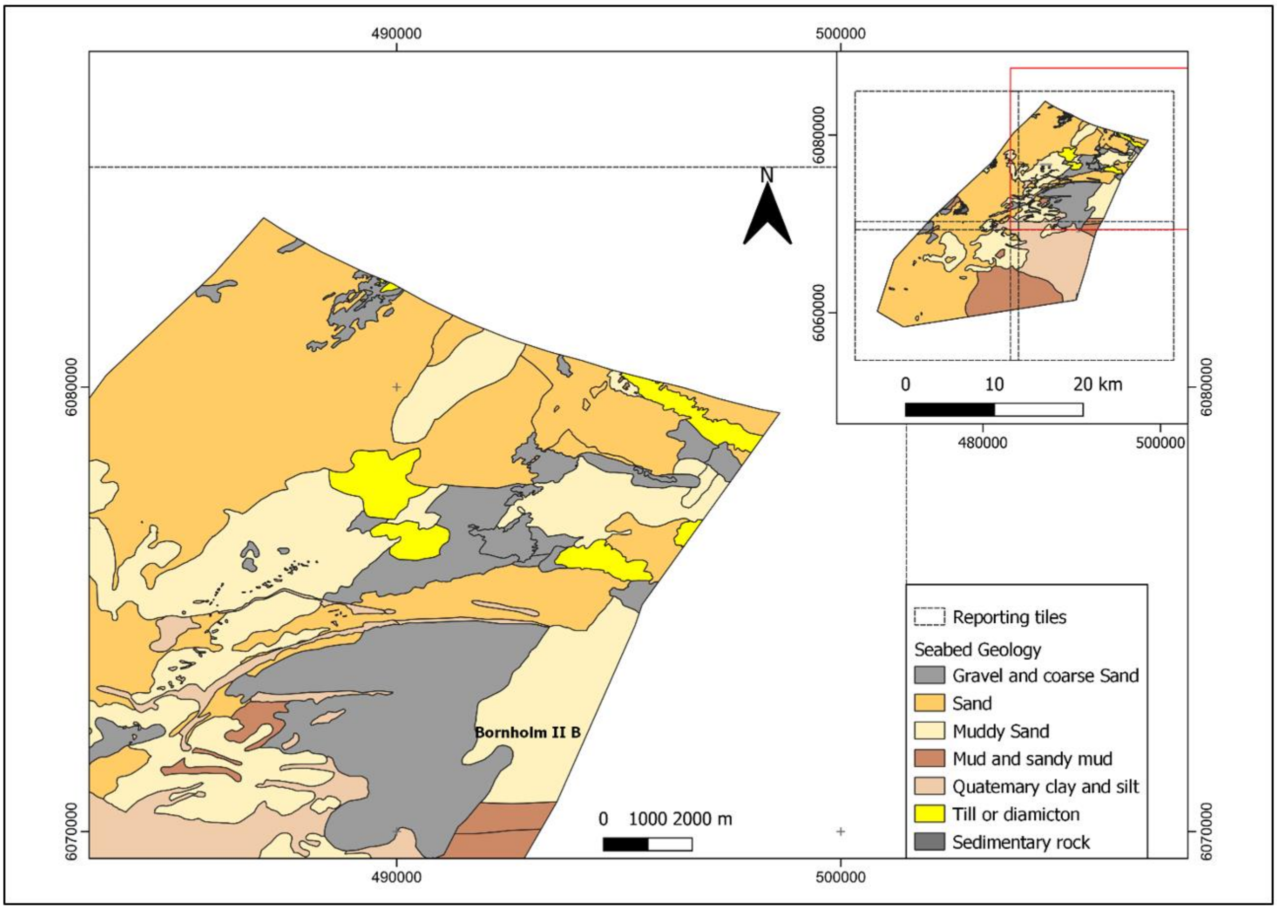


Figure 38: Seabed surface classification: Geology BHII northeast (Bornholm 2 NE)

8.3.2 Seabed surface classification: Geology BHII southeast (Bornholm 2 SE)

The seabed surface sediment of the Bornholm 2 SE region is predominantly fine-grained comprising mostly Clay and Silt as well as Mud and Sandy Mud over the larger portion of the region (Figure 39). Muddy Sand and Sand areas are found in the western and northern parts whereas coarser sediment comprising Gravel and coarse Sand are restricted to the northeast. The geology classification for Bornholm 2 SE is shown in Figure 39.

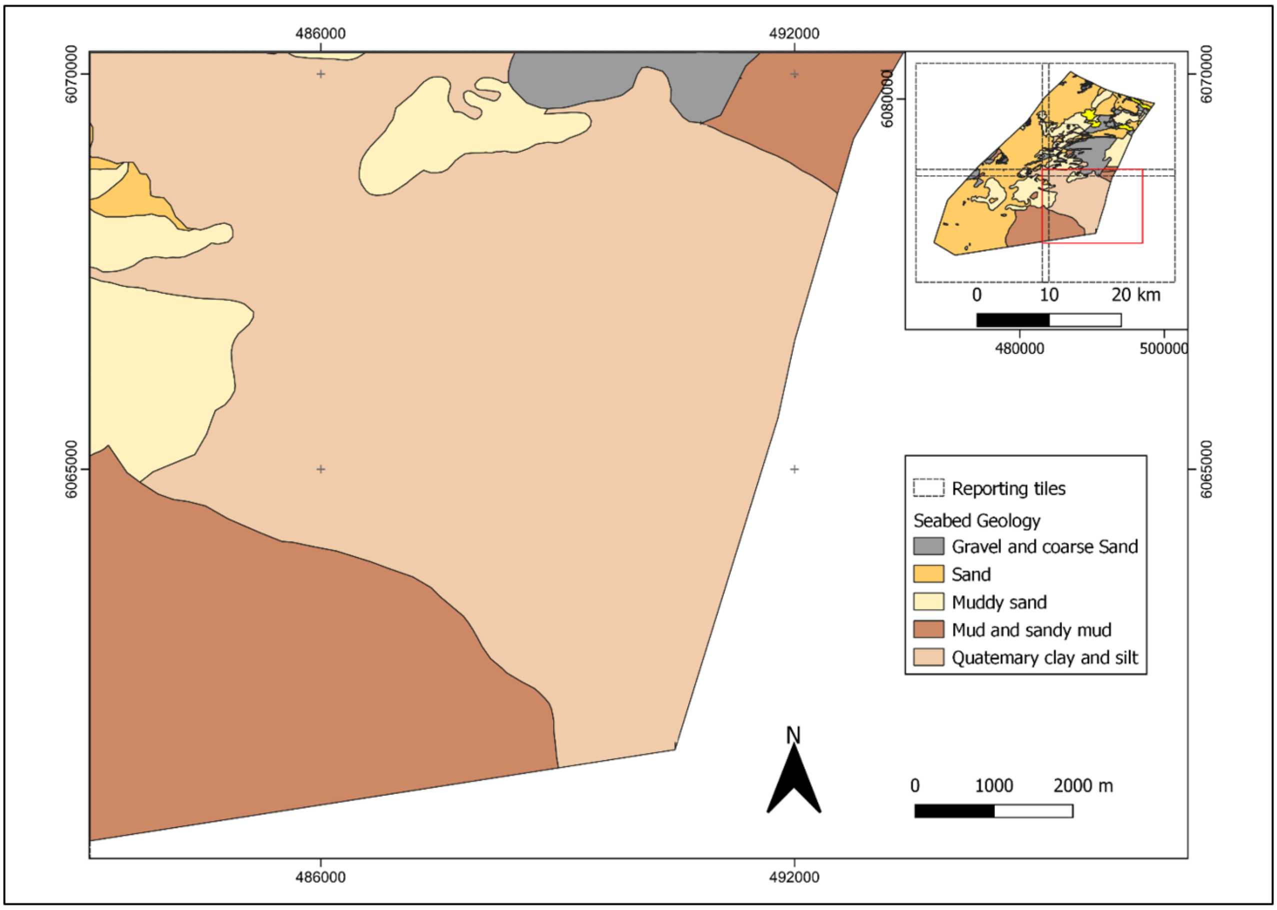


Figure 39: Seabed surface classification: Geology BHII southeast (Bornholm 2 SE)

8.3.3 Seabed surface classification: Geology BHII southwest (Bornholm 2 SW)

The geology of the seabed surface of Bornholm 2 SE is characterised predominantly by Sand and Muddy Sand (Figure 40). Mud and sandy Mud areas are outlined to the east and fine grain sediment comprising Clay and Silt are spotted in the north-eastern part of the region. Limited Gravel and coarse Sand areas exist in the north of Bornholm 2 S. The geology classification for Bornholm 2 SW is described in Figure 40.

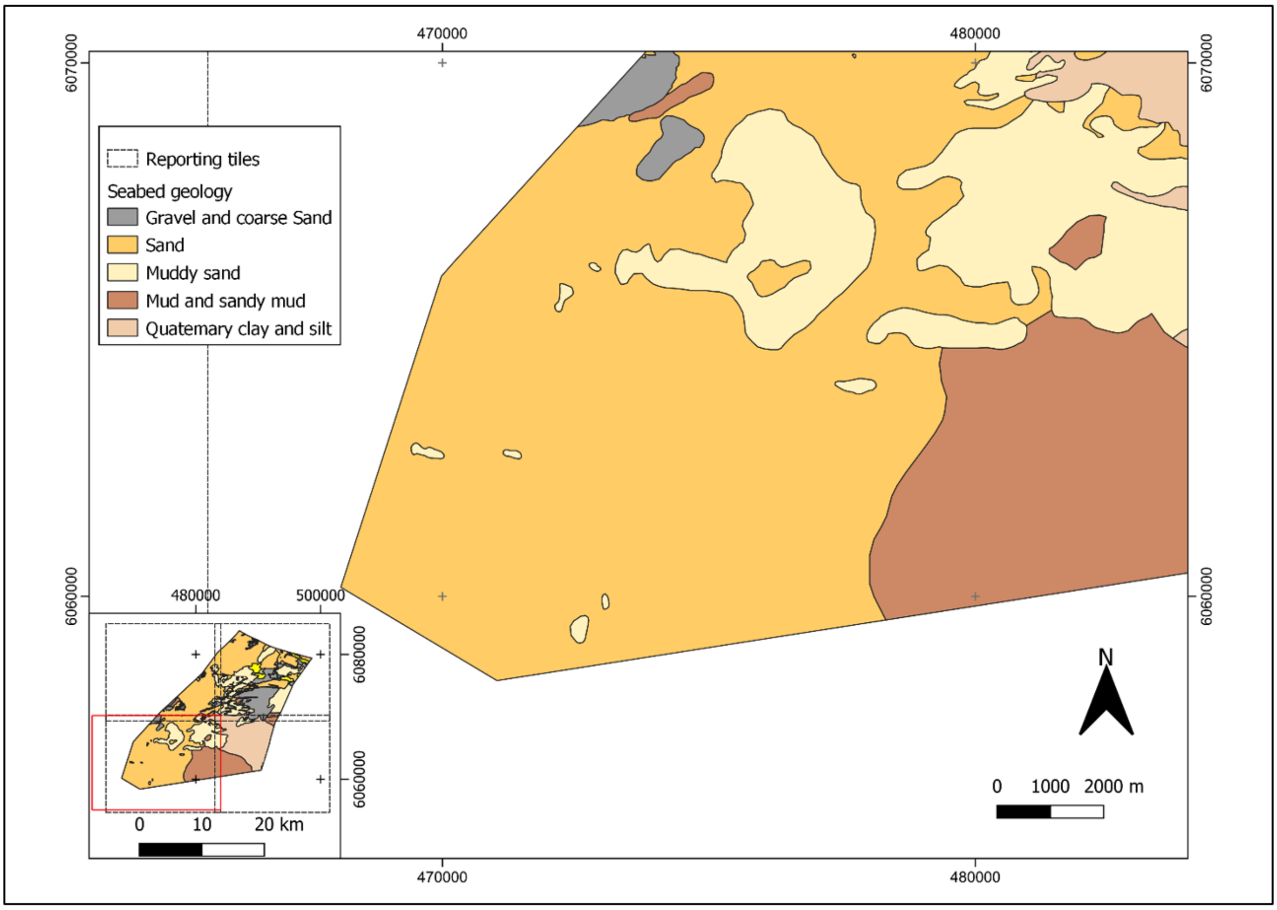


Figure 40: Seabed surface classification: Geology BHII southwest (Bornholm 2 SW)

8.3.4 Seabed surface classification: Geology BHII northwest (Bornholm 2 NW)

The geology of the seabed surface for Bornholm 2 NW is predominantly characterized by Sand whereas Muddy Sand is also outlined over the eastern and northern areas (Figure 41). Gravel and coarse Sand along with Mud and sandy Mud areas are delineated to the west. Two limited areas of Till exist in the western and north-western parts of Bornholm 2 NW and a Sedimentary rock outcrop occurs in the west. The geology classification for Bornholm 2 NW is described in Figure 41.

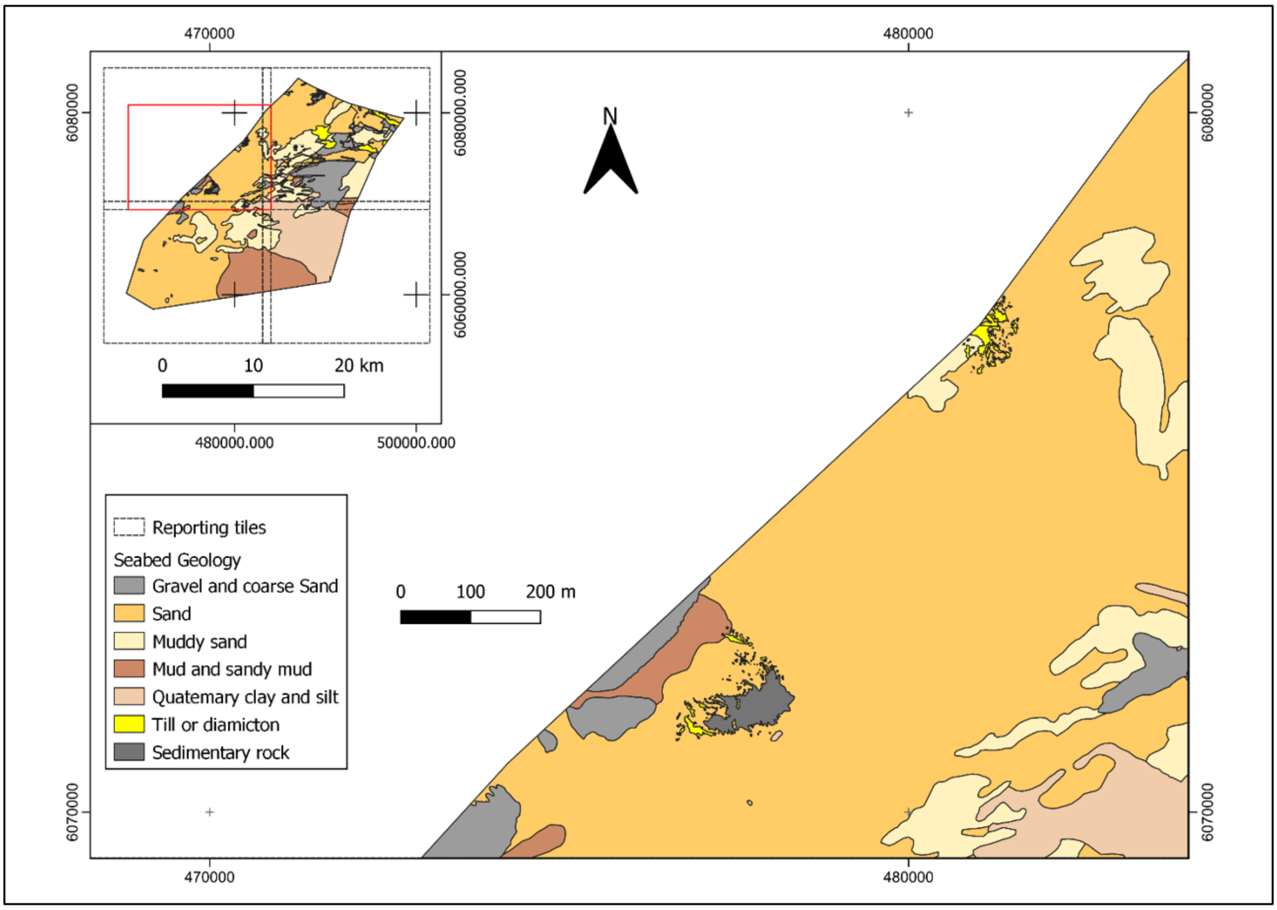


Figure 41: Seabed surface classification: Geology BHII northwest (Bornholm 2 NW)

8.4 SEABED SURFACE CLASSIFICATION: MORPHOLOGY

The seabed morphology for BHII and BHII B was evaluated from interpretation of the low frequency SSS data and backscatter imagery. The resultant seabed surface morphology interpretation is highlighted in Figure 42.

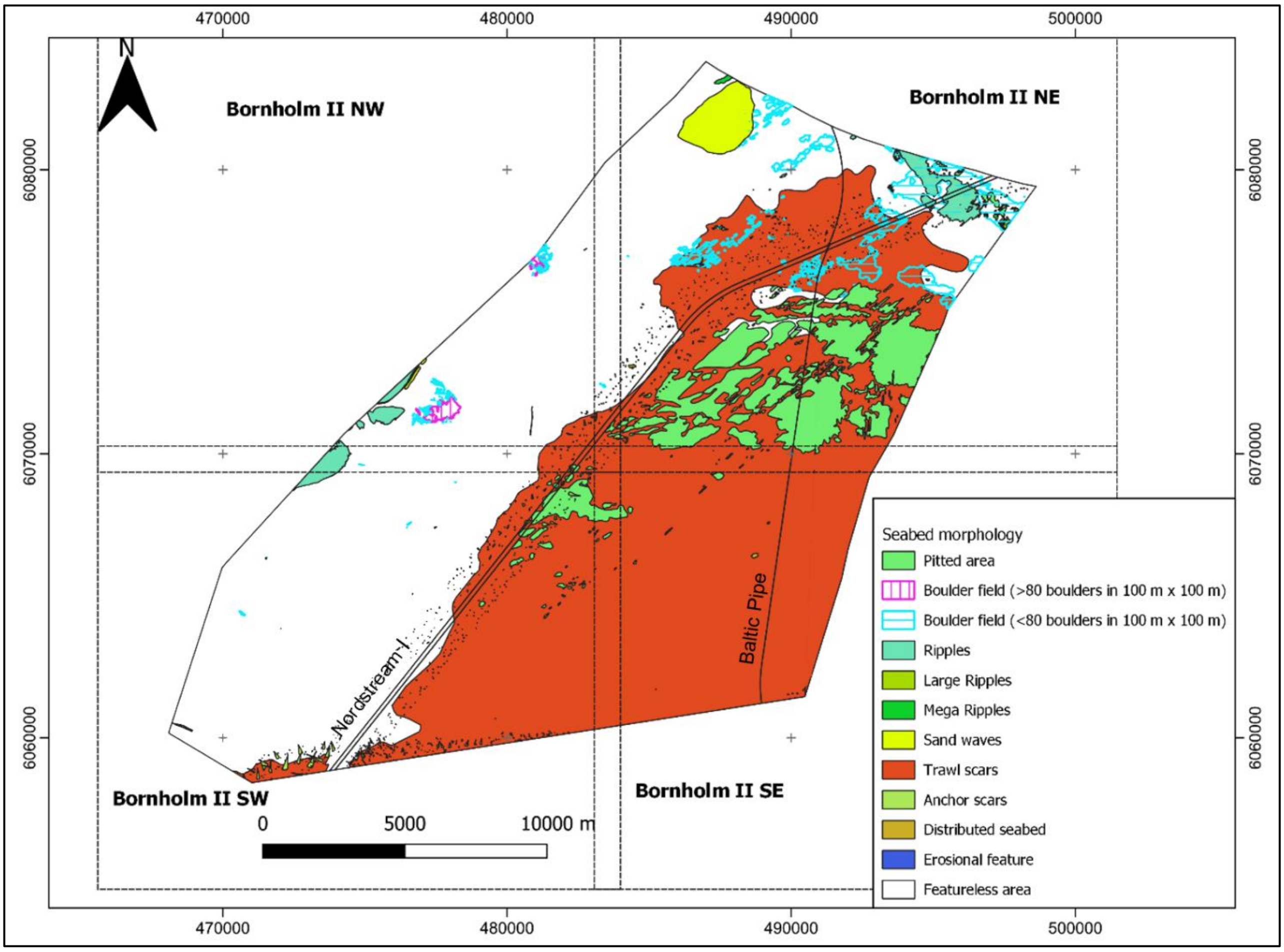
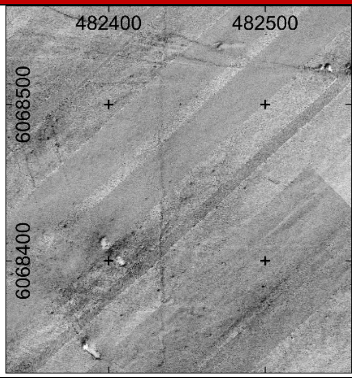
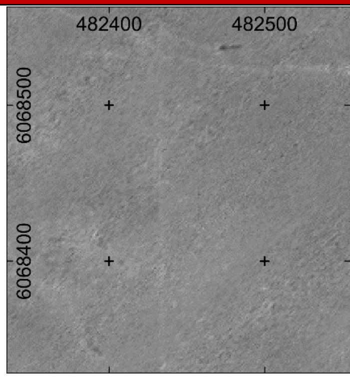
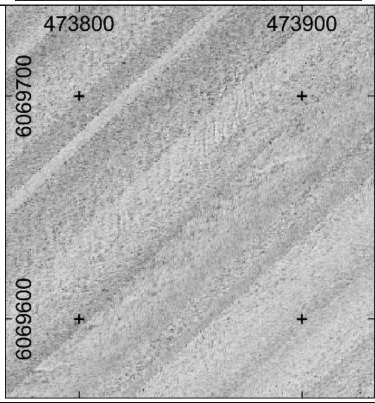
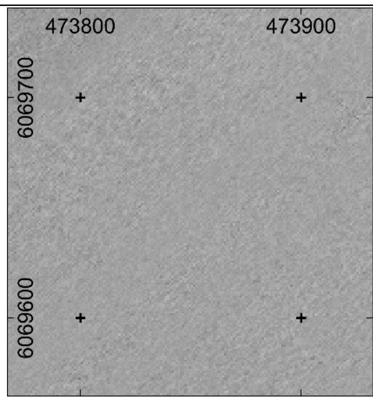
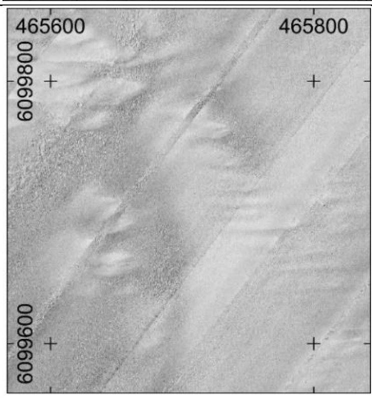
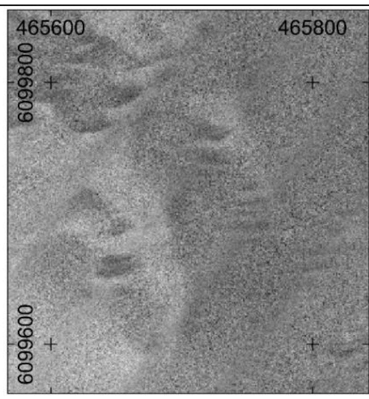
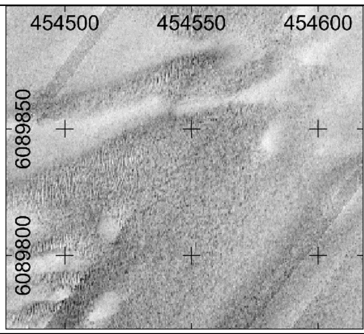
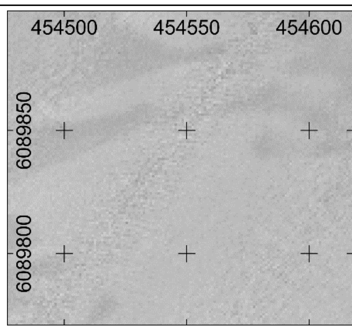


