GeoSurveys

geophysical consultants

Energinet LOT1 Offshore Geophysical Survey

2D M-UHRS GEOPHYSICAL DATA PROCESSING

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SUMMARY

MMT contracted GeoSurveys (GS) to provide offshore M-UHRS offline QC services and to process the M-UHRS data acquired in the scope of the Energinet WP-A Offshore Geophysical Survey, from May 1st to June 12th, 2021, located offshore Thyborøn, Denmark.

This document reports the relevant matters related to the UHRS data processing of 3248 km multi-channel seismic lines acquired with a Triple Sparker system (179 seismic profiles, including re-runs and infills).

The UHRS processing was performed at GS office using RadexPro software and in-house developed processing flows. The processing workflow was divided into two main processing stages: Pre-Stack TRIM Track and FULL Track. The main purpose of the TRIM track was to compute a proper residual motion correction and the vertical statics needed for reducing data to a common vertical datum. The aim of the FULL track processing flow was to create fully processed migrated and non-migrated seismic sections in time (TWT) and depth (DPT).

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

ABBREVIATIONS

ASCII – American standard code for information interchange;

CDP – Common depth point;

COSA – Common Offset Spatial Averaging;

dB – Decibel;

DC – Direct current;

DGPS – Differential global positioning system;

DPT – Depth migrated stack;

EBCDIC – Extended binary coded decimal interchange code;

ETRS89 – European Terrestrial Reference System 1989

FFID – Field file identification number;

F-K – Frequency-wave number;

GMSS – Geo Marine Surveys System;

GNSS – Global Navigation Satellite System;

GPS – Global Positioning System;

GS – Geosurveys;

Hz – Hertz;

J – Joule;

(c, k, m) m – (centi, kilo, milli) Meter;

MBES – Multibeam echosounder;

MIG – Migrated stack;

MUL – Multiple attenuated stack;

MSL – Mean Sea Level

M-UHRS – Multichannel Ultra-high resolution seismic;

NMO – Normal Moveout;

QA – Quality analysis;

QC – Quality control;

RMS – Root mean square;

(μ, m) s – (micro, milli) Second;

SB – Seabed;

SEG-Y – Convention from the society of exploration geophysicist (seg) for pre-stack and post-stack seismic data;

SI – Shot interval;

SRME – Surface-related multiple elimination;

SVM – Standard Velocity Model

SVP – Sound velocity profile;

TVBPF – Time variant bandpass filtering;

TWT – Two-way-time;

UHRS – Ultra-high resolution seismic;

UTM – Universal transverse Mercator.

1. INTRODUCTION

MMT contracted GeoSurveys (GS) and Geomarine Survey Systems (GMSS) to provide offshore 2D M-UHRS offline QC services and to process the M-UHRS data acquired in the scope of the Energinet LOT1 WP-A - Geophysical Survey, located approximately 95 km west of Thyborøn, Denmark, on the East OWF area and Energy Islands site (Figure 1).

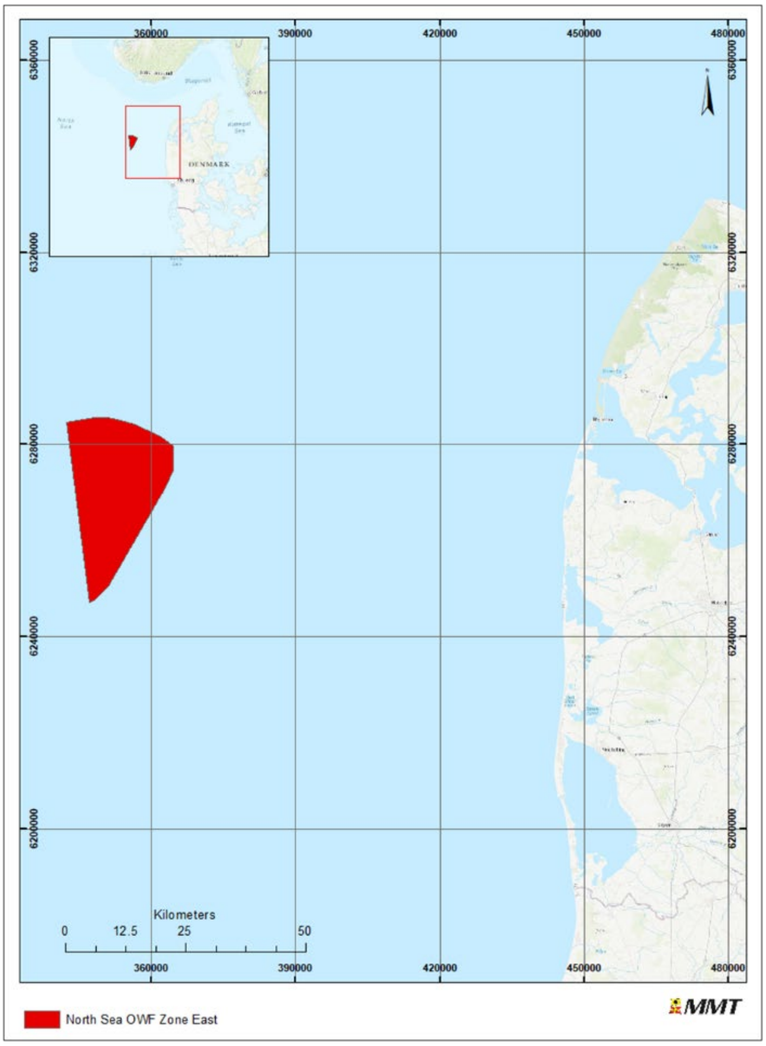


Figure 1 *– Survey site location (red polygon).*

The M-UHRS data acquisition was performed using an Ultra-High Resolution Seismic system that included: (a) three Geo-Spark 6kW power supplies; (b) three Geo-Source 200 tips stacked sparker layers in tuned configuration; (c) a 96-channel gel filled streamer with constant group interval (1.0 m); (d) four multitrace units; (e) GNSS positioning systems for source and streamer front and tail buoys; and (f) a single element reference hydrophone for source quality control and noise tests.

This document reports the M-UHRS data processing of 179 seismic profiles (~3248 km of seismic data), carried out on board of the M/V Relume.

1.1. Survey Area and Line Plan

The survey site covers an area of approximately 600 km2, with its line length varying from almost 39 km to 2 km. The water depths in this area range mainly between 26 to 48 m.

M-UHRS line plan consisted of 102 main lines, orientated NNW-SSE and separated by 210 m, and 38 cross lines, orientated ENE-WSW and separated by 1 km, with a total length of approximately 3248 km (Figure 2). A total of 179 seismic sections were acquired and processed (130 mainlines and 49 crosslines), including infills and reruns.

Some reference lines were selected as site-representative M-UHRS seismic dataset of LOT1. The reference lines were used to perform the processing tests and served as a base for the first geological ground model definition. Four mainlines and five intersecting crosslines were selected for processing. These reference lines are illustrated in the figure below (Figure 3).

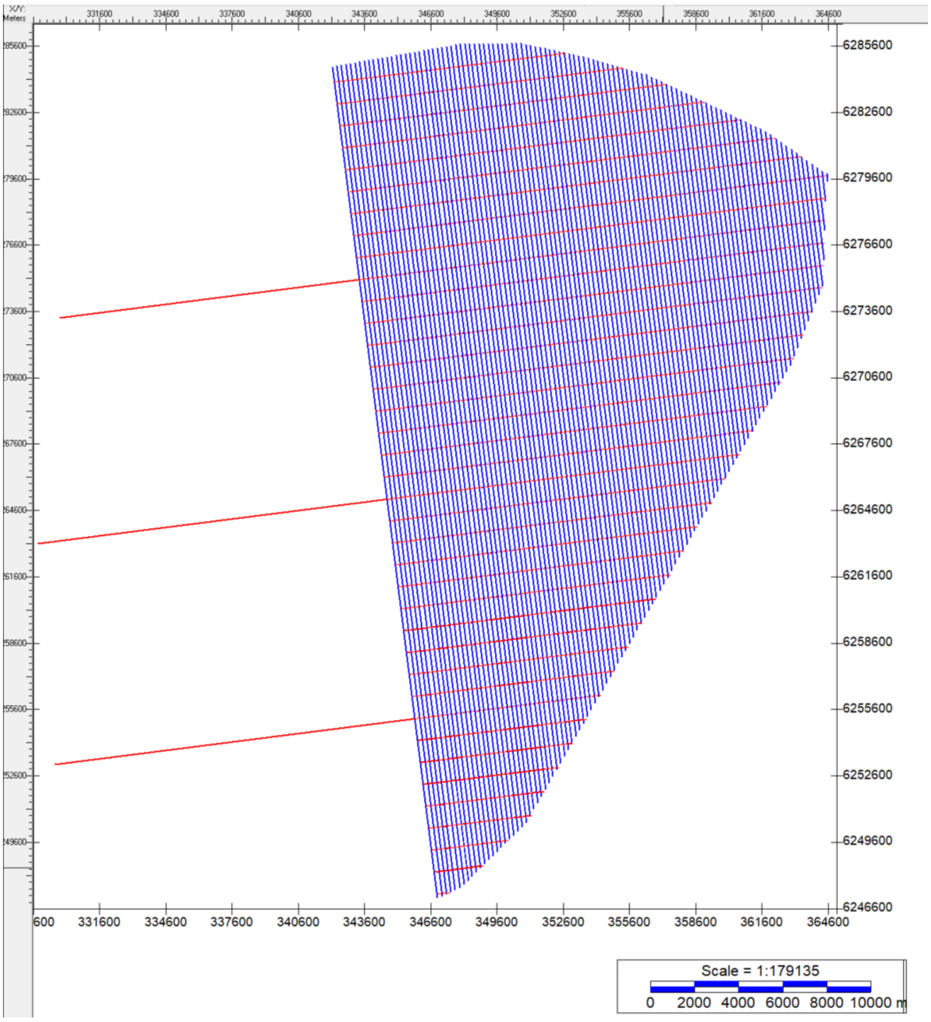


***Figure 2**– Line Plan – M-UHRS main and cross lines*

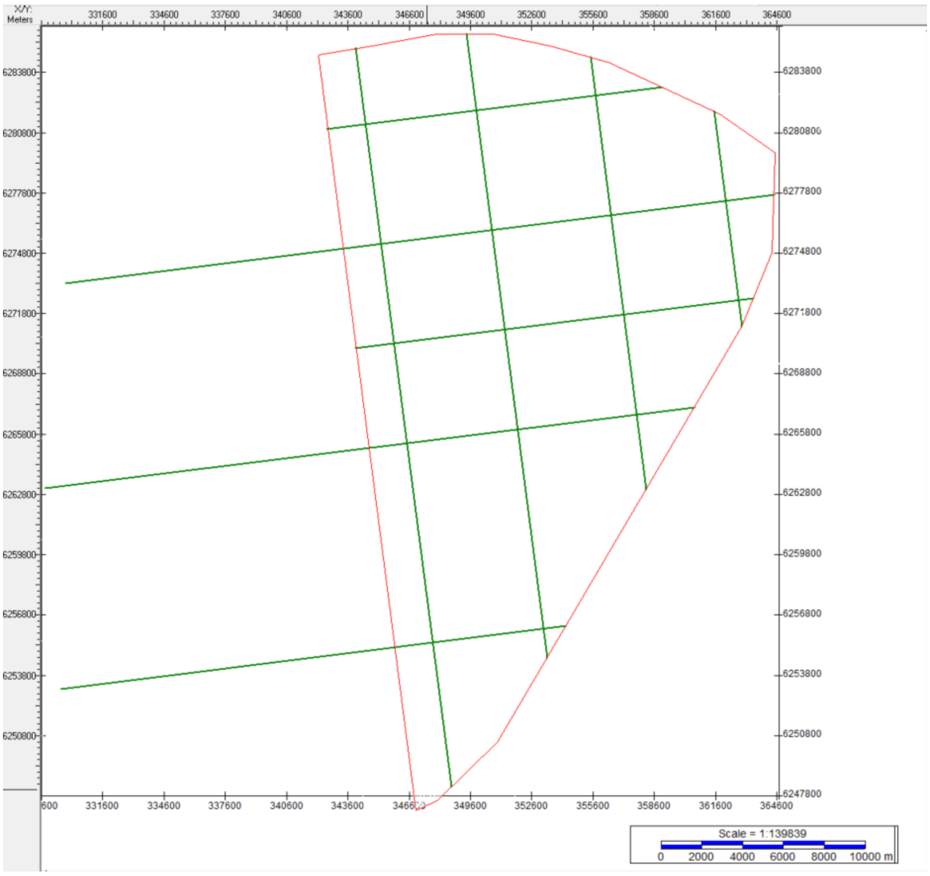


Figure 3 – *M-UHRS reference lines*

1.2. Purpose and Objectives of the Processing

In order to satisfy the necessary criteria, some quality control and processing solutions were specifically developed and tailored.

M-UHRS objectives were:

- 100 m of signal penetration below seabed;
- 0.5 m of horizontal resolution (CDP bin);
- To produce datasets fit for a maximum detail to recognize and map the paleo-horizon reflection and to identify and map deeper stratigraphy.
- To generate adequate seismic imaging, allowing the:
    - Assess of geological features for the wind farm construction;
    - Mapping of all major geological layers and structures to at least 100 m below seabed;
    - Location of structural complexities or geohazards within the shallow geological succession such as faulting, accumulations of shallow gas, buried channels, soft sediments, etc.

The UHRS processing was performed at GS office using RadexPro software and in-house developed processing flows. This workflow was separated into two main processing phases:

- TRIM Track – flow steps to allow a proper residual motion correction and the vertical statics needed for reducing data to a common vertical datum;
- FULL Track – this stage of processing included pre-stack multiple attenuation, F-K filtering, deghosting, post-stack multiple attenuation, migration, post stack deconvolution and depth conversion. A standard velocity model (SVM), produced after the interactive velocity analysis (IVA) for each line, was used for NMO and migration. For TWT-to-Depth conversion, the SVM underwent mistie corrections and griding, in order to minimise velocity discrepancies between lines.

2. DATA ACQUISITION

The M-UHRS data acquisition was carried out onboard the vessel M/V Relume, between May 10th and June 10th, 2021. The multi-channel seismic spread used for data acquisition is described herein as having the following specifications:

(a) Three Geo-Source stacked 200 tips sparkers, towed at 0.5, 0.8 and 1.1 m, all firing at 400 Joules in combination (tuned mode) at 0.5 m interval;

(b) Three Geo-Spark 6 KW power supplies;

(c) A Geo-Sense Ultra Hi-Res 96 channels gel filled streamer towed in slant configuration (from 0.5 m to 1.8 m), with constant group interval of 1 m;

(d) Four multi-trace 24, connected to each section of the streamer (24 channels section);

(e) Geo-Sense single channel reference hydrophone;

(f) Three DGPS for streamer front and tail buoys and the stacked sources.

An overview of the vessel array layout and the seismic spread offset is illustrated in Figure 4. Characterized by the use of 3 stacked sparker sources (layers), in tuned configuration, each one separated by 30 cm. The source depth is the main factor to get constructive interference between the primary pulse and its own sea-surface reflection.

The simultaneous use of this source geometry, with the streamer in a slant configuration allows the recovery of a wider signal frequency and better ghost removal. This is achieved giving the fact that deeper channel geometry, with growing offset, usually infers an incoherent receiver ghost stack, hence, an overall increase in signal to noise ratio.

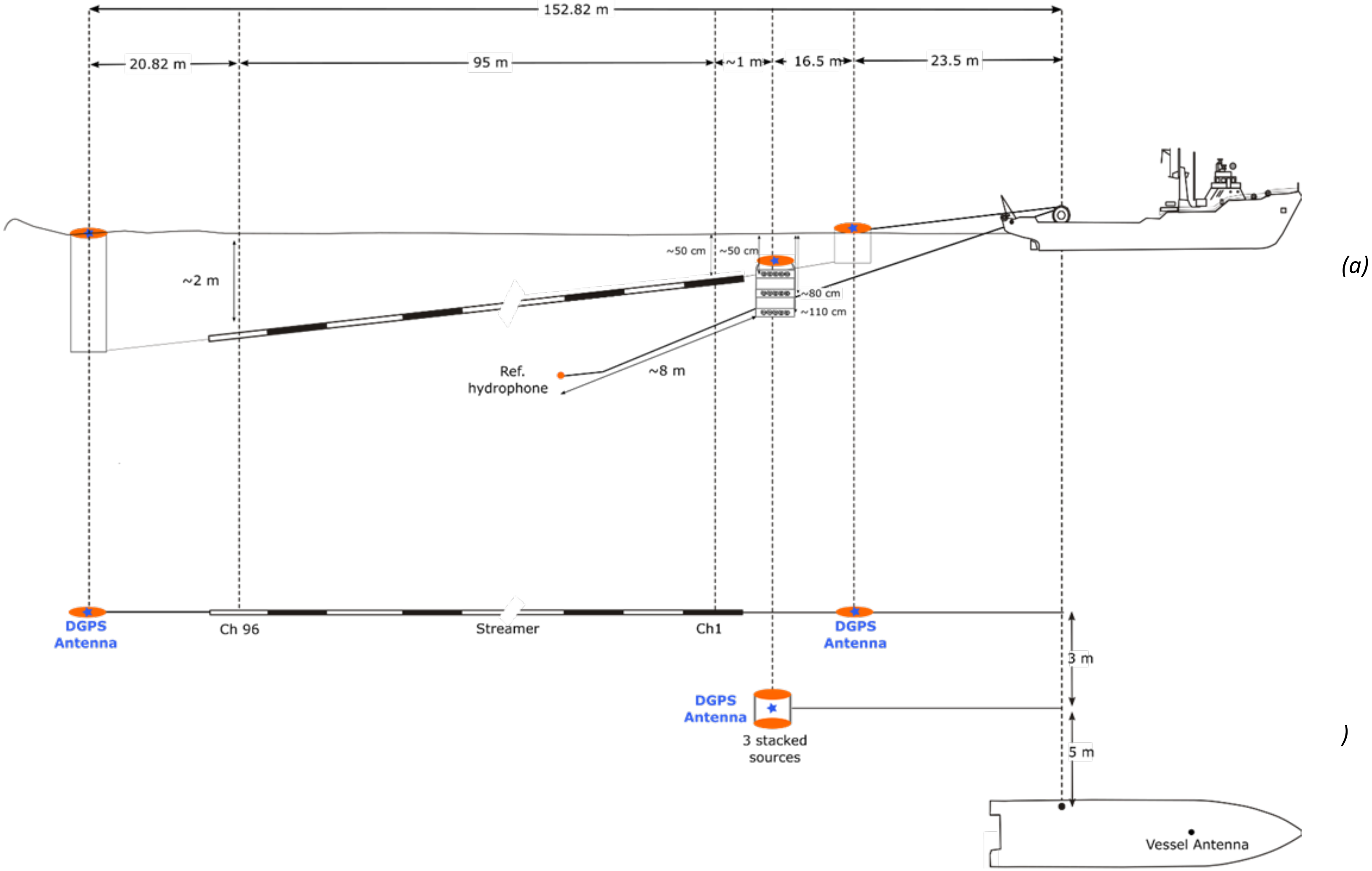


Figure 4 *– Vessel layout M/V Relume and offset diagram to the seismic spread for survey area in (a) cross section and (b) plan view (not to scale).*

2.1. Acquisition Parameters

The deployed 96-channel streamer has hydrophones spaced by 1 m, making a total active length of 95 m. A shooting interval of 0.5 m allowed a nominal fold coverage of approximately 96 for a 0.5 m CDP bin size. The general acquisition parameters are summarized in Table 1.

Table 1 – *Acquisition parameters for Energinet project: Triple sparker acquisition system used for M/V Relume vessel.*

Sources	***3 x Geo-Source stacked 200 LW***
Source Towing Depth	Source 0 (upper) @ 0.5 m, Source 1 (middle) @ 0.8m and Source 2 (bottom) @ 1.1m
SP Interval	0.5 m
Operating Power	Source 0 (upper) @ 400 J, Source 1 (middle) @ 400 J & Source 2 (lower) @ 400 J
Power Supply	3 X Geo-Spark 6KW
CDP Bin Coverage	≈96 fold for 0.5 m CDP bin
Multichannel Streamer	***Geo-Sense Ultra Hi-Res 96 channels***
Streamer Depth	≈ 0.5 – 1.8m
Group Interval	Constant @ 1.0 m
Group Active Length	95 m
Reference hydrophone	***Geo-Sense reference hydrophone***
Hydrophone Depth	≈ 8 m
Group Interval	Single element
Group Active Length	Point receiver
Recorder	***4x Multitrace24 – Geomarine Survey systems***
Sample Rate	0.1 ms
Record Length	225 ms
Format	SEG-Y

2.2. Line Identification

The seismic line plan acquired in the main survey area is composed by mainlines oriented NNW-SSE and crosslines oriented ENE-WSW. They were identified by their:

1) Line orientation/location: “BM” for mainlines and “BX” for crosslines;
2) Block number: From BM1 to BM6 and from BX1 to BX4, followed by OWF_E_2D in case of the mainlines and OWF_E_XL in case of the crosslines.
3) Five digits identification number, which also act as a spacing between adjacent lines (e.g., BM1_OWF_E_2D_00420 is separated by 420 metres from BM1_OWF_E_2D_00000, and BX1_OWF_E_XL_05000 is separated by 4000 metres from BX1_OWF_E_XL_01000). The main lines are separated by 210 metres and the crosslines are spaced 1 km apart.

