Baseline Survey Results Report

Danish Offshore Wind 2030 | North Sea 1, Denmark

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Energinet Eltransmission A/S

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18 August 2023

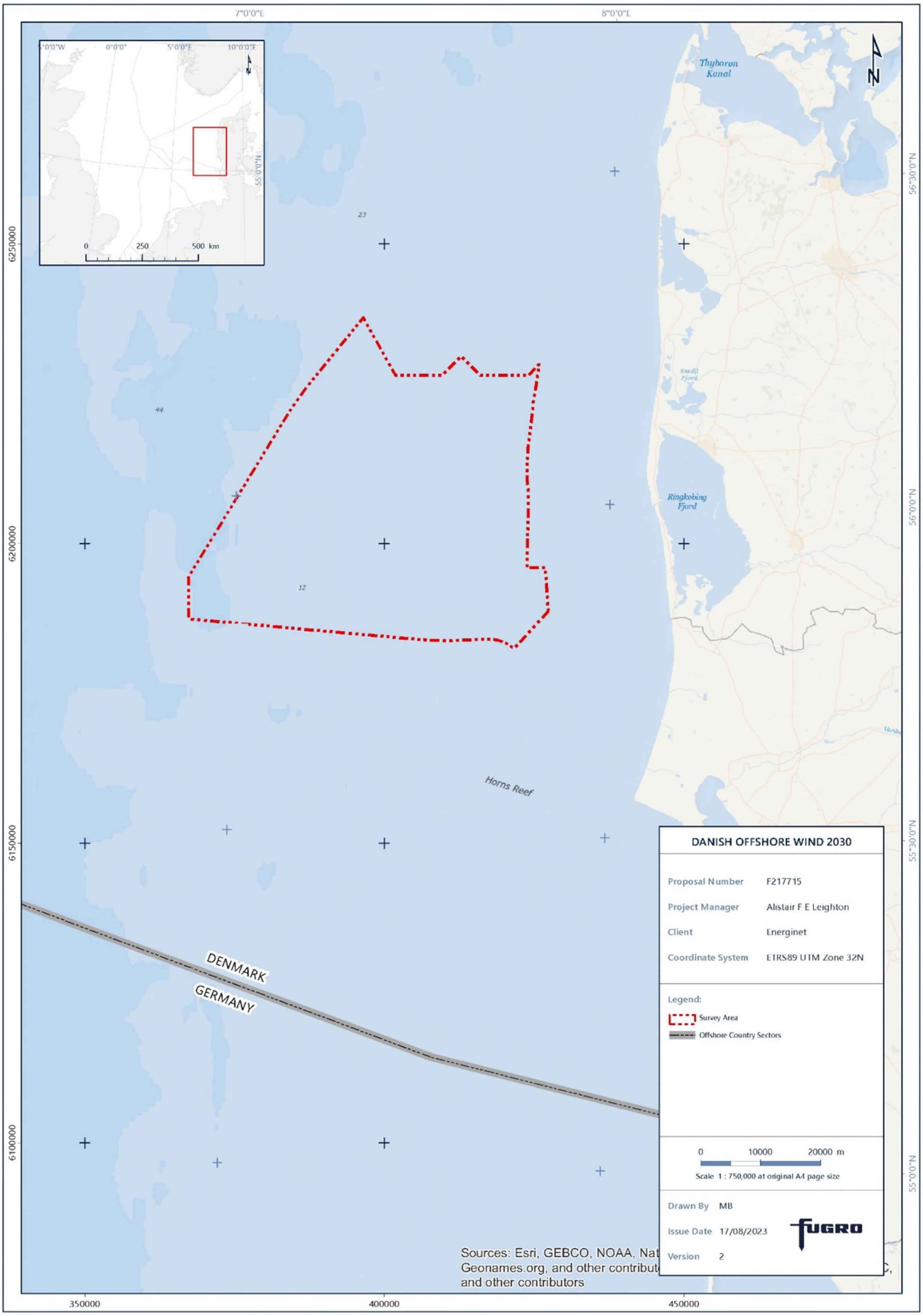
Dear Sir/Madam,

We have the pleasure of submitting the 'Baseline Survey Results Report' for the 'Danish Offshore Wind 2030'. This report presents all the results of the geological site survey.
We hope that you find this report to your satisfaction; should you have any queries, please do not hesitate to contact us.

Yours faithfully,

Malgorzata (Gosia) Nowak
Reporting and Deliverables Project Manager

Frontispiece



Executive Summary

Interpretative Site Investigation	
Survey Dates	14 to 19 April 2023
Equipment	Multibeam echo sounder (MBES), sub-bottom profiler (SBP), 2D ultra high resolution (2D UUHR) seismic
Coordinate System	Datum: European Terrestrial Reference System 1989 (ETRS89) Projection: UTM Zone 32N, CM 3°E
Bathymetry	
Elevation at the time of the survey ranged from -15.9 m to -39.3 m MSL. The site is characterised by gentle seafloor slopes, on average ranging between approximately 0˚ and 6˚.	
Geological History	
During the Miocene to Middle Pleistocene, marine, deltaic and fluvial deposits (BSU and Unit U90) were deposited in the site as a result of the progradation of the Eridanos river system. During the Elsterian and/or Saalian glaciations, tunnel valleys and their infills (Unit U70) were formed, and the BSU was glacially deformed. During the Middle to Late Pleistocene, glaciofluvial sediments (Unit U60 and Unit U35) and interglacial marine sediments (Unit U50 and Unit U30) were deposited. During the latest part of the Pleistocene, channels were eroded which were filled during the Late Pleistocene to early Holocene (Unit U20). During the Holocene marine sediments (Unit U10) were deposited.	
Geological Features and Geohazards	
Peat and/or organic clay	Peat and/or organic clay is present locally in Unit U10, U20, U30, U50, U90 and the BSU.
Shallow gas	No evidence for shallow gas was observed on the 2D UUHR seismic data. However, the presence of gas/fluid charged sediments cannot be excluded entirely.
Gravel, cobbles, and Boulders	Gravel and cobbles are expected in Unit U35 and U60 and may be present in Unit U90. Unit U70 may contain gravel, cobbles and boulders.
Buried channels and tunnel valleys	Unit U20, U35, U50 and U60 locally form channels infill. Unit U70 represents tunnel valleys. Unit U35, U60 and U90 contain internal erosion surfaces.
Glacial deformation	The BSU is locally glacially deformed.
Faults	In the BSU, a thrust faults and an area with normal faults are present. Due to the structureless seismic aspect that characterises a large part of the sub-seafloor, the presence of more faults and/or fractures cannot be ruled out.
Shallow Geology	
Unit U10	Unit U10 is present throughout most of the site and forms a layer of Holocene marine sediments with a maximum thickness of 8 m.
Unit U20	Unit U20 forms spatially variable channels and overbank deposits with a maximum thickness of 30 m.
Unit U30	Unit U30 has a sheet-like geometry and is locally present in the north-west and south-west of the site with a maximum thickness of 11 m.
Unit U35	Unit U35 is a fluvial unit with a sheet-like to channelised geometry and a maximum thickness of 24 m.
Unit U50	Unit U50 has a sheet-like to channelised geometry and an acoustically transparent to stratified seismic character. It has a maximum thickness of 50 m.
Unit U60	Unit U60 is a fluvial unit with a sheet-like to channelised geometry and a maximum thickness of 76 m.
Unit U70	Unit U70 is a tunnel valley infill with a maximum thickness of more than 166 m.

Unit U90	Unit U90 is fluvial unit which is present in the south-west of the site with a maximum thickness of more than 158 m.
BSU (Base Seismic Unit)	The BSU is a stratified Miocene bedrock which is deformed by various types of faults.
Geotechnical Locations	
14 BH locations and 32 CPT locations were assigned to the baseline 2D UUHR lines. These target features identified along these seismic data, as well as considering the existing locations assigned based on the desk-based assessment. The focus of the locations assigned is spatially limited geological features.	

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Appendices

Figures in the Main Text

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Abbreviations

2D UUHR	Two-dimensional ultra ultra high resolution
BH	Borehole
BP	Before present
BPD	Below penetration depth
BSF/BSB	Below seafloor / Below seabed
BSU	Base seismic unit
CM	Central meridian
COG	Centre of Gravity
CPT	Cone Penetration Test
CRP	Common Reference Point
ETRS89	European terrestrial reference system 1989
DTS	Desktop Study
Fm	Geological Formation
GNSS	Global navigation satellite system
ka	Period equal to 1000 years
LGM	Last Glacial Maximum
MBES	Multibeam echosounder
MSL	Mean sea level
OWF	Offshore wind farm
PEP	Project Execution Plan
REP	Report
RTK	Real-time kinematic positioning
SBP	Sub-bottom profiler
TWTT	Two-way travel time
UTM	Universal Transverse Mercator
VRF	Vessel Reference Frame

1. Introduction

1.1 General

Energinet Eltransmission A/S contracted Fugro to perform the Offshore Geological Site Survey for the Danish Offshore Wind 2030 (DOW2030) campaign at the North Sea 1 (NS1) site (Part 5). DOW2030 programme comprises multiple site investigations, the awarded work for this campaign being Part 5. This area of investigation is referred to as North Sea 1, covering an area of ~2200 km^2 of the North Sea west of Jutland with water depths between 10 m and 40 m, roughly between the Horns and Thor offshore windfarm areas.

This report provides the results of the survey performed by vessel MV Arctic, the achieved data quality and interpreted data products. Results of the baseline survey will support the identification of sites for several geotechnical investigation sites (5-10%) and subsequent magnetometer box survey locations.

The geological survey was undertaken between 14 to 19 April 2023 MV Arctic. The data were acquired using multibeam echosounder (MBES), sub-bottom profiler (SBP) and 2D ultra ultra high resolution (2D UUHR) seismic.

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

1.2 Survey Objectives and Scope of Work

The following sub-sections provide details about the main survey requirements and the scope of work for the Client's Work Package A, 2D UUHR Baseline Survey at North Sea 1 work site. The MV Arctic conducted the Baseline Survey at the work site.

1.2.1 Survey Objectives

The Baseline Survey will support the identification of sites for several geotechnical investigation sites and subsequent magnetometer box survey locations.

A 2D UUHR seismic survey is conducted to map the large-scale geology and obtain an understanding of the potential geohazards in the area. From this understanding to suggest geotechnical locations aiming to cover geotechnical interests.

To achieve these objectives Fugro will:

- Acquire 2D UUHR (ultra ultra high resolution seismic) data migrated fully to a depth of 100 metres to determine the deeper sub-surface soil conditions that may influence foundation design below the effective penetration of the SBP.
- Ensure that the quality of the near surface data is comparable enough with the SBP data to tie geological features.

1.2.2 Scope of Work

A summary of the main requirements for the geological survey operations is presented in Table 1.1.

Table 1.1: Survey Requirements Overview

Equipment Method	Energinet DOW2030 requirements
Vessel	MV Arctic
Line Spacing	Baselines to be run at 10,000 m spacing
Max Vessel Speed	Maximum of 4.0 knots (speed through water; ±10%)
Surface Positioning	Dynamic heading accuracy of ± 0.2° or better Static heading accuracy of ± 0.05° or better Horizontal uncertainty of the vessel of ± 0.5 m or better
2D UUHR	1 x Applied Acoustics Engineering Durasprak UHD single array Sparker AAE CSP-sNv 1250 (800 J) Single plate array with 400 tips corresponding to a total power output of 800 J 70 m HV cable Sea ground cable 1 x Geometrics LH16 Geo Eel streamer 1 x 96 channels @ 1.0m group interval 3 hydrophones centred on each group with a 0.20m spacing between hydrophones 4.1 m flat tow ± 0.2 m Geometrics CNT-2 3 x Fugro adaptive drogues located on the tail-end of the streamer between the end of the last live section and the tail buoy Shot Point Interval 1.0 m Record length of 220 ms Sampling interval of 0.125 ms Recording format: SEG-D 1 x Head Buoy with RTK GNSS pod 1 x Tow Cable 1 x Tail Buoy with RTK GNSS pod Sparker and streamer positioning Applied Acoustics Single Level Sparker – 400 tips (800 Joules) RTK GNSS pod on Sparker navigation buoy
MBES/Backscatter	Multibeam echosounder data will be acquired and processed. Backscatter data will be acquired. Bin size: 0.25 m Density: minimum 16/m^2

Equipment Method	Energinet DOW2030 requirements
SBP	Sub-bottom profiler data will be acquired and processed. Depth of interest is 10 m, depending on geology. Resolution: 0.3 m
SVP	The speed of sound in water shall be measured in the survey area. Minimum of SVPs every 6 hours. The Vertical Sound Velocity Profiles should be able to measure within the range 1,350-1,600 m/s

The project area is located offshore Denmark, approximately 45 nm northwest of Esbjerg. (Figure 1.1).

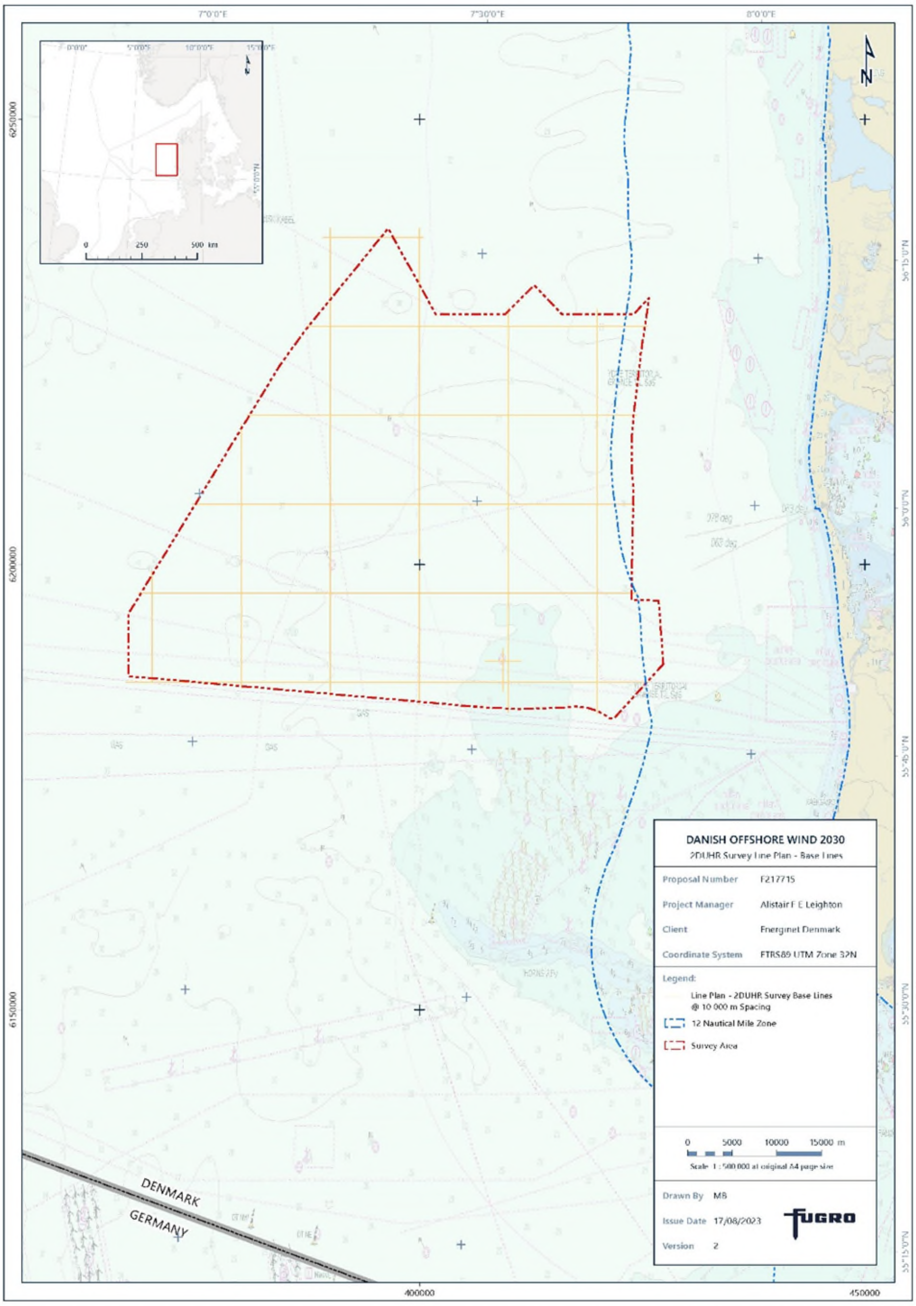

Figure 1.1: Project Location

1.3 Geodetic Parameters

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

Table 1.2: Project Geodetic Parameters

Global Navigation Satellite System (GNSS) Geodetic Parameters	
Datum:	ETRS89 (European Terrestrial Reference System 1989)
EPSG Code:	25832
Semi major axis:	6 378 137.00 m
Reciprocal Flattening:	298.257222101
Project Projection Parameters	
Grid Projection:	Universal Transverse Mercator
UTM Zone:	32 N
Central Meridian:	009° 00′ 00.000″ E
Latitude of Origin:	00° 00′ 00.000″ N
False Easting:	500 000 m
False Northing:	0.000 m
Scale factor on Central Meridian:	0.9996
EPSG Code:	16032
Units:	Metres

Unless stated otherwise, geodetic coordinates presented in this report are as per the datum in Table 1.2.

1.4 Vertical Datum

The vertical datum is mean sea level (MSL). All water depths will be referenced to MSL using post processed GNSS height data collected in real time on board the vessel. GNSS heights will be referenced to MSL by means of the WGS84 to DTU21 MSS ellipsoidal to datum separation model.

2. Vessel Details and Instrument Spread

2.1 MV Arctic – Offshore Scope

The MV Arctic scope of work for this project was to survey the base lines. The survey grid was 10x10 km. Refer to Figure 2.1 for an overview of the survey base lines.

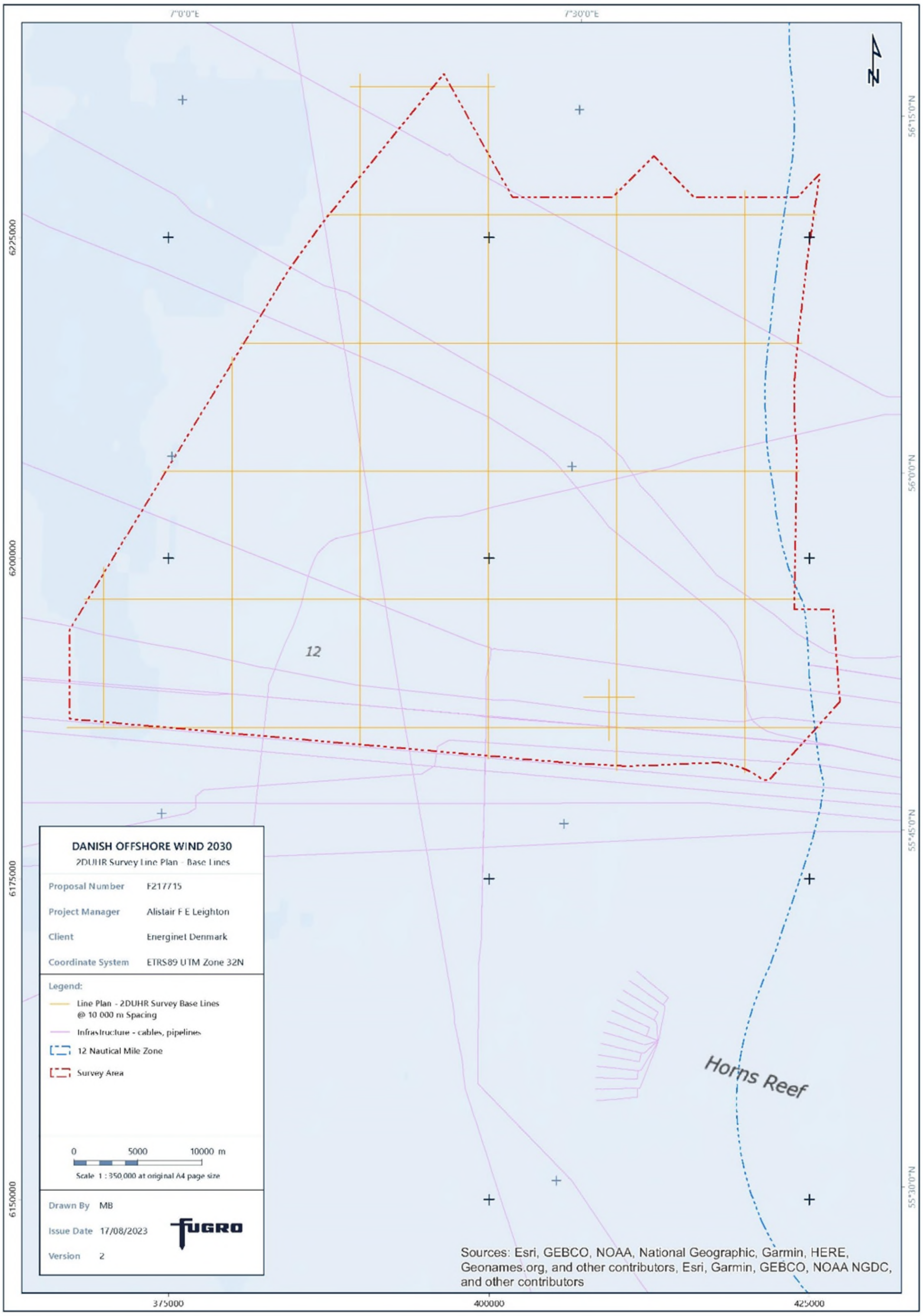

Figure 2.1: Overview of survey base lines

2.1.1 MV Arctic Vessel Details

The MV Arctic (Figure 2.2) is a 51 m vessel that was built in 1986 for the German Hydrographic Service. Being purpose designed for the demanding environments, the MV Arctic has excellent weather capabilities and is an ideal platform for geophysical survey and shallow geotechnical investigations.

Figure 2.2: MV Arctic

The MV Arctic has space for a maximum of 23 persons and is equipped for 24-hour operations. The MV Arctic has a top speed of 10 knots allowing for fast and comfortable transits. Further details of the vessel can be found in MV Arctic Mobilisation & Calibration report.

2.1.2 MV Arctic Instrument Spread

All systems on the vessel were mounted relative to the XYZ reference frame of the vessel. The Y-axis being the fore-aft centre line, the X-axis running perpendicular to the Y-axis through the common reference point (CRP), and the Z axis being positive upwards from the CRP. The online navigation software QPS Qinsy and Starfix.NG use this reference frame to correct vessel nodes for position.

The CRP was defined in the survey navigation software, QPS Qinsy and Starfix.NG, to be the closest to the vessel's Centre of Gravity (COG). The vessel's Centre of Gravity (COG) was defined as the origin of the vessel's survey coordinate system (0,0,0). The COG coordinates were introduced into the vessel's survey coordinate system. The distance offsets, angular offsets and rotations were calculated and Vessel Reference Frame (VRF) derived as part of the vessel dimensional control in October 2021 attached in the MV Arctic Mobilisation & Calibration report.

Vessel offset diagram have been provided in Figure 2.3 and Figure 2.4. All instrument offsets are provided in MV Arctic Mobilisation & Calibration report.

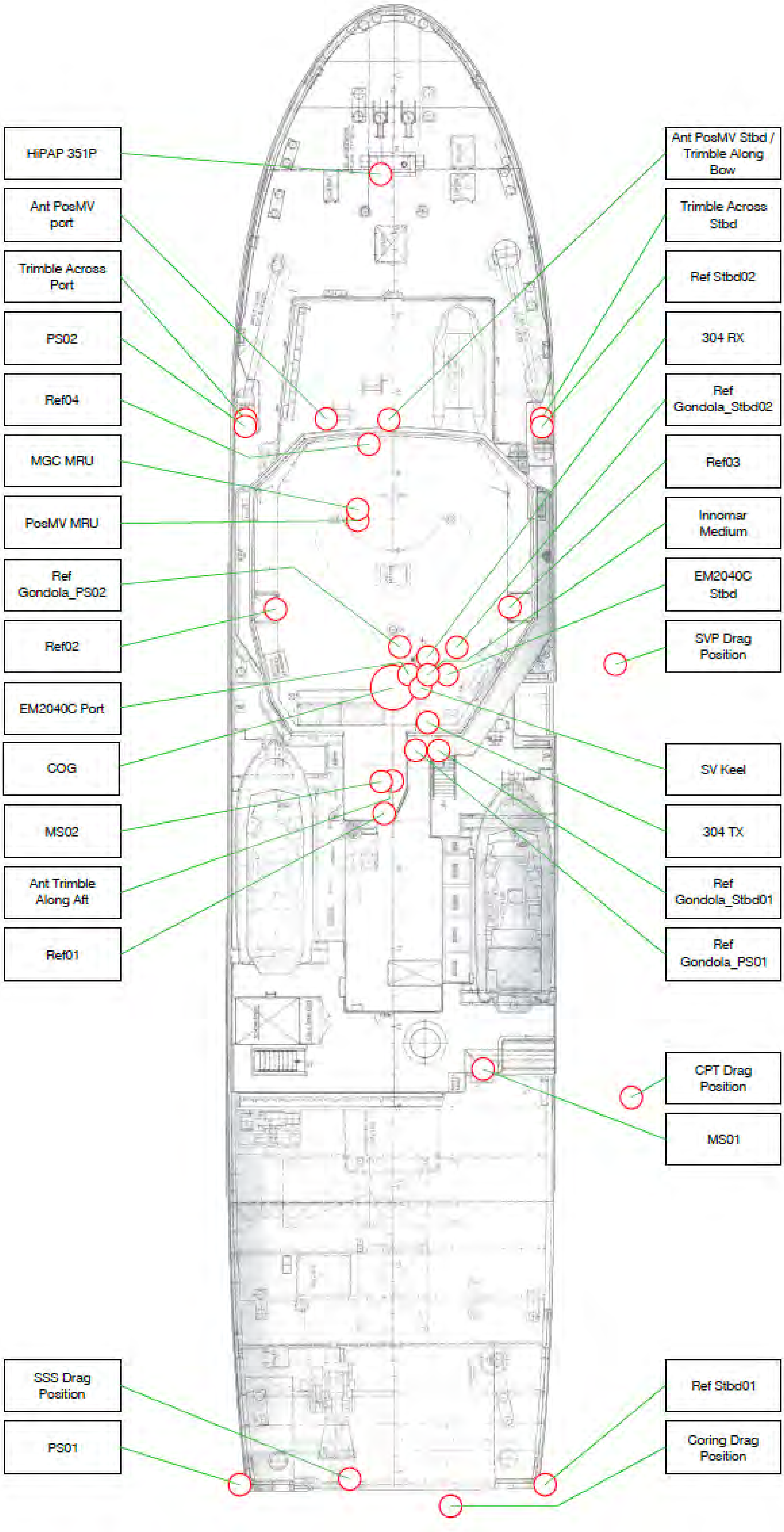

Figure 2.3: MV Arctic offset diagram

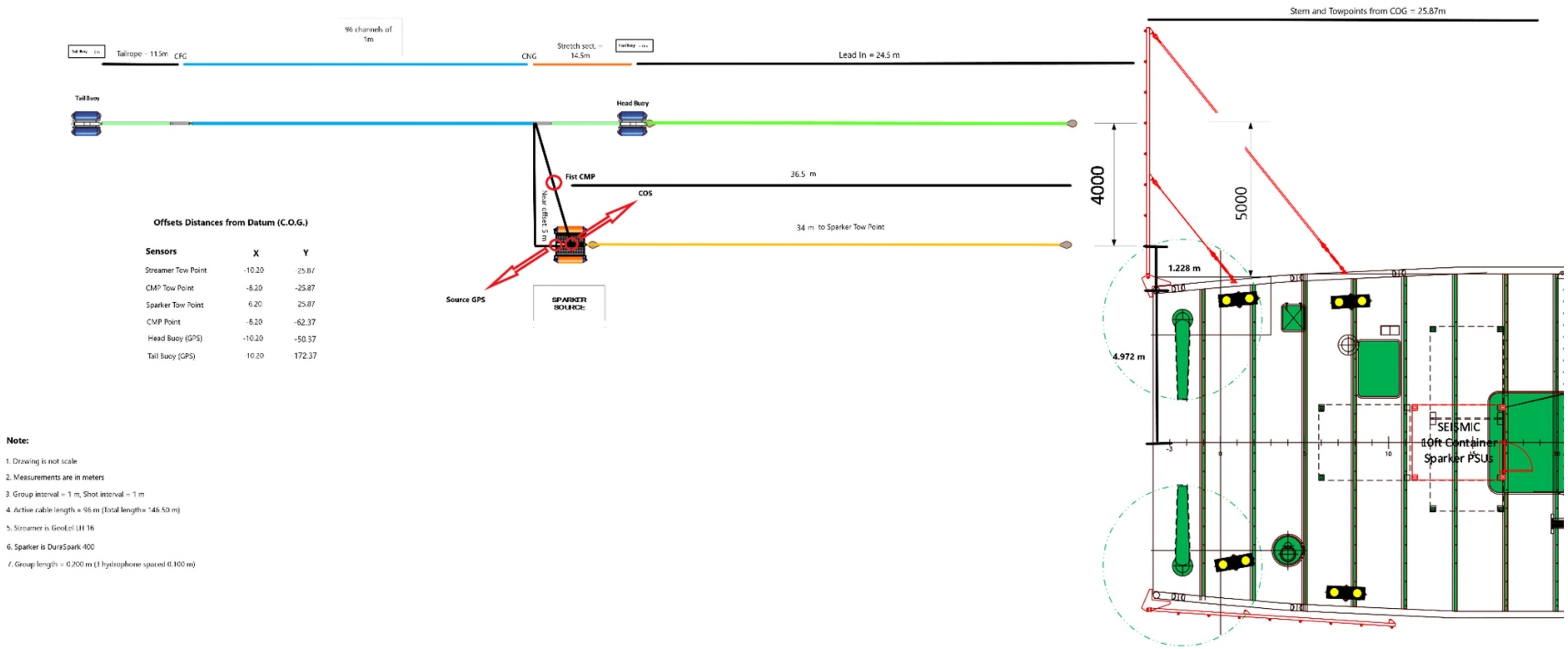

Figure 2.4: MV Arctic 2D UUHR seismic offsets diagram

3. Methodology and Data Quality

3.1 Methodology

The following strategy was applied for SBP and 2D UUHR seismic data interpretation:

- Compiling historical geotechnical, geophysical and geological data from client-provided sources, Fugro database and the public domain;
- Loading SEG-Y files (2D UUHR seismic and SBP data) in HIS Kingdom Suite version 2020, SQL server express version 2014);
- Interpretation of seismically distinct horizons, which forms bases of seismic units in the time-domain;
- Identification and interpretation of key geological features, which can be potential (geo)hazards for offshore infrastructure.

