Hydrographical Survey Report

Energinet Denmark Hesselø Hydrographical Survey | Denmark, Inner Danish Sea, *Kattegat*

F172145-REP-HYD-001 02 | 2 December 2021

Complete

Energinet Eltransmission A/S

Document Control

Document Information

Project Title	Energinet Denmark Hesselø Hydrographical Survey
Document Title	Hydrographical Survey Report
Fugro Project No.	F172145
Fugro Document No.	F172145-REP-HYD-001
Issue Number	02
Issue Status	Complete

Client Information

Client	Energinet Eltransmission A/S
Client Address	Tonne Kjærsvej 65, DK-7000 Fredericia, Denmark
Client Contact	Søren Stricker Mathiasen
Client Document No.	N/A

Revision History

Issue	Date	Status	Comments on Content	Prepared By	Checked By	Approved By
01	15 Nov 2021	Complete	Issued for comments	BSP/SBL	BSP	APA
02	02 Dec 2021	Complete	Comments amended	BSP/SBL	BSP	APA

Project Team

Initials	Name	Role
APA	A. Padwalkar	Project Manager
BSP	Benoit Spinewine	Principal Engineer
SBL	Sébastien Blaise	Senior Engineer

FUGRO
Fugro Netherlands Marine Limited
Prismastraat 4
Nootdorp
2631 RT
The Netherlands

Energinet Eltransmission A/S
Tonne Kjærsvej 65
DK-7000 Fredericia
Denmark Bldg

2 December 2021

Dear Sir/Madam,

We have the pleasure of submitting the 'Hydrographical Survey Report' for the 'Energinet Denmark Hesselø Hydrographical Survey'. This report presents the details of our analyses on comparing the WPA and WP B Bathymetries acquired across the project area of the planned Hesselø Offshore Windfarm (HOWF), Inner Danish Sea, Kattegat.

We hope that you find this report to your satisfaction; should you have any queries, please do not hesitate to contact us.

Yours faithfully,

B. Spinewine
Principal Engineer

Executive Summary

Energinet Eltransmission A/S (Energinet) is developing a new offshore wind farm in the inner Danish Sea, Kattegat, the Hesselo Offshore Windfarm (HOWF). The project area is located between Denmark and Sweden approximately 30km North of Sjælland.

This report is part of the Hydrographical Report associated with the WPB hydrographic survey conducted by the survey vessel Aurora working on the project. Survey operations for WPB on the Aurora occurred between 02 and 23 September 2021. A bathymetric dataset over the same area was also acquired as part of WPA survey, conducted using the survey vessels Fugro Pioneer and Fugro Frontier, between 14 October and 30 December 2020. For further details on WPA operations and results refer to *F172145-REP-OPS-001*, *F172145-REP-OPS-002* and *F172145-REP-GEOP-001*.

This report presents our analyses on a comparison of WPA and WPB bathymetries, in view of identifying seabed changes and areas of potential sediment mobility. The observed seabed elevation changes between the two survey are mapped and interpreted in terms of the survey accuracy, the seabed conditions and the geological context of the area.

From the comparison between the two surveys, the Hesselø site is presumed to have been largely inactive in terms of dynamic seabed mobility over the period separating the two surveys. The observed elevation changes are well within the limits of the vertical accuracy of the respective surveys and are often organized in bands of near-constant differences aligned with the orientation of the survey lines of either WPA or WPB. The project area is known to be characterized by a strong and rapidly varying pycnocline, and the associated change in sound velocity may slightly affect absolute depth measurements of the multibeam echosounder instrument, still within the survey specifications.

The absence of significant morphological changes related to sediment mobility over the period is confirmed by the good preservation of a number of seabed features observed across the project area, such as: (i) widespread minor linear depression marks typically associated with trawling activities, (ii) local depressions of likely anthropogenic origin or unconfirmed origin, (iii) sand ridges, (iv) escarpments. The sand ridges and escarpments observed in the south-western region of the project area are interpreted as geological features associated with the paleo-channels, spits and bars of the Dana river system, and the rapid drainage of the Ancylus Lake via the Dana river system through the Storebælt into the Kattegat between 11.9 and 9.1 ka BP. The lack of net migration of the sand ridges over longer time spans appears to be confirmed by the review of sub-bottom geophysical data. Some seabed features interpreted as boulders, more abundant toward the northern and eastern regions of the site, do present minor depressions around them, amounting to only a fraction of the estimated object dimension, and suggest local scour may occur in association with extreme metocean conditions. No other markers of significant seabed mobility, such as e.g. asymmetrical bedforms, megaripples, sand waves, scour or obstacle marks, were observed.

It is noted that the two surveys are separated by a duration of less than a year, and the metocean conditions experienced over the period are unlikely to be fully representative of the variable metocean conditions over the project area, in particular in terms of the occurrence of extreme events. Therefore,

while the quantitative comparison of WPA-WPB bathymetries reported herein suggests a low degree of sediment mobility activity for normal conditions, it does not represent a comprehensive seabed mobility/morphology study of the site, and should not be used for design purposes that require the consideration of potential extreme events.

Contents

Executive Summary **i**

1. Introduction **1**

1.1 Project location 1
1.2 Geodetic Parameters 2
1.3 Vertical Datum 2

2. Mobilisation and Operations **3**

3. Vessel Details and Instrument Spread **4**

3.1 Vessel Details 4
3.2 Instrument Spread 4

4. Regional Context and Seabed Conditions **6**

4.1 Regional Geological Context 6
4.2 Seafloor Morphology Context 8
4.3 Seafloor Sediment Context 10

5. Comparison of WPA-WPB Bathymetry **12**

5.1 Overview of Bathymetry and Regional Changes 12
5.2 Comparison of Bathymetries at Areas of Interest 17
5.2.1 Regional trends, North-South and East-West profiles 17
5.2.2 Area of sand ridges and gullies 19
5.2.3 Area of seabed escarpment 20
5.2.4 Area of seafloor objects 21
5.2.5 Area of seafloor depression of likely anthropogenic origin 23
5.2.6 Area crossing survey lines 24
5.2.7 Area of multiple seabed depressions of unknown origin 25
5.2.8 Area of newly-formed depression of anthropogenic origin 27

6. Data Quality **29**

6.1 Multibeam Echosounder 29

7. Conclusions **30**

8. References **32**

Appendices

Appendix A Guidelines on Use of Report

Appendix B Charts

Appendix C Digital Deliverables

Figures in the Main Text

Figure 1.1: Project location 1
Figure 1.2: Project geodetic and projection parameters 2
Figure 3.1: RV Aurora 4
Figure 4.1: Paleogeographical map of the Hesselo Bay Area approx. 9.9 ka BP (left) and superimposed location of HOWF Bathymetry (right). Background map reproduced from Bendinxen et al., 2017) 7
Figure 4.2: Map of the Hesselo Bay Area with regional bathymetry and geophysical data locations and profiles (left) and superimposed location of HOWF Bathymetry (right). Background map reproduced from Bendinxen et al., 2015; 2017) 7
Figure 4.3: Sub-bottom and interpreted geophysical profile over the area highlight in red on Figure 4.2 (reproduced from Bendinxen et al., 2015). 8
Figure 4.4: Seafloor morphology features (from Fugro, 2021a) 9
Figure 4.5: Seafloor sediment distribution. Top: interpreted seafloor sediment; Middle: backscatter intensity; Bottom: Grab Sample contents (from Fugro, 2021a) 11
Figure 5.1: WPB Bathymetry block layout for MBES survey 13
Figure 5.2: General overview of WPB Bathymetry 14
Figure 5.3: General overview of WPA Bathymetry 15
Figure 5.4: General overview of bathymetry differences between WPA and WPB. Positive values refer to areas where seabed elevation was interpreted as being higher for WPB than for WPA 16
Figure 5.5: Bathymetric differences along a West to East transect (A) and a South to North transect (B) 18
Figure 5.6: Bathymetric differences along a transect through the observed Sand Ridges and Gullies 20
Figure 5.7: Bathymetric differences along a seabed escarpment 21
Figure 5.8: Bathymetric differences along a seafloor object, in an area where WPB lies higher than WPA 22
Figure 5.9: Bathymetric differences along a seafloor object, in an area where WPB lies lower than WPA 23
Figure 5.10: Bathymetric differences along a transect through seafloor depression of likely anthropogenic origin 24
Figure 5.11: Bathymetric differences along a transect or differences between adjacent survey lines 25
Figure 5.12: Bathymetric differences along a transect through multiple seafloor depressions of unknown origin 26
Figure 5.13: Bathymetric differences along a transect through a seafloor depression of unknown origin 27
Figure 5.14: Bathymetric differences through a newly-formed depression of anthropogenic origin 28

Abbreviations

DGPS	Differential global positioning system
DTU	Technical University of Denmark
EPSG	European Petroleum Survey Group
ESE	East-South-East
ETRS	European Terrestrial Reference System
GEUS	Danmarks Og Grønlands Geologiske Undersøgelse (Geological Survey of Denmark and Greenland)
GNSS	Global navigation satellite system
HOWF	Hesselø Offshore Windfarm
IHO	International Hydrographic Organization
ITRF	International Terrestrial Reference Frame
ka BP	Kilo annum before present
MBES	Multibeam echosounder
MRU	Motion reference unit
MSL	Mean Sea Level
MSS	Mean Sea Surface
RV	Research vessel
SVP	Sound velocity profile
THU	Total horizontal uncertainty
TSG	Template Survey Geodatabase
TVU	Total vertical uncertainty
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
WNW	West-North-West
WPA	Work Package A
WPB	Work Package B

1. Introduction

Energinet Eltransmission A/S (Energinet) is developing a new offshore wind farm in the inner Danish Sea, *Kattegat*, the Hesselo Offshore Windfarm (HOWF). The project area is located between Denmark and Sweden approximately 30km North of Sjælland.

This report is part of the Hydrographical Report associated with the WPB hydrographic survey conducted by the survey vessel Aurora working on the project. Survey operations for WP on the Aurora occurred between 02 and 23 September 2021. A bathymetric dataset over the same area was also acquired as part of WPA survey, conducted using the survey vessels Fugro Pioneer and Fugro Frontier, between 14 October and 30 December 2020. For further details on WPA operations and results refer to *F172145-REP-OPS-001*, *F172145-REP-OPS-002* and *F172145-REP-GEOP-001*.

This report presents our analyses on a comparison of WPA and WPB bathymetries, in view of identifying seabed changes and areas of potential sediment mobility. The observed seabed elevation changes between the two survey are mapped and interpreted in terms of the survey accuracy, the seabed conditions and the geological context of the area.

Guidelines on the use of this report have been provided in Appendix A.

1.1 Project location

The project area is located between Denmark and Sweden approximately 30km North of Sjælland. (Figure 1.1). The water depth varies between 25 m and 35 m MSL.

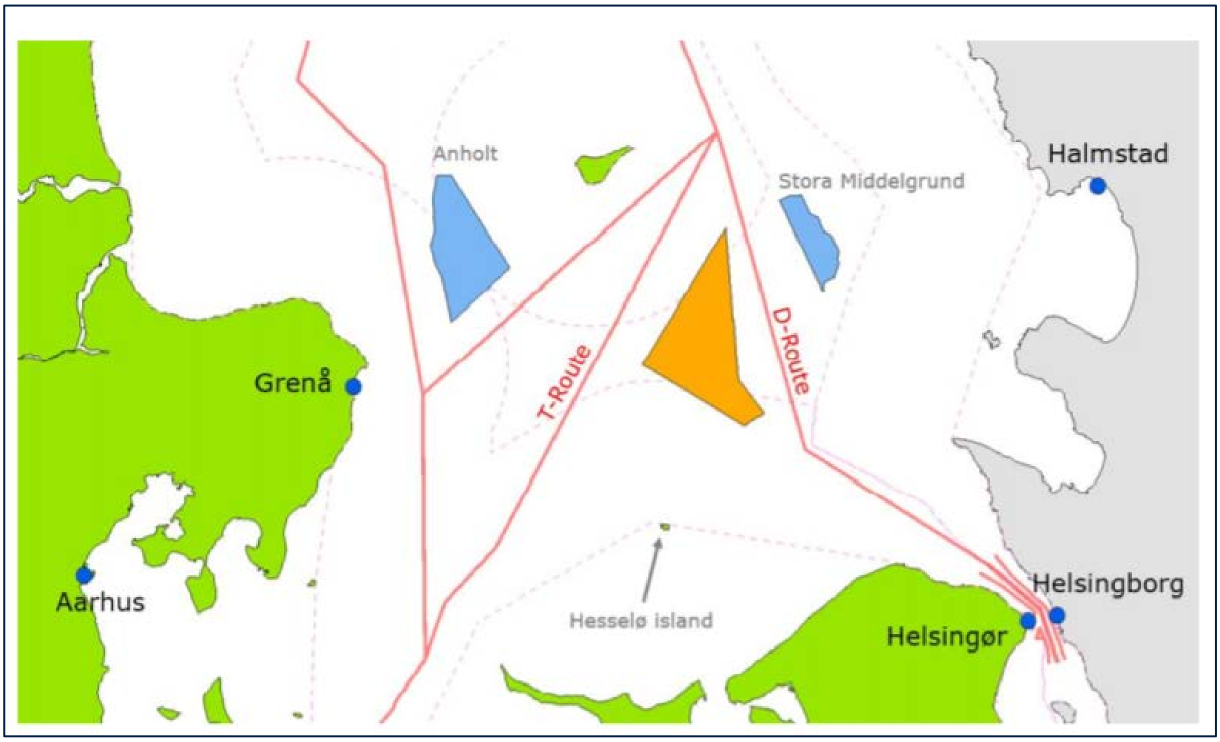

Figure 1.1: Project location

1.2 Geodetic Parameters

The project geodetic and projection parameters are summarised in Figure 1.2.