Infills were identified adding the prefix ‘Inf’ and three digits at the end. Reruns are identified by a numerical suffix (e.g. BM3_OWF_E_2D_05670_01 is the first rerun of BM3_OWF_E_2D_05670; BM4_OWF_E_2D_09450_02 is the second rerun of BM4_OWF_E_2D_09450). On the particular cases where a portion of a line was rejected while offshore, however with a good percentage of the line length within specs, the original line had to be divided into two portions. On these cases, an alphanumeric suffix was added (e.g. BM4_OWF_E_2D_11130_P1 and BM4_OWF_E_2D_11130_P2 are two parts of BM4_OWF_E_2D_11130).

2.3. Navigation and Positioning

The navigation and positioning were carried out with RTK-DGPS as a primary positioning system in 3 specific points of the spread: the seismic stacked sources, the streamer leading buoy and the streamer tail buoy. This particular arrangement allows the control and the positioning of the complete seismic spread. All positioning was referenced according to the projected coordinate system ETRS89, UTM Zone 32 Northern Hemisphere (Table 2).

Depths are relative to MSL (Mean Sea Level), used as the vertical reference.

Table 2 – *ETRS89, UTM Zone 30 Northern Hemisphere geodetic parametres.*

Datum	ETRS89
Ellipsoid	GRS 1980
Semi-major axis	6 378 137.000 m
Semi-minor axis	6 356 752.3142 m
Flattening (1/f)	298.257222101
Chart Projection	
Projection	Universal Transverse Mercator, Z32N
Latitude of Origin	0° N
Central Meridian	9º E
Central Meridian Scale Factor	0.9996
Vertical reference	***MSL***

3. DATA QUALITY CONTROL

The UHRS QC & QA is a seismic processing service that ensures that the acquired UHRS data meets the contracted technical requirements:

- Throughout the survey the data was QC'd and made available for review within 24 hours of completion of survey operations;
- The agreed quality criteria were ensured during the QC/QA of the 2D seismic data in regards to:
    - Coverage;
    - Line keeping;
    - Data resolution;
    - Signal penetration;
    - Signal quality;
    - Feathering;
    - Data fold.

The offline QC was performed with key software and in house developed processing flows necessary to carry out the job to completion. The software used was RadEx Pro from Deco Geophysical.

3.1. Feathering

The feathering angle was calculated along all the seismic profiles (see example in Figure 5). A maximum feathering angle of 8º was initially established for vessel steering and 15º for strong water currents. For the duration of the survey only the steering limit was surpassed on few lines. On the other hand, the feathering values resulting from currents was always substantially below the established limit.

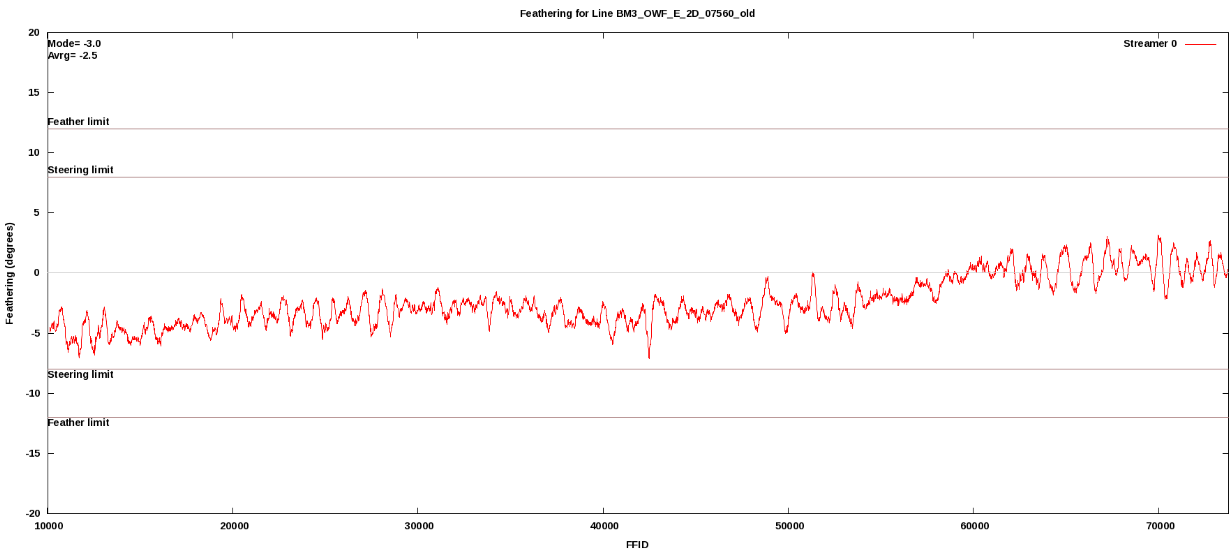


Figure 5 – *Feathering plot calculated for the line BM3_OWF_E_2D_07560.*

3.2. Signal & Noise Analysis

The main sources of noise identified during the survey were (see Figure 6):

- Vessel noise – in red in Figure 6. This is a directional noise, that can be filtered using extended processing techniques without major negative impact on the signal.
- Front and tail cable tugging noise represented in green and blue, respectively, in Figure 6. The front/tail tugging occurs when the front/tail frame is pulled by waves and currents and that creates a low frequency vibration along the streamer. This is a directional noise that can be removed using an F-K filter.
- SIMOPS noise interference (Figure 7 and Figure 8) – Sporadic events when other vessels (Fugro Pioneer) came close to the Relume. In some cases, it was even possible to record a seismic pulse from their equipment (Figure 8).

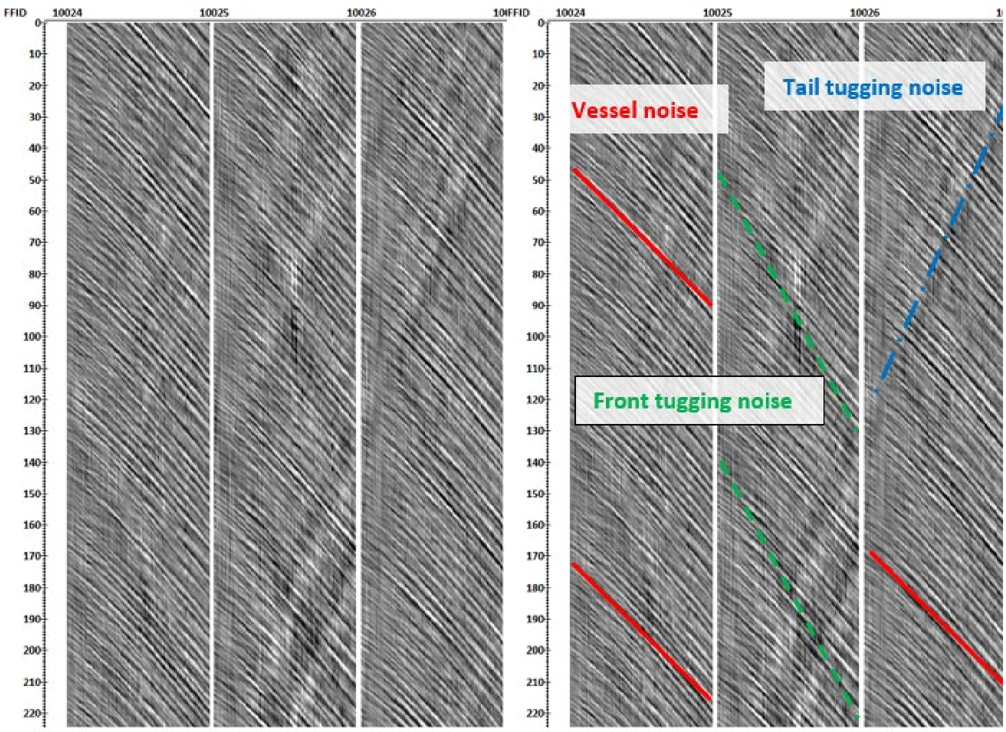


Figure 6 – *Main noise sources identified in the working limit noise test: vessel acoustic noise and cable tugging at the front and tail recorded by the M-UHRS streamer.*

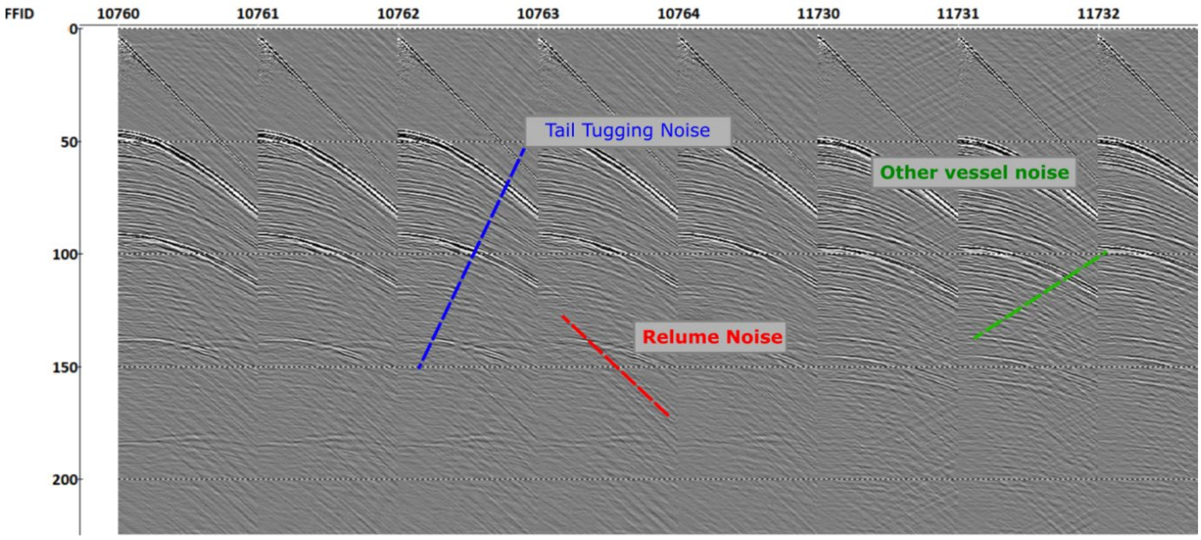


Figure 7 - *Main noise sources identified while in production: Relume acoustic noise (Red), cable tail tugging (Blue) and other vessel passing nearby (Green) recorded by the M-UHRS streamer.*

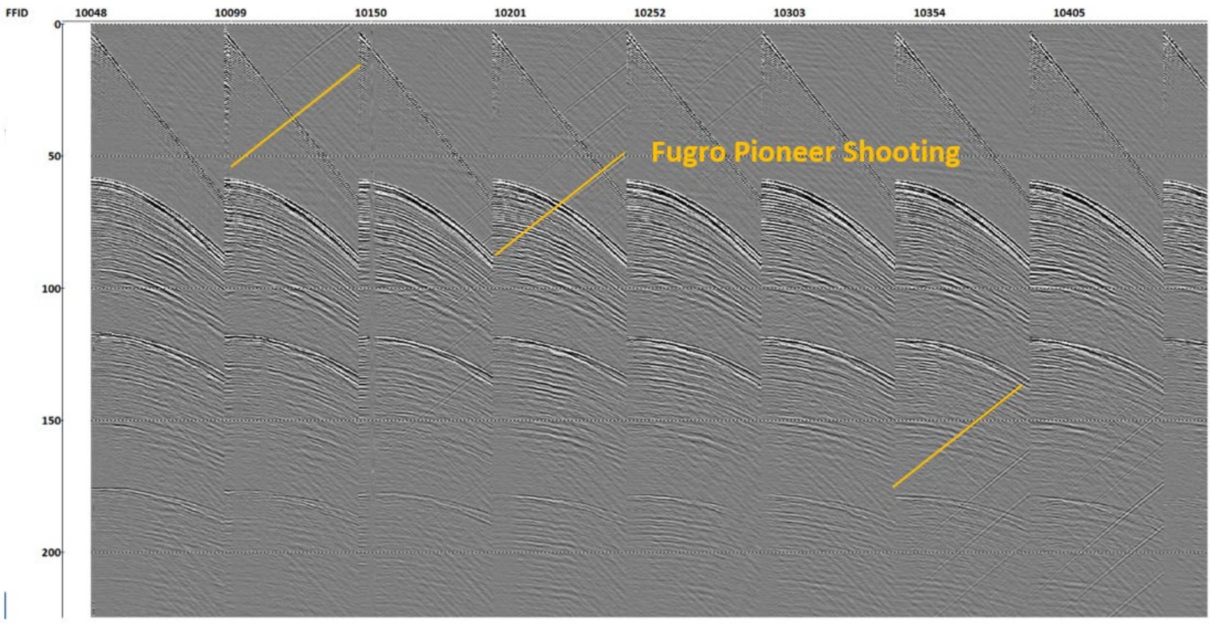


Figure 8 – *Fugro Pioneer shooting while in SIMOPS.*

All the above-mentioned types of noise were thoroughly analysed. On a line-by-line basis, a noise check was performed before and after line acquisition, in order to assess the noise level variations. Generally, a difference of +/- 20 dBs between sparker and noise was achieved (Figure 9). The noise levels did not represent a major risk for the M-UHRS survey.

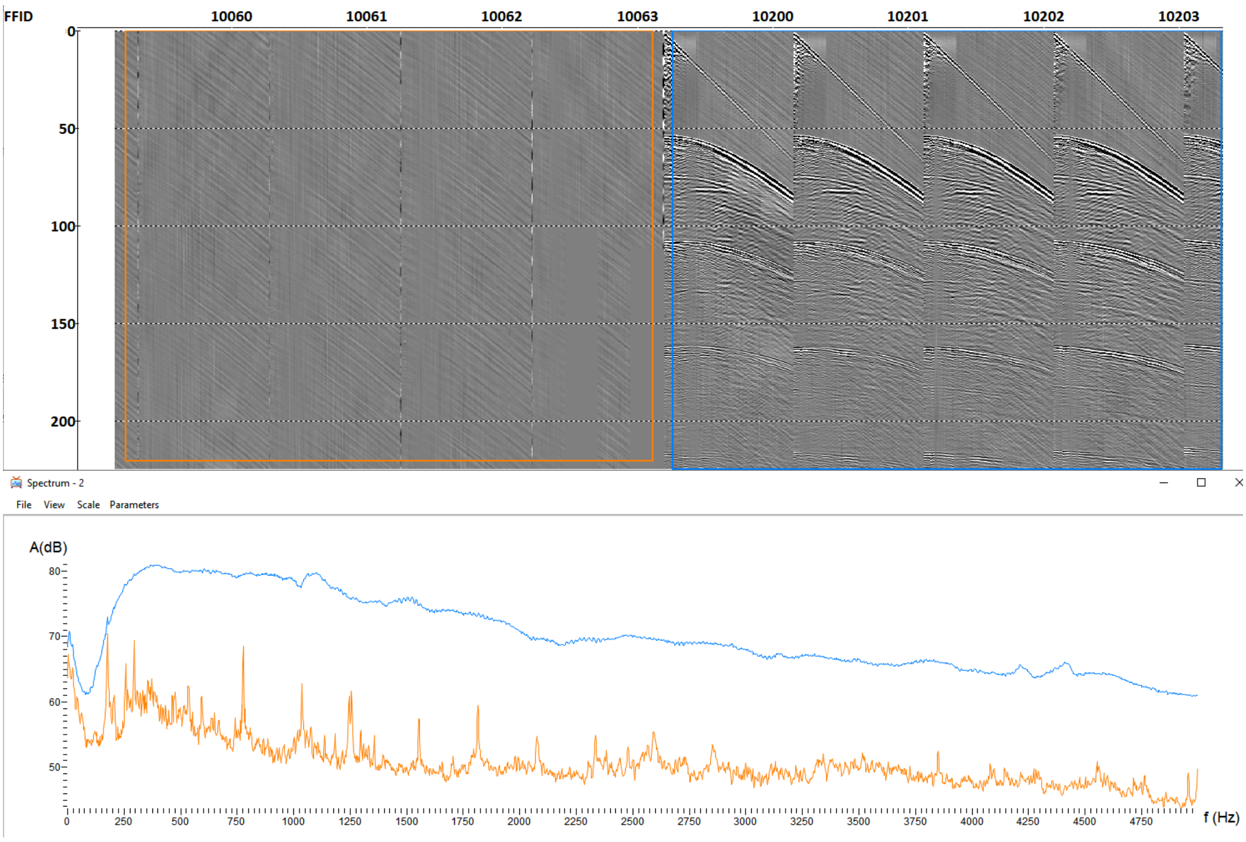


***Figure 9** - Frequency spectrum comparison between background noise (orange) and sparker signal (blue).*

3.3. Source Receiver Offsets

Source and receiver positions and the relative offsets were initially calculated using the DGPS antennas located on top of the sources and on the streamer front and tail buoys. The accuracy of the source and receiver positioning was checked by comparing the offsets calculated from the source and receiver positions with direct arrival times (Equation 1). The offsets were estimated using the calculated distance between two points explained in Equation 1 and converted to time by dividing the obtained offset in metres by the measured water sound velocity (the sound velocity in the water was obtained from measured SVPs during the survey).

$$\boldsymbol{offset} = \sqrt{(\boldsymbol{Sou\_X} - \boldsymbol{Rec\_X})^2 + (\boldsymbol{Sou\_Y} - \boldsymbol{Rec\_Y})^2}$$

***Equation 1 –** Equation used for calculating the offsets based on the positioning.*

On average, the inline offset between the near channel of the streamer and the source was 1 m, and the crossline offset was 3 m (see Figure 4). The source-receiver relative position did not change during the survey, although some variations could occur mainly due to surface currents.

In general, the offsets based on antenna position have a good match with the direct arrival (Figure 10 and Figure 11). Occasional mismatch was observed, mainly due to the loss of differential correction on the DGPS antenna (Figure 12), nevertheless the difference between the direct arrival and calculated offsets was reasonable and most of the time below 1 ms.