Comments are as follows:

- All horizons were interpreted on the 2D UUHR seismic data. The SBP data was used to guide the 2D UUHR seismic data interpretation in the shallowest part (in depths less than 5 m BSF;
- In the areas where horizons are interpreted to be deeper than the maximum depth of penetration of the seismic data (e.g., H70, H90), the horizon were picked at the base of the available seismic section.
- Time-depth conversion of horizons, grids and geological features interpreted on the 2D UUHR data used the RMS velocities, which were picked as stacking velocities. For more details see the seismic processing report (Appendix A);
- Time-depth conversion of SBP data used the velocity of 1600 m/s;
- Gridding of horizons was performed within IHS Kingdom Suite 2020 with the following settings: 'flex gridding' algorithm with min curvature and midway smoothness; 5 m by 5 m cell size and 25 m extrapolation;
- BSF/BSB horizons were calculated by subtracting the seafloor horizon from the picked horizon;
- Isochore grids were calculated by subtracting the grid of the top of the unit from the grid of the base of the unit.
- In the report text, 'thickness' is used as a synonym to isochore.

3.2 Data Quality

The quality of the SBP and 2D UUHR seismic data was monitored throughout the survey and deemed to be good. The technical requirements of the survey with regards to resolution and penetration were met throughout the survey.

A typical penetration depth of 2D UUHR seismic data was approximately 180 m BSF. Detailed description of the quality of the 2D UUHR seismic data collected during the survey is presented in the seismic processing report in Appendix A.

Comments on the quality of the SBP data are as follows:

- The penetration depth is closely related to the geology and may vary depending on lateral variation in sub-seafloor conditions. Typical penetration depth was approximately 10 m BSF with a maximum of approximately 20 m BSF;
- In relatively dense units composed predominantly of sand (e.g. Units U10, U35, U60 and U90), penetration was limited (Figure 3.1, Figure 3.2);
- In units where the soil conditions are expected to be richer in clay (e.g. Units U20, U30 and U50), penetration was greater (Figure 3.3, Figure 3.4);
- The first interpreted horizon below the seafloor (Horizon H10), which forms the base of Unit U10 (see Section 4.3.2.1) is always within the penetration depth of the SBP data.

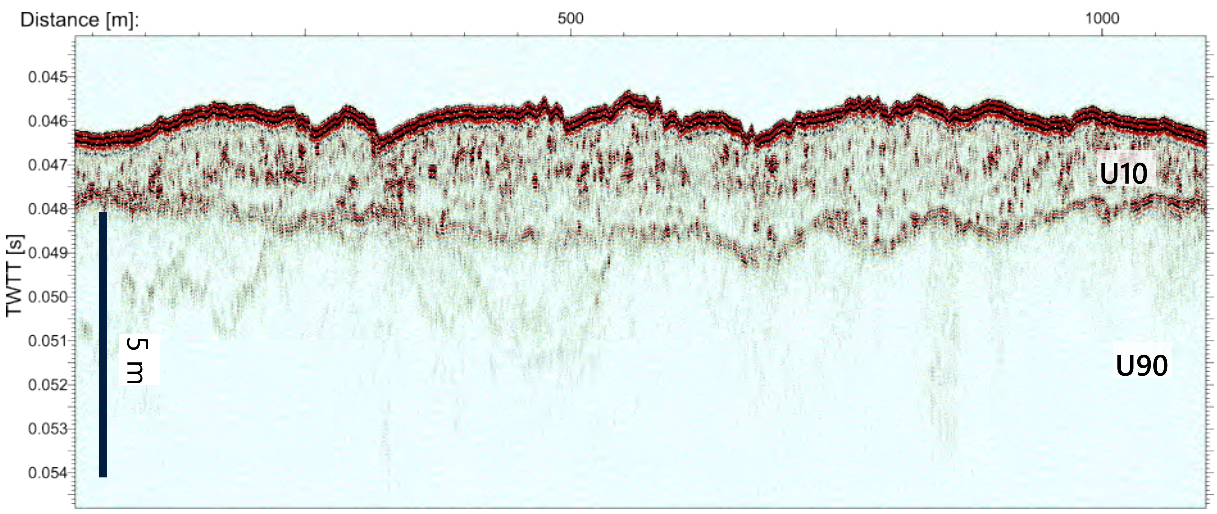

Figure 3.1: Example of SBP data quality where Unit U10 is relatively thin. Line EAAA003P1

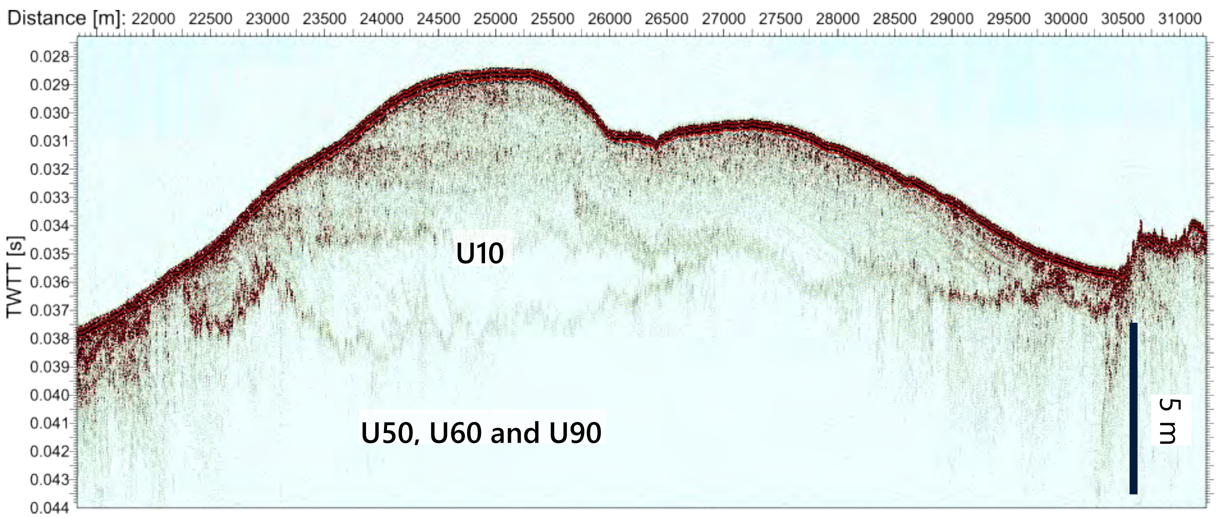

Figure 3.2: Example of SBP data quality where Unit U10 is relatively thick. Line EAAA001P2

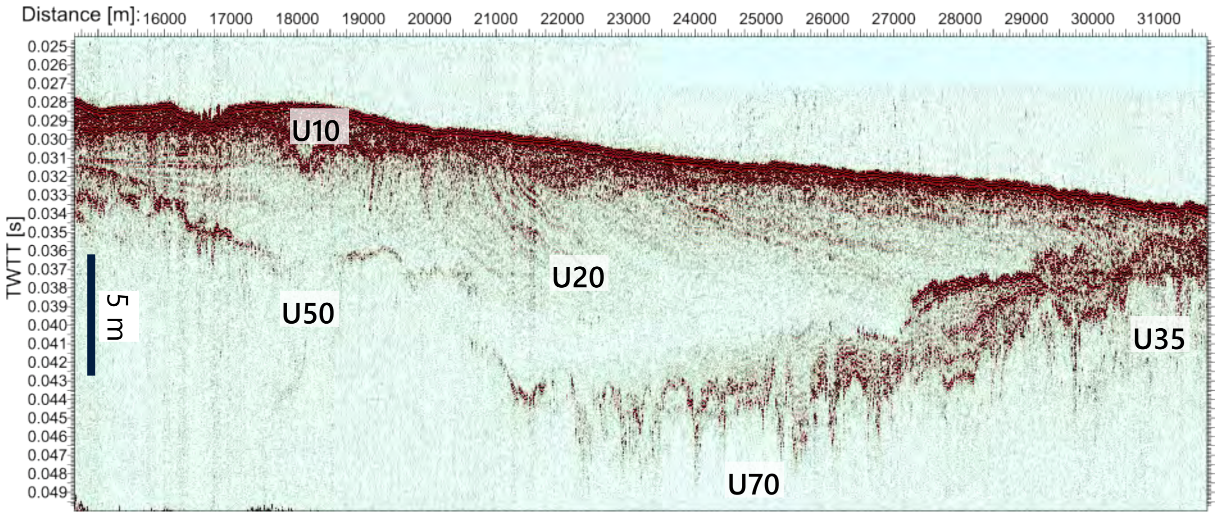

Figure 3.3: Example of SBP data quality where Unit U20 is relatively thick. Line EAAA011P1

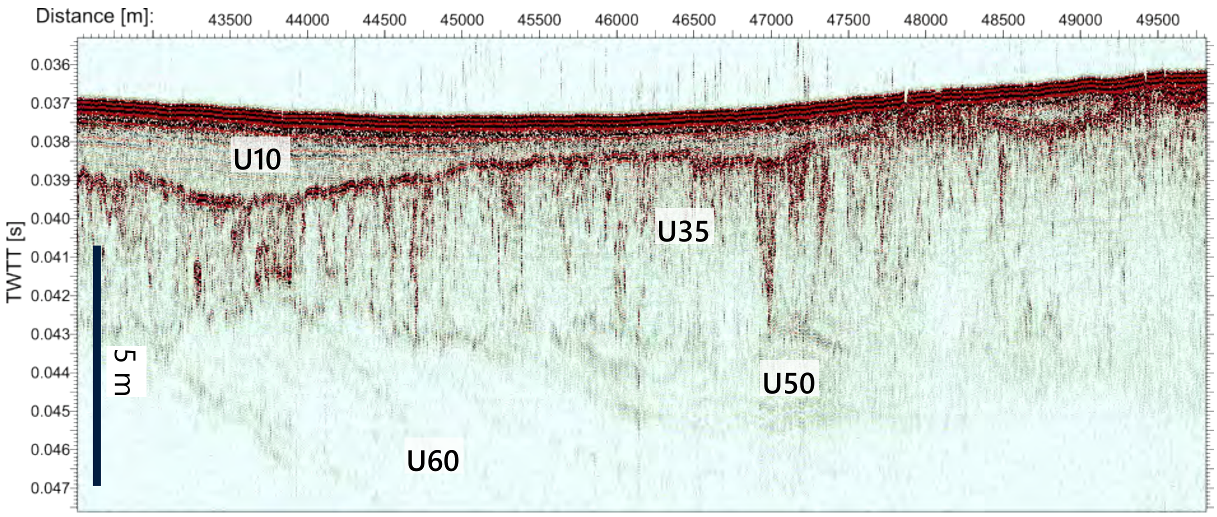

Figure 3.4: Example of SBP data quality with multiple units. Line EAAA003P1

4. Results

4.1 Regional Geological Setting

4.1.1 General

This section presents a summary of the regional geological setting for the study area to provide a spatial and temporal framework for the understanding of the soils, geohazards and location selection for future site work. The site is located in the North Sea, in an area affected by periods of glacial activity during the Quaternary. In addition, within the depth of interest sediments from both the Holocene and pre-Quaternary periods are present. By understanding of the depositional processes and geological history associated, Fugro aims to provide a robust prediction of conditions and variability across the site.

4.1.2 Quaternary Geological Framework

Up to 1000 m of Quaternary deposits, primarily glaciogenic sediments, presently cover the whole of the North Sea, representing the last 2.3 million years of geological time. Generally, Quaternary sediments increase in thickness from the margins of the North Sea towards its centre. The study area is nearer the edge of the North Sea therefore thinner Quaternary sediments may be observed.

The shallow geological profile is dominated by a sequence of Pleistocene (about 2.3 million years to 10,000 years before present (BP)) and Holocene (10,000 years BP to present) sediments, which locally show complex vertical and lateral inter-play. This is primarily attributable to the influence of glacially controlled processes during the Pleistocene glacial intervals, as well as dynamic fluctuations in the type and volume of sediment input during warmer interglacials. Figure 4.1 presents the global sea level curve for the past 550 ka (kilo annum, thousand years ago) with the glacial and interglacial periods annotated.

Based on the location of the study area within the North Sea, the site is expected to have been covered by the two oldest glacial periods, the Elsterian and the Saalian. During the Weichsellian glacial period, ice is anticipated to not have covered the study area, however the site was located in close proximity to the ice sheet therefore is expected to have been heavily influenced by the associated processes. The relative location of all three glacial ice fronts with respect to the study area is presented in Figure 4.2.

Interglacials and intermittent periods of ice retreat were primarily responsible for the accumulation of sediments in the region, due to high concentrations of sediment being deposited by meltwater directly from ice sheets or from rivers. Periods of ice advance were mostly responsible for the removal of sediments by erosion, as well as resulting in direct loading of sediments leading to overconsolidation of clay units. Evidence of erosional episodes ranges from infilled intraformational channels to the incision of large channels which may cross cut units or the entire removal of units causing region-wide unconformities.

Sea levels have varied by up to 120 m over the Pleistocene in the North Sea (Gatliff et al. 1994) and it is expected that the site was sub-aerially exposed which has also added to the complexity of the shallow geology. Channels may also have been incised by terrestrial river systems, and clay deposits may have become desiccated and strengthened where they were subaerially exposed.

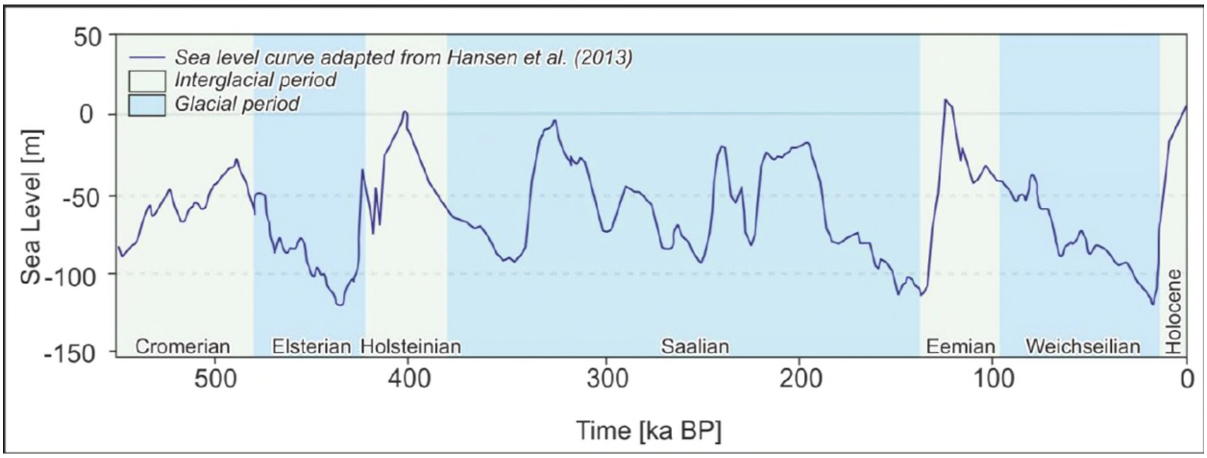

Figure 4.1: Global sea level curve for 550,000 years before present (BP) to present day. Adapted from Hansen et al. (2013) and Cohen and Gibbard (2010). Glacial periods generally correlate with a lowering of mean sea level. All depths referenced against present day sea level (0 m)

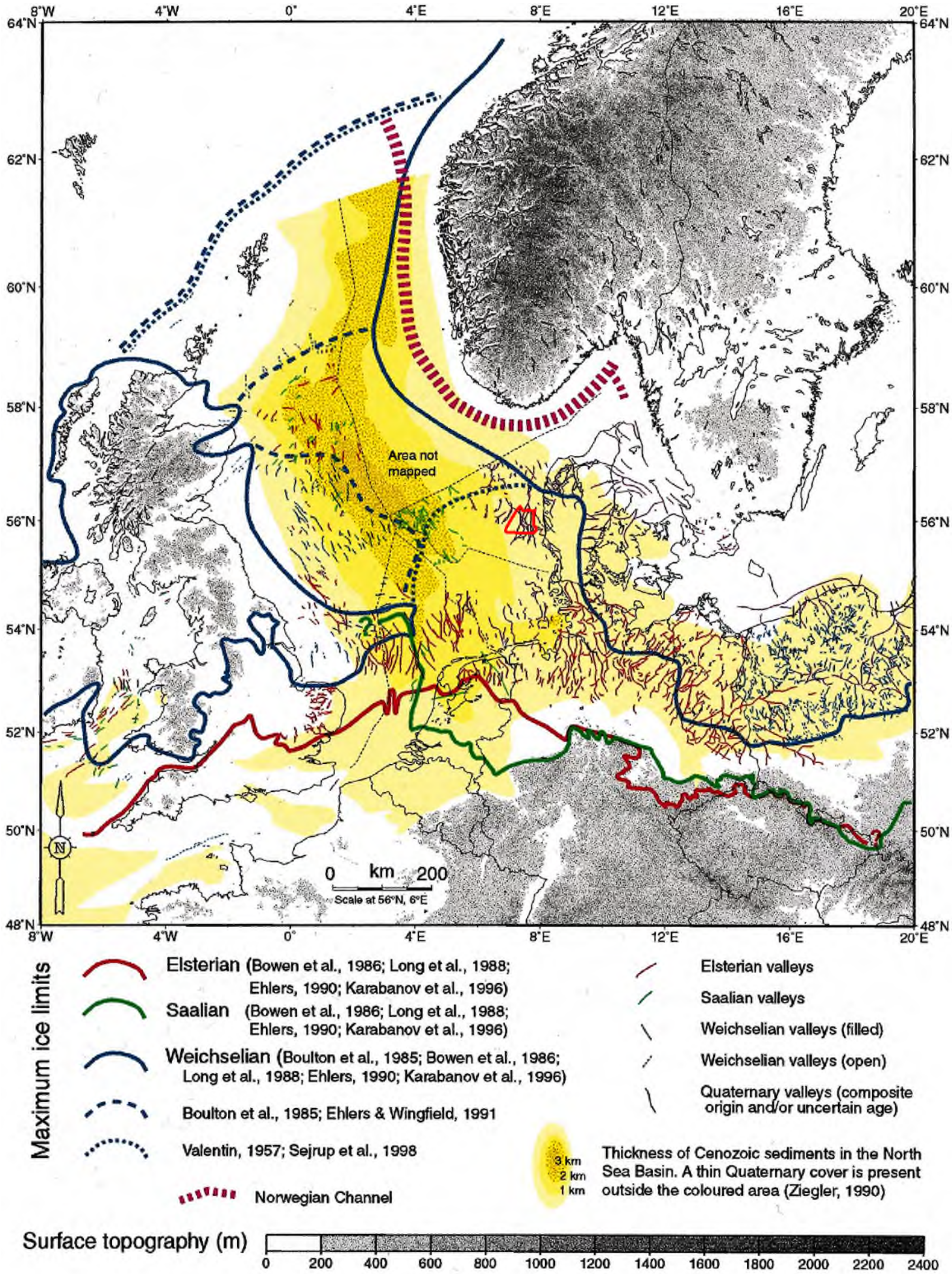

Figure 4.2: Extent of ice sheets and tunnel valleys during glacial periods in the North Sea (after Huuse and Lykke-Andersen, 2000b). The site location is marked in red

4.2 Regional Stratigraphic Framework

4.2.1 Pre-Quaternary

In the Danish sector of the North Sea, pre-Quaternary material varies from Upper Cretaceous chalk to Paleogene. At the site, the depth of the base of the Cenozoic deposits is at approximately 500 m to 750 m below sea level (Knox et al., 2010). The sub-crop below the base of the Cenozoic deposits comprises Upper Cretaceous chalk (Vejbæk et al., 2010). In the region around the study area, sediments sub-cropping the Quaternary are expected to be of Miocene age. EMODnet mapping in the area identifies both Middle and Upper Miocene age sediments. Figure 4.3 presents the location of the lithologies as well as faults mapped in the pre-Quaternary materials.

In the period from Oligocene to late Miocene, the North Sea Basin filled up with deltaic sediments, building out from eroding rivers on the Scandinavian Shield. During the Miocene, marine clays were deposited at the site (Figure 4.4).

The depth to pre-Quaternary sediments within the study area are currently uncertain. To the north of the study area, data from the Thor wind farm suggests that the top of the Pre-Quaternary is at a depth of approximately 50 to 60 m BSB.

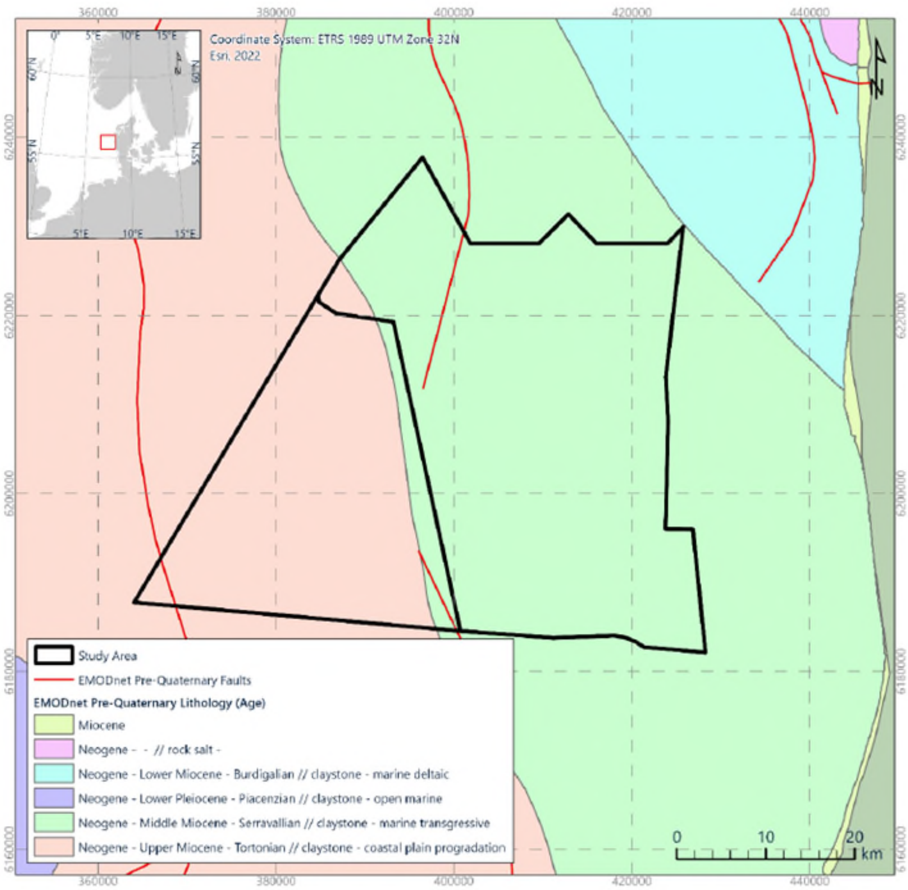

Figure 4.3: Pre-Quaternary geology across the study area (EMODnet, 2023)

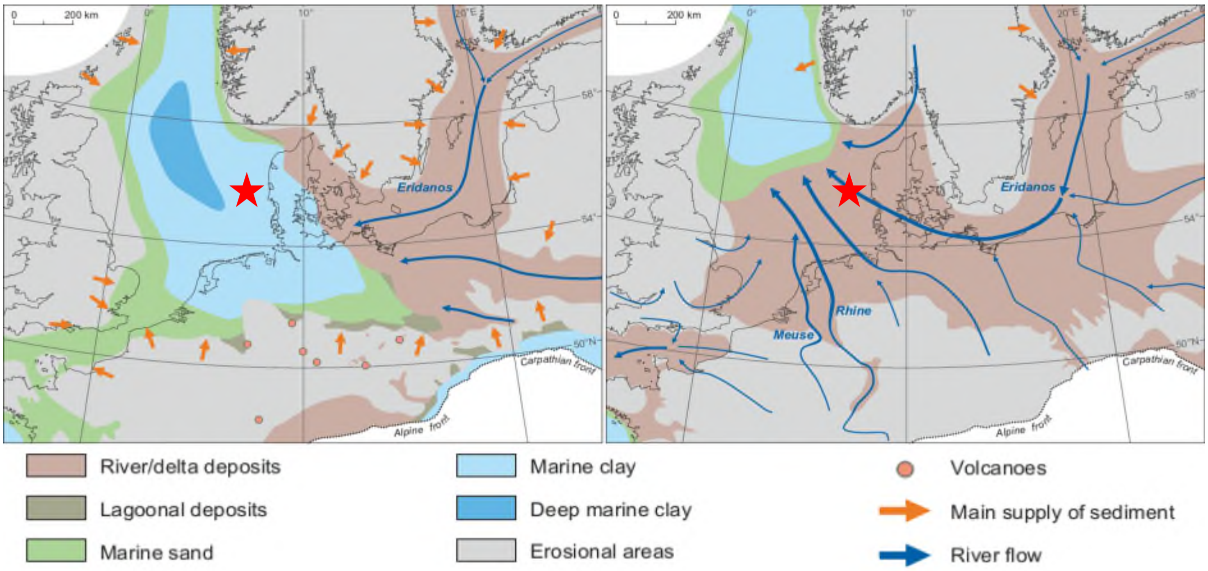

Figure 4.4: Miocene and Early to Middle Pleistocene palaeogeography (after Gibbard and Lewin, 2016). The site location is marked with a red star

4.2.2 Pleistocene

4.2.2.1 Cromerian

During the Early Pleistocene (Cromerian), deltaic deposits filled the North Sea Basin and the coastline prograded towards the north. Many major north-west European rivers drained into the southern North Sea region including the proto-Thames, Rhine and Elbe Rivers. This resulted in the deposition in a fluvial environment (Figure 4.4).