Name: ETRS89 / UTM zone 32N [ETRF2000-ITRF2014],DTU18 MSS height [DTU18 MSS]		
EPSG Code	EPSG:25832	
Global Navigation Satellite System (GNSS) Geodetic Parameters*		
Datum	International Terrestrial Reference Frame 2014	EPSG:1165
Ellipsoid	GRS 1980	
Semi major axis	a = 6 378 137.00 m	
Inverse flattening	1/f = 298.257222101	
Local Geodetic Datum Parameters		
Datum	European Terrestrial Reference System 1989	EPSG:6258
Ellipsoid	GRS 1980	
Semi major axis	a = 6 378 137.00 m	
Inverse flattening	1/f = 298.257222101	
Datum Transformation Parameters from ITRF2014 to ETRS89		
X-axis translation 0.05587 m	X-axis rotation -0.0026459"	Scale difference 0.00340323 ppm
Y-axis translation 0.05337 m	Y-axis rotation -0.0160062"	Coordinate Frame rotation
Z-axis translation -0.09626 m	Z-axis rotation 0.0258713"	FUGRO:41366
Local Projection Parameters		
Map projection	Transverse Mercator	
Grid system	UTM zone 32N	EPSG:16032
Latitude origin	00° 00′ 00.000″ N	
Central meridian	009° 00′ 00.000″ E	
Scale factor on central meridian	0.9996	
False easting	500 000 m	
False northing	0 m	
Project Vertical Parameters		
Vertical coordinate reference system	DTU18 MSS height	FUGRO:41073
Datum	DTU18 MSS height	FUGRO:40939
Transformation	WGS 84 to DTU18 MSS height	FUGRO:41429
Notes * The geodetic datum of Fugro's global GNSS correction data is ITRF2014, epoch 2021.666 (01/09/2021)		

Figure 1.2: Project geodetic and projection parameters

1.3 Vertical Datum

The vertical datum adopted for the analysis of the WPA and WPB bathymetries is reduced to Mean Sea Level (MSL) utilising the DTU18 MSL Tide Model as a vertical offshore reference frame supplied by the Technical University of Denmark (DTU).

2. Mobilisation and Operations

WPA bathymetry was acquired over the period from 14 October to 30 December 2020 with Dual Head Kongsberg EM2040 MBES onboard vessels Fugro Pioneer and Fugro Frontier.

Fugro Frontier mobilisation and calibrations for survey operations were undertaken between 10 October and 12 October 2020 in the port of IJmuiden, The Netherlands; 23 October 2020 and 04 November 2020 near the survey site (see report F172145-REP-MOB-002).

Fugro Pioneer mobilisation and calibrations for survey operations were undertaken between 11 to 20 November 2020 in the port of Great Yarmouth, UK and at an offshore calibration site close to the survey site (see report F172145-REP-MOB-001).

Operations on the Fugro Frontier occurred between 14 October and 26 December 2020. Details are provided in report F172145-REP-OPS-002.

Operations on the Fugro Pioneer occurred between 20 November and 30 December 2020. Details are provided in report F172145-REP-OPS-001.

WPB bathymetry was acquired with a Reson SeaBat 7125 MBES onboard RV Aurora over the period from 06 to 23 September 2021.

RV Aurora mobilisation and calibrations were undertaken between 02 and 06 September 2021 in the ports of Aarhus and Hundested, Denmark and at offshore verification sites close to, and within the survey area.

Operations on the RV Aurora occurred between 06 and 23 September 2021. Details are provided in report F172145-REP-OPS-005.

3. Vessel Details and Instrument Spread

3.1 Vessel Details

Survey Vessel RV Aurora (Figure 3.1) is 28m long equipped with Reason 7125 Multibeam system, POS MV 320 motion sensor and DGPS system to perform offshore operations.

Figure 3.1: RV Aurora

Table 3.1 provides further detail on RV Aurora specifications.

Table 3.1: RV Aurora specifications

Sub-Section	Dimensions
Length	28 m
Beam	8.5 m
Depth mid.	4.35 m
Draft	2.75 m

3.2 Instrument Spread

The equipment used for the survey is presented in Table 3.2.

Table 3.2: Equipment List

Requirement	Equipment
Primary GNSS	Applanix Pos MV 320
Secondary GNSS	Applanix Pos MV 320
MRU and heading sensor	Applanix Pos MV 320
Multibeam echosounder	Reson SeaBat 7125

Requirement	Equipment
Sound velocity probe	Valeport SVP
Tidal heights	Applanix Pos MV 320

4. Regional Context and Seabed Conditions

4.1 Regional Geological Context

The geology at the HOWF site is heavily influenced by the Sorgenfrei–Tornquist fault system, which forms the south-western boundary of the Baltic Shield (Erlström and Sivhed, 2001). The fault system has been active since the Palaeozoic and has been re-activated multiple times, most recently during the Quaternary (Jensen et al., 2002), as result of isostatic (re)adjustments following ice sheet advances and retreats. The Børglum Fault, one of the major faults of the Sorgenfrei–Tornquist Zone, is located in the northern part of the HOWF site with a south-east to north-west orientation.

During the Pleistocene, advances and retreats of the Scandinavian Ice Sheet has resulted in the accumulation of a series of glacial tills and interglacial lacustrine and marine deposits (Jensen et al., 2002; Larsen et al., 2009), as well as a complex series of ice-terminal ridges (terminal moraines or push-moraines), which can still be recognised in the geomorphology of the islands and bathymetry of the southern Kattegat.

In the early Holocene or Postglacial period (~10.5 to 12.6 ka BP) the relative sea level dropped due to isostatic rebound. This resulted in erosion of Late Weichselian deposits and is evidenced by an unconformity in the larger Hesselø area (Jensen et al., 2002; Bendixen et al., 2015, 2017; GEUS 2020). Due to the ongoing eustatic sea level rise, the area was once again inundated, and sediment was deposited in a transgressive, shallow marine environment between 11.7 to 10.8 ka BP. During this time a freshwater lake (Ancylus Lake) was present in the Baltic Sea. Between 11.9 and 9.1 ka BP, the Ancylus Lake drained via the Dana river system through the Storebælt in the south-east, into the Kattegat and resulted in the deposition of coastal sediments in the Hesselø area. From 9.1 ka BP the Holocene marine transgression continued, and a thin layer of marine sediment was deposited (Bendixen et al., 2015, 2017).

The paleochannels of the Dana river system, with associated spits and bars in the paleo coastal area, as well as the drainage of the Ancylus Lake, have shaped the south-western region of the HOWF area. A paleogeographical map of the southern Scandinavia showing the Hesselo Bay Area (Bendinxen et al., 2017) is shown on Figure 4.1, and further highlighted with bathymetry data and geophysical data in Figure 4.2 and Figure 4.3. The 2021 HOWF Bathymetry acquired as part of the project is superimposed on the right panel. It highlights the correlation of observed sand ridges in the south-western region of the HOWF site with the paleocoastline and associated spits and bars of the Dana river system. The East-West oriented gullies are interpreted as erosion unconformities likely associated with the drainage of Ancylus Lake. The features are thus not expected to have formed under present-day conditions or be associated with present-day seabed mobility processes.

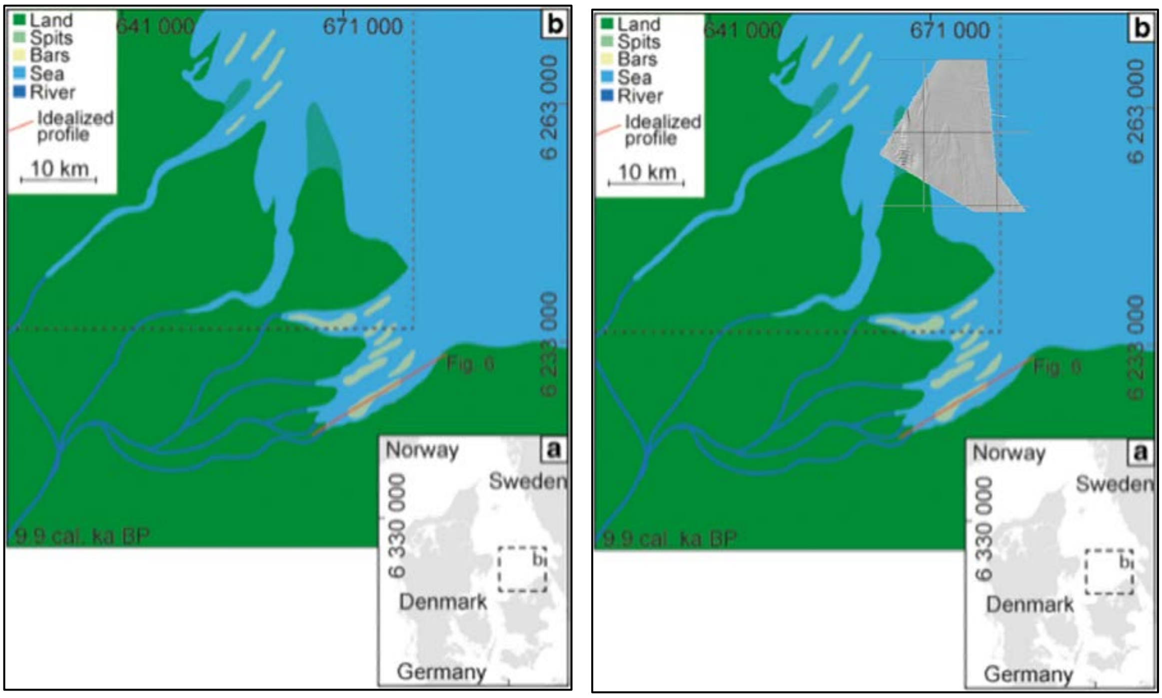

Figure 4.1: Paleogeographical map of the Hesselo Bay Area approx. 9.9 ka BP (left) and superimposed location of HOWF Bathymetry (right). Background map reproduced from Bendinxen et al., 2017)

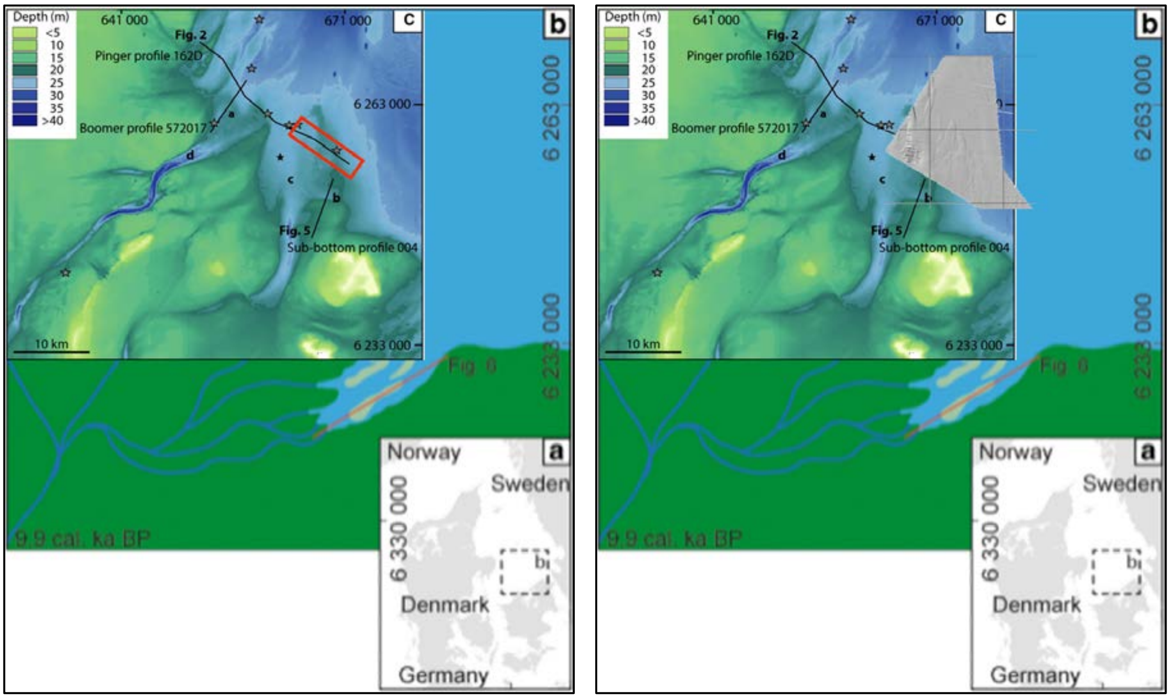

Figure 4.2: Map of the Hesselo Bay Area with regional bathymetry and geophysical data locations and profiles (left) and superimposed location of HOWF Bathymetry (right). Background map reproduced from Bendinxen et al., 2015; 2017)