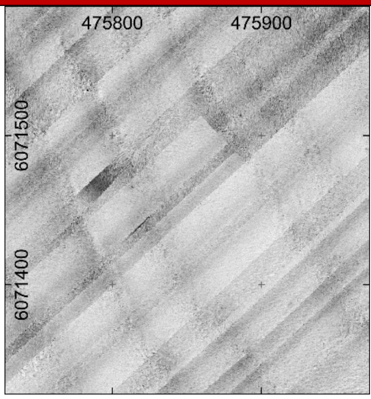
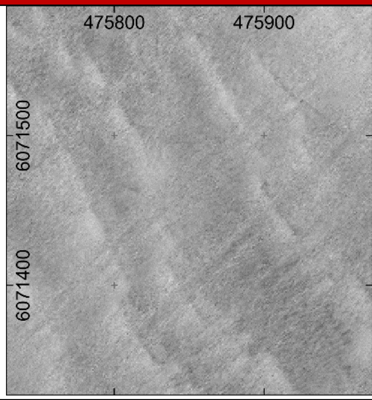
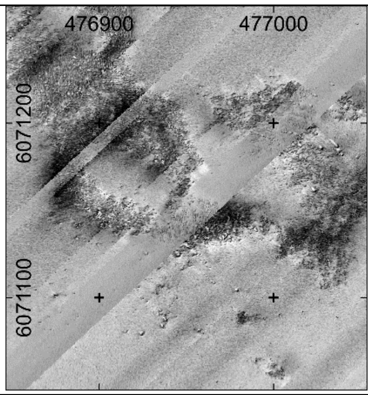
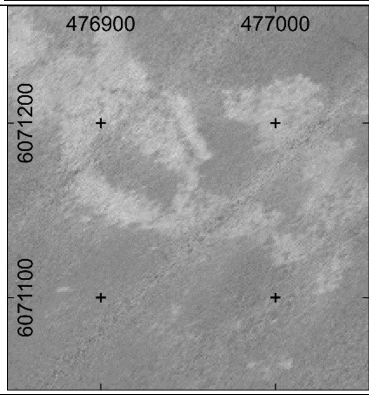
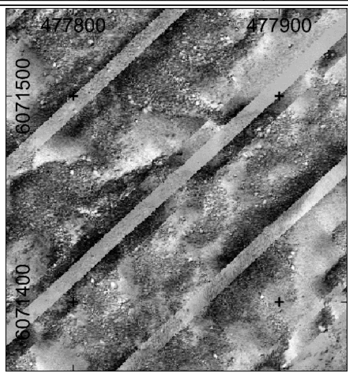
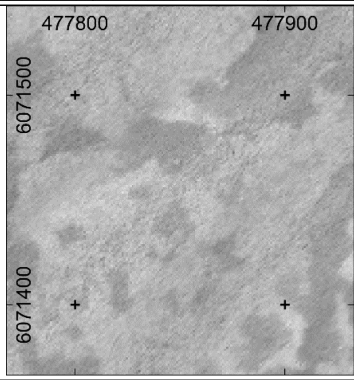
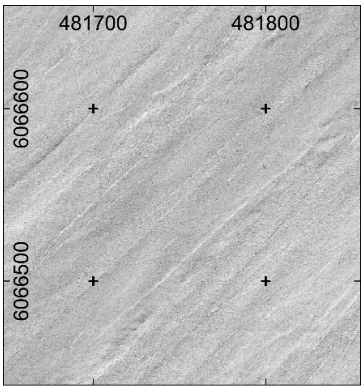
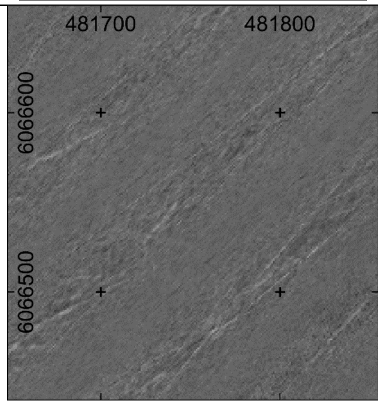
Figure 42: BHII seabed surface morphology classification

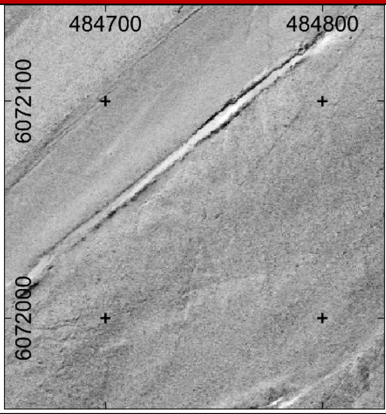
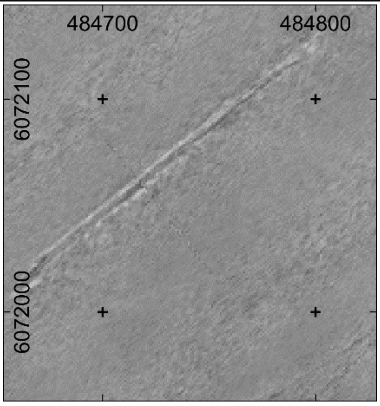
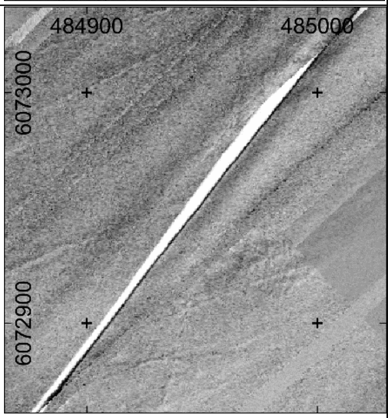
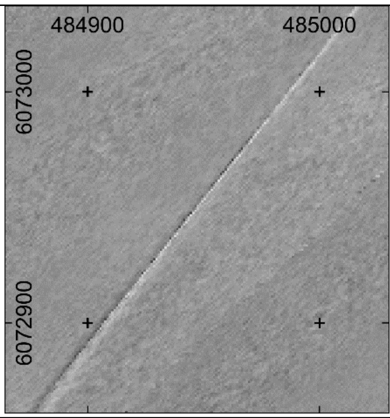
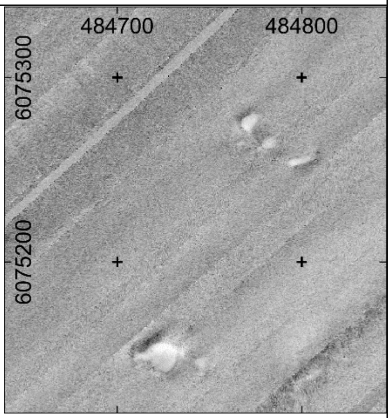
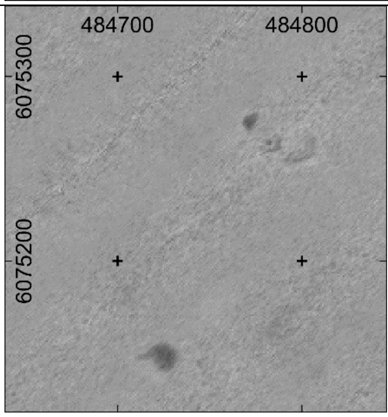
The east of the site is heavily trawl scarred with some interspersed pitted areas. Disturbed sediment areas surrounding the Nordstream 1 and Nordstream 2 pipelines are also present, likely caused by the pipeline construction phase. The west of the site has erosional features, boulder fields and sand ripples present.

Table 22 highlights the seabed morphology classification interpreted across the BHII site. Geological interpretation using geophysical data was guided by the grab sampling campaign.

Table 22: 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)		
Mega-ripples		Mega-ripple bedform areas (10 m – 20 m wavelength)		

<table>
<tr><th>Morphology interpretation</th><th>Colour</th><th>Description</th><th>SSS LF image</th><th>Backscatter image</th></tr>
<tr><td>Sand waves</td><td></td><td>Sand wave areas (30 – 70 m wavelength)</td><td></td><td></td></tr>
<tr><td>Boulder field (> 80 boulders in 100 m x 100 m area)</td><td></td><td>Boulder field with more than 80 boulders per 100 m x 100 m area.</td><td></td><td></td></tr>
<tr><td>Boulder field (< 80 boulders in 100 m x 100 m area)</td><td></td><td>Boulder field with less than 80 boulders per 100 m x 100 m area. Boulders less than 1.0 m in size.</td><td></td><td></td></tr>
<tr><td>Trawl scars</td><td></td><td>Seabed scarring from fishing trawling</td><td></td><td></td></tr>
</table>

<table>
<tr><th>Morphology interpretation</th><th>Colour</th><th>Description</th><th>SSS LF image</th><th>Backscatter image</th></tr>
<tr><td>Anchor scars</td><td></td><td>Seabed areas affected by anchor scarring</td><td>
</td><td>
</td></tr>
<tr><td>Other</td><td></td><td>Disturbed seabed (Wrecks, debris, jack-up depressions, pipelines)</td><td>
</td><td>
</td></tr>
<tr><td>Unknown</td><td></td><td>Erosional features (gravel ridges, trenching artifacts)</td><td>
</td><td>
</td></tr>
</table>

8.4.1 Seabed surface classification: Morphology BHII northeast (Bornholm 2 NE)

The north-eastern part of the Bornholm 2 NE area is heavily trawl scarred, interspersed by pitted areas (Figure 43). Regions of disturbed sediment surround the Nordstream 1 and Baltic Pipe pipelines that cross the site. The disturbed sediment surrounding the Nordstream pipelines are likely associated with their construction. Boulder fields are found in the central part and they are more extended in the north and north-eastern area. Sand waves along NE-SW direction are spotted in the north-western part whereas in the north-east, areas of NW-SE oriented ripples are reported.

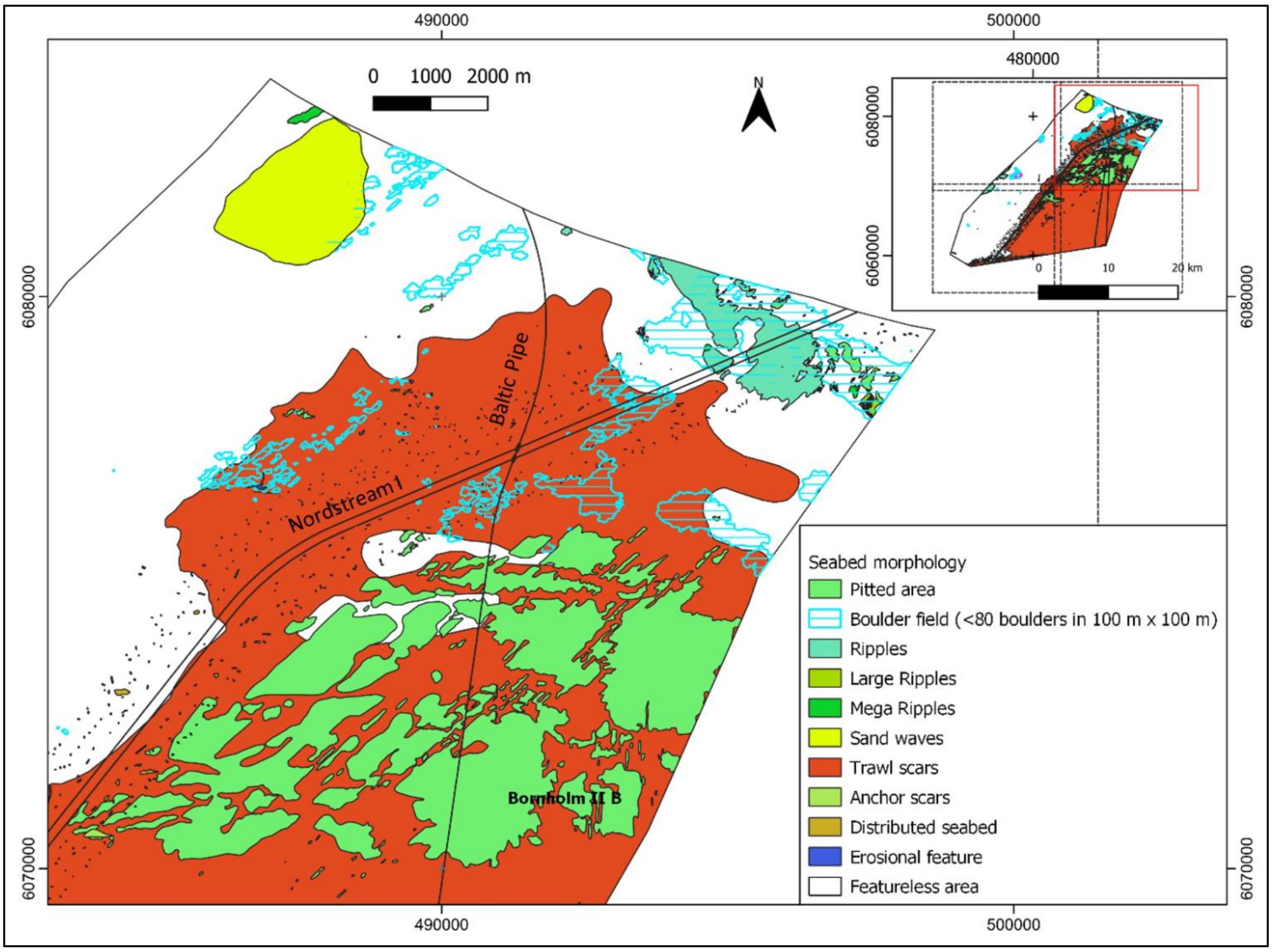


Figure 43: Seabed surface classification: Geology BHII northeast

8.4.2 Seabed surface classification: Morphology BHII southeast (Bornholm 2 SE)

The south-eastern part of the Bornholm 2 SE area is heavily trawl scarred interspersed by some pitted areas in the north-western part (Figure 44). The Baltic Pipe pipeline crosses the area to the east.

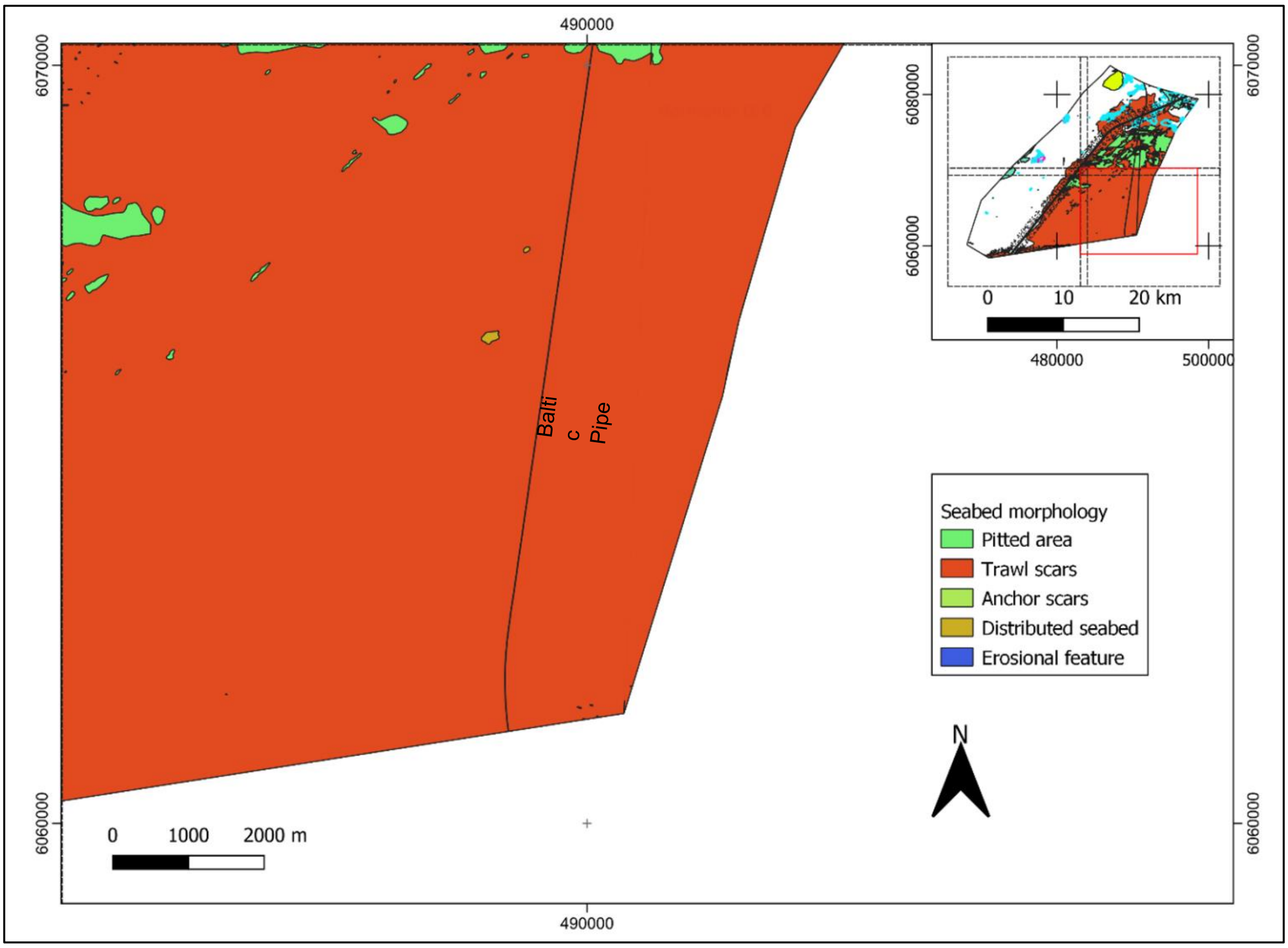


Figure 44: Seabed surface classification: Geology BHII southeast (Bornholm 2 SE)

8.4.3 Seabed surface classification: Morphology BHII southwest (Bornholm 2 SW)

The south-eastern part of the Bornholm 2 SW region is heavily trawl scarred interspersed by some pitted areas in the northeast (Figure 45). Regions of disturbed sediment surround the Nordstream pipelines that cross the area and anchor scars have been mapped along the southern edge. NW-SE aligned Sand waves and Ripples have been reported in the north western tip of Bornholm 2 SW.

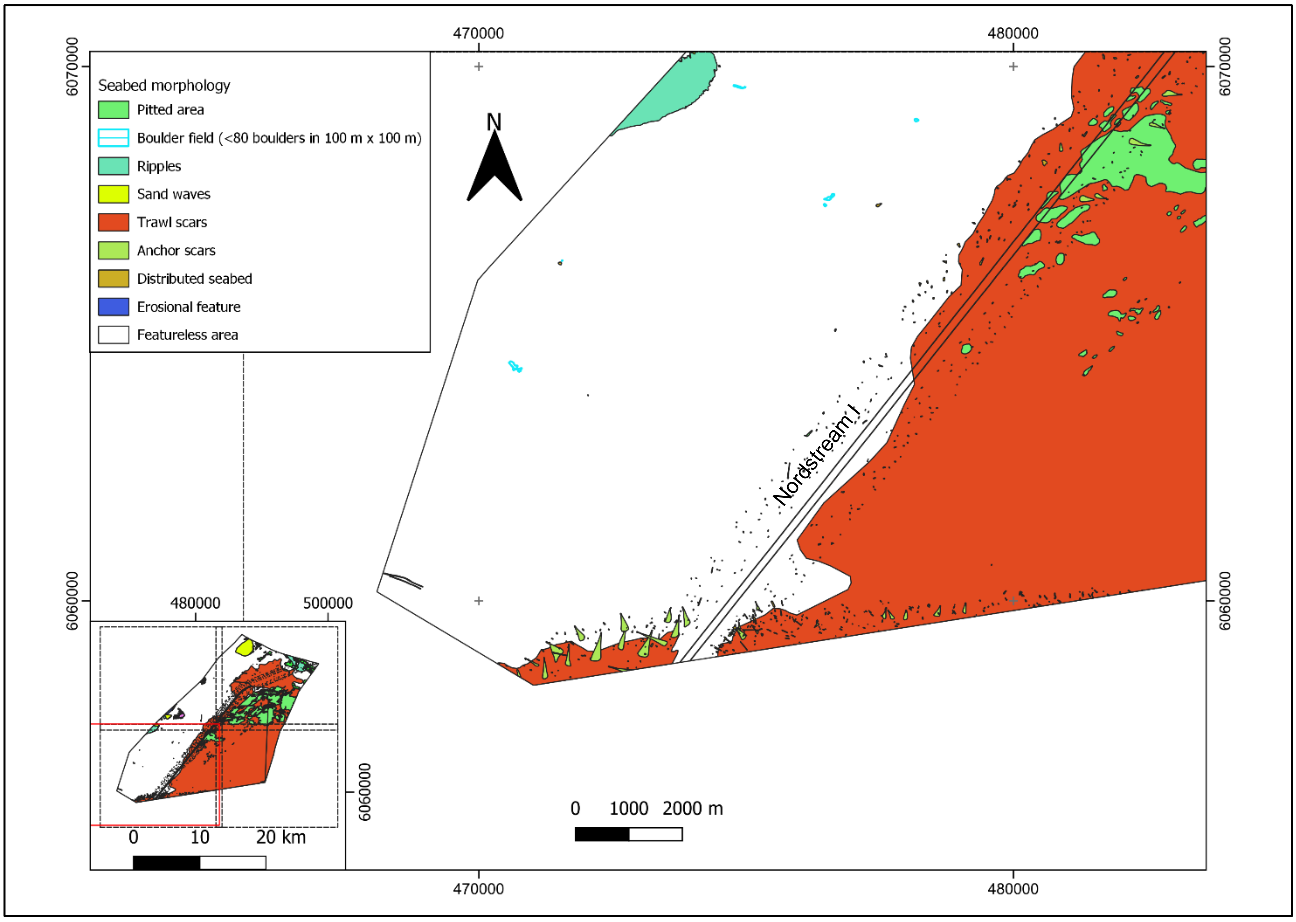


Figure 45: Seabed surface classification: Geology BHII southwest (Bornholm 2 SW)

8.4.4 Seabed surface classification: Morphology BHII northwest (Bornholm 2 NW)

The north-western part of the Bornholm 2 NW has some trawl scarring in the east, which is interspersed by some pitted areas (Figure 46). Sand ripples, erosional features and boulder fields are in the west and north of the area. NW-SE aligned Sand waves and Ripples occur in the western part of Bornholm 2 SW and boulder fields have been mapped in the western and north-western sections. Nordstream pipelines cross the Bornholm 2 NW at the south-eastern edge.

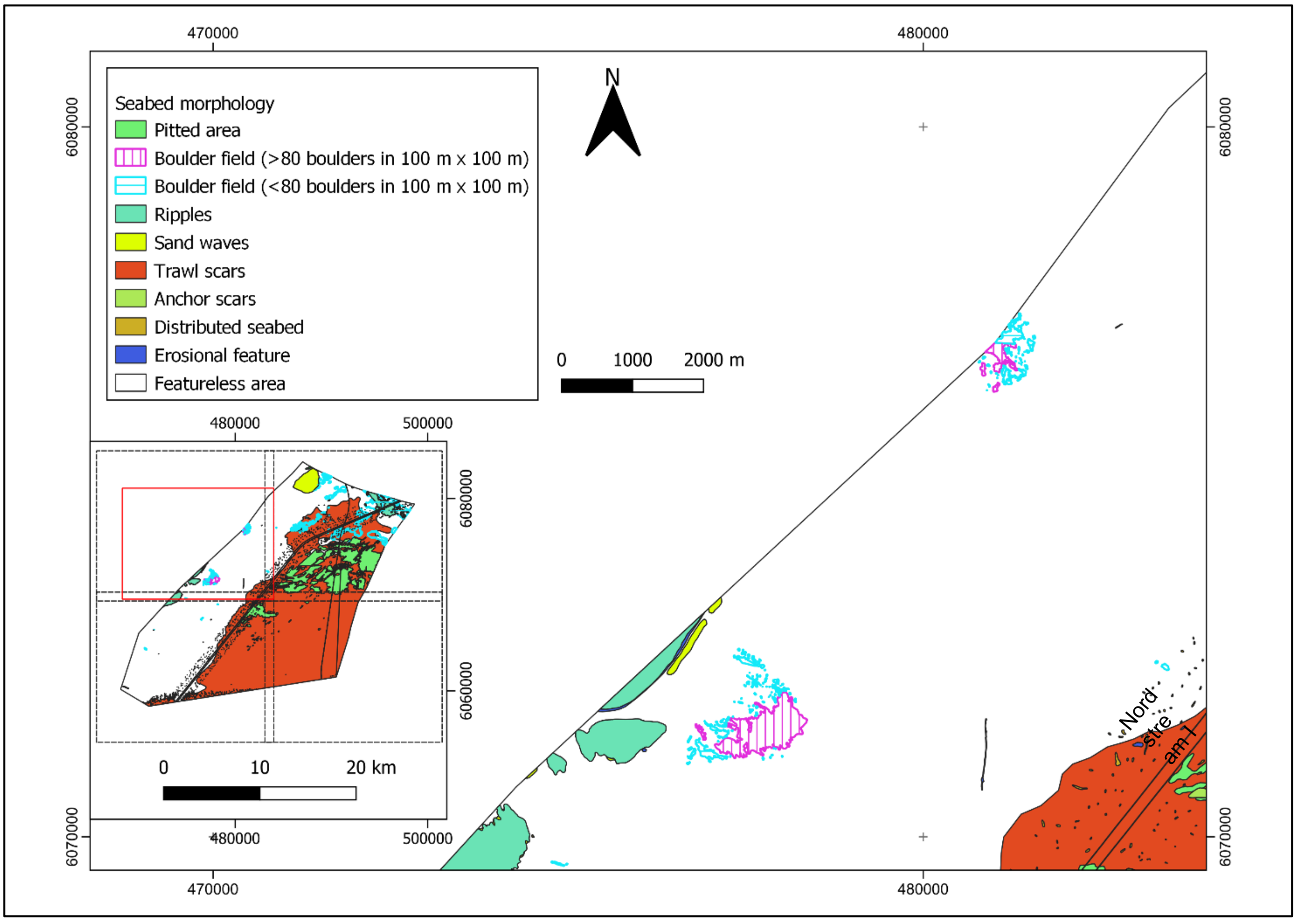


Figure 46: Seabed surface classification: Geology BHII northwest (Bornholm 2 NW)

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 23. A total of 1313 objects were identified through the interpretation of the MBES, SSS and magnetometer datasets with reference to the desk study.

Table 23: Identified man-made features

Feature type	Count	Comment
Wrecks	8 Wrecks	There are eight wrecks in the BHII site in various
Cables	0 (infrastructure) 3 (debris related)	Zero cables infrastructure identified. Three debris relate cable items identified
Pipelines	3	Baltic Pipeline crosses the western part of BHII site. The Nordstream I (2 pipelines) cross through the centre of the BHII site.
Debris	1313	1313 total debris items
Items related to fishing activity	147	147 items possibly associated with fishing activity
Seabed disturbances	37	Seabed disturbances from jack-up platforms and fishing activities

8.5.1 Wrecks

There are eight wrecks or suspected wrecks identified throughout the BHII survey site. The locations of the identified wrecks are shown in Figure 47 and outlined in Table 24. Identified wrecks or suspected wrecks are in differing states of preservation on the seabed; some wrecks are well preserved and others are formed of concentrated areas of debris.