4.2.2.2 Elsterian

The Elsterian glacial period began approximately 478 ka BP (Cohen and Gibbard, 2010) and was the most extensive glacial period recorded across the region during the Quaternary period. At the climax of the Elsterian, the southern North Sea was entirely covered by ice sheets originating from across north-west Europe (Cameron et al., 1992; Graham et al., 2011). Large subglacial channels known as tunnel valleys were incised into the underlying sediments by hydrostatic water pressure at the height of the Elsterian glacial period (Figure 4.2, Figure 4.5). As the ice sheets began to retreat, the channels were progressively filled with clays, silts and sands which were subsequently overconsolidated by successive glacial stages (Huuse and Lykke-Andersen, 2000b; Kirkham et al., 2021).

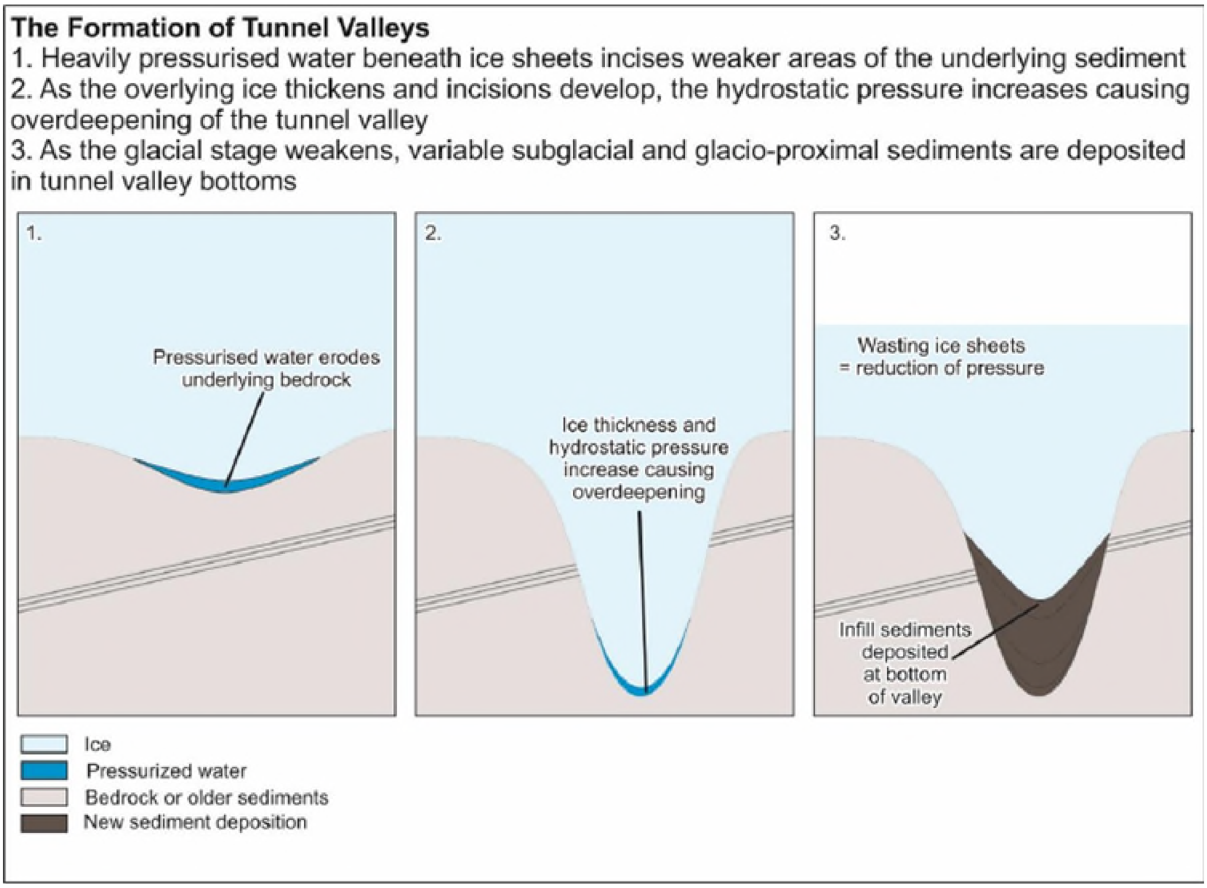

Figure 4.5: Tunnel valley formation

4.2.2.3 Holsteinian

Following the Elsterian, the Holsteinian interglacial was the start of global climate warming and ice sheet collapse. It is interpreted that during the Holsteinian the study area was characterised by a shallow marine environment. Deposition during this time is predicted to be low and any residual channel features would have acted as depocentres for any sediment input to the area. In the Horns Rev area just south of the site, Holsteinian marine clays are present (Jensen et al., 2008). Interglacial conditions prevailed until approximately 380 ka BP, when much of north-west Europe saw a return to glacial conditions during the Saalian.

4.2.2.4 Saalian

The Saalian glacial period lasted for approximately 220 ka and is further refined into multiple stadial and interstadial stages. It is thought that Norway, Denmark and the surrounding regions were covered by a large ice sheet. The maximum ice extent across the North Sea is poorly documented as it has been mostly reworked by subsequent glacial processes during the Weichselian, however, the site is expected to have been fully covered by ice (Figure 4.2).

Sediments throughout the North Sea often show characteristics of having been influenced by glaciotectonism (Huuse and Lykke-Andersen, 2000a; Larsen and Andersen, 2005; Winsemann et al., 2020; Cartelle et al., 2021). Glaciotectonism occurs as a result of the advance of the ice sheet folding previously deposited sediments. The effect of glaciotectonism can be seen in the cohesive sediments as fissures and slickensides. The effect on the geotechnical properties of glaciotectonism will require future assessment for the site.

Thrust fault complexes were mapped in the eastern Danish North Sea (Huuse and Lykke-Andersen, 2000a). Thrusting mainly affected upper Middle Miocene to lower Pleistocene strata. Individual thrust segments are 200–1000 m long and 100–250 m thick with up to 200 m of horizontal displacement. Figure 4.6 presents regional mapping across the Danish North Sea, with area of identified glaciotectonic thrust complexes observed in proximity to the study area.

During the Late Saalian the site was covered by ice sheets which extended to the south. During this time, another set of tunnel valley features were formed below the ice sheet as a result of hydrostatic water pressure (Figure 4.2). Retreat of the ice sheet led to the formation of glaciolacustrine and glaciofluvial conditions and the deposition of clay and sand. The sediments of this period are likely to be variable as a result of sporadic glacial input through minor melting events.

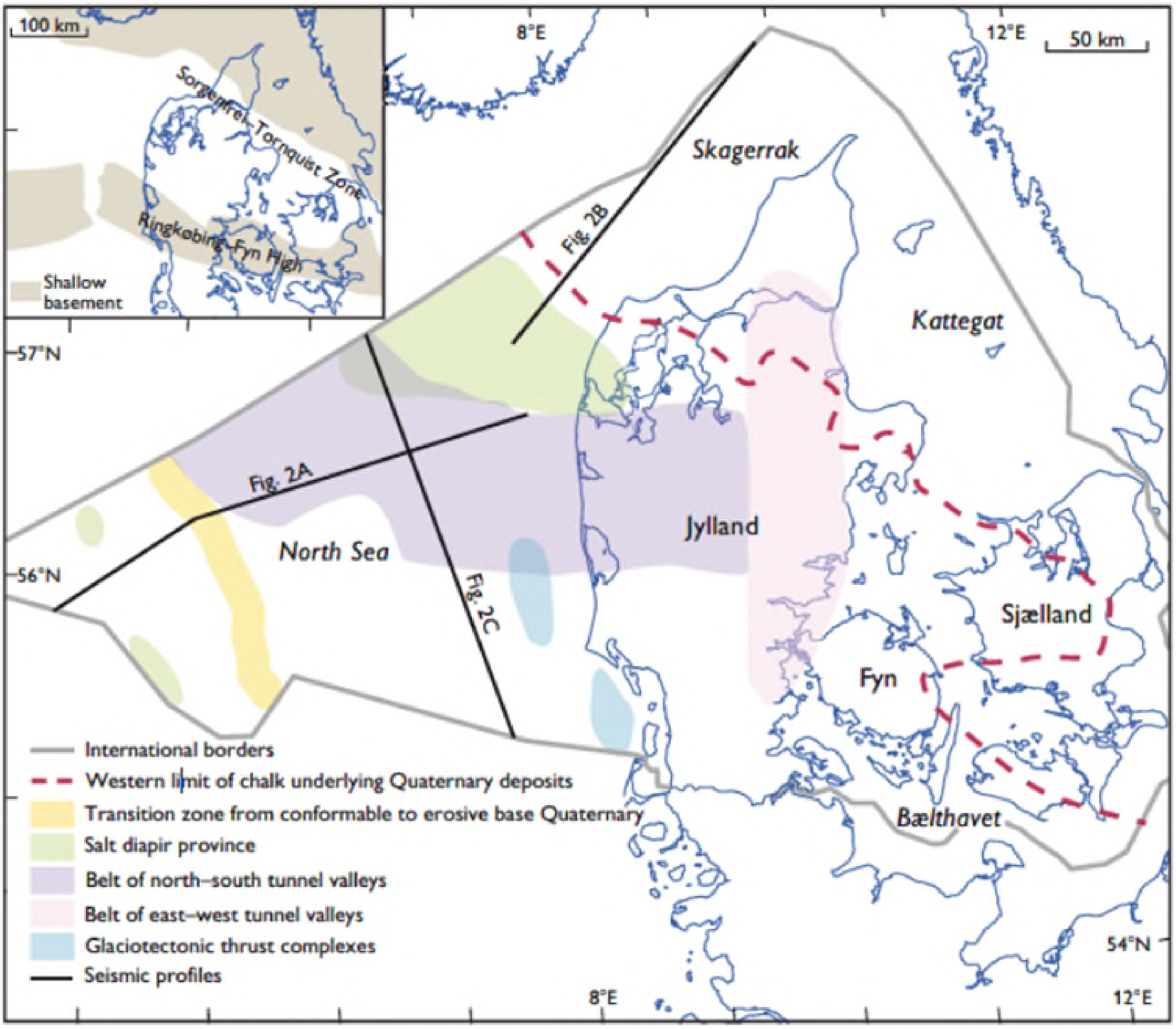

Figure 4.6: Map of Danish North Sea showing regional morphological features (after Nielsen et al. 2008)

4.2.2.5 Eemian and Weichselian

During the Eemian interglacial and subsequent Weichselian glacial period, sea-level variations led to the deposition of variable marine sediments (Eemian) followed by glaciolacustrine and glaciofluvial sediments during the early Weichselian as the site was likely sub-aerially exposed. Unlike the previous glacial periods, ice is not expected to have extended over the study area during the Weichselian glaciation (Figure 4.2). As a result, sediments from the Eemian are not expected to have been as overconsolidated as the preceding Quaternary lithologies. Given the water depths in the area it is possible that the area was terrestrial with braided river systems at the front of the ice margins. Subsequent to this, as sea levels continued to rise the terrestrial environment transitioned to coastal prior to complete flooding at the start of the Holocene. Figure 4.7 presents the process associated with this as described across the Danish North Sea.

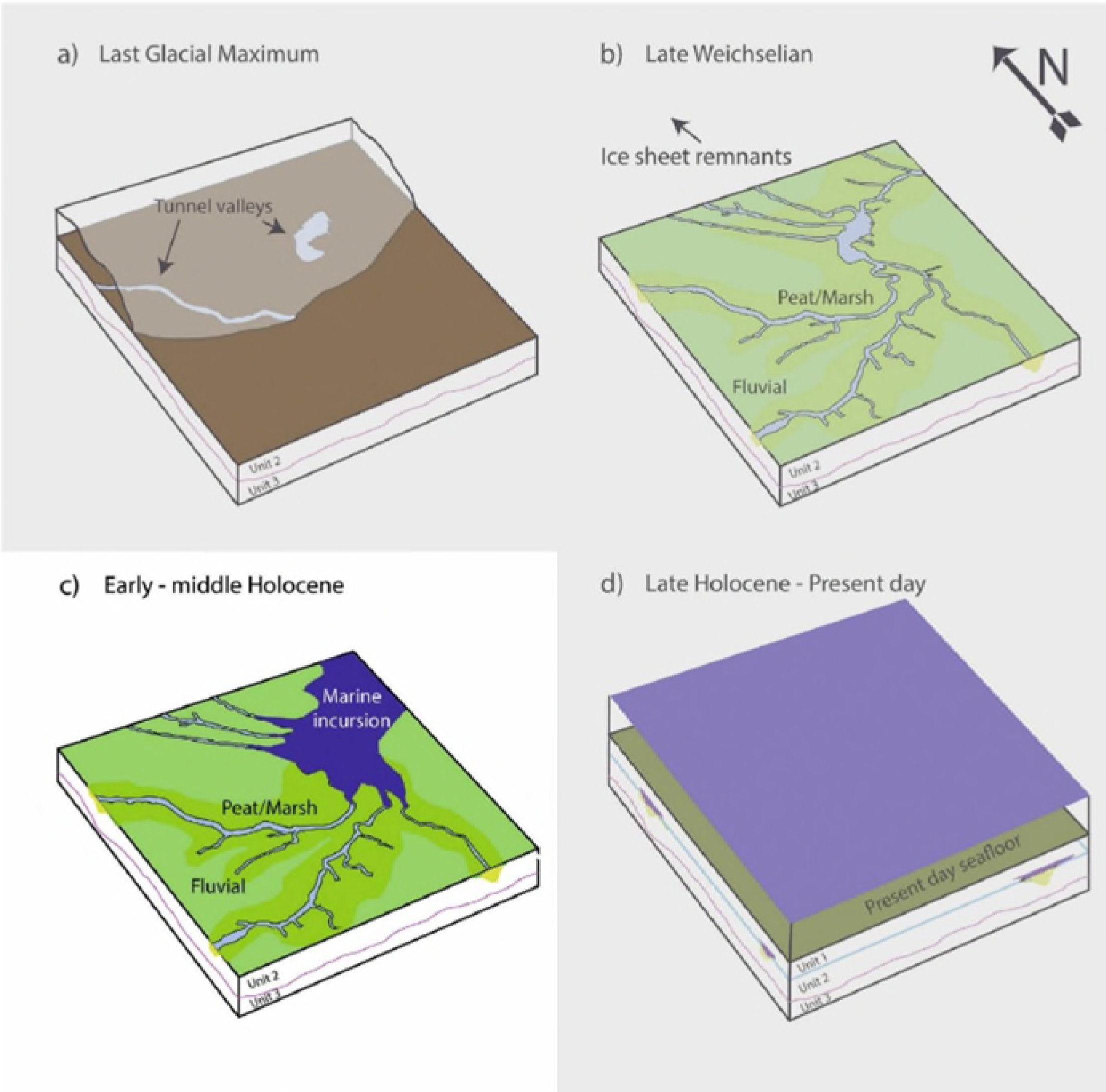

Figure 4.7: Depositional environment associated with study area during the early to middle Holocene (after Prins and Andersen, 2019)

4.2.3 Holocene

Holocene sediments are expected to be present across the study area. The study area has been affected by the marine transgression that took place after the Last Glacial Maximum (LGM). Figure 4.8 presents a sea level curve for the North Sea (Streif, 2004). The North Sea overall is very similar to the global relative sea level evolution with changes in transgression rates linked to isostatic rebound, dry-land flooding and English Channel opening.

Based on the range of water depths seen at the site a majority of the site is expected to have been sub-aerially exposed during the early and middle Holocene between approximately 8500 and 7000 years BP. As a result, Holocene sediments are likely variable with early Holocene material deposited in fluvial and lacustrine environments, with possible presence of peat. Late Holocene sediments are likely deposited in a marine setting, in shallow water conditions, leading to sand dominated sediments (Leth, 1996).

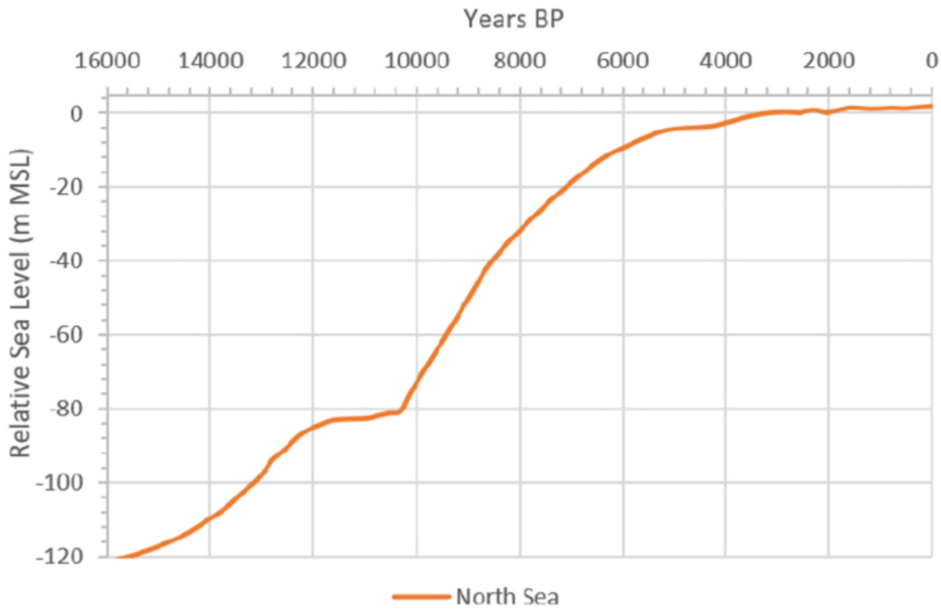

Figure 4.8: Evolution of relative sea level for the North Sea since the LGM (after Streif, 2004)

4.3 Sub-Seafloor Geology

4.3.1 Overview

Table 4.1 and Figure 4.9 provide an overview of the interpreted horizons and seismostratigraphic units.

Nine horizons have been interpreted, which delineate the base of nine seismostratigraphic units. One horizon is interpreted as an internal horizon within a seismostratigraphic unit.

Depositional environment and age are interpreted based on the character of the seismic facies and available literature for the Danish sector of the North Sea.

Table 4.1: Overview of the interpreted horizons and seismostratigraphic units

Unit	Horizon [Colour*]		Seismic Character	Expected Lithology[†]	Depositional Environment	Age	Stress History[‡]
	Base	Internal					
U10	H10 [LightYellow]		Acoustically transparent with point reflectors	SAND with shells and shell fragments	Marine	Holocene	A
U20	H20 [Orange]		Stratified to acoustically transparent; locally forms channel infill	Interbedded SAND and CLAY	Fluvial to estuarine	Late Weichselian to early Holocene	A
U30	H30 [DeepSkyBlue]		Well stratified	CLAY	(Glacio-)marine to (glacio-)lacustrine	Eemian and/or Weichselian	B
U35	H35 [LightOrchid]		Acoustically complex with locally internal erosion surfaces and high amplitude positive internal reflectors; locally forms channel infill	Silty SAND, locally gravelly and with gravel beds	Glaciofluvial	Late Saalian or early Weichselian	B
U50	H50 [Blue]		Acoustically transparent; locally forms channel infill	CLAY	Marine	Holsteinian	C
U60	H65 [VioletRed]		Acoustically complex with internal erosion surfaces and high amplitude positive internal reflectors; locally forms channel infill	Silty SAND, locally gravelly and with gravel beds	Glaciofluvial	Late Elsterian	C
U70	H70 [Red]	H69 [DarkGreen]	Well stratified above internal horizon H69, acoustically chaotic at the base. Forms tunnel valley infill	Clayey SAND to very high strength sandy CLAY	Glacial, fluvial, lacustrine and/or marine	Elsterian	C
U90	H90 [DarkMagenta]		Acoustically complex with internal erosion surfaces, horizontal and inclined stratification	Silty SAND, locally with beds of clay and/or peat	Fluvial delta top	Early to Middle Pleistocene	C
BSU	N/A		Well stratified, locally the stratification is less well defined	Very high strength CLAY to SAND	Marine delta front	Miocene	D

Notes
* - Colour nomenclature follows Kingdom project
[†] - Based on comparison with the Horns Rev Offshore Wind Farm (Jensen et al., 2008), Thor Offshore Wind Farm Zone (COWI, 2021) and 3GW Project Area (Fugro, 2023a).
[‡] - A: Normally consolidated; B: Possibly overconsolidated as a result of subaerial exposure; C: Overconsolidated as a result of glacial loading; D: Pre-Quaternary, therefore possibly lithified.

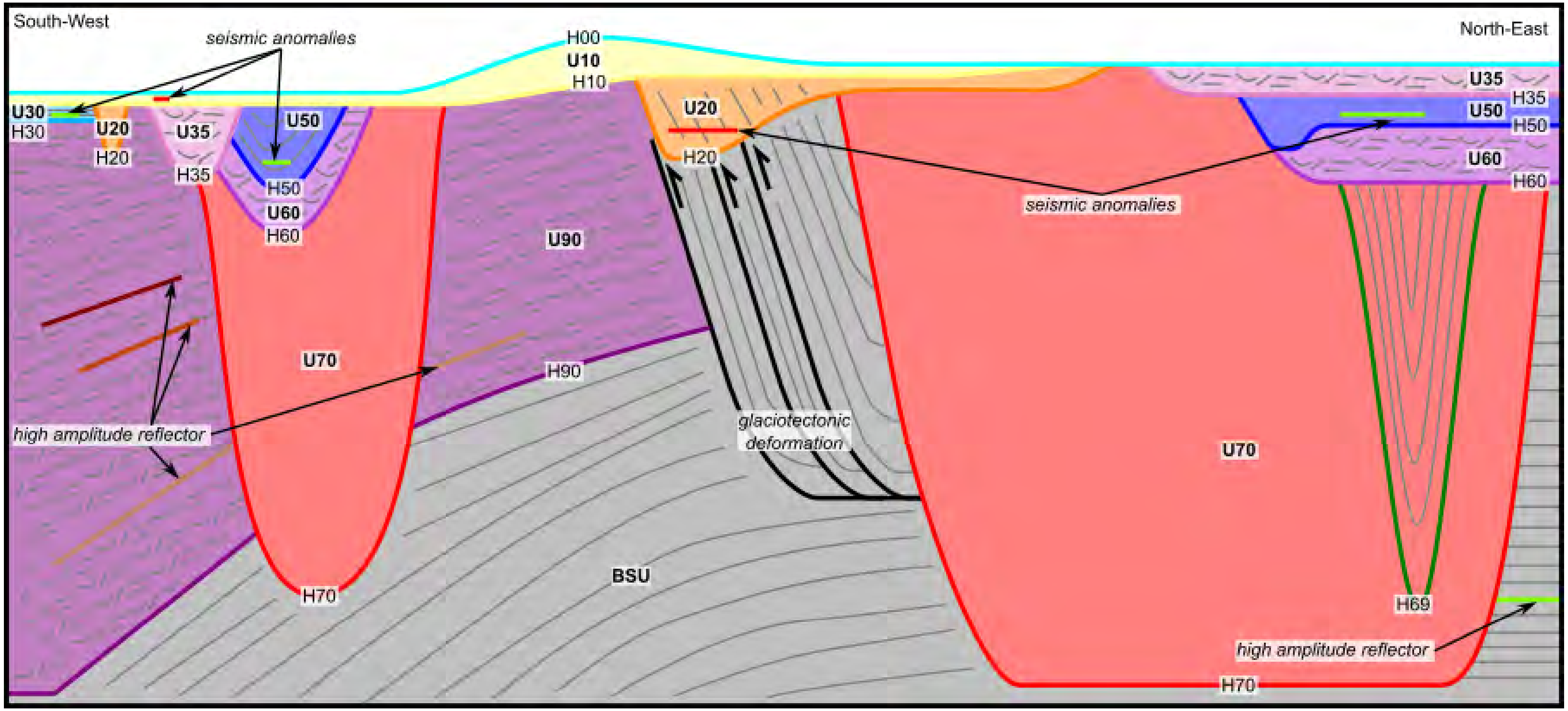

Figure 4.9: Schematic overview of the interpreted horizons and units in the top 200 m of the sub-seafloor

4.3.2 Seismostratigraphic Units

4.3.2.1 Unit U10

Unit U10 is present across almost the entire site (Figure 4.10, Figure 4.11). It is locally absent, most notably in the east of the site. Unit U10 is generally less than 3 m thick (Figure 4.11, Figure 4.12),locally is thicker, reaching a maximum thickness of 8 m (Figure 4.11, Figure 4.13).

The basal horizon H10 is flat to undulating and generally a medium to high amplitude positive reflector. The basal horizon H10 has been interpreted on the 2D UUHR dataset. When the gridded horizon H10 is plotted on the SBP data, there is a very good match with a reflector observed in the SBP data (Figure 4.12, Figure 4.13).

In the area where Unit U10 is relatively thin, i.e., less than approximately 3 m, its internal seismic character is acoustically transparent on the 2D UUHR data and acoustically transparent to chaotic on the SBP data (Figure 4.12).

Where Unit U10 is relatively thick, the internal acoustic character is more variable, from acoustically transparent to acoustically chaotic and discontinuous internal reflectors are present (Figure 4.13).

It is interpreted that the unit represents Holocene marine sediments, which were deposited in the late stages of- and after the Holocene transgression.