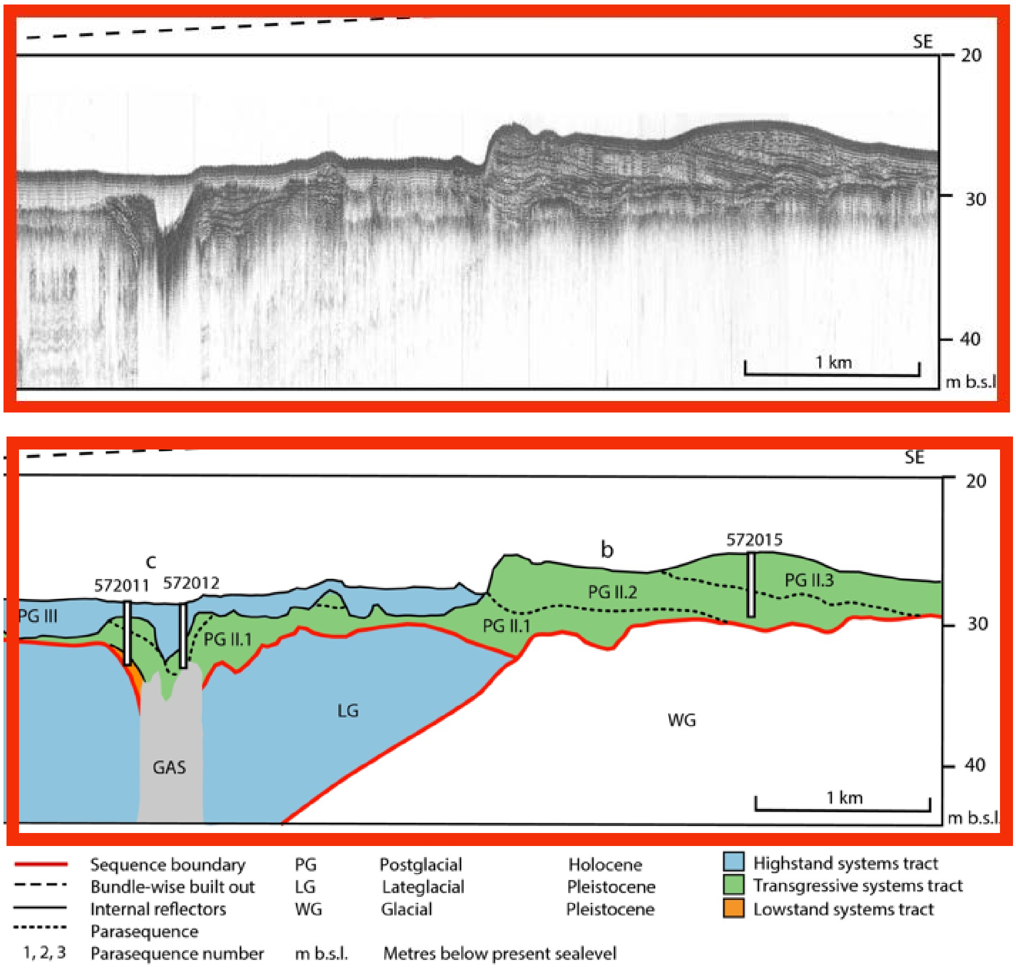

Figure 4.3: Sub-bottom and interpreted geophysical profile over the area highlight in red on Figure 4.2 (reproduced from Bendinxen et al., 2015).

4.2 Seafloor Morphology Context

The HOWF site is characterised by gentle seafloor slopes, on average between approximately 0˚ and 3˚. Seafloor gradients locally exceed 10˚, in areas of seafloor depressions and potential areas of debris.

An interpretation of the HOWF morphology is reported in (Fugro, 2021a). Various morphological features were identified at the seafloor. These include the following features of likely natural origin:

- Areas of circular seafloor depressions;
- Areas with occasional boulders;
- Erosional escarpments;
- Gullies;
- Ice-sculpted areas;
- Shoals.

Additionally, the following morphological features of anthropogenic origin were identified:

- Areas of debris;
- Trawl marks.

Trawl marks, in particular, are ubiquitous over the site. They indicate significant fishing activity, but the persistence of their signatures observed on the seabed suggests little reworking due to sea currents and waves.

Figure 4.4 presents an overview of these features across the project area.

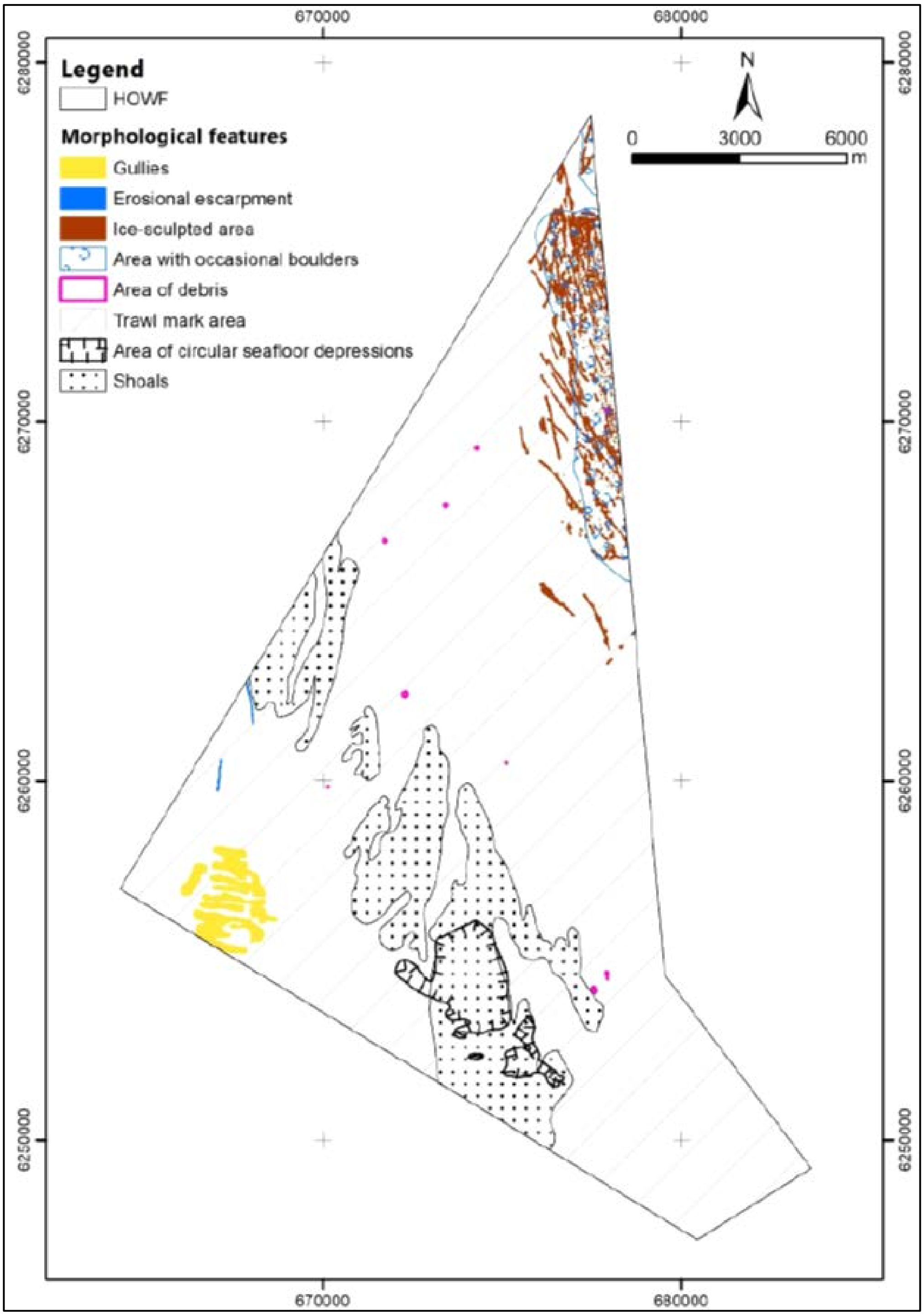

Figure 4.4: Seafloor morphology features (from Fugro, 2021a)

4.3 Seafloor Sediment Context

An overview of the seafloor sediment interpretation and classification is reported in Fugro (2021a) and summarized in Figure 4.5.

The seafloor sediments identified in the HOWF site comprise the following:

- Gravel and coarse sand;
- Sand;
- Muddy sand;
- Mud and sandy mud;
- Quaternary clay and silt.

The majority of the site is covered by fine sediment, muddy sand or sandy mud. The presence of the fine sediment suggests a predominantly depositional environment under present-day conditions.

Larger fractions of coarse sand and gravel are reported toward the north-easter area of the site, coinciding with likely ice-sculpted morphologies. Larger fractions of sand are found in the area of sand ridges and gullies in the south-western portion. This coincides with the area of paleochannels and coastal morphologies from the Dana river system.

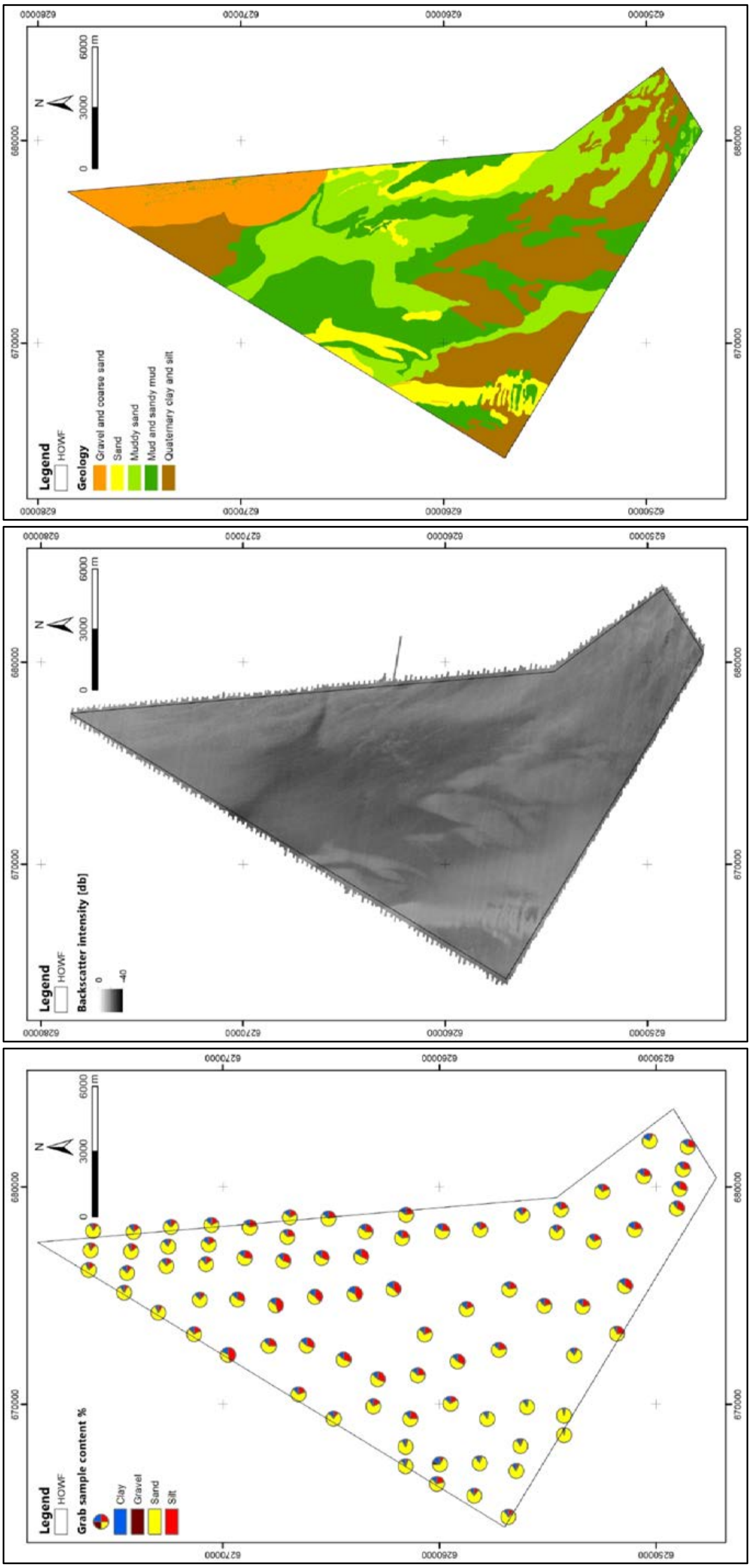

Figure 4.5: Seafloor sediment distribution. Top: interpreted seafloor sediment; Middle: backscatter intensity; Bottom: Grab Sample contents (from Fugro, 2021a)

5. Comparison of WPA-WPB Bathymetry

5.1 Overview of Bathymetry and Regional Changes

The WPB Bathymetry was acquired and processed in 6 blocks labelled E through K, as illustrated in Figure 5.1. Figure 5.2 presents a general view of WPB Bathymetry. Most of the morphological features discusses in section 4.2 are readily visible at that scale, i.e. sand ridges and gullies, shoals, escarpments and ice-shaped areas (Fugro, 2021a). Detailed inspection allows identifying the traces of the survey lines, in a North-North-West to South-South-West orientation.

Figure 5.3 presents a general view of WPA Bathymetry. No noticeable differences with WPB can be visualized at this scale. The traces of survey lines are visible, in a West-North-West to East-South-East orientation. They differ in orientation with those of WPB.

Figure 5.4 presents a visualization of bathymetric differences between WPA and WPB datasets. For the purpose of the comparison, both datasets have been resampled on the same grid at 0.5 m horizontal resolution. Positive values refer to areas where WPB Bathymetry lies higher than WPA, which may be an indication of sediment deposition if these changes were to be attributed to sediment mobility. By contrast, negative values indicate WPB Bathymetry is lower than WPA Bathymetry, possibly attributed to sediment removal or erosion processes.

Areas with differences of less than 5 cm in magnitude, either positive or negative, have been marked as transparent, letting the underlying hill-shaded bathymetry appear in the background. This zone covers most of the project area. The difference averaged over the complete project area amounts to less than 1 cm.

Areas with differences in excess of 25 cm are extremely limited across the site. They cannot be immediately correlated with the location of specific morphological features identified in section 4.2.

Several areas of differences in the range of 5 to 25 cm are observed. One of these areas features a strip of mostly positive values extending through the entire project area. This area roughly coincides with the limits of Survey Block H (Figure 5.1), and the differences should not be attributed to seafloor sediment mobility. Similarly, the area of Block E suggests negative differences generally aligned with the Block limits and should not be directly attributed to seafloor sediment mobility on that basis. A minor alignment of more frequent positive values is also visible along the orientation of the WPA survey lines, crossing the project area in a WNW-ESE orientation toward the northern limit of the sand ridge area. These observed systematic differences are interpreted to be mostly associated with uncertainties of the MBES measurement setup.

