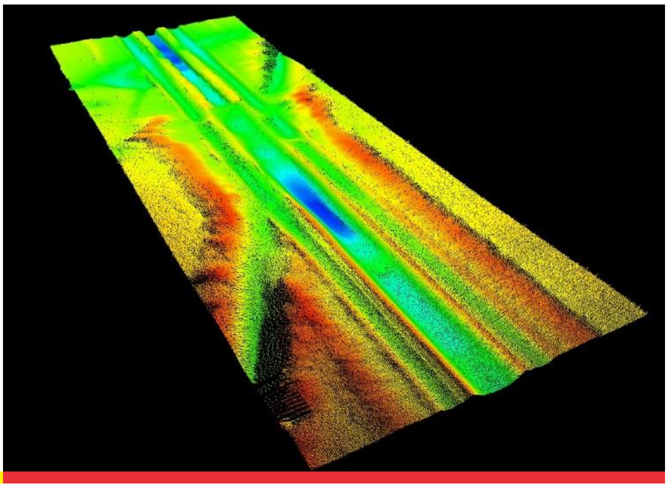
HYDROGRAPHIC SURVEY REPORT

103628-ENN-MMT-SUR-REP-SURVOWF
REVISION 02 | CLIENT REVIEW
OCTOBER 2020

ENERGINET



THOR OFFSHORE WIND FARM

DANISH NORTH SEA
AUGUST-SEPTEMBER 2020

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MMT

EXECUTIVE SUMMARY

THOR OFFSHORE WIND FARM SITE INVESTIGATION – OWF	
INTRODUCTION	
Survey Dates	15 July to 4 September 2020
Equipment	Multibeam Echo Sounder (MBES)
Coordinate System	Datum: European Terrestrial Reference System 1989 (ETRS89) Projection: Universal Transverse Mercator (UTM) Zone 32N, Central Meridian (CM) 9°E

BATHYMETRY AND SEAFLOOR MORPHOLOGY

During the 2020 repeat survey of the OWF coverage was achieved across 88.23% of the total area. The minimum surveyed depth is -20.23 m at 421112.5 m E, 6248235.0 m N in the northern part of the survey. The maximum depth surveyed depth is -35.40 m at 406 209 m E, 6 240 966 m N in the western area. In the 2019 survey the minimum and maximum depths were -20.38 m and 35.43 m, respectively.

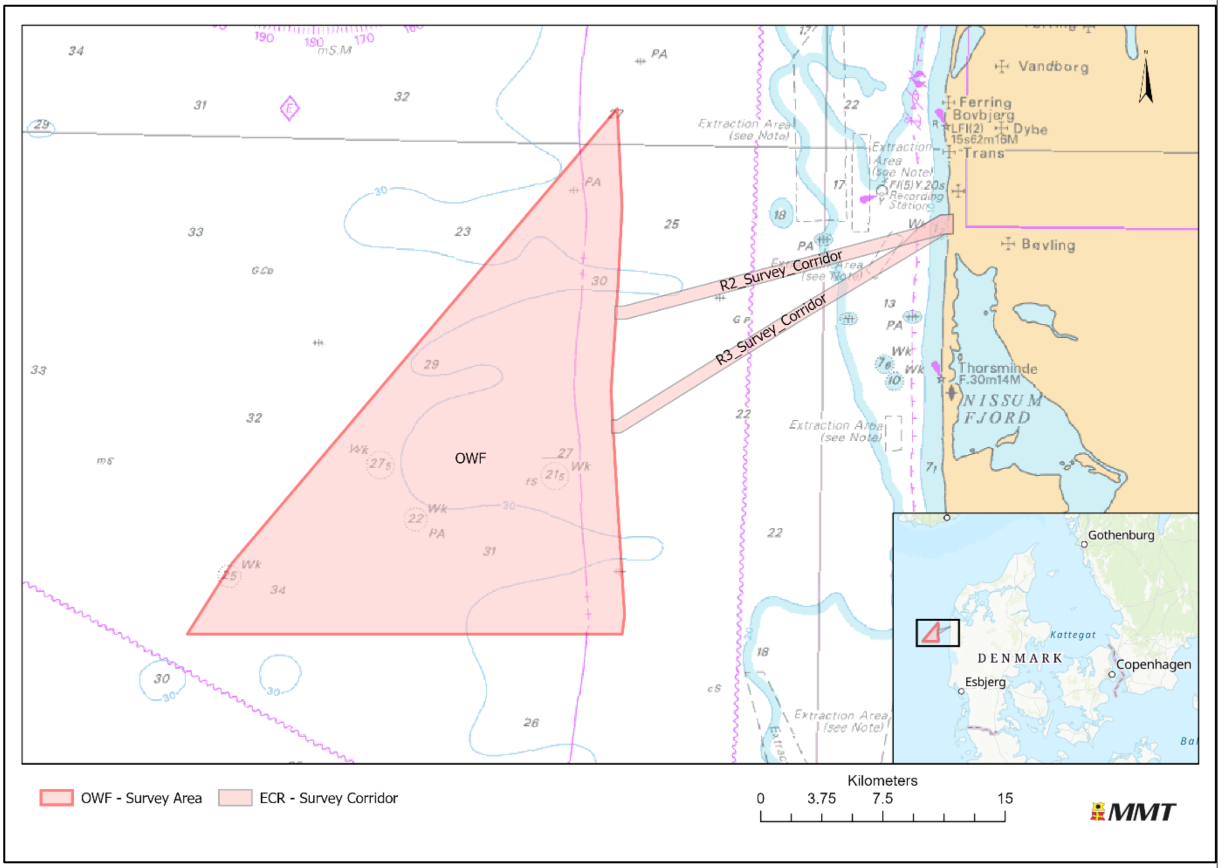

Figure 1 Overview of the THOR Hydro Survey Area.

THOR OFFSHORE WIND FARM SITE INVESTIGATION – OWF

SURFACE DIFFERENCE RESULTS

Surface difference results were derived by comparing the 2019 and 2020 DTMs in ArcGIS Pro. These showed that sediment mobility is widespread and observed across large expanses of the OWF site.

Depth differences either side of the +/-0.15 m zone covered 45.42 km^2 (11.7% of the area surveyed in 2020). The range of depth difference values was found to be -3.19 m to +1.75 m however these were found to correspond with MBES noise within the 2019 dataset. Profiles across the full width of the OWF showed that the depth differences were largely with +/-0.5 m and measurements taken from the areas surrounding profiles specifically targeting mobile areas showed depth differences ranging between -1.35 m and +1.25 m within sandwave areas.

Larger negative changes of -1.8 m were found to occur along the steep, step-like slopes of the mass transport areas identified in 2019. Such large changes result from the repositioning of the slope edge but are not clearly observed in profiles taken across these zones (maximum differences ca. -0.6 m).

Measurements of the horizontal displacements of the migrating bedforms across 10 sites within the OWF were made using EIVA NaviModel. Displacements between 10 m and 55 m were observed with 20 m to 30 m being more typical of the features that could be correlated between the DTMs. The orientation of the displacement was between 000° and 020°

REVISION HISTORY

REVISION	DATE	STATUS	CHECK	APPROVAL	CLIENT APPROVAL
02	2020-10-14	Issue for Client Review	DJO	KG	
01	2020-10-11	Issue for Internal Review	DJO	KG	

REVISION LOG

DATE	SECTION	CHANGE

DOCUMENT CONTROL

RESPONSIBILITY	POSITION	NAME
Content	Senior Data Processor	Andrew Stanley/Chris Bulford
Content, Check	Project Report Coordinator	David Oakley/Darryl Pickworth
Check	Document Controller	Anders Eriksson
Approval	Project Manager	Karin Gunnesson

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ABBREVIATIONS AND DEFINITIONS

CM	Central Meridian
DTU15	Denmark Technical University 2015
DPR	Daily Progress Report
DTM	Digital Terrain Model
EEZ	Exclusive Economic Zone
EPSG	European Petroleum Survey Group
ESRI	Environmental Systems Research Institute, Inc.
ETRS	European Terrestrial Reference System
FME	Feature Manipulation Engine
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GRS80	Geodetic Reference System 1980
INS	Inertial Navigation System
IHO	International Hydrographic Organisation
IMU	Inertial Measurement Unit
ITRF	International Terrestrial Reference Frame
MBES	Multibeam Echo Sounder
MSL	Mean Sea Level
M/V	Motor Vessel
OWF	Offshore Wind Farm
PPS	Pulse Per Second
QC	Quality Control
S-CAN	Scalgo Combinatorial Anti Noise
SOW	Scope of Work
THU	Total Horizontal Uncertainty
TPU	Total Propagated Uncertainty
TVU	Total Vertical Uncertainty
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator

1 | INTRODUCTION

1.1 | PROJECT INFORMATION

Energinet are developing the proposed Thor Offshore Wind Farm in the Danish sector of the North Sea. MMT have been contracted to provide a comparative hydrographic survey covering the Offshore Wind Farm (OWF) and two export cable route (ECR) options connecting the OWF to the landfall location near Søndeby Gårde in Jutland, Denmark.

This report covers the OWF survey area. A summary of project details is presented in Table 1 and an overview image of the OWF and ECR is given in Figure 2.

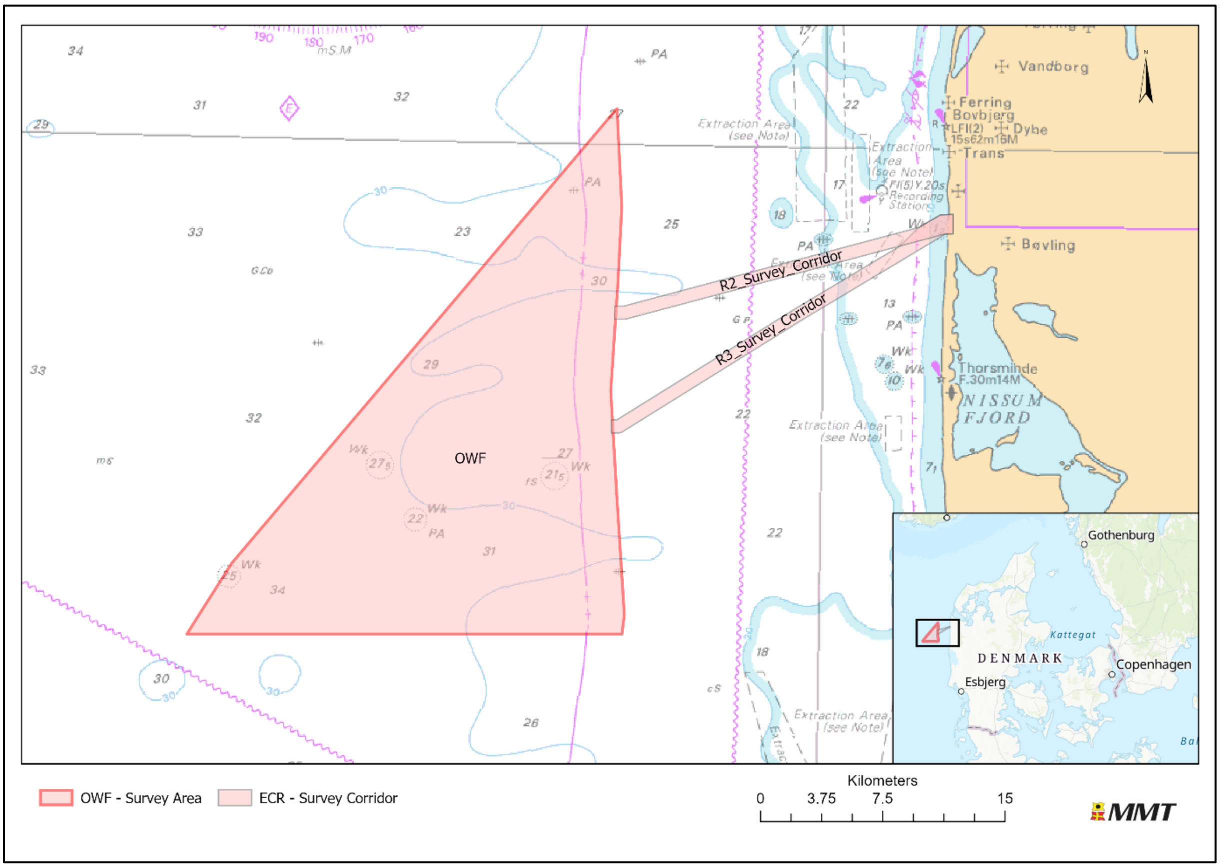

Figure 2 Thor Offshore Wind Farm and Export Cable Routes area overview.

Table 1 Project details.

CLIENT:	Energinet
PROJECT:	THOR Hydrographic Survey
MMT SWEDEN AB (MMT) PROJECT NUMBER:	103628
SURVEY TYPE:	Hydrographic offshore windfarm site survey
AREA:	Danish North Sea
SURVEY PERIOD:	July – September 2020
SURVEY VESSELS:	M/V Guardian
MMT PROJECT MANAGER:	Karin Gunnesson
CLIENT PROJECT MANAGER:	Jens Colberg-Larsen

1.2| SURVEY OBJECTIVES

The survey objectives for this project were to acquire bathymetric soundings and compare the change in morphology of the Thor OWF site and ECR routes. The acquisition of a full, comprehensive bathymetric and geophysical data set in 2019 has allowed for further insight by attempting to achieve maximum coverage from the budget available. The interpretation of the datasets was charted and reported to inform cable route micro-routeing and subsequent engineering. Due to the detailed nature of the 2019 survey, any new findings will be outlined in this report including, bathymetric variations and seabed variations.

1.3| SCOPE OF WORK

The survey encompassed bathymetric mapping through hull-mounted Multi-Beam Echo-Sounding with coverage of the OWF area (OWF) and the proposed cable routes R2 and R3 (ECR). A spatial resolution of 4 (four) soundings per square meter was achieved.

The results of the bathymetric mapping are to be processed, interpreted and compared with the bathymetric datasets from 2019 with the purpose of investigating the dynamic nature of the seabed. This is in the form of this report as well as charts and digital deliverables.

1.4| PURPOSE OF DOCUMENT

This report details the interpretation of the hydrographic survey results from the Thor OWF Site..

The report summarises the results of the surface difference analysis that was performed on the 2020 and 2019 bathymetry data.

A separate report includes the results of the Export Cable Route survey. A full list of reports is given in Table 2 (Reference Documents).

1.5| REPORT STRUCTURE

The results from the Lot 1 survey campaign are presented in two separate reports.

- Operations Report – Covering the field operations conducted
- Hydrographic Survey Report (this report) – Includes a chart series of results.

The Geophysical Survey Report (this report) chart series includes:

- Overview Chart
- Trackline Charts
- Bathymetry Charts
- Surface Difference Results Charts

1.5.1| CHARTS

The MMT Charts describe and illustrate the results from the survey. The charts include an overview chart with a scale of 1:50 000, north up charts at a scale of 1:10 000 and longitudinal profile charts with a horizontal scale of 1:10 000 and a vertical scale of 1:500.

The overview and north up charts contain background data (existing infrastructure, Exclusive Economic Zones (EEZ), 12 nautical mile zone and wreck database) alongside survey results.

A list of all produced charts is presented in **Error! Reference source not found.**.

OVERVIEW CHART

Shows coastlines, EEZ, large scale bathymetric features and area of investigations.

TRACKLINE CHARTS

The actual performed survey lines are presented.

BATHYMETRY CHARTS

The bathymetry is presented as a shaded relief colour image with 0.5 m colour interval, overlain with contour lines (1 m (minor) and 5 m (major)) with depth labels.

SURFACE DIFFERENCE CHARTS

The surface difference results are presented as a colour image with variable colour intervals (step increasing with increasing displacement either side of 0.0 m).

1.6| REFERENCE DOCUMENTS

The documents used as references to this report are presented in Table 2.

Table 2 Reference documents.

Document Number	Title	Author
103282-ENN-MMT-MAC-REP_A1	Mobilisation and Calibration Report – Guardian	MMT
103282-ENN-MMT-SUR-REP-OPEREPL1	Operations Report OWF	MMT
103282-ENN-MMT-SUR-REP-SURVLOT1-B	Geophysical Survey Report	MMT

1.7| AREA LINE PLAN

The OWF survey line spacing and minimum parameters are detailed in Table 3.

A breakdown of the survey lines is provided in Table 4.

Table 3 Survey line parameters.

GEOPHYSICAL SURVEY SETTINGS	SCOPE
Investigation area	Ca. 440 km^2
Line spacing Geophysical Main Lines	80 m

Table 4 Survey line breakdown.

SURVEY LINE BREAKDOWN	SCOPE	ACTUAL SURVEYED
Geophysical Main Lines	5594.0 km/335 Lines	6025.7 km/369 Lines

1.7.1 | SURVEY BLOCKS

To facilitate survey data management and survey planning the same block division principle from the 2019 survey was followed, with the exception that no Cross Blocks were required. As such the OWF was divided into four blocks (B1 to B4) shown in Figure 3.

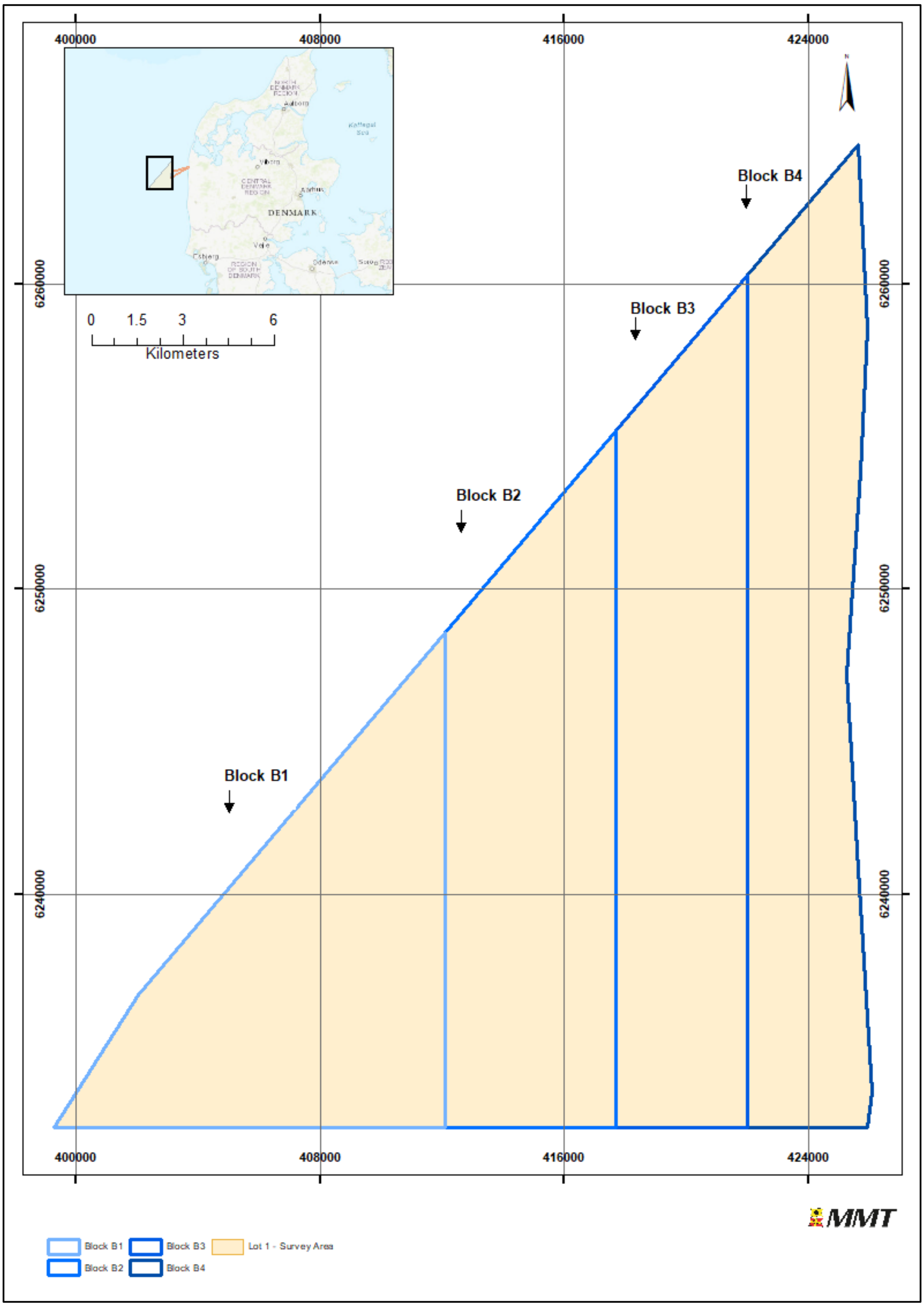

Figure 3 Overview of survey block divisions.

2| SURVEY PARAMETERS

2.1| GEODETIC DATUM AND GRID COORDINATE SYSTEM

2.1.1| ACQUISITION

The geodetic datum used for survey equipment during acquisition are presented in Table 5.