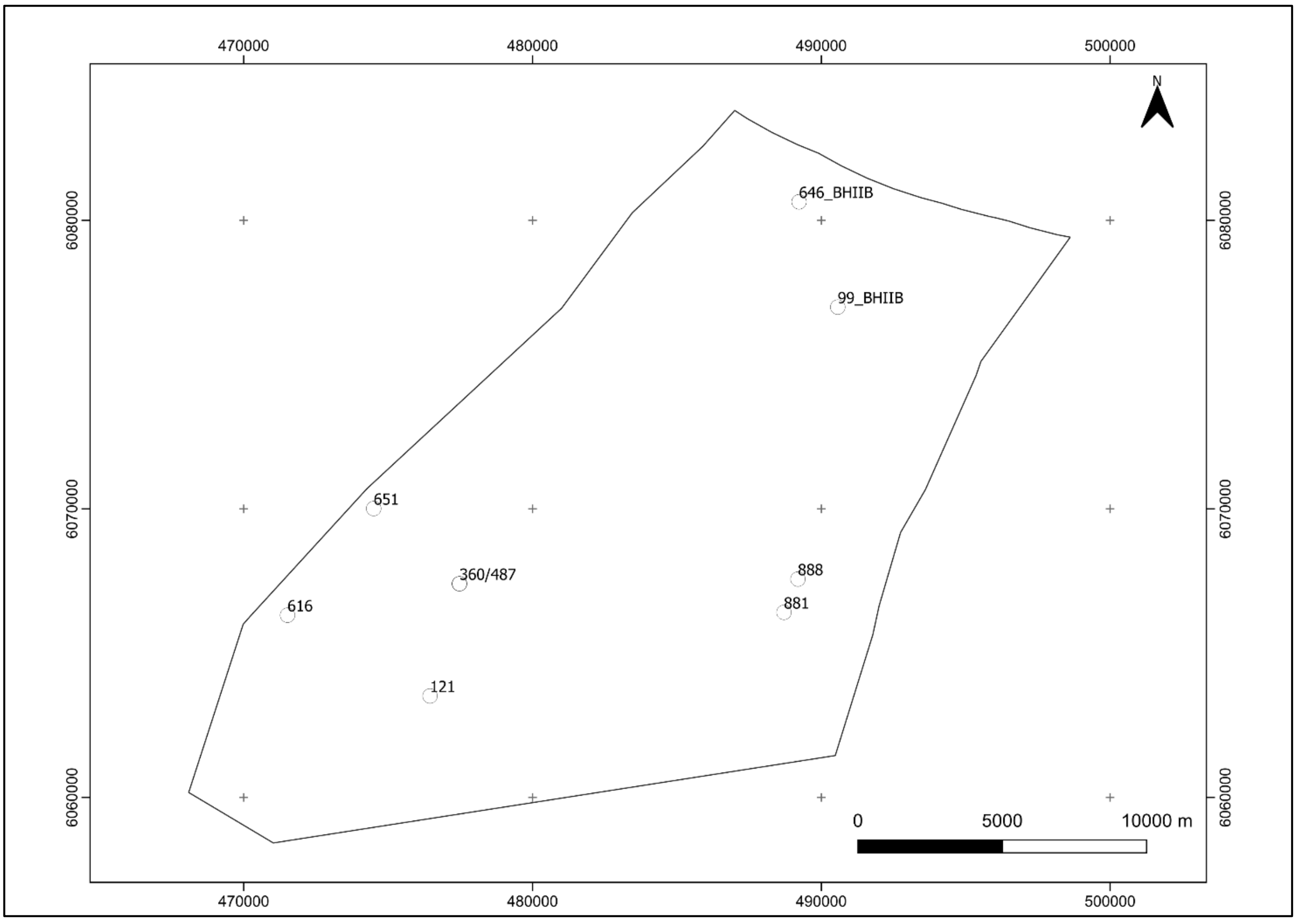
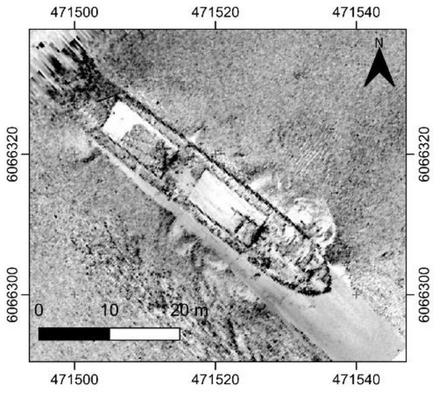
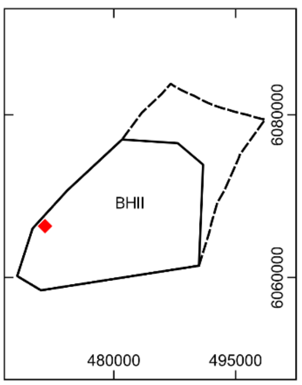
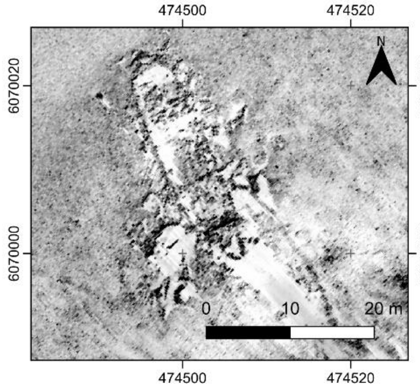
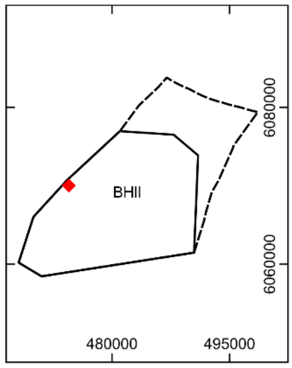
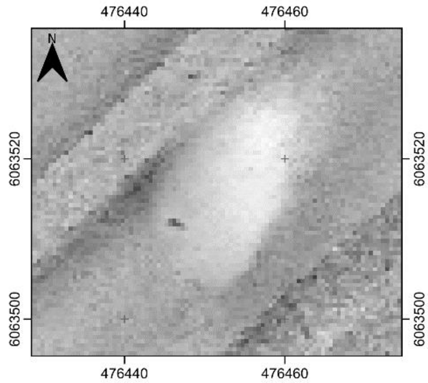
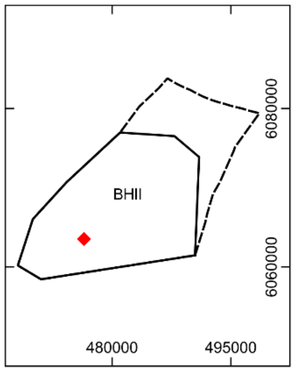
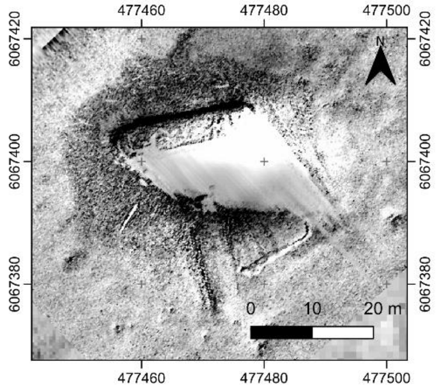
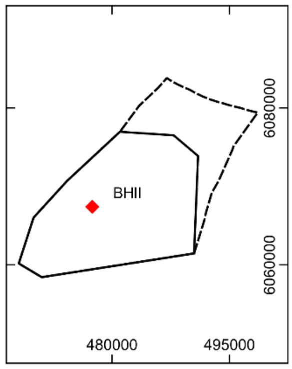
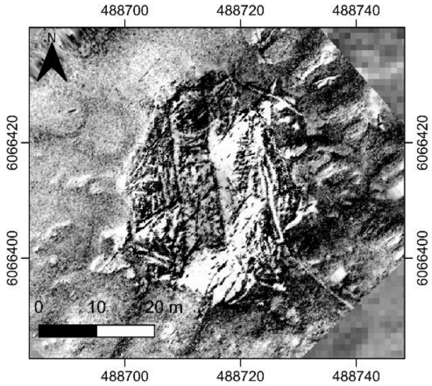
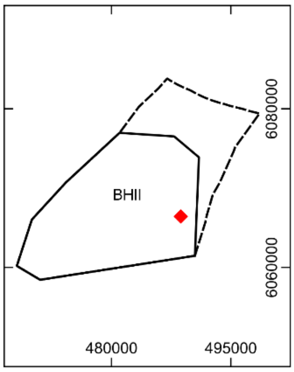
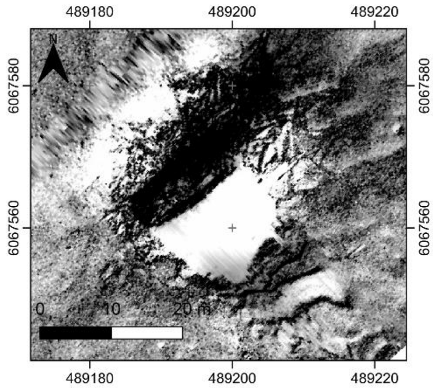
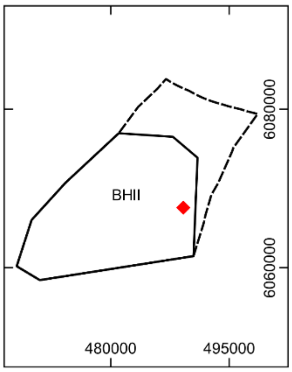
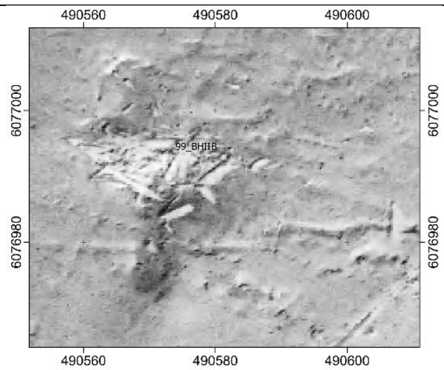
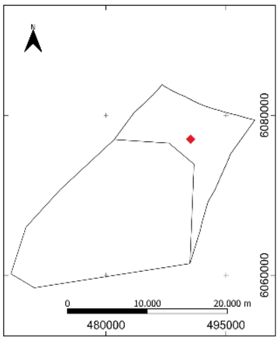
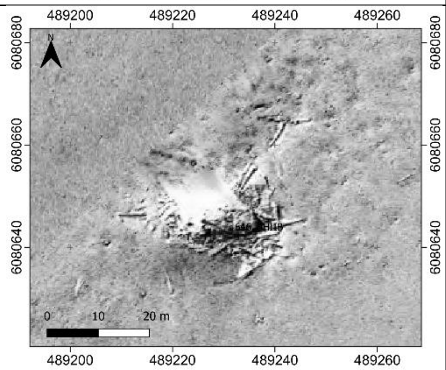
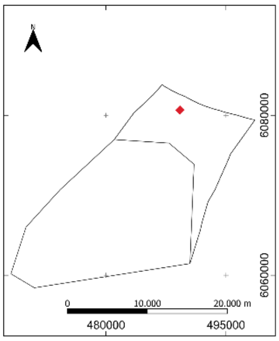


Figure 47: BHII wreck locations with MMO Target IDs

Table 24: Identified wrecks

MMO ID	Dimensions	Description	SSS image	Location
616	L: 55 m W: 9 m	Well preserved wreck with some debris items close by. SSS: BHII_SSS_6522 MAG: BHII_MAG_0439		

<table>
<tr><th>MMO ID</th><th>Dimensions</th><th>Description</th><th>SSS image</th><th>Location</th></tr>
<tr><td>651</td><td>L: 30 m
W: 8 m</td><td>Wreck with some debris objects close by.
SSS: BHII_SSS_6678
MAG: BHII_MAG_0600</td><td>
</td><td>
</td></tr>
<tr><td>121</td><td>L: 25
W: 16</td><td>Depression related with wreck.
SSS: BHII_SSS_479</td><td>
</td><td>
</td></tr>
<tr><td>360/487</td><td>L: 25 m
W: 7 m</td><td>Wreck with large debris area (45 m diameter area).
SSS: BHII_SSS_3091
BHII_SSS_4558
MAG: BHII_MAG_1091
BHII_MAG_1091</td><td>
</td><td>
</td></tr>
</table>

MMO ID	Dimensions	Description	SSS image	Location
881	L: 43 m W: 33 m	Possible wreck and debris area. SSS: BHII_SSS_8171		
888	L: 33 m W: 6 m	Wreck with large debris area (45 m diameter area). SSS: BHII_SSS_8178 MAG: BHII_MAG_0497		
99_BHIIB	L: 26 m W:18 m	Associated with known wreck SSS: BH2B_B2_5002		
646_BHIIB	L: 22 m W:13 m	Possible wreck and debris area. SSS: BH2B_B2_5002		

8.5.2 Cables, wires and ropes

Zero infrastructure or communication related cables were identified in the BHII site. There are 80 cables/ropes/wires identified from SSS interpretation. For 72 of the objects (e.g. MMO IDs 864 and 931), there was no discernible linear magnetic response, suggesting a non-ferrous construction, possibly a rope. Examples of the fishing equipment related origin cables are highlighted in Figure 48 and Figure 49. For 4 of the contacts, (MMO_LIN IDs 35, 36, 37, 71) there are associated with point mag targets, which are interpreted as possible non-ferrous ropes or wires with a ferrous object attached. For 3 of the contacts (MMO_LIN IDs 6, 12, 13 and 14) there is good alignment to associated linear magnetic responses, suggesting the existence of cables or cable fragments.

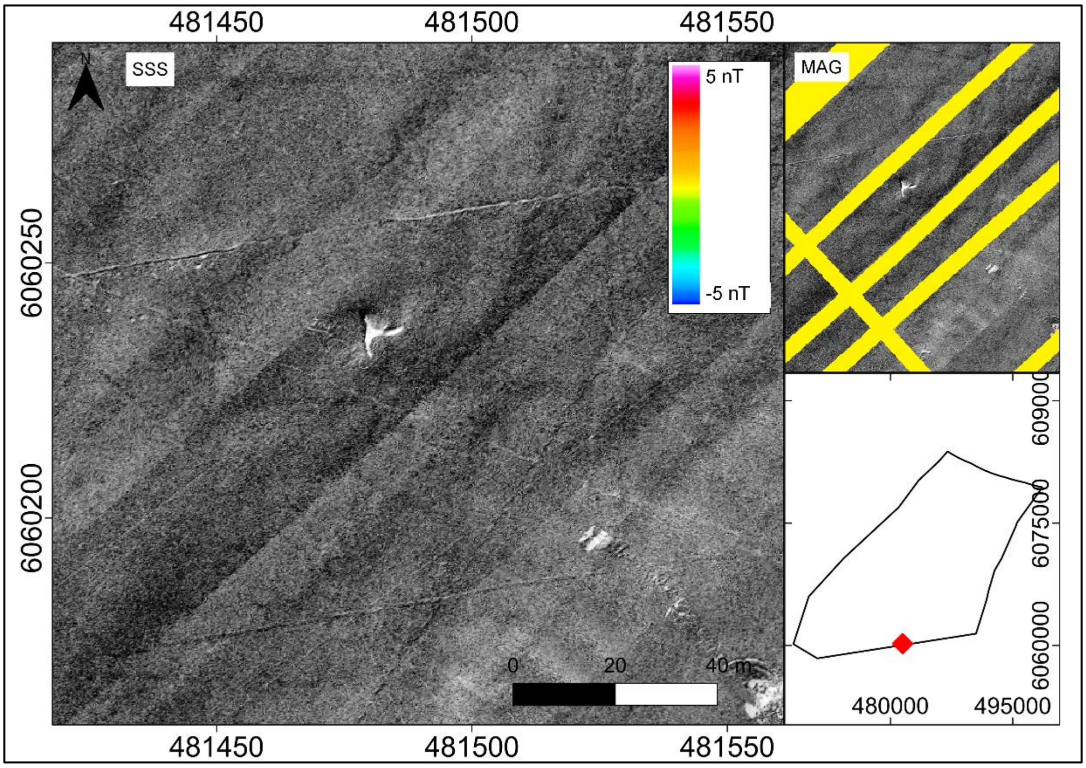


Figure 48: BHII fishing related equipment cable example (MMO 864)

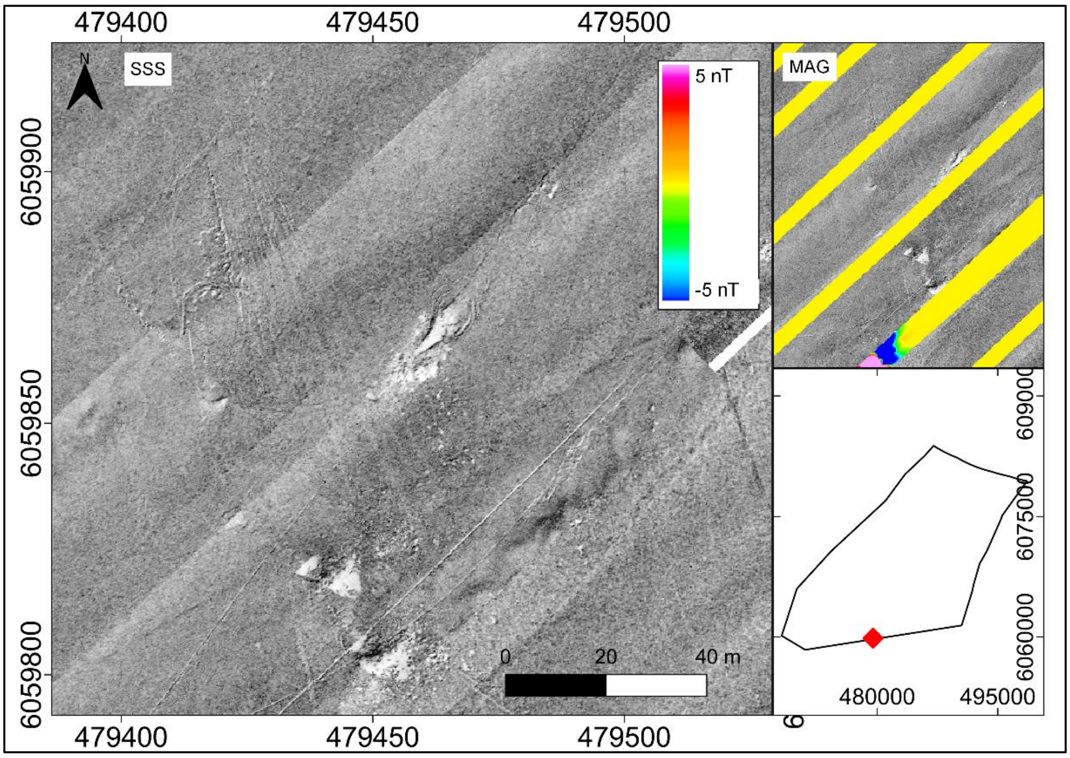


Figure 49: BHII fishing related equipment cable example (MMO 931)

8.5.3 Pipelines

The Baltic Pipe pipeline crosses the western and the northern section of the BHII site. The Nordstream I pipelines run through the centre of the Bornholm II survey area in a SW-NE direction. The Nordstream II (Denmark route) pipeline runs to the south of Bornholm II outside the survey area. Construction activities for Nordstream II are ongoing. The Nordstream pipelines that pass through the BHII site, as seen in the magnetometer dataset, are presented in Figure 50. No other pipelines were identified.

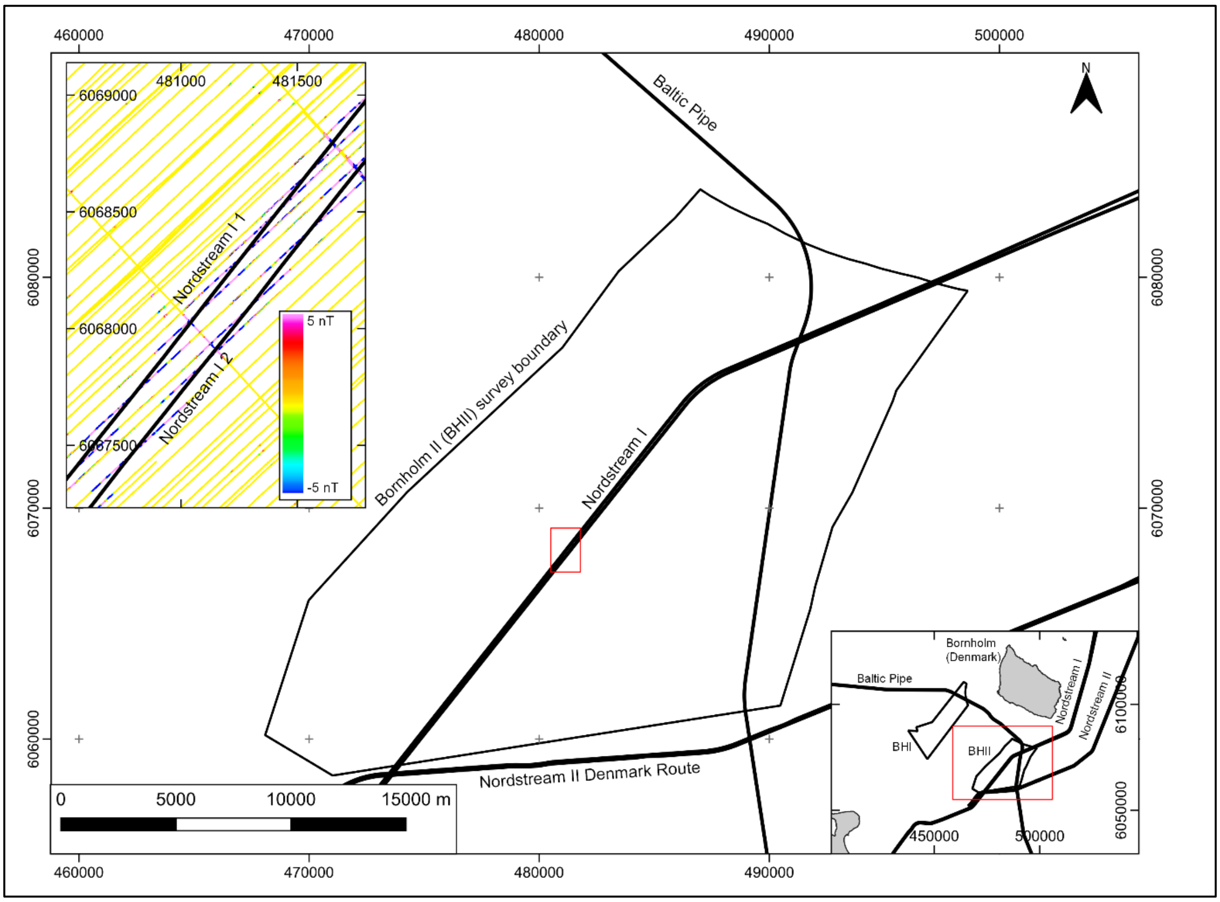


Figure 50: Baltic Pipe pipeline extent through the BHII site

8.5.4 Debris

There are 1313 debris objects in BHII site, identified from the interpretation of the MBES, SSS and magnetometer datasets. An example of a debris item as seen in SSS HF imagery (MMO 253, BHII_SSS_1636) is shown in Figure 51.

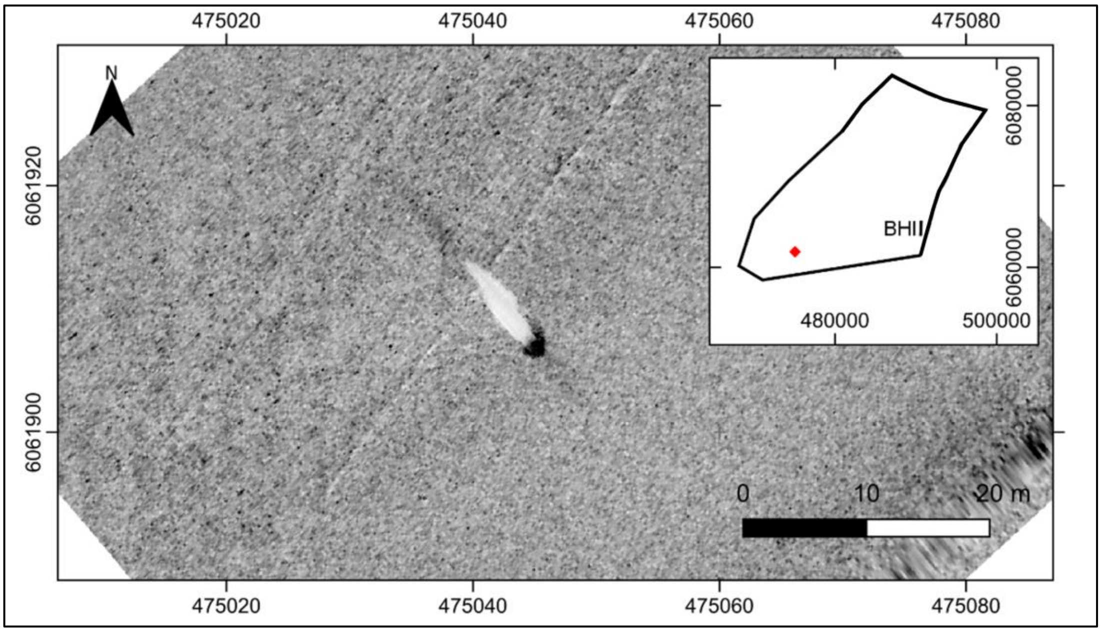


Figure 51: Debris object example as seen in SSS HF imagery (MMO 253, BHII_SSS_1636)

8.5.5 Items related to fishing activity

In BH2 site there are 147 items related to fishing activity. These are objects with a rope connected to a collection of other debris objects as shown in Figure 52 (MMO 824, BHII_SSS_8049). These objects are believed to be fish traps or other discarded fishing gear. There was no discernible magnetic response from these items.