These uncertainties can be attributed to:

1. Difference in previous survey performed on Work Package A with IHO Special Order and Work Package B with IHO Order 1 A specifications.
2. Effect on sound velocity due to a dynamic pycnocline observed across the Hesselo site.
3. Significant effect of pycnocline to bathymetry data observed during Work Package A executed in January 2021 and Work Package B executed in September 2021.

Altogether, the regional analysis of the difference map does not reveal evident patterns of changes to be immediately attributed to sediment mobility. The differences are minor, and the observed changes appear to be mostly within the bounds of the inherent limitations of accuracy of the surveys, which are both meeting project specifications. The western region of the project area, where the sand ridges, gullies and escarpments are located, does reveal minor changes that merit further investigation. This is also the shallowest region of the site and the area where sand mostly prevails at seabed surface, and therefore the area most likely to feature mobile sediment. The next section presents a more detailed look at selected difference maps and seabed profiles in vicinity of several features of interest.

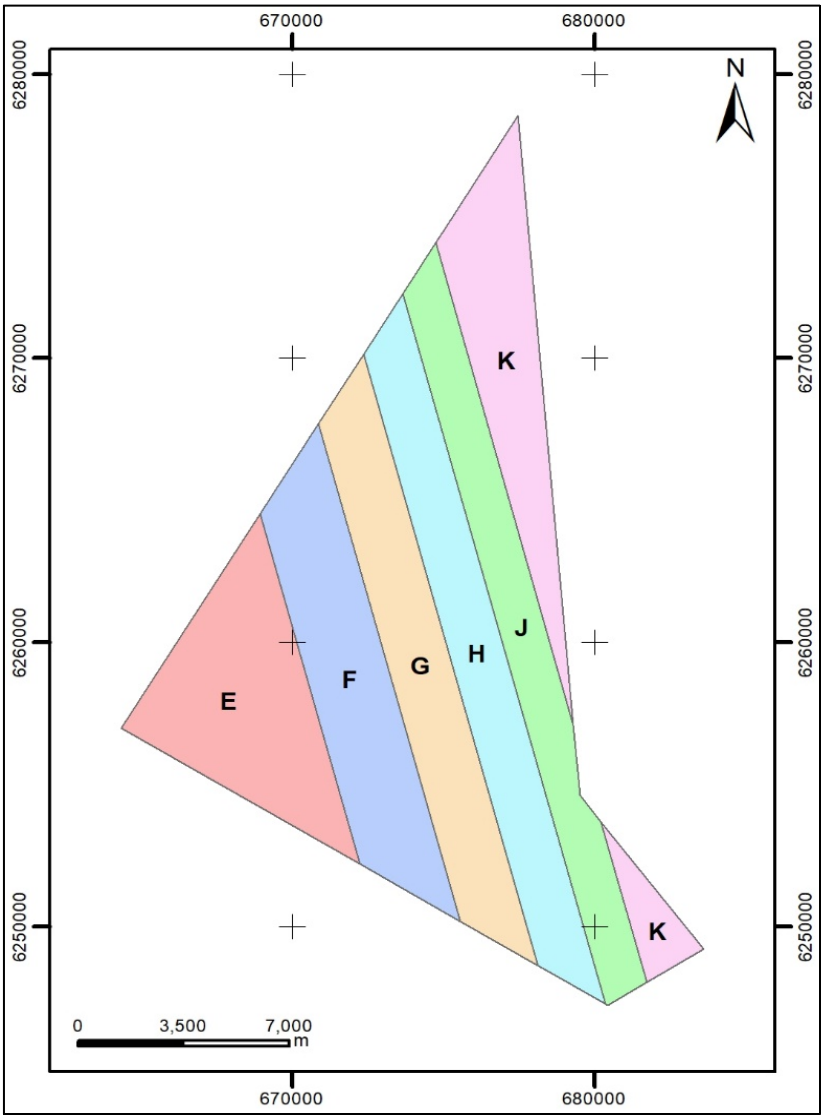

Figure 5.1: WPB Bathymetry block layout for MBES survey

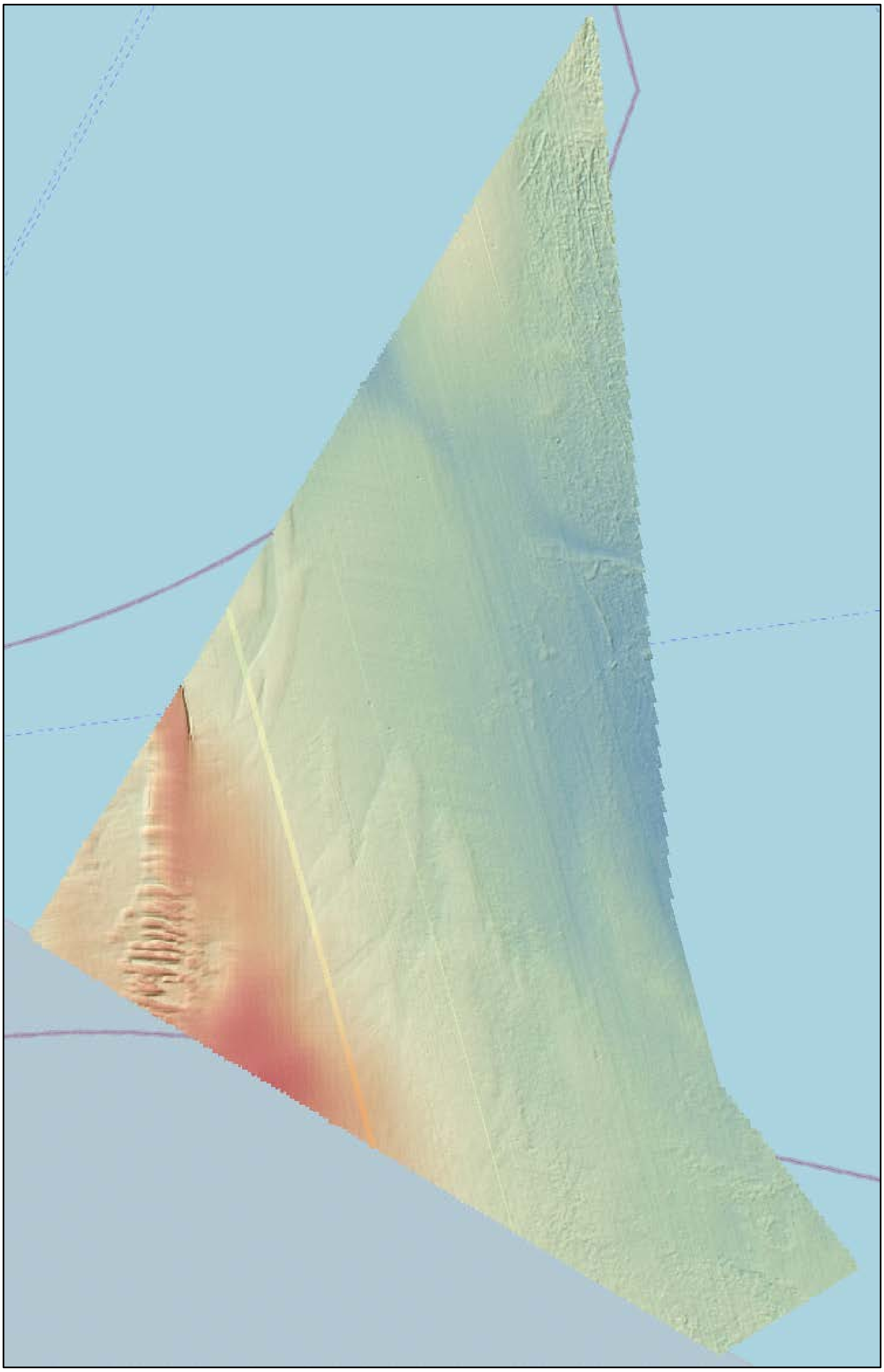

Figure 5.2: General overview of WPB Bathymetry

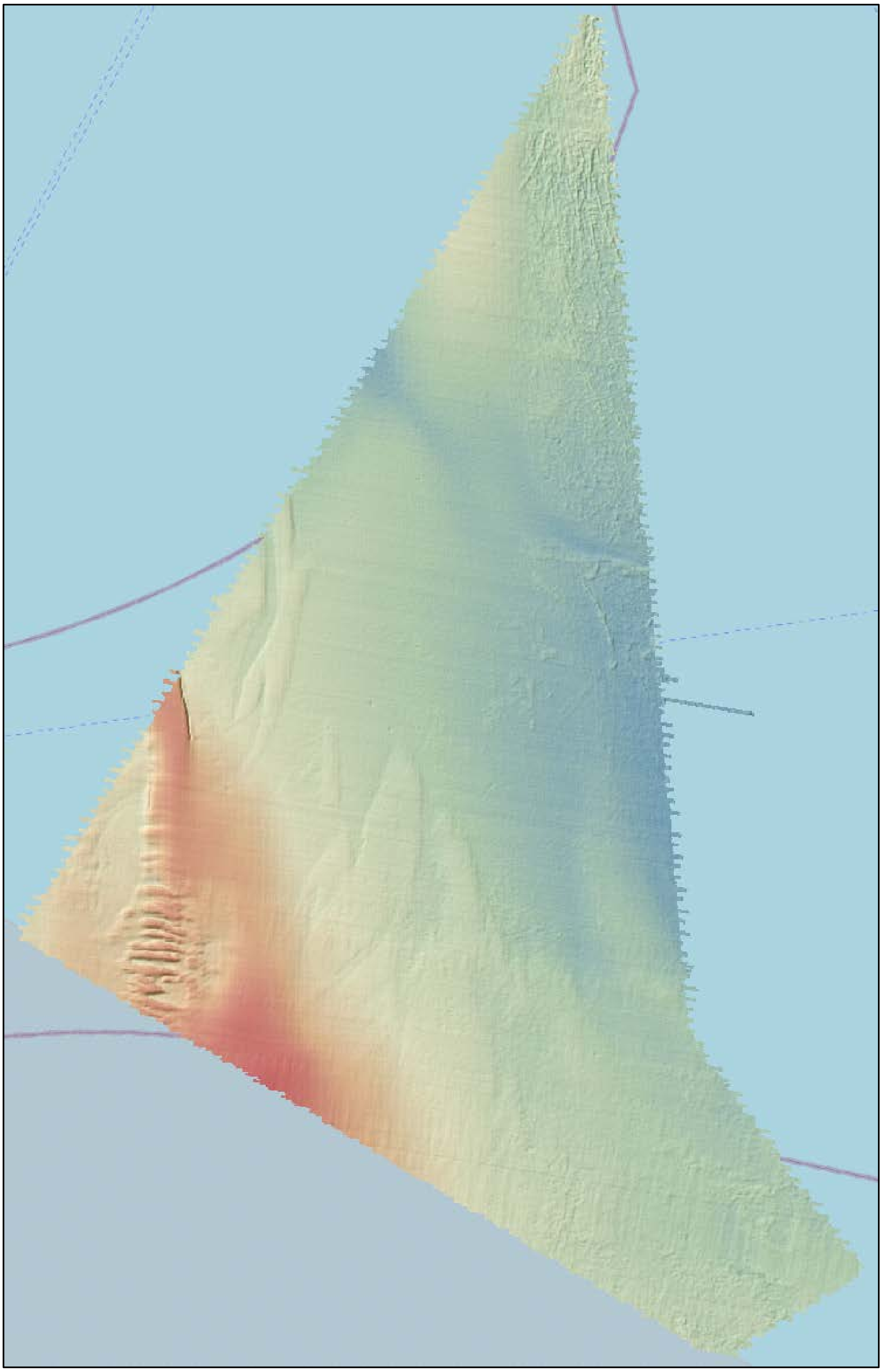

Figure 5.3: General overview of WPA Bathymetry

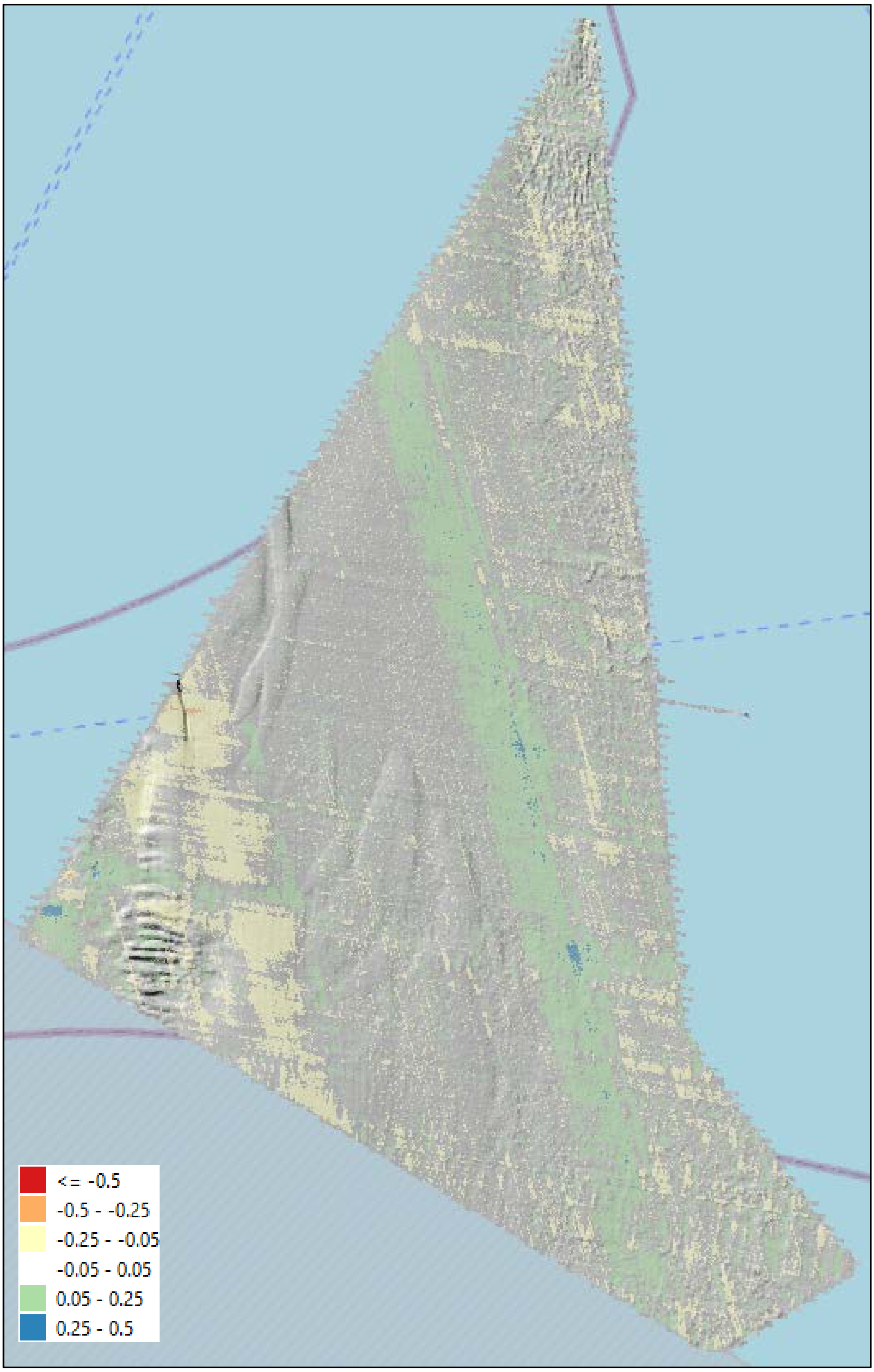

Figure 5.4: General overview of bathymetry differences between WPA and WPB. Positive values refer to areas where seabed elevation was interpreted as being higher for WPB than for WPA

5.2 Comparison of Bathymetries at Areas of Interest

5.2.1 Regional trends, North-South and East-West profiles

Figure 5.5 shows two transects across the entire project area in a general E-W and N-S orientation. The comparison of bathymetric profiles for WPA and WPB is shown for the two transects. Good general correlation is observed, and no obvious general trend of seabed evolution can be depicted at this large scale.