Table 5 Geodetic parameters used during acquisition.

Horizontal datum: International Terrestrial Reference Frame 2014 (ITRF2014)	
Datum	ITRF2014
ESPG Datum code	1165
Spheroid	Geodetic Reference System 1980 (GRS80)
Semi-major axis	6 378 137.000m
Semi-minor axis	6 356 752.314m
Inverse Flattening (1/f)	298.257222101

2.1.2| PROCESSING

The geodetic datum used during processing and reporting are presented in Table 6.

Table 6 Geodetic parameters used during processing.

Horizontal datum: European Terrestrial Reference System 1989 (ETRS89)	
Datum	ETRS89
European Petroleum Survey group (EPSG) Datum Code	4936
Spheroid	GRS80
Semi-major axis	6 378 137.000m
Semi-minor axis	6 356 752.314m
Inverse Flattening (1/f)	298.257222101

2.1.3| TRANSFORMATION PARAMETERS

The transformation parameters used to covert from acquisition datum (ITRF2014) to processing/reporting datum (ETRS89) are presented in Table 7.

Table 7 Transformation parameters.

DATUM SHIFT FROM ITRF2014 TO ETRS89 (RIGHT-HANDED CONVENTION FOR ROTATION - COORDINATE FRAME ROTATION)	
PARAMETERS	**EPOCH 2019.5**
Shift dX (m)	+0.099440
Shift dY (m)	+0.064160
Shift dZ (m)	-0.120400
Rotation rX (“)	-.0.00313900

DATUM SHIFT FROM ITRF2014 TO ETRS89 (RIGHT-HANDED CONVENTION FOR ROTATION - COORDINATE FRAME ROTATION)	
Rotation rY (“)	-0.01334000
Rotation rZ (“)	+0.02369500
Scale Factor (ppm)	+0.0030100000

In order to verify that the transformation parameters have been correctly entered into the navigation system the test coordinates supplied in the official transformation document the Simplified transformations from ITRF2014/IGS14 to ETRS89 for maritime applications [L. Jivall, Lantmäteriet, 2018] have been used (Table 8).

Table 8 Official test coordinates
Transformation ITRF2014/IGS14, epoch 2019.5 to ETRS89, central Europe

ITRF 2014 epoch 2019.5	54°59’59’’998378	13°29’59.989138	-0.6034
ETRS, central Europe (2019.5)	54°59’59’’980974	13°29’59.958899	-0.6201
ETRS89, Baltic Sea (2019.5)	54°59’59’’981291	13°29’59.958886	-0.6567
SWEREF99, southern Sweden (2019.5)	54°59’59’’981520	13°29’59.959222	-0.6272

2.1.4| PROJECTION PARAMETERS

The projection parameters used for processing and reporting are presented in Table 9.

Table 9 Projection parameters.

Projection Parameters	
Projection	UTM
Zone	32 N
Central Meridian	09° 00’ 00’’ E
Latitude origin	0
False Northing	0 m
False Easting	500 000 m
Central Scale Factor	0.9996
Units	metres

2.1.5| VERTICAL REFERENCE

The vertical reference parameters used for processing and reporting are presented in Table 10.

Table 10 Vertical reference.

Vertical Reference Parameters	
Vertical reference	MSL
Height model	DTU15

2.2| VERTICAL DATUM

Global navigation satellite system (GNSS) tide was used to reduce the bathymetry data to Mean Sea Level (MSL) the defined vertical reference level (Figure 4). The vertical datum for all depth and/or height measurements was MSL via DTU15 MSL Reduction from WGS84-based ellipsoid heights.

This tidal reduction methodology encompasses all vertical movement of the vessel, including tidal effect and vessel movement due to waves and currents. The short variations in height are identified as heave and the long variations as tide.

This methodology is very robust since it is not limited by the filter settings defined online and provides very good results in complicated mixed wave and swell patterns. The use of high-accuracy RTK positioning online means that there is no need to post-process the vessel navigation before it is applied onto the multibeam echo sounder (MBES) data.

The GNSS tide methodology has proven to be very accurate as it accounts for any changes in height caused by changes in atmospheric pressure, storm surge, squat, loading or any other effect not accounted for in a tidal prediction.

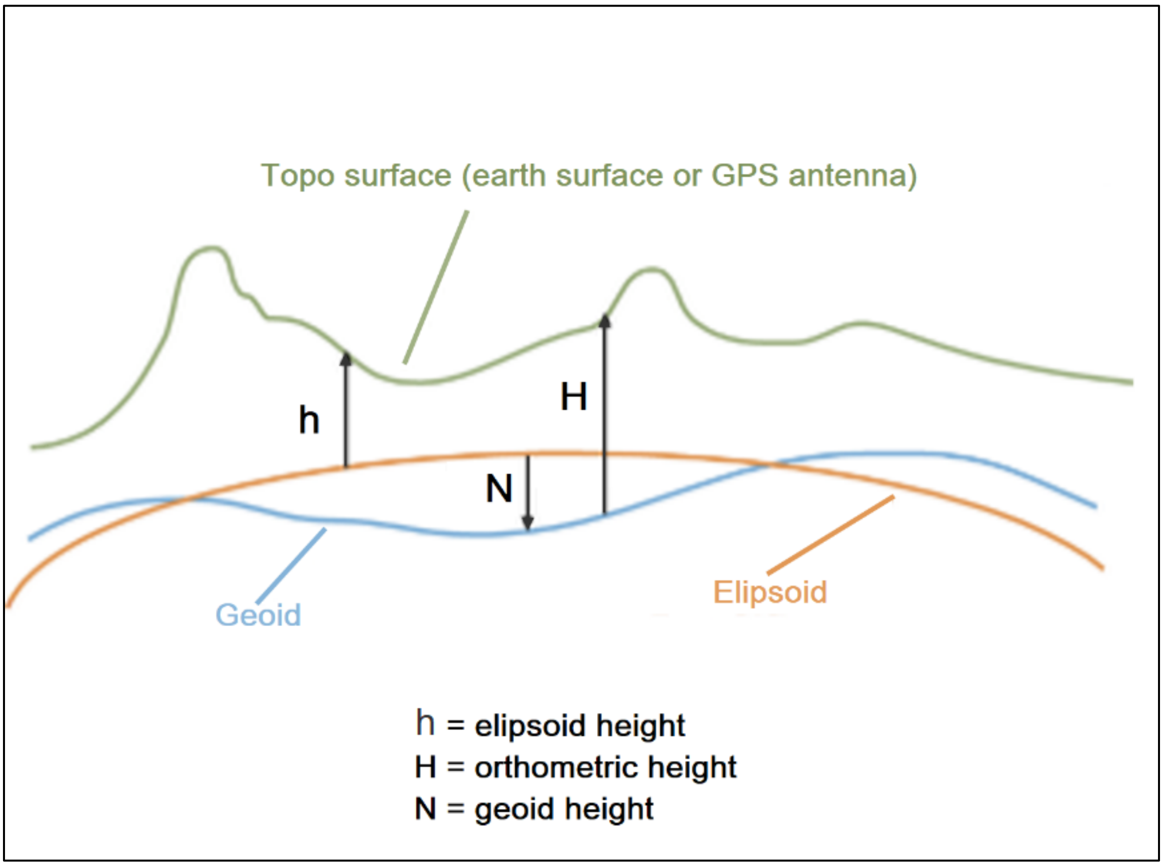

Figure 4 Overview of the relation between different vertical references.

2.3| TIME DATUM

Coordinated universal time (UTC) is used on all survey systems on board the vessel. The synchronisation of the vessels on board system is governed by the pulse per second (PPS) issued by the primary positioning system. All displays, overlays and logbooks are annotated in UTC as well as the daily progress report (DPR) that is referred to UTC.

3| VESSELS AND EQUIPMENT

3.1| M/V GUARDIAN

The M/V Guardian is a multipurpose vessel that is operated by MMT. All of the survey equipment is regularly calibrated, references to which are made within the MAC report where appropriate. The proposed project development area, offshore wind farm blocks and two proposed cable routes, off the coast of Jutland for Energinet was surveyed by M/V Guardian in water depths between 4 m and 35 m MSL.

Figure 5 M/V Guardian

Table 11 Vessel-mounted equipment

Instrument	**Name**
Primary Positioning System	Septentrio AsteRx-U Marine
Secondary Positioning System	C&C Technologies C-Nav3050 (C1/C2 corrections)
Primary Gyro and INS System	IxBlue Hydrins III
Survey Navigation System	QPS QINSy
Multibeam Echo Sounder (Medium to Shallow Water)	Reason Seabat T50-R
Sound velocity	MVP30 / AML Base X2 / Valeport MiniSVS

4| DATA PROCESSING AND INTERPRETATION METHODS

4.1| BATHYMETRY

The objective of the processing workflow is to create a Digital Terrain Model (DTM) that provides the most realistic representation of the seabed with the highest possible detail. The processing scheme for MBES data comprised two main scopes: horizontal and vertical levelling in order to homogenise the dataset and data cleaning in order to remove outliers.

The MBES data is initially brought into QPS Qimera to check that it has met the coverage and density requirements. The quality of the online RTK positioning solution (from the C-NAV system) was checked by examining the standard deviation of the sounding data and checking the gridded surfaces for tidal busts. Since the vessel used a high-accuracy online position the vertical reduction of the bathymetry data to the specified DTU15 MSL survey datum was performed in real-time.

In addition to the checking the standard deviation of the soundings, the quality of the position solution can be assessed by calculating the Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU) within the dataset. These surfaces are generated in Qimera and are checked for deviations from the THU and TVU thresholds as specified by the client. This is discussed in further detail in Section 5.1|.

Once the data has passed these checks it is ready to start the process of removing outlying soundings which can be undertaken within Qimera.

In the Qimera workflow an average surface is derived from the sounding data and from this it is possible to remove outliers that lie at a specified numerical distance from the surface, or by setting a standard deviation threshold. Manual cleaning can also be performed using 3D point editor tool to clean areas around features that would be liable to being removed by the automatic cleaning processes.

The work flow diagram for MBES processing is shown in Figure 6.

If the dataset then passes the QC check to project specifications the DTM is exported in ASCII XYZ format for delivery to the client and for further internal use.

MMT use EIVA's NaviModel software to generate products for charting, such as contours and shaded relief images. Bathymetric contours were generated from the 1 m DTM in combination with scaling factors applied to generalise the contours to ensure the charting legibility. The contour parameters used are shown in Figure 7 and an example of the exported contours presented over the DTM is shown in Figure 8. FME was also used to clip the higher resolution ASCII XYZ files into 1 km x 1 km tiles using the 2019 tile schema.

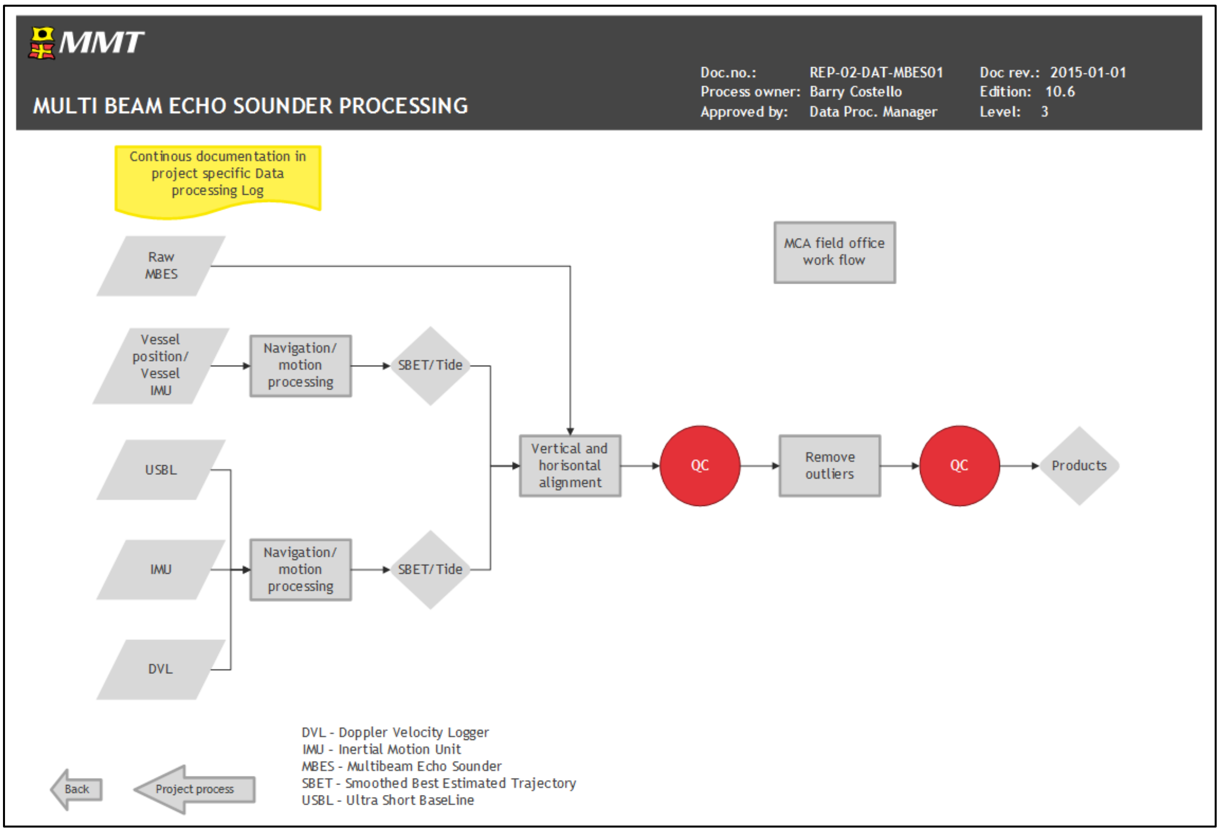

Figure 6 Workflow MBES processing.

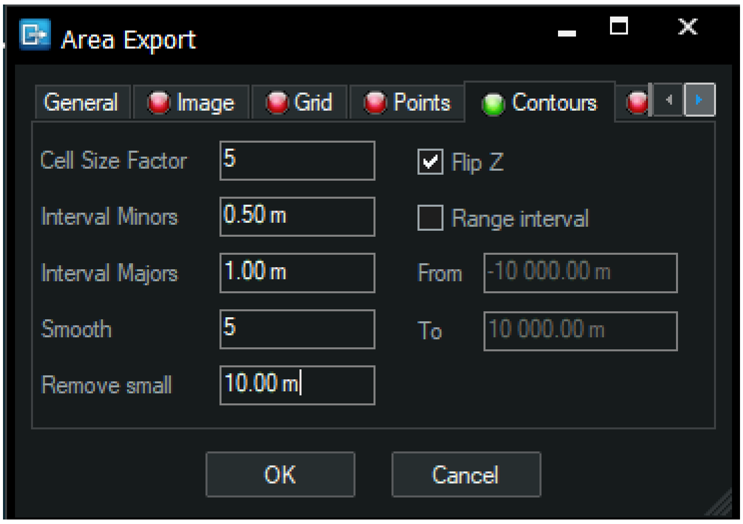

Figure 7 OWF & ECR contour export parameters.

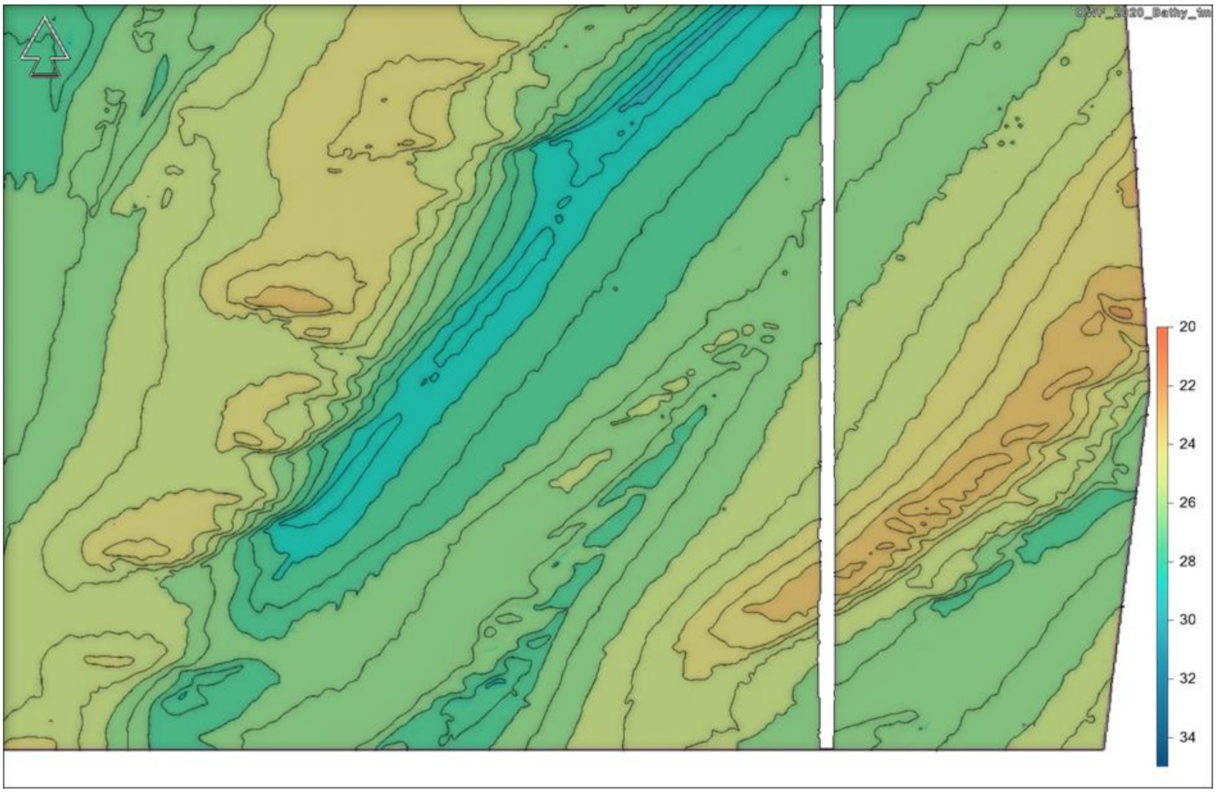

Figure 8 Example of exported contours with 50 cm interval in the southeast corner of the OWF. NaviModel depth convention is positive down.

5| PROCESSED DATA QUALITY

5.1| BATHYMETRY DATA

The processed MBES bathymetry data meets the required specifications. The horizontal and vertical uncertainty of the soundings data were, for the vast majority of the survey area, within the 0.5 m threshold as specified by the client. Checks were made during acquisition to ensure that sounding density conformed to the 4 soundings per 1 m cell criteria. Due to maximise the attainable coverage possible within the project constraints there are some data gaps in the final dataset. These range from missing survey lines to small areas of that did not meet the infill threshold criteria (i.e. 4 or more missing 1 m cells that shared a long side) or were flagged as rejected during office data cleaning after both vessels had left the survey area. Figure 9 shows an example of the OWF DTM and corresponding profile highlighting distance between the missing lines in Block 1. This occurs in Block 1 & 2 but there is no impact on data quality

The MBES data was QC'd on a block by block basis as it was acquired by generating Qimera surfaces from all MBES data within the block. A range of properties are computed for each surface and these are checked systematically to ensure the data falls within specification. The Standard Deviation at 95% confidence interval is checked in order to highlight areas where the vertical spread of soundings within a DTM grid node is high and checks can be made to determine the cause. If necessary, action can be taken to bring the soundings into closer alignment. Regions that have high standard deviations can occur where there are sound velocity errors, errors in the post-processed navigation, acquiring data in heavy weather and where there are steep slopes such as boulder fields.

In addition to the Standard deviation, checks were made from the Total Horizontal and Vertical Uncertainty surfaces at 1 m resolution. A single threshold value of 0.5 m was used for both THU and TVU across the survey area. THU and TVU values were found to fall below this threshold value across the OWF site and indicated that the survey data was of sufficient quality.