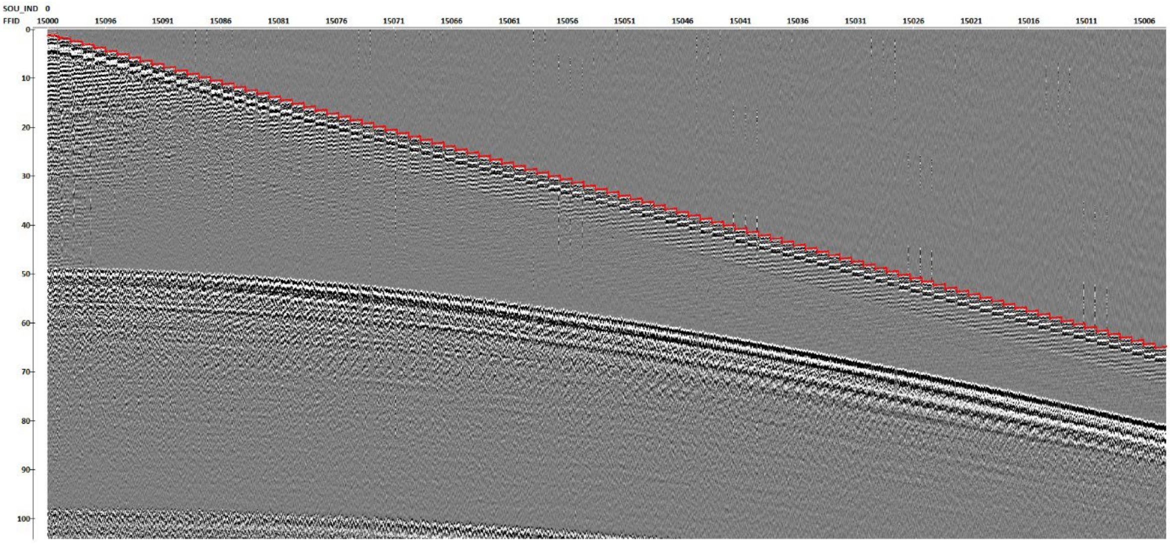


***Figure 10** – Channel domain showing the calculated offsets based on the DGPS positioning (red line) on top of the direct arrival, for all 96 channels, for line BM2_OWF_E_2D_02730. Vertical scale in TWT (ms).*

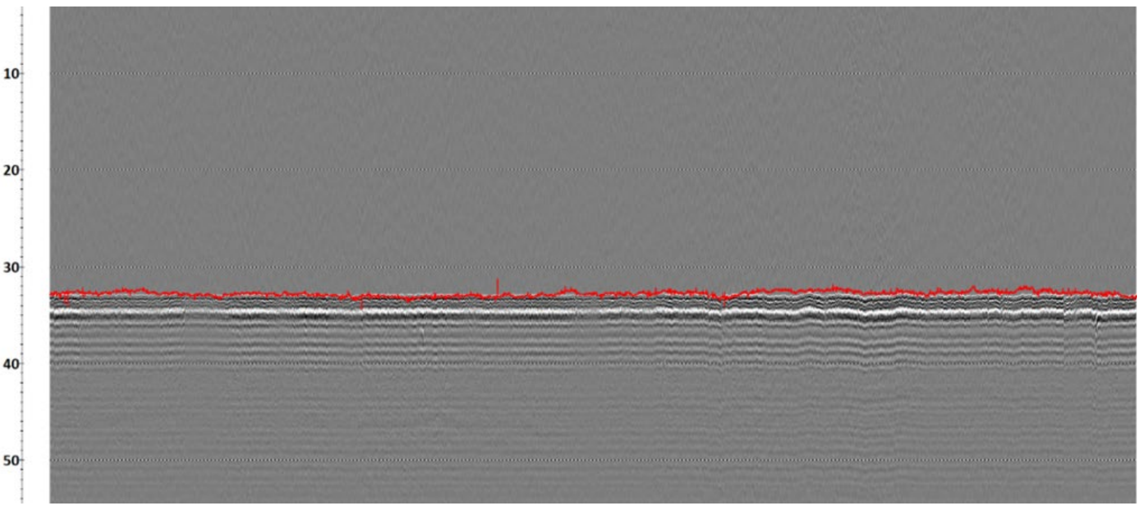


***Figure 11** – Profile BM4_OWF_E_2D_08820 in channel domain, showing the calculated offsets based on the DGPS positioning (red line) on top of the direct arrival for channel 48. Vertical scale in TWT (ms).*

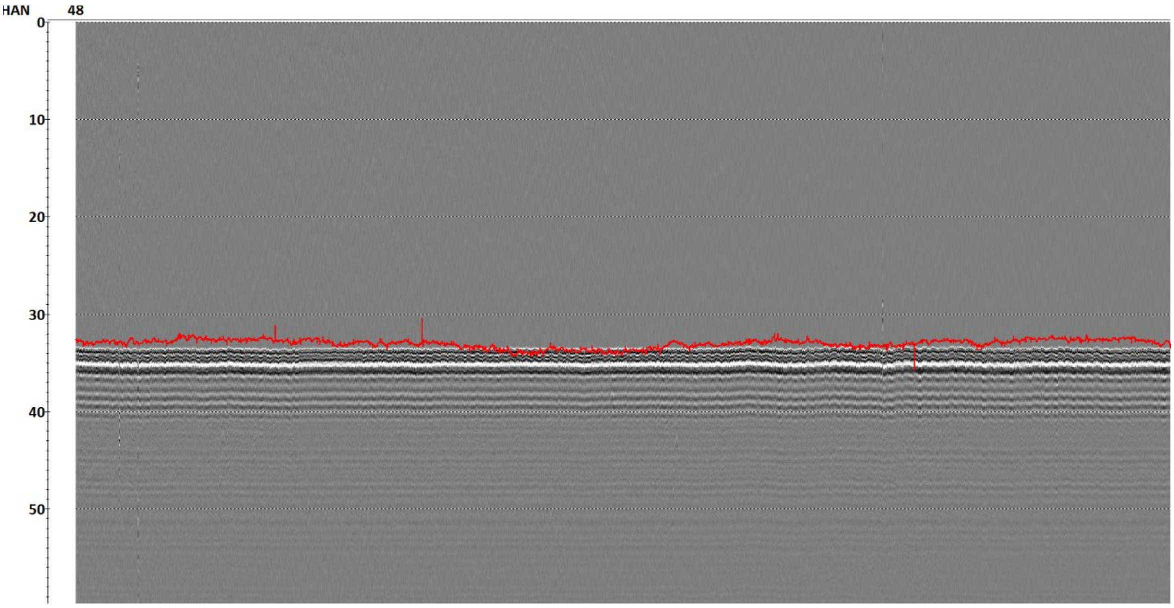


Figure 12 – *Profile BM5_OWF_E_2D_15540 in channel domain, showing the calculated offsets based on the DGPS positioning (red line) on top of the direct arrival for channel 48. Vertical scale in TWT (ms).*

3.4. *Streamer group balancing*

The streamer was balanced for the survey speed range of 3.5-3.8 knots STW. Along the streamer, several lead weights were placed in order to achieve the slant shape. To evaluate if the cable was properly slanted, a direct observation of the receiver ghost along all channels was done on a line-by-line basis (Figure 13).

Streamer balance integrity can vary depending on sea conditions, wave motion, vessel steering, surface currents, acquisition velocity, positioning precision and minor modifications of the system geometry during equipment recovery and deployment operations. All these factors may have negative impact on the final UHRS data.

All the seismic profiles underwent to QC/QA in order to assess the streamer balancing and to ensure that the data could be successfully processed.

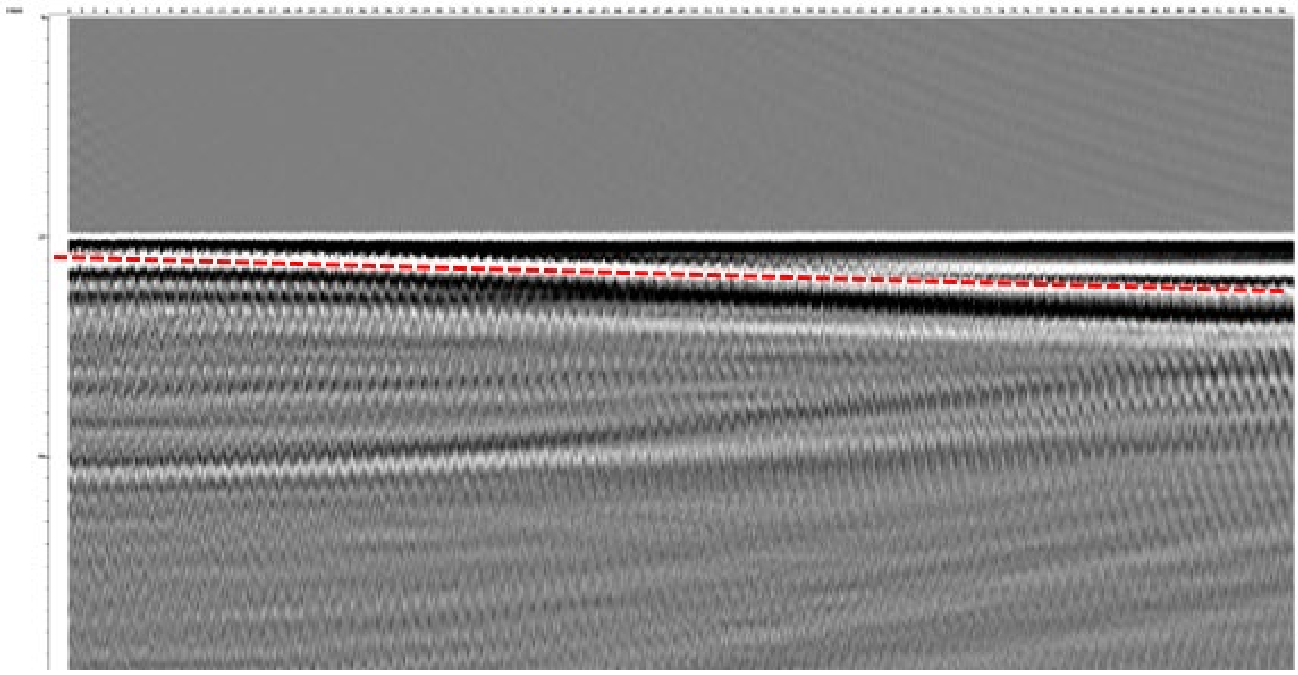


Figure 13 *– Channel domain with flatten seabed showing the increasing ghost reflection depth along the channels (see the ghost reflection – red dashed line) for line BM3_OWF_E_2D_05880, vertical scale in TWT (ms).*

3.5. Interactive Velocity Analysis

Supergathers were generated every 1000 CDP comprising 3 CDP to build the dynamic stack. RMS velocity curves were generated through the interactive velocity analysis for all lines and were used for NMO corrections and stacking (Figure 14). Interactive velocity analysis was also used as a tool for data QC, mainly regarding penetration.

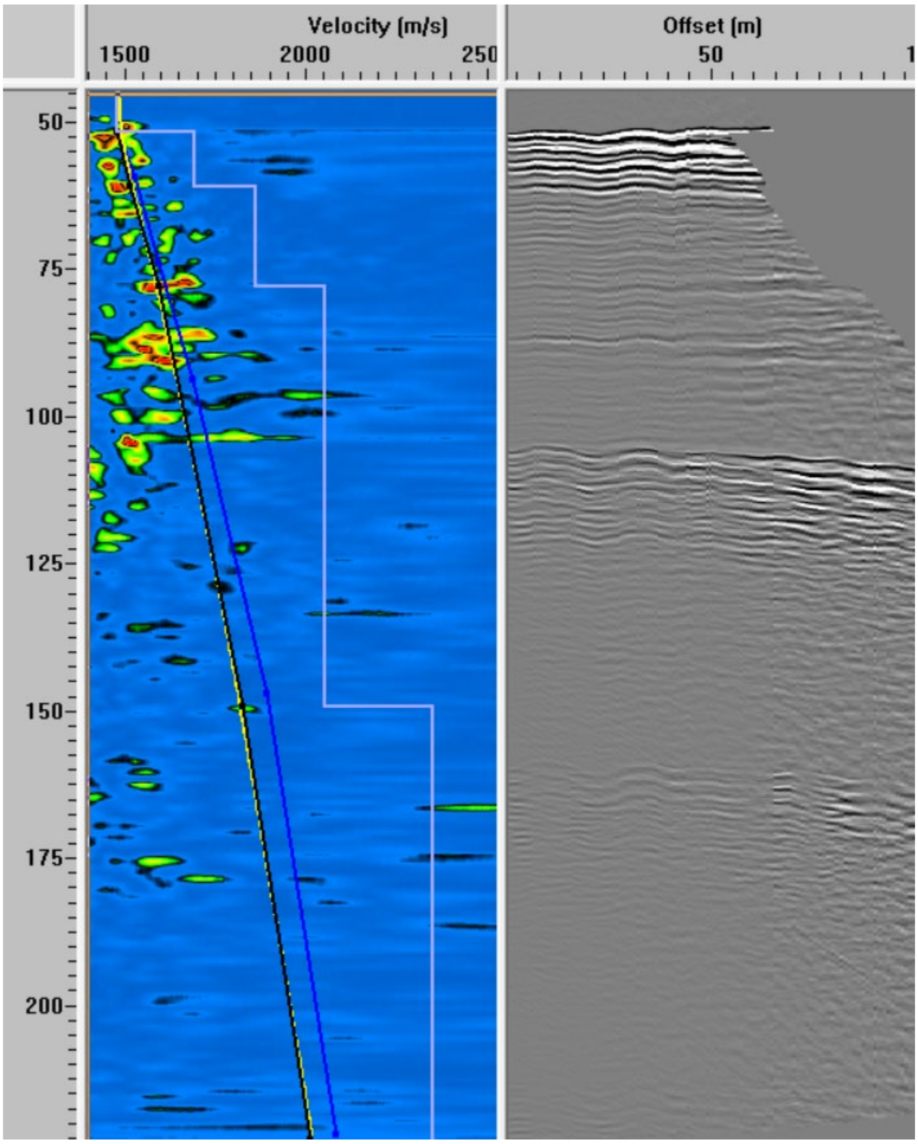


Figure 14 – *Velocity Analysis display for line BM3_OWF_E_2D_07770. The grey line represents the interval velocities and the black line shows the RMS velocity in the actual CDP gather; vertical scale in TWT (ms).*

3.6. CDP Fold

The impact of the positioning solution, triggering, steering, feathering, navigation and amount of bad shots on the CDP bin fold regularity was assessed with CDP fold track plots (Figure 15). With minor deviations, all processed lines show a mean CDP fold around 192. Trace fold header recorded values were used to assess the cumulative impact of steering & feathering and bad shots on the seismic data.

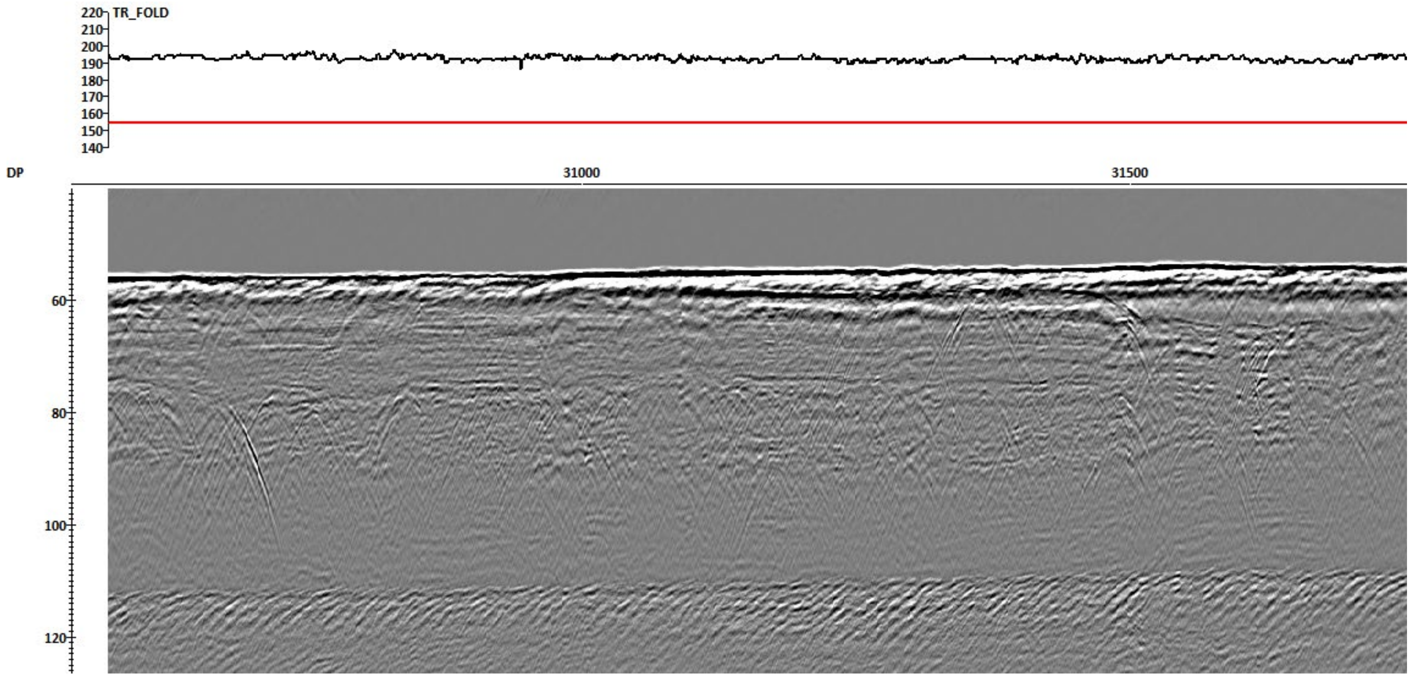


__Figure 15__ - Trace fold values plotted on the top of stacked sections for line BM2_OWF_E_2D_05040 (black curve). Vertical scale in TWT (ms).

3.7. Brutestack

The offshore brutestack of every seismic profile provided a quick image of expectable data quality and signal penetration (Figure 16). Several parameters were considered:

- Coverage – confirm by MMT if there were no gaps in the seismic data. Verified by MMT in QGIS project with the CDP Track Plots supplied by Geosurveys;
- Line keeping and coverage – verify if the steering of the vessel were along the line plan with a maximum error of 25 m – verified by MMT in QGIS project with the CDP Track Plots supplied by Geosurveys;
- Signal penetration – Identification of correlative reflections in the brutestack up to 225 ms below seabed, fulfilling the 100 m of required penetration;
- Signal quality – verification of the existence of any artefacts on the seismic data.

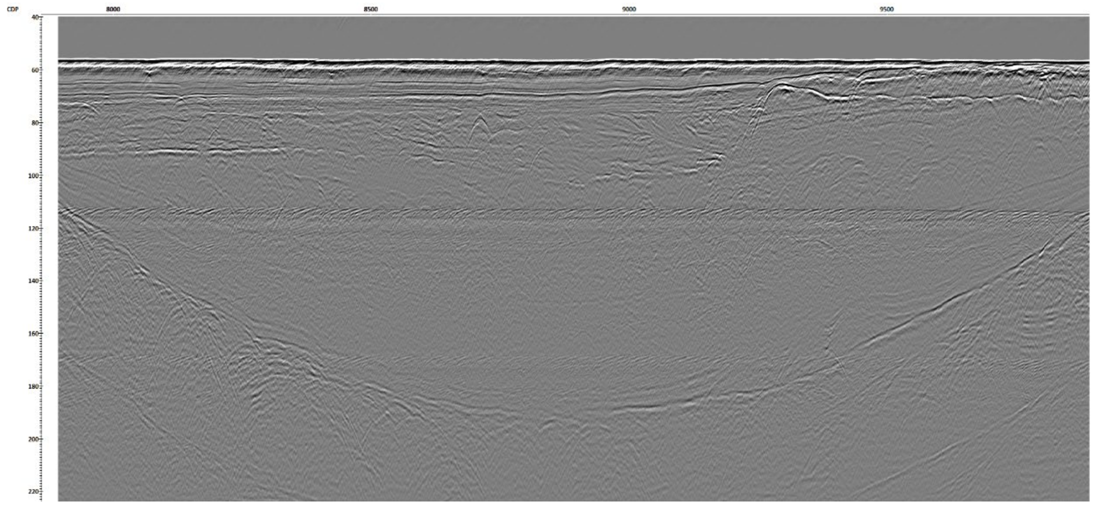


Figure 16 *– Brustestack for line BM4_OWF_E_2D_10080_01 showing penetration until the end of the record and good signal to noise ratio. Vertical scale in TWT (s).*

3.8. GEOM Output

The raw SEG-Y data acquired by GMSS had the following information on the headers:

- FFID number (Byte location 9);
- Channel number (Byte location 13);
- Source positions (SOU_X - Byte location 73, SOU_Y - Byte location 77);
- Receiver positions (REC_X - Byte location 81, REC_Y - Byte location 85).

The raw SEGY data was then imported into RadEx Pro (by GS personnel offshore) for data QC/QA, geometry assignment and tidal values import. Due to the more limited computational power on the offshore laptops, the geometry was assigned with a bin size of 1 m. This bin size was used for QC/QA purposes, with no impact on data quality assessment. Once the data arrived to GS office, the bin size was then recalculated to the agreed 0.5 m bin. Crooked-line geometry assignment gives a truer picture of the subsurface when compared with other geometry assignment methods because it considers the angular relationships between the shots and their receivers.

The GEOM SEGY dataset (raw data with filled headers - Linename_GEOM.sgy) was then exported with the additional headers filled:

- CDP number (CDP – Byte location 21);
- Source Receivers Offset (OFFSET – Byte location 37);
- CDP position (CDP_X – Byte location 181, CDP_Y – Byte location 185);
- Tide Height (TIDE_HGHT – Byte location 233).

4. SEISMIC DATA PROCESSING SEQUENCE

Within the present chapter a detailed description of all processing flow steps will be addressed.

4.1. Processing Sequence

The flow was divided into two main processing tracks: Pre-Stack TRIM track and FULL track (Figure 17). The main purpose of the TRIM track was to estimate a proper residual static correction for the swell, source and receiver groups motion. Another objective of the TRIM track stage is to output a depth converted dataset with the purpose of determining a set of vertical corrections (tidal corrections, mean streamer towing depth correction and seismic misties) for the seismic profiles in order to have the full dataset reduced to a common vertical datum (MSL). The procedure includes a series of diagnostic materials for concomitant quality control of the seismic processing steps, relevant to vertical datum reduction.

The aim of the FULL track processing flow was to create a fully processed seismic section. FULL track procedures included pre-Stack demultiple, denoise, receiver deghosting, NMO corrections, CDP ensemble stacking, post-stack multiple attenuation using zero-offset demultiple procedure, migration using post-stack Kirchhoff time migration to recover the true geometry of primary reflections, Post-stack deconvolution, Time Variant BandPass Filter (TVBPF), Amplitude Correction and Depth convertion.