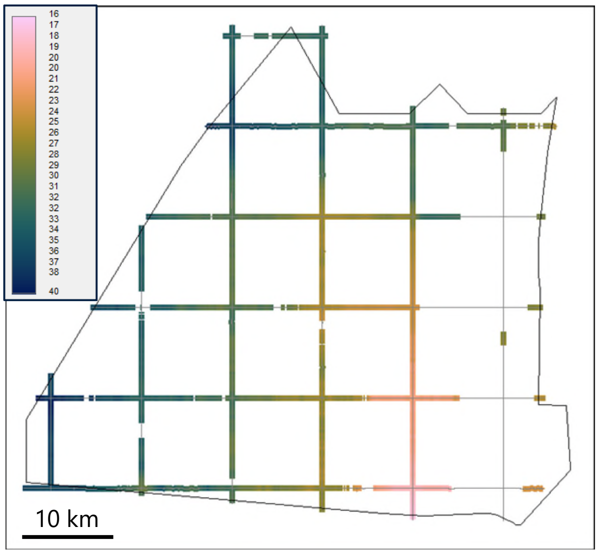

Figure 4.10: Depth to horizon H10 (base of Unit U10) relative to MSL

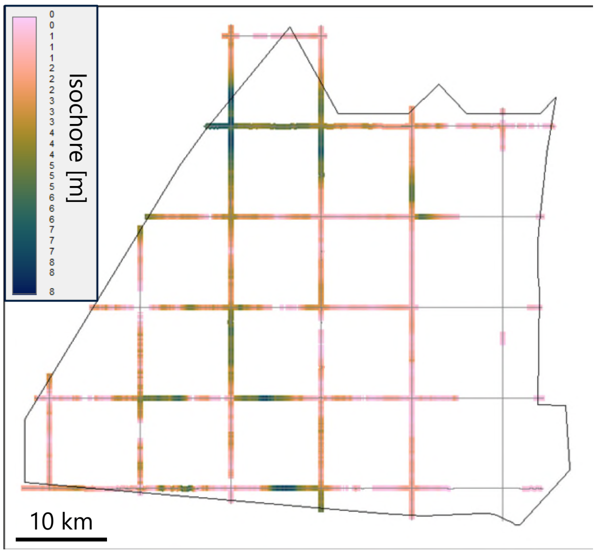

Figure 4.11: Isochore map of Unit U10

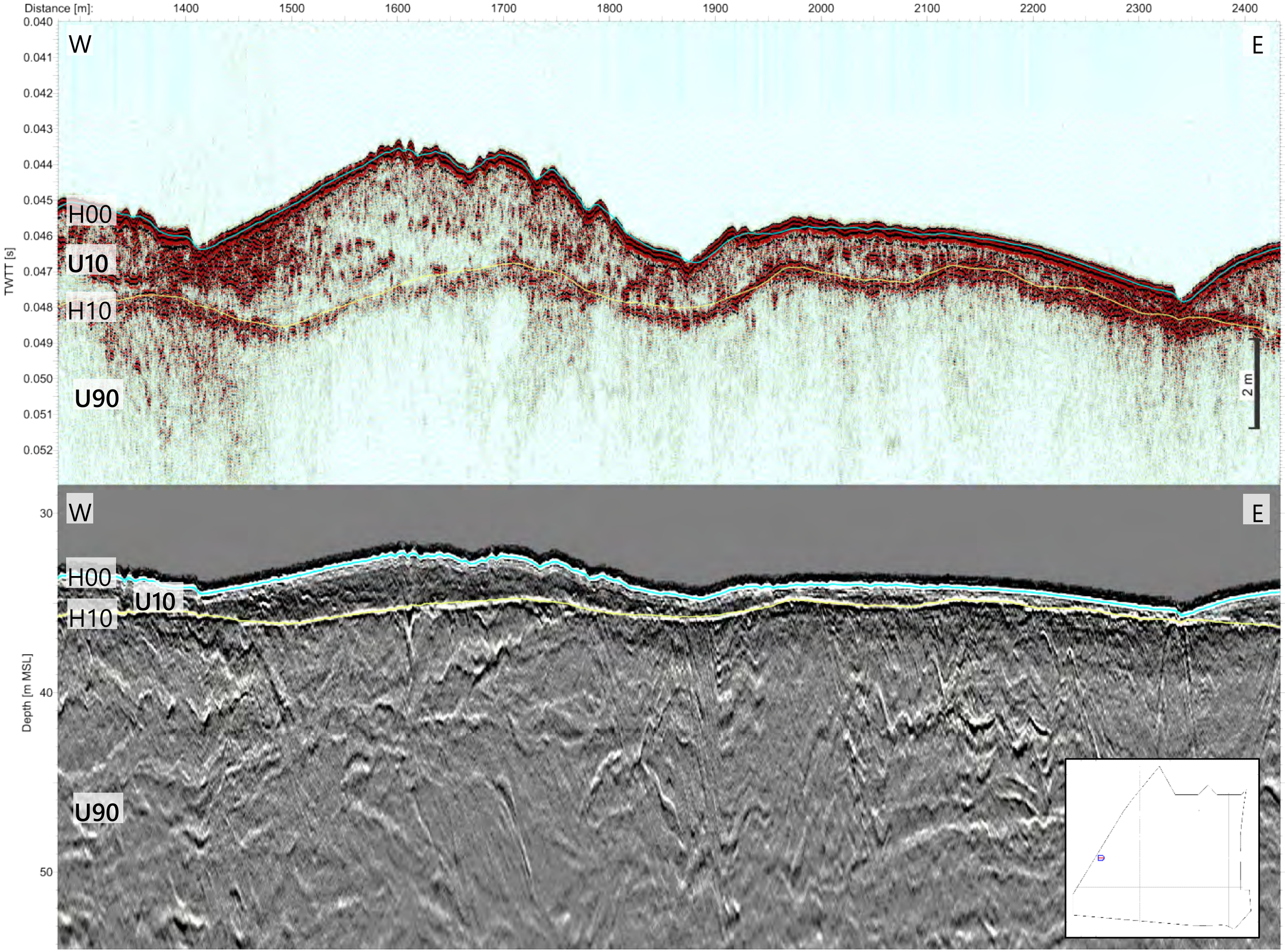

Figure 4.12: SBP (top) and 2D UUHR (bottom) seismic data examples of Unit U10 where it is relatively thin. Line EAAA003P1

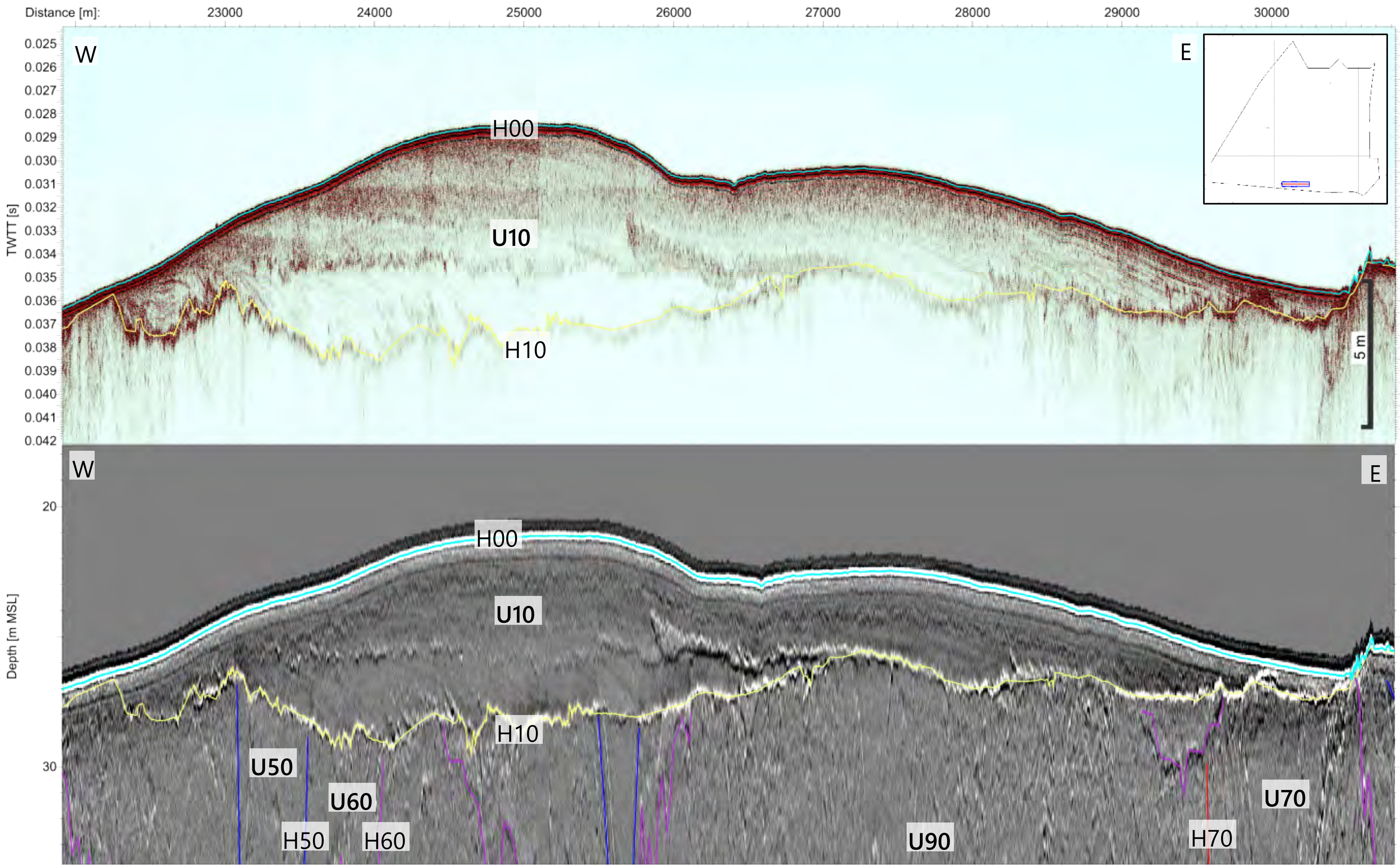

Figure 4.13: SBP (top) and 2D UUHR (bottom) seismic data examples of Unit U10 where it is relatively thick. Line EAAA001P2

4.3.2.2 Unit U20

Unit U20 forms the infill of spatially variable (in depth and size) channels and locally overbank deposits of these channels. The maximum thickness reaches approximately 30 m (Figure 4.14, Figure 4.15). The base of Unit U20 is marked by horizon H20, which is a low to high amplitude positive reflector. Internally, the unit is acoustically transparent or stratified with low to medium amplitude parallel reflectors.

Unit U20 forms two channels (Channel 1 and Channel 2 in Figure 4.14 and Figure 4.15) with a north-west to south-east orientation which join each other into a single channel in the centre of the site. These two channels are up to approximately 15 km wide and 30 m thick (). In the north, a less than 10 m thick and approximately 10 km wide channel (Channel 3 in Figure 4.14 and Figure 4.15) is present with a west to east orientation (Figure 4.17). Elsewhere, Unit U20 comprises narrow (up to 1 km) and shallow (less than 8 m) channels (Figure 4.18).

Unit U20 is not confined to the channels but is also present as a thin (up to 10 m) layer outside of the channels (Figure 4.16).

It is interpreted that the unit was deposited in fluvial and estuarine depositional environments when the site was flooded after the Last Glacial Maximum (LGM) during the late Weichselian to early Holocene (Figure 4.7; Prins and Andresen, 2019). The two wide and deep channels with a north-west to south-east orientation have a similar geometry and seismic character to the Elbe palaeovalley (Özmaral et al., 2022). Therefore, these two channels may be the palaeovalleys of rivers that drained Jutland towards the north-west.

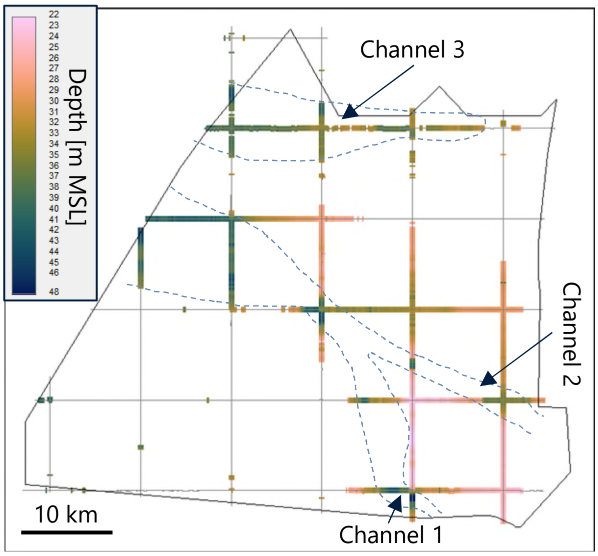

Figure 4.14: Depth to horizon H20 (base of Unit U20) relative to MSL

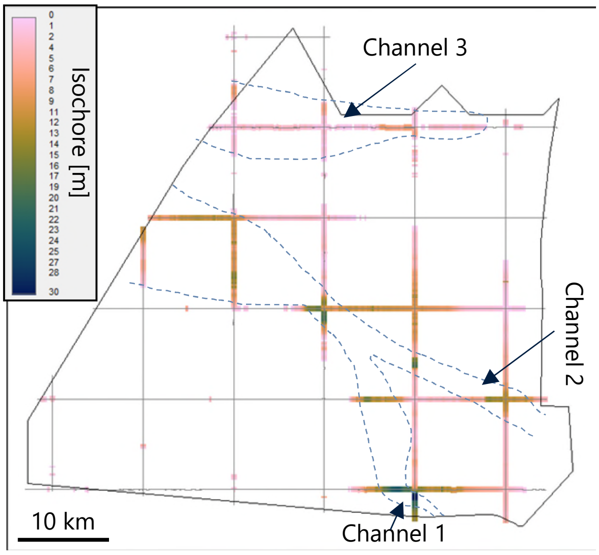

Figure 4.15: Isochore map of Unit U20

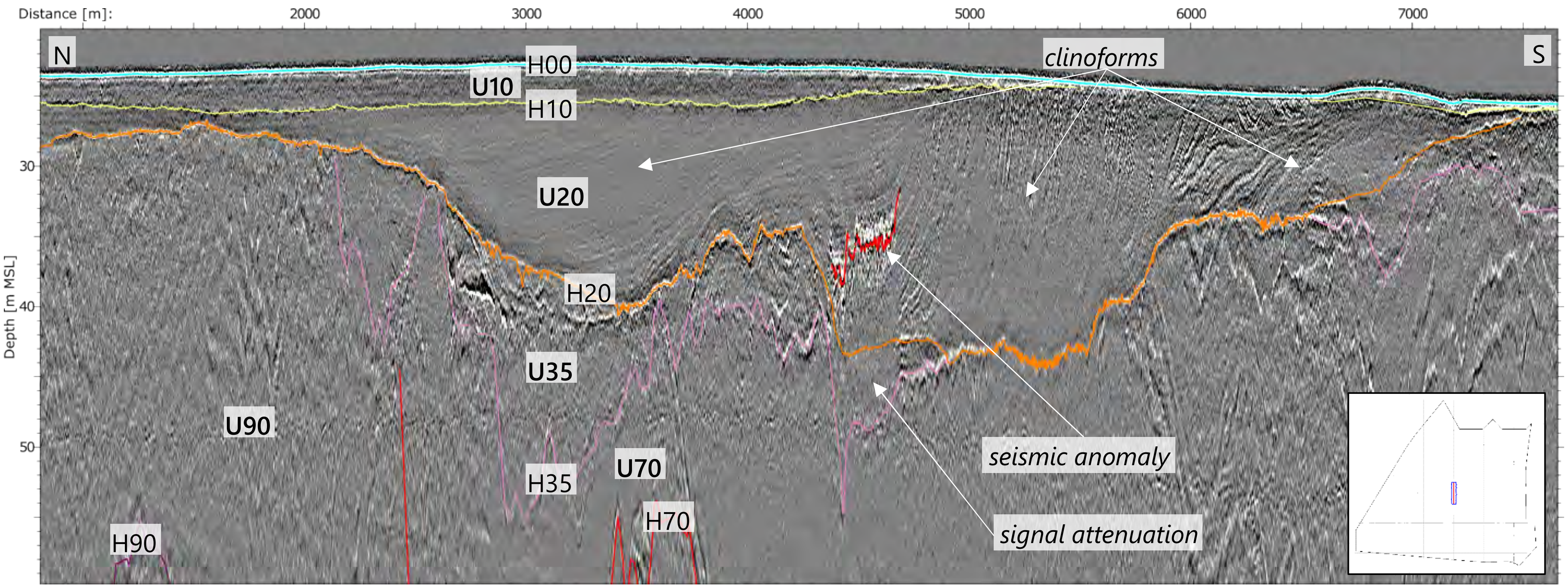

Figure 4.16: 2D UUHR seismic data example showing the wide and deep channel of Unit U20. Line EAAA010P1

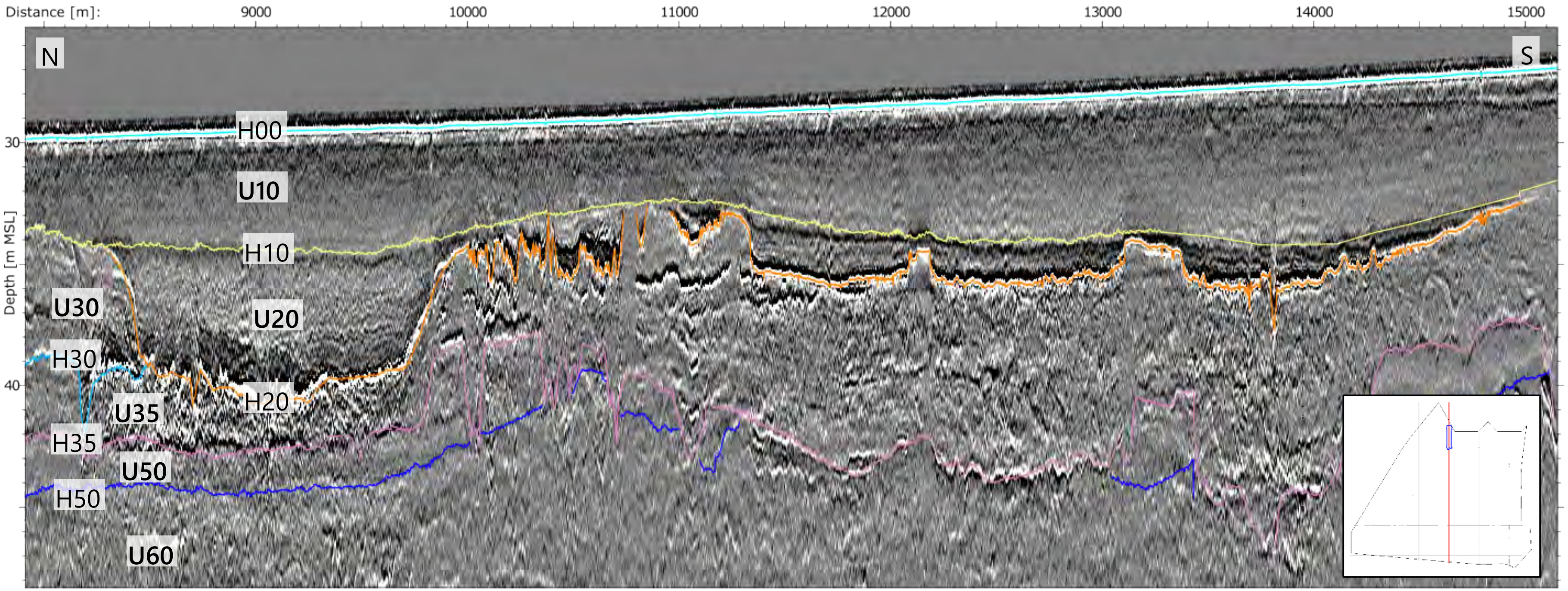

Figure 4.17: 2D UUHR seismic data example showing the Unit U20 channel in the north. Line EAAA010P1

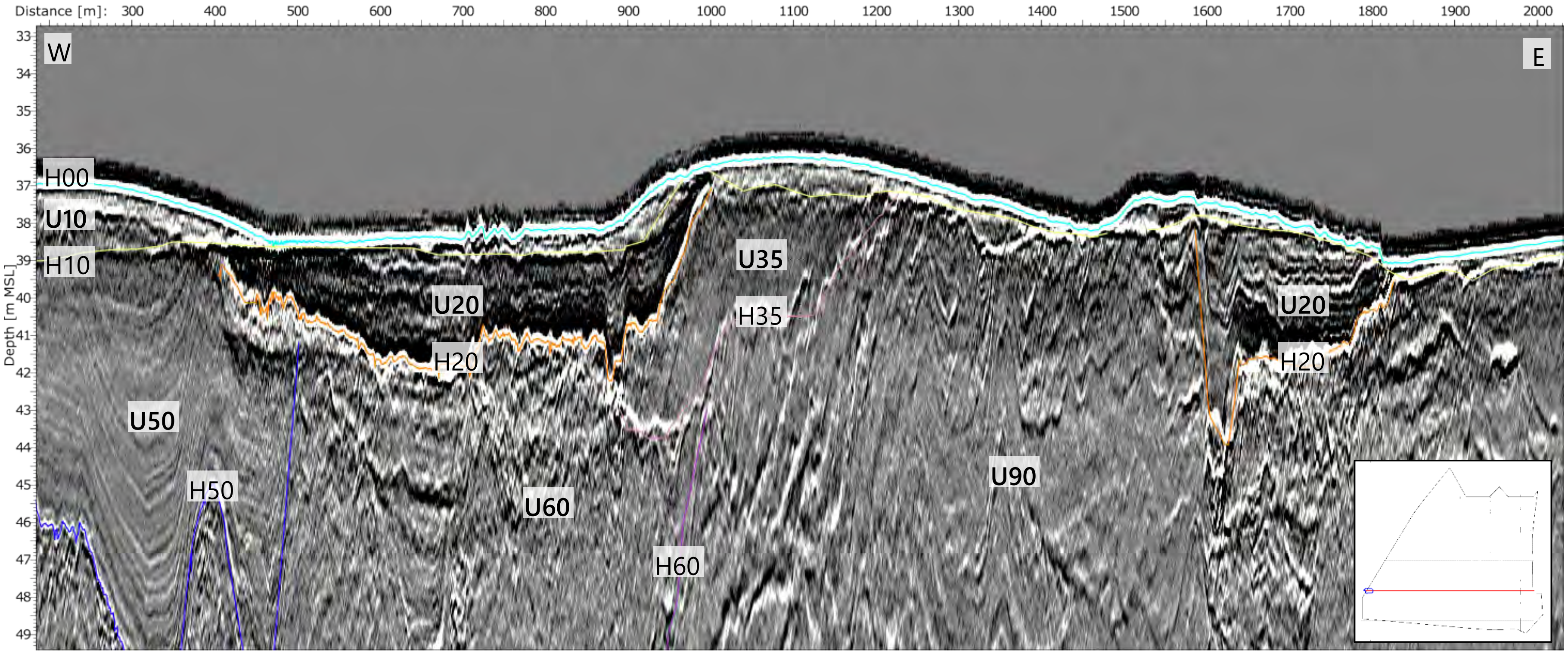

Figure 4.18: 2D UUHR seismic data example of two small Unit U20 channel. Line EAAA002P1

4.3.2.3 Unit U30

Unit U30 is only locally present in small areas in the north-west and south-west of the site and reaches a maximum thickness of 11 m (Figure 4.19, Figure 4.20). The unit has a sheet-like geometry with a horizontal to undulating base. The base is marked by horizon H30, a low to medium amplitude positive reflector.

Internally, the unit is acoustically transparent to locally stratified with medium amplitude parallel reflectors (Figure 4.21, Figure 4.22).

It is interpreted that the stratified part of Unit U30 was deposited in a (glacio-) marine or (glacio-) lacustrine environment (Larsen and Andersen, 2005). The stratigraphic position of this unit between deposits interpreted as Saalian or early Weichselian (Unit U35) and late Weichselian to early Holocene (Unit U20) indicates an Eemian to Weichselian age.

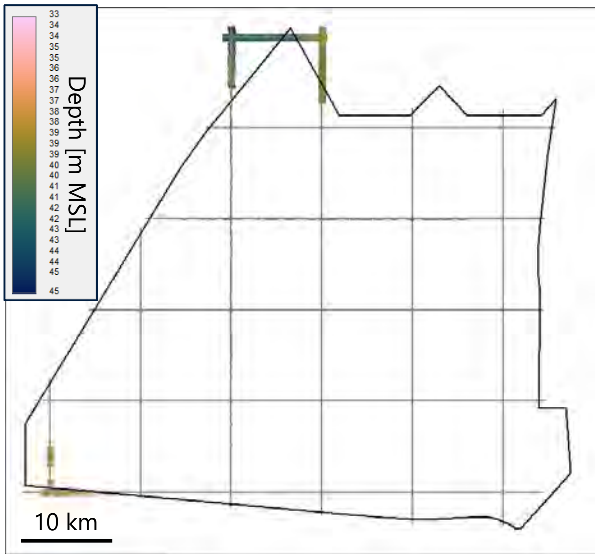

Figure 4.19: Depth to horizon H30 (base of Unit U30) relative to MSL

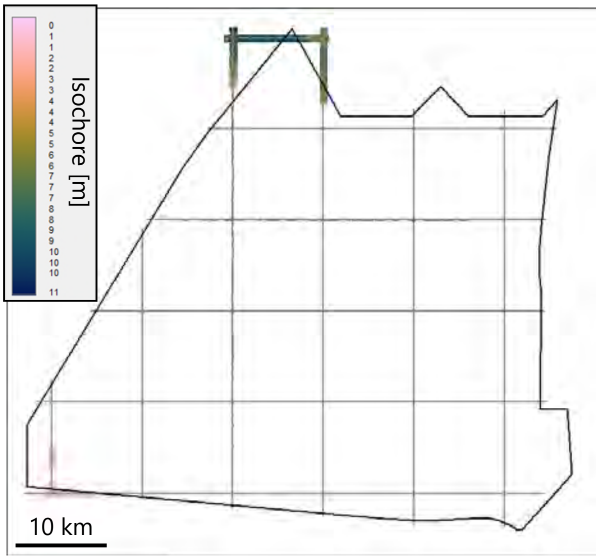

Figure 4.20: Isochore map of Unit U30

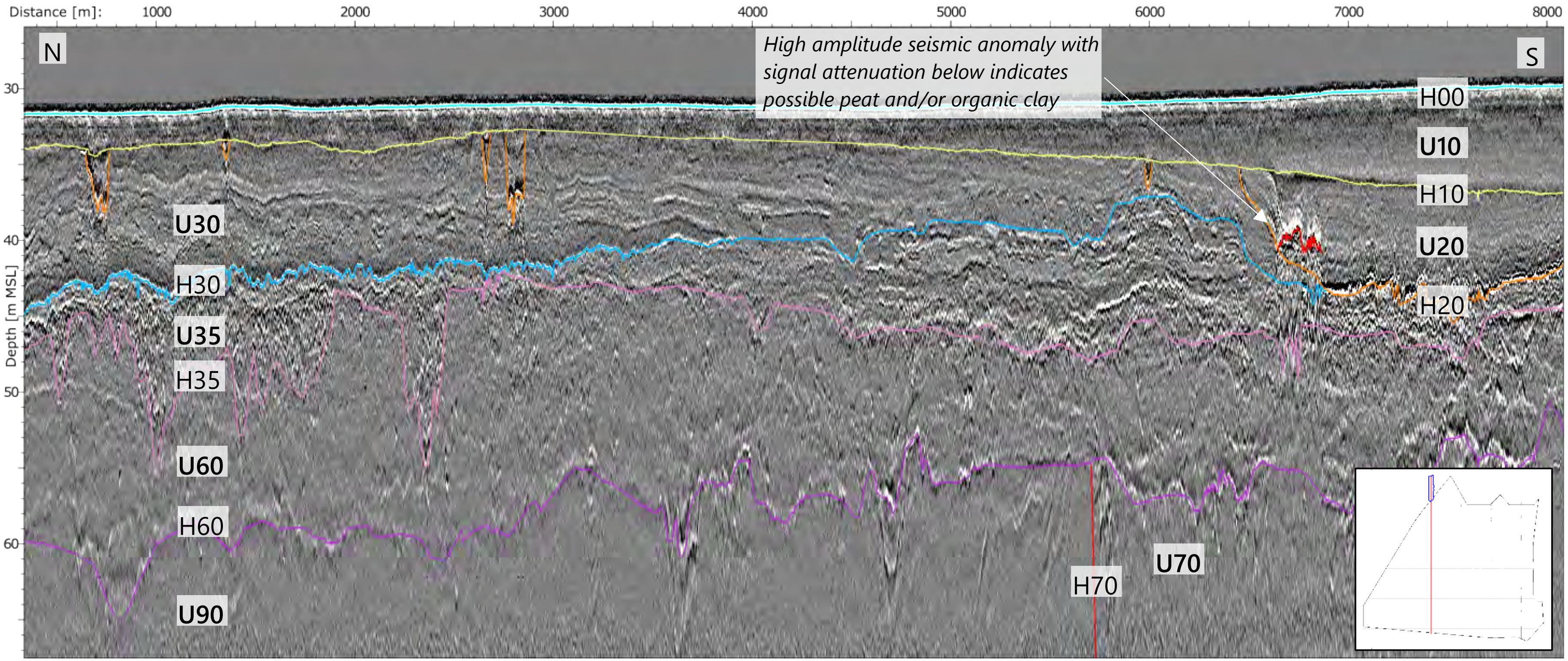

Figure 4.21: 2D UUHR seismic data example of Unit U30 in the north-west. Line EAAA009P1

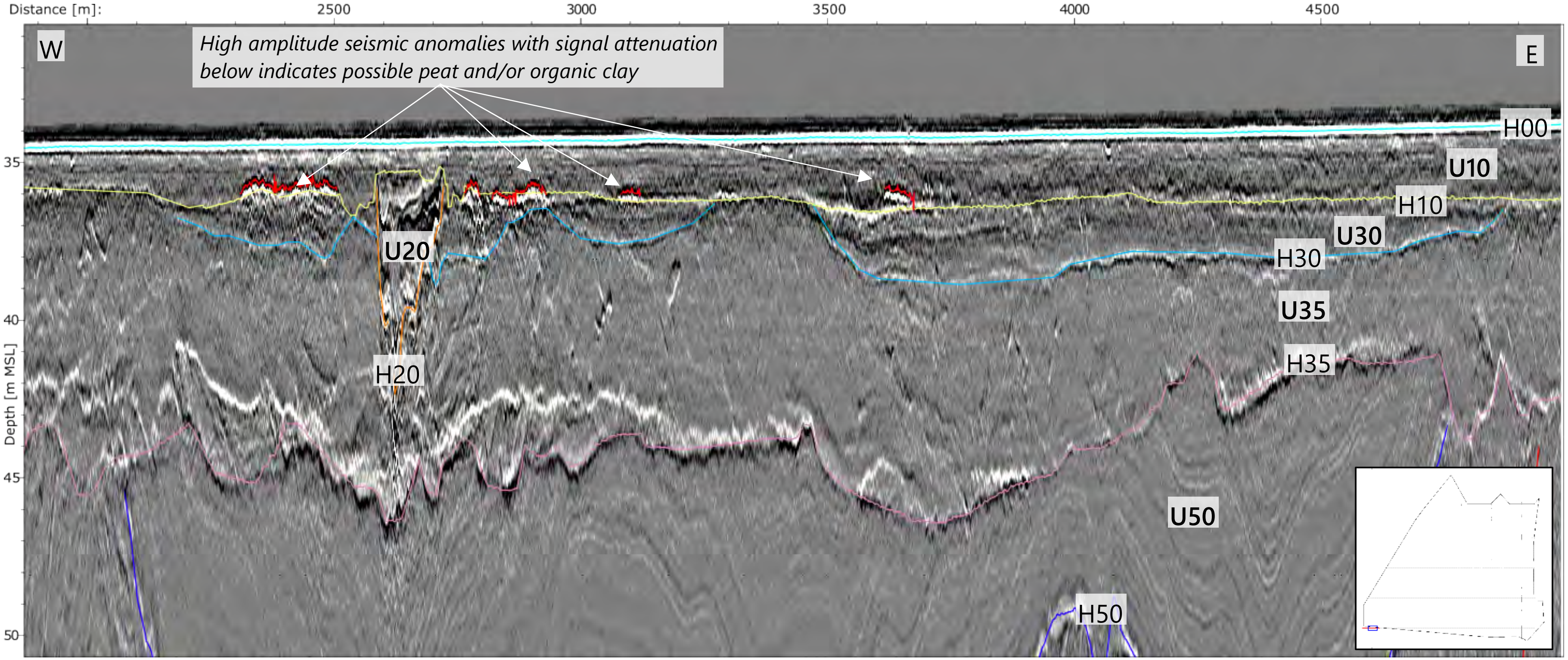

Figure 4.22: 2D UUHR seismic data example of Unit U30 in the south-west. Line EAAA001P1

4.3.2.4 Unit U35

Unit U35 is present in the north and east of the site (Figure 4.23 to Figure 4.25). The unit has a sheet-like to channelised geometry. The basal horizon H35 is flat to undulating and locally has steep erosional margins. The thickness of this unit in this area is typically approximately 5 m. In the west of the site, the unit is only locally present as an infill of channels. The maximum thickness is approximately 24 m (Figure 4.26).