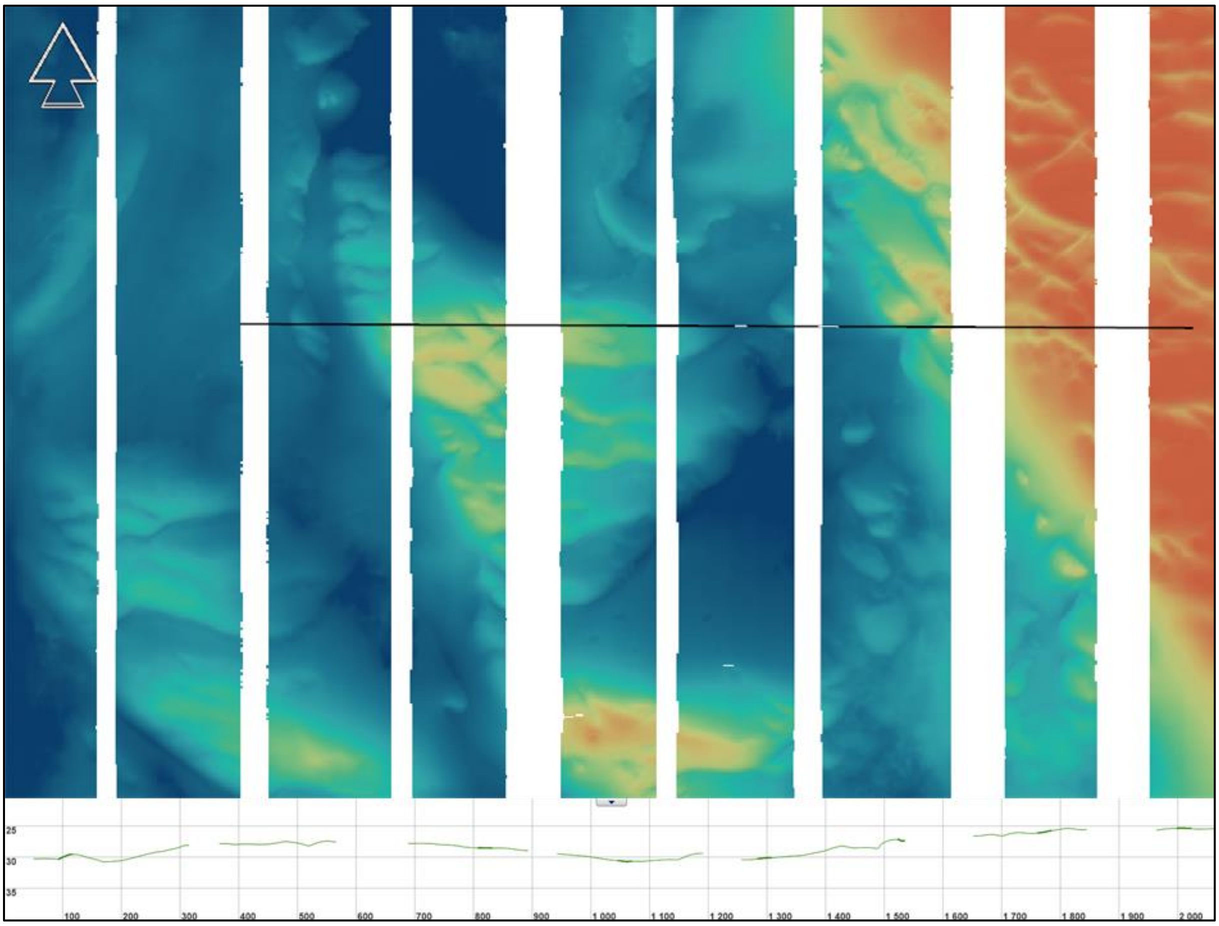

Figure 9 Example of OWF DTM and corresponding Profile highlighting lack of swath overlaps. Values are presented in metres. NaviModel depth convention is positive down.

6| RESULTS

6.1| GENERAL BATHYMETRY

Overall the bathymetric depth changes moderately across the OWF. The minimum surveyed depth is -20.23 m at 421112.5 E, 6248235.0 N in the northern part of the survey. The maximum depth surveyed is -35.40 m at 406 209 E, 6 240 966 N in the western area. The depth range across the site is 15.0 m. Figure 10 shows an overview of the bathymetry within the OWF.

Due to firm financial limits being placed on the project it was not possible to obtain 100% coverage of the entire OWF survey area. The area covered by the 2020 survey was 388.23 km^2 (based on the 1 m DTM surface area). This is equivalent to 88.23% of the total area of the OWF. Since this possibility was a known factor during the planning stage a series of widely spaced lines were surveyed across the entire OWF so that, should the project limits be reached before 100% coverage was achieved, then an indication of mobility would be obtained in all parts of the survey area.

Once the first pass of the OWF was achieved the survey vessel prioritised the eastern half of the area since this is where the majority of mobile bedforms identified by the 2019 survey were located. In particular, in the southeast quarter there is a series of banks of sediment that have a large range in depths. It was decided that these should be prioritised as migration of large features, such as these, could have design implications for the construction of the OWF.

In 2019 a series of prominent features were observed in the MBES data that appeared to be MBES artefacts. In 2020 the survey lines were run with the aiming of covering the majority of these features again so that their presence or absence could be confirmed with a second set of data.

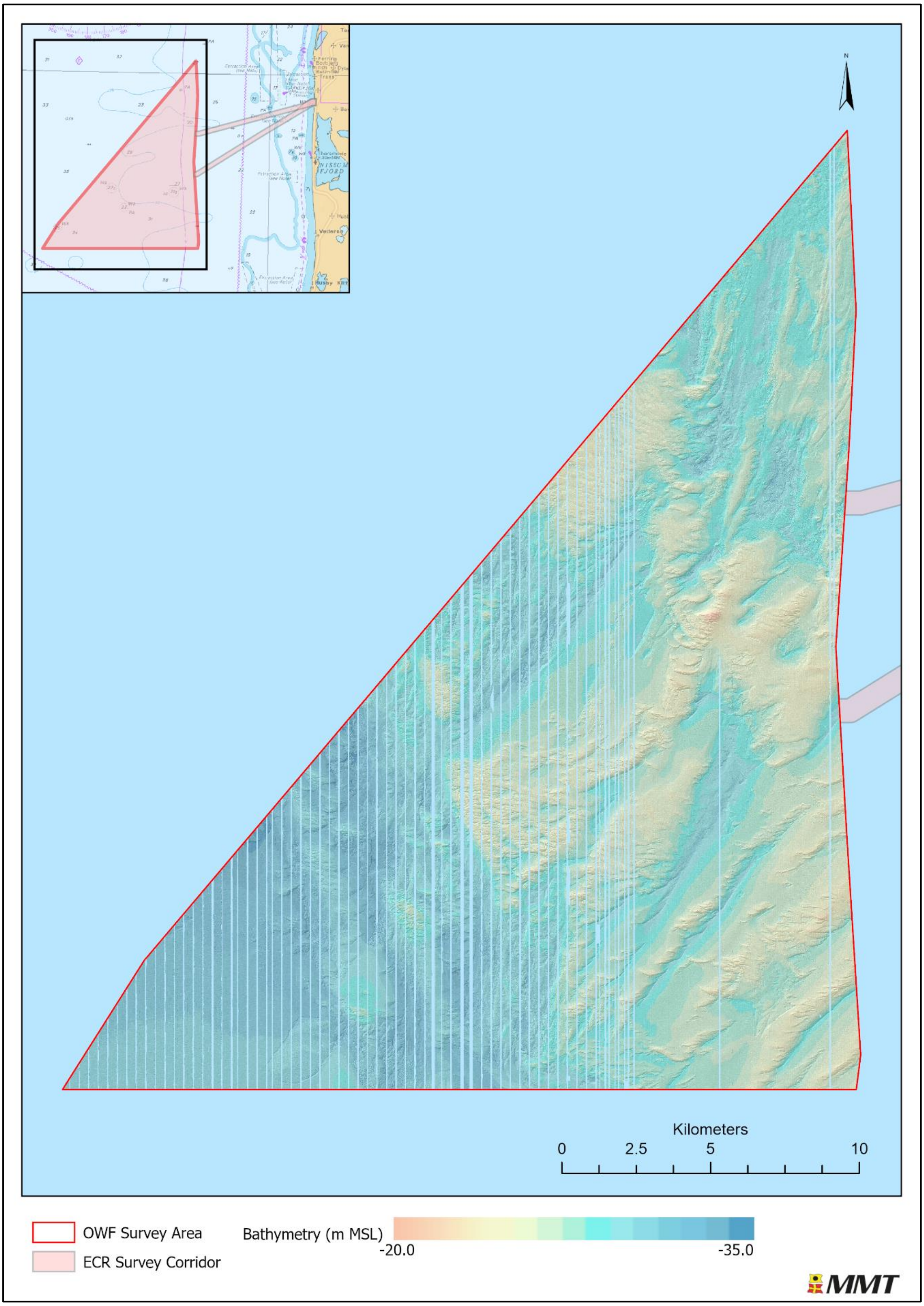

Figure 10 Overview of the OWF bathymetry to show coverage achieved in 2020.

6.2| SURFACE DIFFERENCE RESULTS

The surface difference results were calculated in ArcGIS Pro by using the Minus function to calculate the vertical differences between the two rasters. The operation was performed using the following equation:

OWF 2020 Bathymetry – OWF 2019 Bathymetry = OWF Surface difference

The results of this calculation were checked by creating profiles across the bathymetry and surface difference surfaces. This showed that positive difference values corresponded to areas where the 2020 bathymetry was shallower than in 2019. Positive values therefore correspond to accumulations of sediment and negative values where sediment has been eroded. A colourmap was created with highlighted these changes with large increases in depth appearing blue and purple and large reductions in depth appearing in orange and red.

To present clear imagery in the report small depth changes have been excluded from the colourmap. This is because small changes in vertical position of the two survey vessels can impose distracting artefacts in the surface difference results. These differences in depth are within the permitted vertical uncertainty for the bathymetry data and means that small changes in depth between the two surveys cannot be clearly associated with seabed movement alone. Assessment was made over the ECR and OWF survey areas and it was found that this exclusion zone would span +/-0.15 m. The exclusion was made by making the cell values within this range appear transparent. For context and interest the shaded relief surface from the 2020 bathymetry is shown in these transparent areas. The same colourmap has been used for both sets of results.

An overview of the surface difference results for the entire OWF area is shown in Figure 11. The colourmap here has been restricted to +/-0.5 m in order to highlight the positive and negative depth changes at a scale that can be observed at the image scale.

The range of surface difference values in the OWF was found to be **-3.19 m** to **+1.75 m**. The minimum value of -3.19 m is located near the northernmost corner of the OWF at 423677 E, 6261046 N which corresponds to one of the areas identified as an area of suspect noise in the 2019 survey (Figure 12). This feature was measured in 2019 as standing 3.47 m above the surrounding seabed and the slightly smaller depth change reflects the fact that the difference values were derived from an average surface with 1 m resolution. Other examples of suspected MBES noise were examined and these had a reduced impact in the surface difference results (as a result of the gridding process) and some of the smaller features corresponded to contacts that were observed in the 2020 bathymetry.

The maximum surface difference value, +1.75 m, is also located near the northern corner of the OWF at 422001 E, 6257251 N (Figure 13). Examining the bathymetry surfaces for 2019 and 2020 do not show an obvious accumulation of sediment in the recent survey. It is therefore likely that there is some MBES noise in the 2019 survey that lies below the surrounding seabed and causes this anomalously high value.

Since these minimum and maximum high values are associated with MBES noise it is likely that, should they be removed from the datasets, that the spatial analysis tools within ArcGIS would find more examples where the end member values are associated with random or systematic MBES noise across such a large survey. It might be more feasible to down sample the surfaces to find the end member values and locations for real seabed change. Subsets of these areas could be made at full resolution to define and locate the absolute end-members.

The surface area of the OWF that was above and below the threshold of reliable mobility (+/-0.15 m) were calculated in ArcGIS. The results of this analysis are shown in Table 12. These showed that coverage of 88% of the total OWF survey area was achieved and of this 11.7% lies outside of the +/-0.15 m threshold value. A point of interest is that the area of erosion (<-0.15 m) is nearly twice as large as the area across which deposition had occurred. Volumetric analysis would be required in order to determine whether the OWF site had experienced net erosion since 2019 as it is possible that the eroded sediment had been deposited in a smaller area.

Table 12 Total area of seabed undergoing erosional and depositional changes since 2019.

	Coverage m^2 (km^2)	**Percentage of OWF Survey Area**
Area of OWF	440004320 (440.00)	-
2020 MBES Coverage	388228613 (388.23)	88%
Area < -0.15 m (Erosion)	30588710 (30.59)	7.9%*
Area +/-0.15 m (Stable)	342806415 (342.81)	88.3%*
Area > +0.15 m (Deposition)	14833488 (14.83)	3.8%*

*percentage value based on 2020 coverage of 388.23 km^2.

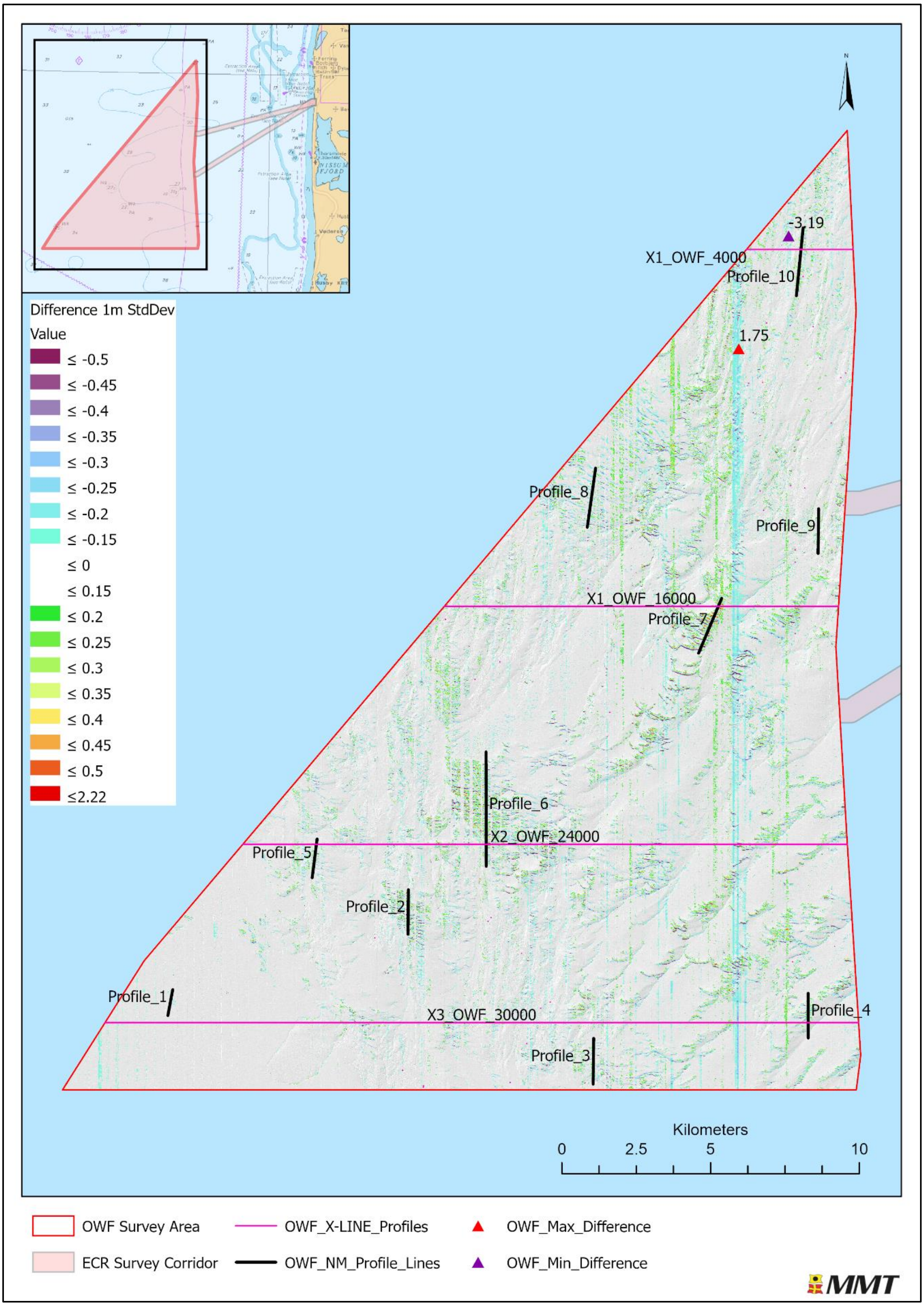

Figure 11 Overview of the OWF surface difference results.
The colourmap is forced to emphasize positive and negative depth changes when viewed at this scale.

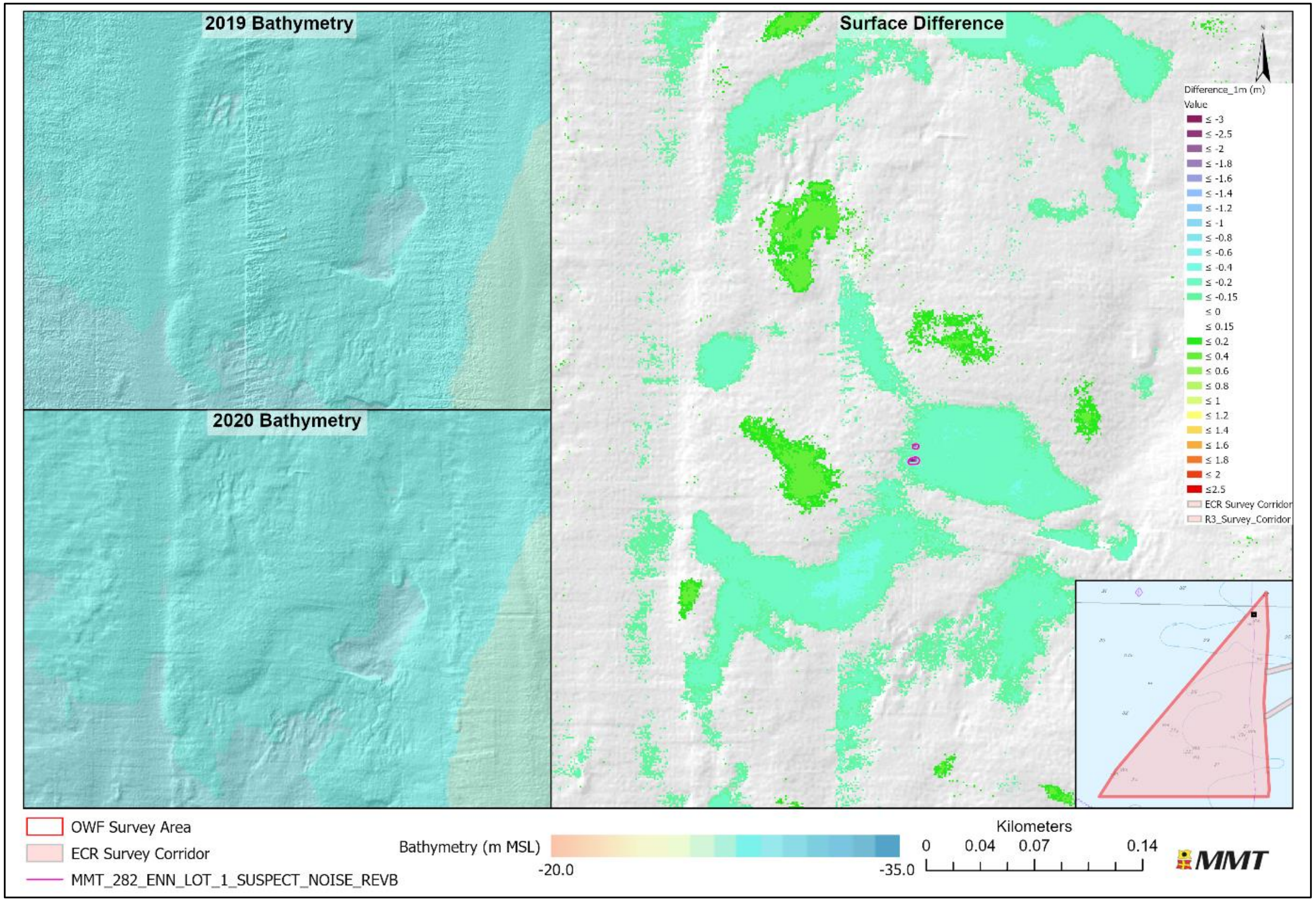

Figure 12 Location of Minimum surface difference

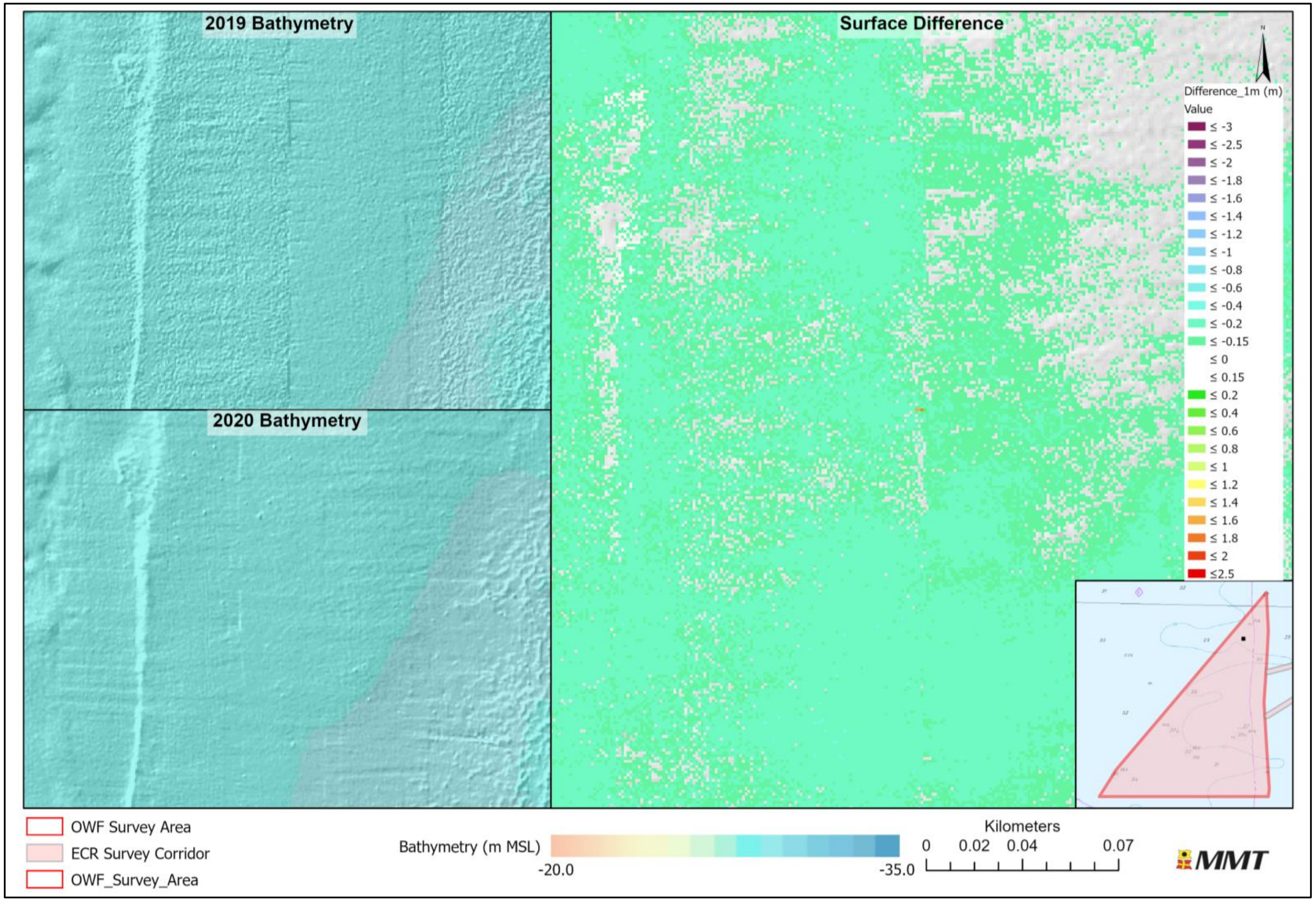

Figure 13 Location of Maximum surface difference

Figure 11 shows the X-line profile positions that were used in the 2019 report to provide an overview of the depth variation for the OWF. These profiles have been used again in 2020 to present the depth differences between the two surveys. Figure 14 to Figure 17 show the depth profiles that were obtained from the 2019 (blue) and 2020 (orange) bathymetry data as well as the difference surface (grey).