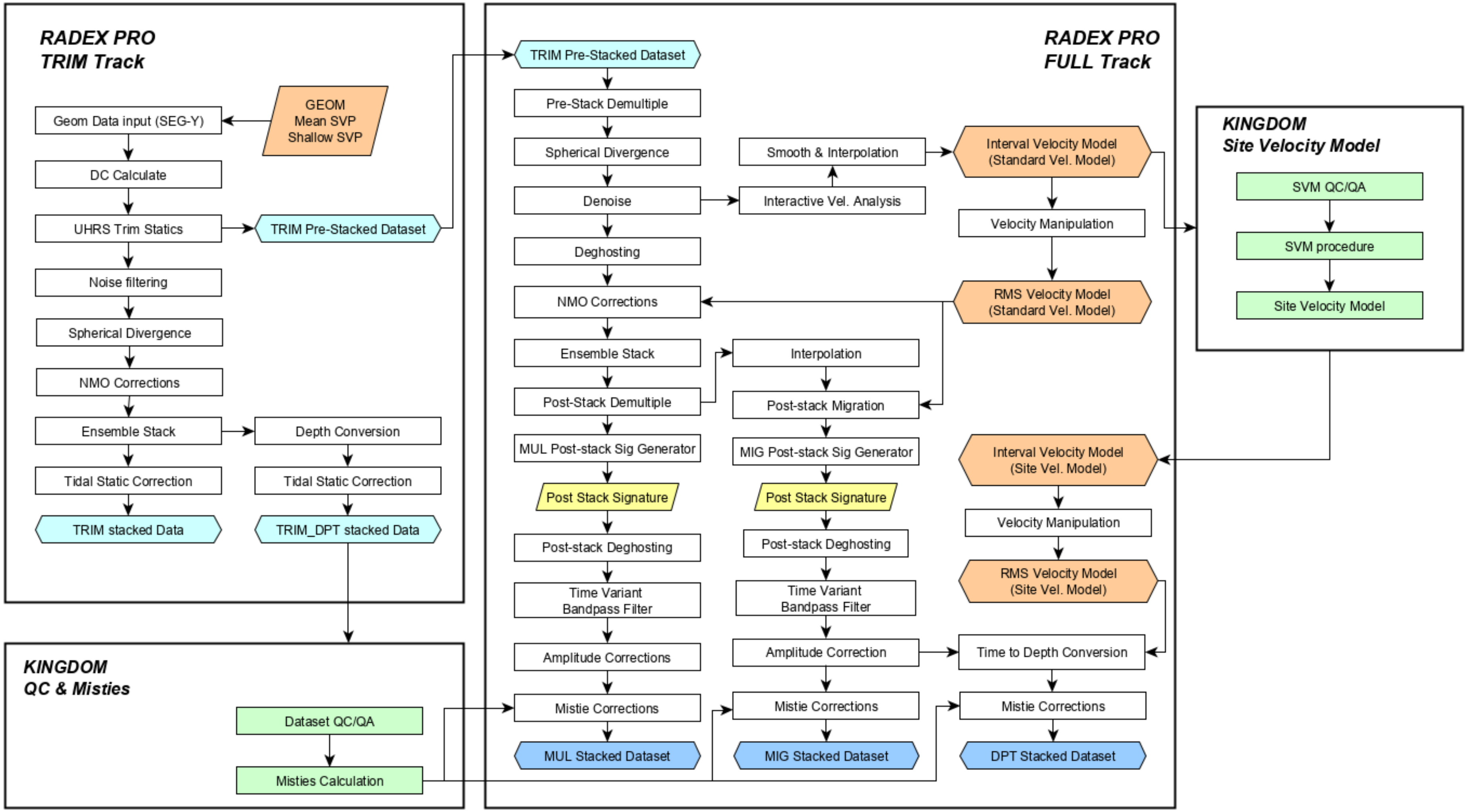


***Figure 17** – Processing workflow applied to all seismic lines.*

4.2. TRIM Track

The TRIM track is the first subroutine procedure used for the UHRS data processing. The Geom SGY is imported into RADEXPRO, taking into account all the necessary information provided on the QC Log (Mean and Shallow Sound Velocity, Accepted FFIDs and other relevant information described on the operator and/or QC comments).

4.2.1. DC removal

After loading the raw data, the DC removal was used to attenuate the DC bias of each channel. In this step the median DC bias is eliminated based on a moving average window which run per channel. The calculation window was limited between 100 and 190 ms.

4.2.2. UHRS TRIM Statics Estimation

The procedure to determine static corrections is an in-house-developed methodology and is a variation on the COSA method developed by Wardell *et al* (2002).

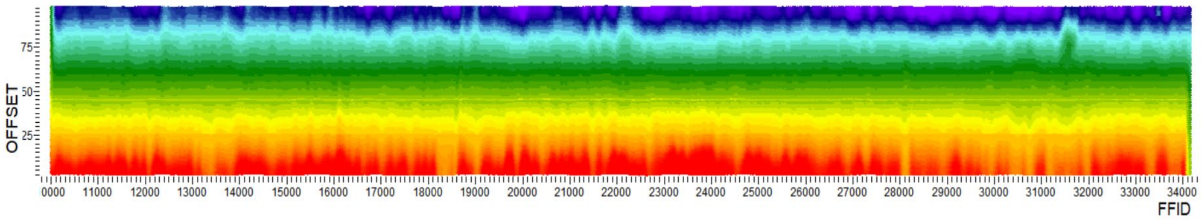
The data is reduced to a common local floating datum by deriving the main vertical relative motion components that affect the system:

- Mean array depth;
- Mean cable slant;
- Source heave relative to mean array depth;
- Receiver heave relative to mean cable slant.

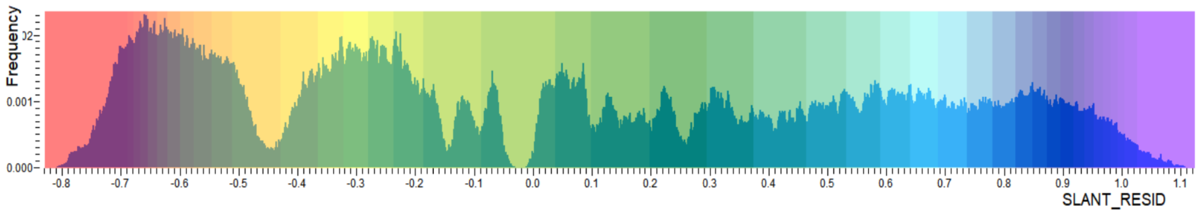
Static correction methodology calculates all the mentioned static components for every shot and every trace recorded and includes a trace-by-trace residual static correction procedure to compensate for the vertical motion of the towed equipment.

I. Mean Cable Depth

As previously mentioned, the mean cable slant is the mean of the depths of individual receivers relative to the mean array depth. This static component was used in order to assess the mean streamer depth variations during profile/acquisition (Figure 18) and to correct for the streamer depth.



(a)



(b)

Figure 18 ***–*** *Streamer depth relative to the mean array depth along the profile BM4_OWF_E_2D_10080: (a) streamer depth variation per offset along the seismic line and (b) histogram of the streamer depth relative to the mean array in milliseconds. The histogram values and colours correspond to a "colour bar" for streamer relative depths – negative values correspond to channels that are shallower than mean array depth (warm colours - redish) and positive values represent deeper channels (colder colours - purple).*

II. Source Heave and Receiver Heave

Source/streamer geometry and motion can vary depending on sea conditions, wave motion, vessel steering, surface currents, acquisition velocity, and minor unintentional modifications of the system geometry during equipment recovery and deployment operations. Source, and mainly streamer geometry and balancing may have a negative impact on final UHRS data as these effects may add up. Deghost and demultiple are some of the processing steps very sensitive to poor streamer geometries.

All seismic profiles underwent an onshore QC/QA in order to assess the source and streamer balancing and to ensure that the data could be successfully processed. The seismic profiles were analysed regarding the following motion components of the equipment: source heave, cable heave and cable relative depth.

The source motion was almost always below 1 ms (blue line between -0.5 and 0.5 ms in Figure 19). The receiver motion component (green line Figure 19) is usually smaller than the source motion due to the physical properties (weight and length) of the streamer. More information about the statics estimation and corrections is given in section 4.2.2. Whenever the raw source movement is greater than swell movements of +/- 1.5 m, corresponding to predefined acceptance threshold of 0.8 ms, the trace is flagged for removal (its value is changed to the constant arbitrary value of 1, represented as kill flag).

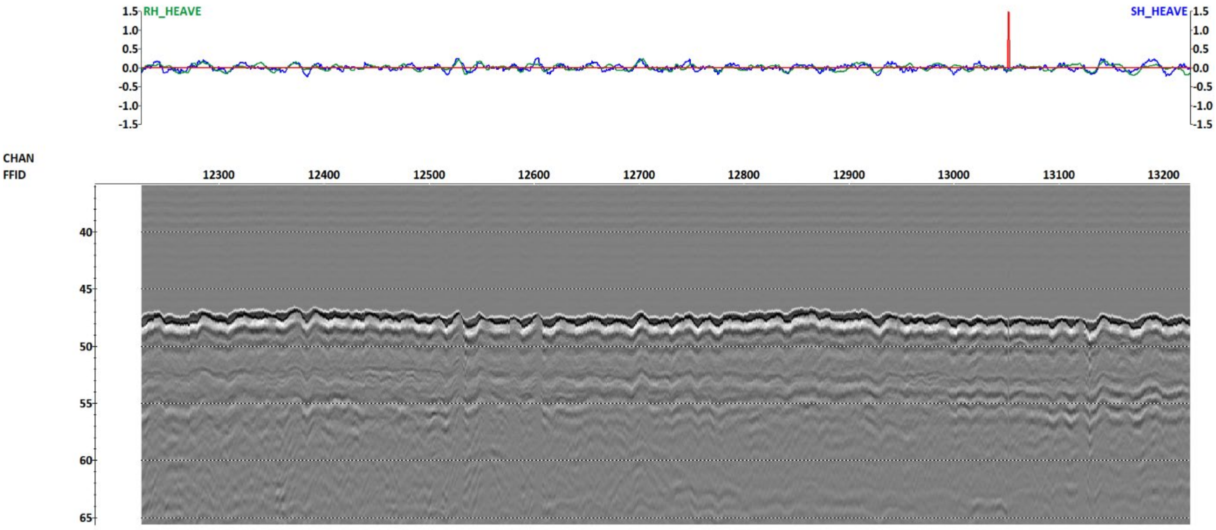
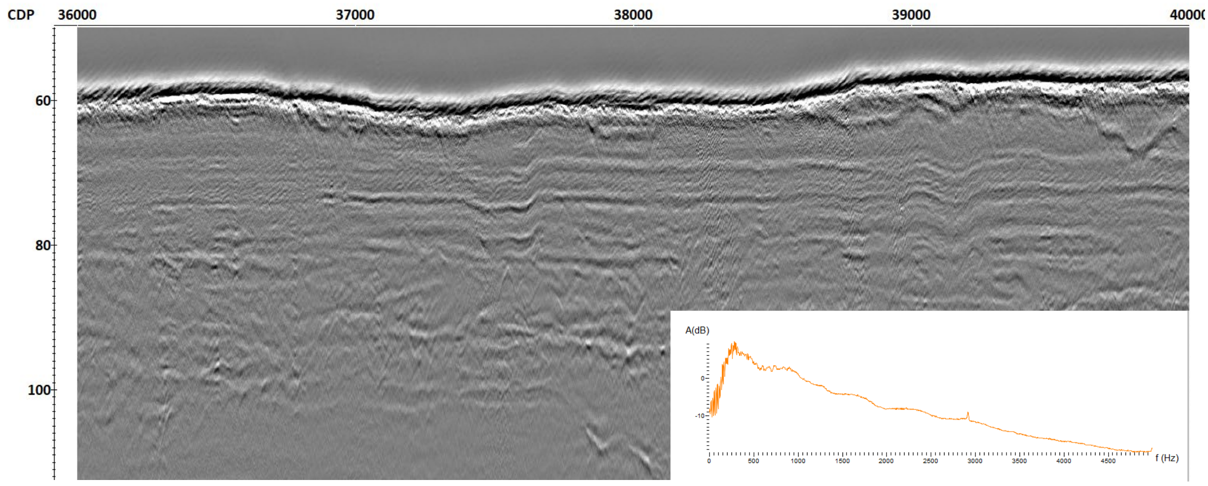


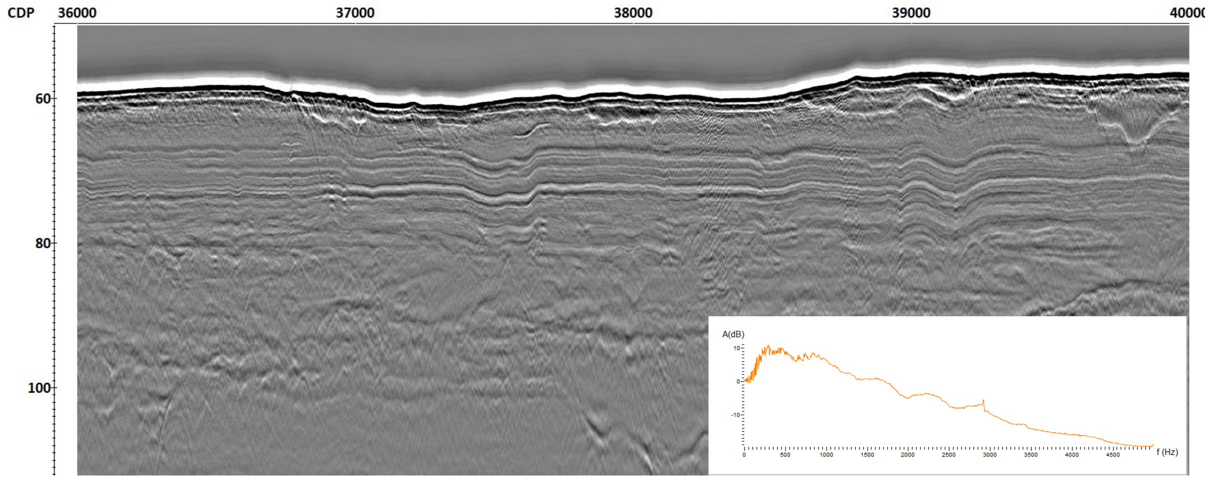
***Figure 19** – Source and receiver heave along profile BM3_OWF_E_2D_05880: source motion in blue and receiver motion in green and shots to kill in red. Vertical scale in TWT (ms).*

III. TRIM STACK

Results from before and after the UHRS TRIM static corrections are shown in Figure 20 (a) and (b). As can be observed from Figure 20, greater detail is achieved as higher frequency components of the signal are stacked coherently.



(a)



(b)

Figure 20 – *Line (a) before and (b) after UHRS TRIM static corrections. Vertical scale in TWT (ms).*

4.3. FULL Track

Within the present chapter, a detailed description of the processing FULL track flow steps will be addressed.

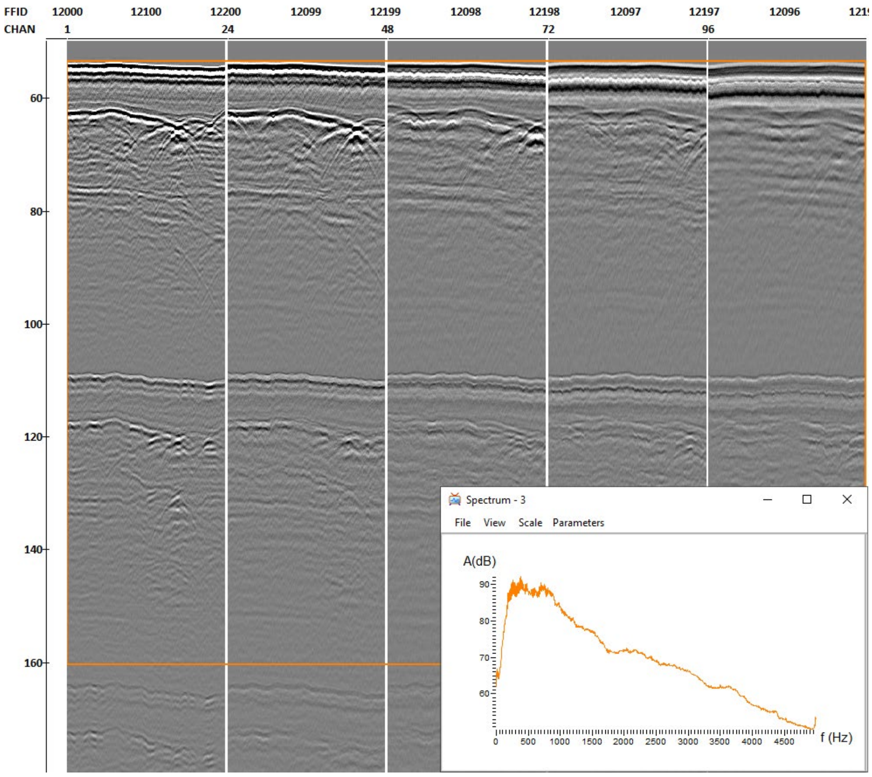
4.3.1. Pre-stack Multiple Attenuation & Deconvolution (SRME & Tau-P domain)

Surface-related multiple elimination (SRME) was used to eliminate surface related multiples in the seismic data by utilizing the reflections in pre-stack seismic data to predict surface multiple models. SRME does not require subsurface information, but it predicts a model of the surface multiples from water surface information.

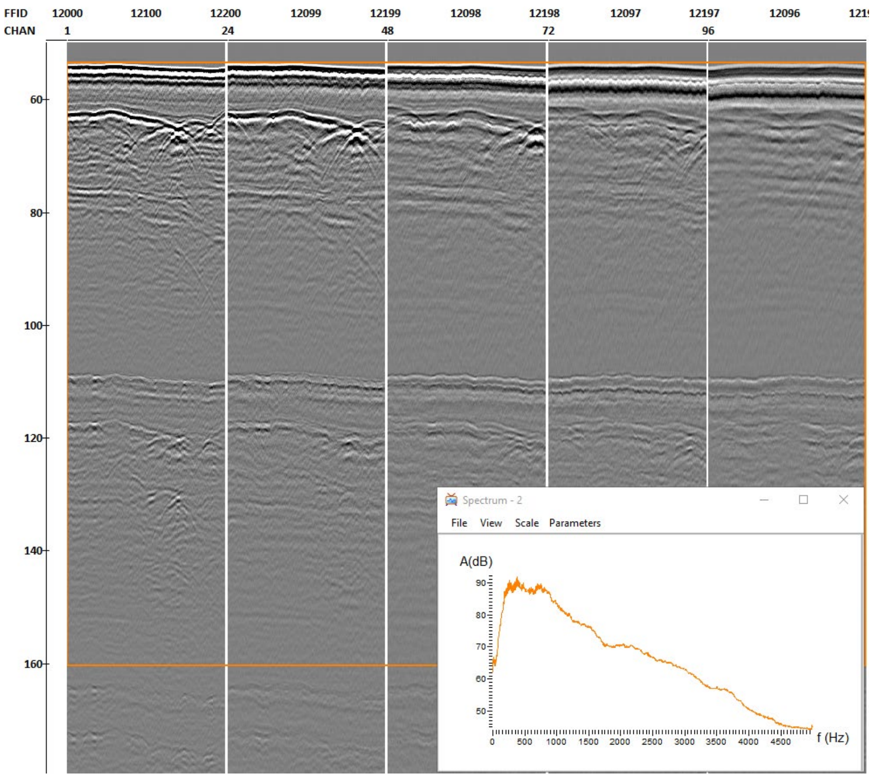
Pre-stack multiple attenuation specific procedure is based on the adaptive subtraction of the prementioned SRME model of multiples. A multiple attenuation technique named “Wave Field Subtraction” was used within the pre-stack multiple attenuation procedure to attenuate the seismic data multiple energies in order to improve geology imaging at multiple depths.

Additionally to the SRME, a Tau-P domain demultiple was applied in order to attenuate better the reminiscent multiple in the data without affecting primary energy.