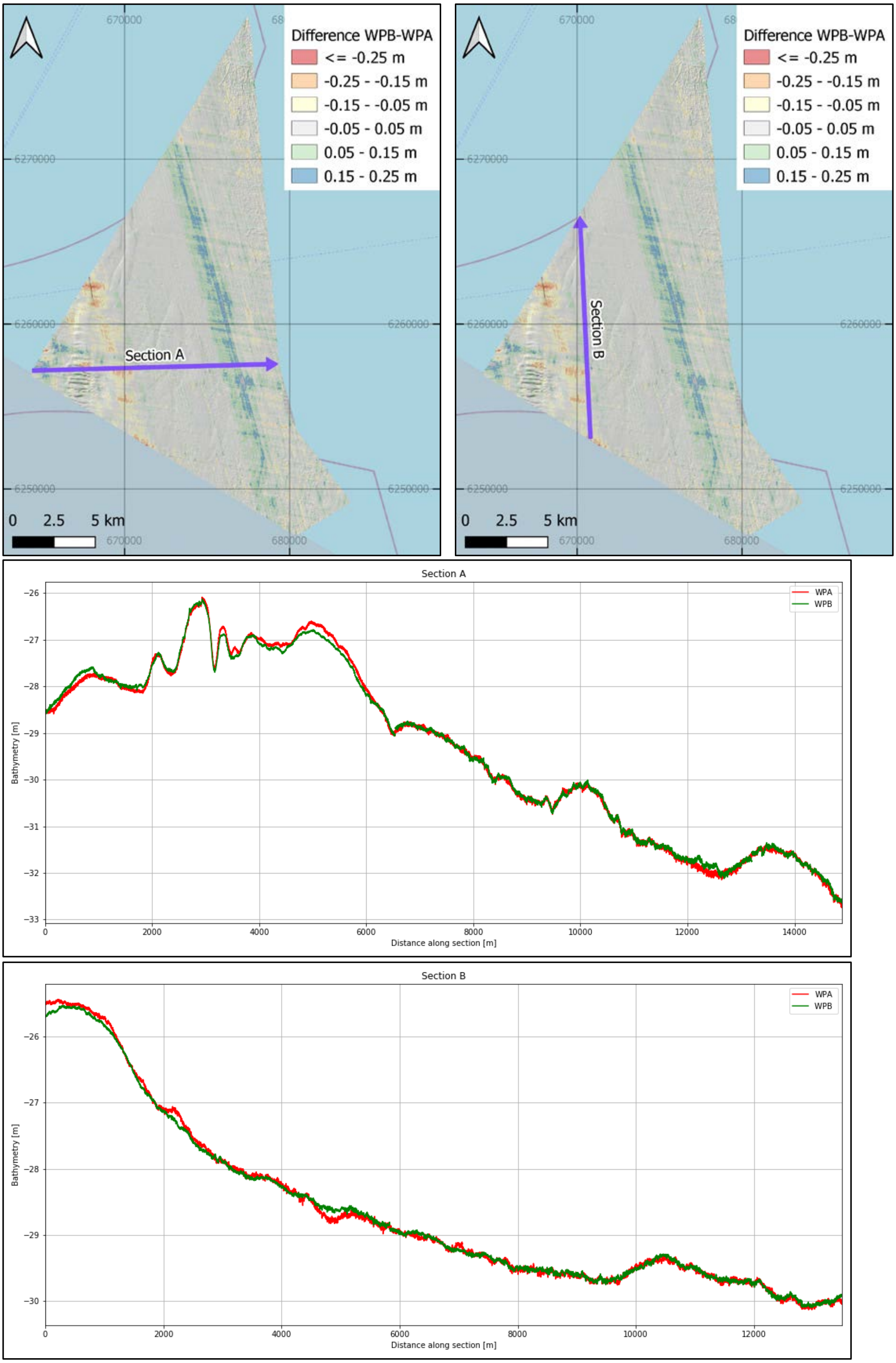

Figure 5.5: Bathymetric differences along a West to East transect (A) and a South to North transect (B)

5.2.2 Area of sand ridges and gullies

Figure 5.6 shows the difference in bathymetries across the gullies observed in the western portion of the site. For this and all subsequent Figures, on the top left panel a general map is shown, depicting in red the location of the sub-area shown on the top right panel. The colormap for the top right panel is according to the differences, identical to top-left panel.

The comparison suggests an apparent degree of seabed aggradation (~0.1 m) over most of the crests, especially toward the southern, shallower region, with the exception of one instance where both the crest and trough appear to undergo degradation. This particular instance is aligned with the stripe of more pronounced differences aligned with the WPA survey lines, as discussed in section 5.1. No net pattern of migration of the gullies is apparent.

Overall, the pattern of apparent changes is not reminiscent of typical patterns of sandwave migration, which is consistent with the interpretation that these features are primarily inherited from paleo-channel features as discussed in section 4.1.

Further investigation of the seabed mobility potential in this area, and its correlation with the prevailing metocean conditions, is advised.

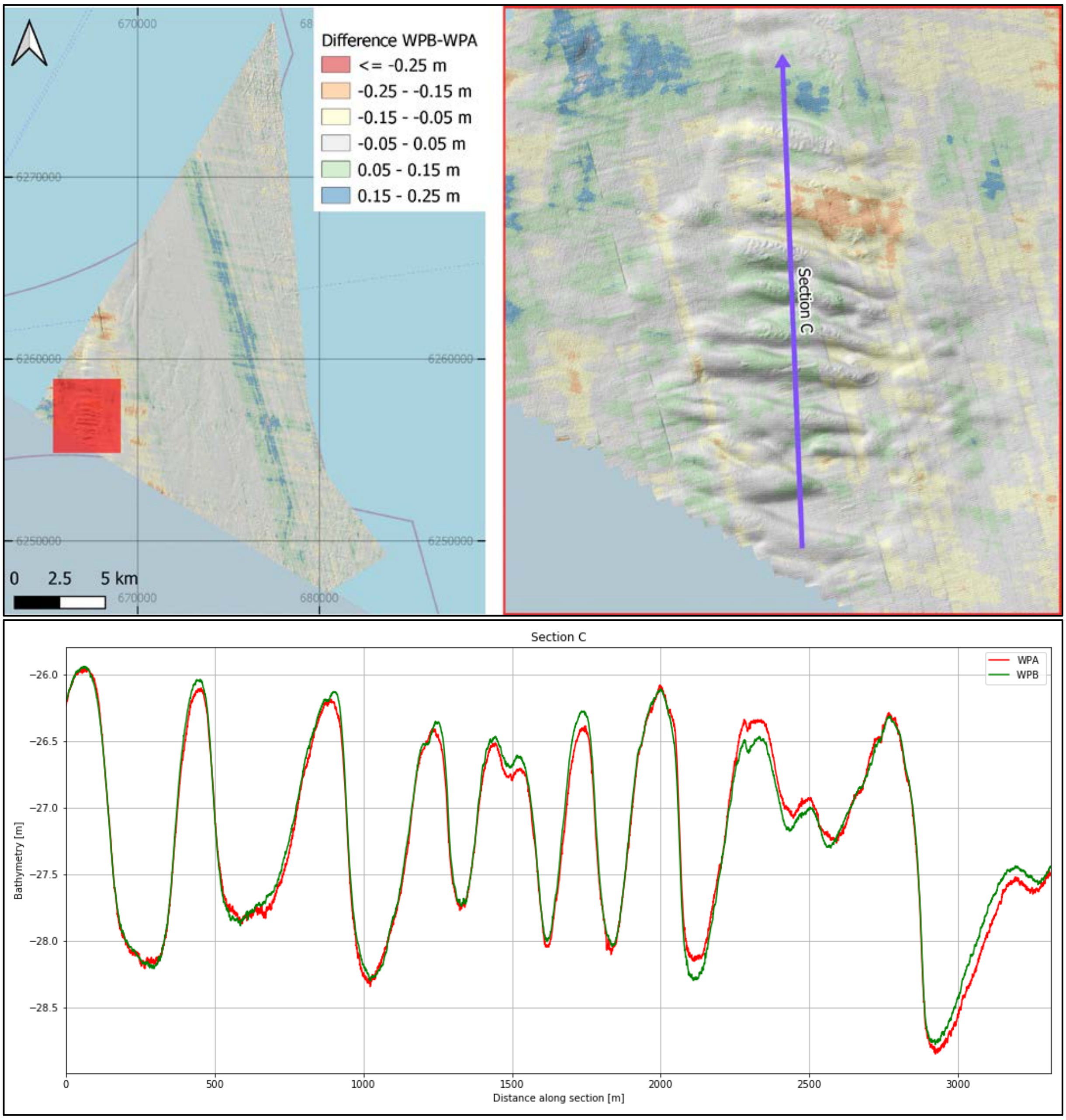

Figure 5.6: Bathymetric differences along a transect through the observed Sand Ridges and Gullies

5.2.3 Area of seabed escarpment

Figure 5.7 shows the differences along a transect perpendicular to a seabed escarpment to the North of the sand ridge area. The two bathymetric profiles for WPA and WPB are very similar, up to a constant offset of ~0.2 m. The morphology of the escarpment, trough and berm at the toe is very well preserved between the two surveys. The vertical offset is very likely not attributed to actual sediment mobility.