The profiles graphs are presented here to span the full width of the line however the data was exported at 1 m intervals, so permits close scrutiny. The data and graphs are included as an excel file in Appendix B| should the reader like to examine a particular section of the profile. The extents of the X-axes of the graphs can be adjusted to a customised range.

The profile data generally showed that the largest scale features (which are the only ones visible at this scale) remained stable in the period between the surveys as the 2019 profile is closely matched by that from 2020.

The profiles show that the differences are typically within +/-0.5 m with exceptions being present in profiles X1_OWF_16000 and X3_OWF_24000. The range of depth differences along the profiles is presented in Table 13. The profiles were chosen in 2019 to cover a variety of seabed types including boulder fields, sandwaves and banks however the surface difference results cover a much larger range of values.

Table 13 Depth ranges for OWF Cross Profiles

Profile	Minimum Depth Difference (m)	Maximum Depth Difference (m)
X1_OWF_4000	-0.44	+0.39
X1_OWF_16000	-0.58	+0.46
X3_OWF_24000	-0.73	+0.61
X3_OWF_30000	-0.42	+0.41

The minimum and maximum depth differences for each 1 km tile were extracted from the ASCII XYZ data. This showed that larger negative changes of -1.8 m were occurring along the steep, step-like slopes of the mass transport areas. Such large changes result from the repositioning of the slope edge but are not clearly observed in profiles taken across these zones (maximum differences ca. -0.6 m). A possible reason for this is that the grid node positions are slightly different between the 2019 and 2020 data and so a small horizontal shift of 0.5 m in the data causes upper and lower slope data to overlap, creating difference values with anomalously high magnitudes.

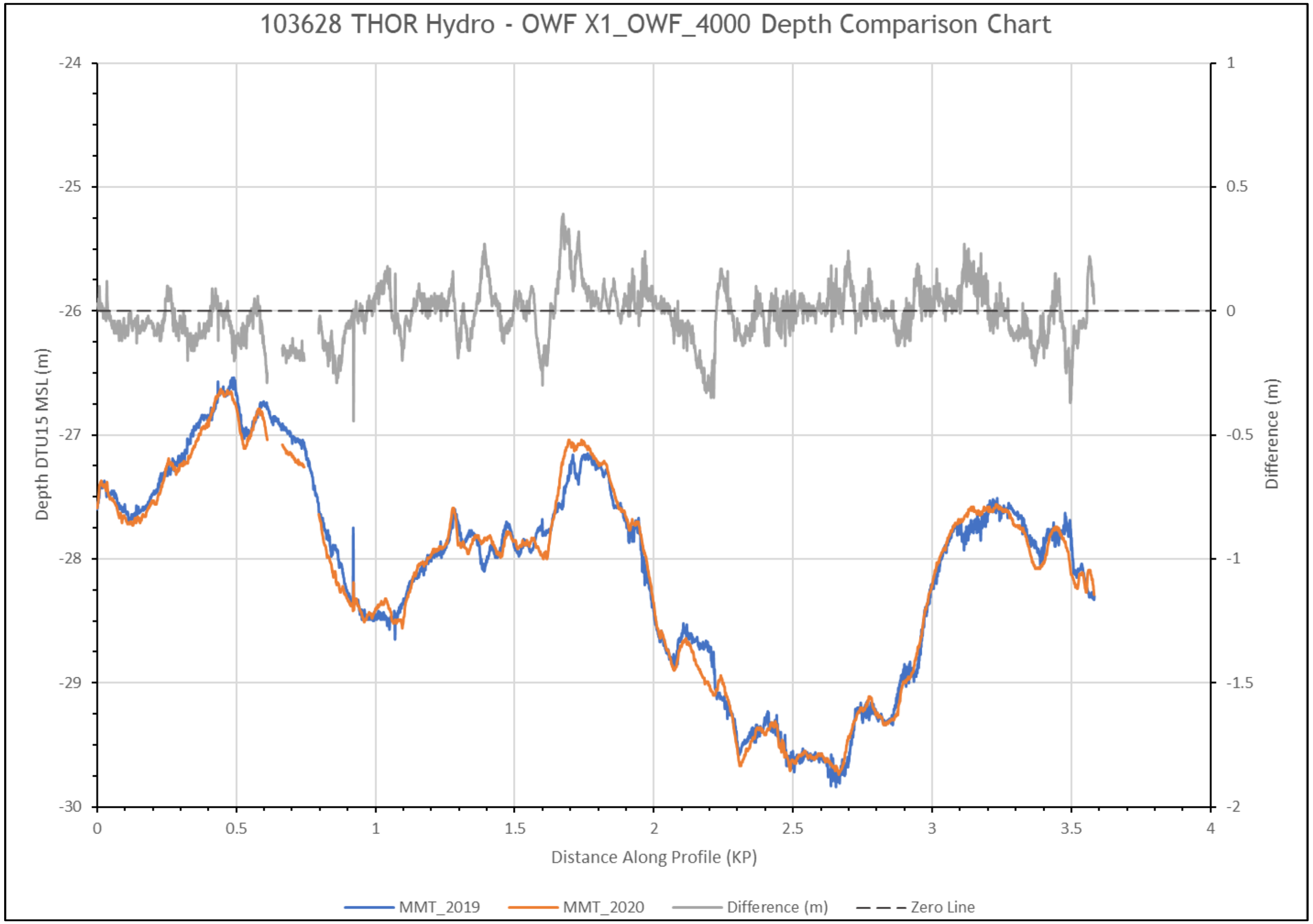

Figure 14 Bathymetric depth and surface difference profiles for line X3_OWF_16000.
Bathymetry from 2019 in blue, 2020 in orange and surface difference in grey. The dashed zero line is provided as a guide for the surface difference.

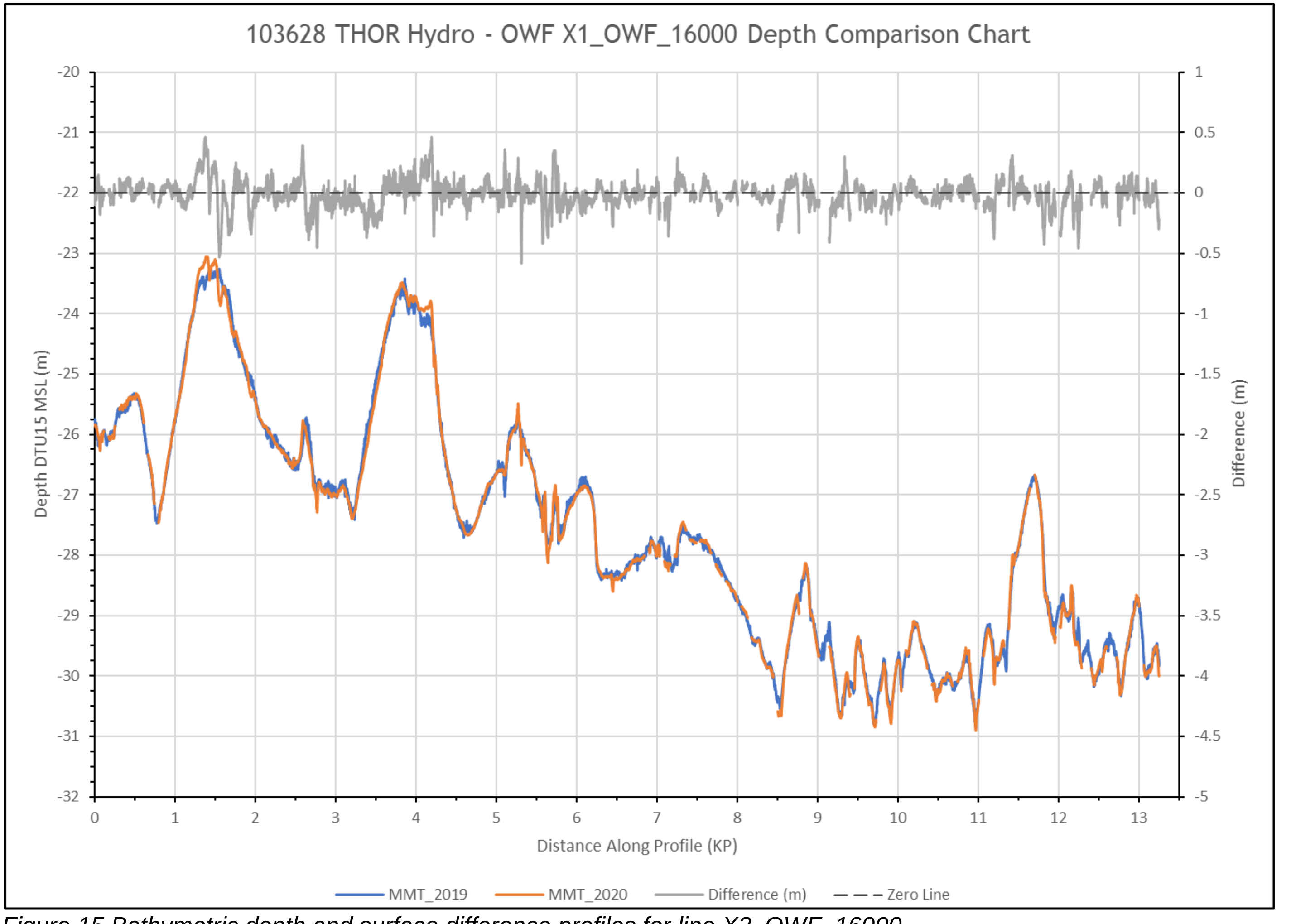

Figure 15 Bathymetric depth and surface difference profiles for line X3_OWF_16000.
Bathymetry from 2019 in blue, 2020 in orange and surface difference in grey. The dashed zero line is provided as a guide for the surface difference.

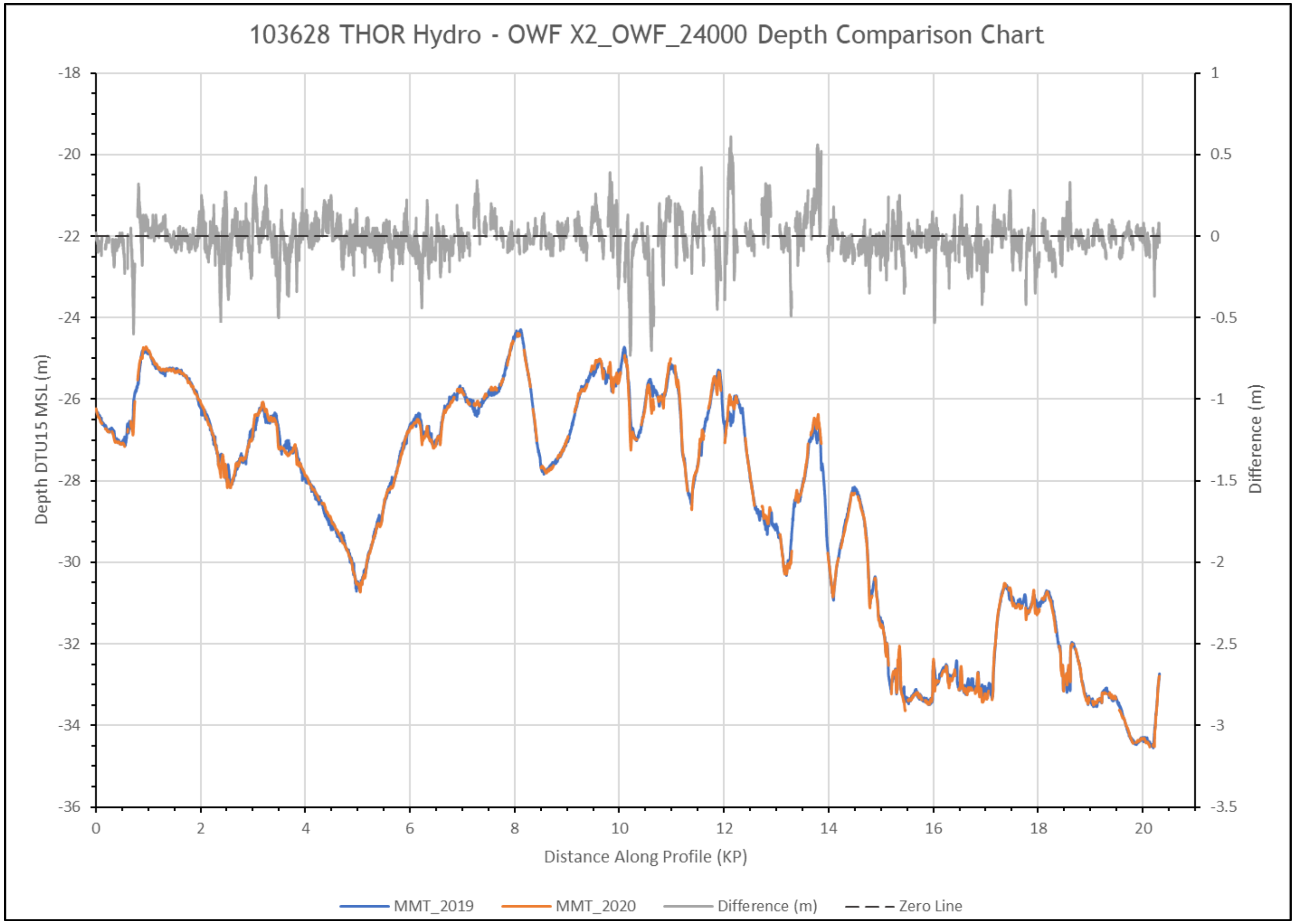

Figure 16 Bathymetric depth and surface difference profiles for line X3_OWF_24000.
Bathymetry from 2019 in blue, 2020 in orange and surface difference in grey. The dashed zero line is provided as a guide for the surface difference.

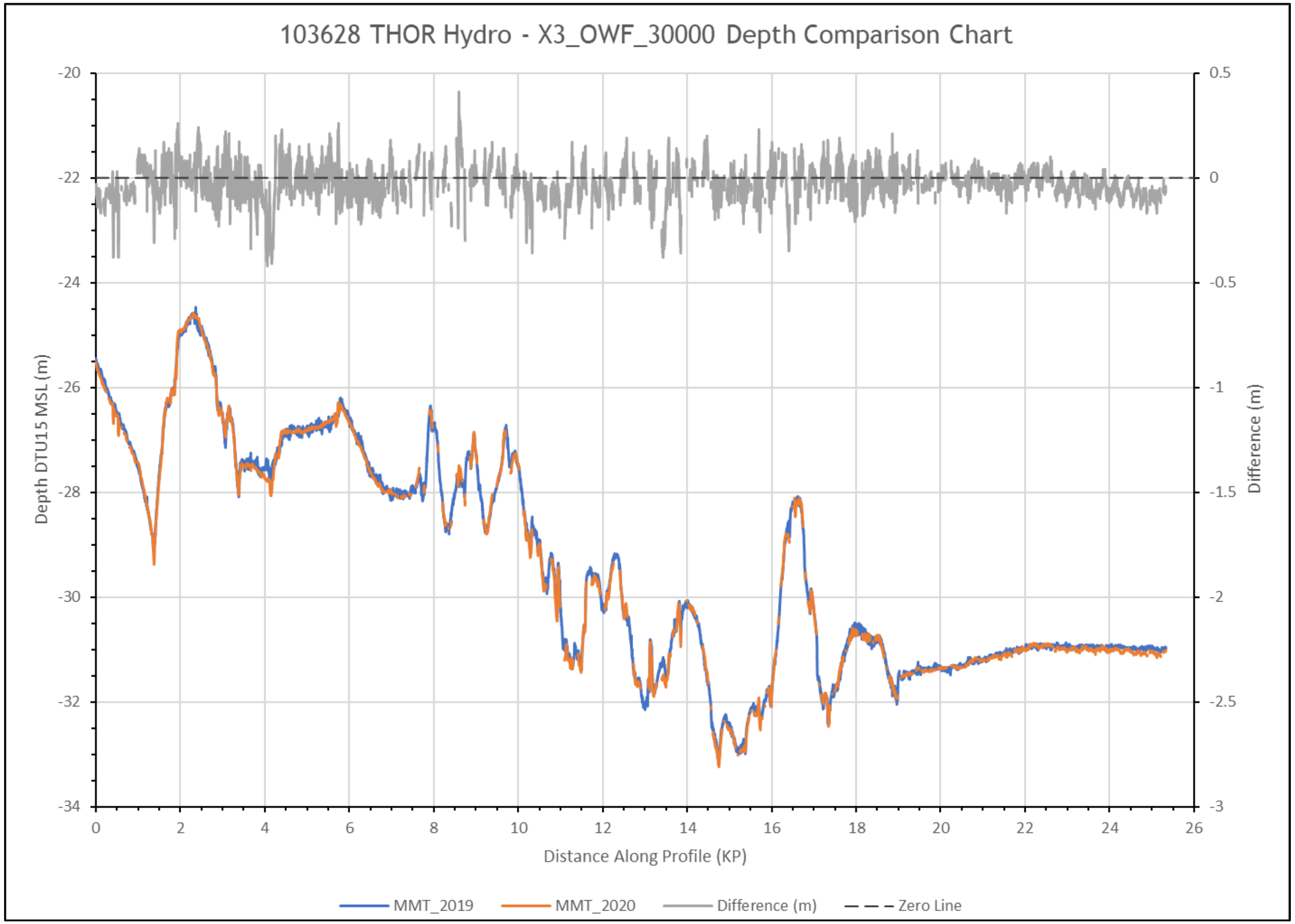

Figure 17 Bathymetric depth and surface difference profiles for line X3_OWF_30000.
Bathymetry from 2019 in blue, 2020 in orange and surface difference in grey. The dashed zero line is provided as a guide for the surface difference.

To summarise the mobility across the large area covered by the OWF the site was split into 10 zones and profiles were created in EIVA NaviModel in order to measure the horizontal displacement of the bedforms in each zone. From these profiles and the surface difference results in ArcGIS a picture of the typical sediment movements across the site could be established.

The horizontal displacement was determined by taking measurements between bedforms on the separate profiles that have similar shapes and are therefore inferred to be the same bedform. The bedforms within the OWF are largely indistinct with typically gentle slope gradients and smooth profiles which makes inferring the direction of sediment difficult to determine from the morphology of the bedform itself. The measurement of displacement also provides the orientation of inferred movement, which is not dependent on interpreting the bedform morphology.