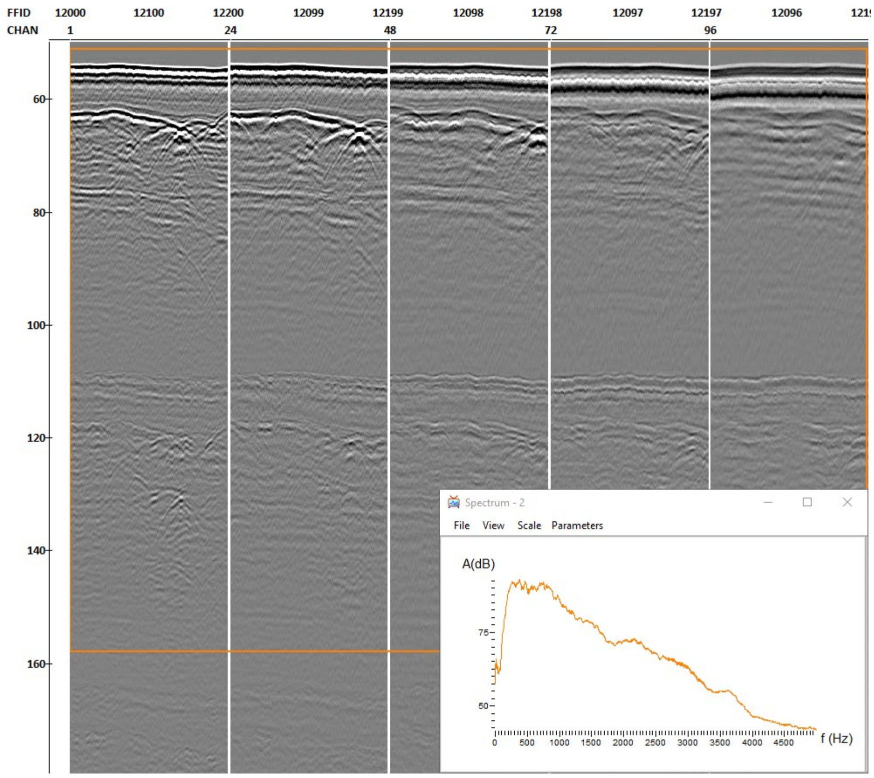
The processing parameters applied in the previous mentioned procedures were specifically tailored for this project in order to achieve the best possible results (Figure 21).


FFID 12000 12100 12200 12099 12199 12098 12198 12097 12197 12096
CHAN 1 24 48 72 96
60
80
100
120
140
160
Spectrum - 3
File View Scale Parameters
A(dB)
90
80
70
60
0 500 1000 1500 2000 2500 3000 3500 4000 4500
f (Hz)

(a)


FFID 12000 12100 12200 12099 12199 12098 12198 12097 12197 12096
CHAN 1 24 48 72 96
60
80
100
120
140
160
Spectrum - 2
File View Scale Parameters
A(dB)
90
80
70
60
50
0 500 1000 1500 2000 2500 3000 3500 4000 4500
f (Hz)

(b)



(c)

Figure 21 - *Line BM3_OWF_E_2D_06930 showing 200 shots for channels 1,24,48,72 and 96 (a) before, (b) after the SRME pre-stack multiple attenuation in shot domain, and (c) after the demultiple attenuation in Tau-P domain. Vertical scale in TWT (ms).*

4.3.2. Pre-stack Source Signature Deconvolution

The pre-stack source signature deconvolution was used to collapse the outgoing primary source pulse. The recorded source signature was modelled and stacked for all the reference lines, in order to obtain a signature based on seabed Raypath angle (Figure 22).

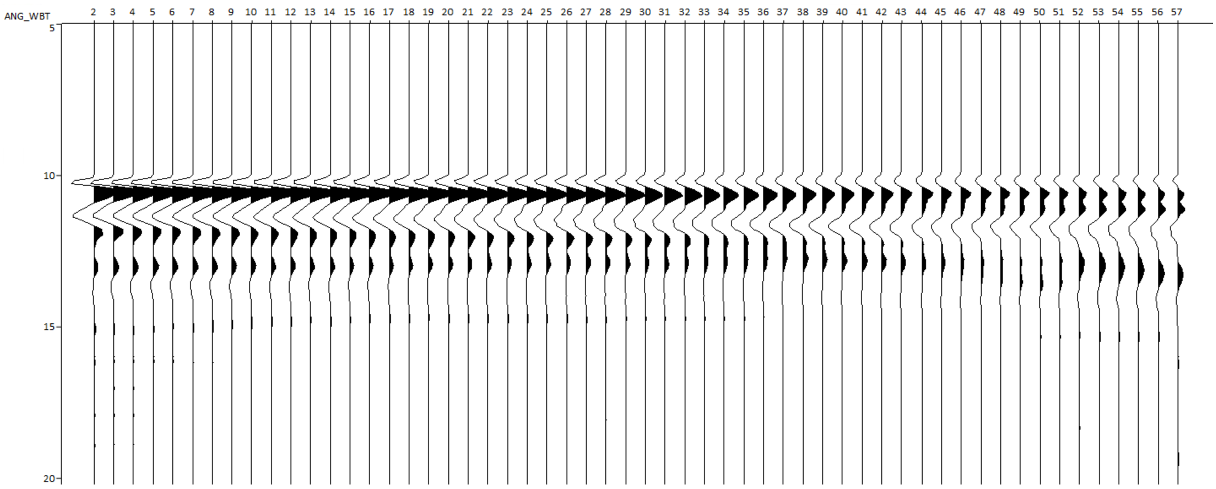
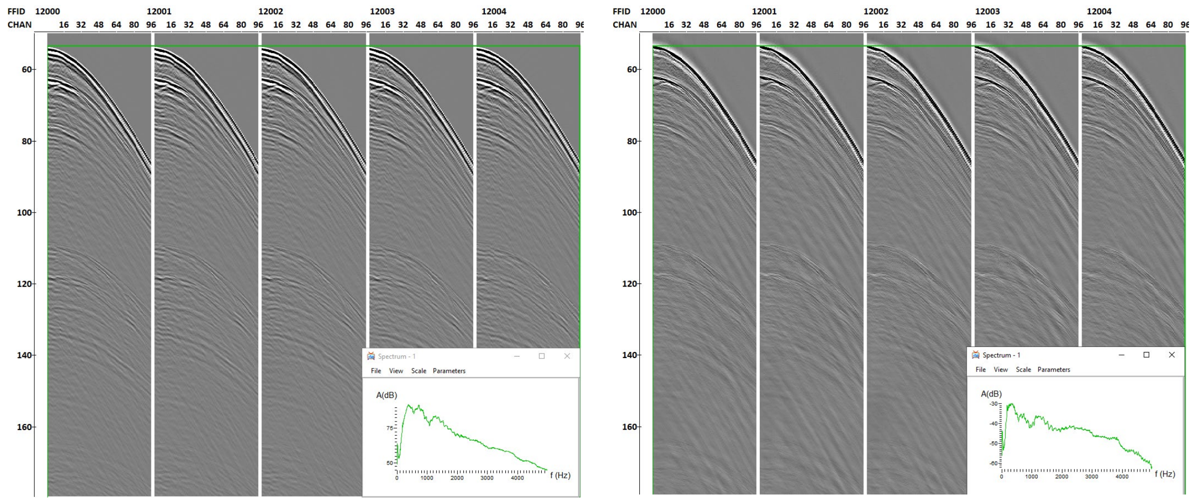


Figure 22 – *Signature for sparker source.*

The signature deconvolution was performed using the “Custom Impulse Trace Transforms” module using the extracted signature with white noise of 0.1 %. By comparing the same seismic data prior to deconvolution, Figure 23, the deconvolution operation procedure was assessed for its effectiveness, as seabed signature arrivals become thinner and a flatter frequency spectrum is achieved (Figure 23). In general, results show a compression of the basic wavelet and an overall increase of vertical resolution of the seismic profile (Figure 23).



(a) *(b)*

Figure 23 – *Shot gather of profile Line BM3_OWF_E_2D_06930 showing FFID 12000 to 12004 (a) before and (b) after source deconvolution with respective spectrums. Vertical scale in TWT (ms). Vertical scale on the left amplitude spectrum in dB and on the right amplitude spectrum in mV.*

4.3.1. Noise Filtering & Deghosting

After demultiple, a low frequency butterworth filter was used for directional noise removal/attenuation such as streamer tugging, vessel noise and low frequency burst noise.

In order to attenuate the receiver ghost component, an in-house developed procedure was applied to the data in order to flatten this. This allows for the removal of the horizontal component of the signal (receiver ghost) using a specifically designed F-K polygon. The ghost attenuation (blue arrows) and the increase in signal to noise ratio (green arrows) are depicted on Figure 24.

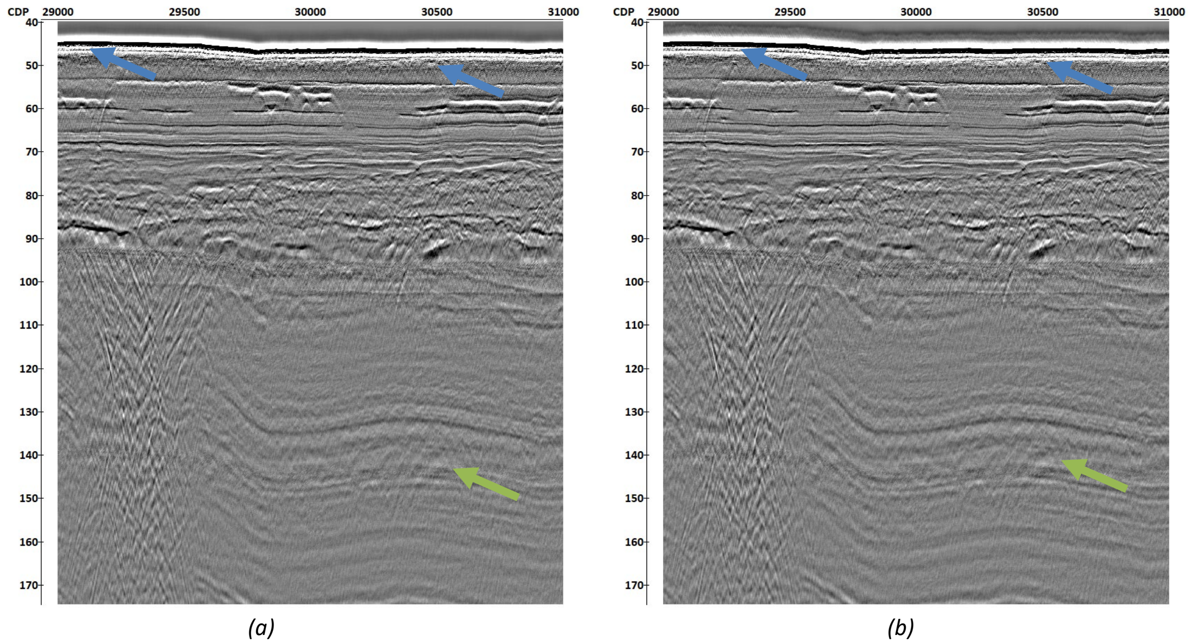


Figure 24 – *FULL stack of line BM3_OWF_E_2D_06930 between CDP interval 29000-31000: (a) without deghost and (b) with deghost.*

4.3.2. Standard Velocity Model

A good velocity model is the basis for: NMO and stacking (signal to noise ratio improvement), geometrical corrections (migration) and appropriate conversion from travel time into depth.

Velocity picking was thoroughly carried out for all lines of the site, based on the Interactive Velocity Analysis (IVA) picks every 500 m (1000 CDPs for a 0.5 m bin) (Figure 25). The velocity pick data was converted from RMS to interval velocities, interpolated and smoothed for all traces along each line. This Standard Interval Velocity Model was then converted to RMS and used for NMO and migration.

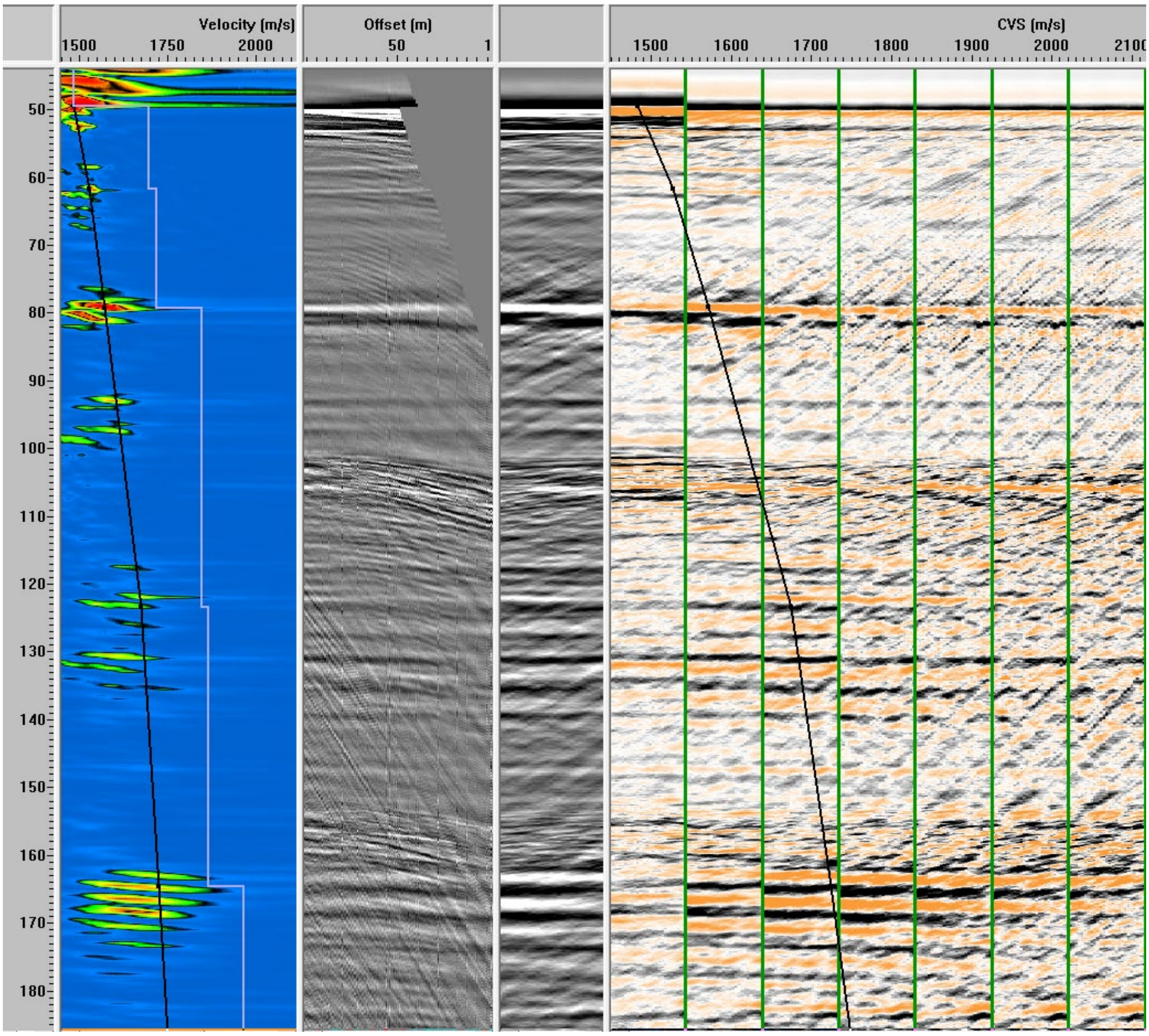


Figure 25 - IVA panel with representation of, from left to right, semblance display, gather display, stack display, and constant velocity stack (CVS) display for Line BM3_OWF_E_2D_06930, CDP 46100, with the velocity picking. Vertical scale in TWT (ms).

The same velocity model was later used for Depth conversion of both seismic and horizon data (please refer to section 4.3.10).

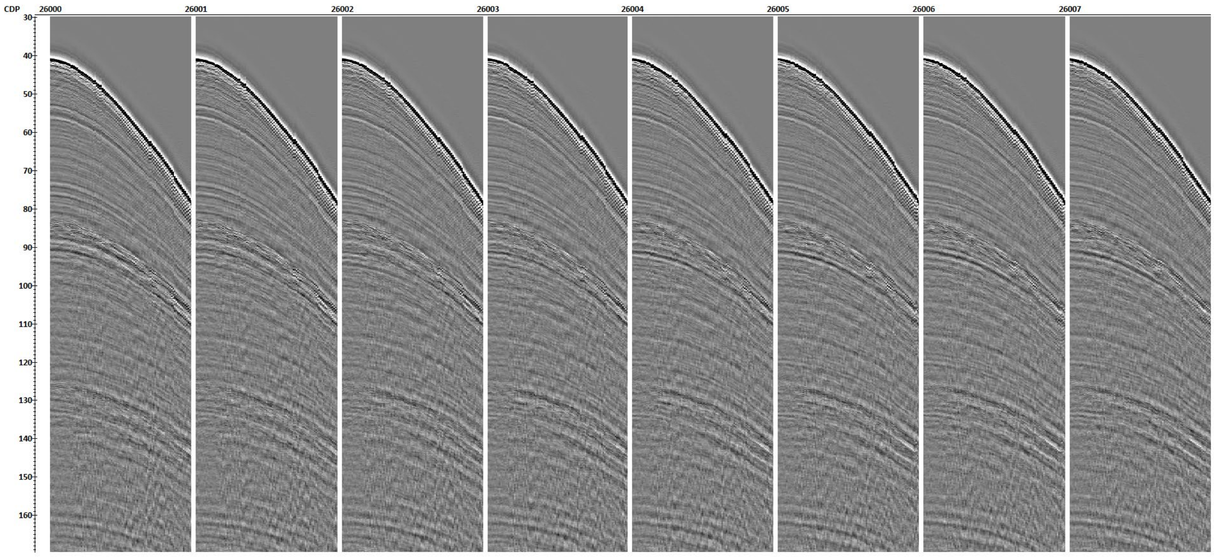
4.3.3. Amplitude Recovery

Spherical divergence on a power time base of 1.3 was applied to the data to compensate loss of amplitude due to wave front spreading and attenuation. The spherical divergence correction was applied prior to NMO.

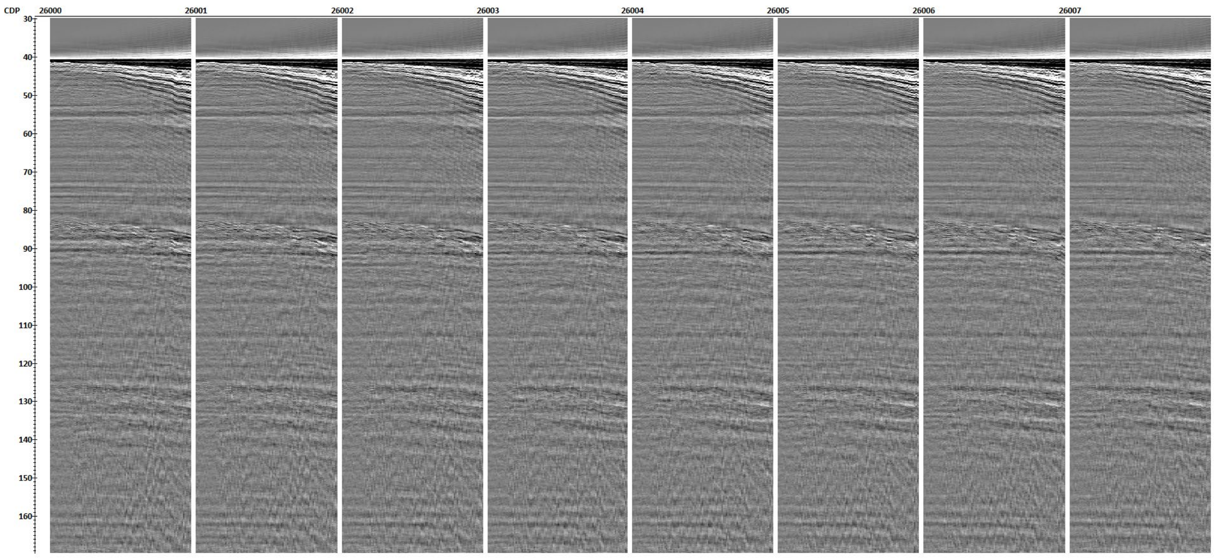
4.3.4. NMO Correction and Ensemble Stack

The RMS standard velocity model obtained from the IVA picked velocity model (for every individual CDP) was used to apply the NMO corrections to the CDP gathers. As it is shown from Figure 26a and b, the standard velocity model assigned for each seismic line flattens the reflectors in most portions of the seismic lines, showing that this methodology represents a good compromise.