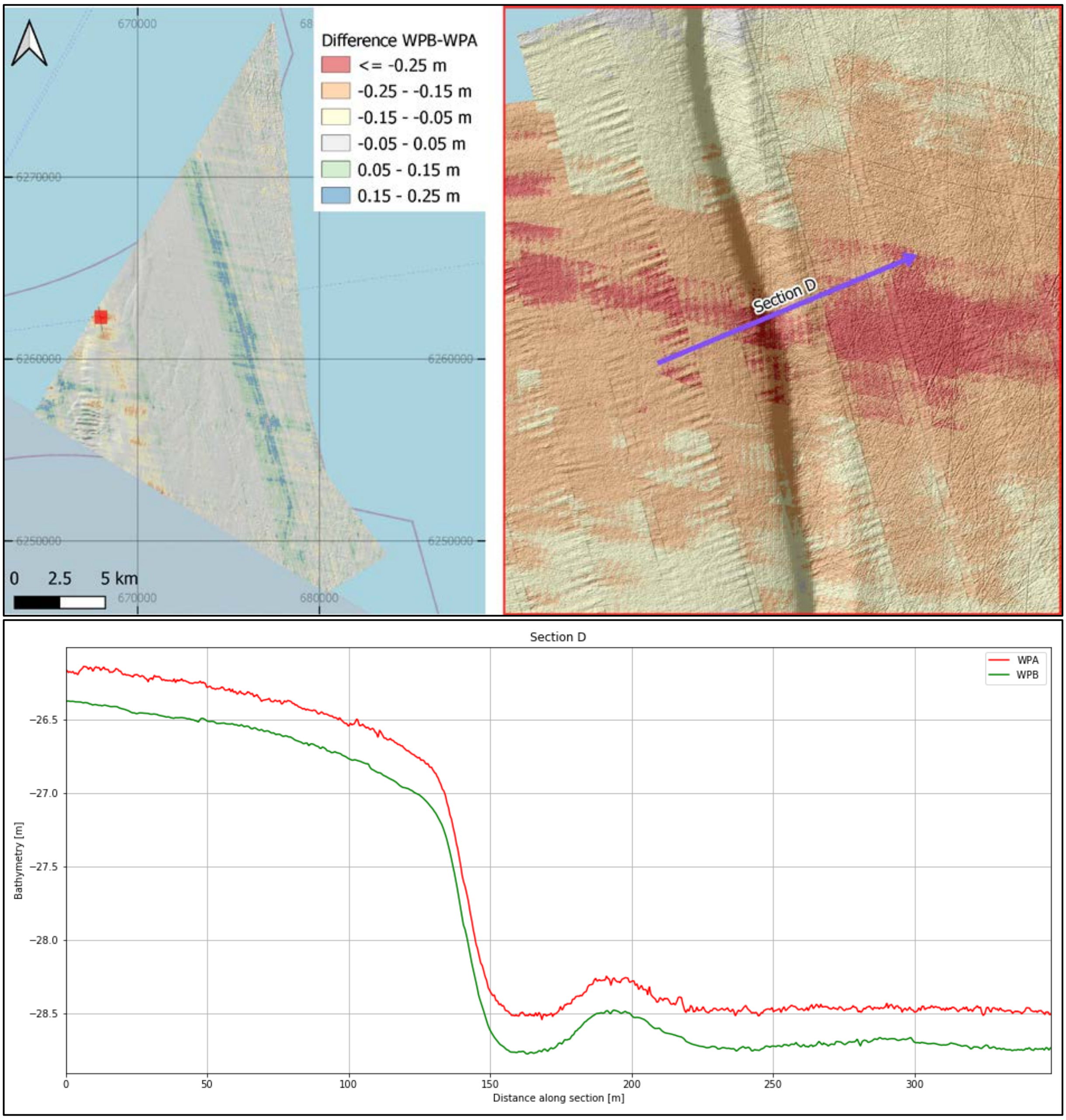

Figure 5.7: Bathymetric differences along a seabed escarpment

5.2.4 Area of seafloor objects

Figure 5.8 and Figure 5.9 show two transects across seabed objects/features. The features may represent boulders at seafloor. The two reported here have heights in the range of 0.1-0.2 m. Both profiles indicate a general preservation of the seafloor morphology at and around the object, again with a slight offset. For the first, WPB lies ~5 cm above WPA, for the second it lies 5 to 10 cm below WPA. In both instances, there is no clear indication that these would be attributed to actual sediment erosion or deposition over the inter-survey period. Indeed, in case of erosion, one would not anticipate the object/boulder to erode similarly to the neighbouring seabed.

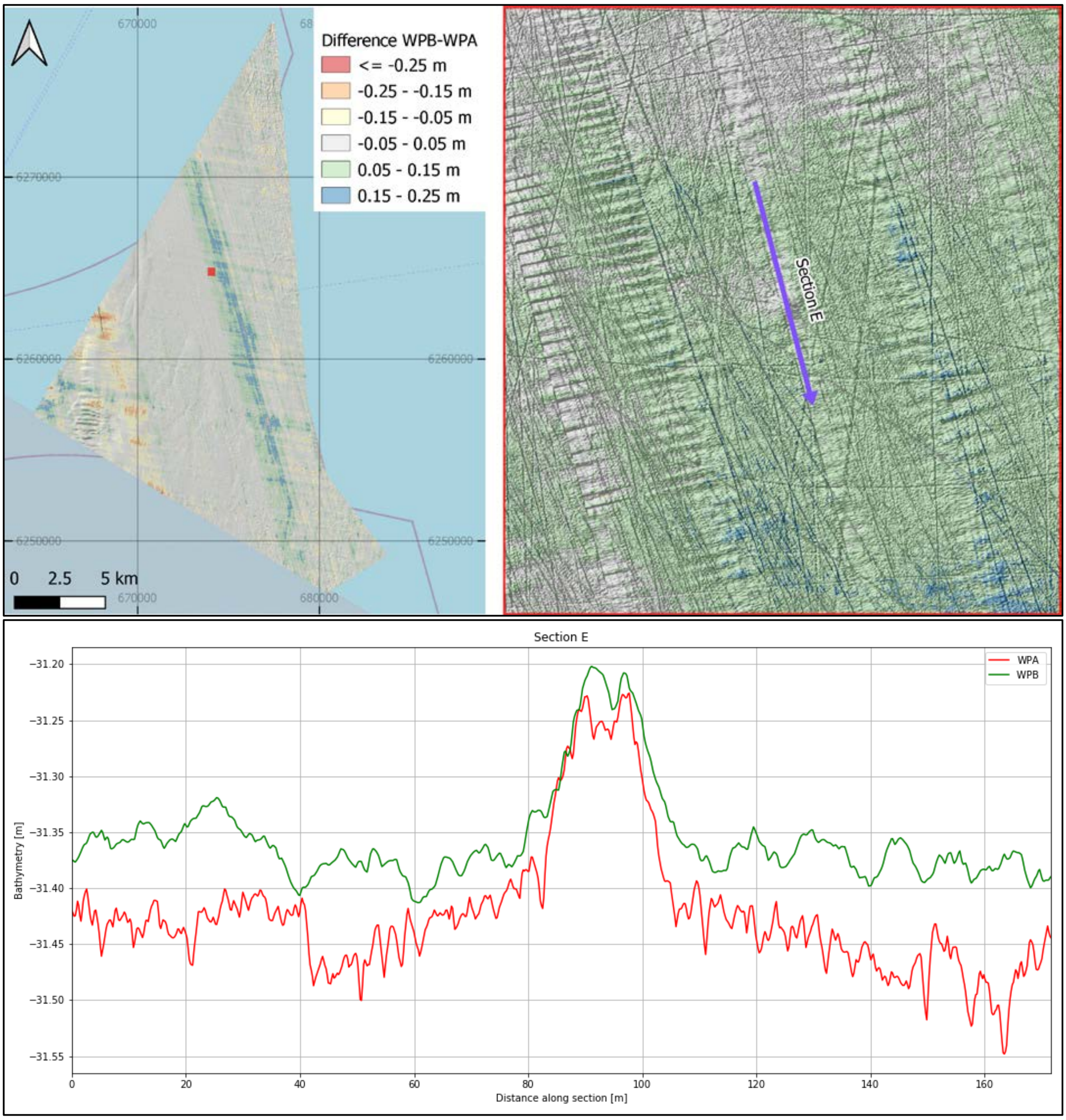

Figure 5.8: Bathymetric differences along a seafloor object, in an area where WPB lies higher than WPA

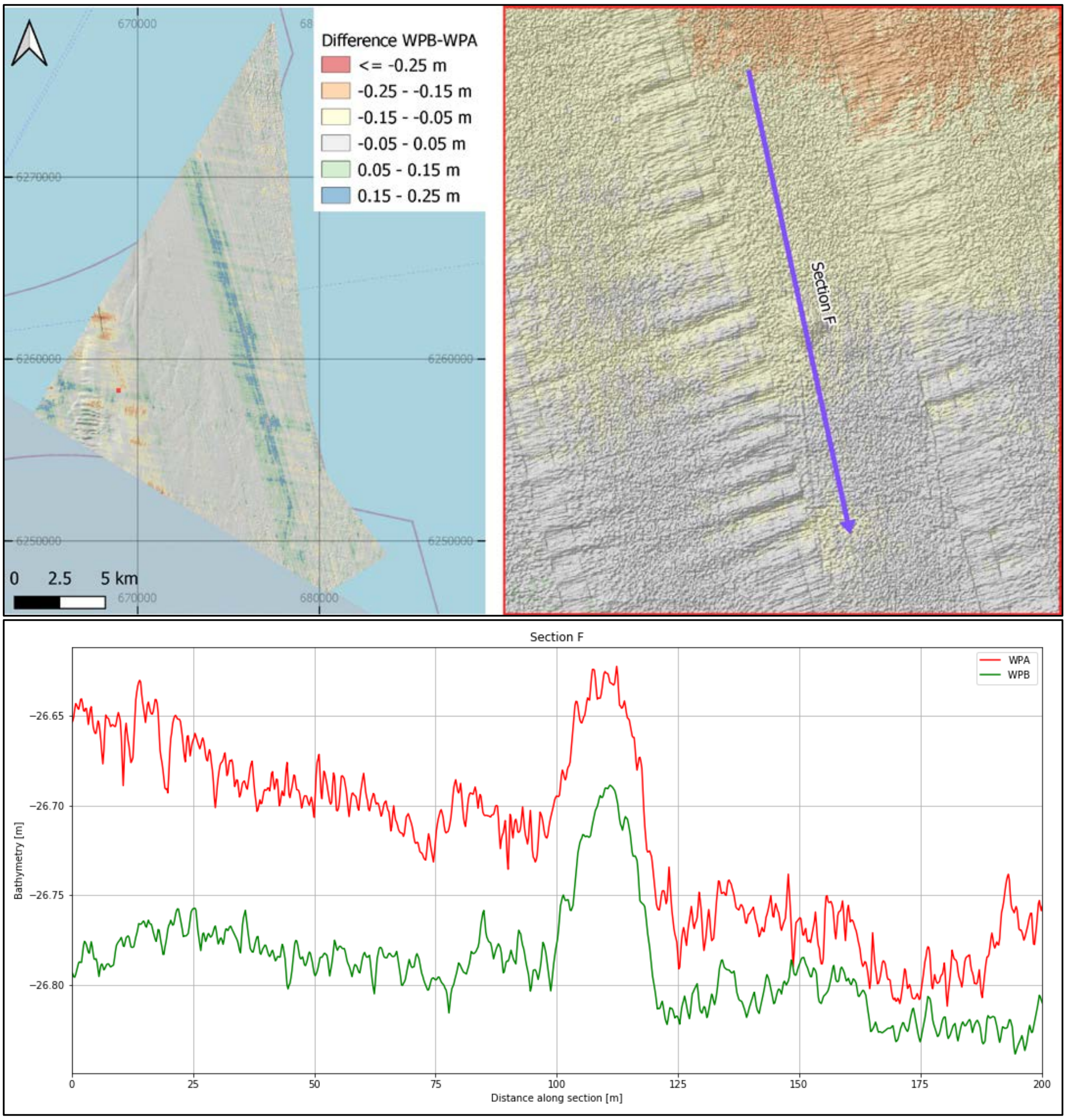

Figure 5.9: Bathymetric differences along a seafloor object, in an area where WPB lies lower than WPA

5.2.5 Area of seafloor depression of likely anthropogenic origin

Figure 5.10 highlights the differences around a mapped seabed depression in the area of the sand ridges. The depression is circular, has a depth of ~0.5 m and two representative diameters, an inner circle with a diameter of ~~10 m which is steeper, and an external diameter of ~100 m which features more gentle gradients. Several such depressions of similar shape and dimensions are visible, equally spaced in a western orientation. It is expected that these depressions are of anthropogenic origin.

The pattern of differences again suggests preservation of the feature, no sign of migration or differential behaviour between the two edges of the depression. Again, the near-constant offset of ~10 cm that is very unlikely attributable to sediment mobility.

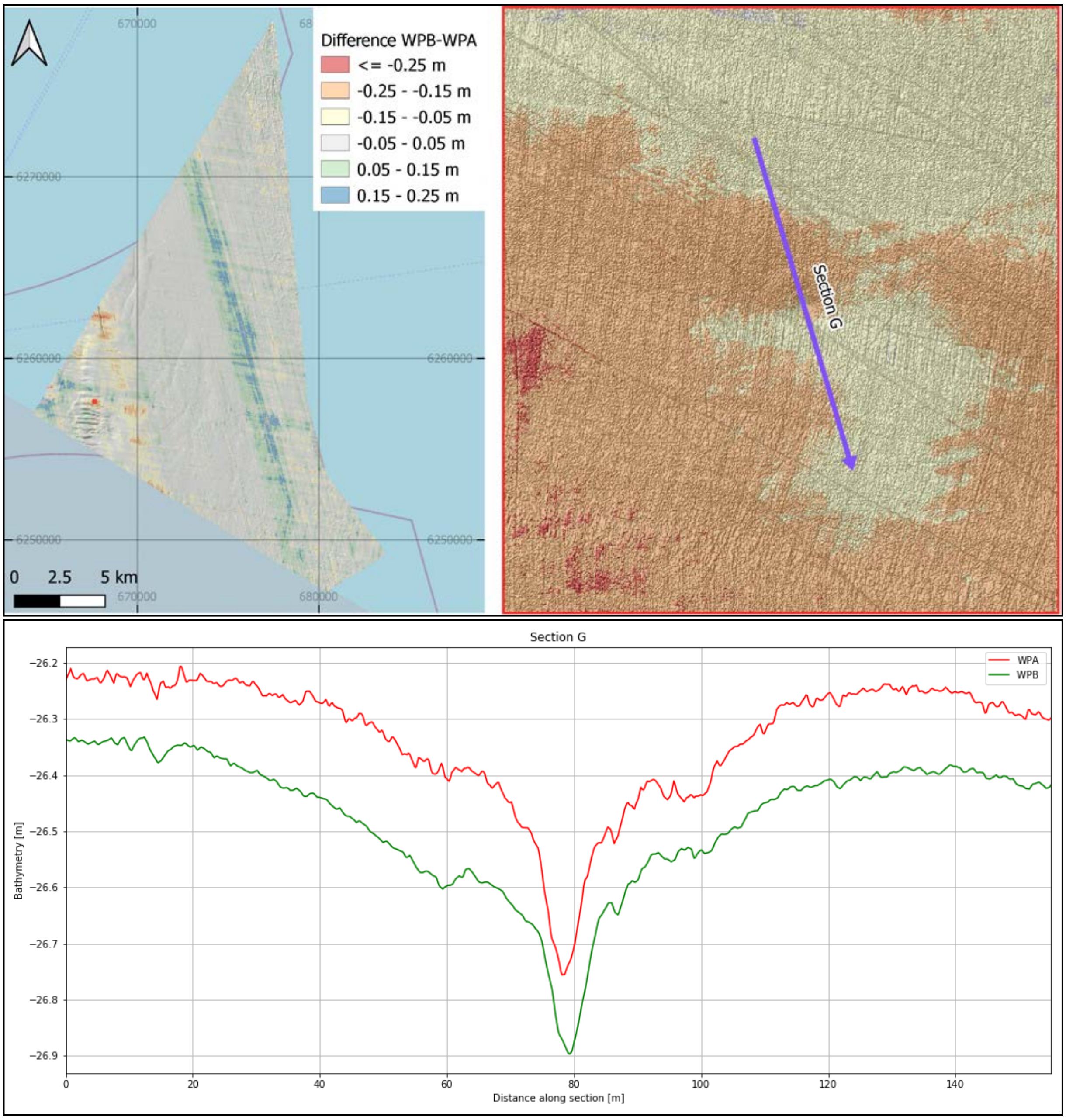

Figure 5.10: Bathymetric differences along a transect through seafloor depression of likely anthropogenic origin

5.2.6 Area crossing survey lines

Figure 5.11 highlights another area with minor changes observed between adjacent survey lines, which are within the limitations of the survey accuracy, and that should not be attributed to sediment mobility on that basis. The profile shows good agreement across the central WPB survey line, and slight positive or negative offsets of only a couple of centimetres on the adjacent lines.