Internally, this unit has a complex seismic character. This includes chaotic seismic facies to horizontal and inclined stratification and internal erosion surfaces. Locally high amplitude positive reflectors are present in the lower part of Unit U35, which may represent gravel beds (see Section 4.3.3.2).

Based on the geometry of this unit, internal erosion surfaces and complex internal seismic character, it is interpreted that this unit was deposited in a braided fluvial depositional environment during a glacial period when sea level was low.

The stratigraphic position of this unit between deposits interpreted as Eemian to Weichselian (Unit U30) and Holsteinian (Unit U50) indicates an Elsterian or early Weichselian age.

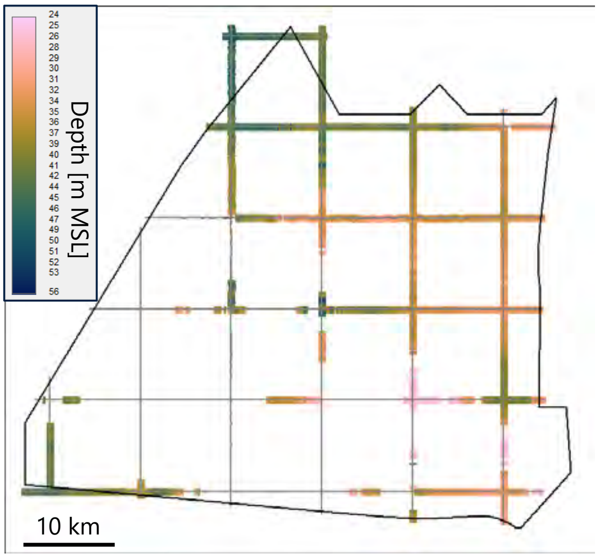

Figure 4.23: Depth to horizon H35 (base of Unit U35) relative to MSL

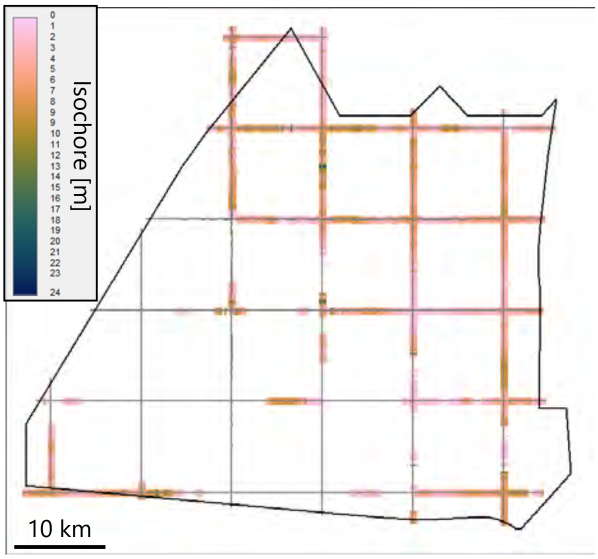

Figure 4.24: Isochore map of Unit U35

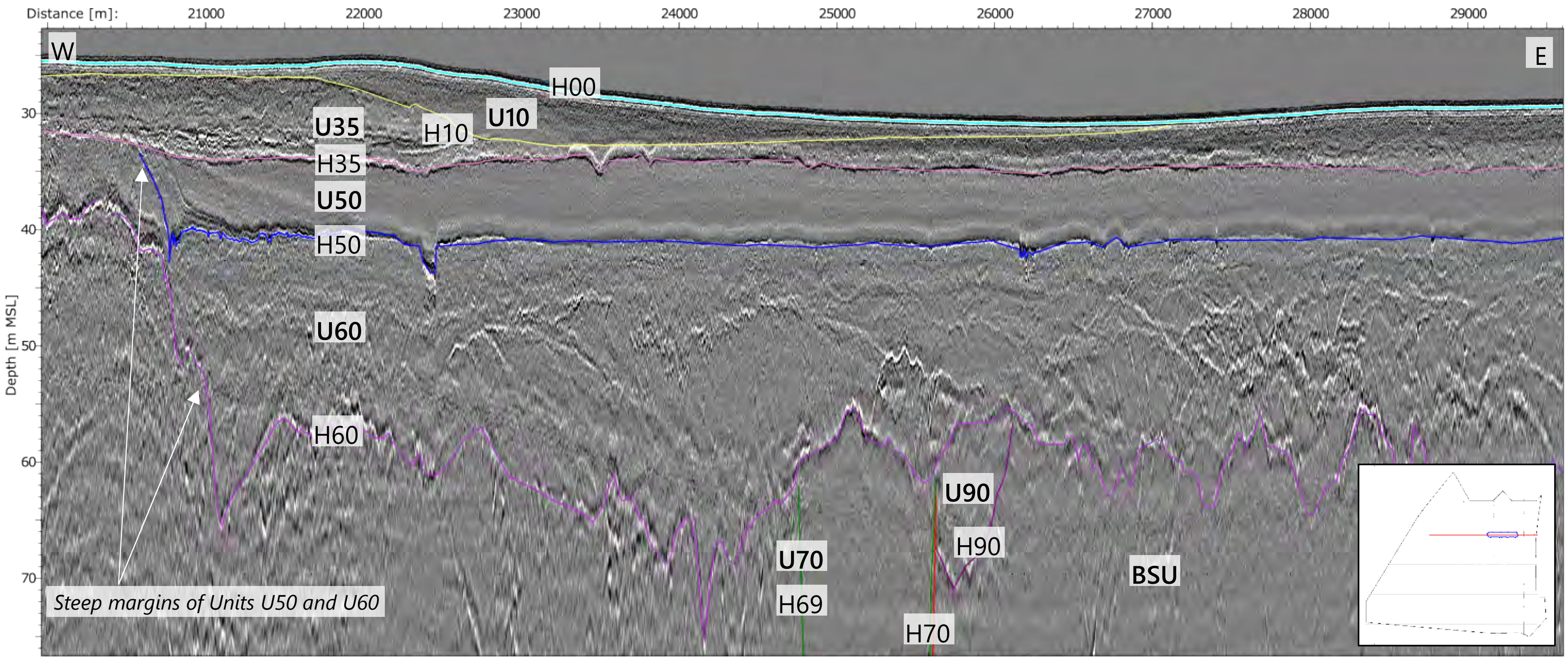

Figure 4.25: 2D UUHR seismic data example of Unit U35, U50 and U60 in the east. Line EAAA004P2

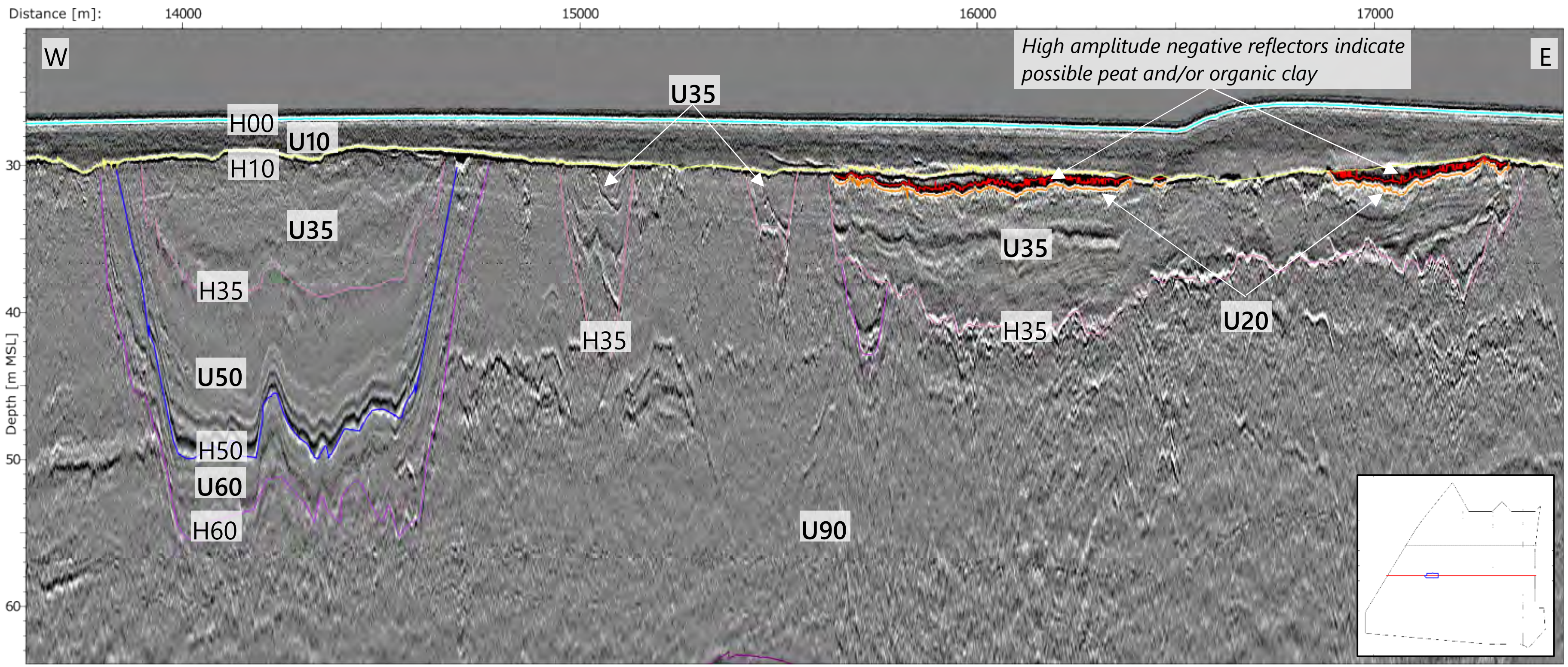

Figure 4.26: 2D UUHR seismic data example of channels of Unit U35. Line EAAA003P1

4.3.2.5 Unit U50

Unit U50 is present mainly in the north-east, east, and locally in the south-west of the site (Figure 4.27, Figure 4.28). The unit has a sheet-like to channelised geometry. In the north-east and east, the basal horizon H50 is flat and locally has steep margins (Figure 4.25). The thickness in this area is up to 10 m and locally reaches approximately 20 m. In the south-west of the site, the unit is present as channel infill with a maximum thickness of 50 m (Figure 4.26, Figure 4.29). Unit U50 often forms internal channels in larger channels (associated with Units U60 and U70).

Internally, Unit U50 is acoustically transparent to weekly stratified in the north-east and east and stratified in the south-west.

The sheet like geometry and uniform acoustically transparent character in the north and east of the site, may suggest that this unit was deposited in a low energy environment. Similar sheet-like unit with an acoustically transparent seismic character at the Horns Rev OWF (south of the site), comprises Holsteinian interglacial marine clay (Jensen et al., 2008).

In the west of the site, the stratified seismic character also indicates a low energy depositional environment. Here, Unit U50 is also interpreted as the Holsteinian (Jensen et al., 2008), and channels fills formed during the preceding glacial period (Elsterian).

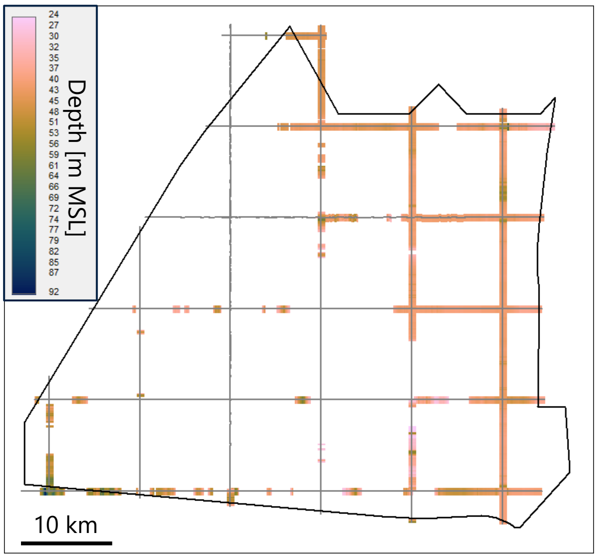

Figure 4.27: Depth to horizon H50 (base of Unit U50) relative to MSL

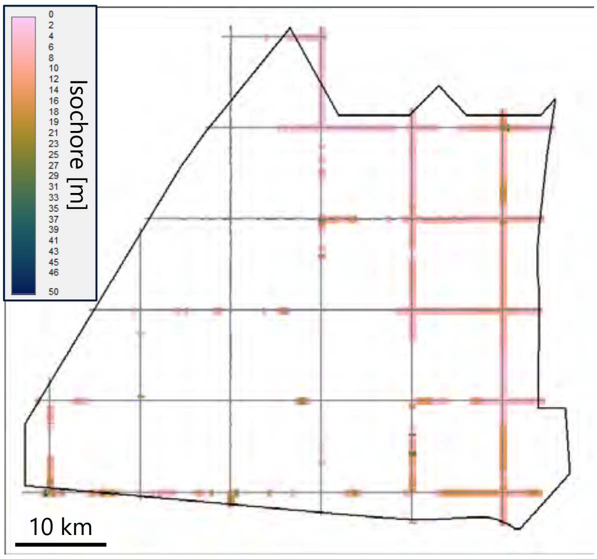

Figure 4.28: Isochore map of Unit U50

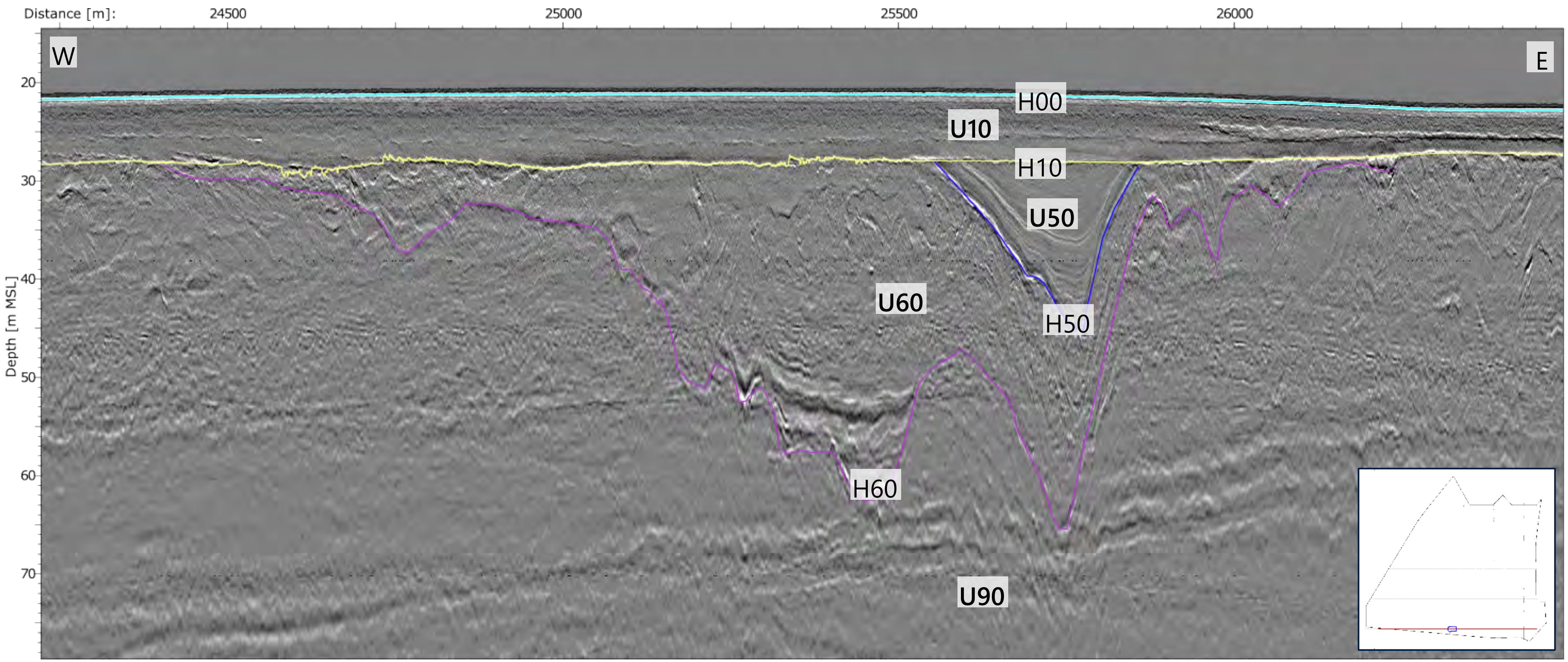

Figure 4.29: 2D UUHR seismic data example of Unit U50 and Unit U60. Line EAAA001P2

4.3.2.6 Unit U60

Unit U60 is present across almost the entire site (Figure 4.30, Figure 4.31). It is locally absent in the central and south-west part. The unit has a sheet-like to channelised geometry. In the north and east of the site, the basal horizon H60 is flat to undulating and locally has steep erosional margins (Figure 4.25). The thickness of this is up to approximately 20 m. Locally, where the base is channelised, Unit U60 reaches maximum thickness of 76 m.

In the west, Unit U60 forms channel infills. In this area, these channels are often associated with internal channels that form the infill of Unit U50. Unit U50 and Unit U60 represent two different stages of channel infill (Figure 4.29).

Internally, Unit 60 has a complex seismic character. This includes chaotic seismic facies to horizontal and inclined stratification, presence of internal erosion surfaces. Locally high amplitude positive reflectors are present, which may represent gravel beds (see Section 4.3.3.2).

Based on the channelised base, internal erosion surfaces and complex internal seismic character, it is interpreted that this unit was deposited in a braided fluvial depositional environment during a glacial period when sea level was low.

Unit U60 is older than Unit U50, which is interpreted to be Holsteinian (Jensen et al., 2008) and younger than the glacial tunnel valleys of Unit U70, which are interpreted to be Elsterian in age. Based on the stratigraphic position, this unit is late Elsterian in age.

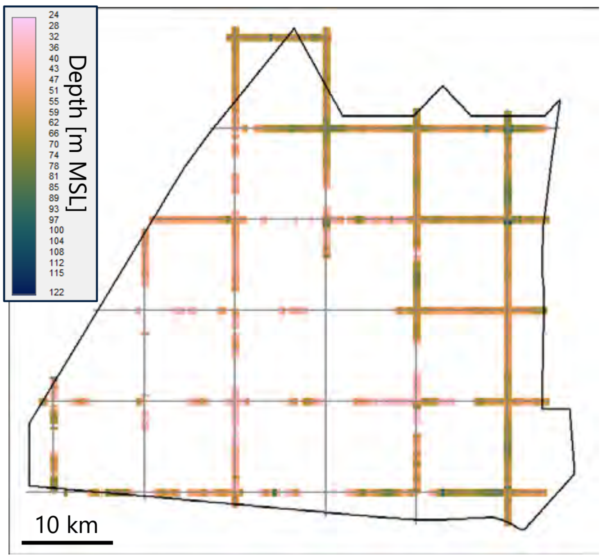

Figure 4.30: Depth to horizon H60 (base of Unit U60) relative to MSL

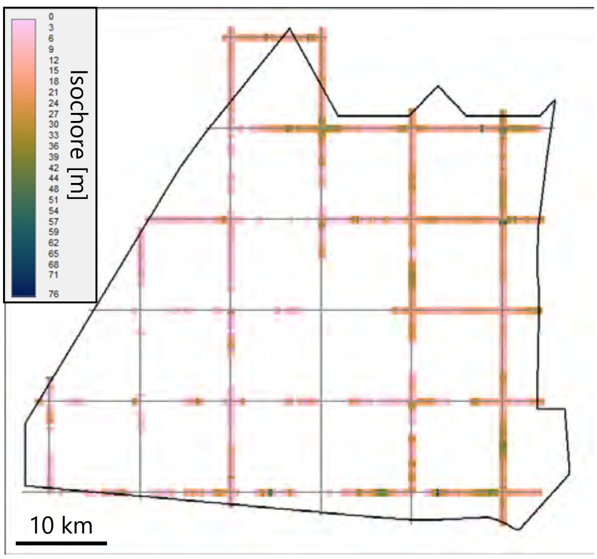

Figure 4.31: Isochore map of Unit U60

4.3.2.7 Unit U70

Unit U70 forms the infill of deep tunnel valleys with generally a north to south orientation (Figure 4.32, Figure 4.33). The base is marked by horizon H70, which often lies deeper than the maximum penetration of the 2D UUHR seismic data (i.e., approximately 200 m below MSL). In the east of the site, these tunnel valleys form a network of valleys which crosscut each other (Figure 4.34). In the west of the site, Unit U70 is only locally present (Figure 4.35).

Two seismic facies are observed in Unit U70. The lower part of the valley-fill is often acoustically chaotic to transparent, whereas towards the top it is stratified. The boundary between the acoustically chaotic a stratified intervals is marked by internal horizon H69 (Figure 4.34). Internal horizon H69 is not always present in Unit U70.

Unit U70 is interpreted to be the syn- to post-glacial infill of glacial tunnel valleys (Huuse and Lykke-Andersen, 2000b; Kirkham et al., 2021). In the area, tunnel valleys are often age-dated as Elsterian and/or Saalian (Figure 4.2; Huuse and Lykke-Andersen, 2000b). Since Unit U70 is older than Unit U50, which is Holsteinian in age (Jensen et al., 2008), Unit U70 is interpreted to be Elsterian in age.

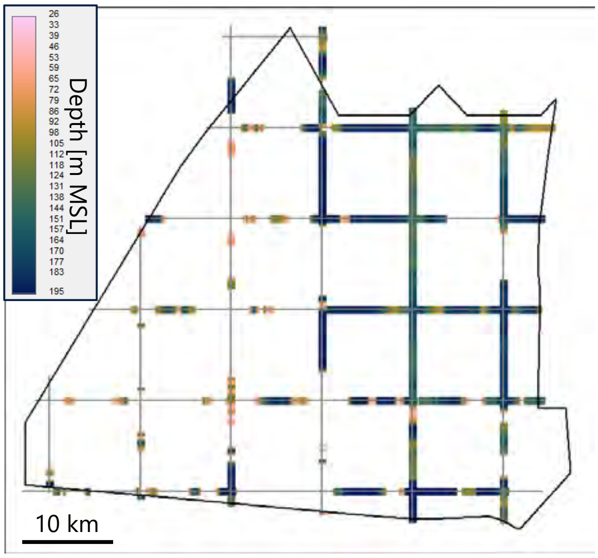

Figure 4.32: Depth to horizon H70 (base of Unit U70) relative to MSL

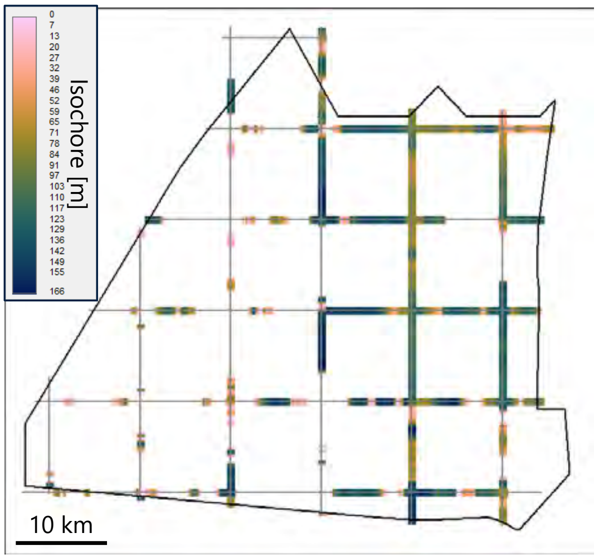

Figure 4.33: Isochore map of Unit U70

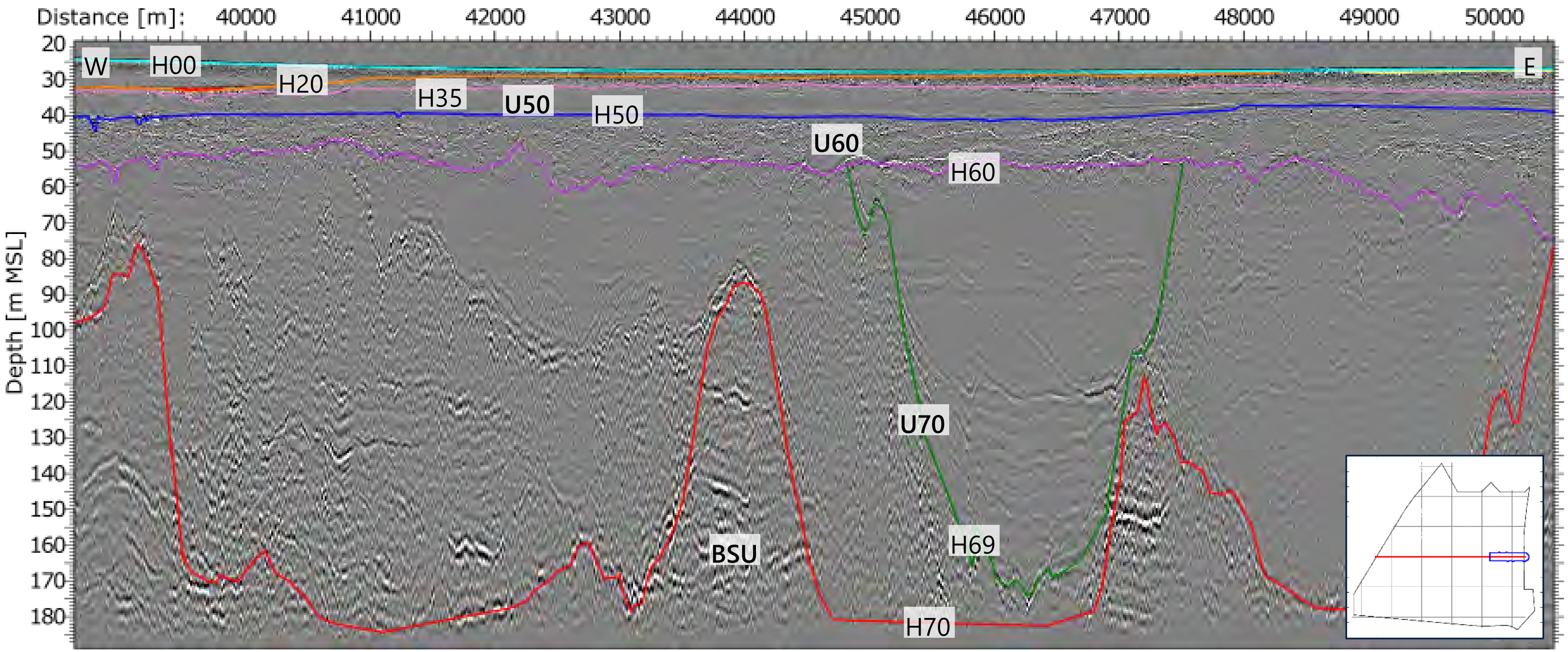

Figure 4.34: 2D UUHR seismic data example of tunnel valleys of Unit U70 in the east. Line EAAA003P1