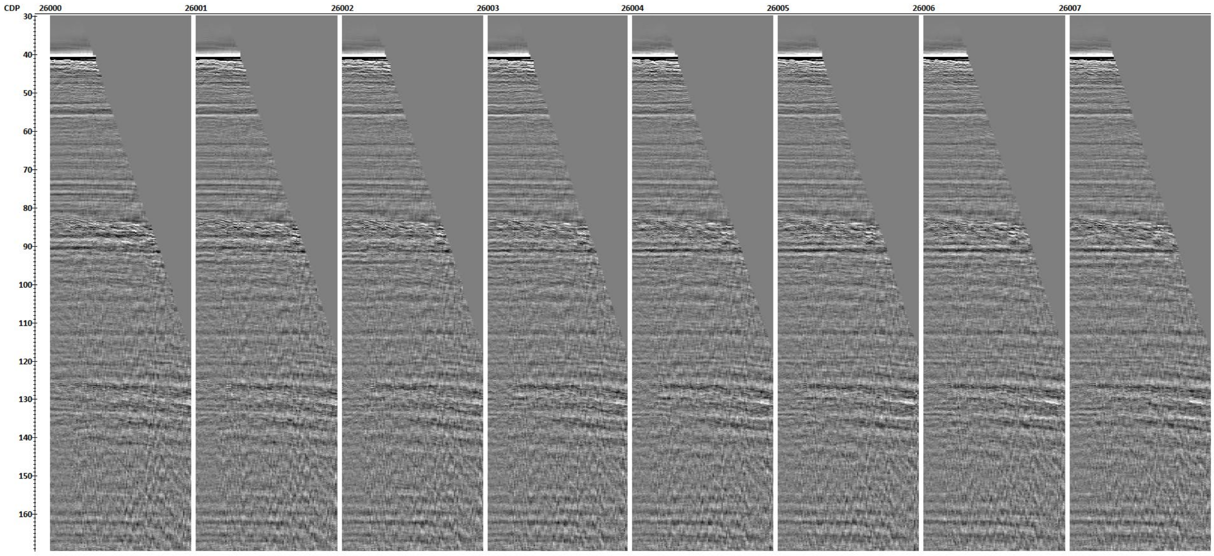
In order to optimize the offsets contributing to the stack near the seabed, the CDP gathers were stacked using a top muting window to remove data with ray path angles above 40° (Figure 26c). An alpha trimmed mean with a rejection of 35 % of the sample outliers were used for stacking as a mean to reject the occasional burst/spikes as well as to prevent the coherent stacking of the receiver ghost.



a)



b)



c)

Figure 26 *– CDP gather for line BM3_OWF_E_2D_06930: (a) before NMO, (b) after NMO correction using standard velocity model, and (c) after top muting window to remove data with ray path angles above 40°. Vertical scale in TWT (ms).*

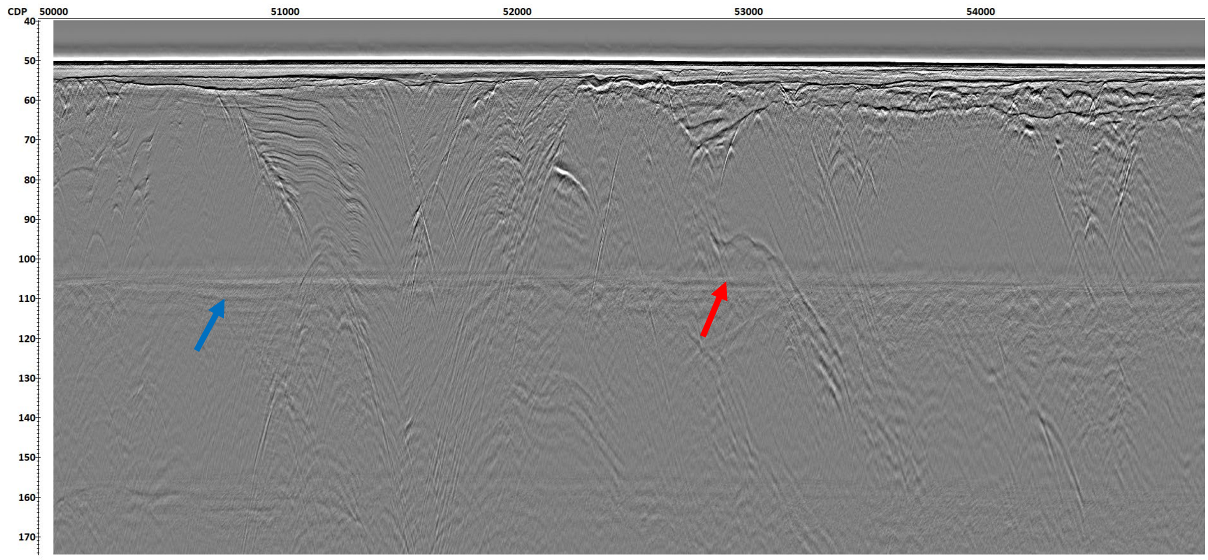
4.3.5. Post-stack Multiple Attenuation

For an improved seismic imaging at multiple depths, the post-stack multiple attenuation procedure was applied using a surface-related multiple attenuation technique called “Zero-Offset DeMultiple”. This procedure modules and attenuates the remaining multiple energy train, mainly the internal multiples, left after pre-stack demultiple.

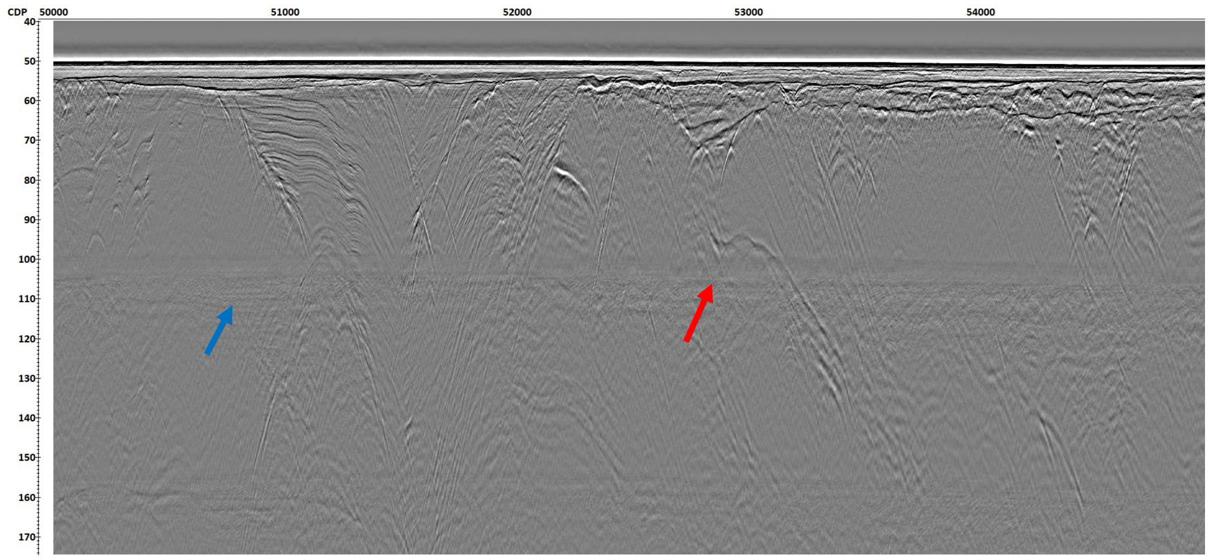
The post-stack multiple attenuation is based on the adaptive subtraction of a model of multiples. The model of multiples was determined from the data itself by auto-convolution of the traces. This technique allowed for a fine-tuned search and attenuation of the data multiples. Hence, for optimum imaging, two iterations were applied.

During the QC stage, it was noticed that the initial “Zero-Offset DeMultiple” parameters were not particularly effective on the NW corner of the survey site. The DeMultiple effectiveness was accessed on a line-by-line basis. The lines that presented a not so satisfactory multiple attenuation were flagged for further parameter testing. From this assessment, a total of 36 lines were flagged. These lines required a more comprehensive set of parameters, that allowed for a better multiple/primary compromise. This set of parameters was not applied to the remaining lines, as it was producing worst results, when compared to the original set.

Figure 27 and Figure 28 outline the results of the combined “Zero-Offset DeMultiple” iterations for the two sets of parameters used on this project. It is possible to observe that the multiples lose their relative strength (see red arrows for seabed multiple and blue arrows for internal multiples), mainly the first seabed multiple and the internal multiples, and allow for the recovery of otherwise much concealed seismic information.

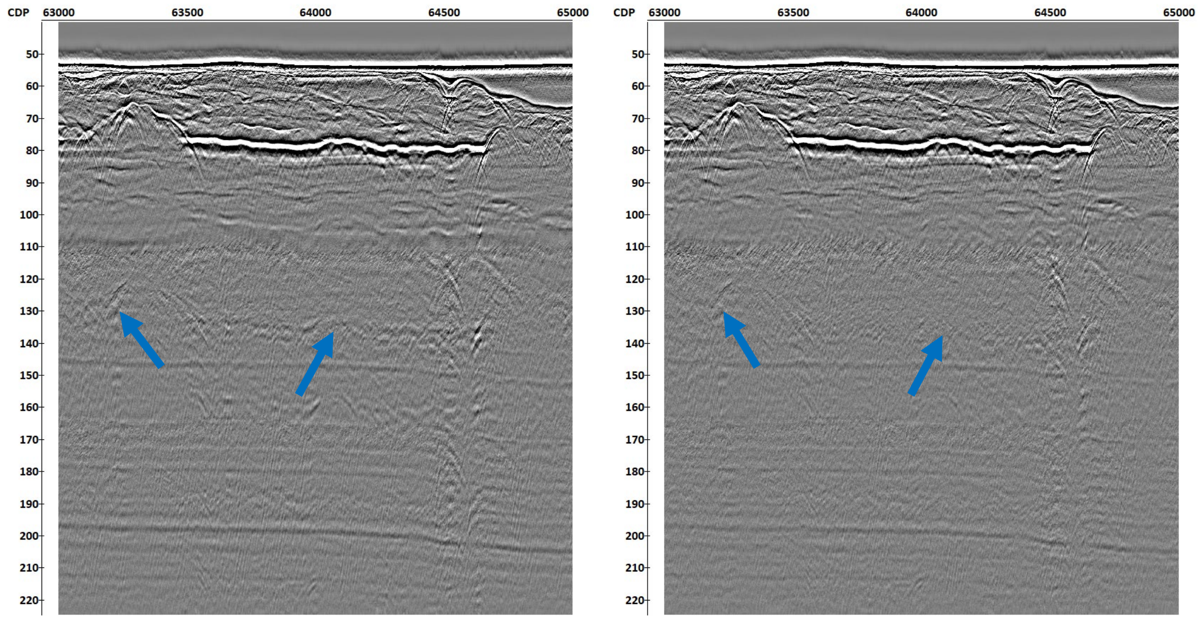


(a)



(b)

Figure 27 *- Line BM3_OWF_E_2D_06930 (a) before and (b) after post-stack multiple attenuation procedure. Vertical scale in TWT (ms).*



(a) (b)

Figure 28 *– Line B01_OWF_E_2D_00210 (a) with initial and (b) with optimised post-stack multiple attenuation procedure. Vertical scale in TWT (ms).*

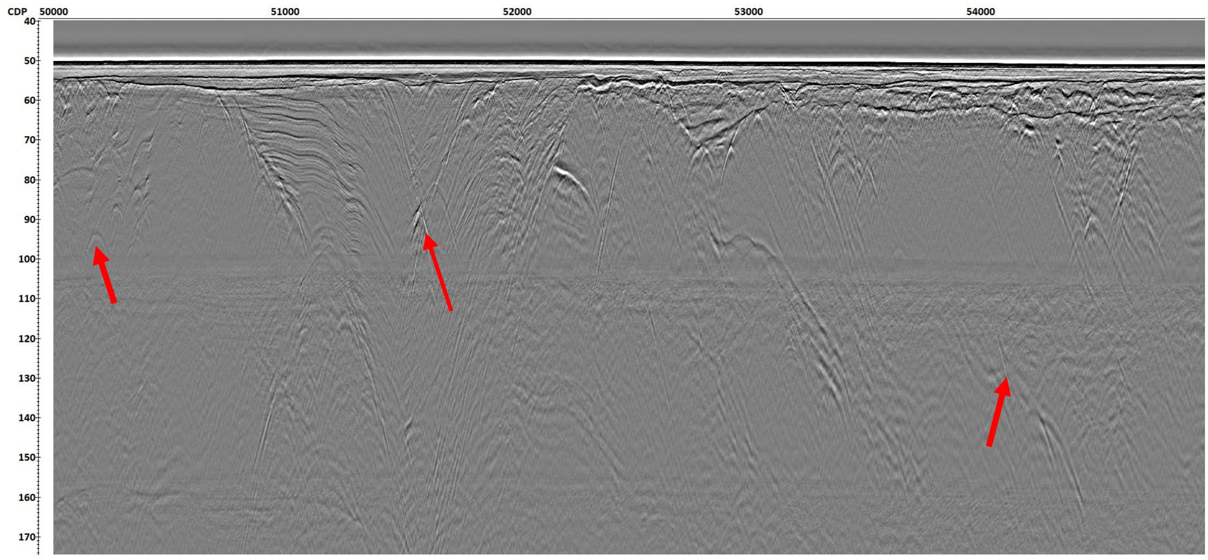
4.3.6. Spatial Interpolation and Post-stack Kirchhoff Time Migration

To prevent spatial aliasing during the migration procedure the stacked datasets were interpolated to a distance of 0.2 m between traces, as opposed to the initial 0.5 m spacing.

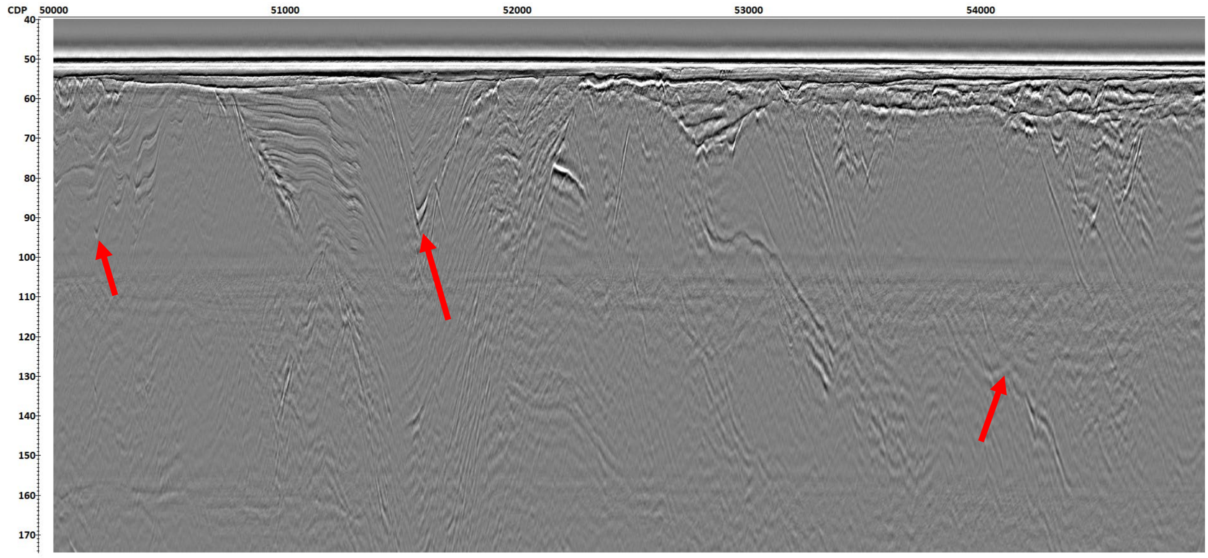
The post-stack Kirchhoff time migration is a time domain processing module used to migrate the seismic data. The standard velocity model was used to perform the Kirchhoff time migration, with a maximum frequency of 5000 Hz and 50 % for the aperture taper. The aperture parameters were tailored the project objectives:

- Aperture of 70, 150 and 300 m for the times of 80, 160 and 300 ms, respectively;

2D shaping filter and anti-aliasing filter were not applied to the data. Results are shown on Figure 29, highlighted by the red arrow that indicate the spots where the post-stack migration procedure is more visible.



(a)



(b)

Figure 29 *– Line BM3_OWF_E_2D_06390 (a) before and (b) after post-stack Kirchhoff time migration. Vertical scale in TWT (ms).*

4.3.7. Post-stack Signature Generation and Deconvolution

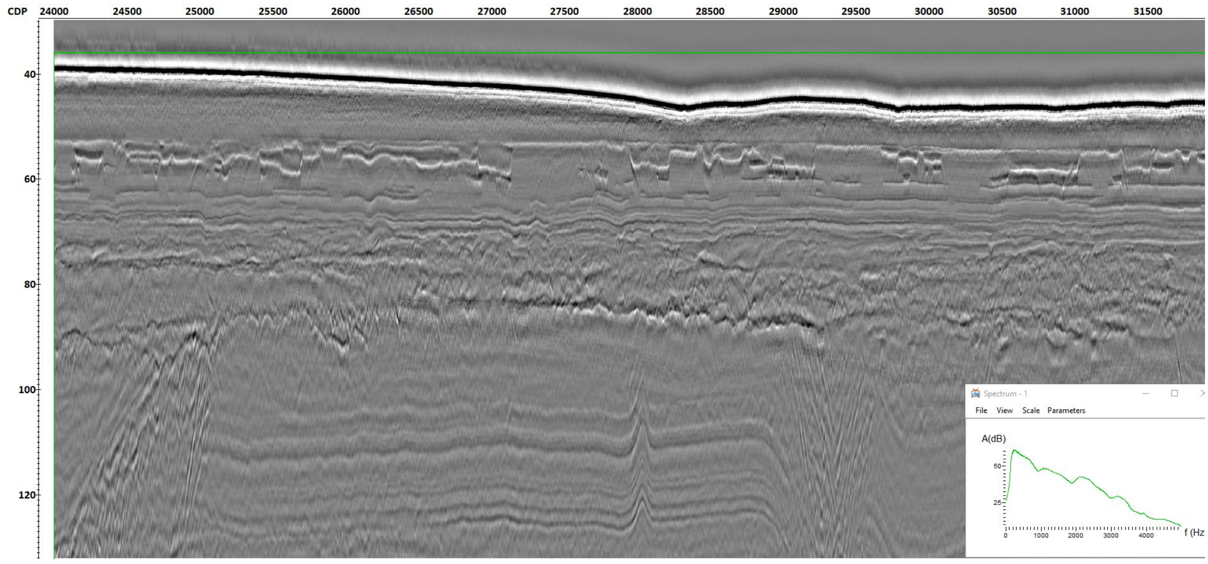
The signature used for the deconvolution was modelled by stacking the seabed primary reflection over each seismic line. A sea bottom signature was used to collapse the outgoing primary source pulse, improve the vertical resolution of the stack and attenuate the receiver ghost in the "Custom Impulse Trace Transforms" module. A zero-phase butterworth filter was applied to the deconvolved dataset to eliminate any possible artefacts created by the deconvolution.

The zero-phase butterworth parametres applied were the following (for all the survey data):

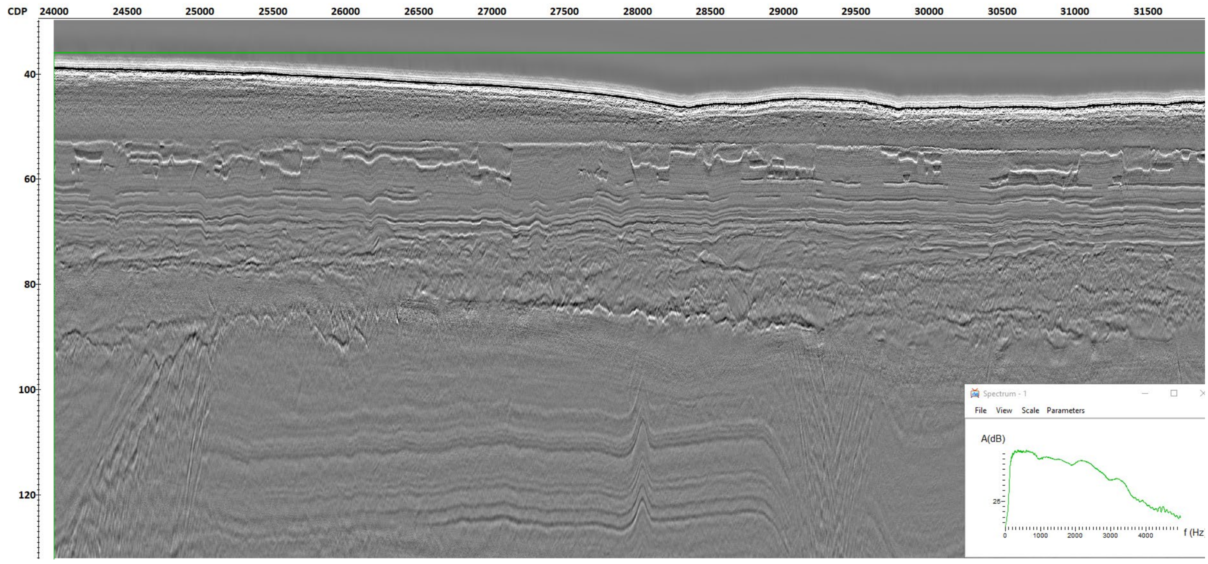
Low-cut freq.: 150 Hz	Low-cut slope: 12 dB/octave
High-cut freq.: 4500 Hz	High-cut slope: 24 dB/octave

After the deconvolution, a compression of the basic wavelet is achieved, leading to a sharper and higher resolution imaging. Also, the relative frequency spectrum signatures are different, showing for the later stage a flatter shape, a wider frequency and higher dynamic ranges.