In the far southwestern corner of the OWF the seabed appears to be largely stable since the 2019 survey was completed. However, mobility was observed where an area with irregularly-shaped depressions (Figure 18 and Figure 19) are observed. The horizontal displacement of the correlating features was 55 m towards 010°. Around this area the range of depth change was between -0.47 m to +0.38 m.

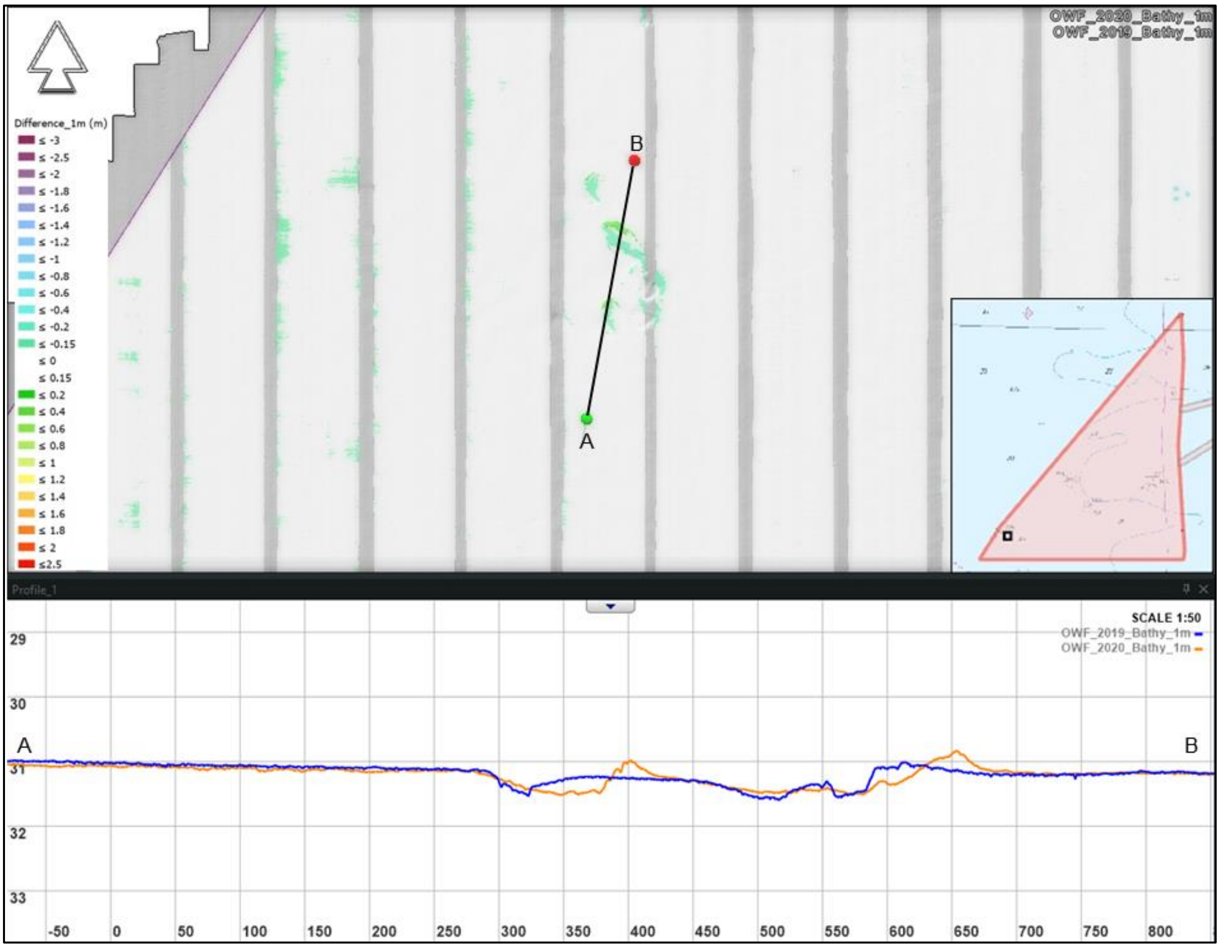

Figure 18 Seabed mobility and depth comparison profile 1.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

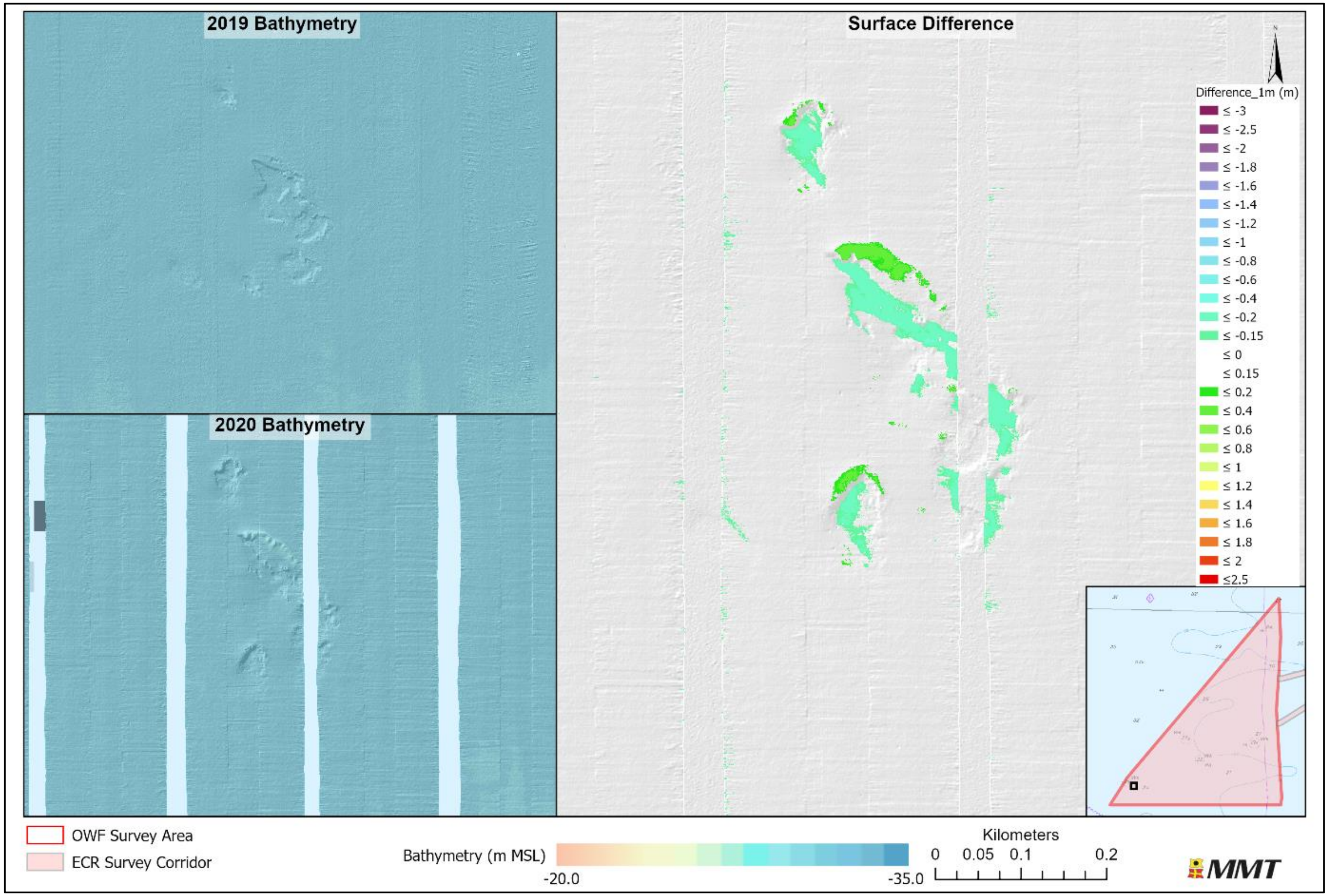

Figure 19 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 1.

Profile 2 is located in the south-central part of the OWF and runs through a mobile field of sandwaves (Figure 20 and Figure 21). Here the horizontal displacement was between 10 m and 20 m towards 000° and the range of depth difference within the surrounding area is -1.0 m and +0.7 m.

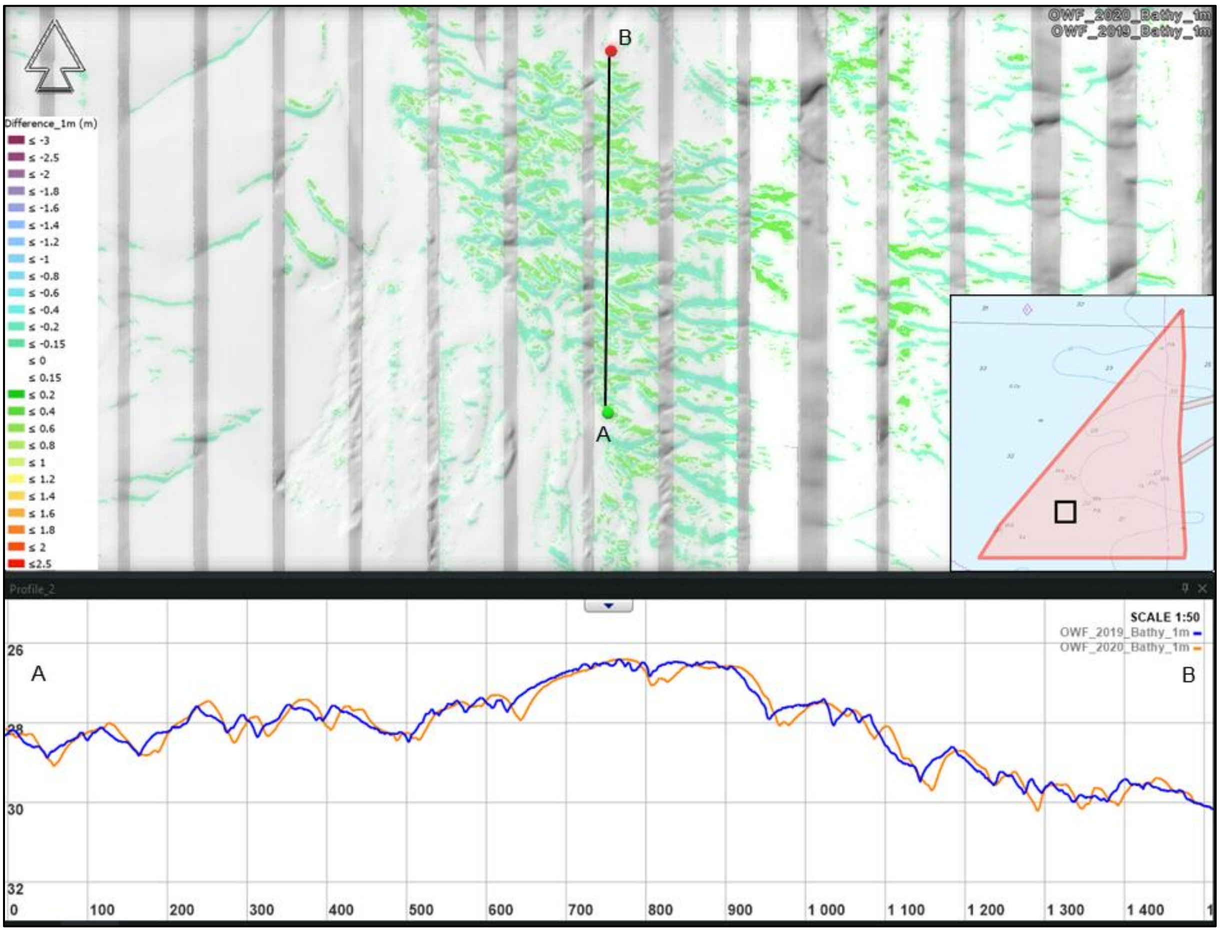

Figure 20 Seabed mobility and depth comparison profile 2.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50

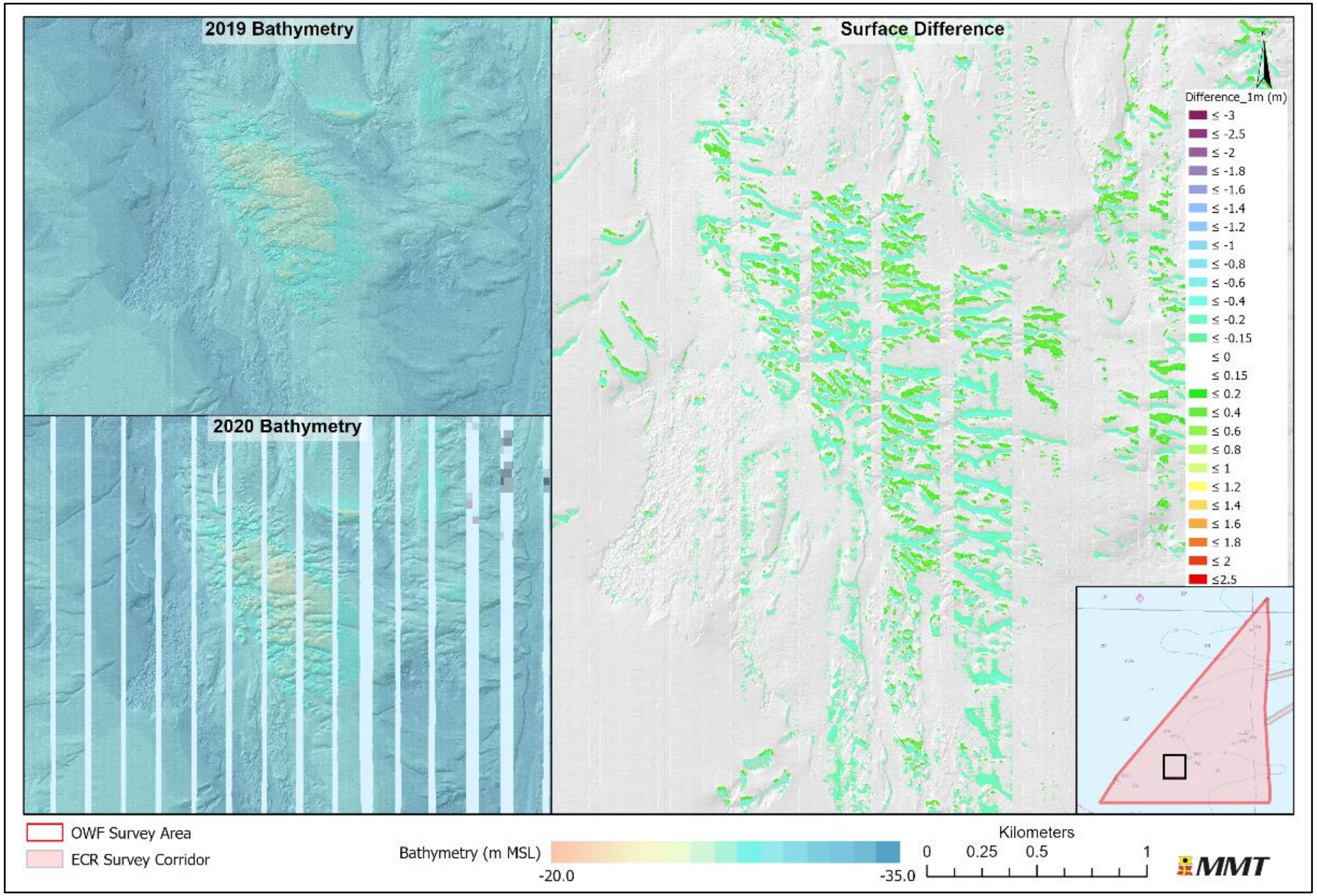

Figure 21 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 2.

Profile 3 is located midway along the southern border of the OWF and was taken through an area of seabed 1.5 km long (Figure 22 and Figure 23). Measurements of the sandwave displacement indicated approximately 20 m of movement towards 000°. Depth differences within the surrounding sandwave field range between -0.70 m and +0.53 m.

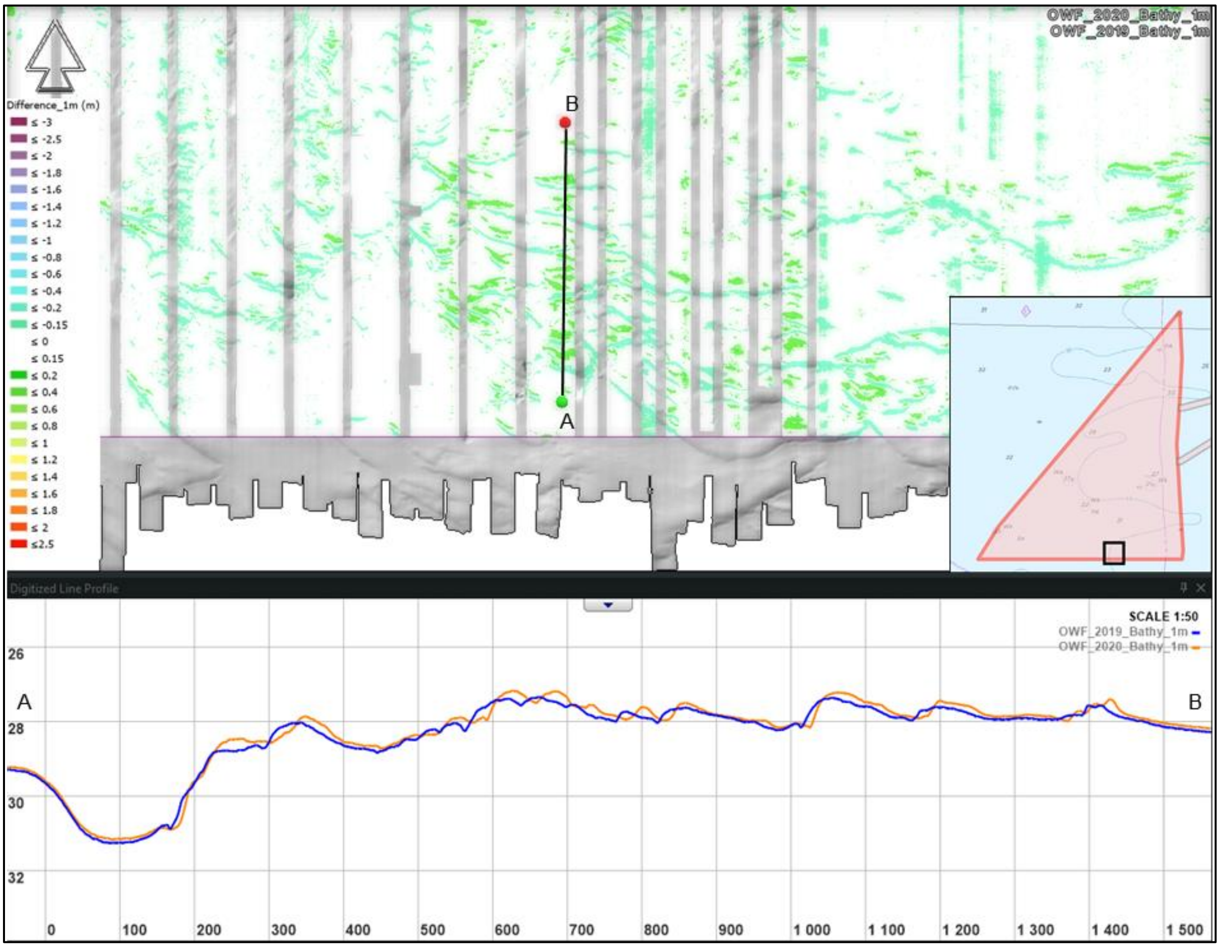

Figure 22 Seabed mobility and depth comparison profile 3.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

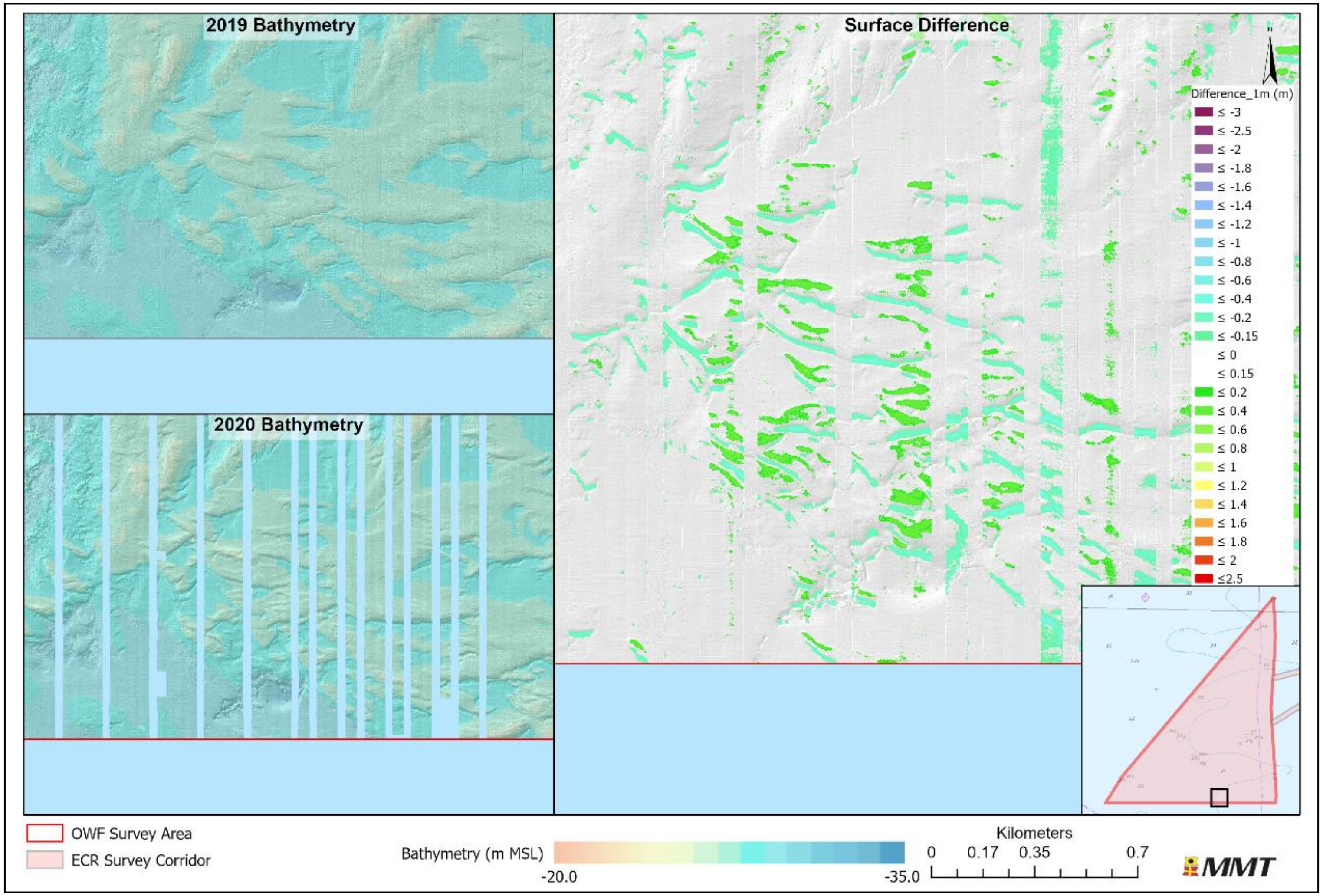

Figure 23 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 3.