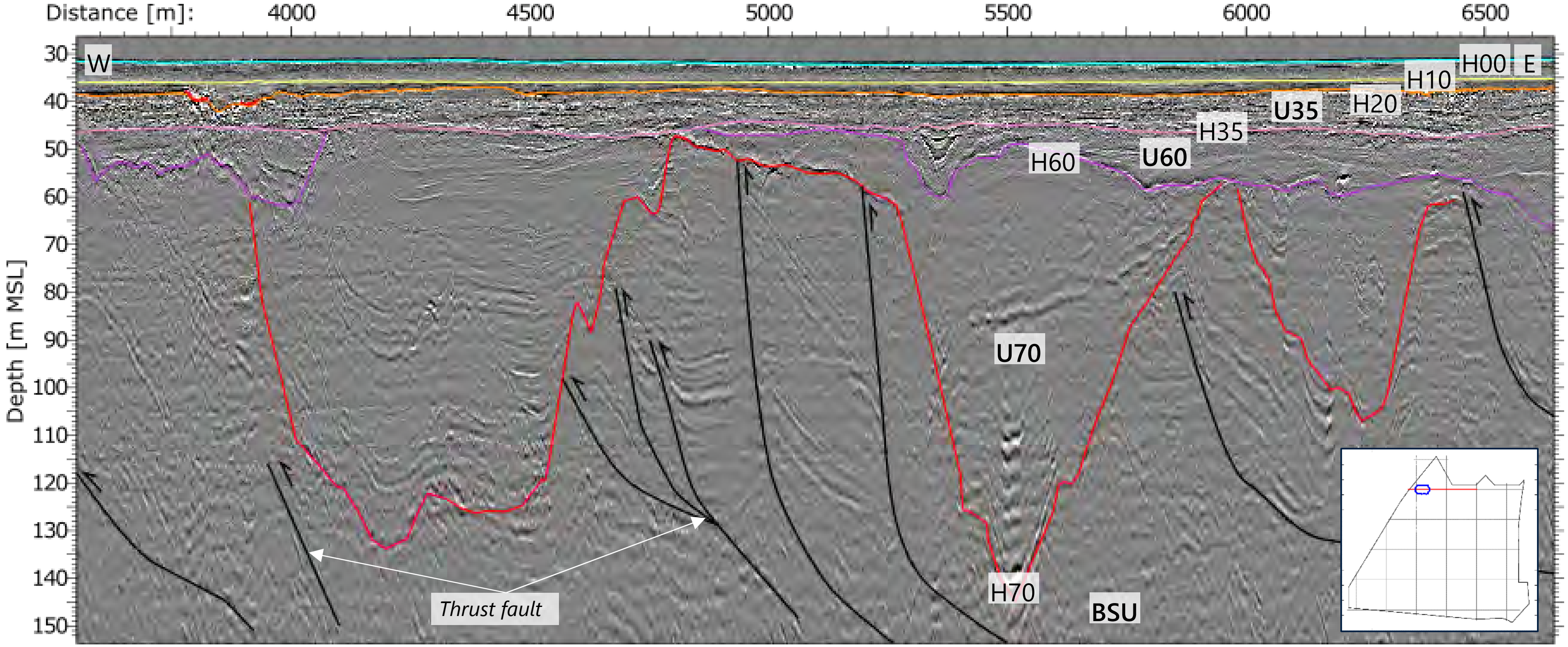

Figure 4.35: 2D UUHR seismic data example of tunnel valleys of Unit U70 in the west. Line EAAA005P2

4.3.2.8 Unit U90

Unit U90 is present mainly in the south-west of the site (Figure 4.36, Figure 4.37). In the east of the site, it is only locally present between the tunnel valleys of Unit U70. The unit has a sheet-like geometry. In the most south-west part of the site the base lies below the maximum penetration of the 2D UUHR seismic data (Figure 4.38).

Internally, this unit has a variable seismic character (Figure 4.39), including acoustically chaotic and transparent intervals and horizontal and inclined stratification. Locally internal erosion surfaces and negative high amplitude reflectors are present in this unit (see Section 4.3.3.1).

Based on the internal complexities and internal erosion surfaces, this unit is interpreted to have been deposited in a braided fluvial depositional environment. Possible peat and/or organic peat beds may have been deposited in a coastal plain.

It is interpreted that Unit U90 forms fluvial delta-top deposits of the Cenozoic delta system of the Eridanos River (Figure 4.4; Overeem et al., 2001; Gibbard and Lewin, 2016) and is Early to Middle Pleistocene (Cromerian) in age.

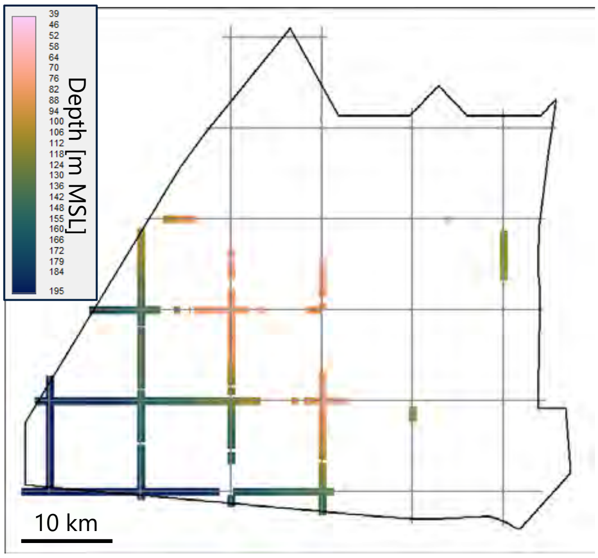

Figure 4.36: Depth to horizon H90 (base of Unit U90) relative to MSL

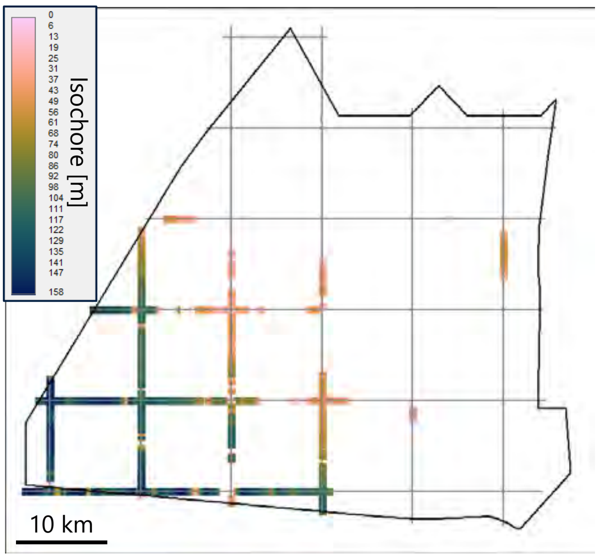

Figure 4.37: Isochore map of Unit U90

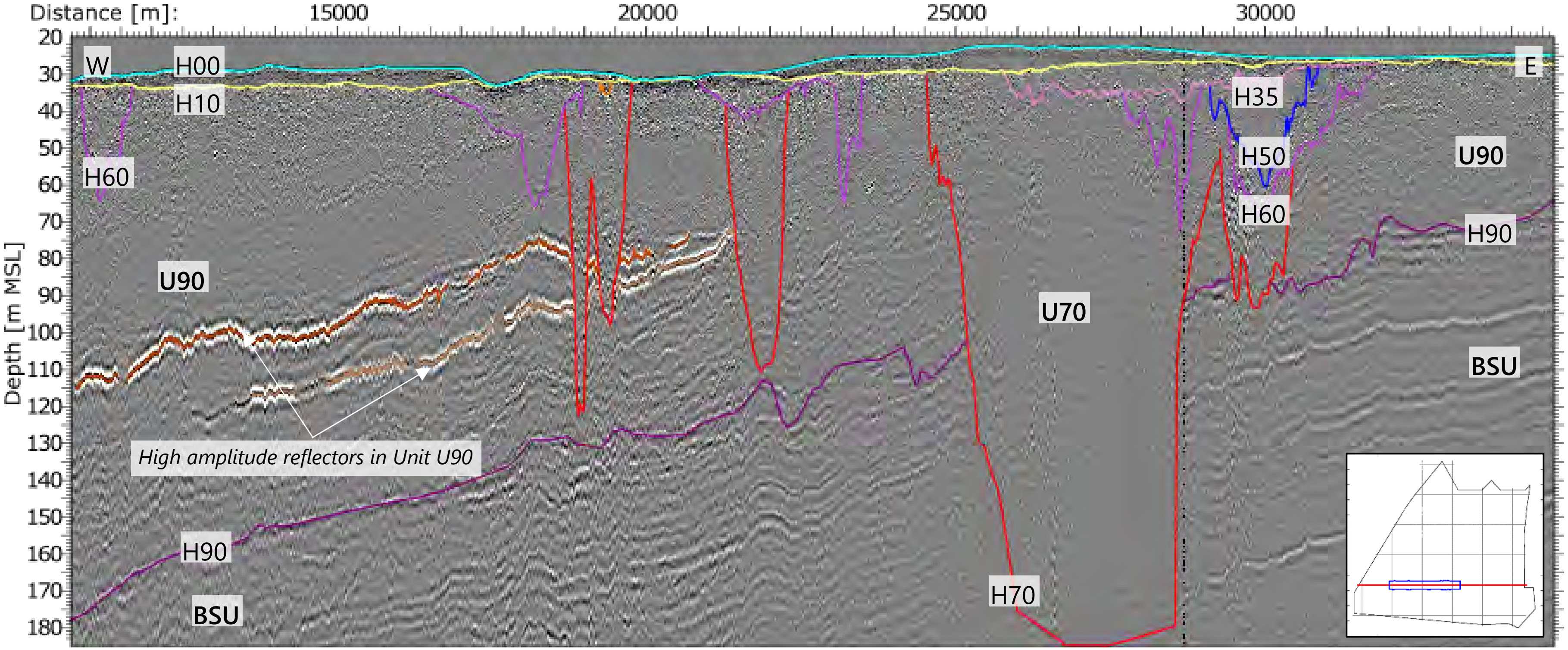

Figure 4.38: 2D UUHR seismic data example of Unit U90. Line EAAA002P1

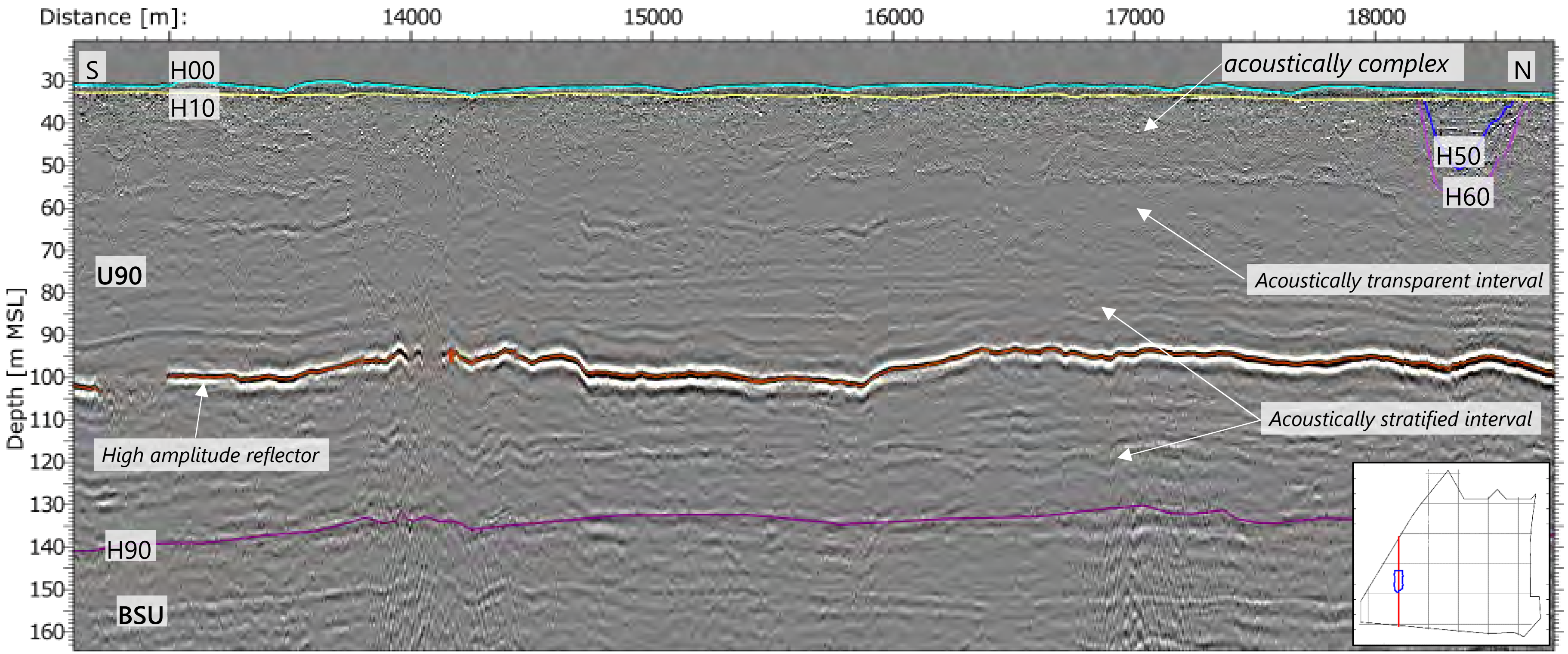

Figure 4.39: 2D UUHR seismic data example of Unit U90. Line EAAA008P1

4.3.2.9 Unit BSU (Base Seismic Unit)

The BSU is the deepest interpreted unit within the depth of penetration of the 2D UUHR seismic data. The top of the BSU is locally very close to the seafloor, namely in area where it is thrusted upward by glaciotectonic deformation.

Internally, the unit is stratified. The parallel reflectors are horizontal to gently dipping towards the south-west (Figure 4.38, Figure 4.40). The boundary between the BSU and the overlaying Unit U90 is not marked by a clear reflector but is depicted by the change in seismic character between the two units. In the south-east of the site, a negative high amplitude reflector is present (see Section 4.3.3.1).

In the north, centre, and south-east of the site, the BSU is deformed by thrust faults that generally dip towards the east and north (Figure 4.35, Figure 4.41; see Section 4.3.3.5). In the east of the site, locally steep normal faults are present in this unit (see Section 4.3.3.6). In the west of the site, a single thrust fault is present (see Section 4.3.3.6).

Based on literature, BSU is considered to be bedrock of Miocene age (Figure 4.3). It is interpreted that the unit comprises coarsening upward pro-delta clay to delta-front sand deposits of the Eridanos River (Figure 4.4). The westward dip of the strata may be a structural dip or delta clinoforms (Overeem et al., 2001; Gibbard and Lewin, 2016).

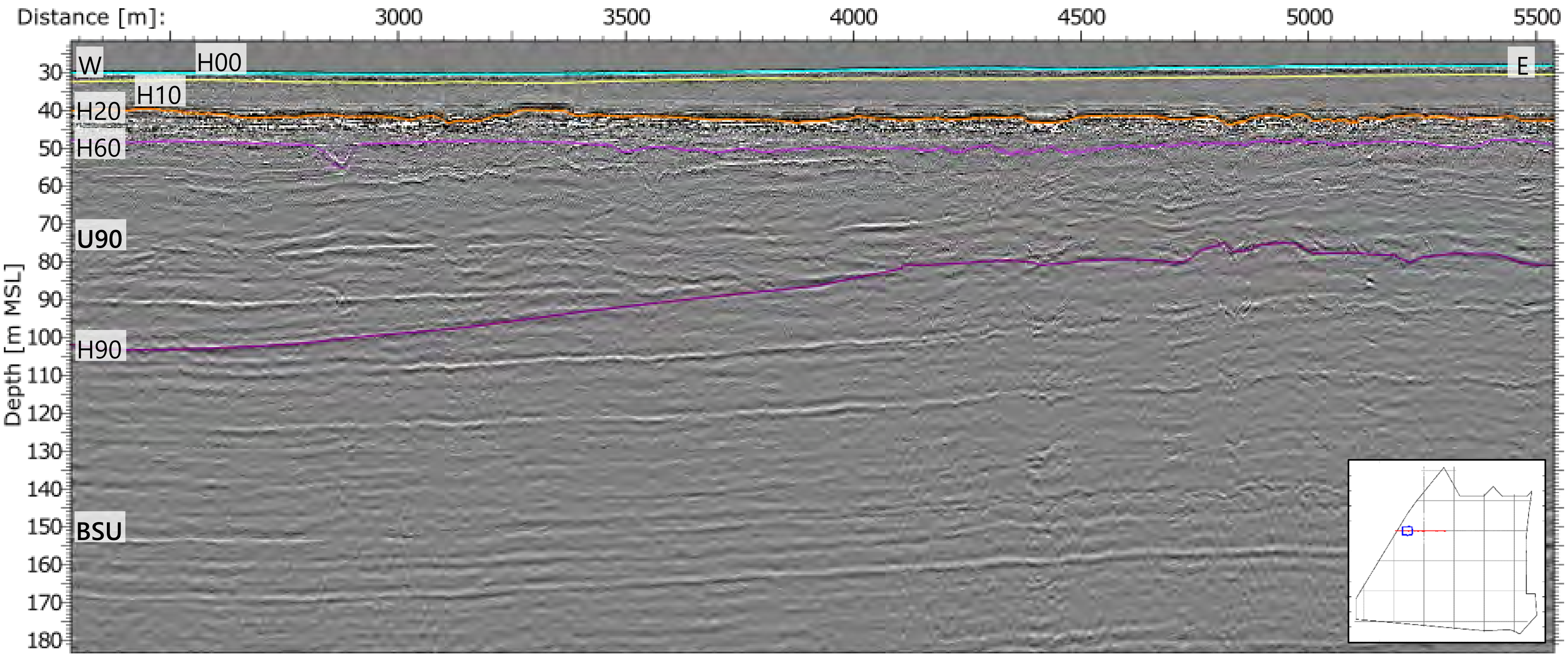

Figure 4.40: 2D UUHR seismic data example of stratified BSU. Line EAAA004P1

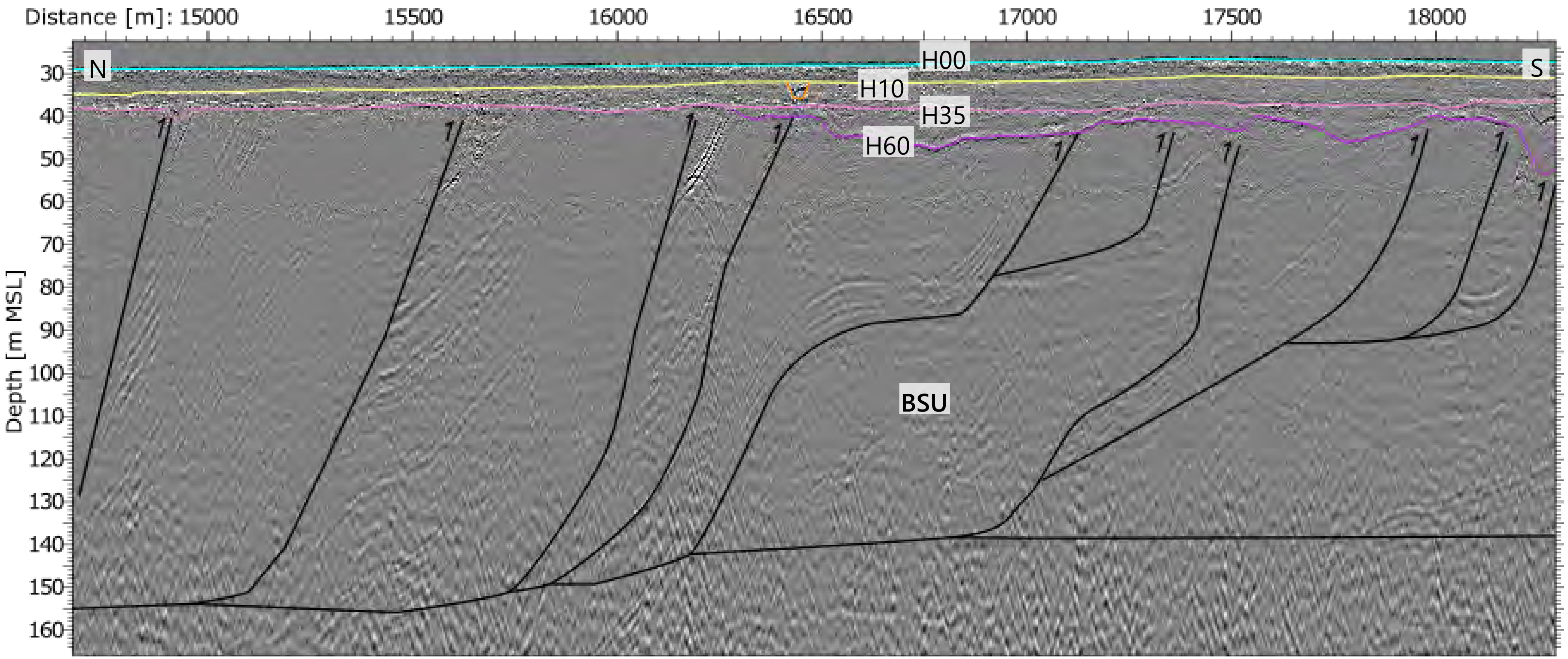

Figure 4.41: 2D UUHR seismic data example of thrust faults in the BSU. Line EAAA009P1

4.3.3 Geological Features and Geohazards

This section describes sub-seafloor geological features and geohazards for engineering work identified in the SBP and 2D UUHR seismic data in the survey area.

4.3.3.1 Peat and/or Organic Clay

High negative amplitude reflectors were observed in several units. They may indicate beds of peat and/or organic clay.

In Unit U10, U20, U30 and U50, high negative amplitude reflectors are present with a length of up to 3 km (Figure 4.16, Figure 4.21, Figure 4.26, Figure 4.22). Locally signal attenuation is observed below. These seismic anomalies are typically at the base of these units and/or associated with buried channels. These high amplitude reflectors are mapped as '*2DUUHR_seismic_anomalies_U1020*' and '*2DUUHR_seismic_anomalies_U30U50*'.

In Unit U90, continuous negative high amplitude reflectors are present at multiple levels with a length of up to 20 km (Figure 4.38, Figure 4.39). These high amplitude reflectors are mapped as '*2DUUHR_seismic_anmolies_U90a*', '*2DUUHR_seismic_anmolies_U90b*' and '*2DUUHR_seismic_anmolies_U90c*'.

In the BSU, a continuous negative high amplitude reflector is present at a depth of 95 m to 167 m BSB and a length of up to 13 km (Figure 4.42). This high amplitude reflector is mapped as '*2DUUHR_seismic_anomalies_BSU*'. It may indicate a bed with a different soil type within the BSU such as a bed of organic clay/peat, or a bed of sand within clay.

Peat and organic clay have a high compressibility, which may result in uneven and non-uniform support. It may also cause a chemical reaction between the soil and steel.

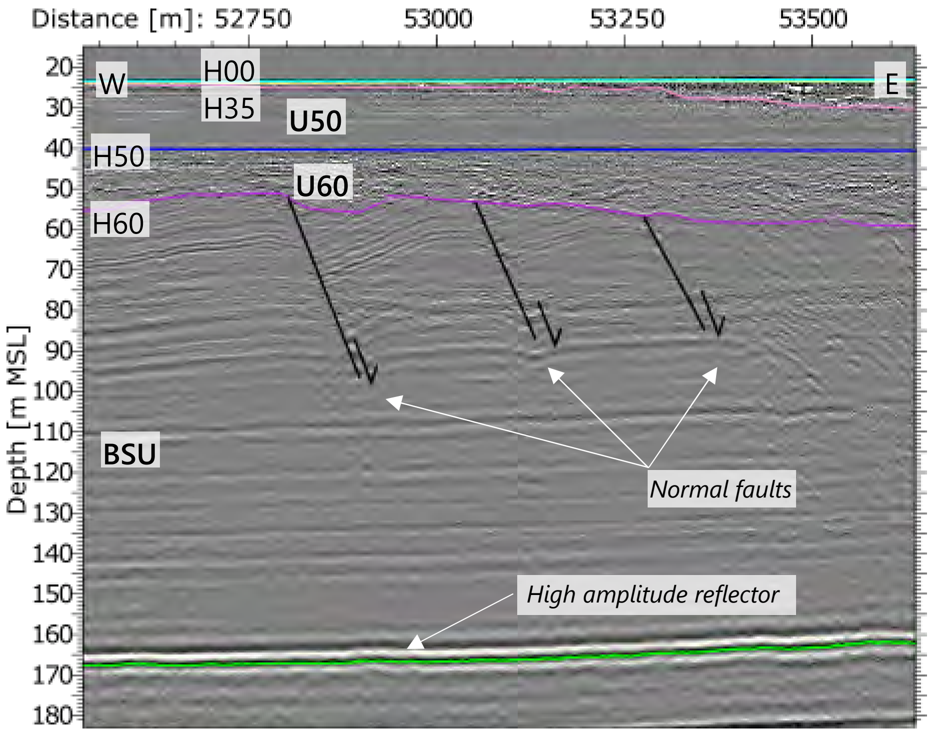

Figure 4.42: 2D UUHR seismic data example of normal faults and the high amplitude reflector in the BSU. Line EAAA001P2

4.3.3.2 Shallow Gas

No evidence for shallow gas was observed on the 2D UUHR seismic data. The signal attenuation that was observed below some of the high negative amplitude anomalies in Units U10 and U20 is thought to be the results of the presence of peat and/or organic clay (Figure 4.16, Figure 4.21). However, the presence of gas/fluid charged sediments cannot be excluded.

Gassy soils may have high compressibility, low and laterally variable soil strength, and reduced bearing capacity. Migration of gas into skirted foundation may occur. There may be a risk of blowout and gas release during drilling and piling operations.

4.3.3.3 Gravel, Cobbles, and Boulders

Unit U35, Unit U60, and Unit U90 are fluvial units interpreted to be deposited in a braided river environment. Braided rivers may be associated with the presence of gravel and cobbles. In Unit U35 and Unit U60, relatively high amplitude positive internal reflectors are present which may represent gravel beds.

Unit U70 is interpreted to be the infill of glacial tunnel valleys. Glacial deposits are often poorly sorted deposits and may contain gravel, cobbles, and boulders.

Gravel, cobbles, and boulders may form an obstruction and result in insufficient or non-uniform support and/or penetration of piles and suction cans. They may also form an obstruction for trenching for cables.

4.3.3.4 Buried Channels and Tunnel Valleys

Unit U20, Unit U35, Unit U50 and Unit U60 locally form channel fills. Part of these units form relatively narrow channels with a low width over depth ratio. Part of these unit, especially in the east of the site, form relatively wide valleys with a high width over depth ratio.

Unit U35, Unit U60 and Unit U90 are interpreted to be deposits of braided river systems and contain internal channels and erosion surfaces.

Unit U70 forms the infill of tunnel valleys.

Buried channels and tunnel valleys may be associated with laterally variable soil conditions and uneven support of foundations.

4.3.3.5 Glacial Deformation

Thrust faults have been observed within the BSU in the north, centre and south-east of the site (Figure 4.43). The thrust faults generally dip towards the east and north (Figure 4.35, Figure 4.41). The thrust faults in BSU are interpreted to be the result of ice-push (Huuse and Lykke-Andersen, 2000a; Larsen and Andersen, 2005; Winsemann *et al.,* 2020; Cartelle *et al.,* 2021). The orientation of the thrust faults indicate that the ice-push came from the north-east.