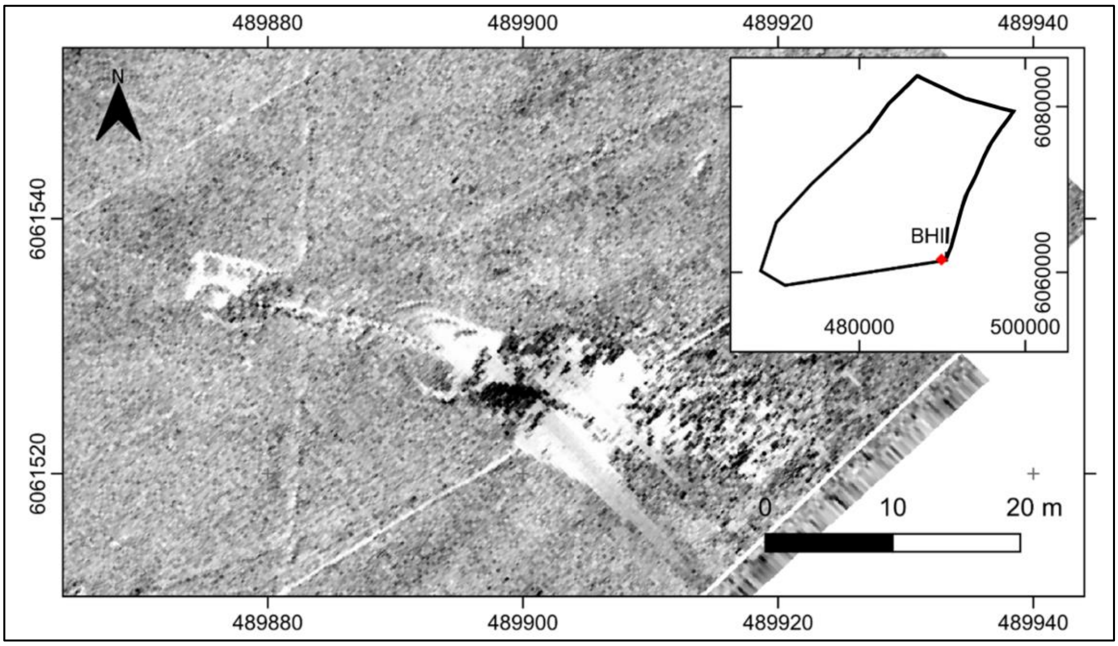


Figure 52: Fishing activity related item as seen in SSS HF imagery (MMO 824, BHII_SSS_8049)

8.5.6 Seabed disturbances

Seabed disturbances due to natural, human and unknown seabed interference were identified in the BHII site. These disturbances are outlined in Figure 53. Trawl scarred areas exist in the east of the BHII site with the majority of disturbed seabed being related to the construction of the Nordstream pipelines in the centre of the BHII site and to the south. Figure 54 is an example of disturbed sediment relating to the construction of the Nordstream pipelines as seen in SSS HF dataset.

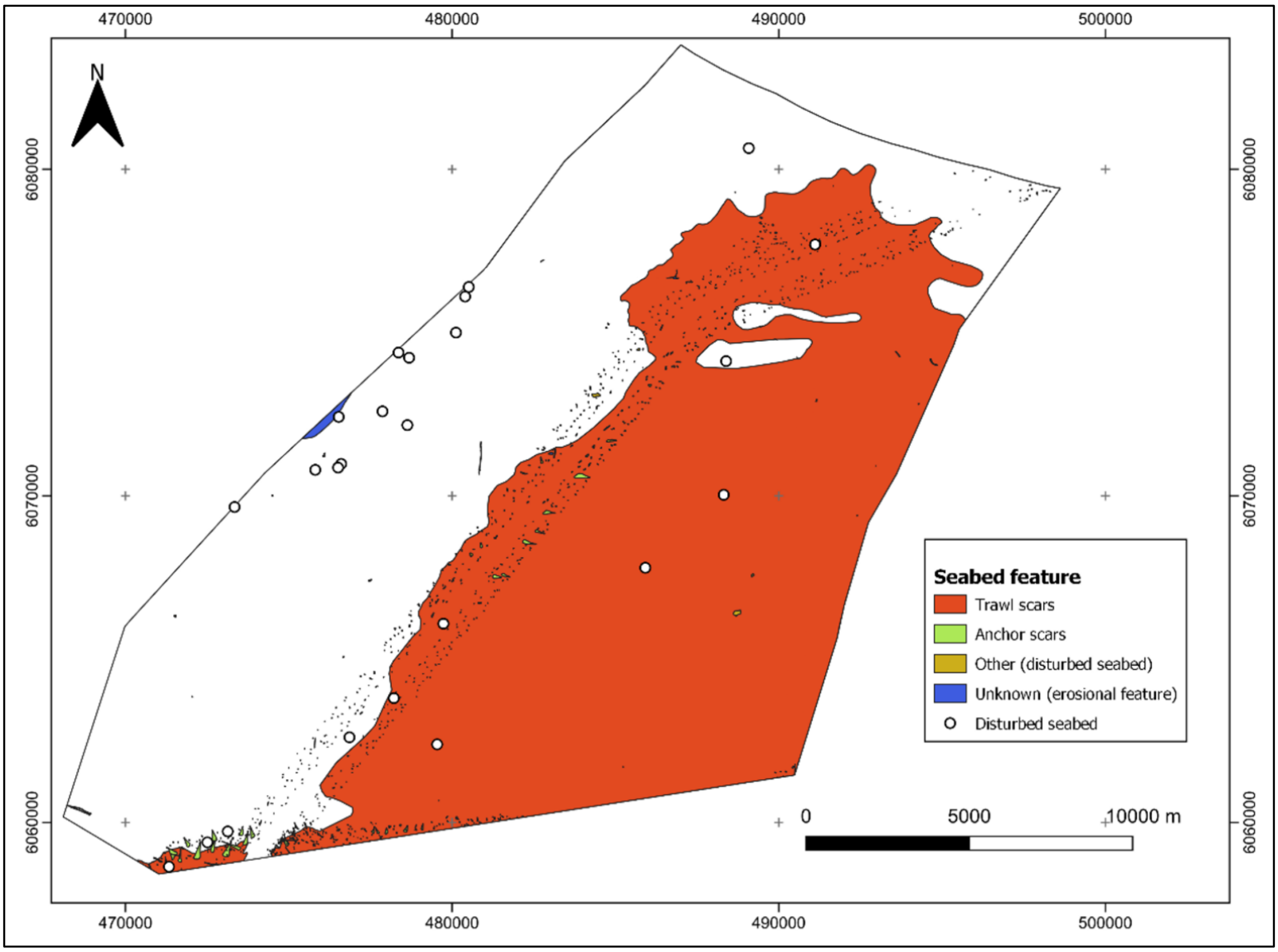


Figure 53: BHII Seabed disturbances

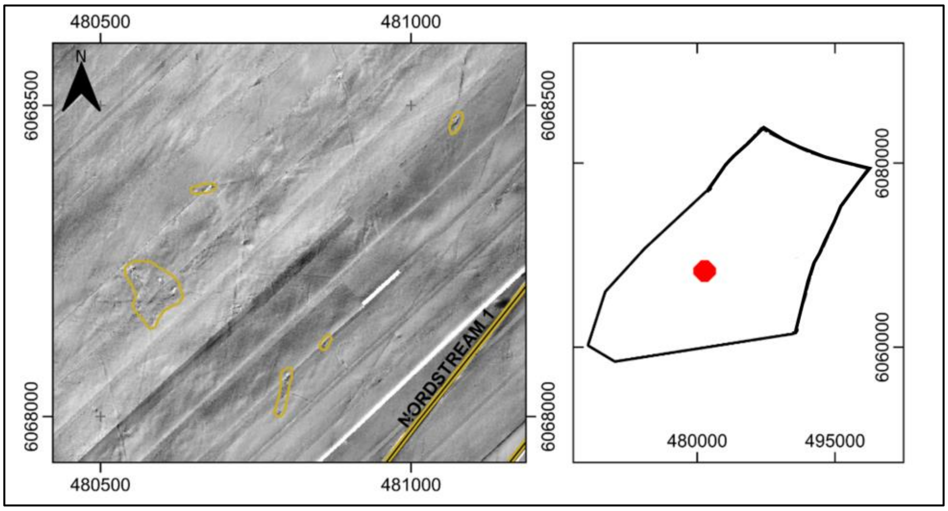


Figure 54: BHII Seabed disturbances related the construction of the Nordstream pipelines (SSS HF)

8.6 SEABED SURFACE CLASSIFICATION: SUBSTRATE TYPE

The seabed substrate for BHII and BHII B was evaluated from interpretation of the low frequency SSS data and backscatter imagery. The resultant seabed surface substrate interpretation is highlighted in Figure 55. Western and southern areas of the BHII site are predominately sand, whereas the eastern part is characterised by clay areas to the east and gravel and larger stone areas to the north.

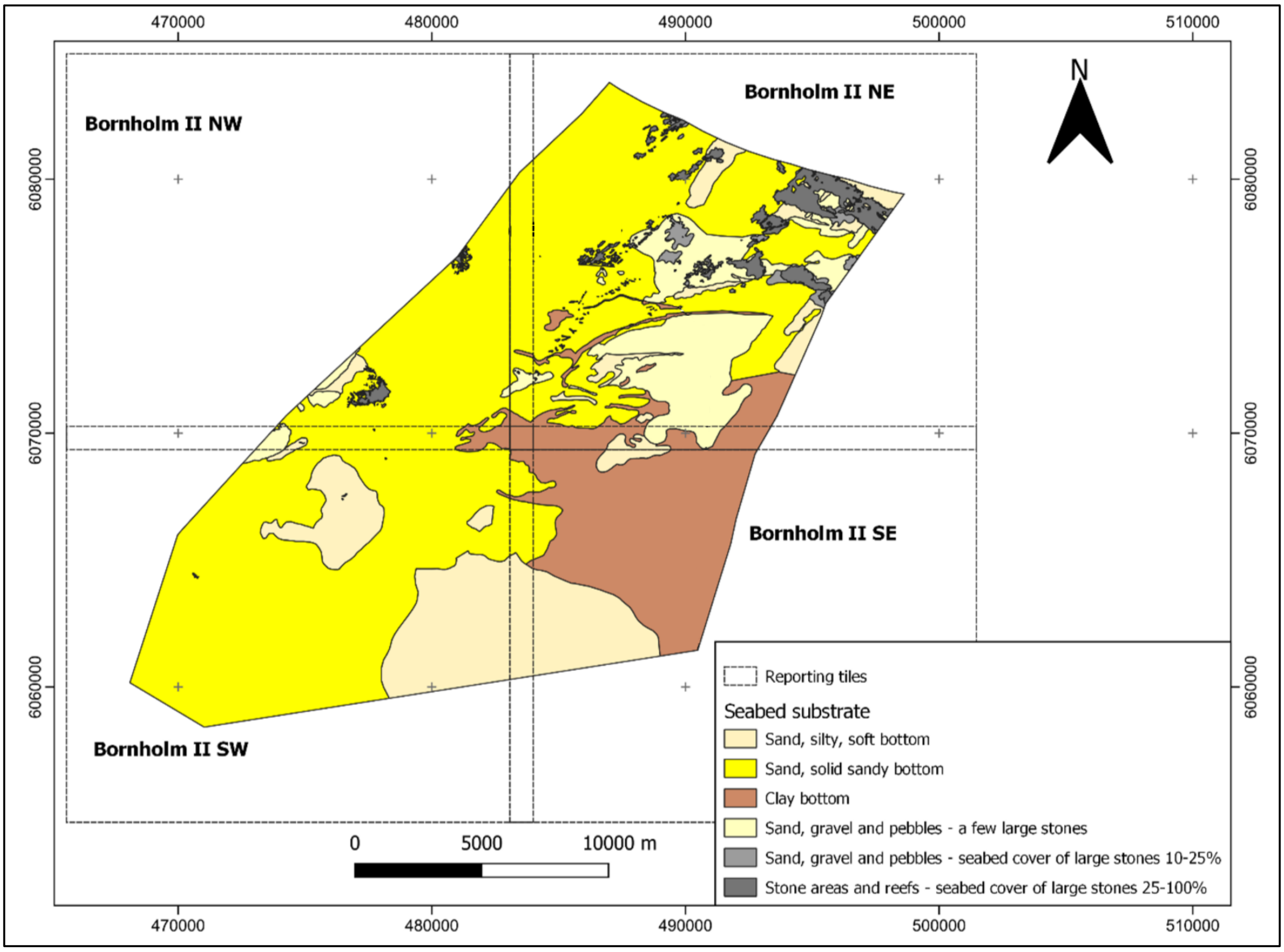
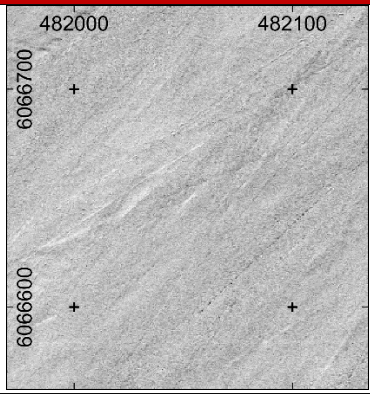
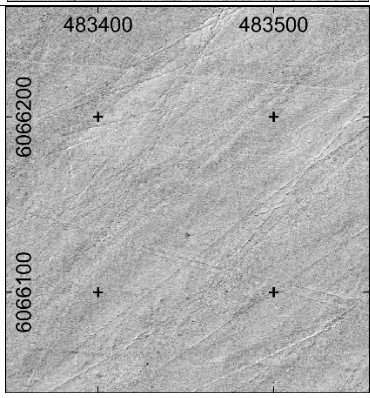
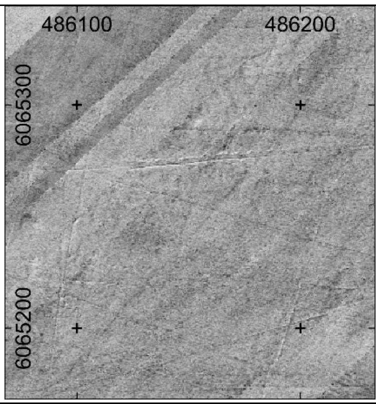
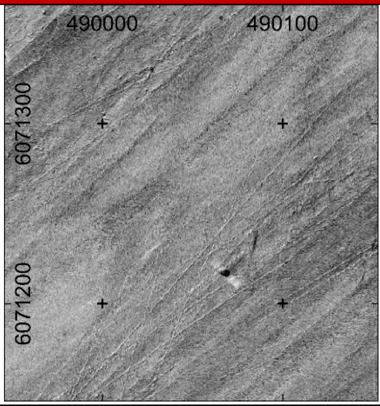
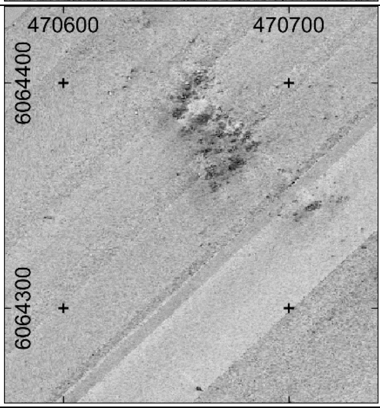
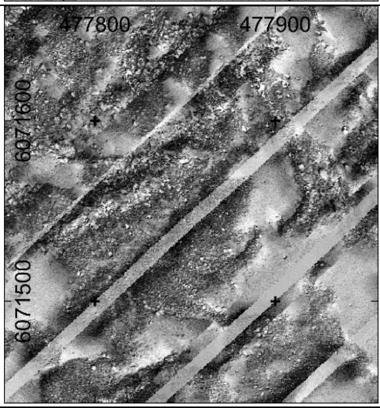


Figure 55: BHII Substrate classification

Examples of substrate classification from the SSS dataset are described in Table 25.

Table 25: Substrate interpretation from SSS data

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

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 BHII northeast (Bornholm 2 NE)

Sand is predominant in the Bornholm 2 NE region (Figure 56). Extended areas of sand and gravel occur at the central and southern parts, whereas silty sand exists in limited zones in the north and east of Bornholm 2 NE. Sand with gravel and pebbles as well as stone areas with increased percentage of large stones exist in the central, northern and mainly north-eastern extent of the region. The southern part is interspersed with clay areas, some of which are likely related to disturbed seabed from the construction of the Nordstream pipelines.

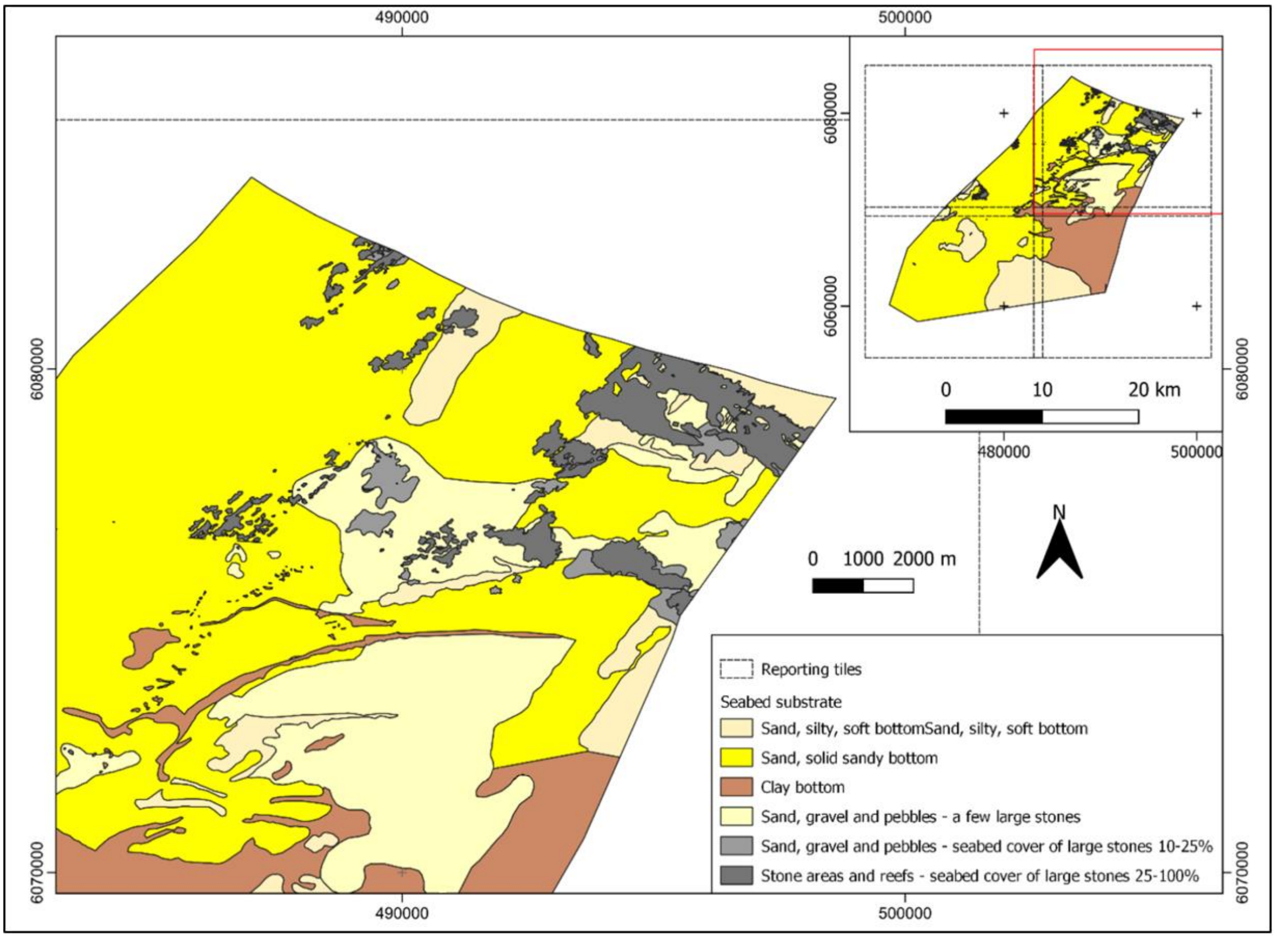


Figure 56: BHII Substrate classification (Bornholm 2 NE)

8.6.2 Seabed surface classification: Substrate BHII southeast (Bornholm 2 SE)

The south-eastern part of Bornholm 2 SE region was found to be a predominately clay bottom in central and eastern areas, with sand to the north-west, sandy gravel to the north-east and sand and silty soft bottom in the southwestern part (Figure 57).

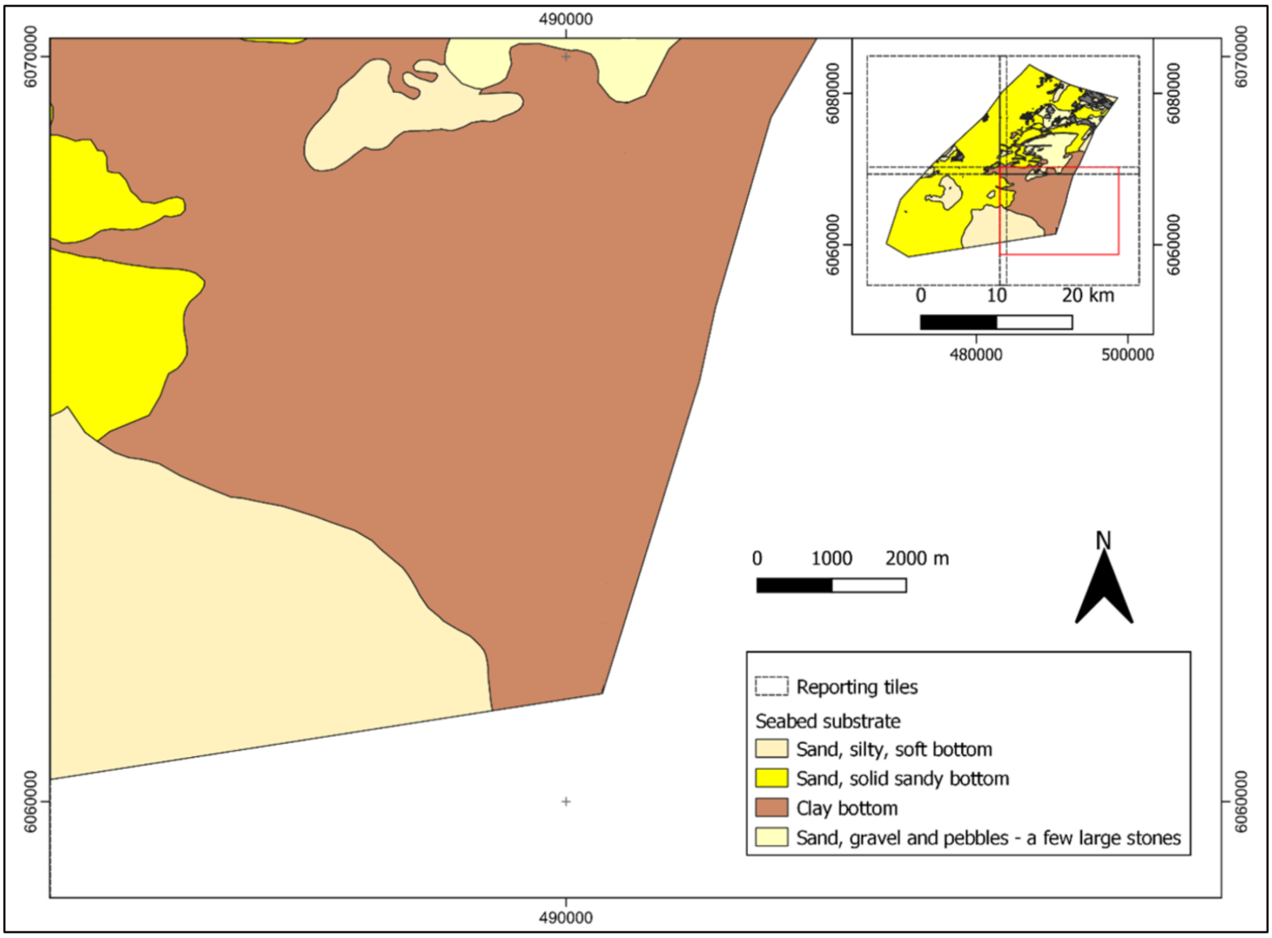


Figure 57: BHII Substrate classification (Bornholm 2 SE)

8.6.3 Seabed surface classification: Substrate BHII southwest (Bornholm 2 SW)

Sand is predominant in Bornholm 2 SW region (Figure 58). Areas of sand and silty bottom occur in the central and south-eastern part of the area whereas clay is outlined to the north-east (Figure 58).