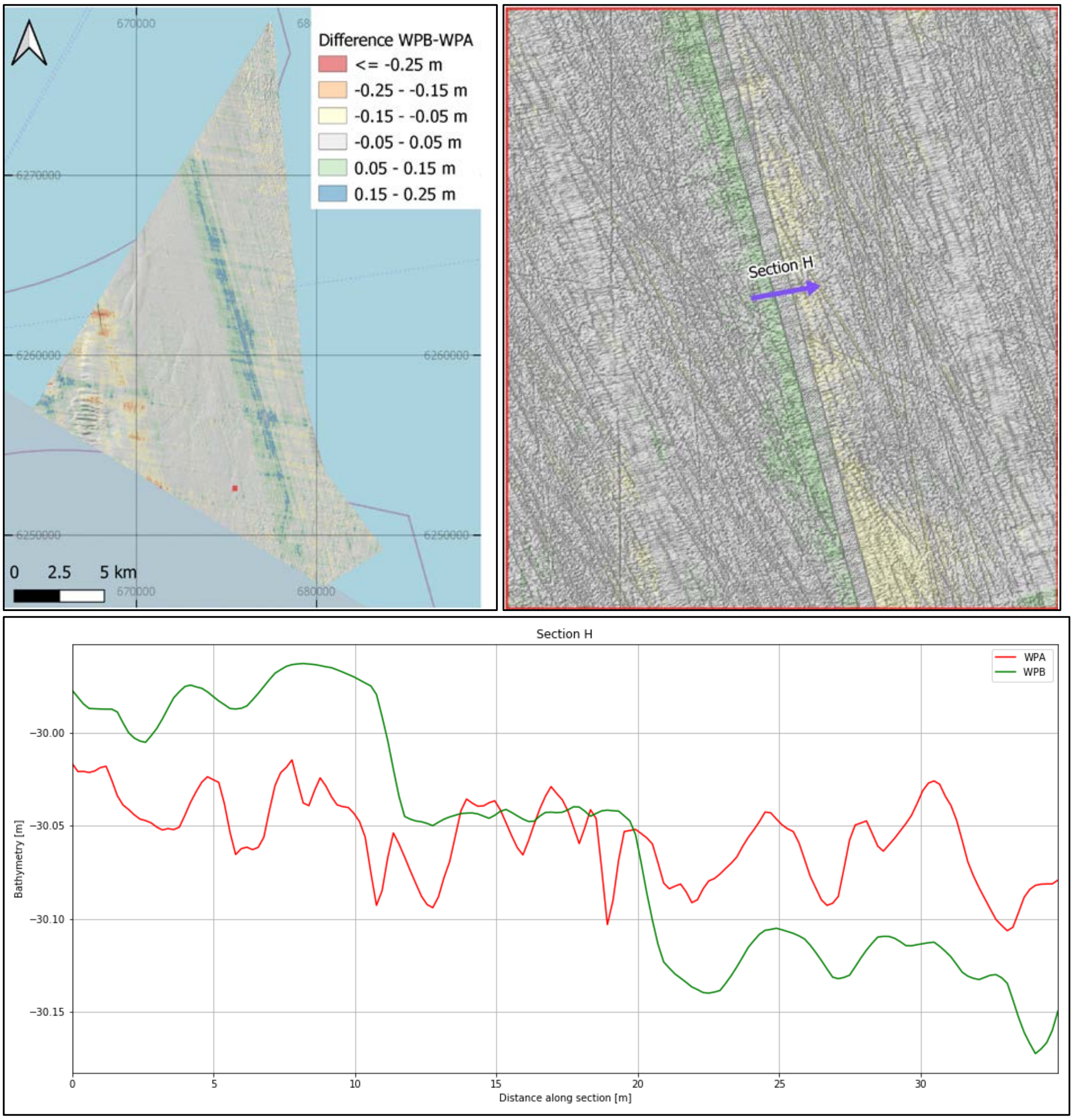

Figure 5.11: Bathymetric differences along a transect over adjacent survey lines

5.2.7 Area of multiple seabed depressions of unknown origin

Figure 5.12 and Figure 5.13 show the conditions at two areas of multiple seabed depressions of unknown origin. Multiple inconclusive hypotheses for their origin have been reported in the geophysical results report (Fugro, 2021a). In both cases, the morphology and sequence of the depressions is very well preserved between the two surveys. That is especially true for the second one. The first depression lies in the previously noted larger differences associated with survey Block H.

Altogether, these observations suggest no difference that is likely attributable to sediment mobility.

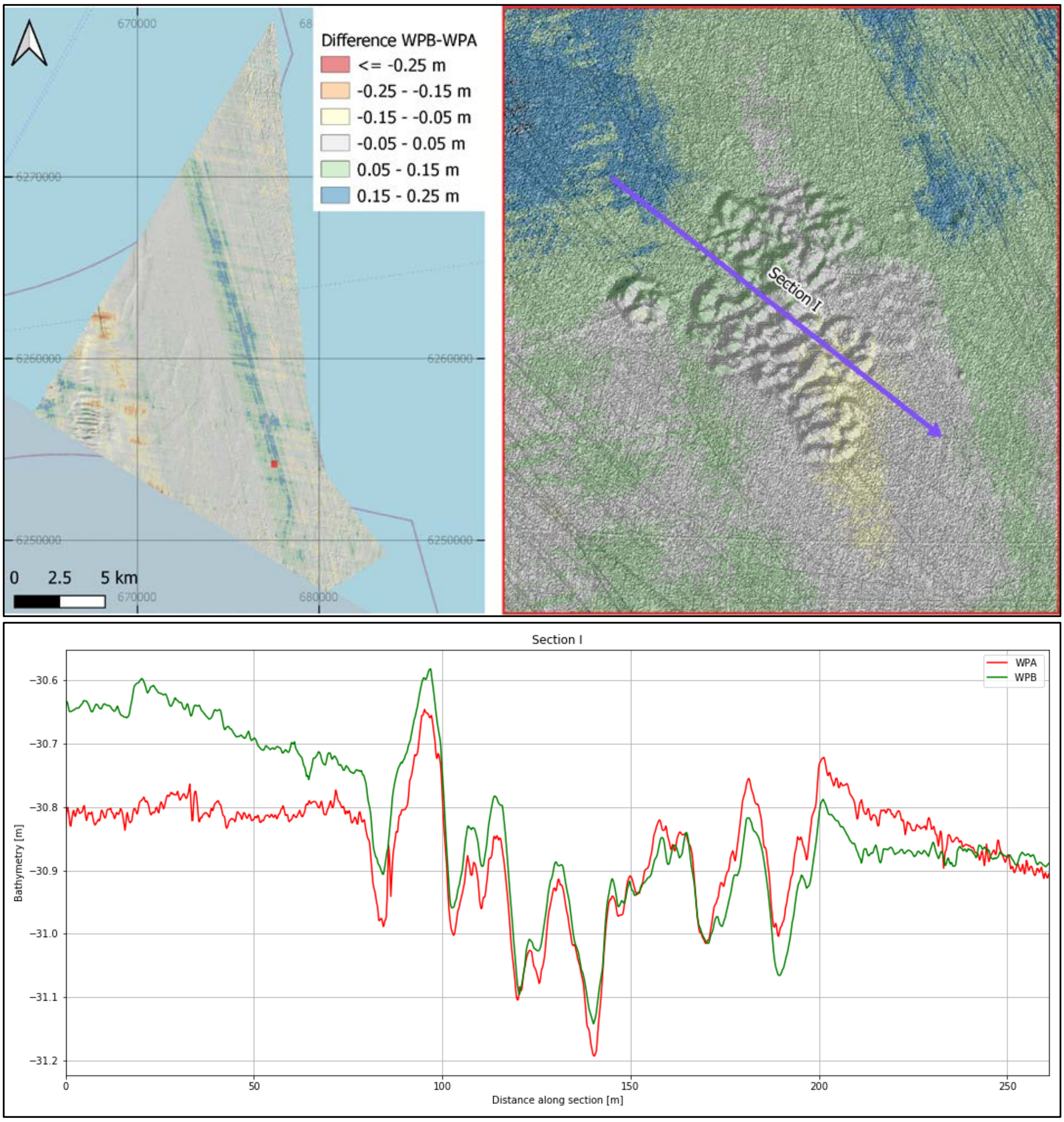

Figure 5.12: Bathymetric differences along a transect through multiple seafloor depressions of unknown origin

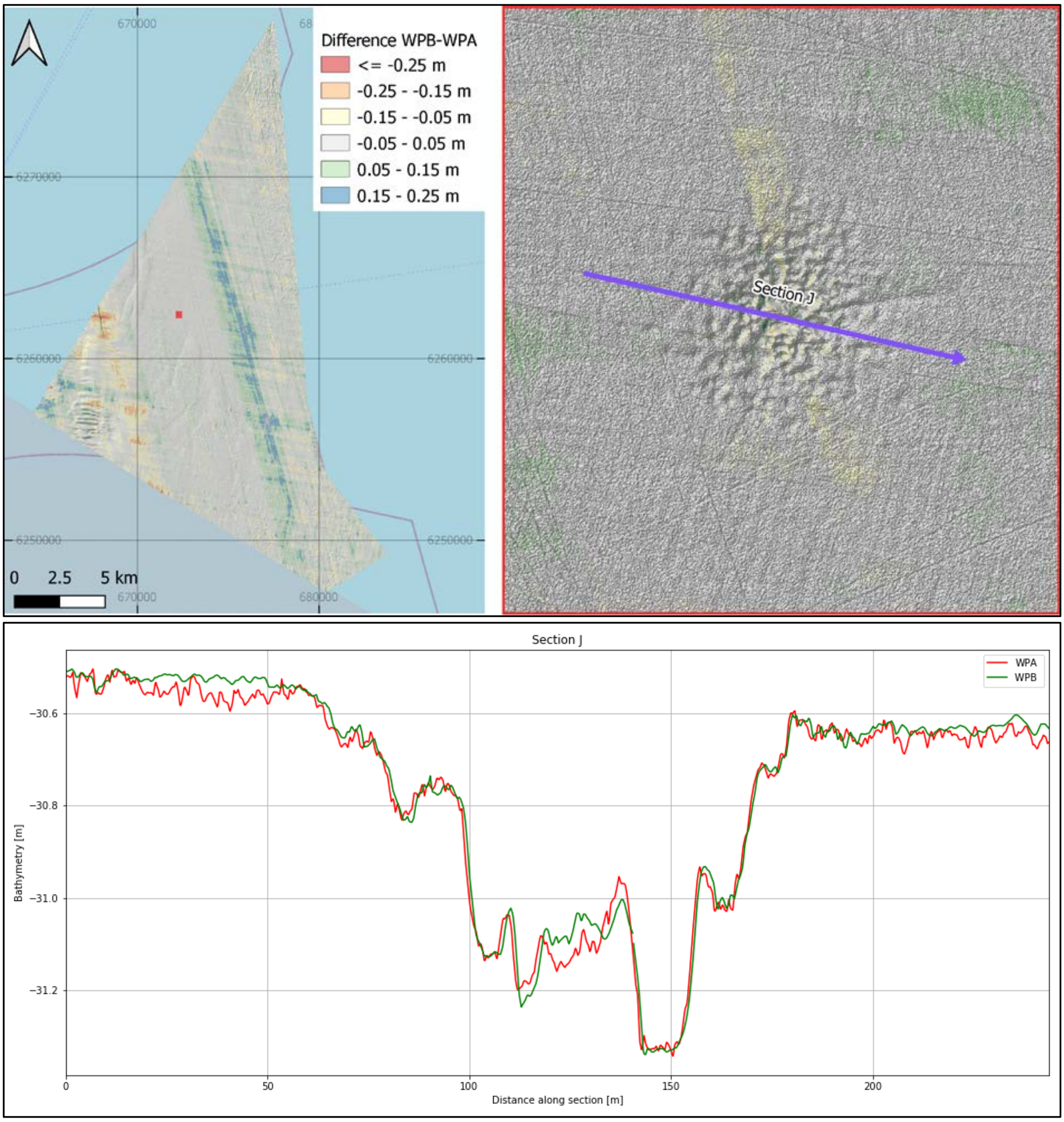

Figure 5.13: Bathymetric differences along a transect through a seafloor depression of unknown origin

5.2.8 Area of newly-formed depression of anthropogenic origin

Figure 5.14 presents one of the very few locations where significant and irrefutable changes in the seabed conditions have been observed to occur over the period separating WPA and WPB surveys. In that area, WPA reveals a largely featureless seabed with the exception of multiple trawl marks. WPB bathymetry reveals two significant depressions, with depths of ~0.7 to ~0.9 m, and extending over 20 to 50 m horizontally.