Only the BSU is deformed. In the overlying units Unit U90 (Elsterian) and Unit U50 (Holsteinian) no deformation features were observed. Therefore, it is interpreted that glacial deformation took place during the Elsterian prior to the formation of the tunnel valleys (Unit U70).

Glacial deformation features may be associated with variable soil conditions and lower lateral resistance. Soil properties may vary laterally resulting in non-uniform support of foundations.

4.3.3.6 Faults

In the west of the site, a single thrust fault with associated folding is present within the BSU (Figure 4.43, Figure 4.44). This fault may be a pre-existing fault which was reactivated by ice-push during the glacial deformation.

In the south-east of the site, a small area with a series of normal faults is present within the BSU (Figure 4.42, Figure 4.43).

Small-scale faults associated with possible glaciotectonism or dewatering features may be present, as well as faults associated with the steep flanks of the tunnel valleys. Due to the structureless seismic aspect that characterises a large part of the sub-seafloor, the presence of more faults and/or fractures cannot be ruled out.

Due to the presence of faults and faulted strata, soil properties may vary laterally resulting in non-uniform support of foundations. Faults may still be active or be re-activated due to human interference. Active faults may be associated with critical stress and possible failure of structures.

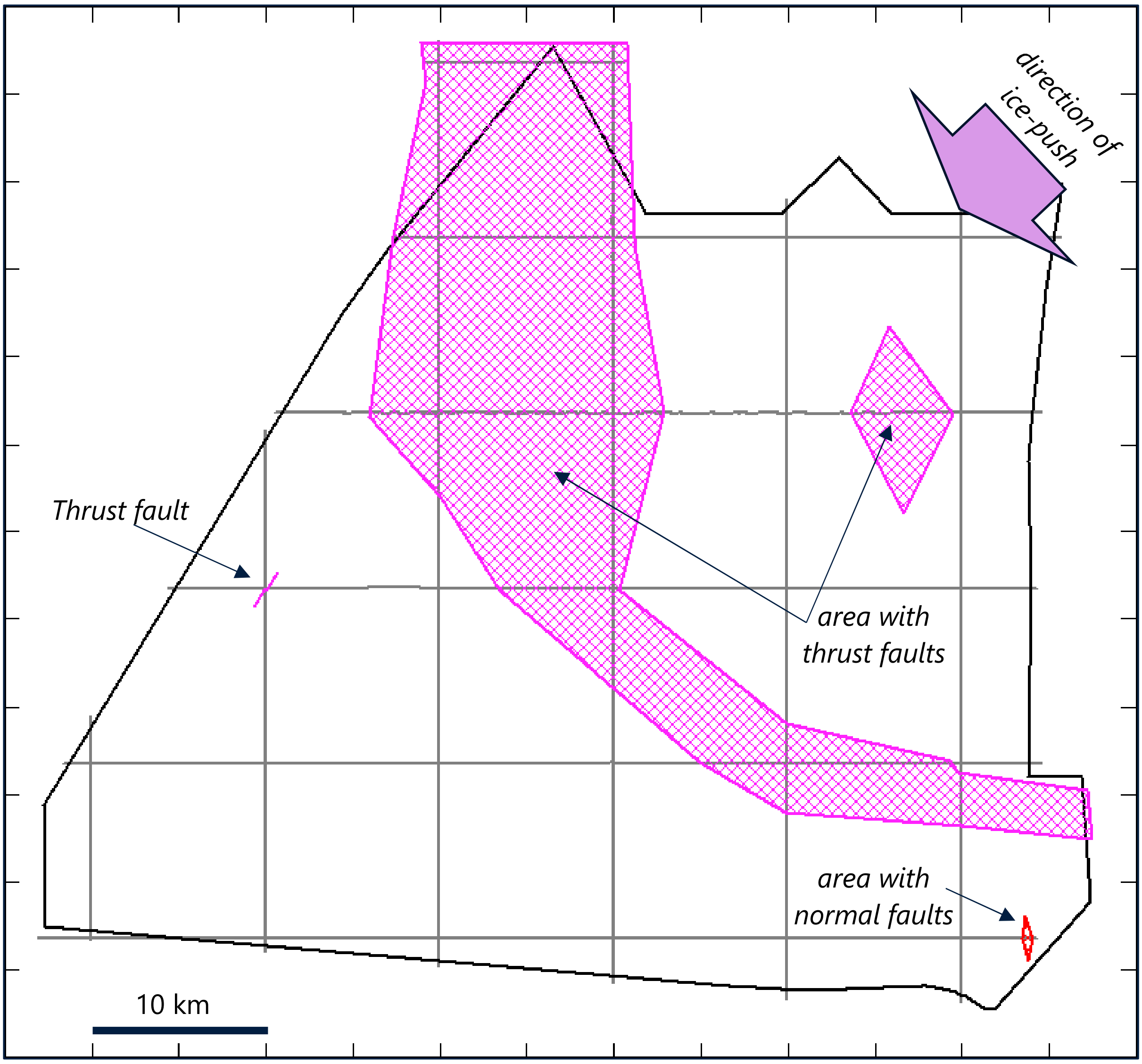

Figure 4.43: Map of the extend of glacial deformation and faulted areas in the BSU

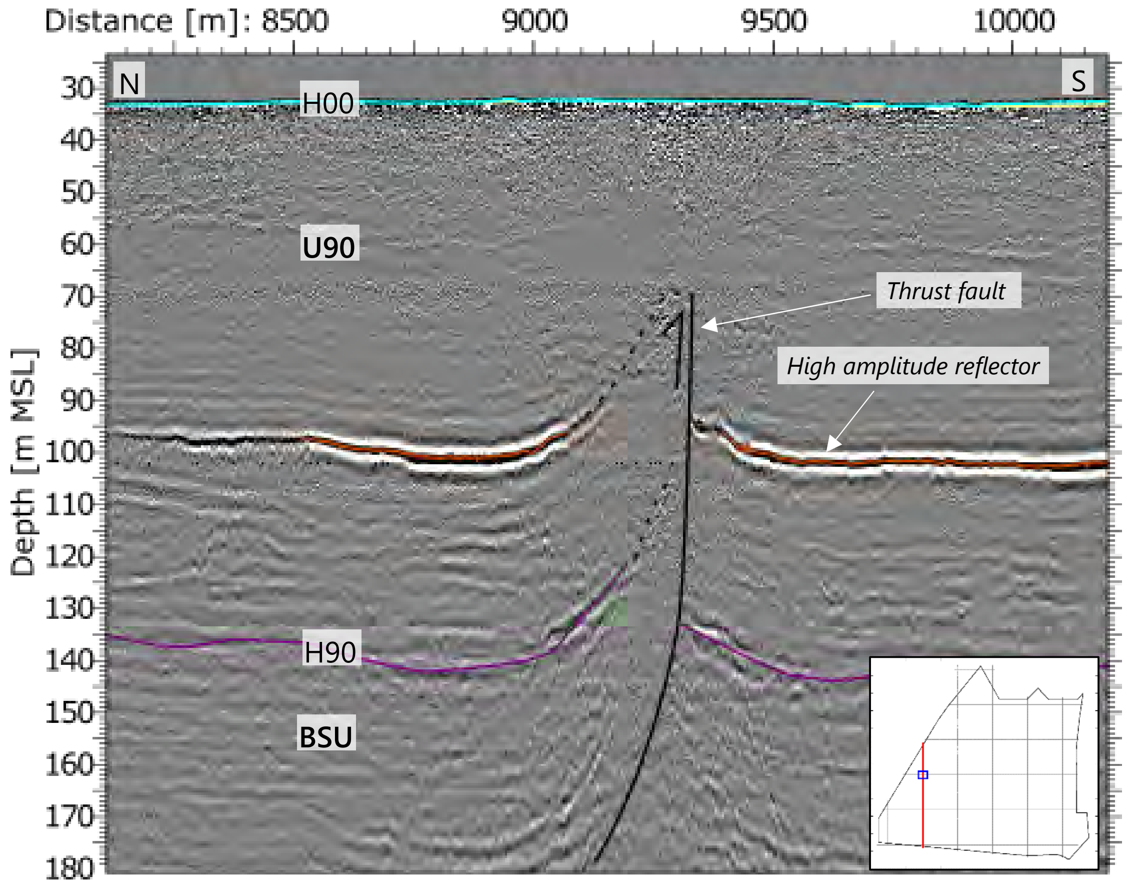

Figure 4.44: 2D UUHR seismic data example of the thrust fault. Line EAAA008P1

4.4 Bathymetry

The seabed of the DOW2030 site was characterised by very gentle seafloor slopes, on average ranging between approximately 0˚ and 6˚.

Minimum water depths recorded was 15.9 m MSL associated with a sediment mount in the southeast of the survey area. Maximum water depth was 39.3 m MSL observed on westernmost part of the survey area.

The overview of the bathymetry at DOW2030 site is presented below in Figure 4.45.

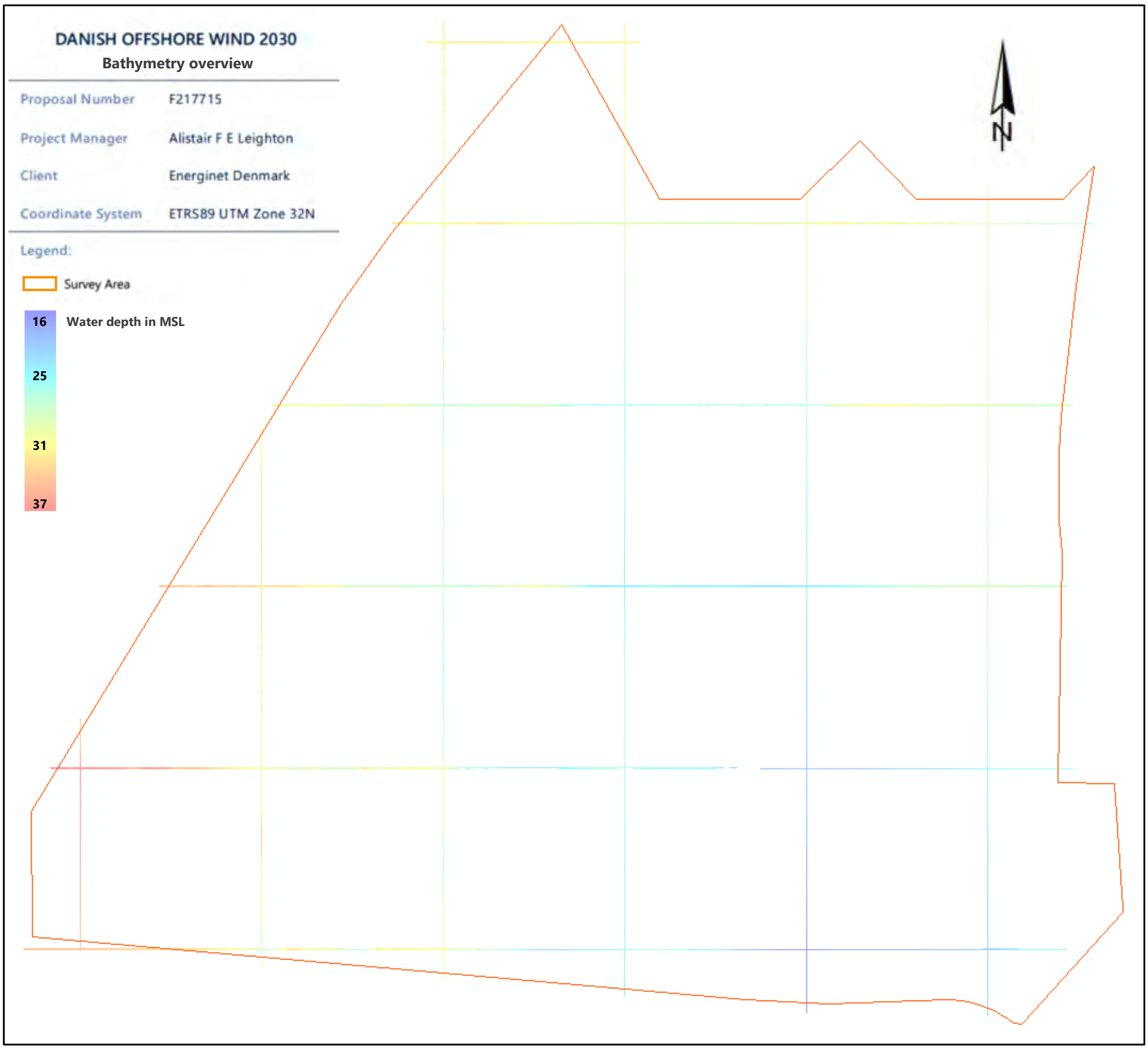

Figure 4.45: Bathymetry overview at DOW2030 site

5. Geotechnical Locations

5.1 Overview

The following section outlines the approach to the assignment of geotechnical locations at the North Sea 1 Development area. Previously Fugro have assigned 90 % of the proposed geotechnical locations based on the results of a desk-based assessment of conditions. These were previously presented in 220717-R-001 report. Coordinates for these locations are presented in Table 5.3. In total, the following geotechnical data will be collected during 2023 and 2024 at the site:

- 336 continuous seafloor cone penetration tests (CPT) to a target depth of 55 m below seafloor;
- 144 geotechnical boreholes (BH) with soil sampling to a target depth of 70 m below seafloor.

This section summarises the approach taken to assign the final 10% of locations. This was based on the results of the preliminary geophysical survey work.

For the final 10% of geotechnical locations, preliminary geophysical results presented in Section 4 were used to determine the optimal locations along the preliminary 2D UUHR lines. The intention of these locations is to provide information for future integration work. The following number of locations were sited on acquired geophysical lines:

- 32 CPT locations;
- 14 BH locations.

These remaining locations are targeted on the as-acquired geophysical lines detailed in this report. By selecting locations on the 2D UUHR lines, the sampling can target specific features, ensuring that future integration work has sufficient ground truthing data.

5.2 Location Selection Approach

To understand the approach for the location selection, the overall objective of the geotechnical sampling and future integration work needs to be understood. Geotechnical data in the future will help ground truth interpretation in geophysical data, allowing point specific geotechnical data to be extrapolated across the site using the 2D UUHR datasets as part of an integrated ground model. As a result, the selection of locations considers the need to integrate data and allow features observed in the geophysical data, both regional and local, to be benchmarked and sampled by geotechnical data. In addition to seismic unit variability, the objective of the geotechnical locations is to support the understanding of internal seismic character changes within seismostratigraphic units that are not possible to sub-divide based on acoustic character alone.

The desk study-based locations are targeted to sample regional variability in units that extend across the site. The intention of the "data specific" locations is to target more constrained units such as channel features. In addition, areas of local seismic character variability within units are also considered for locations, to ensure that local geotechnical variations are well understood.

The key geological considerations for the selection of locations were as follows:

- Channelised areas (e.g. west of site H20 deposits) and channel units are sampled to ensure understanding of internal variability;
- Seismic character variability within units to ensure future integration and possible subdivision of units can completed;
- Seismic anomalies are sampled.

The process followed for the selection of locations is outlined in Figure 5.1.

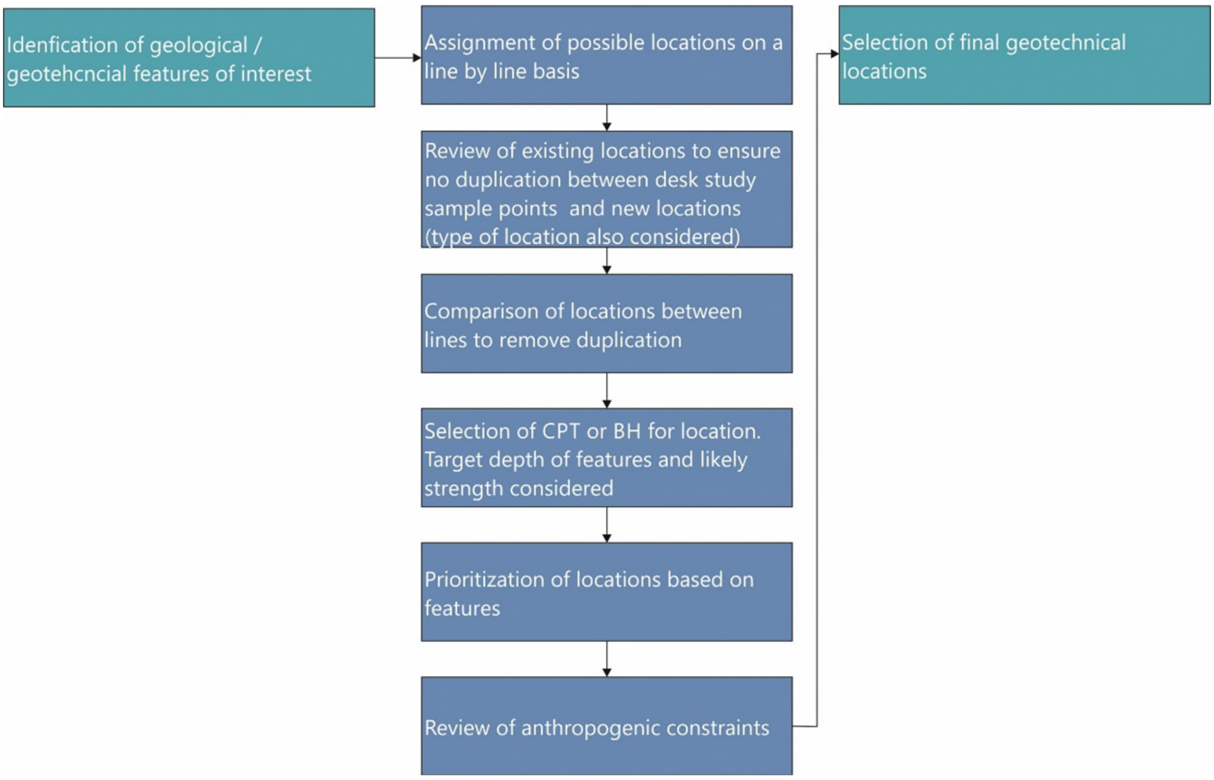

Figure 5.1: Overview of location selection process

All seismic lines were individually reviewed with suggested locations added to the lines. The geological features outlined in Section 4.3 were targeted with proposed locations and, if possible, locations were targeted in areas where multiple geological features of interest were present. This allowed efficient use of the limited location numbers.

Once this line by line assessment was complete, the locations were then categorised based on if CPT or BH acquisition is most appropriate at each location. This division was based on the target depths of the features observed as well as consideration to the expected strength of the sediments in that area. In areas of shallow high strength units (U60 and below) BH locations have been prioritised.

After locations were assigned, a prioritisation was assigned to them. This was based on the number of features that were captured at that location as well as the commonality of those features when considering all proposed sample locations.

In addition to these geological considerations the existing desk study assigned locations were also reviewed alongside the proposed locations to ensure that the feature or areas are not already sampled.

A final review of locations based on anthropogenic constraints will also take place once selection is completed to ensure features such as cables, pipelines and wrecks are not present at the proposed locations.

5.3 Geological Features Targeted

The following section provides an overview of some of the features that are targeted by the sample locations. These features were also considered alongside the existing 90% locations, therefore may not all be specifically targeted by the new locations.

5.3.1 Tunnel Valley Features – U69 and U70

Tunnel valley features are mapped by U70 with a subdivision of the unit captured by U69. Current assignment of locations considered the large scale tunnel valley features observed from public data and mapped in the east of the site as part of the desk study. Tunnel valley features observed in the west of the site, were not mapped in the desk study stage and therefore were not previously targeted. As a result, BH locations were assigned to capture these features. Subdivision of the tunnel valley features by H69 was also not considered by the original locations, therefore new locations are assigned to capture this feature.

5.3.2 Variability in U60

Seismic characteristics within U60 are observed to vary within the study area. An erosional base and internal variability within the unit is observed. Locations are selected to ensure that should regional variability be observed this can be mapped in future integration exercises.

5.3.3 U50 Channelised Areas

In the west of the site, U50 is observed to become more channelised and less laterally extensive. To ensure the channelised area is sampled, locations were targeted within the features. This will ensure that geotechnical characteristics within the spatially limited areas are captured for future integration work. Some limited seismic character changes are also observed near the base of U50 sediments. In these areas locations are selected to capture if this change is geotechnically significant.

5.3.4 H20 Channelised Areas

A wide range of seismic character changes are observed within U20. In addition, seismic anomalies within U20 (Section 4.3.3) are also observed. Channel areas are observed in seismic data. As a result, locations were targeted to ensure any further subdivision of this unit in the future can take place.

It is anticipated that sediment characteristics within the unit are likely to change with depth. Locations will also be used to understand these variabilities.

5.3.5 BSU Unit

The BSU is present throughout the site except where it is cut by valleys of Unit U70 and where Unit U90 is thickest in the south-west of the site. Sample locations are required to characterise areas where it is close to seafloor. In areas of thrusting, it is observed in close proximity to seafloor (Figure 4.43). In addition to the south-west of this area, it is observed at its shallowest when not affected by glacial deformation.

In the area not affected by thrust faulting the following locations are expected to sample BSU sediments:

- BH_015;
- BH_024;
- BH_144.

Within the thrusted sediments, multiple locations are expected to sample the thrusted material; however, of these the following locations are in areas of the shallower thrusted sediments:

- BH_034;
- BH_103.

5.4 Proposed Sample Locations

Based on the approach outlined, a total of approximately 60 potential sampling locations were identified within the site. From these locations, the approach outlined in Figure 5.1 was followed.

The proposed sample locations for the site are detailed in Table 5.1 and Table 5.2. Rationale for the locations are presented in the tables.

Table 5.1: Proposed BH Locations

Location Name	Easting [m]	Northing [m]	Bathymetry Depth [m]	Baseline 2D UUHR Line	Comments
BH_001	379953	6191525	31	EAAA008P1	U20 channel and south-west U70 channel with seismic character variability to be sampled
BH_002	409950	6212976	25	EAAA011P1	H20 sediment changes over depth and U70 seismic character changes to be sampled
BH_003	405693	6226774	28	EAAA005P2	U70 seismic character changes / internal reflector to be sampled. Location to characterise any geotechnical changes associated
BH_004	394835	6216771	28	EAAA004P2	U70 seismic character changes / internal reflector to be sampled. Location to characterise any geotechnical changes associated
BH_005	388756	6196773	31	EAAA002P1	U90 Seismic character changes to be sampled. Location to characterise possible geotechnical changes. Acoustic anomalies within U90 also to be sampled
BH_006	394190	6196779	23	EAAA002P1	U70 channel in the south-west as well as seismic character changes / internal reflector to be sampled. Location to characterise any geotechnical changes
BH_007	420133	6196775	24	EAAA002P1	U20 variability and U20 seismic anomaly to be sampled. U70 seismic character changes also to be sampled
BH_008	402412	6186746	25	EAAA001P1	Internal variability within U70 to be sampled
BH_009	372645	6196777	35	EAAA002P1	Shallow south-west H70 channel flank to be sampled
BH_010	389955	6209156	28	EAAA009P1	Internal changes in U20 sediments in area of thick deposits to be sampled. U20 channel in west of site also to be sampled
BH_011	379951	6199760	31	EAAA008P1	U90 Seismic character changes to be sampled. Location to characterise possible geotechnical changes. Acoustic anomalies within U90 also to be sampled
BH_012	399949	6218831	25	EAAA010P1	H69 inclined beds in east of site to be sampled
BH_013	381366	6216802	30	EAAA004P1	Thick U20 sediments to sample any changes with depth to be sampled.U70 tunnel valley in west of site to be characterised.
BH_014	382816	6206777	31	EAAA003P1	U70 tunnel valley in the west to be characterised. Internal variability will be sampled
Notes: Locations will be micro sighted based on magnetometer data. When this is carried out, alignment of locations onto the as collected 2DUUHR lines is critical					

Table 5.2: Proposed CPT Locations

Location Name	Easting [m]	Northing [m]	Bathymetry Depth [m]	Baseline 2D UUHR Line	Comments
CPT_001	369948	6194485	36	EAAA007P1	Channelised area of U50 in the west of the site, U60 seismic character variability to be sampled
CPT_002	379950	6204168	32	EAAA008P1	Channelised area of U50 in the west of the site, U60 seismic character variability to be sampled
CPT_003	389948	6191219	27	EAAA009P1	U60 seismic character changes. Location may also sampleU70 if penetrated by CPT
CPT_004	389956	6203023	25	EAAA009P1	Internal U60 seismic character changes to be sampled
CPT_005	389953	6224272	29	EAAA009P1	Area of thick U10 sediments, area of thicker U35 sediments to be sampled
CPT_006	389950	6228502	30	EAAA009P1	Area of thick U10 sediments, U35 sediment variations with internal seismic reflector to be sampled
CPT_007	399944	6190076	2	EAAA010P1	Localised U50 channel to be sampled
CPT_008	399944	6207251	23	EAAA010P1	Thick U20 sediments to be sampled to identify changes with depth.
CPT_009	399966	6212610	25	EAAA010P1	U50 channel to be sampled. Change in seismic character within unit to be sampled
CPT_010	399955	6216981	25	EAAA010P1	U20 and associated seismic anomaly to be sampled
CPT_011	409950	6187083	17	EAAA011P1	U50 channel and U60 channel with more stratified seismic to be sampled
CPT_012	409953	6196205	21	EAAA011P1	U20 seismic anomaly, U50 channel area to be sampled
CPT_013	409955	6200673	21	EAAA011P1	Thick U20 sediments and seismic anomaly to be sampled
CPT_014	409955	6218035	26	EAAA011P1	U50 seismic anomaly to be sampled
CPT_015	396827	6236790	32	EAAA006P1	Spatially limited U30 sediments sampled to be sampled
CPT_016	419913	6187222	21	EAAA012P2	U50 channel and seismic character change in U60 to be sampled
CPT_017	419962	6209718	27	EAAA012P2	Localised U20 channel area to be sampled, U69 sediments may also be sampled if location penetrates to sufficient depth
CPT_018	419963	6215439	28	EAAA012P2	Possible U69 sediments if location penetrates sufficient depth. Internal variability within U60 to be sampled

Location Name	Easting [m]	Northing [m]	Bathymetry Depth [m]	Baseline 2D UUHR Line	Comments
CPT_019	401349	6226783	29	EAAA005P2	U20 seismic anomaly (in area where may interact with U10) to be sampled. H25 seismic character change observed to be sampled
CPT_020	417706	6226746	29	EAAA005P1	Deep U60 channel to be sampled
CPT_021	420598	6226768	30	EAAA005P1	Deep U50 and U50 seismic anomaly to be sampled
CPT_022	389953	6214097	28	EAAA009P1	Deep H20 channel and anomaly to be sampled. Small H70 channel may also be sampled if sufficient penetration is achieved
CPT_023	407244	6216787	26	EAAA004P2	Localised U50 and U60 channel area to be sampled
CPT_024	388495	6206804	27	EAAA003P1	U35 channel above U50 channel with seismic character change at base to be sampled
CPT_025	393637	6206777	29	EAAA003P1	U50 channel and small U70 valley feature to be sampled
CPT_026	397845	6196773	25	EAAA002P1	Deep U50 and U60 channel to be sampled to establish strength with depth
CPT_027	392365	6216779	27	EAAA004P2	U20 and seismic anomaly to be sampled. Internal reflector within U70 to be sampled if penetration sufficient
CPT_028	376767	6186726	32	EAAA001P1	Thick U50 channel to be sampled. Seismic character change in U35 sediments may also be captured
CPT_029	382093	6186771	31	EAAA001P1	Inclined reflectors within U35 to be sampled. U50 channel sediments will also be characterised
CPT_030	386233	6186789	32	EAAA001P1	U35 and U50 channel sediments to be sampled
CPT_031	407546	6186777	19	EAAA001P1	U20 seismic anomaly in area of thick deposit of this unit to be sampled
CPT_032	399957	6185941	23	EAAA010P1	Small U20 channel observed in south to be sampled. U90 sediments and anomaly if penetration depth sufficient

Notes:
Locations will be micro sighted based on magnetometer data. When this is carried out, alignment of locations onto the as collected 2DUUHR lines is critical

The original locations presented in the desk study are also included and presented in Table 5.3.