Profile 4 was drawn over one of the large banks of sediment in the southeast corner of the OWF (Figure 24 and Figure 25). The eastern parts of the OWF were prioritized as they contained some of the largest sedimentary features and which may have implications for the design of the windfarm should they show evidence of significant mobility. The profile location was chosen to cross the full width of the bank as well as show the mobility on the upper parts of the bank. The profile supports the surface difference results which shows that the extents of the bank have remained stable, although to the east of the profile location the trough on the southern side of the bank shows evidence of deepening (up to -0.55 m). The superimposed ripples and megaripples on top of the bank are, however mobile with displacement orientation towards 000° and distances between 20 m and 30 m. In the area surrounding the profile depth differences range from -0.70 m to +0.50 m.

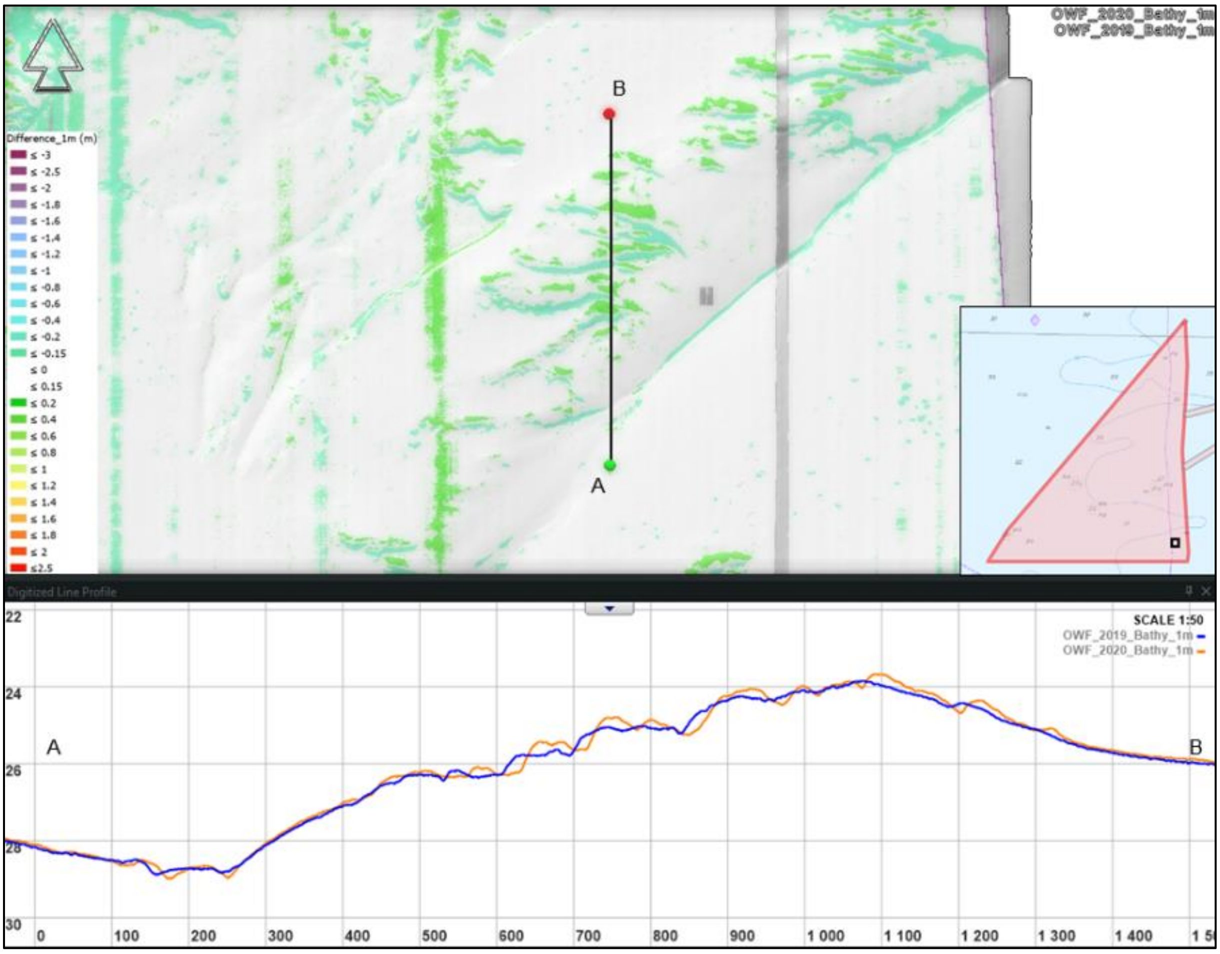

Figure 24 Seabed mobility and depth comparison profile 4.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

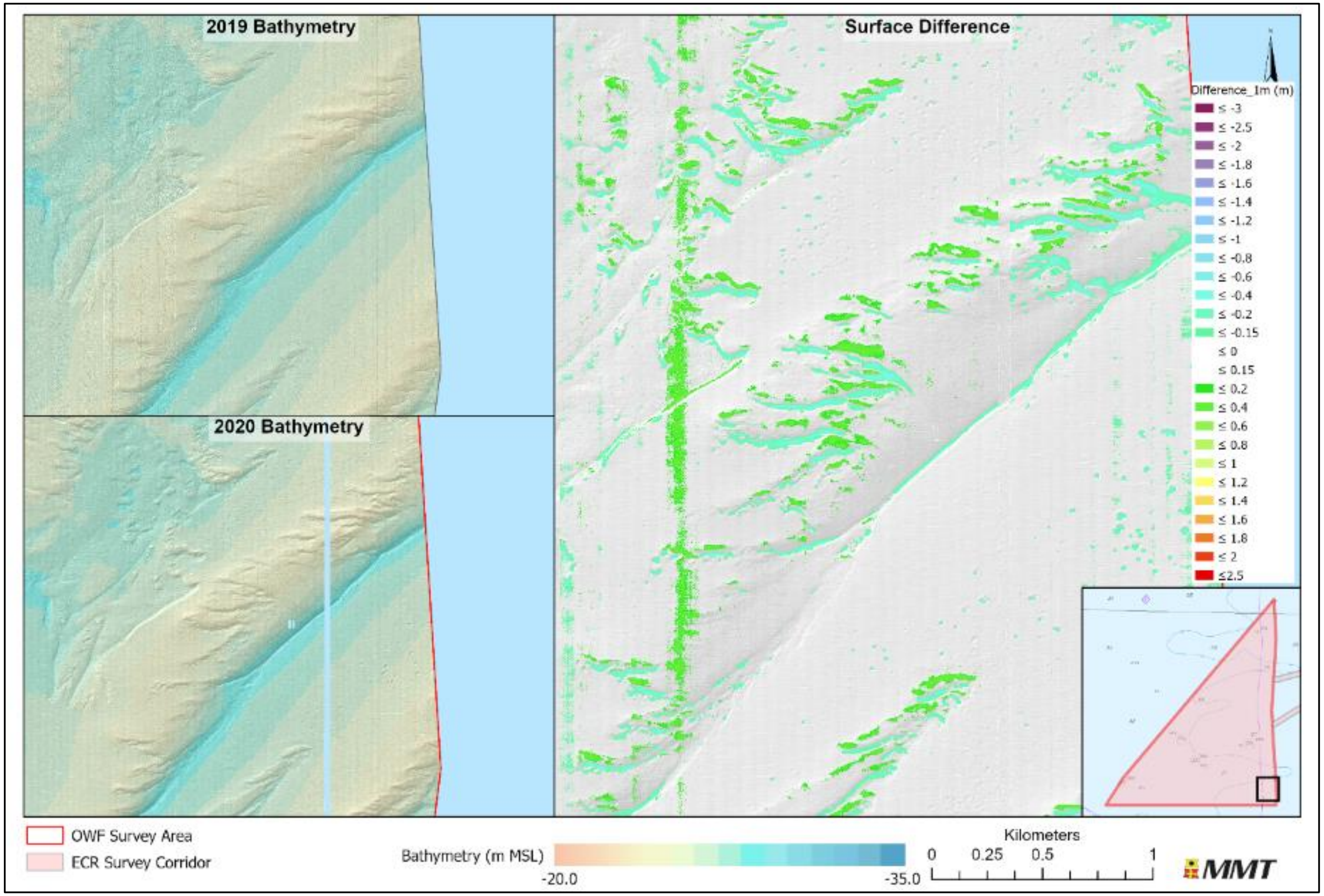

Figure 25 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 4.

Profile 5 passes through a patch of mobile seabed on the southwestern side of the OWF (Figure 26 and Figure 27). The sandwaves here have been displaced by approximately 10 m towards 007°. Depth differences in the surrounding area of the profile range between -0.70 m and +0.55 m.

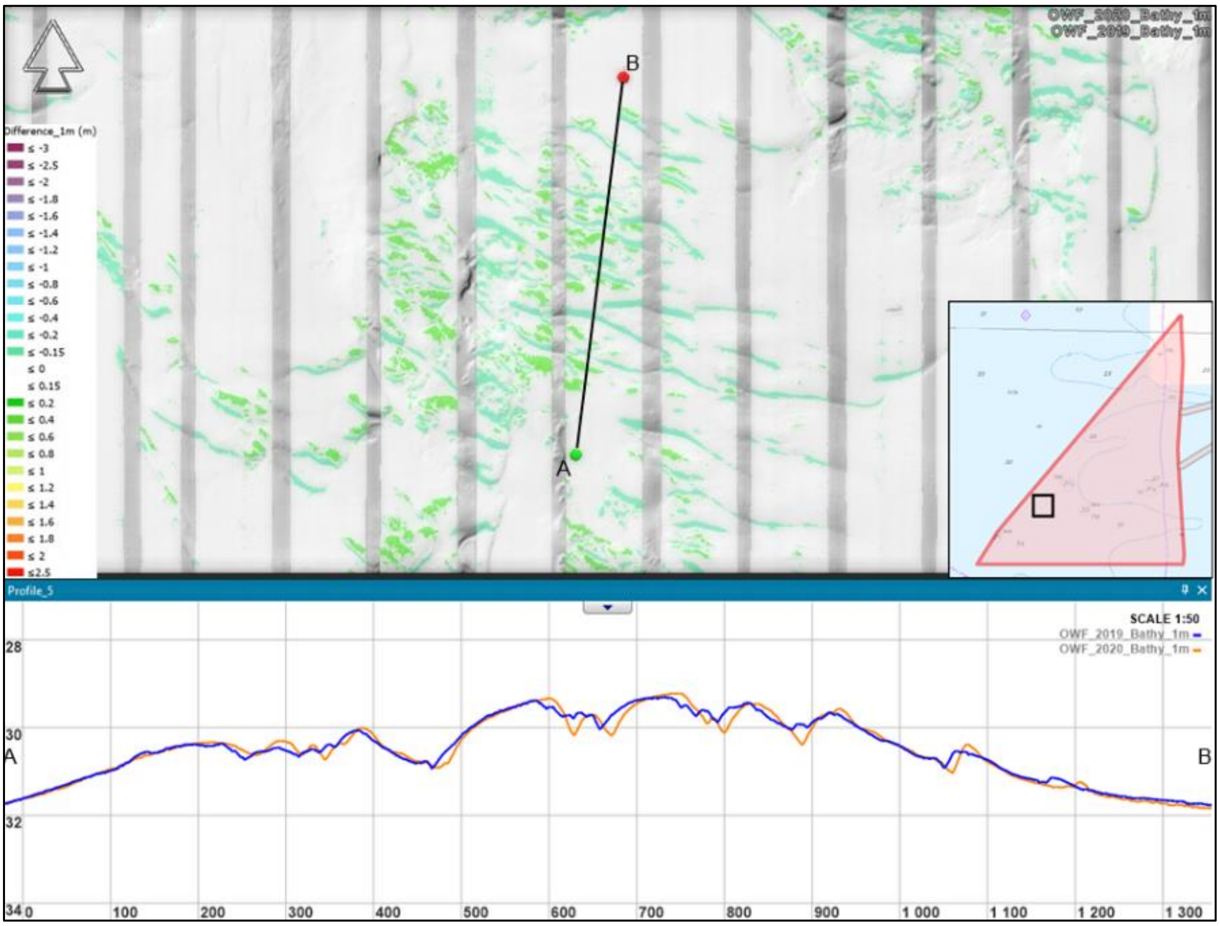

Figure 26 Seabed mobility and depth comparison profile 5.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

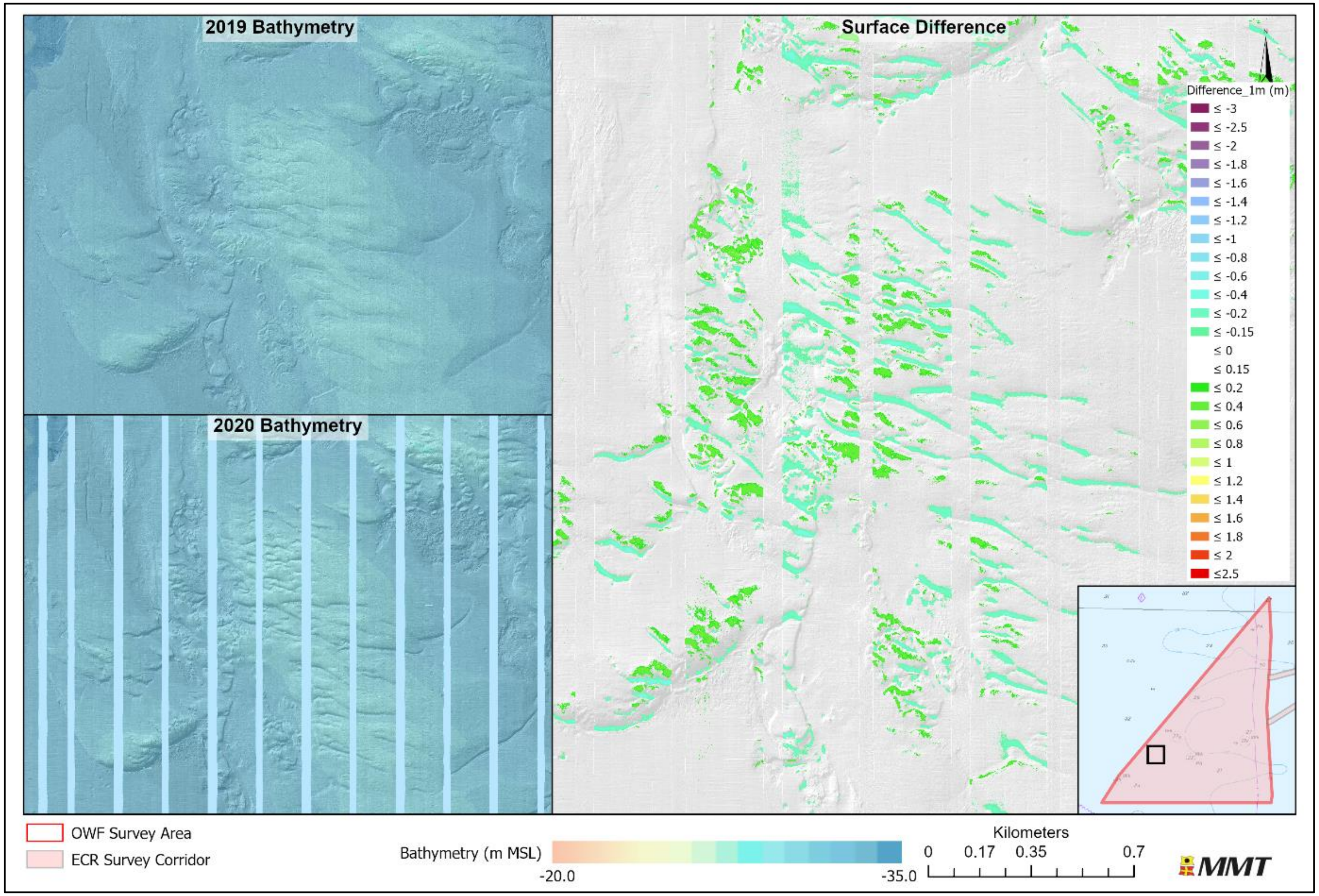

Figure 27 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 5.

Profile 6 covers 4000 m of the large sandwave area that lies in the central part of the OWF (Figure 28 and Figure 29). Measurements were taken from the more prominent features along the profile, which were often the bottoms of the troughs as these were more distinct than the sandwave crest positions. These showed migration towards 000° of between 20 m and 30 m. The range in depth differences across this large sandwave area is -1.30 m to +1.10 m.