Careful inspection of the survey logs of WPB have revealed that a buoy was located in that area and requires a slight local deviation of the survey vessel. Detailed inspection of the point cloud of the MBES data allowed to locate traces of a submerged cable at the edge of one of the depressions, which would confirm that the depression is of anthropogenic origin and associated with the buoy deployment and anchoring.

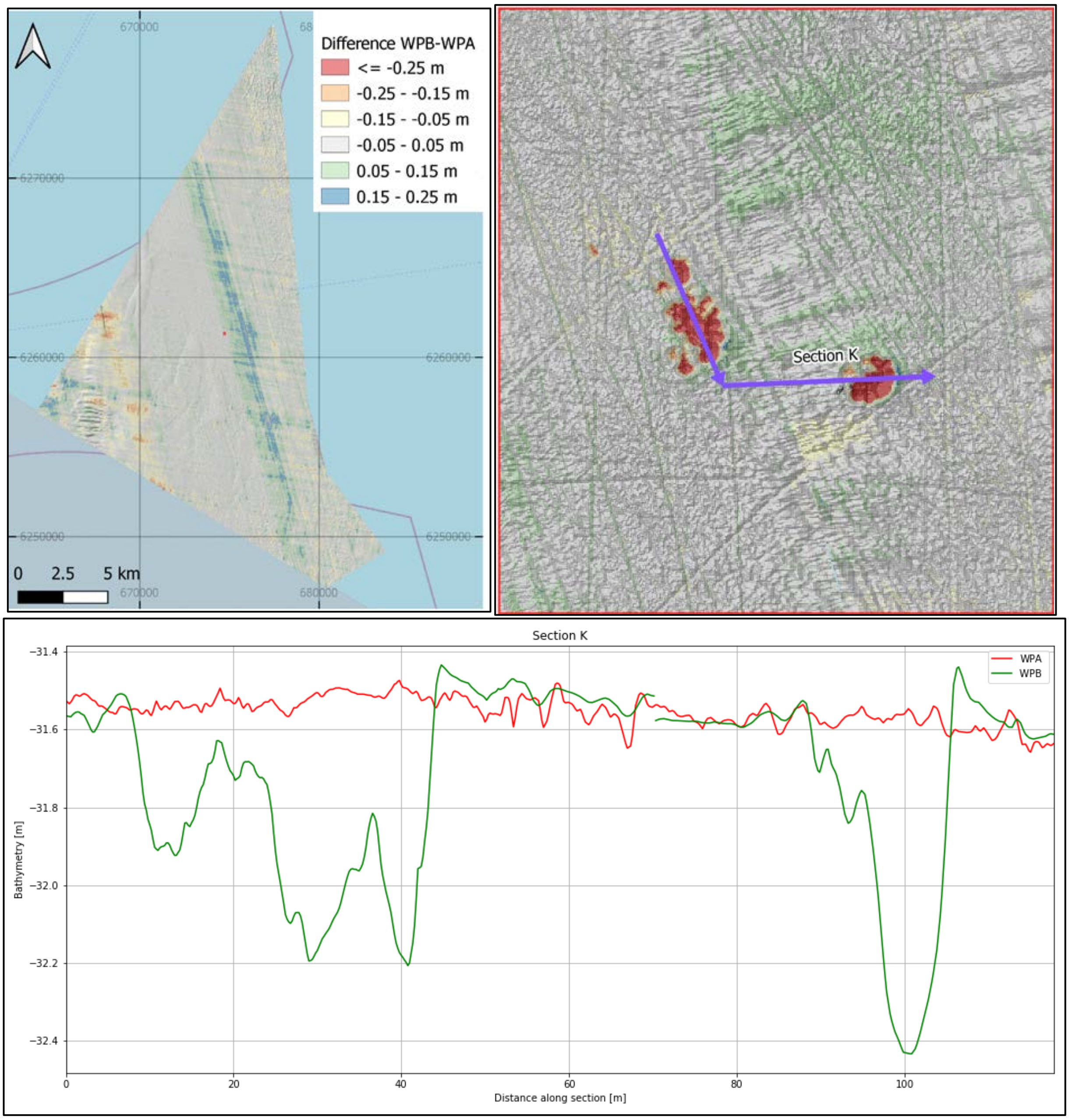

Figure 5.14: Bathymetric differences through a newly-formed depression of anthropogenic origin

6. Data Quality

6.1 Multibeam Echosounder

The multibeam bathymetry data collected were of good quality. Any noise present in the data was removed and the remaining data were corrected for variations in tidal height.

The spatial accuracies achieved for MBES sensor met the requirements set for the present project. THU was < 0.5 m and TVU are depth dependent values and the results were satisfying IHO Order 1A (IHO Standards for Hydrographic surveys, S-44 Edition).

Optimum power and gain settings were utilised during data acquisition to ensure high quality acquisition. During the survey, multibeam range changes were minimised to maintain the quality of the MBES data.

7. Conclusions

This report is part of the Hydrographical Survey Report associated with the WPB hydrographic survey conducted by the survey vessel Aurora for a new offshore wind farm in the inner Danish Sea, Kattegat, the Hesselo Offshore Windfarm (HOWF). The project area is located between Denmark and Sweden approximately 30km North of Sjælland. Survey operations for WPB on the Aurora occurred between 02 and 23 September 2021. A bathymetric dataset over the same area was also acquired as part of WPA survey, conducted using the survey vessels Fugro Pioneer and Fugro Frontier, between 14 October and 30 December 2020.

This report presents our analyses on a comparison of the two bathymetries, separated by a duration of circa 10 months, in view of documenting observed seabed changes and possibly link these with areas of potential sediment mobility. The observed seabed elevation changes between the two survey are mapped and interpreted in terms of the survey accuracy, the seabed conditions and the geological context of the area.

From the comparison between the two surveys, the Hesselø site is presumed to have been largely inactive in terms of dynamic seabed mobility over the period separating the two surveys. The observed elevation changes are well within the limits of the vertical accuracy of the respective surveys and are often organized in bands of near-constant differences aligned with the orientation of the survey lines of either WPA or WPB. A plausible explanation for these differences lies in a strong and rapidly varying pycnocline in the area, and the associated change in sound velocity may slightly affect absolute depth measurements of the multibeam echosounder instrument, still within the survey specifications.

The absence of significant morphological changes related to sediment mobility over the period is confirmed by the good preservation of a number of seabed features observed across the project area, such as: (i) widespread minor linear depression marks typically associated with trawling activities, (ii) local depressions of likely anthropogenic origin or unconfirmed origin, (iii) sand ridges, (iv) escarpments. The sand ridges and escarpments observed in the south-western region of the project area are interpreted as geological features associated with the paleo-channels, spits and bars of the Dana river system, and the rapid drainage of the Ancylus Lake via the Dana river system through the Storebælt into the Kattegat between 11.9 and 9.1 ka BP. The lack of net migration of the sand ridges over longer time spans appears to be confirmed by the review of sub-bottom geophysical data. This area, which coincides with the shallowest area of the site and the presence of more abundant sand fractions at seabed, would merit further assessment of the sediment mobility potential in conjunction with an analysis of the prevailing metocean conditions. Some seabed features interpreted as boulders, more abundant toward the northern and eastern regions of the site, do present minor depressions around them, amounting to only a fraction of the estimated object dimension, and suggest local scour may occur in association with extreme metocean conditions. No other markers of significant seabed mobility, such as e.g. asymmetrical bedforms, megaripples, sand waves, scour or obstacle marks, were observed.

An area of newly-formed depressions on the seabed between the two surveys has been mapped, and has been interpreted as likely linked with the deployment of a buoy and associated anchor cables.

It is noted that the two surveys are separated by a duration of less than a year, and the metocean conditions experienced over the period are unlikely to be fully representative of the variable metocean conditions over the project area, in particular in terms of the occurrence of extreme events. Therefore, while the quantitative comparison of WPA-WPB bathymetries reported herein suggests a low degree of sediment mobility activity for normal conditions, it does not represent a comprehensive seabed mobility/morphology study of the site, and should not be used for design purposes that require the consideration of potential extreme events.

8. References

Fugro (2021a) Geophysical Results Report. Energinet Denmark Hesselø Geophysical Survey. Fugro report F172145-REP-GEOP-001(02), 13 August 2021.

Bendixen, C., Jensen, J.B., Boldreel, L.O., Clausen, O.R., Bennike, O., Seidenkrantz, M.-S., Nyberg, J., and Hübscher, C. (2015). The Holocene Great Belt connection to the southern Kattegat, Scandinavia: Ancylus Lake drainage and Early Littorina Sea transgression. Boreas 46(1), 53-68. https://doi.org/10.1111/bor.12154

Bendixen, C., Boldreel, L.O., Jensen, J.B., Bennike, O., Hübscher, C., and Clausen, O.R. (2017). Early Holocene estuary development of the Hesselø Bay area, southern Kattegat, Denmark and its implication for Ancylus Lake drainage. Geo-Marine Letters 37, 579-591. https://doi.org/10.1007/s00367-017-0513-7

Erlström, M., and Sivhed, U. (2001). Intra-cratonic dextral transtension and inversion of the southern Kattegat on the southwest margin of Baltica – Seismostratigraphy and structural development. Sverige Geologiska Undersökning. Research Paper C 832.

GEUS. (2020). General geology of southern Kattegat; the Hesselø wind farm area; Desk Study. GEUS Rapport 2020/53.

Jensen, J.B., Petersen, K.S., Konradi, P., Kuijpers, A., Bennike, O., Lemke, W., and Endler, R. (2002). Neotectonics, sea-level changes and biological evolution in the Fennoscandian Border Zone of the southern Kattegat Sea. Boreas 31(2), 133-150. https://doi.org/10.1111/j.1502-3885.2002.tb01062.x

Larsen, N.K., Knudsen, K.L., Krohn, C.F., Kronborg, C., Murray, A.S., and Nielsen, O.B. (2009). Late Quaternary ice sheet, lake and sea history of southwest Scandinavia – a synthesis. Boreas 38(4), 732-761. https://doi.org/10.1111/j.1502-3885.2009.00101.x

Appendices

Appendix A Guidelines on Use of Report

Appendix B Charts

Appendix C Digital Deliverables

Appendix A

Guidelines on Use of Report

FUGRO

This report (the "Report") was prepared as part of the services (the "Services") provided by Fugro for its client (the "Client") and in accordance with the terms of the relevant contract between the two parties (the Contract"). The Services were performed by Fugro in accordance with the obligations in the Contract and based on requirements of the Client set out in the Contract or otherwise made known by the Client to Fugro and any other information affecting the Services at the time; save that the extent to which Fugro relied on Client or third party information in carrying out the Services was set out in the Contract.

Fugro's obligations and liabilities to the Client or any other party in respect of the Services and this Report are limited to the extent and for the time period set out in the Contract (or in the absence of any express provision in the Contract as implied by the law of the Contract) and Fugro provides no other representation or warranty whether express or implied, in relation to the Services, or for the use of this Report, for any other purpose. Furthermore, Fugro has no obligation to update or revise this Report based on any future changes in conditions or information which emerge following issue of this Report unless expressly required by the provisions of the Contract.

The Services were performed by Fugro exclusively for the Client and any other party expressly identified in the Contract, and any use and/or reliance on the Report or the Services for purposes not expressly stated in the Contract, will be at the Client's sole risk. Any other party seeking to rely on this Report does so wholly at its own and sole risk and Fugro accepts no liability whatsoever for any such use and/or reliance."

Appendix B

Charts

Charts (detailed below) have been presented as a separate PDF file.

Chart Type	Chart Name
OVERVIEW CHART	SN2020_031_Hesselo_OWF_WPB_01_NU_25k_OVERVIEW_NORTH
OVERVIEW CHART	SN2020_031_Hesselo_OWF_WPB_02_NU_25k_OVERVIEW_SOUTH
CRP TRACKS CHART	SN2020_031_Hesselo_OWF_WPB_03_NU_25k_CRP_TRACK_NORTH
CRP TRACKS CHART	SN2020_031_Hesselo_OWF_WPB_04_NU_25k_CRP_TRACK_SOUTH
SHADED RELIEF BATHYMETRY CHART	SN2020_031_Hesselo_OWF_WPB_05_NU_25k_SHR_BTY_NORTH
SHADED RELIEF BATHYMETRY CHART	SN2020_031_Hesselo_OWF_WPB_06_NU_25k_SHR_BTY_SOUTH
BATHYMETRY DIFFERENCE CHART	SN2020_031_Hesselo_OWF_WPB_07_NU_25k_BTY_DIFF_NORTH
BATHYMETRY DIFFERENCE CHART	SN2020_031_Hesselo_OWF_WPB_08_NU_25k_BTY_DIFF_SOUTH

Appendix C

Digital Deliverables

Deliverable Type	Sensor	Deliverable ID	Deliverable Content	Format
Final Deliverable	ALL	FD_001	Electronic database of deliverables	XLSX
Final Deliverable	ALL	FD_002	TSG Geodatabase	GDB
Final Deliverable	MBES	FD_003	Fugro Point file (0.5 m)	XYZ
Final Deliverable	MBES	FD_004	Fugro Point file (1.0 m)	XYZ
Final Deliverable	MBES	FD_005	Fugro Point file (5.0 m)	XYZ
Final Deliverable	MBES	FD_006	TVU (1.0 m)	XYZ
Final Deliverable	MBES	FD_007	THU (1.0 m)	XYZ
Final Deliverable	MBES	FD_008	MBES Soundings data	XYZ
Final Deliverable	SVP	FD_009	SVP Profiles	XLSX