By comparing the same seismic data prior to and after deconvolution (Figure 30), the procedure was assessed for its effectiveness, as seabed signature arrivals become thinner, the seismic reflectors are sharper, the receiver ghost is attenuated and a flatter frequency spectrum is achieved.



(a)



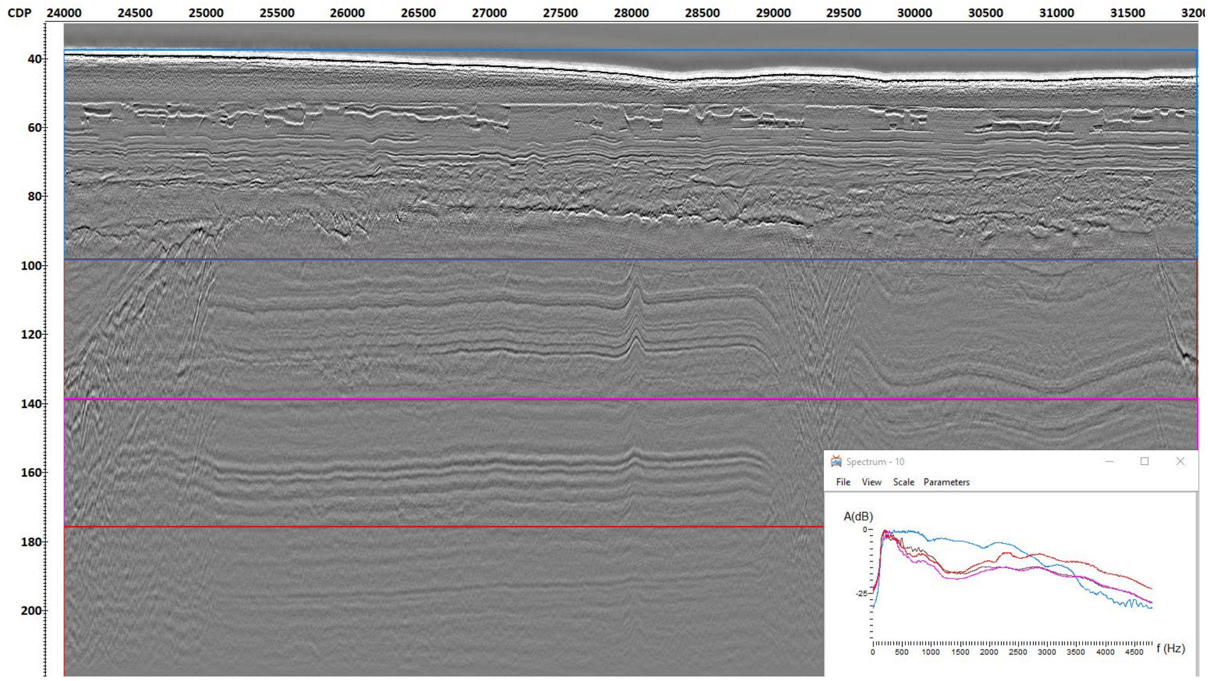
(b)

Figure 30 *– Line BM3_OWF_E_2D_06930 (a) before (b) and after post-stack deconvolution. Vertical scale in TWT (ms).*

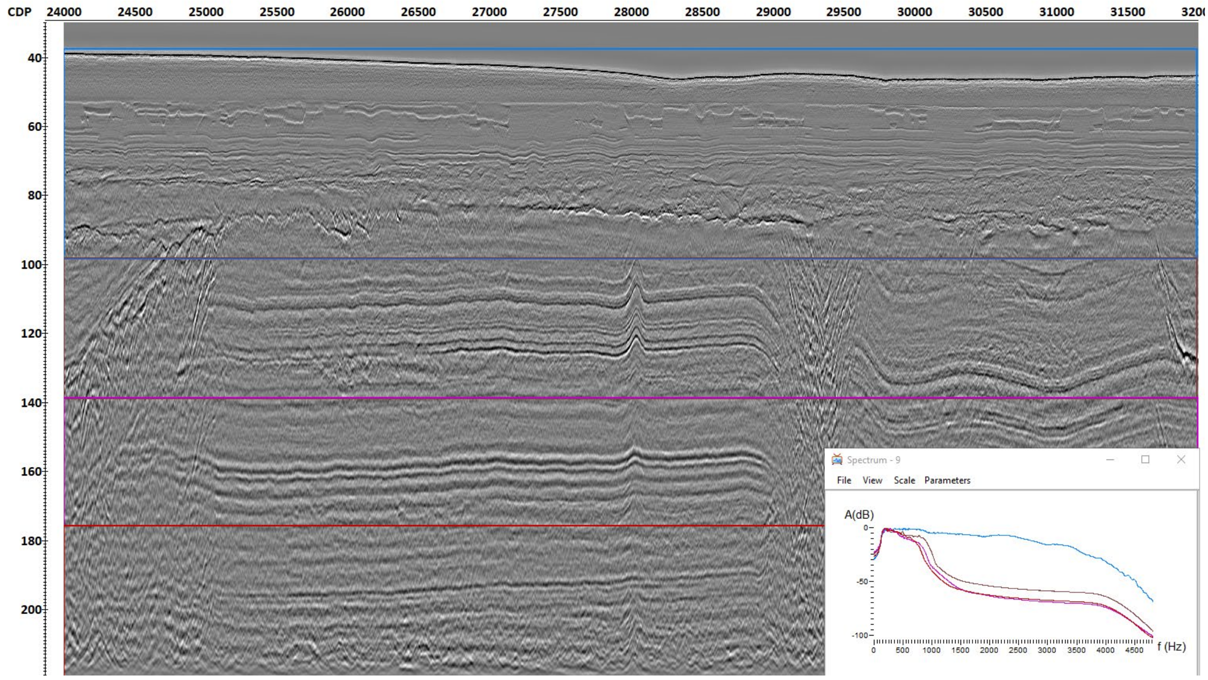
4.3.8. TVBPF Filtering and Amplitude Correction

In order to improve S/N at depth, without reducing the relevant spectrum bandwidth of the signal, an Ormsby Time Variant BandPass Filter (TVBPF) was applied to the data. Having the seabed as a reference, higher frequencies are filtered with increasing depth. A well-balanced frequency spectrum was achieved as high resolution is maintained over the recorded signal length.

The amplitude correction strives to provide a seismic section in which the seismic amplitudes accurately portray the values of the reflection coefficients at different depths trying to correct the loss of energy by different means, i.e., spherical divergence. An amplitude correction procedure was implemented in order to mitigate those losses. A gain curve was calculated for each trace and then applied to the dataset. The combined results of those processes TVBPF and amplitude correction are shown in Figure 31.



(a)



(b)

***Figure 31** – Line BM3_OWF_E_2D_06930 (a) before and (b) after applying TVBPF and amplitude correction. Vertical scale in TWT (ms).*

4.3.9. Tidal correction and MSL Reduction

Provided by MMT, tidal values were derived from post-processing GNSS. The tidal values were imported into the UHRS data headers by GS during the offline QC procedure on board, using the seismic processing software RadEx Pro. This header was applied to the stacked sections and standard velocity model for the site in order to correct the tidal shift of the data, on a trace-by-trace basis.

When the tidal correction is applied, the data can be corrected in terms of misties, i.e. the small shift between lines that occurs due to swell, static corrections, feathering, among others. Once the misties are corrected and the data is all in the same "seismic datum" the residual correction was calculated (bulk shift) to all data, necessary to reduce it to the required vertical datum (MSL). This procedure was performed in Kingdom Suite and was based on the bathymetric information (MBES) provided by MMT.

4.3.10. Time-to-Depth Conversion (Site Standard Velocity Model)

The TWT migrated sections were converted to depth (DPT datasets), using the standard velocity model for the site (see section 4.3.2), also called depth conversion velocity model.

For Depth conversion, the vertical corrections were applied to the velocity model for each seismic line and then exported in the SEGY format, in the resolution of the site/mistie datum (MBES).

Based on the main horizon's observation and overall dispersion throughout the site, several "layer cake" surfaces derived from the seabed in TWT were generated and the interval velocities were extracted for each surface. Those velocity surfaces at the site scale were then smoothed in order to mitigate the possible misties between lines. Some examples of the velocity surfaces generated, shown from Figure 32 to Figure 36, allow a general analysis of the spatial distribution of velocity variations for the entire site.