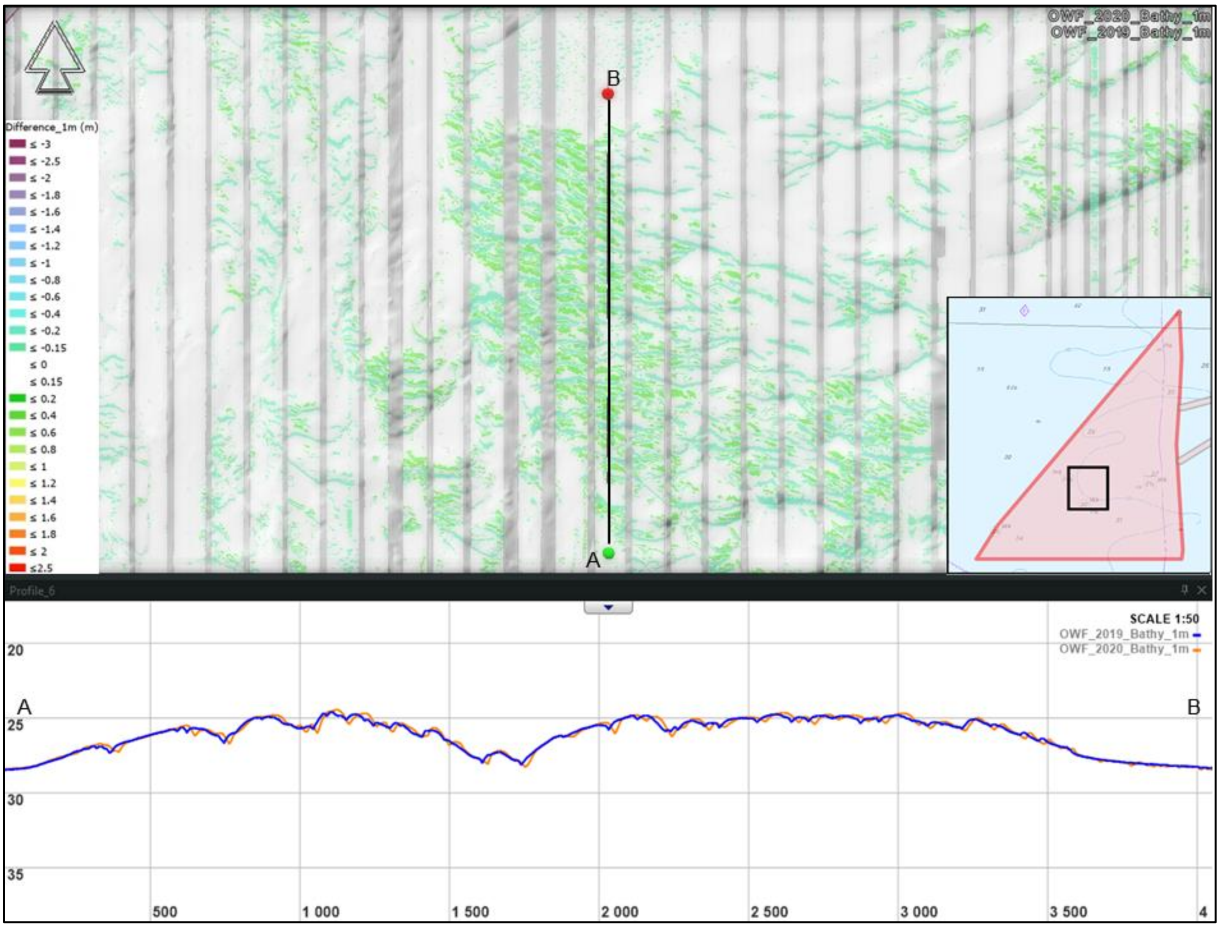

Figure 28 Seabed mobility and depth comparison profile 6.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

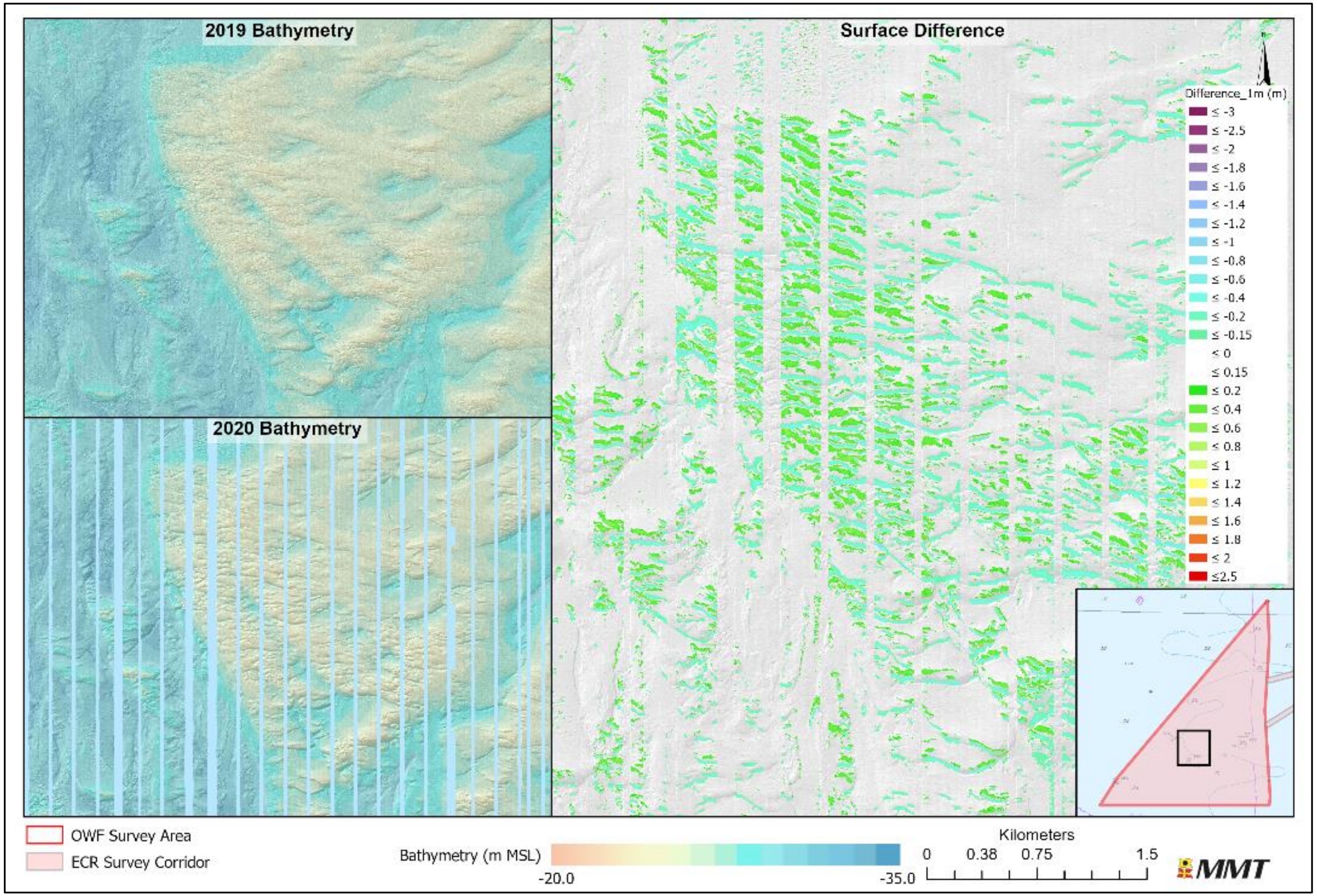

Figure 29 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 6.

Profile 7 lies in a mobile sandwave field in the eastern-central part of the OWF (Figure 30 and Figure 31). Measurements along the profile indicated that movement was between 10 m and 30 m towards 020°. In the area around the profile depth differences range between -1.35 m and +1.25 m.

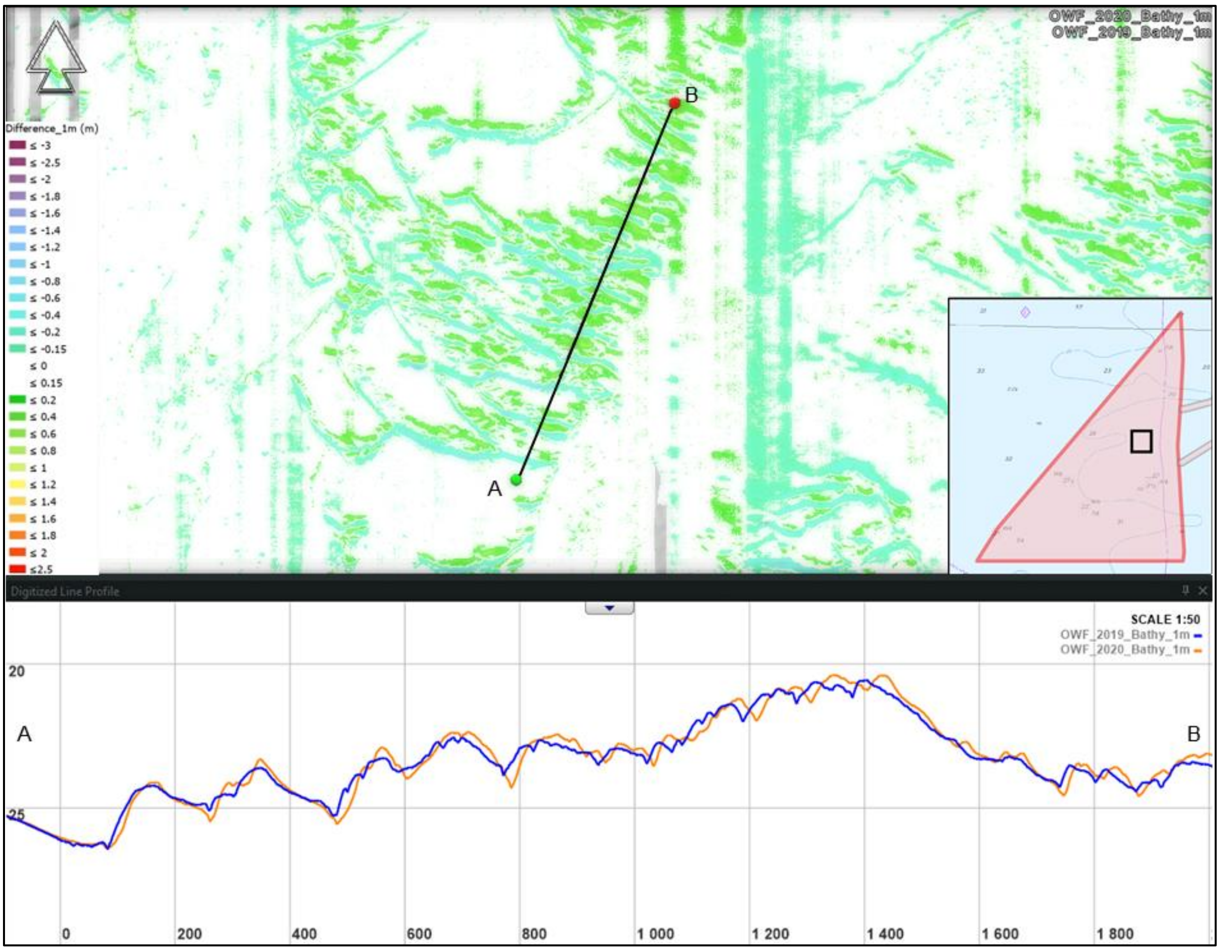

Figure 30 Seabed mobility and depth comparison profile 7.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

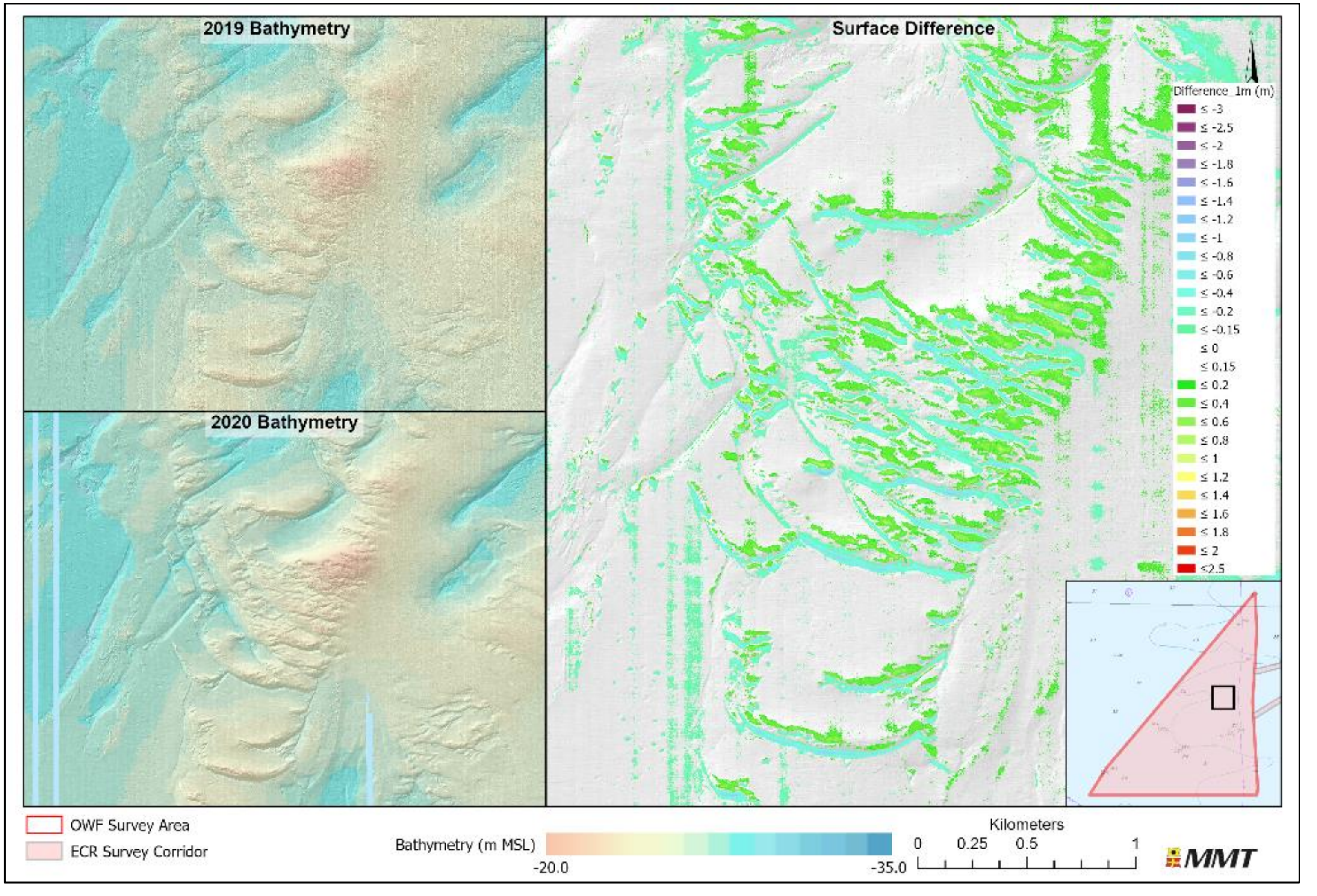

Figure 31 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 7.

Profile 8 lies in the northwest of the OWF and passes across an area with smooth, rounded bedforms (Figure 32 and Figure 33). The surface difference results show that there are more increases in depth below the +/-0.15 m threshold than above it. This is represented by the greater prevalence of the blue-green colour along the profile than the apple-green. The profile shows that the troughs have typically increased in depth by 0.20 m to 0.30 m. Where the form of the seabed can be correlated between the 2019 and 2020 surveys, migration appears to be 10 m to 20 m towards 010°. Depth differences in the area around the profile range from -0.90 m to +0.60 m.

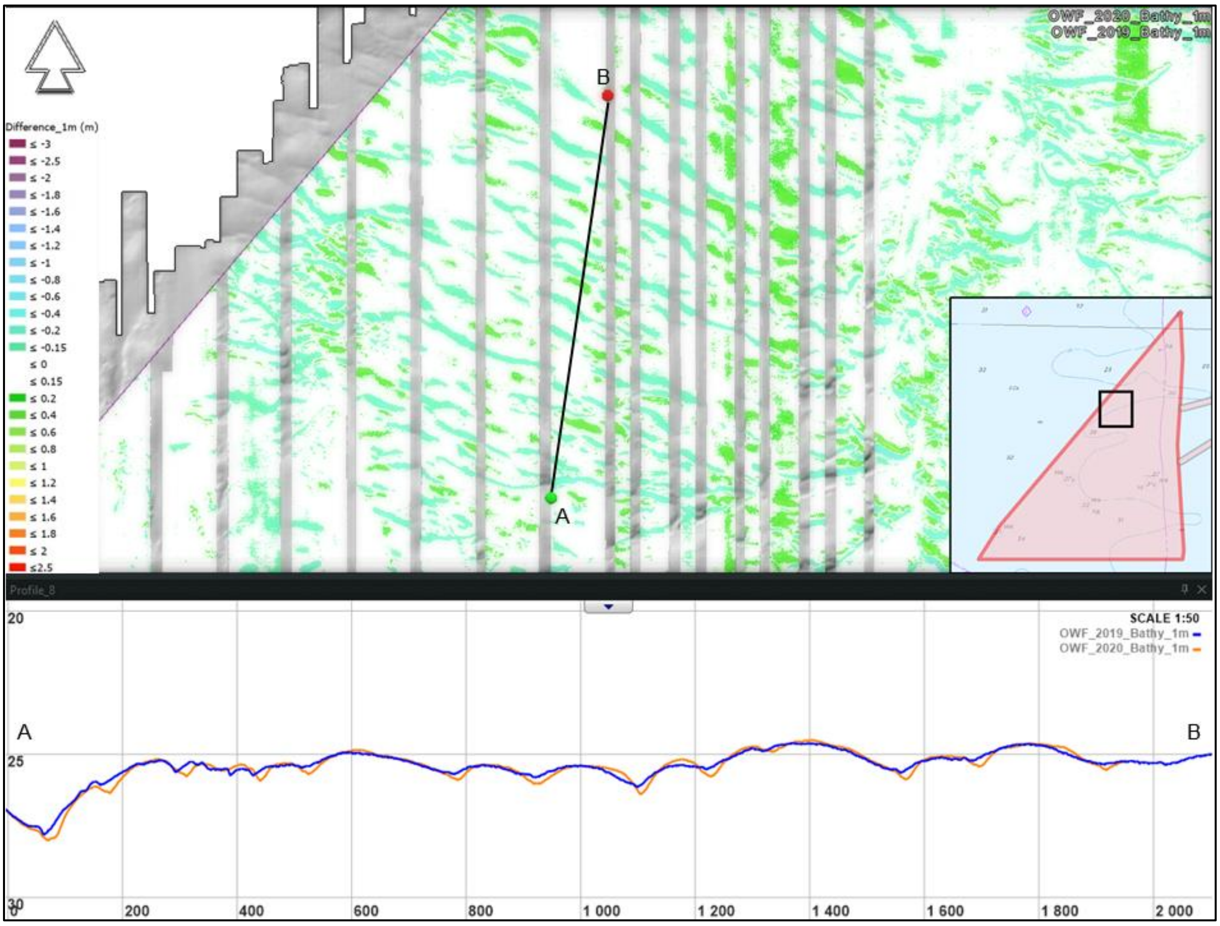

Figure 32 Seabed mobility and depth comparison profile 8
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

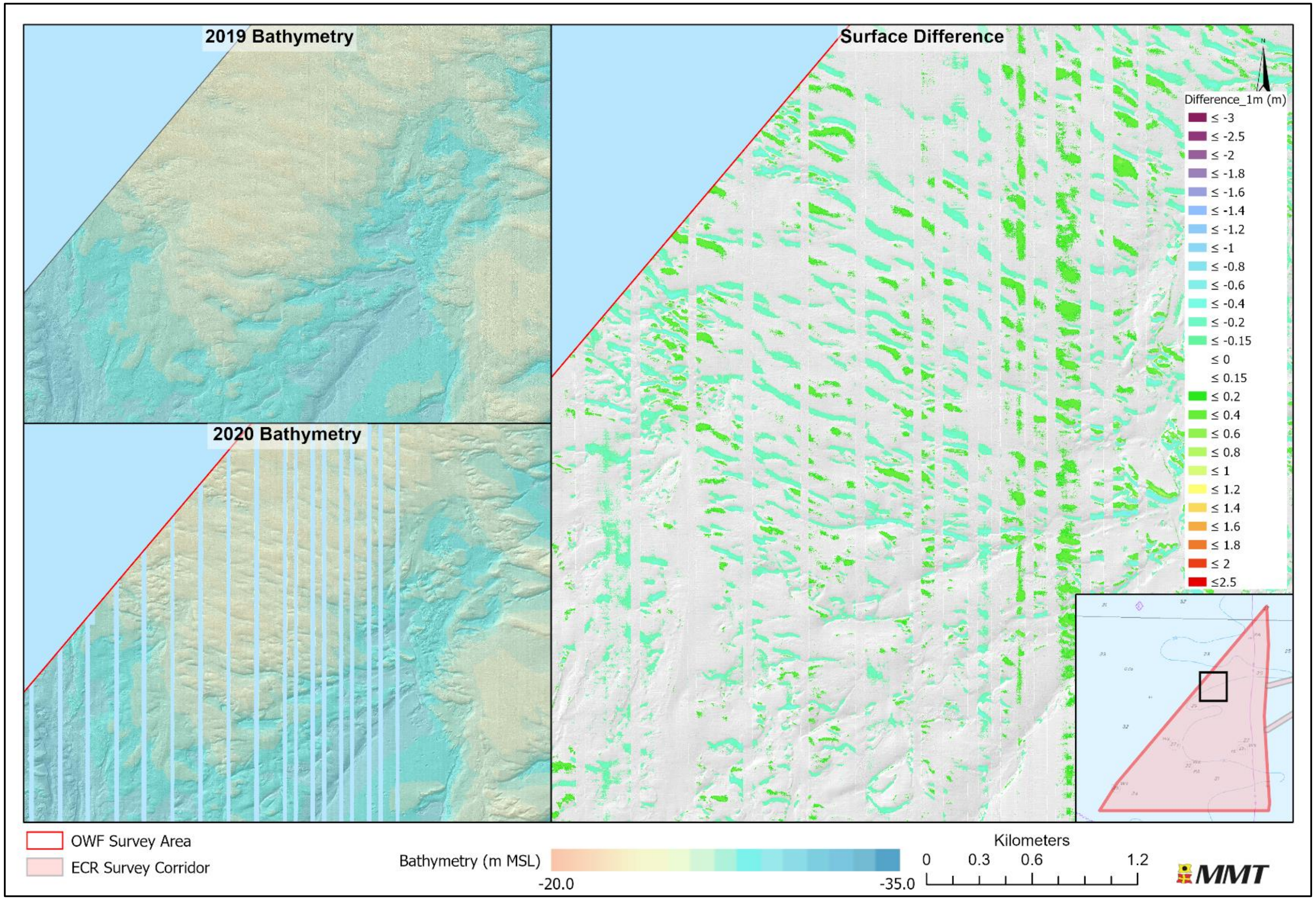

Figure 33 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 8.