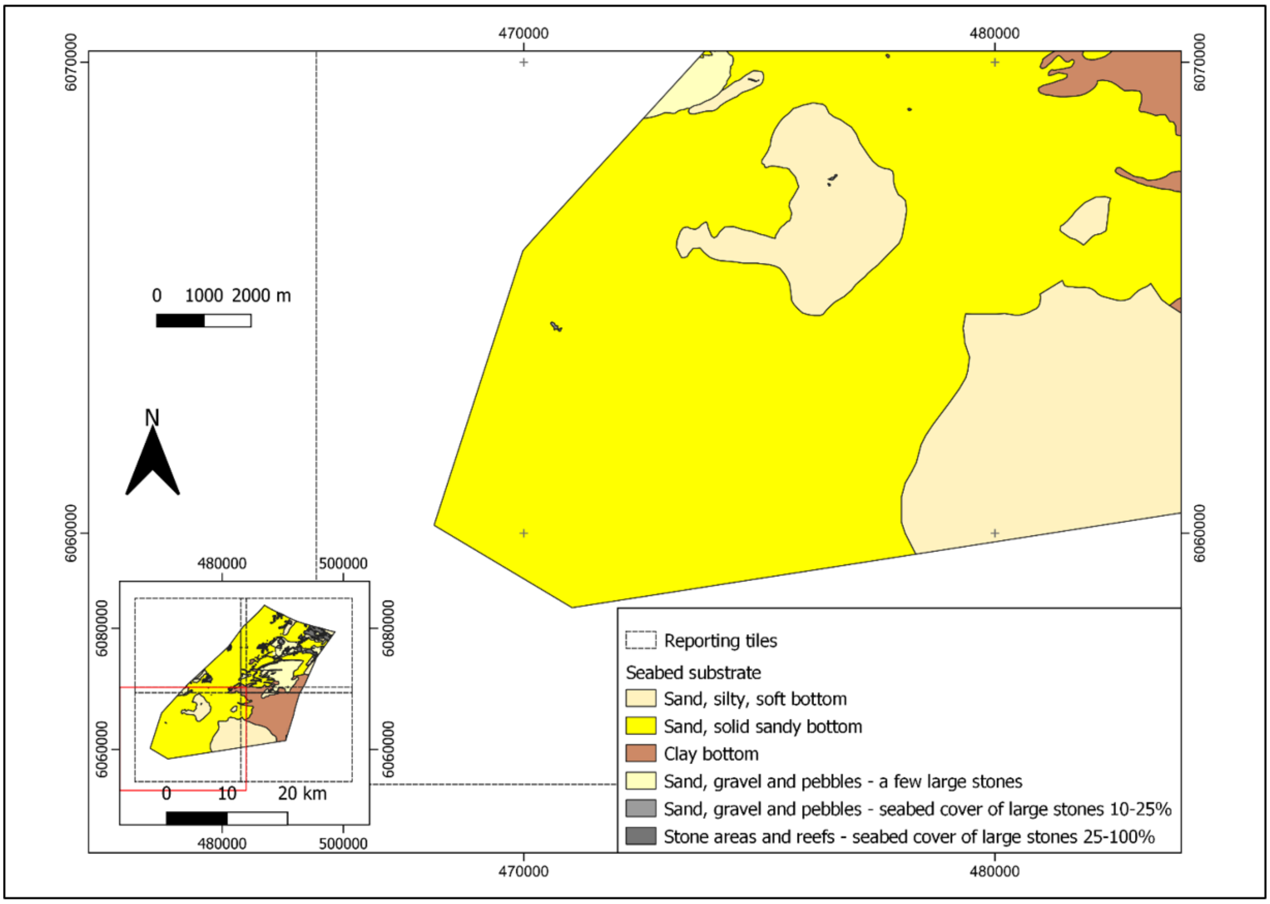


Figure 58: BHII Substrate classification (Bornholm 2 SW)

8.6.4 Seabed surface classification: Substrate BHII northwest (Bornholm 2 NW)

The Bornholm 2 NW region is dominated by sand (Figure 59). Silty sand occurs in large areas over the south-east and north-west and clay bottom is restricted to the north-east. Seabed is covered with large stones in two limited areas, one in the central and one in the northern part of the area.

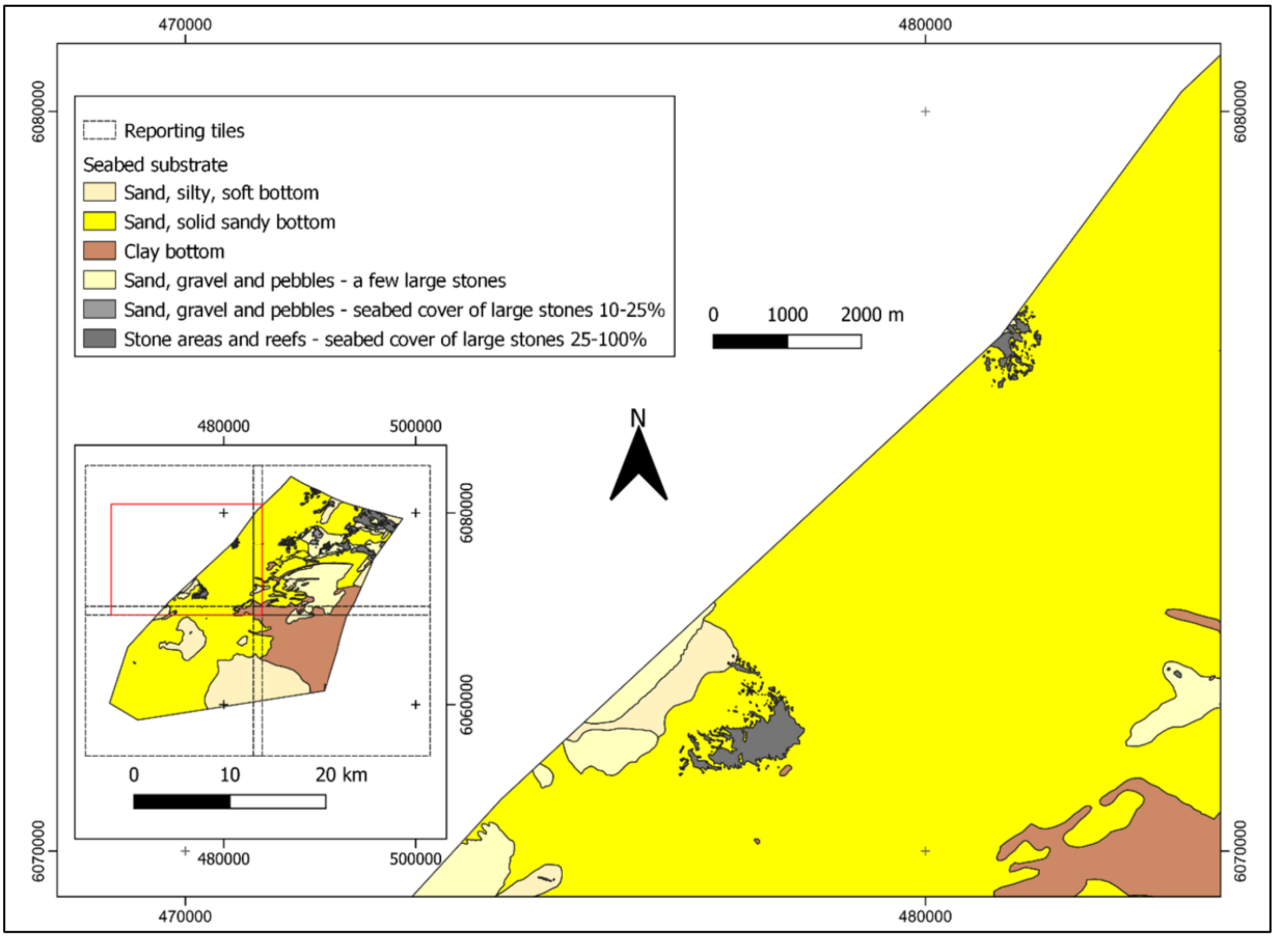


Figure 59: BHII Substrate classification (Bornholm 2 NW)

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. 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.

The seabed gently dips to the south-east. The distribution and thickness patterns of the post glacial units follow this trend with the youngest sediments being thickest in the deep water, south-eastern, part of the area.

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 desk study. This will allow for consistency in nomenclature between this survey report and the desk study.

9.2 SOIL UNIT INTERPRETATION

9.2.1 Shallow Geological Overview

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. This desk study applies a stratigraphic model developed by Jensen et al (2017) in conjunction with archive seismic data and limited ground truth information. There is generally a very good correspondence between the shallow geology imaged in this project's sub-seabed data and the desk study. This project's unit names are aligned with those in the desk study (for example Unit III in this report is the same as Unit III within the desk study) this means that it will be easier for future workers to use these survey reports and the desk study together.

In overview, the area has a glacial to post-glacial sequence of relatively recent sediments over much older carbonate and clastic bedrock. The recent sediments are generally 10 m – 20 m thick, although in some areas these recent sediments are interpreted to be much thicker. The seabed gently dips to the south-east. The distribution and thickness patterns of the post glacial units follow this trend with the youngest sediments being thickest in the deep water, south-eastern, part of the area.

9.2.2 Stratigraphy and general arrangement of units

Figure 60 shows the arrangement of units within Bornholm II.

Table 26 shows the basic characteristics of the stratigraphic units.

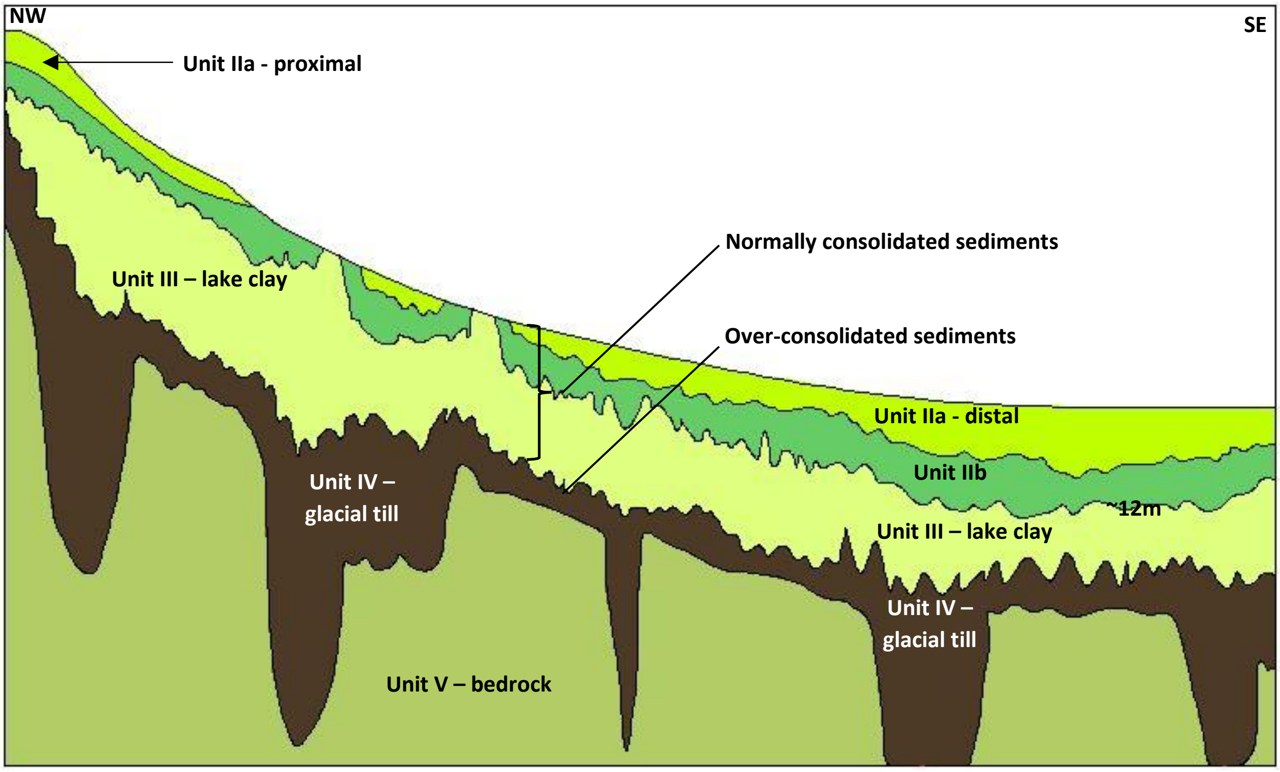


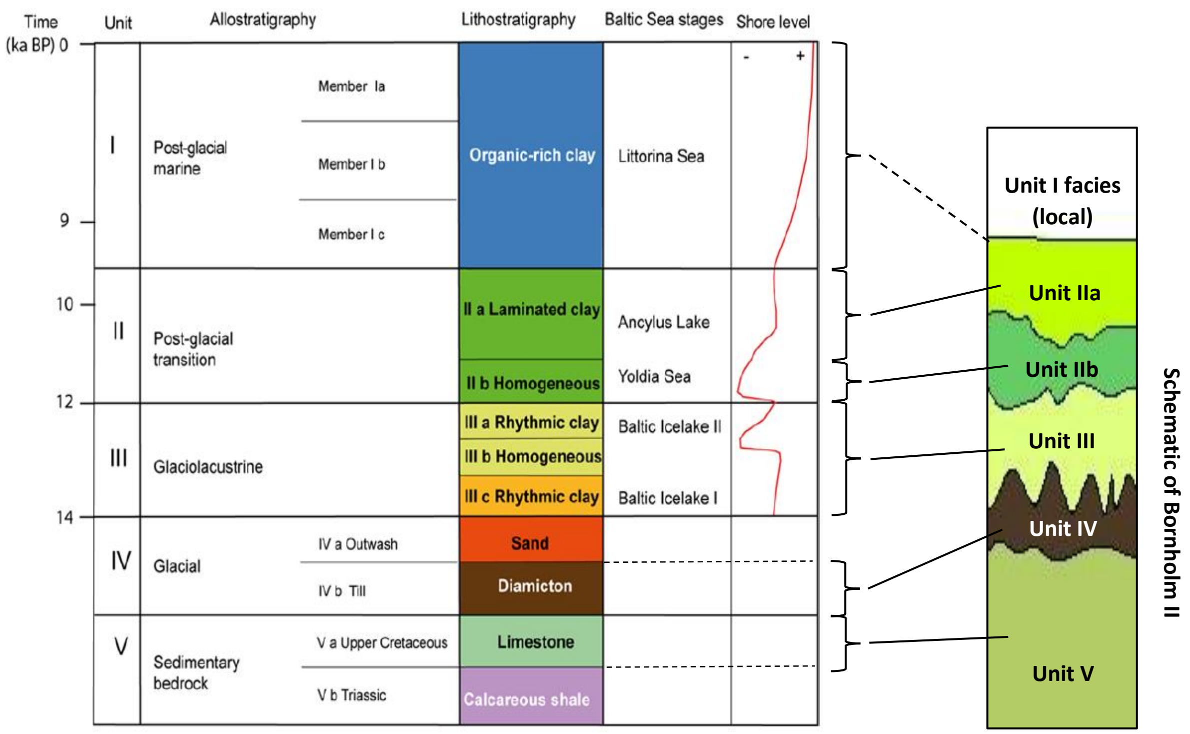
Figure 60: Geological Schematic, general arrangement of units

Table 26: Shallow Geological Units

Unit	Upper surface	Lower surface	Main Soil Description	Depositional Environment
I	Seabed	NA. May exist as lateral facies change in extreme SE of area	Organic-rich CLAY	Post-glacial marine
IIa	Seabed	H10	Laminated CLAY, increased silt/sand fraction in proximal areas	Post-glacial, Ancylus Lake
IIb	Seabed/H10	H20	CLAY, laminated towards top	Post-glacial, Yoldia Sea
III	Seabed/H10/H20	H35/H50	CLAY, locally silty	Post-glacial estuarine/lacustrine (Holocene)
IV	H35	H50	CLAY prone diamicton	Ice contact till (upper parts)
V	H50	Not imaged >70m BSB	LIMESTONE/Clastics	Ancient shallow marine/marine

Figure 61 illustrates the stratigraphic model from Jensen et al. (2017) and the correlation of the stratigraphic model to the BHII project. 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 61: Stratigraphic model (Jensen et al, 2017) with correlation to Bornholm II



9.2.3 Quaternary Deglaciation History

Table 27 uses information derived from the desk study to link the stratigraphic units to the changing paleoenvironments.

Table 27: 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. This unit may not be present in Bornholm II or may exist in the deepest water of the area as a lateral facies variation of seismostratigraphic Unit IIa

9.2.4 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 28).

Table 28: 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

9.2.5 Unit I facies

On a regional basis Unit I is a thin package of organic-rich post-glacial marine CLAY. The desk study indicates that it is thin or absent within the Bornholm II area. Profiler data indicate that Unit I is not present as a distinct seismostratigraphic package. However, Unit IIa does show a near seabed lateral facies transition to a lower amplitude acoustic character. In the most distal south-eastern parts of the area the seabed reflection displays a very low amplitude and acoustic transparency immediately below seabed (Figure 62). These characteristics are similar to those of Unit I in Bornholm I where Unit I is more clearly defined. The Unit I type facies occurs in water depths greater than ~45 m. Some settlement of seabed equipment was reported from this area during geotechnical acquisition.

Unit 1 facies are interpreted to be thin, probably less than 1 m thick, perhaps reaching a thickness of 2 m in easternmost parts of the area.

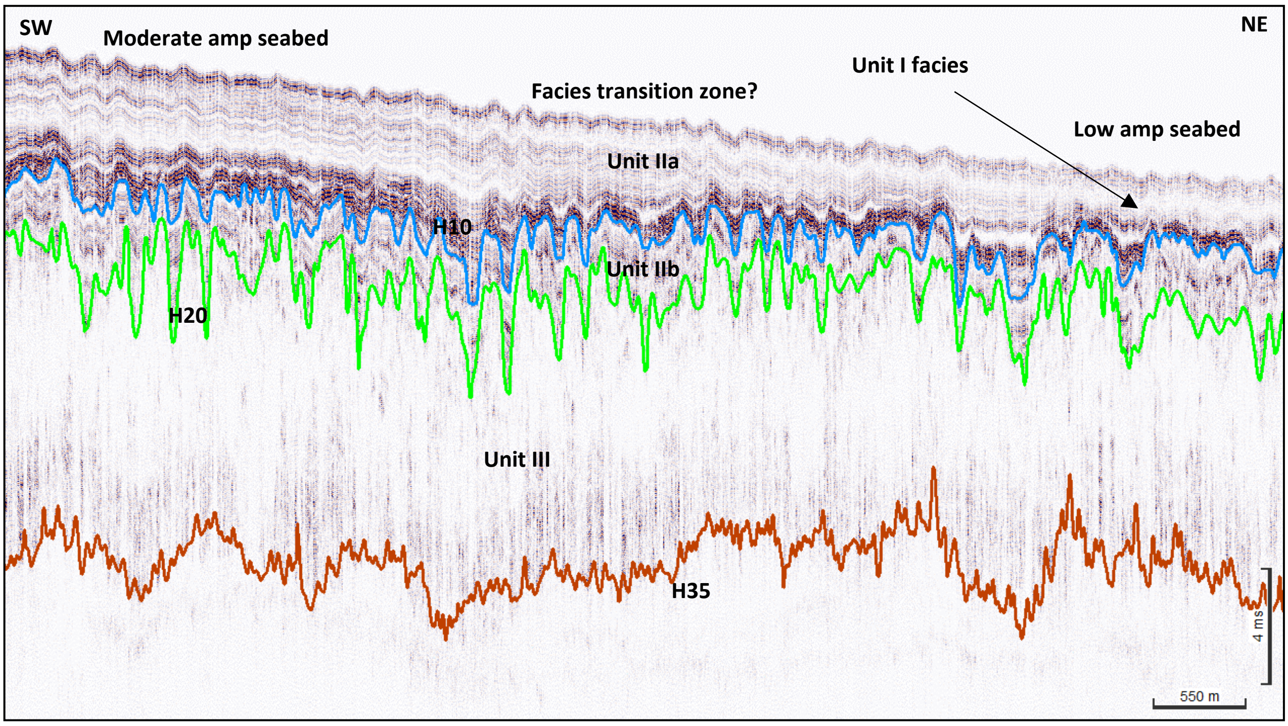


Figure 62: SBP data example, line P_052, Unit I facies, lower slope

Where it is thick enough for such features to be resolved, the facies shows seismic evidence of internal laminations. 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 II – the unit appears to be a passive drape.

Unit I facies has seismic characteristics which indicate that it is extremely soft/weak. Where Unit I facies occurs the seabed is of very low reflection amplitude.

From these seismic indications Unit I facies have 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 of Unit I was taken during geophysical acquisition in Bornholm I. This confirmed that these sediments are extremely soft/weak CLAY.

9.2.6 Unit IIa

This laminated clay was deposited in the Ancylus Lake. As a post-glacial deposit it will be normally consolidated.

The interval generally thickens (to a maximum thickness of 5 m) to the south-east with increasing water depth though there is also a bias toward the west – mid-slope mainlines show that Unit IIa is thicker and more widely distributed in the west than the east. The unit shows good acoustic evidence of internal bedding (Figure 63). The lowermost parts of the interval nullify relief at the basal surface and generally have a high reflection amplitude. Middle and upper parts of Unit IIa show smooth, continuous internal reflections which are more similar in form to the seabed than the unit's base. The upper part of this seismostratigraphic interval is interpreted to have Unit I type characteristics in water depths beyond ~45 m, this is described in the proceeding section.

Unit IIa is widely distributed over the middle and lower slope parts of Bornholm II, generally pinching out on the middle to upper slope (Figure 64). Around the up-dip edge of its distribution Unit IIa becomes patchy, infilling relative lows.

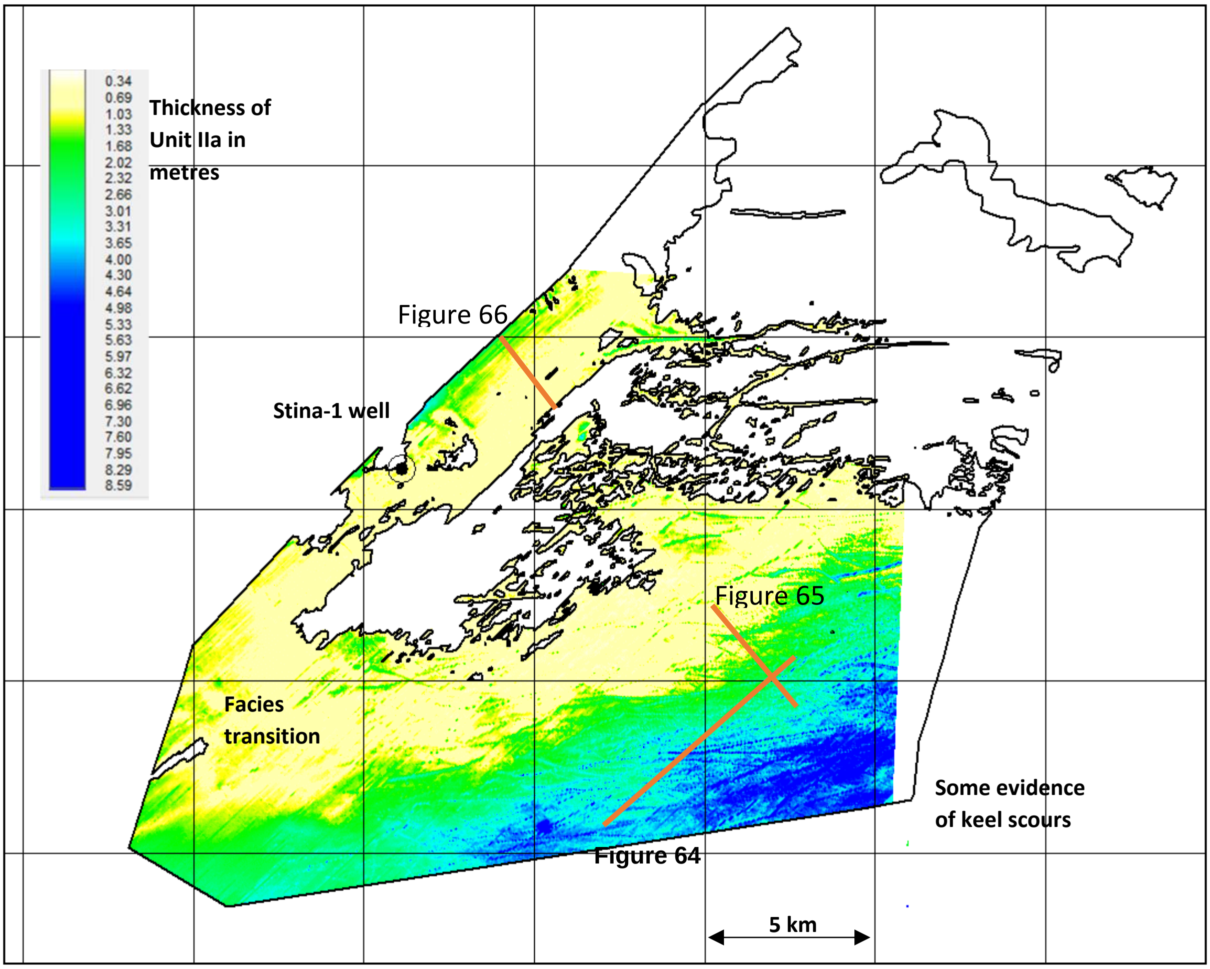


Figure 63: Thickness and distribution of Unit IIa

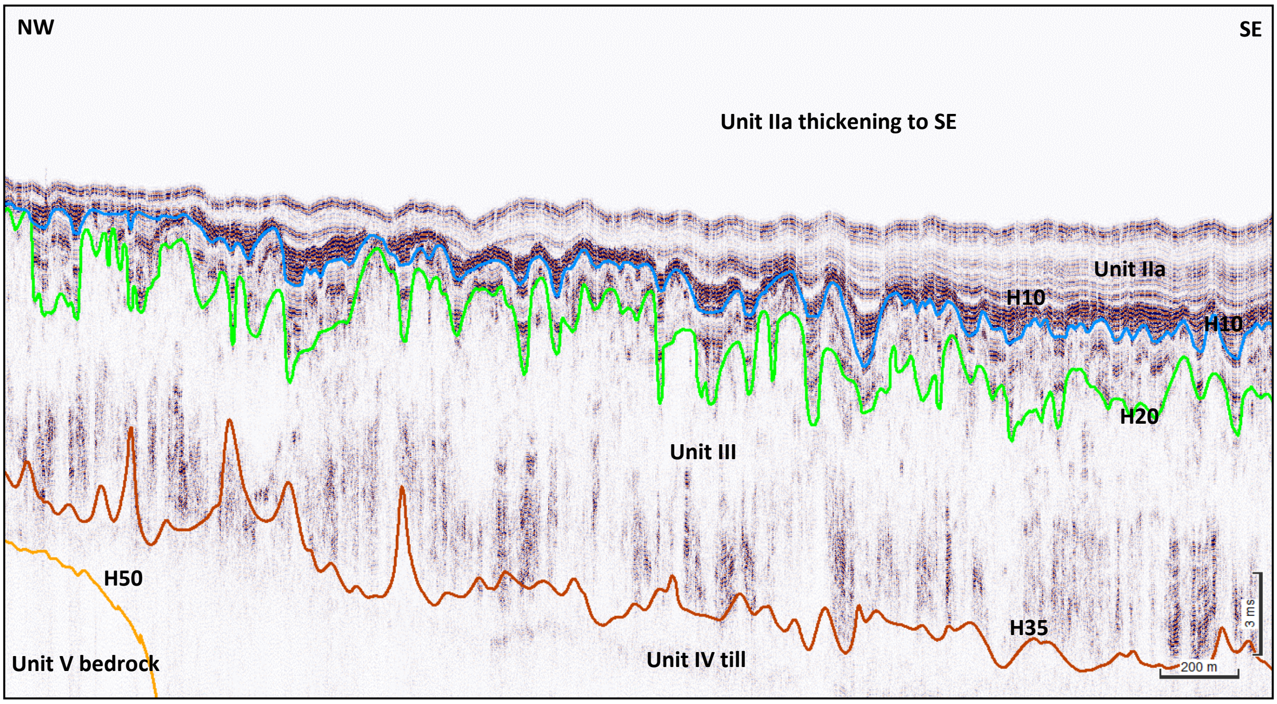


Figure 64: SBP data example, line X_018, Unit IIa distal facies, middle-lower slope