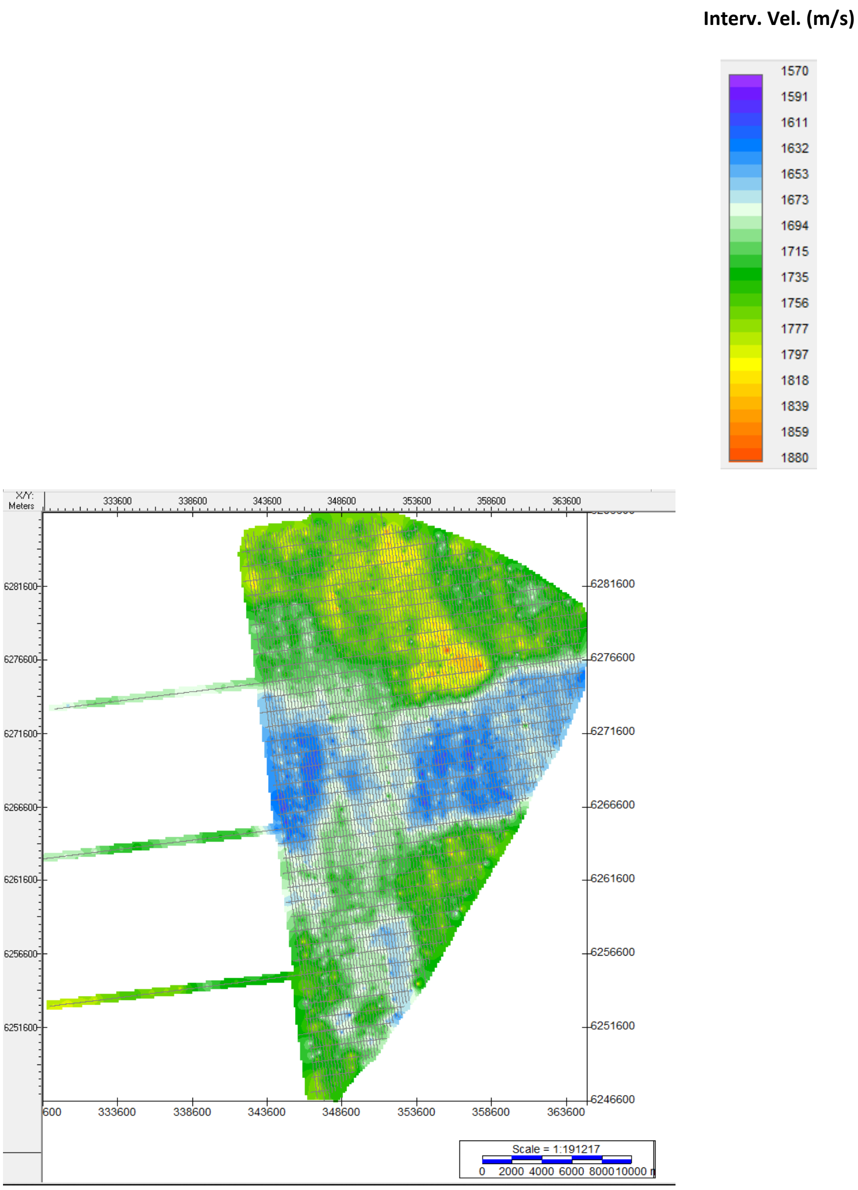


Figure 32 – *Velocity Surface for the Layer Cake horizon at SB + 10 ms.*

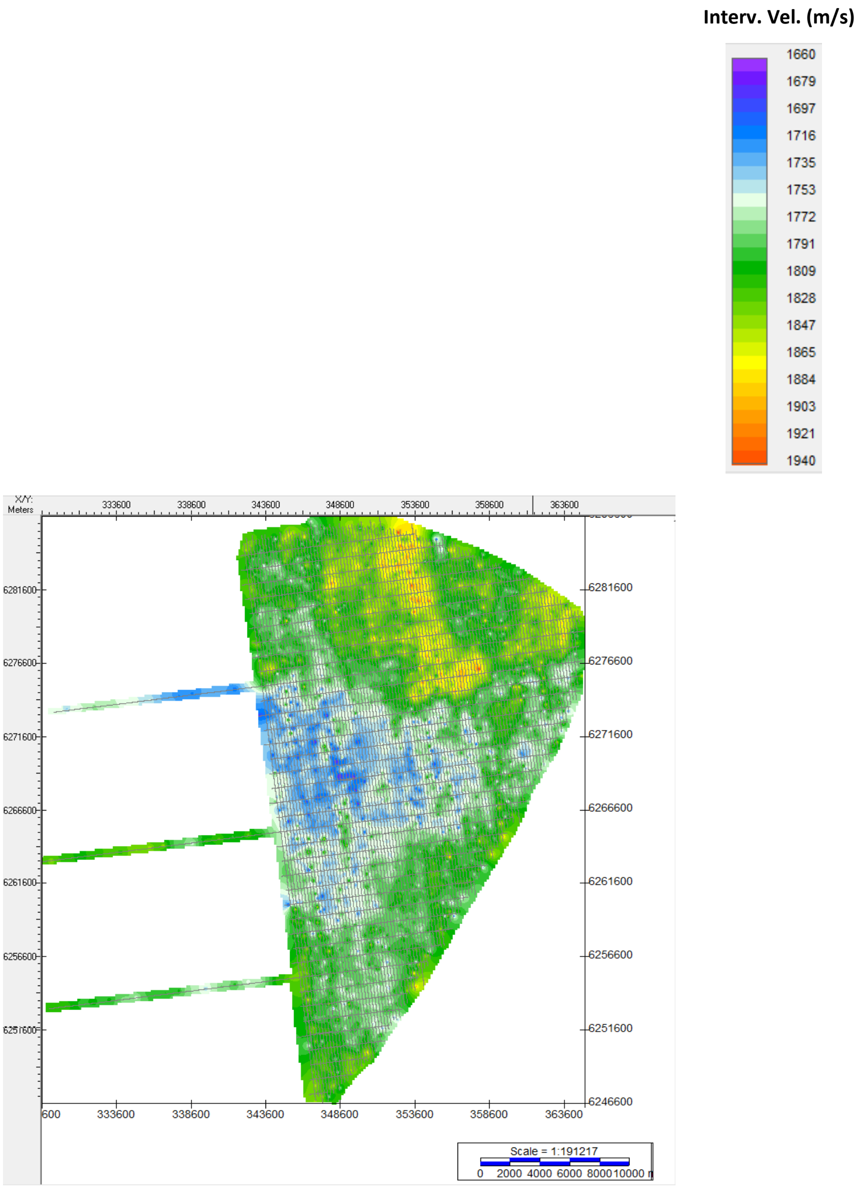


***Figure 33** – Velocity Surface for the Layer Cake horizon at SB + 30 ms.*

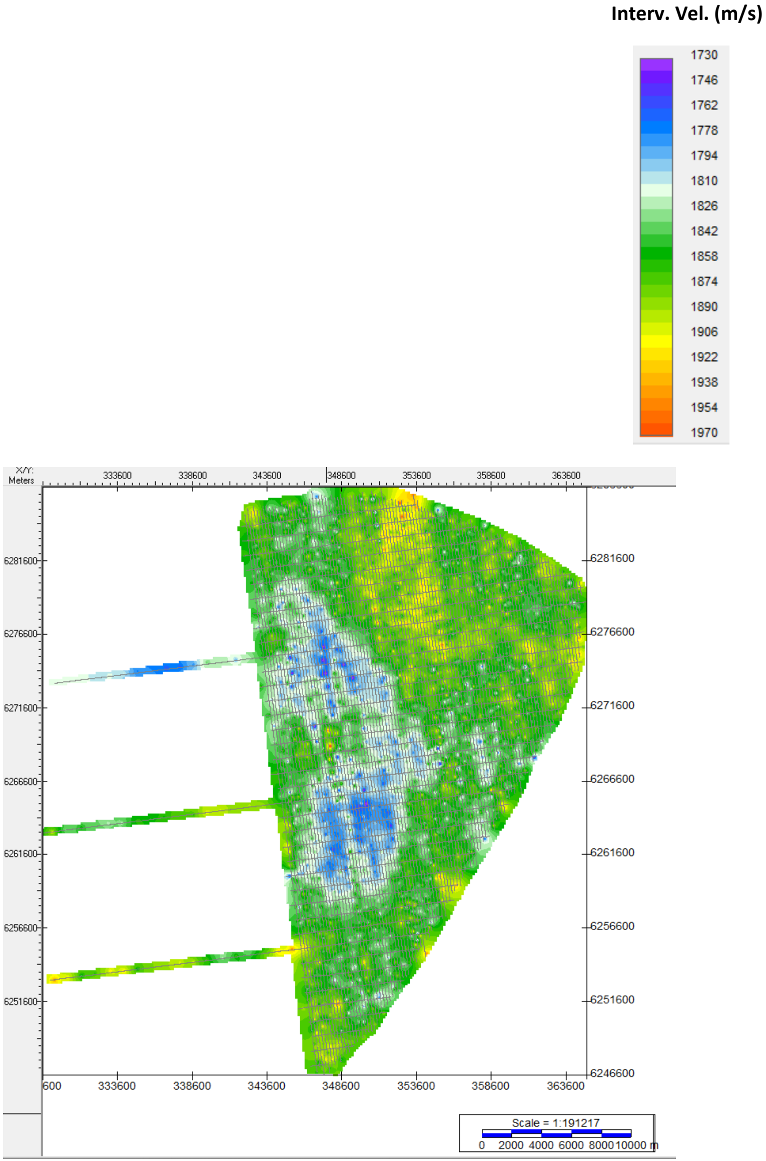


***Figure 34** – Velocity Surface for the Layer Cake horizon at SB + 50 ms.*

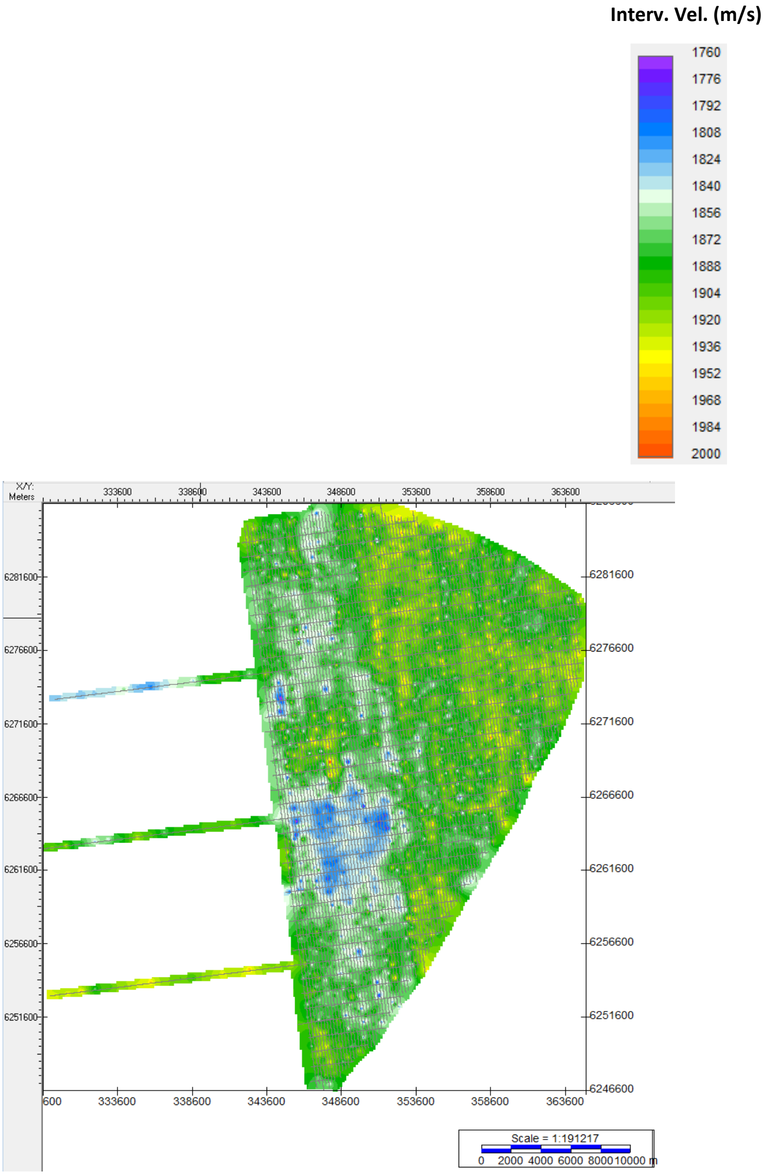


Figure 35 *– Velocity Surface for the Layer Cake horizon at SB + 80 ms.*

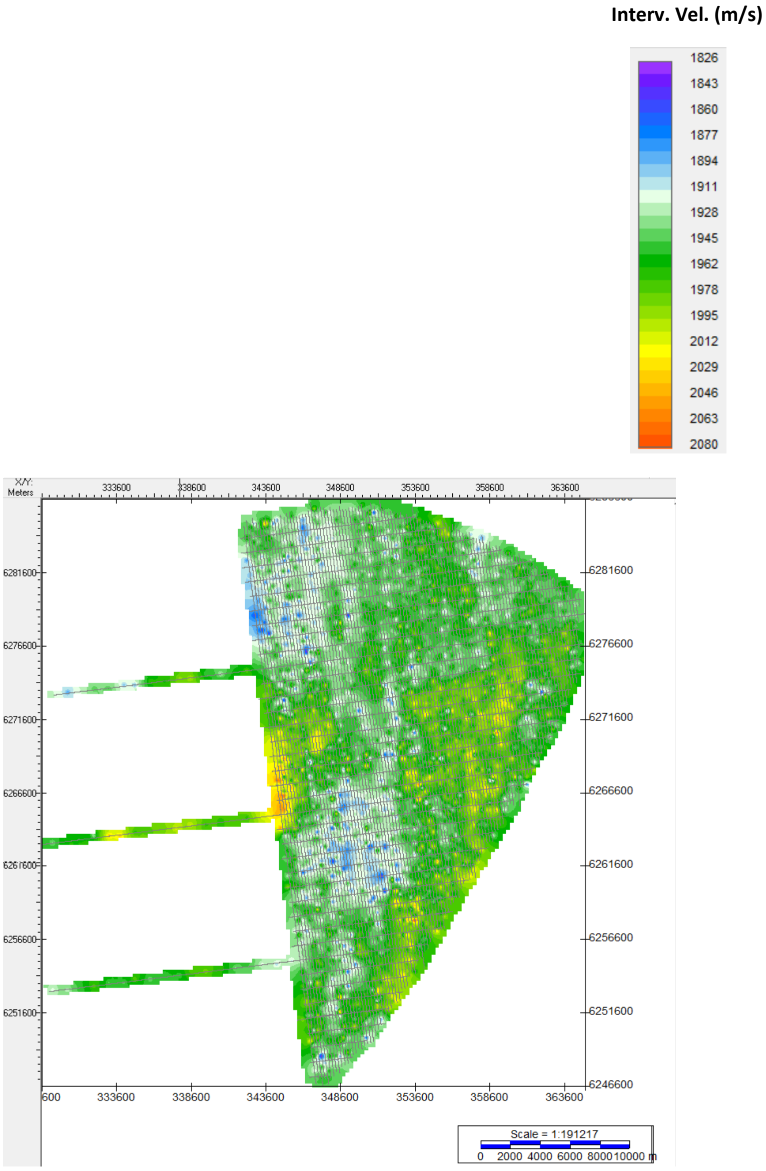


Figure 36 *– Velocity Surface for the Layer Cake horizon at SB + 120 ms.*

All the previous mentioned velocity surfaces were concatenated and the standard velocity model for the site was then imported to Radex in order to be used for depth conversion.

The depth conversion velocity model of each seismic line, in both RMS and interval velocities, were exported in SEG-Y and ASCII formats.

Due to the nonlinear relationship between time and space (a sample in time at shallow depths represents a much smaller distance than a sample in time at greater depth) and in order to preserve maximum resolution, the sample interval of the DPT datasets is half of the maximum graphical resolution of 10 cm that the system can achieve at shallow depths, i.e., 5 cm. Therefore, the data in depth has a greater number of samples than the datasets in time (MUL and MIG).

The next figures (Figure 37 to Figure 39) represent the final comparison between the velocity model and the seismic section in TWT and Depth.

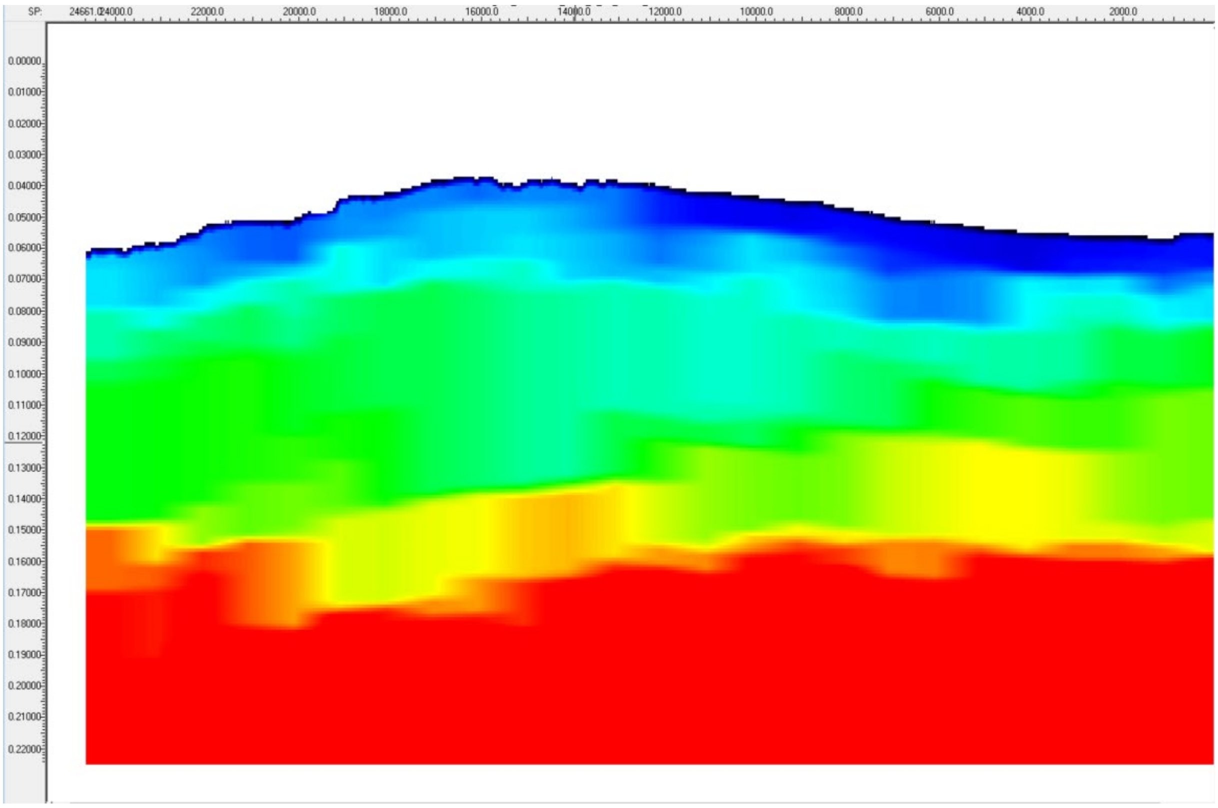


Figure 37 – *Line BX3_OWF_E_XL_19000_01 velocity picks dataset. Vertical scale in TWT*

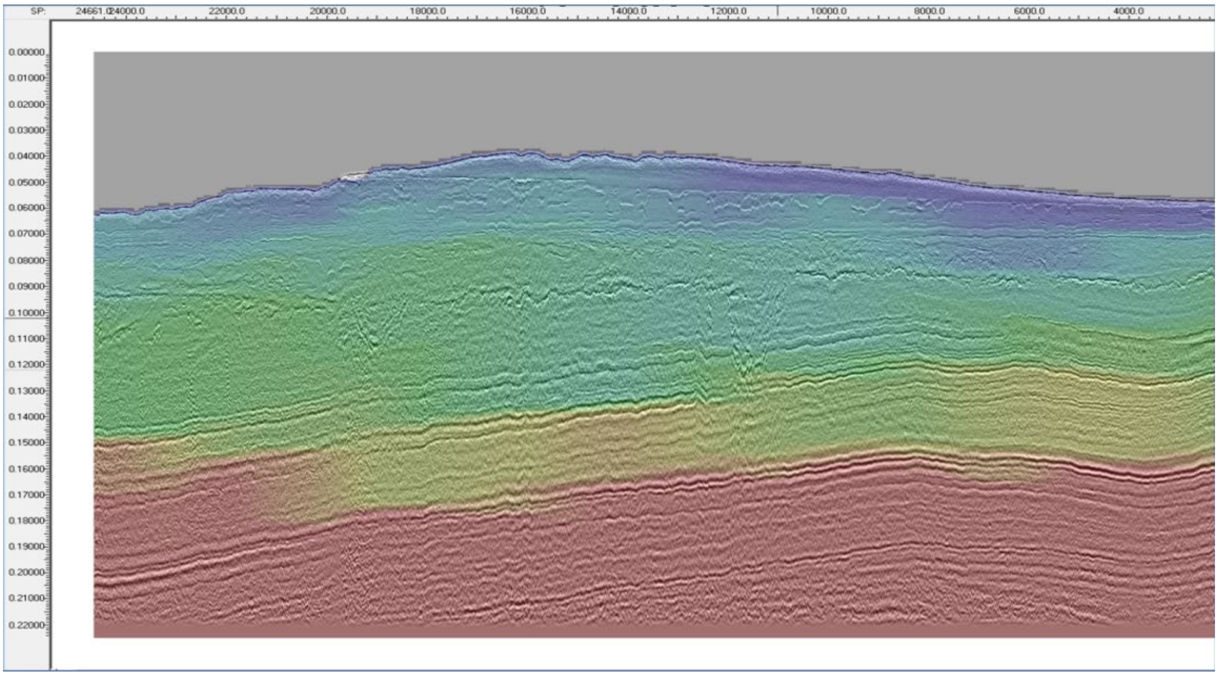


Figure 38 – *Line BX3_OWF_E_XL_19000_01 velocity picks dataset vs MIG dataset. Vertical scale in TWT*

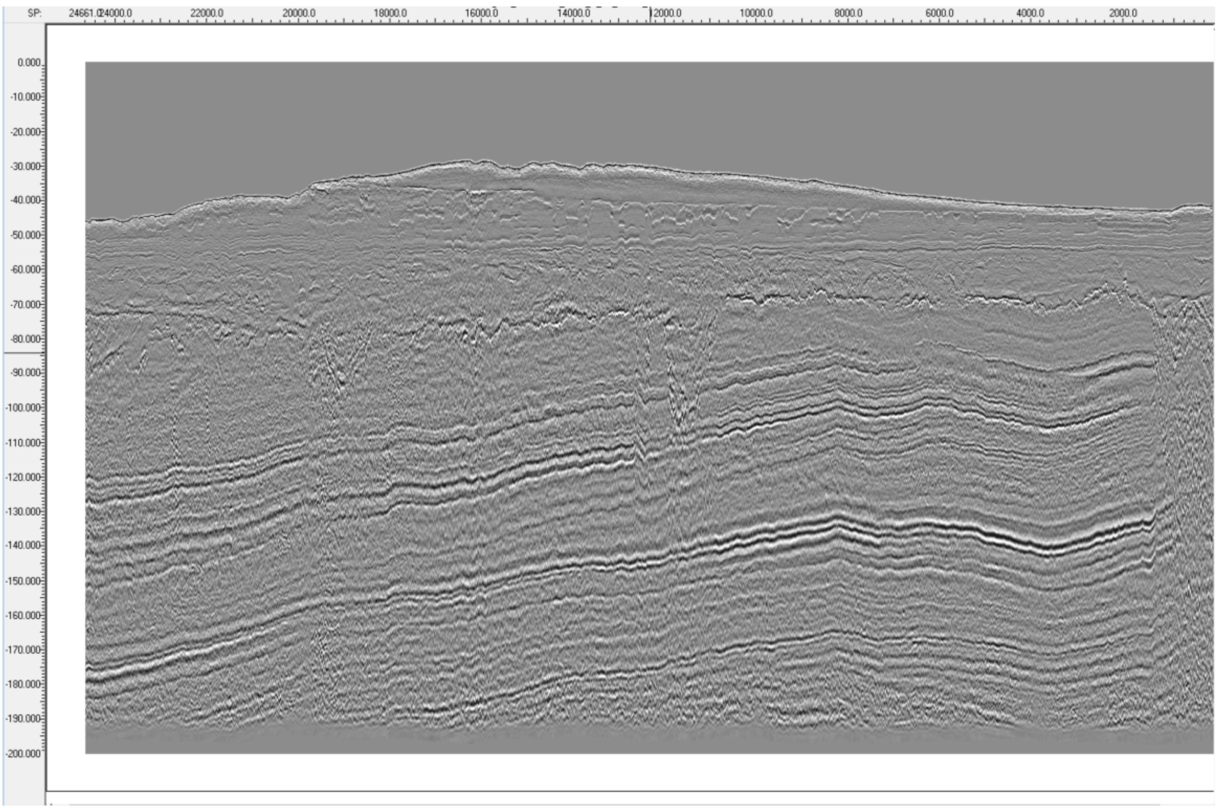


Figure 39 – *Line BX3_OWF_E_XL_19000_01 DPT dataset. Vertical scale in metres.*

5. PROCESSED DATA QUALITY CONTROL

Quality control procedures were carried out throughout the processing scheme, as detailed within the present report. All processing steps were checked for the proper application of the seismic imaging enhancement. Several of these quality controls were delivered as part of this project submission, such as trace and offset QC; streamer slant check; source and receiver heave; image of the TRIM stack (including CDP trace fold) and stack image of the final migrated dataset (FULL track).

Furthermore, at some stages, quality control supervision was carried out by the project's Principal Processor to ensure that the seismic processing was being properly applied as well as for troubleshooting purposes. Finally, and after all intermediate quality controls, lines were inspected by both geophysicists and geologists for acceptance.

The following remarks can be done, regarding the processing stage of the 2D-UHRS seismic dataset received:

- Data processing on some profiles was negatively affected by sea conditions;
- Seismic amplitude balancing was corrected in order to all seismic profiles have a similar imaging of the subsurface;
- Fine tuning of the post-stack Demultiple and post-stack migration in order not to erase real geological features but also to attenuate the multiple energy and undesired diffraction effects, respectively;
- Seismic resolution improvement, both horizontal and vertical, was always a main concern in all processing steps.

6. DELIVERABLES

From the UHRS data and after the UHRS data processing scheme the following digital deliverables were produced:

1. Multiple attenuation stacks (SEGY file) – Linename_MUL.sgy;
2. Migrated stacks (SEGY file) – Linename_MIG.sgy;
3. Depth converted migrated stacks (SEG-Y file) – Linename_DPT.sgy;
4. Interval Standard Velocity Model (SEGY file) – Linename_HV_INT.sgy;
5. RMS Standard Velocity Model (SEGY file) – Linename_HV_RMS.sgy;
6. Interval Standard Velocity Model (ASCII file) – Linename_Vel_INT.dat;
7. RMS Standard Velocity Model (ASCII file) – Linename_Vel_RMS.dat;
8. QC plots from TRIM and FULL track flows:
    a. Fig1_Linename_Trace&Offset_QC;
    b. Fig2_Linename_Source&Cable_Heave;
    c. Fig3_Linename_Slant_Check;
    d. Fig4_Linename_TRIM_STK;
    e. Fig5_Linename_FULL_MIG.
9. Processor Log.

The EBCDIC headers of the delivered SEGYs (MUL, MIG, DPT, HV_INT and HV_RMS) were filled with information such as the acquisition and geometry parametres, coordinate system and the main processing steps used for each specific file type. A script was created to allow for batch process for the entire survey seismic profiles; this batch process was carried out separately for each dataset type as each dataset type has its unique EBCDIC header.

An example EBCDIC header for line BM1_OWF_E_2D_00000_MIG.sgy is here presented:

```
C 1 CLIENT: ENERGINET; PROC. COMPANY: GEOSURVEYS; CONTRACTOR: MMT SWEDEN AB;
C 2 VESSEL: M/V RELUME; AREA: NORTH SEA OWF AND E.ISLANDS; SURVEY: OWF - EAST;
C 3 LINE: BM1_OWF_E_2D_00000                               ACQDATE: 11/05/2021
C 4 SPS:10004-86655  CDP:1-38347     SPV MEAN:1477m/s    PROC DATE: 28/05/21
C 5 RECORD SYSTEM: Multitrace; RECORD FORMAT: SEG-Y; RECORD LENGTH: 225.00ms;
C 6 SAMPLE INTERVAL: 0.1ms; SAMPLES/TRACE: 2250;
C 7 FILTERS: N/A;
C 8 SRC TYPE: SPARKER; N.TIPS: 200 in EACH SPARKER; ENERGY: 400 Joules;
C 9 NBR OF SRC: 3; ACTIVE SRC: 0=UPPER, 1=MIDDLE 2=LOWER;
C10 SRC DEPTH: 0.5m (UP); 0.8m (MID); 1.1m (LOW); Delay: 0.250ms;
C11 LEAD BUOY DEPTH: 0.5m; LEAD BUOY OFFSET: 23.5m; TAIL BUOY DEPTH: 1.80m;
C12 STR LENGTH: 95.0m; CHAN INT: 1-96@1m; NBR OF CHAN: 96;
C13 CMP/SHOT: 1/1; SHOT INT: 0.5m (TUNED MODE);
C14 CMP INT: 0.5m; CMP FOLD: Variable ~96;
C15 INLINE OFFSET: 1.00 m; XLINE OFFSET: 3.00 m;
C16 NAV SYSTEM: RTK-DGPS GMSS; GRID UNIT: METRES;
C17 PROJECTION TYPE: UTM Zone 32N; GEODETIC DATUM: ETRS89;
C18 VERTICAL DATUM: MSL; SCALE FACTOR: 1;
C19 DATASET TYPE: MIG; SORT ORDER: CDP; POLARITY: NORMAL; PHASE: ZERO;
C20 PROCESSING FLOW:
C21 01)GEOMETRY ASSIGNMENT; 02)DENOISE; 03)UHRS TRIM STATICS;
C22 04)PRE-STACK DECONVOLUTION 05)PRE-STACK DEMUL;
C23 06)STACK VELOCITY MODEL; 07)ENSEMBLE STK;
C24 08)POST-STACK DEMUL; 09)POST-STACK DEGHOST; 10)POST-STACK MIGRATION;
C25 11)TVBPF; 12)AMPLITUDE CORRECTION; 13)MISTIE CORRECTION.
C26
C27
C28 SEGY FORMAT : IBM Floating-Point
C29 HEADER         BYTE  FORMAT  MULT
C30 CDP_NUMBER      21     4I      1
C31 TIDE_HGHT (m)   57     4I     100
C32 CDP_X          181     4I     100
C33 CDP_Y          185     4I     100
C34
C35
C36
C37
C38
C39
C40 END TEXTUAL HEADER ENERGINET LOT1 SURVEY SEG Y VERSION 1.0.0
```

7. CONCLUDING NOTES

Approximately 3248 km of 2D Ultra-High-Resolution Seismic reflection data (sail length) were processed. The processing flow carried out has several stages, each of them with specific goals, as detailed next:

1) In a first stage (TRIM track), a trace-by-trace residual static correction procedure to compensate for the vertical motions of the source and cable was estimated. Static corrections applied to the data can be divided into four major components: cable depth, source heave, cable heave and swell;
2) The second stage (FULL track) was carried out in order to produce three datasets: unmigrated, migrated, and migrated converted to depth seismic section. FULL track main procedures included pre-stack multiple attenuation (both SRME and in Tau-P domain), denoise, pre-stack ghost mirror procedures, stacking using standard velocity model, post-stack multiple attenuation, Kirchhoff time migration to recover true geometry of primary reflections using standard velocity model, deconvolution, and time-to-depth conversion using the standard velocity model for the site.

In general, the UHRS data processing focused on improving the seismic section resolution and signal quality mainly within the first 100 m below the seabed. Overall, the main concluding notes are:

- Geometry QC shows good CDP fold with a mean fold of ~96 in all lines;
- UHRS TRIM statics allowed for the correction for the motion of the towed equipment resulting in good consistency of the CDP gathers, greater seismic detail, as finer collapse of the overall seismic data is recognizable, and in a broader frequency content;
- The stack preserved a broad frequency content between 100 and 4500 Hz, allowing for improved reflector lateral continuity and resolution;
- A good SRME multiple attenuation was achieved in the majority of the seismic profiles.

On behalf of Geosurveys, Aveiro, Portugal

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