Profile 9 is located near the eastern border of the OWF, on the southern side of the ECR entry point 2 (Figure 34 and Figure 35). The profile crosses a patch of sand which shows the change in character observed in the ECR and around the OWF, where numerous, small depressions seen in 2019 are replaced by broader and more widely spaced depressions in 2020. This can also be seen across a large expanse to the west of the profile line. Where bedforms can be correlated between the two surveys the horizontal displacement measures 10 m to 20 m towards 000°. The depth differences in the area surrounding the profile range from -0.85 m to +0.55 m.

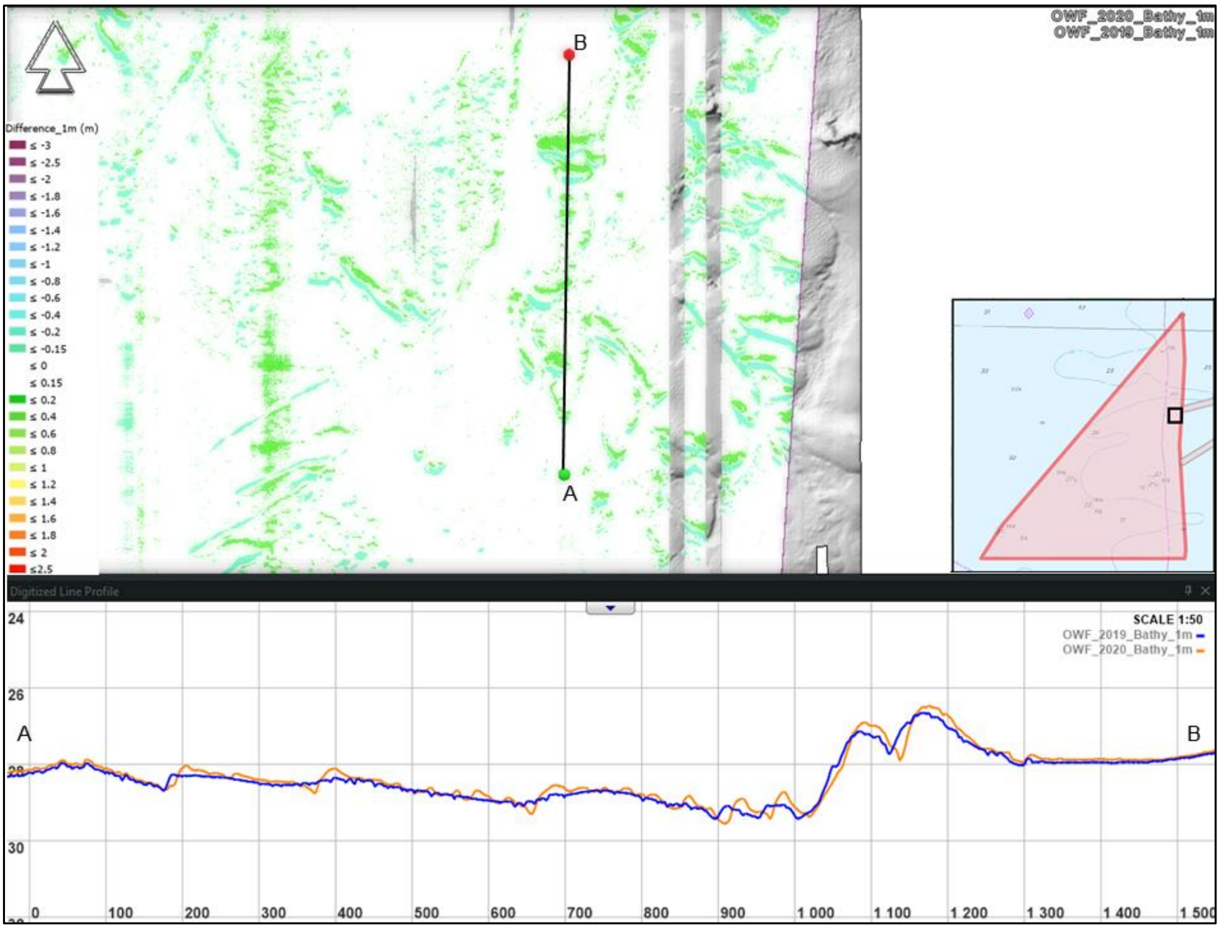

Figure 34 Seabed mobility and depth comparison profile 9.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

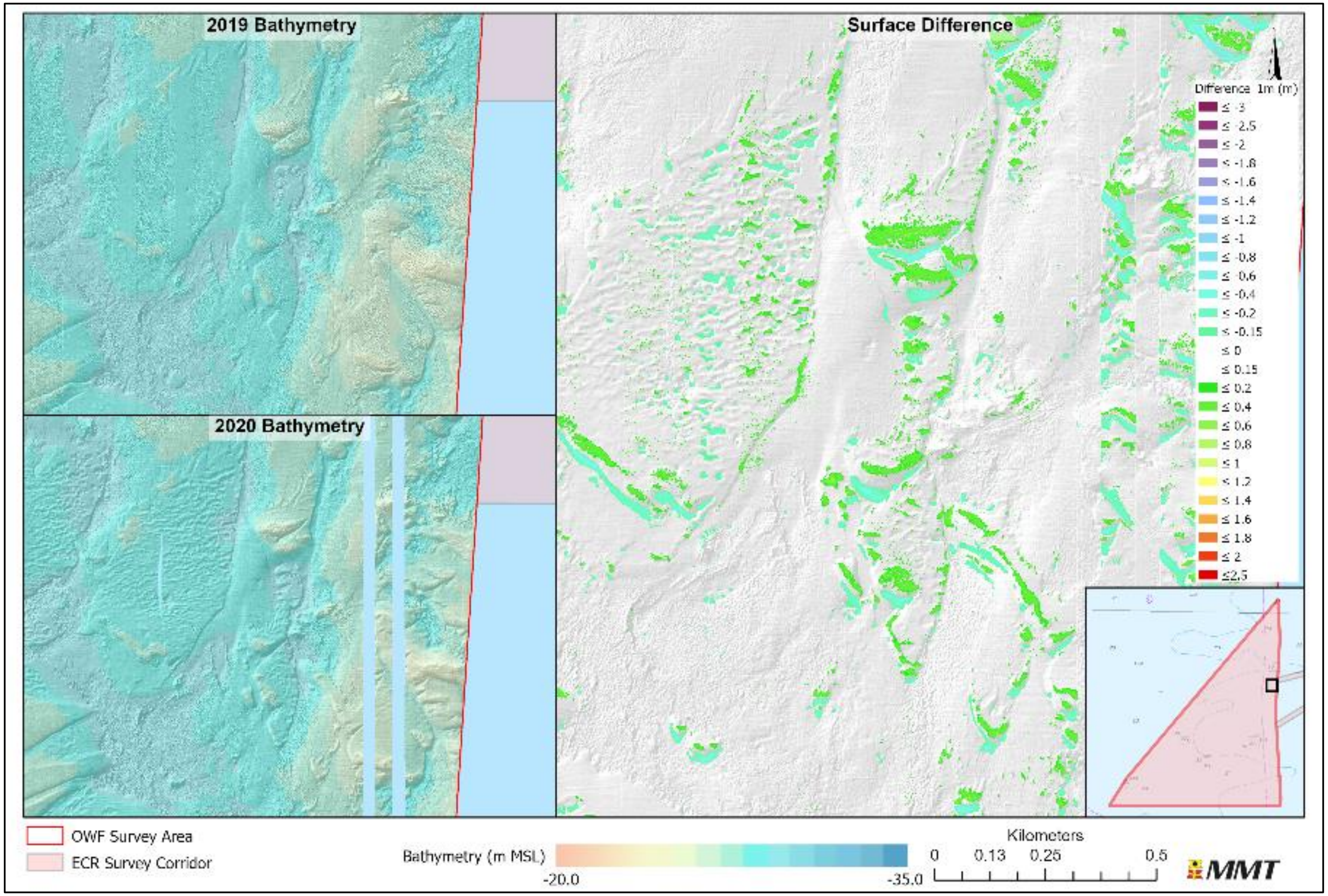

Figure 35 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile 9.

Profile 10 lies in the northern corner of the OWF and crosses over patches of sand and other mixed sediments with a stable section separating two areas of mobility (Figure 36 and Figure 37). The bedforms present have migrated towards 005° by between 15 m and 30 m. Depth differences in the area surrounding the profile range between -1.30 m and +1.10 m.

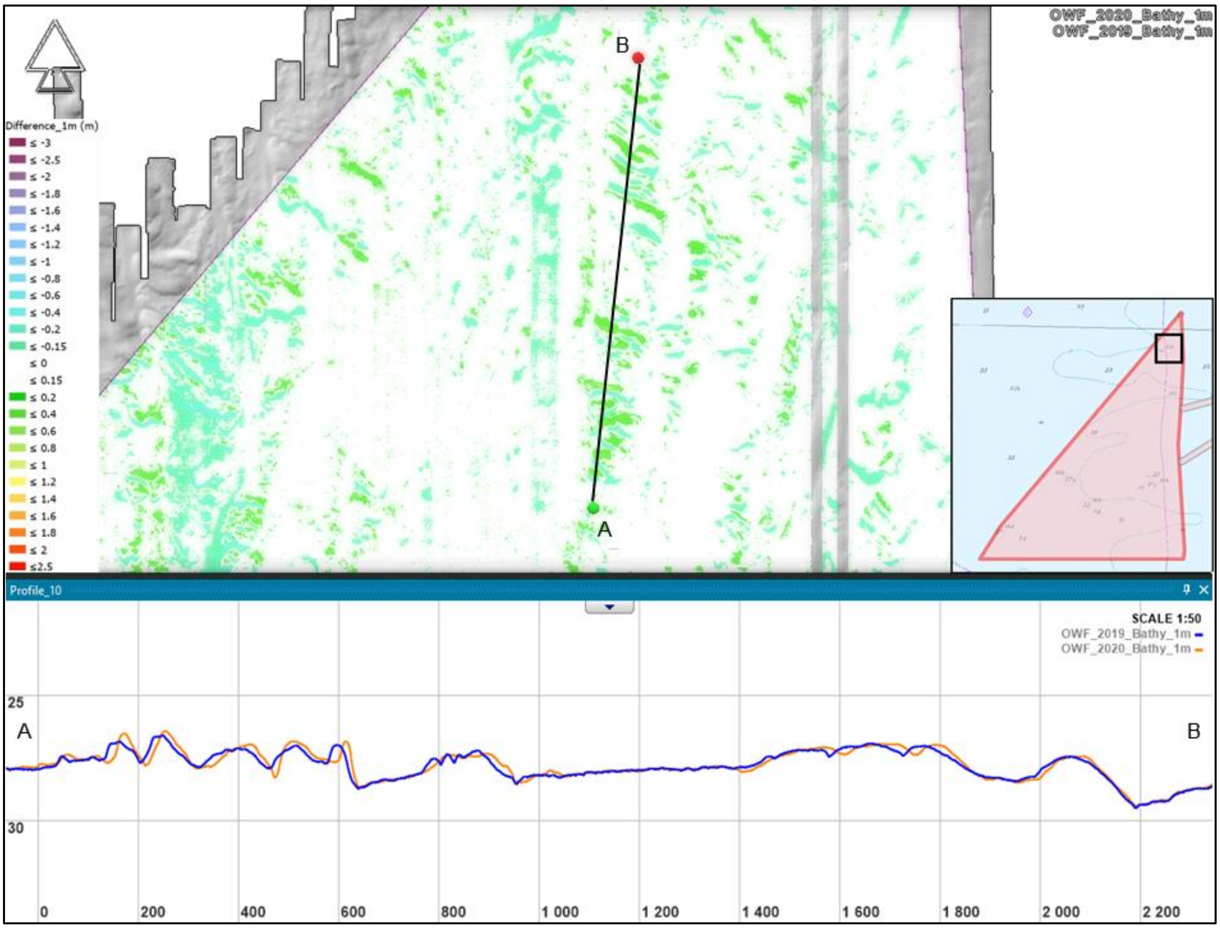

Figure 36 Seabed mobility and depth comparison profile 10.
Upper panel shows the surface difference results with seabed depth from 2019 (blue) and 2020 (orange) below. NaviModel depth convention is positive down, vertical exaggeration of profile x50.

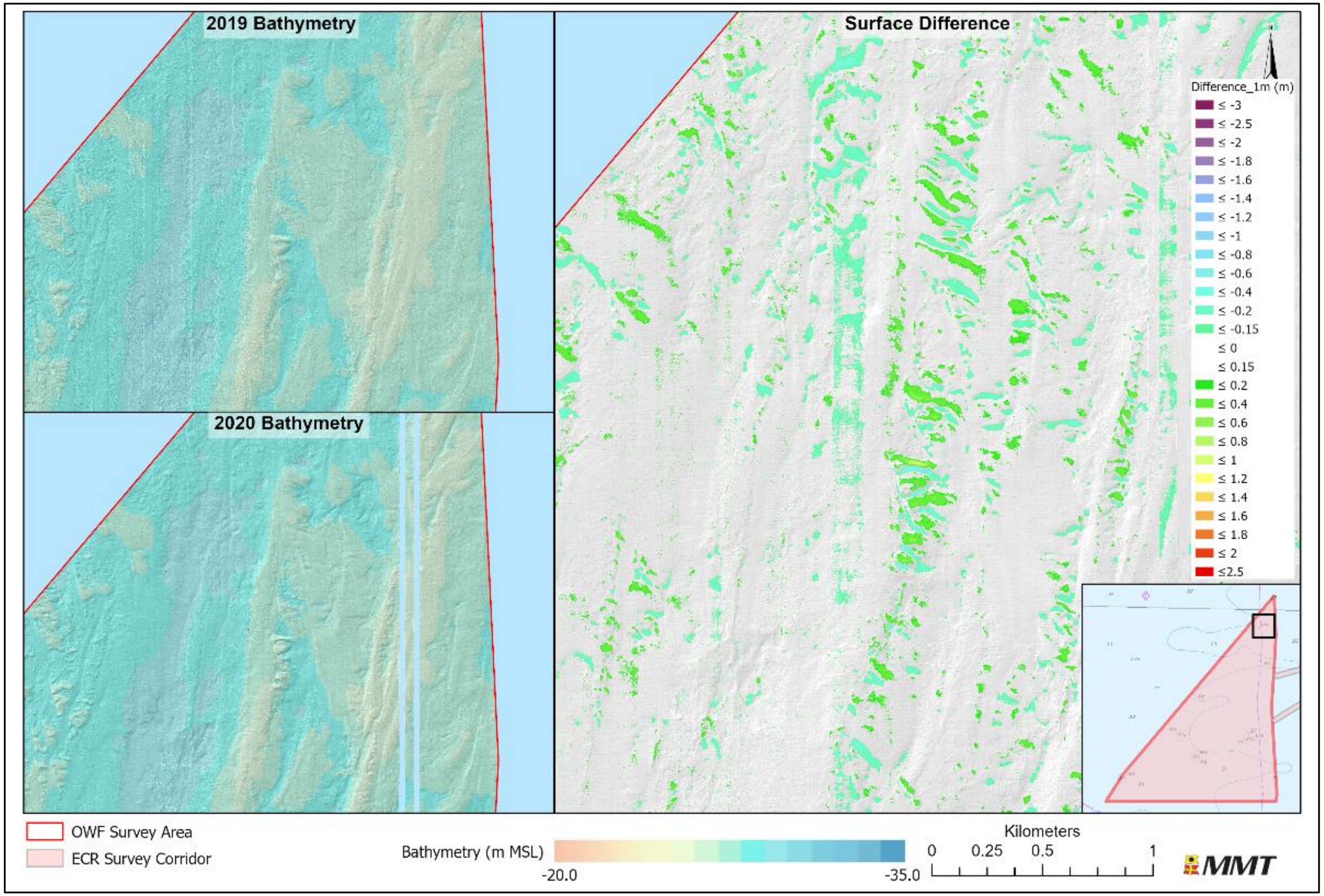

Figure 37 Chart showing bathymetric surfaces from 2019 and 2020 in the region around Profile10.

7| CONCLUSIONS

During the 2020 repeat survey of the OWF coverage was achieved across 88.23% of the total area. The minimum surveyed depth is -20.23 m at 421112.5 E, 6248235.0 N in the northern part of the survey area. The maximum depth surveyed is -35.40 m at 406 209 E, 6 240 966 N in the western area.

Surface difference results were derived by comparing the 2019 and 2020 DTMs in ArcGIS Pro. The results, which were the main purpose of this survey, indicated that sediment mobility is widespread and observed across large expanses of the OWF site. Depth differences either side of the +/-0.15 m zone covered 45.42 km^2 (11.7% of the area surveyed in 2020). The range of depth difference values was found to be -3.19 m to +1.75 m however these were found to correspond with MBES noise within the 2019 dataset. Profiles across the width of the OWF showed that the depth differences were largely with +/-0.5 m and measurements taken from the areas surrounding the profile zones showed real differences of -1.35 m and +1.25 m within sandwave areas.

The minimum and maximum depth differences for each 1 km tile were extracted from the ASCII XYZ data. This showed that larger negative changes of -1.8 m were occurring along the steep, step-like slopes of the mass transport areas. Such large changes result from the repositioning of the slope edge but are not clearly observed in profiles taken across these zones (maximum differences ca. -0.6 m). A possible reason for this is that the grid node positions are slightly different between the 2019 and 2020 data and so a small horizontal shift of 0.5 m in the data causes upper and lower slope data to overlap creating difference values with anomalously high magnitudes.

Measurements of the horizontal displacements of the migrating bedforms across 10 sites within the OWF were made using EIVA NaviModel. Displacements between 10 m and 55 m were observed with 20 m to 30 m being more typical of the features that could be correlated between the DTMs. The orientation of the displacement was between 000° and 020°

8 | RESERVATIONS AND RECOMMENDATIONS

The surface difference results provide a useful insight into the sediment dynamics within the surveyed area and performing this repeat survey 1 year on from the original informs the viewer on the annual rates of change. It may be useful to conduct repeat surveys, possibly focussing on key areas once the design of the windfarm is finalised to determine, but extending the time period between them so that the changes to the seabed during the life of the windfarm can be assessed. For example, seeing what changes occur over a 5 and then 10 year cycle may be of use. It may be deemed that 100% coverage is not required and a series of widely spaced survey lines or a grid would be sufficient if they covered key areas within the site.

When performing longer term comparisons, it would be beneficial to include the 2019 survey as the benchmark historical dataset. As has been seen in this report, using a mobile platform introduces small misalignments between datasets that could mask minor vertical changes if the comparison is only made from year to year. Having the earliest dataset as the benchmark means that these smaller scale changes in the seabed sum up to larger changes that can be identified when a longer term view is taken.

In addition to the site wide survey, MBES surveys to monitor the seabed-structure interactions post-construction would be recommended. This could be restricted to the immediate vicinity of the WTG (or other structure) and volumetric assessment may become more relevant since you can determine whether sediment is being eroded or deposited within the zone and if the rates of change require any remediation works to be performed.

9 | DATA INDEX

The deliverables listed in Table 14 accompany this report.

Table 14 Deliverables.

No	Data Type	Data Product
1	101_MBES	01_Ungridded_Soundings
2	101_MBES	02_Grid_0_50_ascii
3	101_MBES	03_Grid_0_50_geotiff
4	101_MBES	04_Grid_1_00_ascii
5	101_MBES	05_Grid_1_00_geotiff
6	101_MBES	06_Grid_5_00_ascii
7	101_MBES	07_Grid_5_00_geotiff
8	101_MBES	08_Contour_curves
9	101_MBES	09a_TVU_1_00_ascii
10	101_MBES	09b_TVU_1_00_geotiff
11	101_MBES	09c_THU_1_00_ascii
12	101_MBES	09d_THU_1_00_geotiff
13	101_MBES	09f_SVP
14	101_MBES	09g_SurfDiff_1_00_ascii
15	101_MBES	09h_SurfDiff_1_00_geotiff
16	109 Operations Report	103628-ENN-MMT-SUR-REP-OPEREP
17	110 Geophysical Report	103628-ENN-MMT-SUR-REP-SURVECR-02.docx
18	Charts (A3 Booklet)	103628-ENN-MMT-SUR-MXD-NUOWF_Bathymetry
19	Charts (A3 Booklet)	103628-ENN-MMT-SUR-MXD-NUOWF_Surface_Difference
22	GIS Database (Features)	SN2020_011_F_OWF_20201013.gdb
23	GIS Database (Rasters)	SN2020_011_R_OWF_20201013.gdb

APPENDIX A | CHART LIST

APPENDIX B | PROFILE GRAPHS