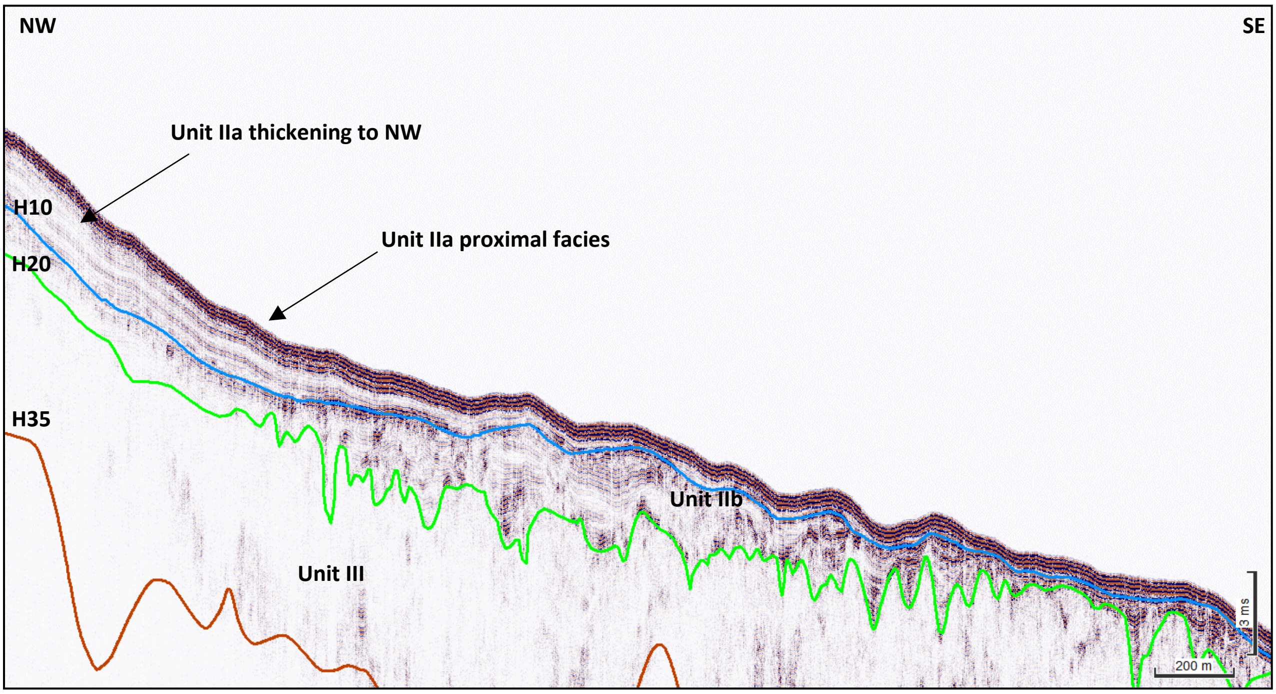


Figure 65: SBP data example, line X_018, Unit IIa proximal facies, upper slope

Unit IIa has also been mapped in proximal areas, along the north-western edge of the area (Figure 65). This should be considered a distinct, approximately age equivalent, proximal facies which was probably sourced from the north-west of the area and is likely to be sandier than the deeper water, typical, lake facies. This proximal facies is considered broadly equivalent to Bornholm I's Unit II mounded facies.

In the extreme East of the area, there is another proximally sourced package of Unit IIa sediment. This package has a sigmoidal geometry and forms the youngest, western side of a sedimentary high. The package is approximately 6 km long and 1.2 km wide (Figure 66).

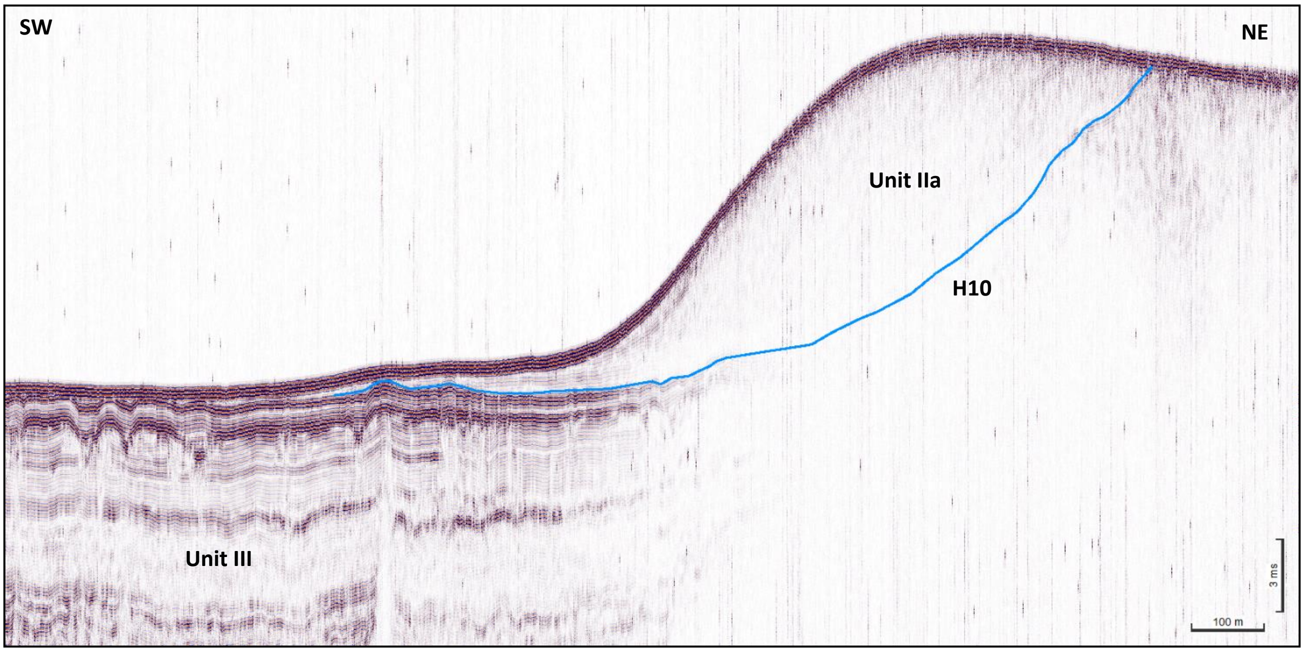


Figure 66: SBP data example, line B_ P_039, Unit IIa proximal facies, extreme east of area

Unit IIa is at or close to outcrop over its entire distribution.

9.2.7 Unit IIb

This clay was deposited in the Yoldia Sea.

The unit is widely distributed within Bornholm II, pinching out along parts of the north-west edge of the area and becomes patchy over eastern parts of the area. The pinch out along the north-western margin has an irregular pattern, the pinch out is up to 5 km from the edge of the area whereas in other places the unit extends to the survey limit (Figure 68). Unit IIb deposits are at or close to outcrop where they exist beyond the distribution of Unit IIa.

Unit IIb has a more irregular internal appearance than Unit IIa (Figure 67). In general, the internal reflectors mimic the significant relief at the basal surface, the top of Unit III. The interface of Units IIb and III can be indistinct in places as both units are locally acoustically transparent. The irregularity of the basal surface means that the thickness of Unit IIb varies by up to 2 m - 3 m over very short distances. This irregularity is aliased in plan view, even by this survey's closely spaced lines. This means that there is limited confidence in the exact thickness of this unit in areas between survey lines. This is in contrast to intervals with smooth bases where maps are likely to show true thickness even between lines (Figure 69).

The unit is interpreted to comprise normally consolidated CLAY, possibly with iron sulphide-rich laminations in upper parts.

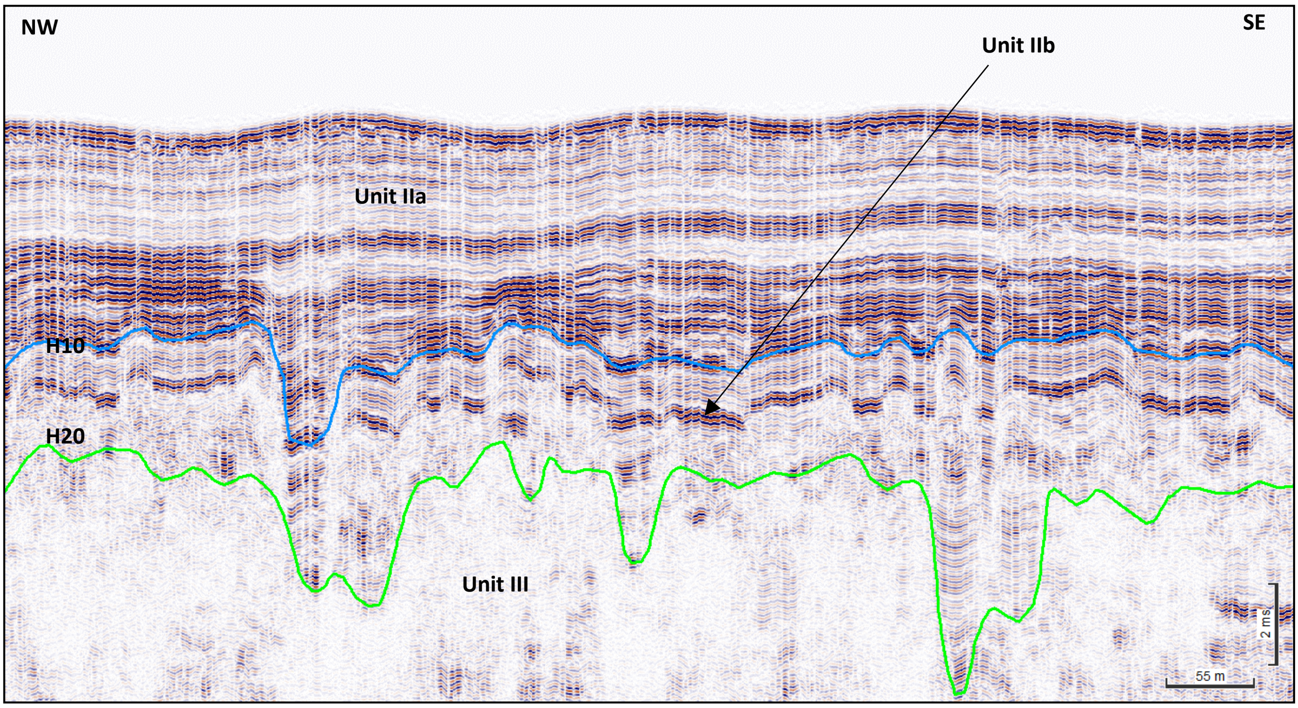


Figure 67: SBP data example, line X_015, Unit IIb, lower slope

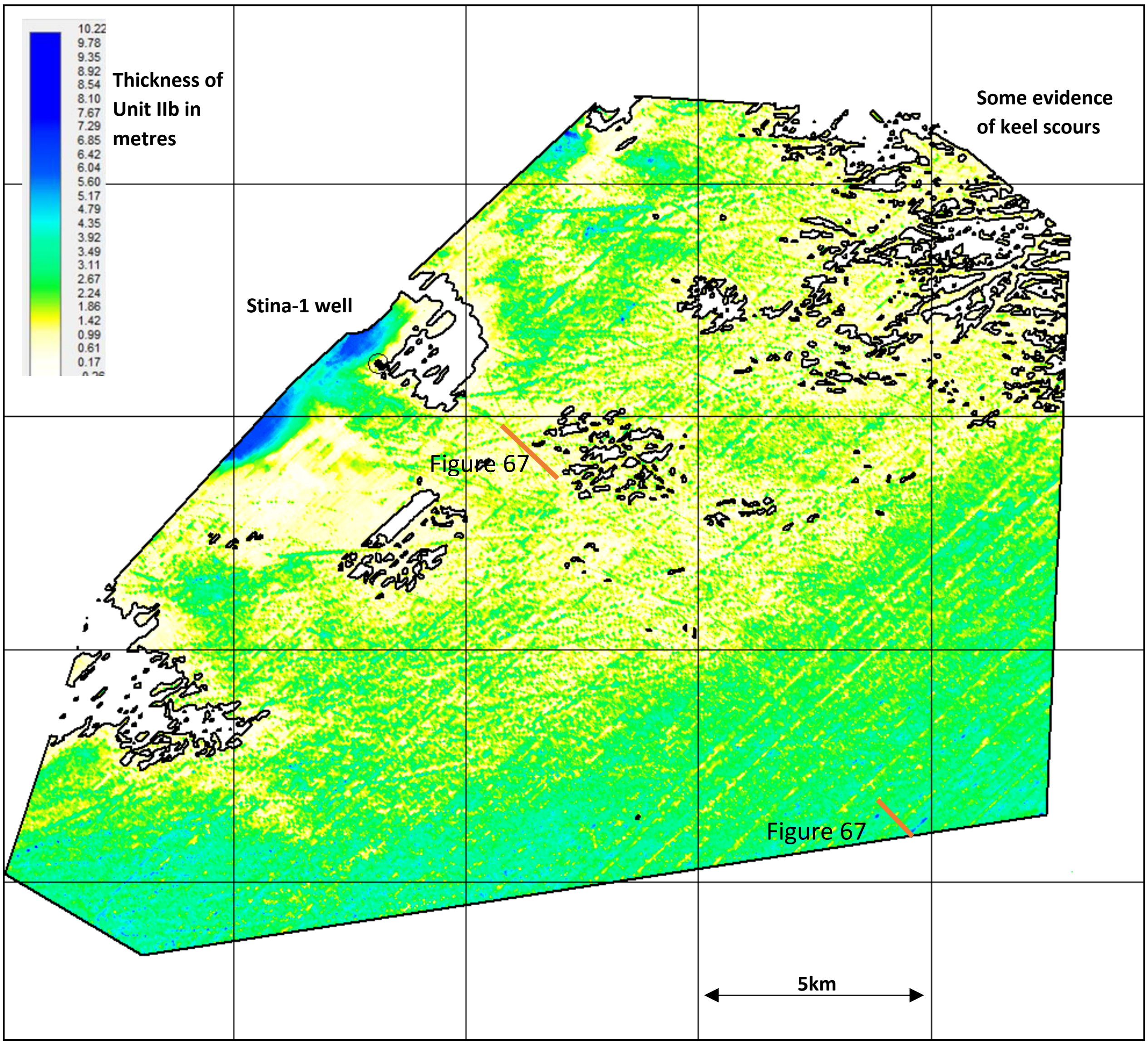


Figure 68: Thickness and distribution of Unit IIb

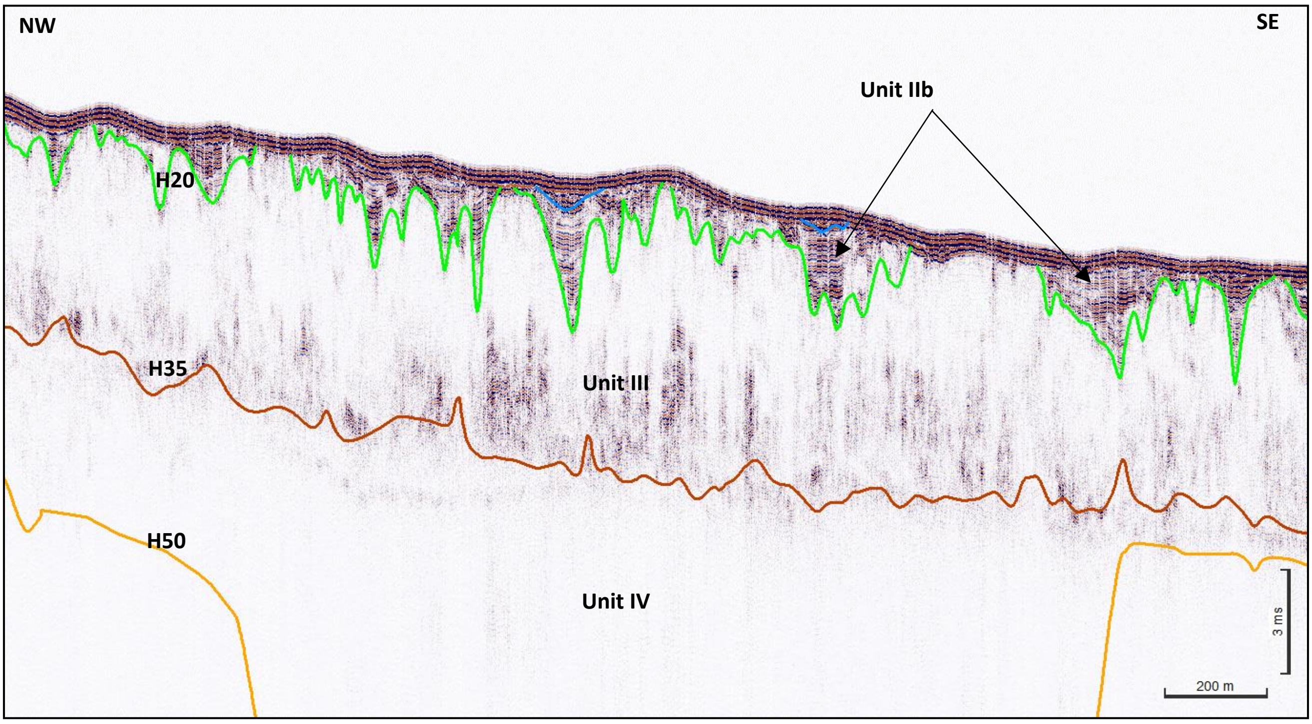


Figure 69: SBP data example, line X_015, Unit IIb, middle to upper slope

9.2.8 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 ~6-8 m thick within Bornholm II and extends over most of the area, pinching out against the top of the Unit IV till or locally bedrock, along the north-west margin of the site (Figure 70). In detail, there is significant thickness variation of this unit over short distances as the top of the underlying till is very irregular and forms steep sided ridges and gullies.

Jensen et al.'s 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 71). 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. Further complication may be related to the reworking effect of flooding events during and after Unit III times. Over limited areas it may be possible to sub divide Unit III though it is probably not possible to make meaningful continuous maps of these sub units.

The entire interval is clay-prone, though the upper part of the interval may be silty. As post-glacial deposits these sediments will be normally consolidated.

The irregularity of the bounding surfaces means that the thickness of Unit III varies by up to 2-3m over very short distances. This irregularity is aliased in plan view, even by this survey's closely spaced lines. This means that there is limited confidence in the exact thickness of this unit in areas between survey lines (this is in contrast to intervals with smooth bases where maps are likely to show true thickness even between lines).

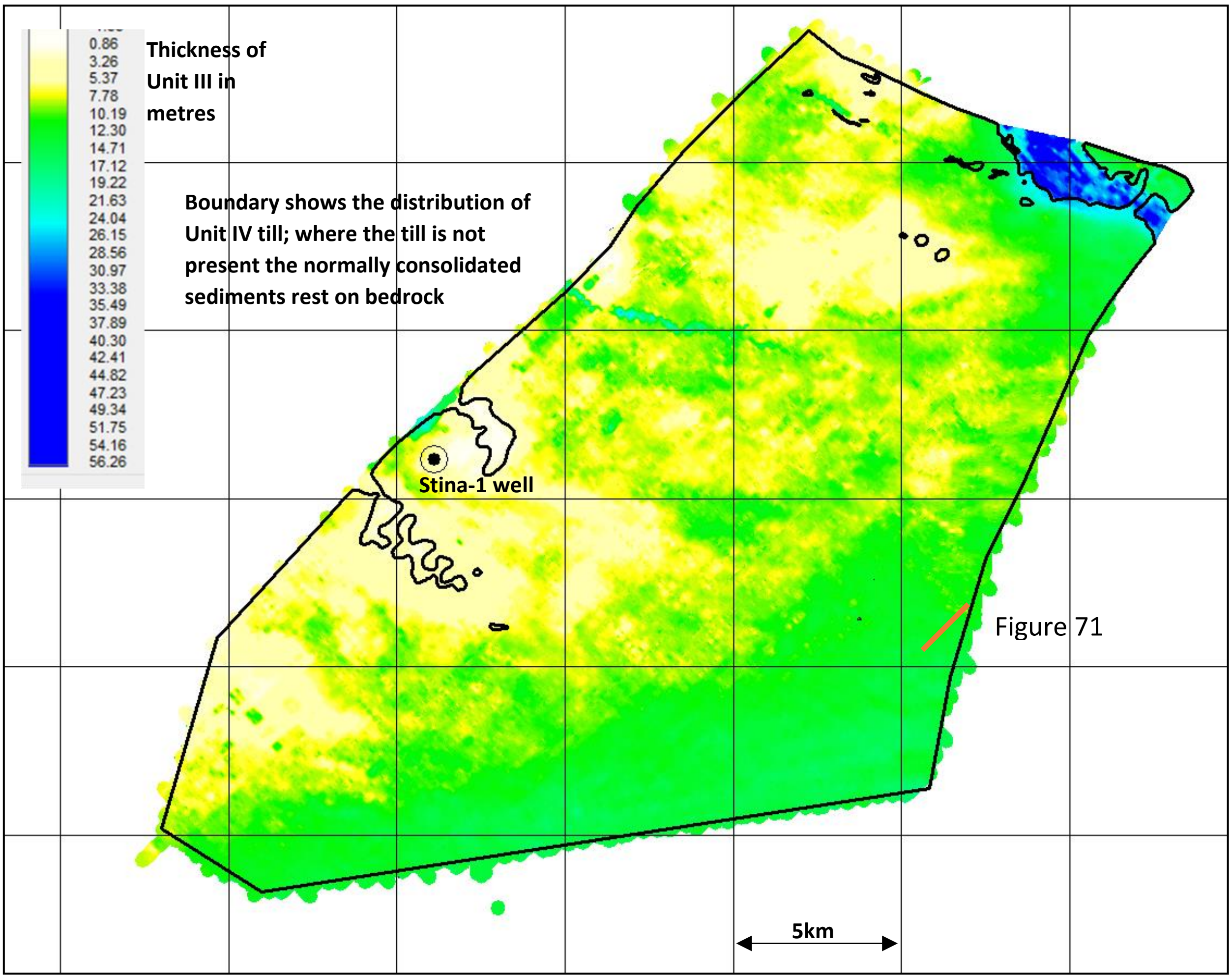


Figure 70: Thickness and distribution of Units I to III, normally consolidated sequence

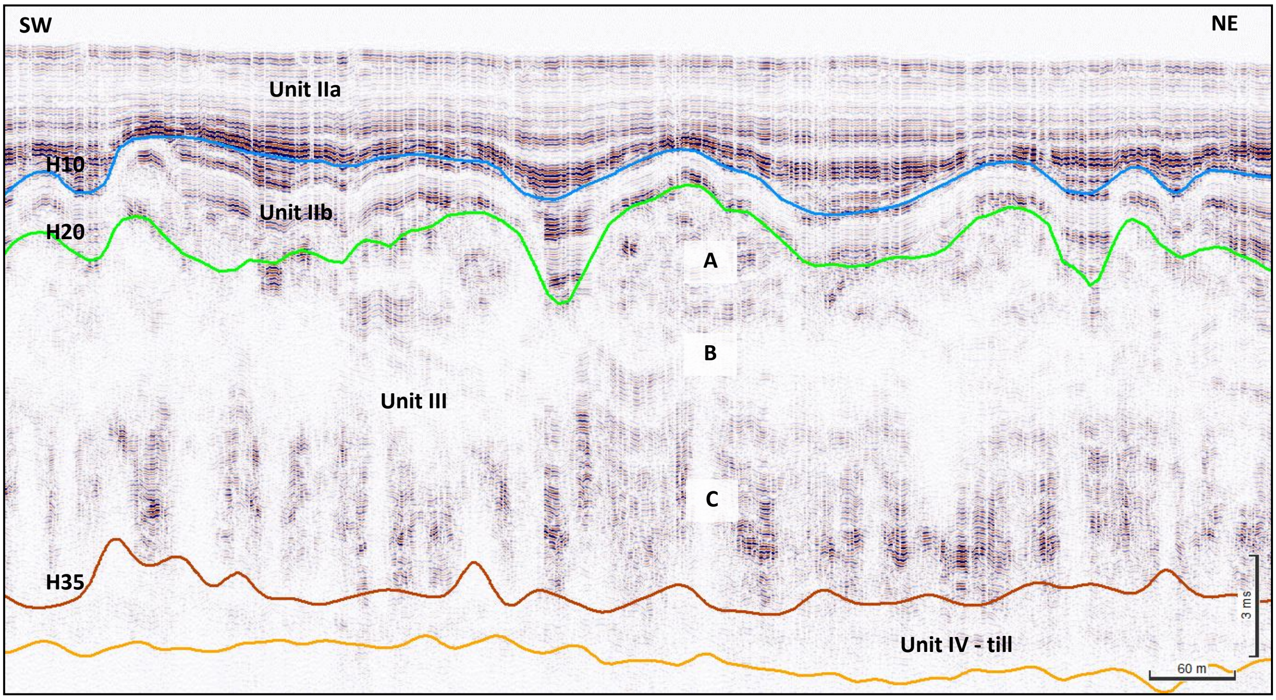


Figure 71: SBP data example, line P_056, Unit III, lower slope

In the extreme east of the area there is a sedimentary mound which comprises post Unit IV sediments (Figure 72 and Figure 73). In this area, sediments of early Unit III age appear to have been laid down from a sediment source to the east or north-east. These sediments may be slightly sandier than the remainder of the Unit III sediments and may have been laid down from a river discharging into the ancient lake or an immediately post glacial unit. The package does appear to predate the remainder of the Unit III sequence.

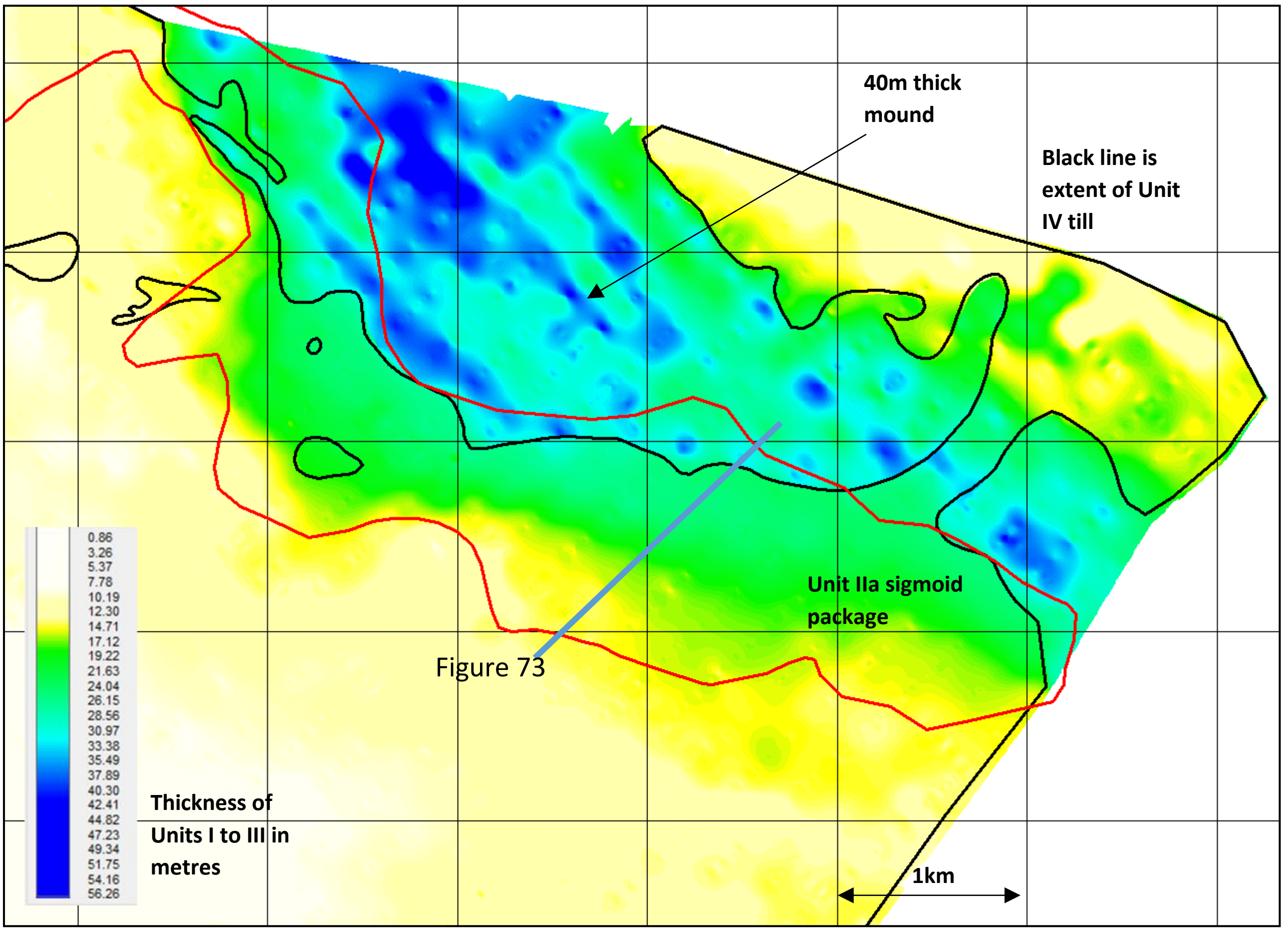


Figure 72: H35 depth BSB, sedimentary mound, extreme east

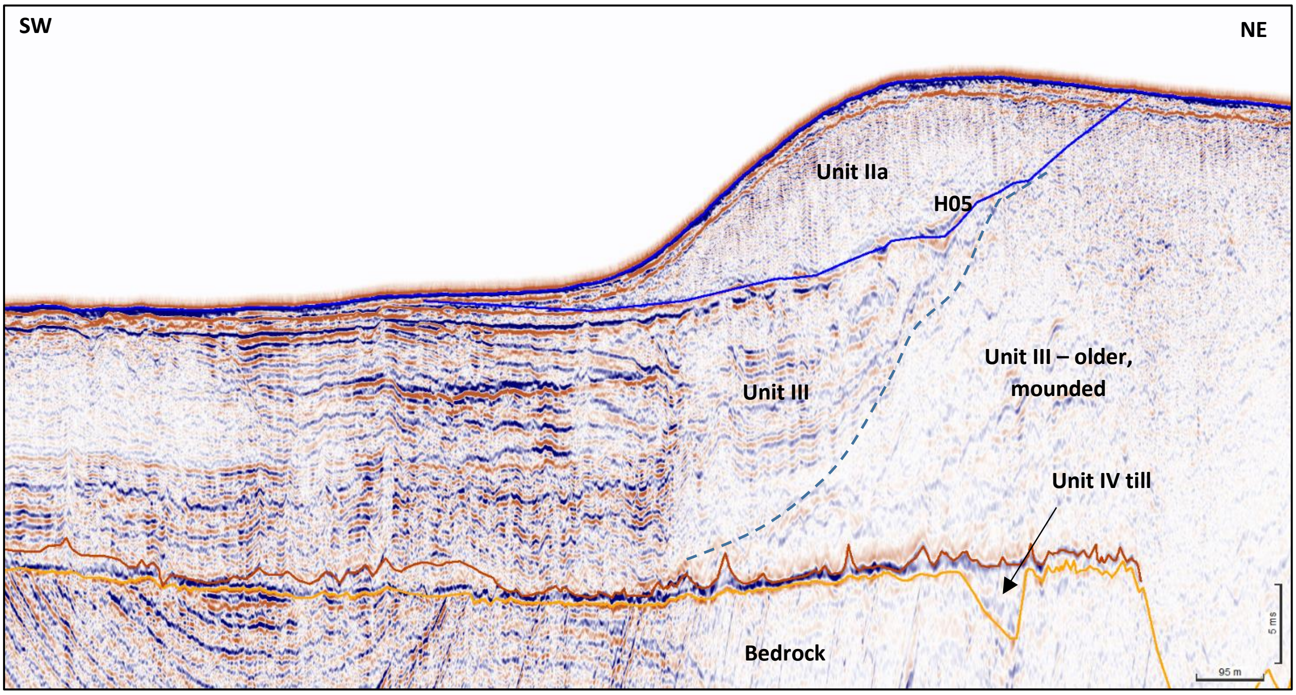


Figure 73: UHR data example, line P_039, Unit III, sediment mound, extreme east

9.2.9 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. Unit IV will be over-consolidated. Consolidation levels may significantly vary over short distances.

Unit IV occurs throughout Bornholm II other than over limited areas in the north-west, where it pinches out against the bedrock, and is at or close to outcrop in other parts of the north-west (Figure 74). It is also absent in the extreme east under the sediment mound, though imaging problems in this area, along with a very irregular top bedrock unconformity, make interpretation uncertain.

The upper surface of the till appears to be arranged into a series of ridges (Figure 74 and Figure 75), 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 m – 2 m thick over the bedrock unconformity.

Jensen et al.'s stratigraphic model includes sub-unit IVa, an outwash deposit. This is not clearly imaged in Bornholm II. Unit IV appears to be more equivalent to Unit IVb in the stratigraphic model, described as a diamicton.

Unit IV thickens in proximal areas and in channels farther south-east, where the top bedrock is interpreted to be eroded beneath the level of the truncation surface. Some of these thicker areas seem to infill what look like drainage channels cut into the bedrock, in other places the bedrock appears at greater depth in association with faults. 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.

Some structure is imaged within these deeper part of Unit IV. These deposits may be outwash deposits sourced from the north-west which were then buried by tills of a subsequent ice advance. If this is the case then these sediments may be sandy.

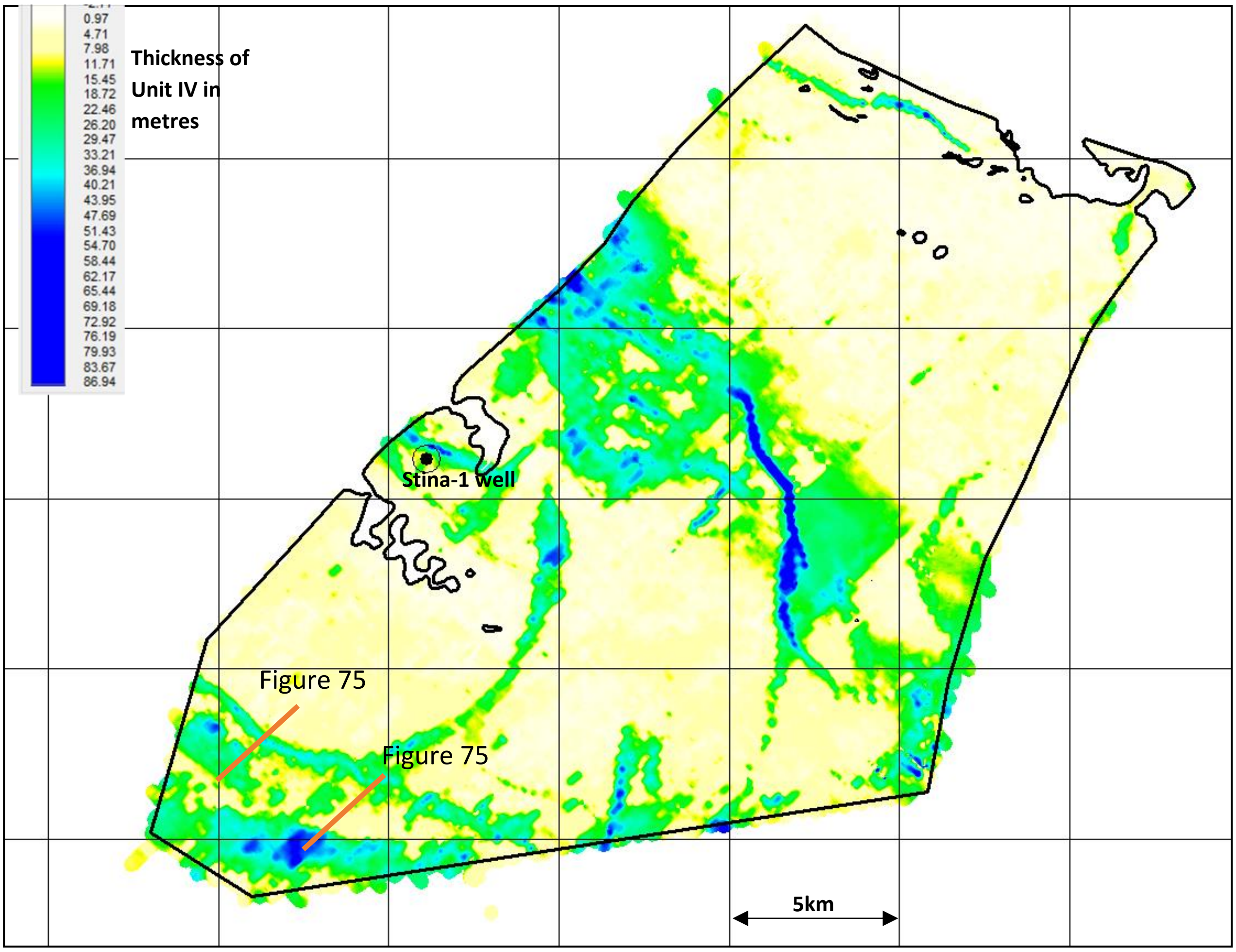


Figure 74: Thickness and distribution of Unit IV

The infill of the deeply eroded areas further south-east is probably older tills but may be neotectonic 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 the geotechnical acquisition.

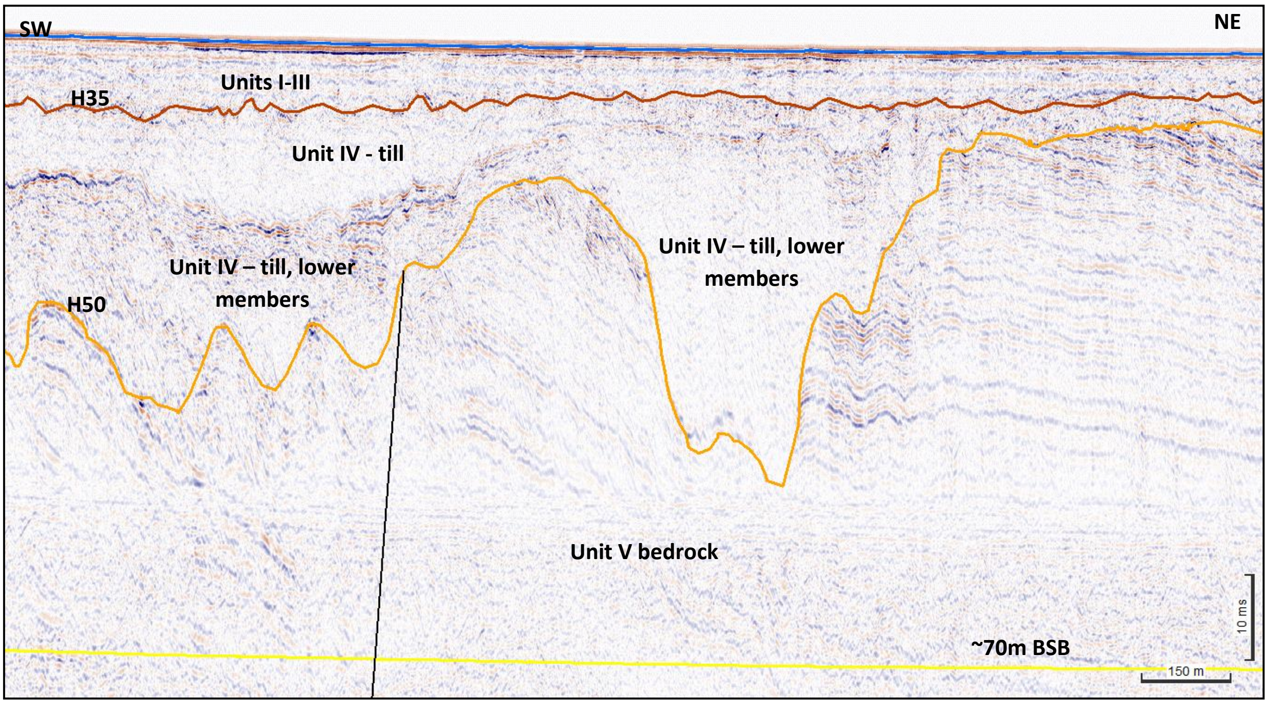


Figure 75: UHR data example, line P_016, Unit IV

9.2.10 Unit V Bedrock

Within Bornholm II, the bedrock within the foundation zone (to 70 m below seabed) comprises limestone of late Cretaceous or Paleogene age and older Jurassic clastic rocks (Figure 76). This is confirmed in the Stina-1 well, towards the north-west of the area. Figure 77 differentiates the sub crop footprint of the Limestone and older clastic bedrock. Younger Limestone bedrock occurs over most of the study area. Older clastic bedrock crops out in the central part of the north-west edge of the area, and in the south-west and north-east. These areas tend to show a stronger imprint of compressional tectonics than the younger limestones. The tectonic influence is especially strong in the north-west where there is a steep-sided collapsed anticline. To the south-west structure is complex with numerous faults.

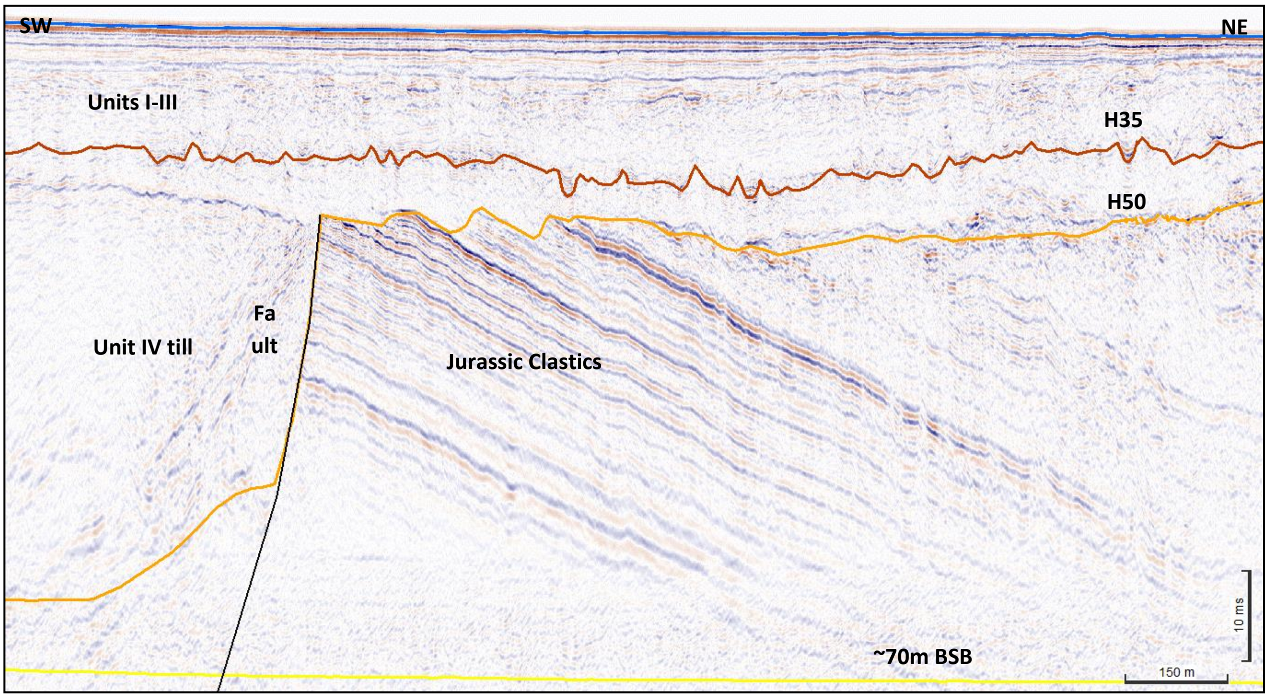


Figure 76: UHR data example, line P_028, older bedrock in the south-west

The potential interface of the carbonates and older clastic rocks has been very tentatively mapped as H70. This surface does separate more heavily deformed rocks (below) from their overburden and represents a change in the seismic character of layering. The unconformity was selected based on its appearance and on the grounds that the plan view pattern of its termination at the top bedrock unconformity approximates the bedrock subcrop patterns shown in the desk study. There are problems with mapping this surface. These include:

- Uncertainty over whether this is the base of the Chalk Group;
- Uncertainty over continuation of surface across areas where the unconformity is over 100 m below seabed and is poorly imaged, leading to miss ties;
- Great difficulty in mapping around the eastern side of the structure in the north-west of the area;
- The wide spacing of cross lines.

In this phase of work this H70 pick is useful in determining sub crop patterns of relatively older, deformed bedrock and younger carbonates at H50 (top bedrock), but is not good enough to form the basis of a plan view depth map. Once the interface of the clastics and limestones is proved in boreholes it may be worth mapping this in a future phase of work – this may or may not correspond with H70. Archive exploration seismic data may be available. Such data might allow an intra bedrock unconformity to be mapped across areas where it occurs >100 m below seabed.

The intervening areas of younger limestones form a gentle syncline.

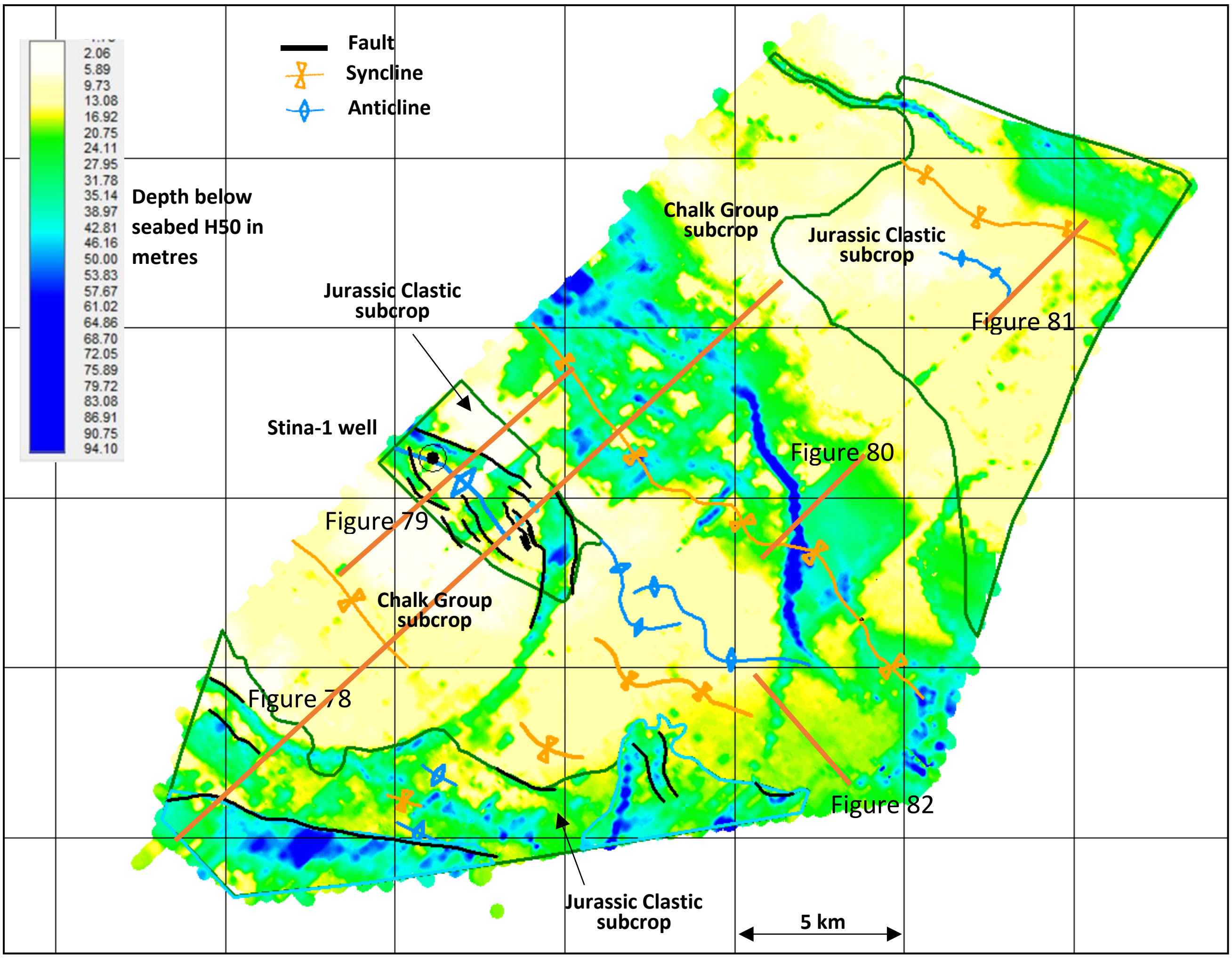


Figure 77: Depth below seabed of H50 and subcrop structure

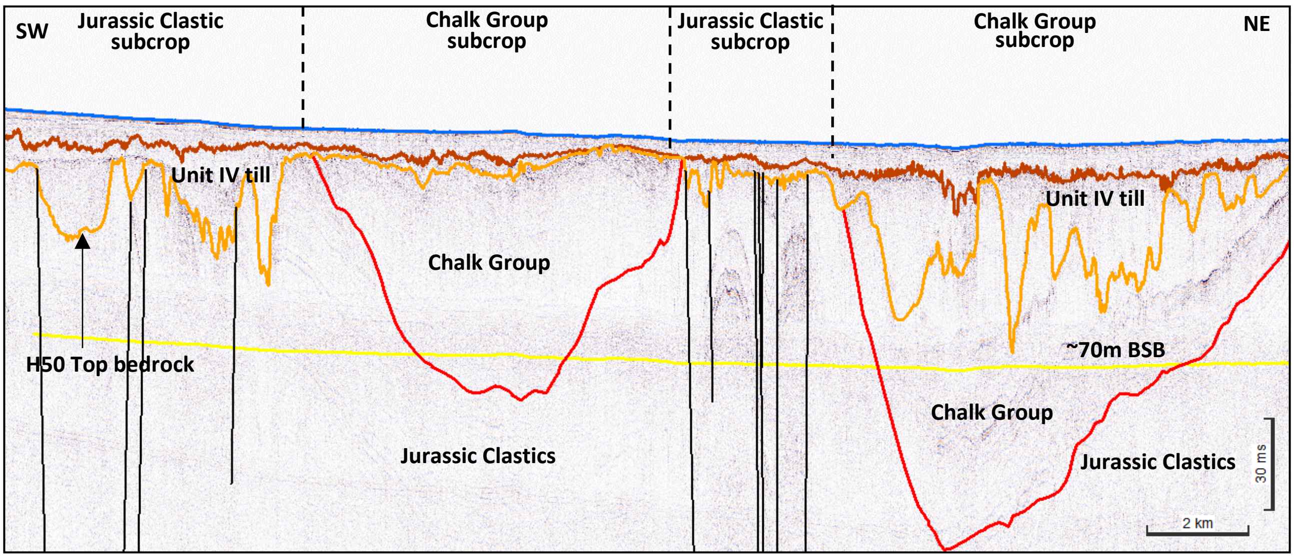


Figure 78: UHR data example, line P_016, Unit V, subcrop patterns north of area

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 (Figure 78).

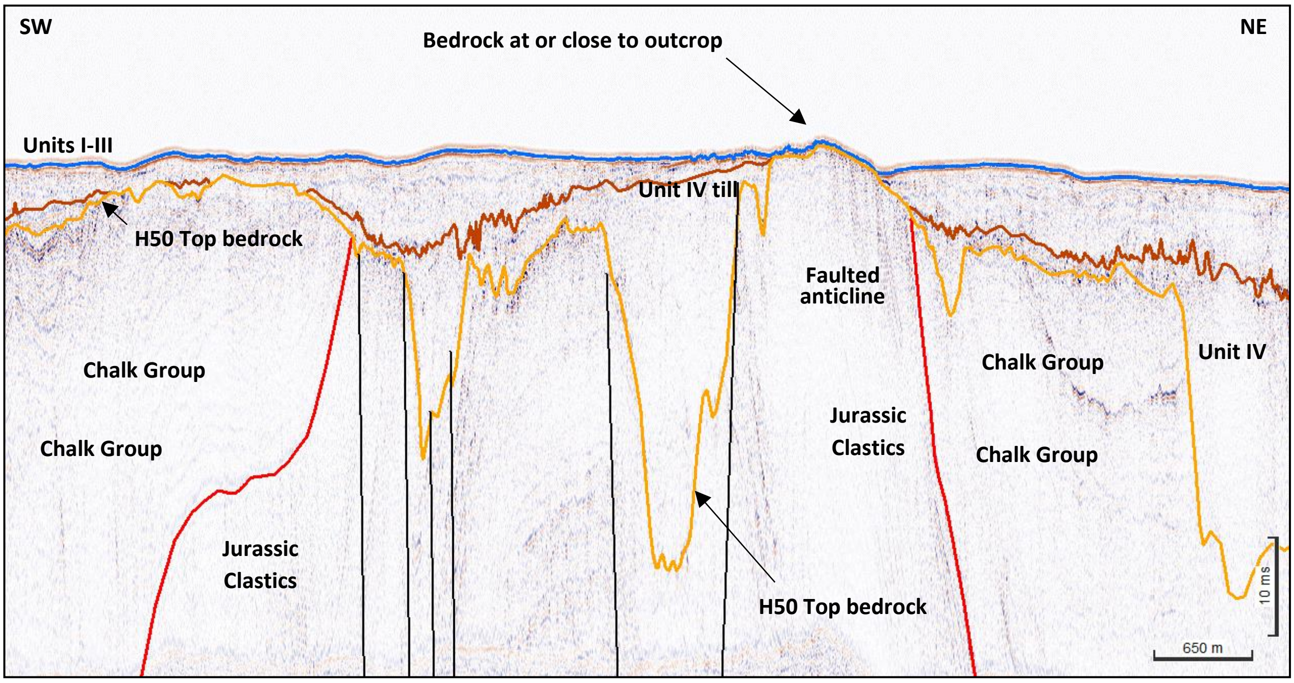


Figure 79: UHR data example, line P_008, Unit V, at or close to outcrop, north-west of area

The upper truncation surface (H50) was initially eroded off in response to this tectonic uplift but the bedrock may have been subjected to further phases of erosion during early glaciations (Figure 79). There is a baseline bedrock truncation surface which is relatively flat and within 10 m -15 m of the seabed (Figure 81). There are areas of deeper erosion in the areas of older subcrop (Figure 82). In these zones the deeper erosion may be related to the fault-induced weakening of the bedrock. In the east of the area there appears to be a drainage pattern cut into the bedrock. This pattern is complex in the north of the area and trends north-west to south-east. Further south the drainage pattern consolidates into a single channel which is ~450 m - 500 m wide and trends north-south (Figure 80). This channel is cut to around 80 m below seabed: in these areas the channel fill (assigned to Unit IV in this project) comprises the entire foundation zone. This drainage pattern may have been cut by sub-glacial rivers during the mid to late Pleistocene.

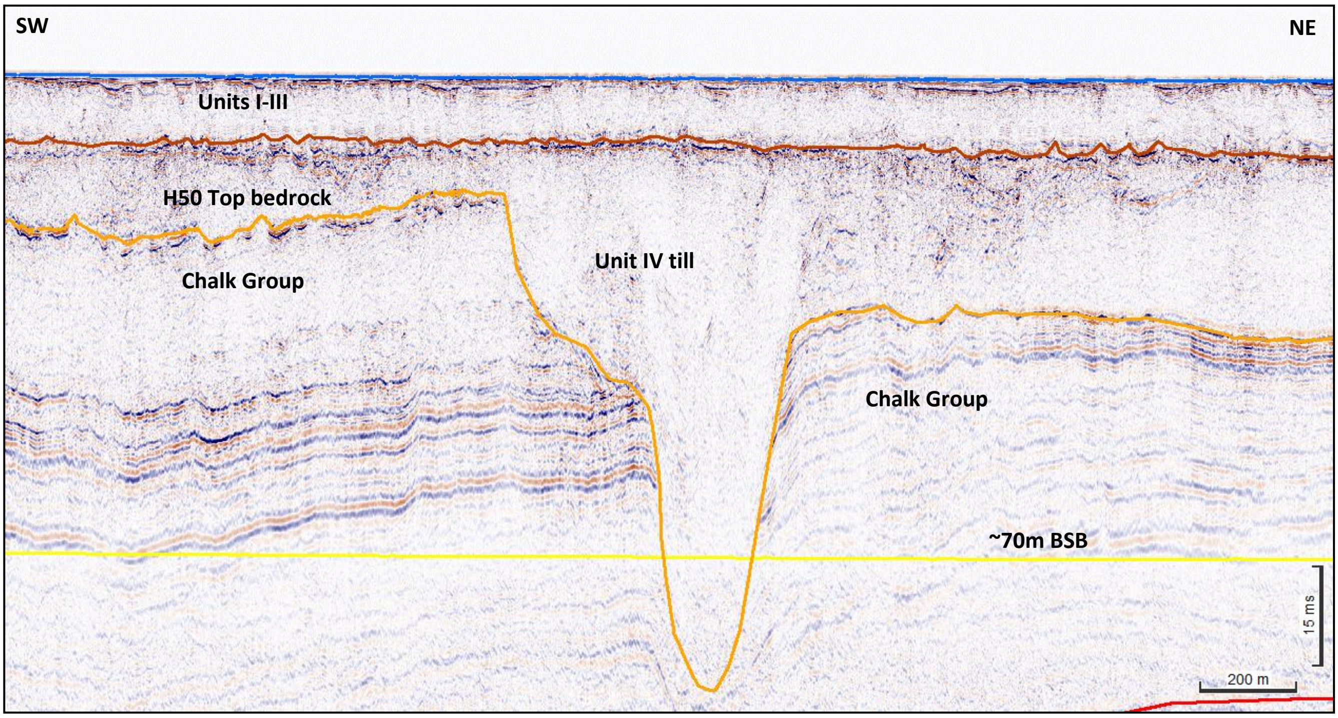


Figure 80: UHR data example, line P_040, Unit V, deep channel, centre/east of area

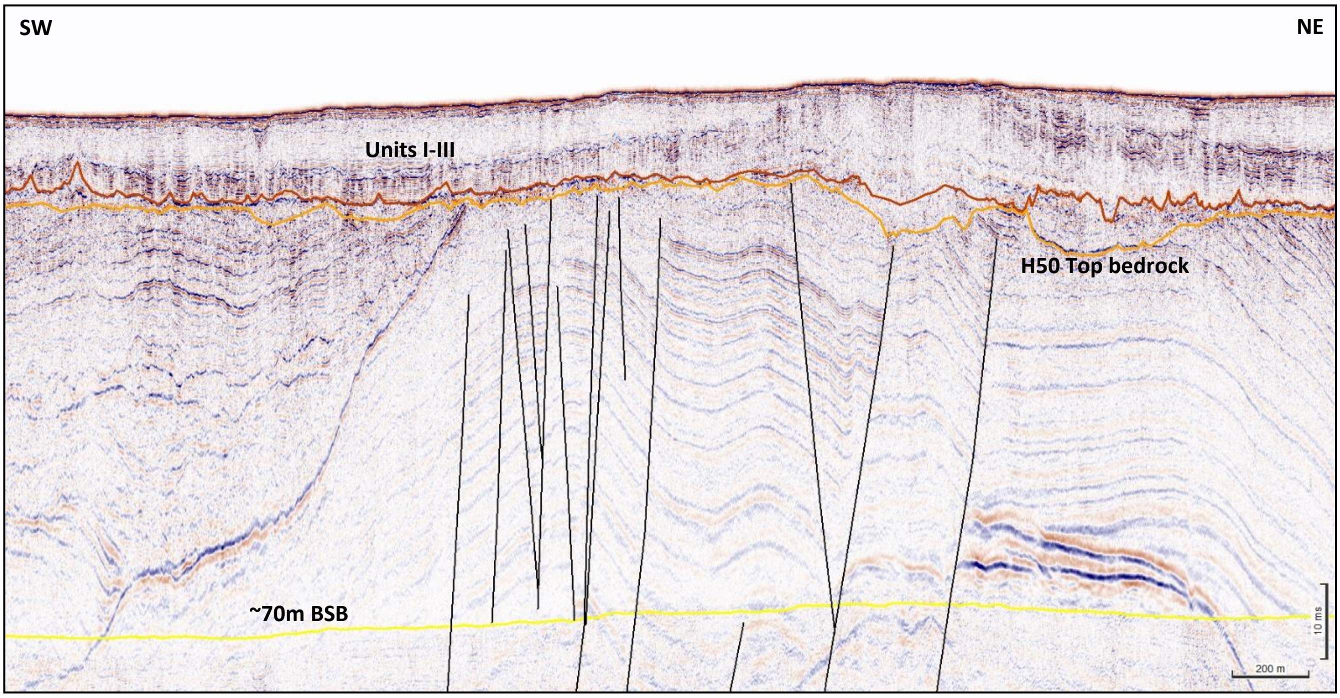


Figure 81: UHR data example, line 2B P_042, Unit V, faults, east of area

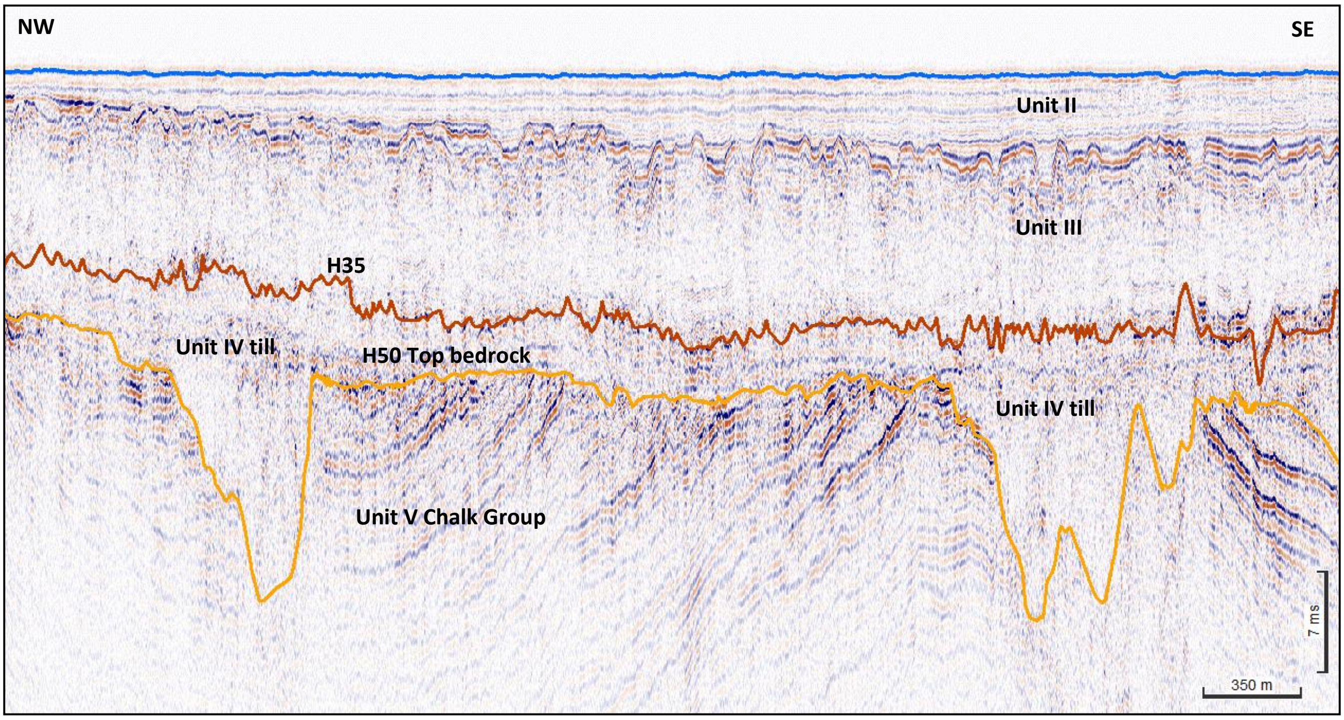


Figure 82: UHR data example, line X_016, Unit V, south of area

9.2.11 Shallow Geological installation constraints

- Unit I facies 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.

9.2.12 Shallow Geological comparison of BHI and BHII

There is a good correspondence between the shallow geology of the Bornholm I and Bornholm II sites (Figure 83). 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 BHI and to the south-east in BHII.

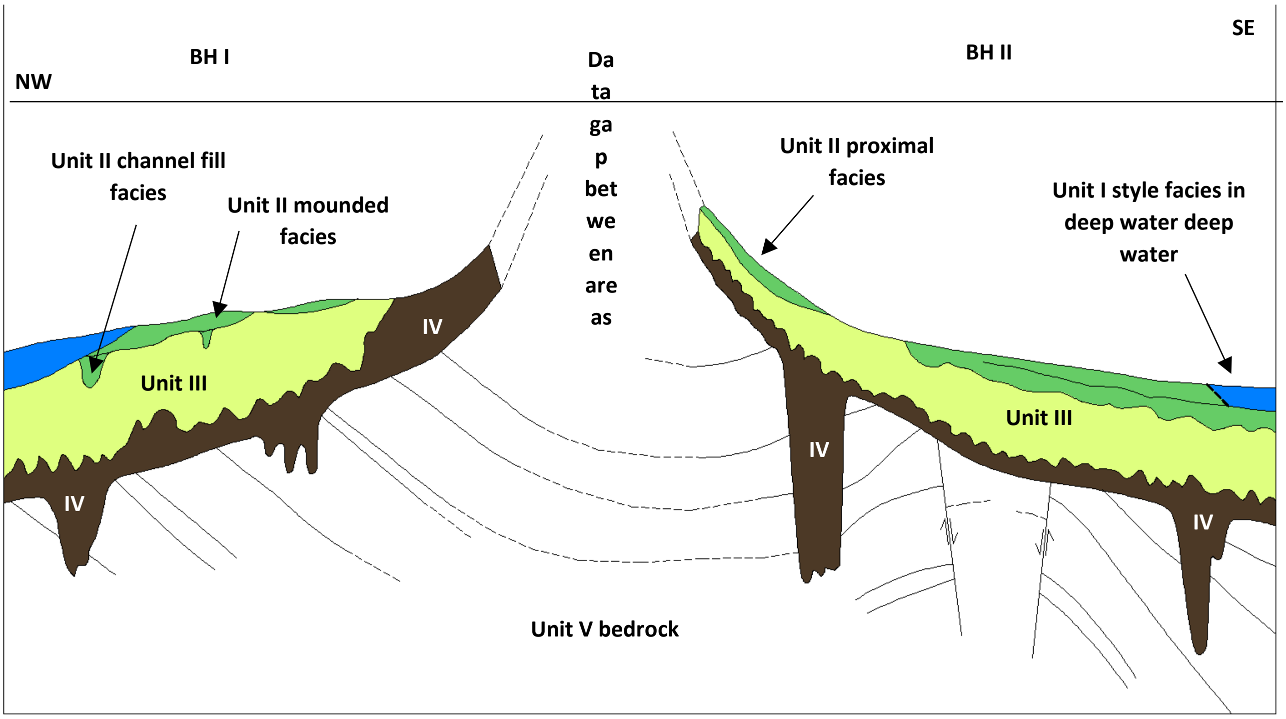


Figure 83: Schematic comparison of BHI and BHII

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 BHII 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 BHII 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 COMPARISION BETWEEN SEABED AND SUB-SEABED FINDINGS

Seabed geology interpretation was based on the low frequency SSS mosaics. The high frequency SSS mosaics, as well as the MBES and the BKS exports were also considered. Till and Sedimentary rock boundaries interpreted in SSS, were correlated to the top of Till (H35) and the top of Bedrock (H50) grids extracted from the seismic profiles. It is evident that there is not an exact match, however seabed geology boundaries ties very well with the H35 and H50 grids derived from sub-seabed data.

Horizon H35 (top of Till) is close to seabed in the western part of the region (Figure 70).The Till polygons that have been marked on the SSS mosaics in Bornholm 2 NW region (Figure 37,Figure 41), correlate well to the H35 grid (Figure 70). In the southern occurrence of Till and Sedimentary rock (Figure 41), H35 (top of Till) is close to the seabed in a wider area than the mapped as Till on the SSS, but it shows rough morphology and it is possibly related to Sedimentary rock outcrops rather than Till. In the northern outline of Till in Bornholm 2 NW region (Figure 37, Figure 41), there is a good match between the SBP and the SSS interpretation (Figure 37, Figure 41). In Bornholm 2 NE region (Figure 38), the Till outlined areas on the surficial geology (Figure 38) are matching well the subcroping/outcropping Till grid.

Horizon H50 (top of Bedrock) is close to seabed in the western part of the region (Figure 79) and it subcrops/outcrops with good correlation to the Sedimentary rock outcrops as those have been outlined on the SSS records (Figure 41).

11 CONCLUSIONS

The bathymetric survey results show that the water depth varies moderately across the Bornholm II site, ranging between 15.04 m in the western part of the site (Bornholm 2 NW) and 57.30 m in the northern area (Bornholm 2 SE). The mean depth across the site is 46.41 m. Terrain profiles show a gradual increase in the water depth from west to east and from south to north across the Bornholm II site. In the northern region the depth variation occurs more drastically at the west and east ends. In this region, a rough topography is observed and is associated with high concentration of trawl mark areas, seabed scar areas and bedform areas. In the central region, depth variation occurs abruptly at the western part, in the vicinity of the shallowest zone of the site. At the southern part of the site there are not prominent slopes and water depth varies smoothly and dips eastwards.

Slope angles across the site are typically very gentle (<1º) and gentle (1º-5º). Very high slope values (>15º) are associated with features such as wrecks, the Nordstream and the Baltic Pipe pipelines, a seabed escarpment at the western part of the site, as well as fishing or dragging activities.

The seabed surface geology is characterised by Sand and Silt. The northeast section of the site (Bornholm II NE) is predominantly Sand with large areas of Gravel and coarse Sand extending mainly across eastern area. Till is reported in the central and north-eastern parts of Bornholm II NE. The southeast section of the site (Bornholm 2 SE) comprises Clay and Silt as well as Mud and Sandy Mud over the larger portion of the region. Sand areas are found in the north and west of Bornholm 2 SE. The southwest of the site (Bornholm 2 SW) is predominantly Sand and Muddy Sand with Mud and sandy Mud areas in the southeast and some Gravel areas occurring northwards. The northwest section (Bornholm 2 NW) is predominantly Sand with Muddy Sand to the east and north of Bornholm 2 NW and Gravel and coarse Sand areas to the west. An area of Till occurs in the northern Bornholm 2 NW whereas Till and Sedimentary rock outcrop areas are spotted in to the west.

The northeast, the southeast and the southwest sections of the site (Bornholm II NE, Bornholm 2 SE and Bornholm 2 SW) are dominated by heavily trawl scarred areas interspersed by pitted parts. Regions of disturbed sediment are likely associated with the construction of the Nordstream 1 and the Baltic Pipe pipelines that cross the site and the construction of Nordstream 2 that is close to the southern part of the site. Boulder fields are generally restricted to the north and north-east. Limited areas of bedforms, mainly ripples but also large ripples, mega-ripples and sand waves, extend at the western and northern areas.

A total of 34193 seabed surface objects were detected in Bornholm II site, some of them are determined to be of man-made origin and include: 8 wrecks or suspected wrecks, 3 debris related cable items, 3 pipelines that cross the site (Nordstream 1 with 2 pipelines and Baltic Pipeline), 1313 debris items, 147 items possibly related to fishing activity and 37 seabed disturbances possibly related to pipeline construction and/or fishing activity.

The geological foundation zone extends to 70 m below seabed. The area has a glacial to post-glacial sequence of recent sediments over much older carbonate and clastic bedrock. The recent sediments are 10 m – 20 m thick, although in some areas these recent sediments are interpreted to be much thicker. The seabed gently dips to the south-east. The distribution and thickness patterns of the post glacial units follow this trend with the youngest sediments being thickest in the deep water, south-eastern, part of the area. Five units were identified from the sub-surface imagery. 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 facies are interpreted to be thin, passive drape, less than 1 m thick, organic-rich post-glacial marine CLAY. It reaches a thickness of 2 m in easternmost parts of the area and occurs in water depths greater than ~45 m. It has seismic characteristics which indicate that it is extremely soft/weak and it occurs the seabed is of very low reflection amplitude.

Unit IIa is a post glacial, lacustrine, normally consolidated, laminated CLAY that was deposited in the Ancylus Lake. It is close to outcrop over its entire distribution and It reaches a thickness of 5 m to the southeast but is thicker and more widely distributed in the west. The unit shows good acoustic evidence of internal bedding. It is widely distributed over the middle and lower slope parts of Bornholm II, pinching out on the middle to upper slope and becomes patchy, infilling relative lows. Unit IIa has also been mapped in proximal areas, along the north-western edge of the area and is considered broadly equivalent to Bornholm I's Unit II mounded facies.

Unit IIb is a post glacial, marine, normally consolidated, laminated CLAY possibly with iron sulphide-rich laminations in upper parts, that was deposited in the Yoldia Sea. It is widely distributed, occurring everywhere apart from parts of the extreme north-west where pinches out. It has a more irregular internal appearance than Unit IIa and generally, the internal reflectors mimic the significant relief at the basal surface, the top of Unit, III resulting in varying thickness up to 2 m - 3 m over very short distances and in limited confidence in the exact thickness of this unit in areas between survey lines.

Unit III comprises of post glacial sediment s deposited in ice-dammed lakes. The unit is clay-prone with a silty upper part and is normally consolidated. In the extreme east of the area sediments of Unit III age form a large scale mound which is 6km long and 1.2km wide.

Unit IV is a glacial till with a clay-prone diamicton containing silt, sand, gravel, cobbles and boulders. The unit is found throughout the BHII site, except in the north-west of the site where the underlying Unit V bedrock outcrops. Unit IV is thicker in some areas, up to 80 m in thickness, suggesting a channel fill of the underlying Unit V bedrock.

Unit V bedrock is comprised of late Cretaceous or Paleogene age limestone and older Jurassic clastic rocks, which have been confirmed in the Stina-1 well, towards the north-west of the BHII area.

Folds and faulting within the sub-seabed on BHII, within 70 m of the seabed, are interpreted to be related to the late Cretaceous or early Paleogene inversion episode, caused by compressional strike slip movements. The tectonic uplift resulted in erosion of the bedrock, with later phases of erosion occurring due to early glaciations. Erosion within areas of older subcrop are possibly due to fault induced bedrock weakening. A north-south trending channel is present up to 80 m below seabed.

11.1 ARCHAEOLOGICAL FINDINGS

Considering that Quaternary Sea level fluctuations have affected the area and the formation of the paleo shorelines and 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.

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