Table 5.3: Desk study based geotechnical locations

Location ID	Easting [m]	Northing [m]
BH_015	386296	6206277
BH_016	421185	6219979
BH_017	397976	6199600
BH_018	418595	6222487
BH_019	406770	6216854
BH_020	397471	6191305
BH_021	387567	6200413
BH_022	406754	6208665
BH_023	398090	6195532
BH_024	392583	6205594
BH_025	410762	6197255
BH_026	382388	6190082
BH_027	423205	6222463
BH_028	421350	6194434
BH_029	403464	6212045
BH_030	402128	6215848
BH_031	404801	6192894
BH_032	415029	6209436
BH_033	410175	6209407
BH_034	390562	6218457
BH_035	391167	6199147
BH_036	391526	6195132
BH_037	412878	6218179
BH_038	402064	6198440
BH_039	392256	6225987
BH_040	414135	6188778
BH_041	395712	6197063
BH_042	380726	6198930
BH_043	378951	6196499
BH_044	400272	6203167
BH_045	415859	6212685
BH_046	419331	6191950
BH_047	381213	6214384

Location ID	Easting [m]	Northing [m]
BH_048	407110	6189192
BH_049	377876	6193196
BH_050	370090	6192532
BH_051	412977	6205921
BH_052	409394	6200028
BH_053	414848	6226791
BH_054	420291	6199321
BH_055	416023	6202489
BH_056	398512	6208925
BH_057	416331	6219950
BH_058	400792	6219652
BH_059	410535	6190044
BH_060	414279	6216436
BH_061	383463	6193384
BH_062	378640	6209734
BH_063	396637	6234099
BH_064	407177	6222059
BH_065	417035	6188383
BH_066	399196	6215213
BH_067	411363	6223989
BH_068	406850	6227104
BH_069	379636	6187439
BH_070	408743	6194771
BH_071	386216	6196027
BH_072	396087	6185889
BH_073	413759	6199952
BH_074	406020	6223854
BH_075	401251	6188031
BH_076	400400	6222636
BH_077	370774	6198819
BH_078	422897	6205002
BH_079	385790	6213330
BH_080	369960	6188411
BH_081	394846	6223479
BH_082	423579	6226637
BH_083	391087	6188897

Location ID	Easting [m]	Northing [m]
BH_084	392211	6186071
BH_085	397161	6204539
BH_086	424055	6187858
BH_087	421870	6210919
BH_088	390533	6186731
BH_089	375058	6188493
BH_090	408335	6204915
BH_091	397289	6224008
BH_092	376523	6204159
BH_093	402909	6225227
BH_094	388104	6209739
BH_095	396898	6226993
BH_096	412194	6211891
BH_097	393086	6229237
BH_098	416184	6222988
BH_099	417294	6196625
BH_100	415454	6192133
BH_101	410161	6185870
BH_102	394798	6214259
BH_103	389503	6223344
BH_104	390156	6213253
BH_105	382337	6211558
BH_106	405582	6202272
BH_107	384276	6203793
BH_108	419068	6214404
BH_109	408350	6213104
BH_110	402557	6206755
BH_111	402700	6195508
BH_112	385643	6216368
BH_113	419476	6204260
BH_114	425651	6192297
BH_115	386816	6222761
BH_116	394179	6210032
BH_117	388073	6193360
BH_118	396394	6218698
BH_119	418725	6226609

Location ID	Easting [m]	Northing [m]
BH_120	421677	6189389
BH_121	373576	6195334
BH_122	410027	6227793
BH_123	374471	6200644
BH_124	375307	6197755
BH_125	404392	6218385
BH_126	421302	6185215
BH_127	411414	6202513
BH_128	388431	6189345
BH_129	398203	6206812
BH_130	380497	6207067
BH_131	420062	6207457
BH_132	377615	6200302
BH_133	404395	6187689
BH_134	406397	6197332
BH_135	393660	6193548
BH_136	394620	6200919
BH_137	380856	6203051
BH_138	410858	6215694
BH_139	386474	6219618
BH_140	400351	6228765
BH_141	413220	6221322
BH_142	423222	6215305
BH_143	422963	6191714
BH_144	388674	6204746
CPT_033	404407	6226575
CPT_034	412747	6229406
CPT_035	408186	6223301
CPT_036	407308	6210832
CPT_037	414069	6202065
CPT_038	409004	6187665
CPT_039	387519	6191194
CPT_040	377142	6208386
CPT_041	390937	6222631
CPT_042	388623	6226223
CPT_043	426140	6192403

Location ID	Easting [m]	Northing [m]
CPT_044	394682	6233675
CPT_045	396702	6236160
CPT_046	398070	6233387
CPT_047	406052	6224885
CPT_048	396768	6222872
CPT_049	393968	6211010
CPT_050	404132	6210143
CPT_051	382207	6207437
CPT_052	398724	6207948
CPT_053	403595	6200818
CPT_054	412829	6224307
CPT_055	411754	6221005
CPT_056	411689	6218944
CPT_057	404654	6195931
CPT_058	412341	6208853
CPT_059	412716	6213027
CPT_060	414247	6215406
CPT_061	420257	6213639
CPT_062	418776	6205132
CPT_063	423109	6204025
CPT_064	422914	6197843
CPT_065	420112	6201329
CPT_066	409443	6193900
CPT_067	408138	6214081
CPT_068	402193	6217909
CPT_069	405290	6193000
CPT_070	396853	6187078
CPT_071	403564	6184440
CPT_072	412572	6185369
CPT_073	402112	6207659
CPT_074	393609	6215025
CPT_075	387077	6215655
CPT_076	374568	6203735
CPT_077	374438	6199614
CPT_078	379586	6193567
CPT_079	374211	6192402

Location ID	Easting [m]	Northing [m]
CPT_080	391346	6197140
CPT_081	372403	6188940
CPT_082	385725	6211270
CPT_083	390790	6225669
CPT_084	396719	6229001
CPT_085	405190	6220605
CPT_086	402322	6222030
CPT_087	398382	6204804
CPT_088	398953	6199812
CPT_089	397210	6198411
CPT_090	394897	6202002
CPT_091	385416	6209156
CPT_092	416640	6222064
CPT_093	391820	6189056
CPT_094	395172	6218433
CPT_095	394015	6220229
CPT_096	418500	6188701
CPT_097	372793	6201304
CPT_098	379455	6204794
CPT_099	391394	6206359
CPT_100	389652	6204958
CPT_101	407112	6219998
CPT_102	395450	6204169
CPT_103	389260	6207943
CPT_104	424736	6224842
CPT_105	422962	6207062
CPT_106	375009	6194621
CPT_107	395563	6215449
CPT_108	416413	6214852
CPT_109	411333	6192263
CPT_110	414314	6186770
CPT_111	381590	6187862
CPT_112	395305	6191858
CPT_113	419360	6223677
CPT_114	414884	6197126
CPT_115	393657	6224244

Location ID	Easting [m]	Northing [m]
CPT_116	422507	6192639
CPT_117	400677	6223720
CPT_118	368038	6189017
CPT_119	410597	6222800
CPT_120	398562	6202797
CPT_121	406544	6194295
CPT_122	401316	6190092
CPT_123	399782	6218409
CPT_124	408316	6227422
CPT_125	410240	6211467
CPT_126	387061	6207466
CPT_127	411460	6227080
CPT_128	382030	6194097
CPT_129	382371	6197241
CPT_130	388249	6222049
CPT_131	375074	6196682
CPT_132	389797	6217268
CPT_133	378348	6200461
CPT_134	418514	6212238
CPT_135	389327	6194655
CPT_136	421188	6189283
CPT_137	384862	6206990
CPT_138	402570	6191387
CPT_139	389718	6191670
CPT_140	386410	6202209
CPT_141	408825	6189673
CPT_142	385708	6218428
CPT_143	416300	6203572
CPT_144	408042	6195643
CPT_145	407945	6192552
CPT_146	401364	6199311
CPT_147	394585	6230585
CPT_148	422801	6186563
CPT_149	409490	6218467
CPT_150	391099	6227783
CPT_151	400287	6211356

Location ID	Easting [m]	Northing [m]
CPT_152	376817	6198083
CPT_153	394049	6205911
CPT_154	395354	6185730
CPT_155	378983	6197529
CPT_156	379033	6191401
CPT_157	402683	6202667
CPT_158	371800	6192903
CPT_159	404082	6216272
CPT_160	383005	6209657
CPT_161	388414	6196504
CPT_162	381866	6204293
CPT_163	417947	6186534
CPT_164	394731	6227547
CPT_165	392910	6200548
CPT_166	402876	6224196
CPT_167	416705	6224124
CPT_168	411868	6216936
CPT_169	411723	6204626
CPT_170	397993	6192441
CPT_171	406069	6217726
CPT_172	419054	6190867
CPT_173	400417	6215477
CPT_174	388625	6210875
CPT_175	407716	6200688
CPT_176	408873	6198892
CPT_177	416871	6198580
CPT_178	388218	6205670
CPT_179	416314	6227109
CPT_180	419804	6183867
CPT_181	421494	6222093
CPT_182	411675	6195407
CPT_183	406592	6203514
CPT_184	420553	6192215
CPT_185	396217	6190010
CPT_186	401120	6209508
CPT_187	386639	6194073

Location ID	Easting [m]	Northing [m]
CPT_188	400697	6185865
CPT_189	399279	6194766
CPT_190	395466	6212358
CPT_191	377941	6195257
CPT_192	370220	6196653
CPT_193	408203	6216142
CPT_194	396248	6206388
CPT_195	380335	6201915
CPT_196	418483	6195859
CPT_197	385531	6205088
CPT_198	422359	6211025
CPT_199	422734	6199851
CPT_200	414996	6208406
CPT_201	386262	6220595
CPT_202	408610	6221346
CPT_203	386802	6199224
CPT_204	383330	6219959
CPT_205	394198	6187525
CPT_206	416643	6191368
CPT_207	408174	6184416
CPT_208	384620	6191589
CPT_209	391884	6191117
CPT_210	418221	6218313
CPT_211	419786	6206374
CPT_212	397354	6226069
CPT_213	384179	6200702
CPT_214	415112	6188989
CPT_215	416234	6216859
CPT_216	396426	6219728
CPT_217	418757	6227639
CPT_218	399391	6221394
CPT_219	422912	6213191
CPT_220	379424	6188416
CPT_221	412406	6210914
CPT_222	424182	6222675
CPT_223	391866	6213624

Location ID	Easting [m]	Northing [m]
CPT_224	415715	6185027
CPT_225	419639	6209412
CPT_226	383591	6212853
CPT_227	411724	6189278
CPT_228	401752	6227022
CPT_229	411870	6201588
CPT_230	373902	6190288
CPT_231	389129	6219170
CPT_232	414083	6225602
CPT_233	414653	6220610
CPT_234	408921	6208112
CPT_235	399149	6190645
CPT_236	388756	6199648
CPT_237	383511	6202604
CPT_238	397390	6196403
CPT_239	396572	6232039
CPT_240	376834	6190924
CPT_241	420650	6195306
CPT_242	376524	6188811
CPT_243	392274	6203480
CPT_244	419070	6199056
CPT_245	407422	6206764
CPT_246	402991	6220128
CPT_247	415470	6200322
CPT_248	394458	6195768
CPT_249	416741	6194458
CPT_250	422782	6209070
CPT_251	425716	6194358
CPT_252	372142	6196046
CPT_253	401314	6205440
CPT_254	411576	6207664
CPT_255	412261	6198604
CPT_256	397795	6216955
CPT_257	421153	6218949
CPT_258	403742	6197780
CPT_259	414362	6195989

Location ID	Easting [m]	Northing [m]
CPT_260	380073	6209021
CPT_261	423010	6216282
CPT_262	399033	6210061
CPT_263	419133	6216465
CPT_264	388397	6203663
CPT_265	422572	6194699
CPT_266	425032	6188070
CPT_267	381199	6190847
CPT_268	381361	6195998
CPT_269	392112	6198329
CPT_270	413954	6206133
CPT_271	416038	6210678
CPT_272	376589	6206219
CPT_273	377924	6202416
CPT_274	386200	6187838
CPT_275	390499	6201049
CPT_276	388070	6224056
CPT_277	372451	6198160
CPT_278	419019	6220533
CPT_279	405987	6222824
CPT_280	397031	6200418
CPT_281	384799	6189581
CPT_282	417619	6206928
CPT_283	404215	6189697
CPT_284	387745	6213754
CPT_285	368412	6193191
CPT_286	378543	6206643
CPT_287	370514	6190577
CPT_288	386248	6197058
CPT_289	392696	6216873
CPT_290	391722	6185966
CPT_291	400696	6201213
CPT_292	381948	6199195
CPT_293	396834	6209585
CPT_294	390077	6187655
CPT_295	421091	6186192

Location ID	Easting [m]	Northing [m]
CPT_296	405663	6212522
CPT_297	384457	6186437
CPT_298	423856	6227721
CPT_299	391817	6219752
CPT_300	414344	6218496
CPT_301	384017	6195551
CPT_302	404246	6206075
CPT_303	381979	6215573
CPT_304	395126	6193866
CPT_305	398885	6228447
CPT_306	403385	6186447
CPT_307	394767	6197881
CPT_308	419670	6225790
CPT_309	421103	6225078
CPT_310	420129	6194170
CPT_311	383837	6197558
CPT_312	421122	6202571
CPT_313	394569	6222396
CPT_314	391705	6193124
CPT_315	417945	6201882
CPT_316	393381	6207813
CPT_317	402423	6194425
CPT_318	391441	6230926
CPT_319	400110	6198016
CPT_320	391736	6209503
CPT_321	413744	6191762
CPT_322	402030	6212757
CPT_323	406773	6186158
CPT_324	405972	6214635
CPT_325	398642	6213046
CPT_326	405550	6201242
CPT_327	379682	6212006
CPT_328	415159	6213557
CPT_329	410826	6214664
CPT_330	406426	6198363
CPT_331	405533	6208401

Location ID	Easting [m]	Northing [m]
CPT_332	409736	6203172
CPT_333	410906	6224914
CPT_334	384177	6216050
CPT_335	398840	6188532
CPT_336	414542	6193982

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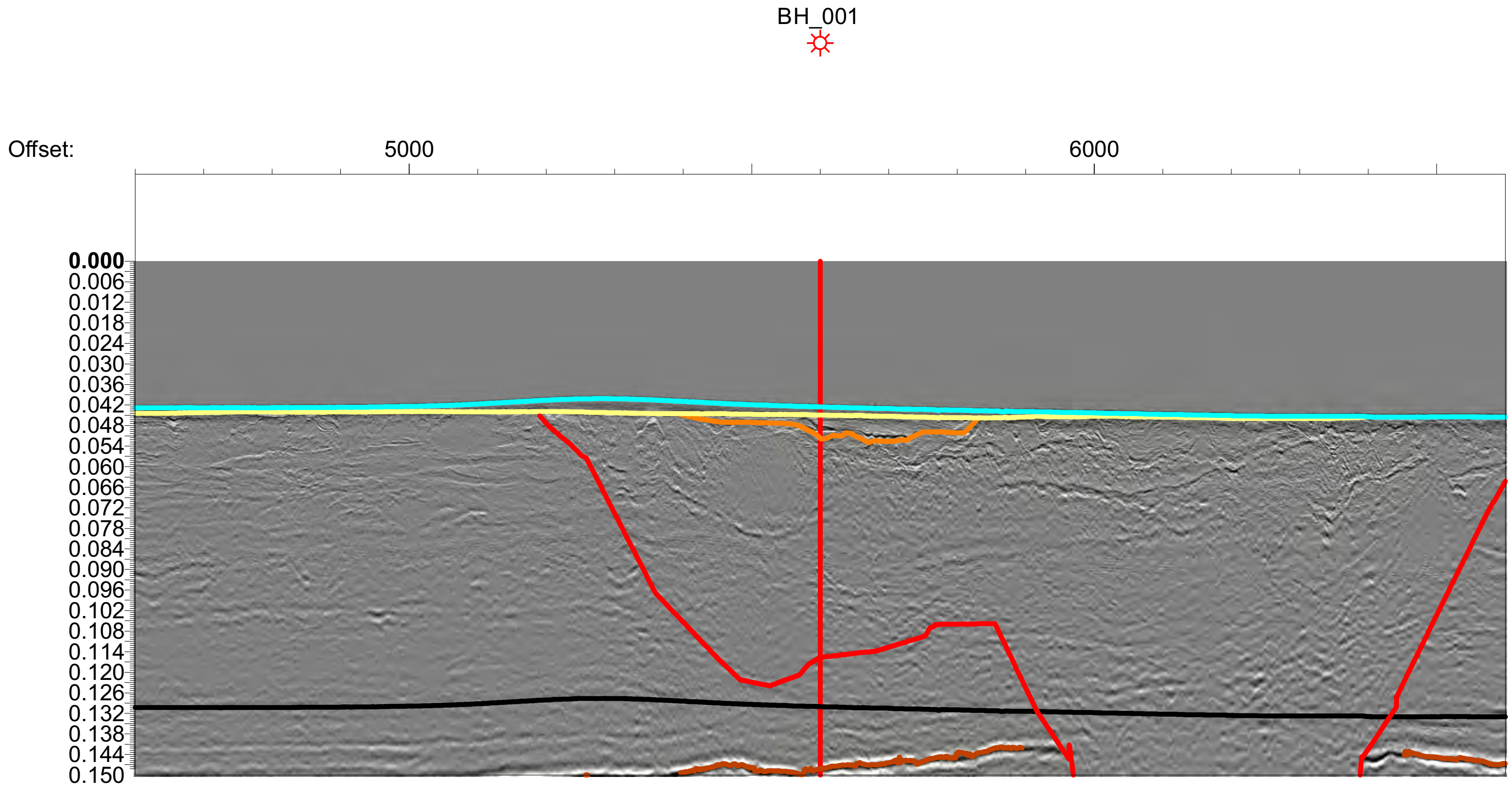
7. Digital Deliverables

The final deliverables were structured as per Table 7.1.

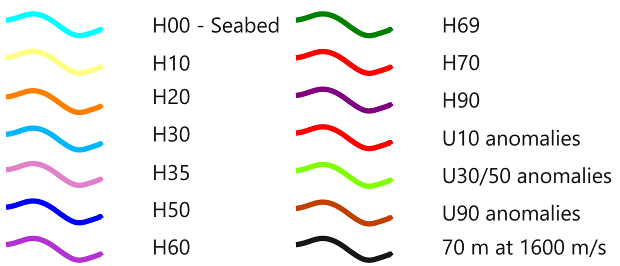
Table 7.1: Summary of digital deliverables

Sensor	Type	Description	Resolution	Format
MBES	Ungridded bathymetry	-	n/a	ASCII
	Grid (average)	MSL	0.25 m	ASCII
	Grid (average)	MSL	0.25 m	Geotiff
	SVP profiles	-	n/a	ASCII (csv)
SBP+ 2D UUHR	SBP + 2D UUHR	Processed	n/a	SEG-Y (time)
	SBP + 2D UUHR	Processed	n/a	SEG-Y (depth)
	2D UUHR	Processed	n/a	SEG-Y (velocity)
	Horizons	MSL	n/a	ASCII (csv)
	Grids	MSL	5 m	Geotiff
	Grids	MSL	5 m	ASCII
	Grids	BSB	5 m	Geotiff
	Grids	BSB	5 m	ASCII
	Grids	Isochore	5 m	Geotiff
	Grids	Isochore	5 m	ASCII
	Kingdom project	SBP + 2D UUHR		Time (both) + depth (both)
TSG	Vessel tracks	MBES, SBP, 2D UUHR	n/a	Shp
	SBP Target list	SBP + 2D UUHR	n/a	Pts
	SBP Target list	SBP + 2D UUHR	n/a	Line feature
	SBP Target list	SBP + 2D UUHR	n/a	Polygon
	Survey ID tab	MBES, SBP, 2D UUHR	n/a	n/a

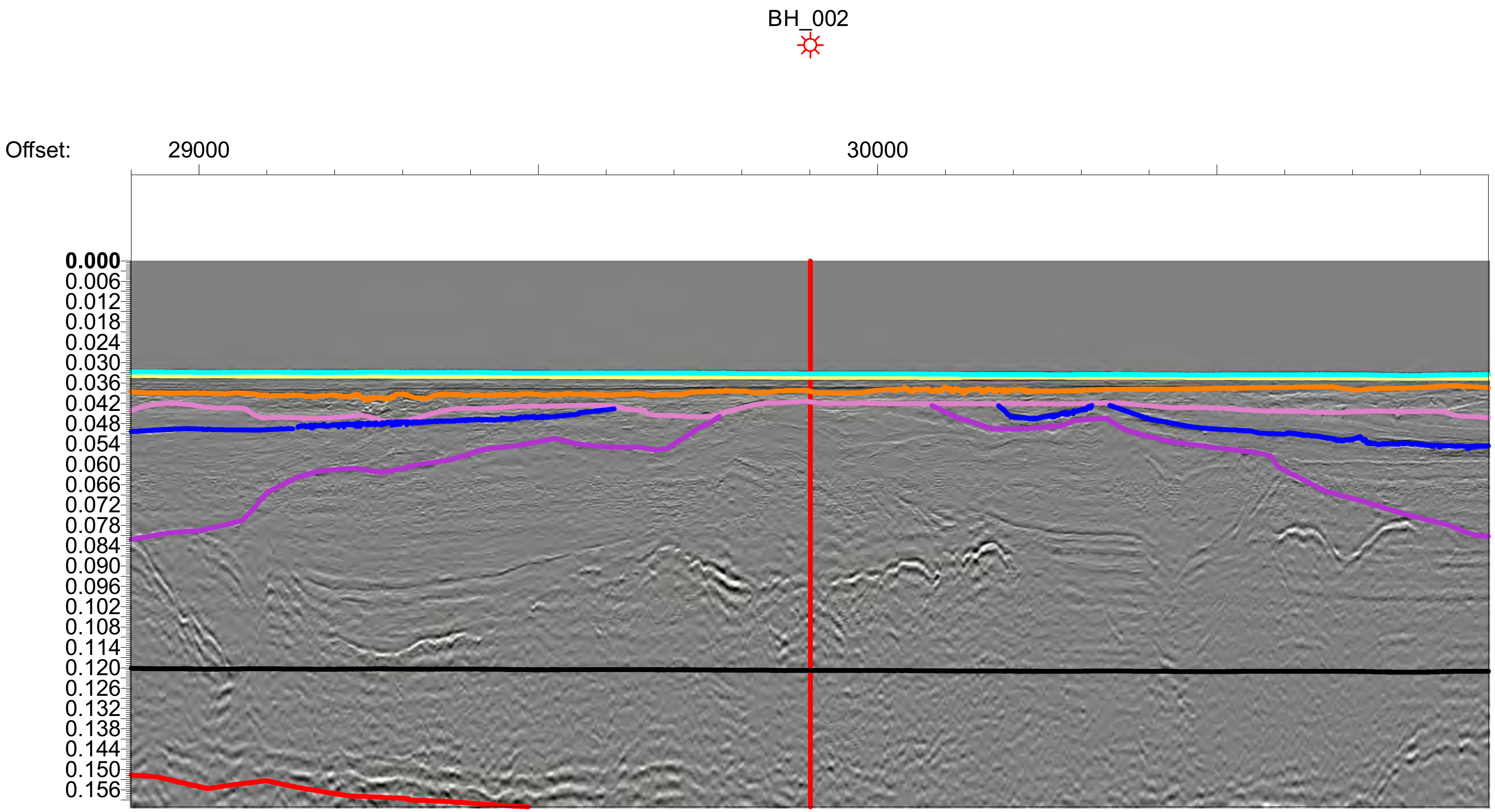
List of Plates



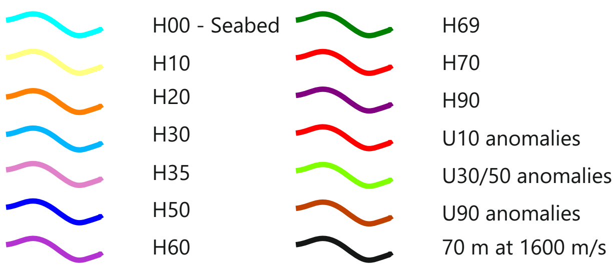
Location Name	Easting [m]	Northing [m]	Rationale
BH_001	379953	6191525	U20 channel and south-west U70 channel with seismic character variability



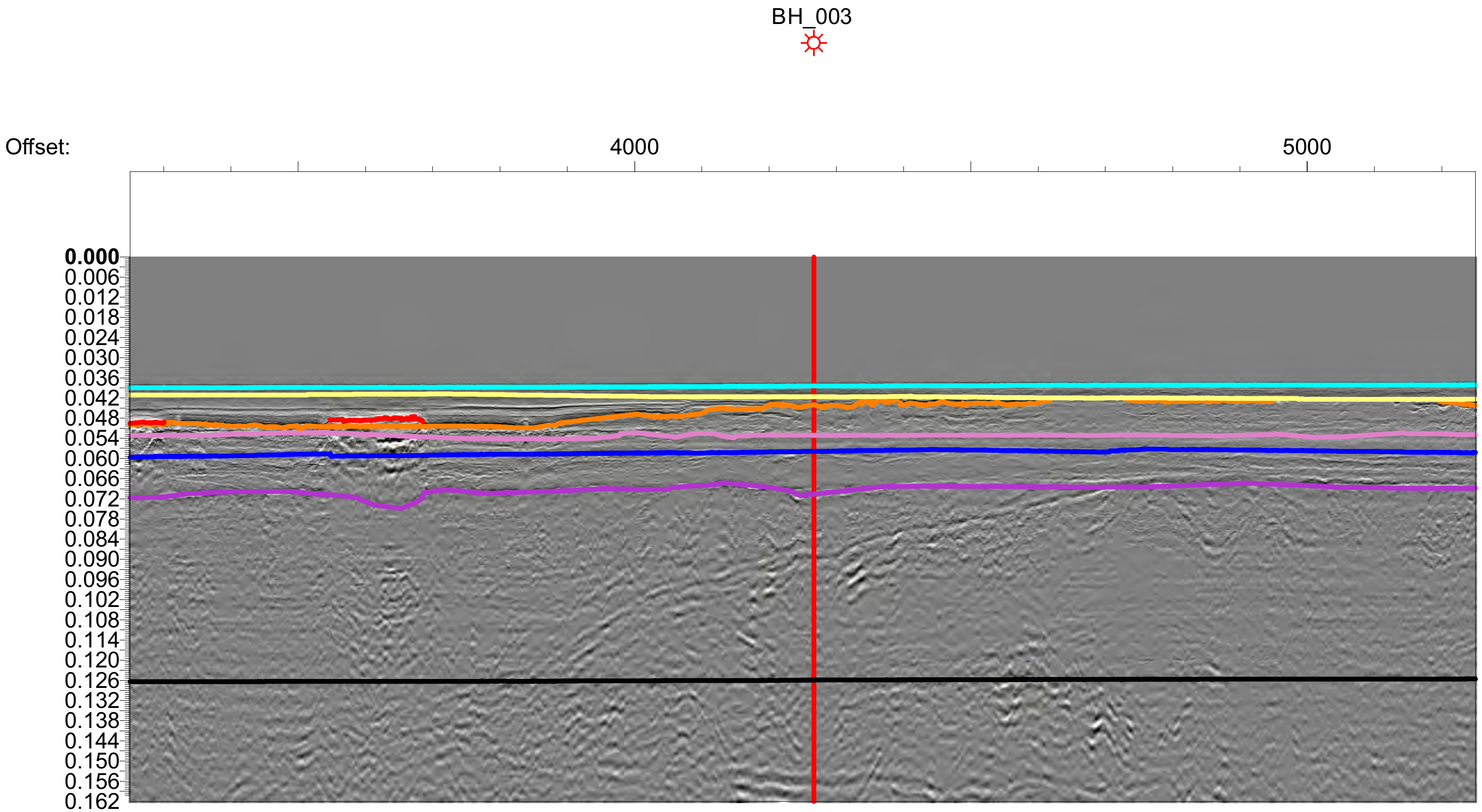
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
BH_002	409950	6212976	U20 sediment changes over depth and U70 seismic character changes



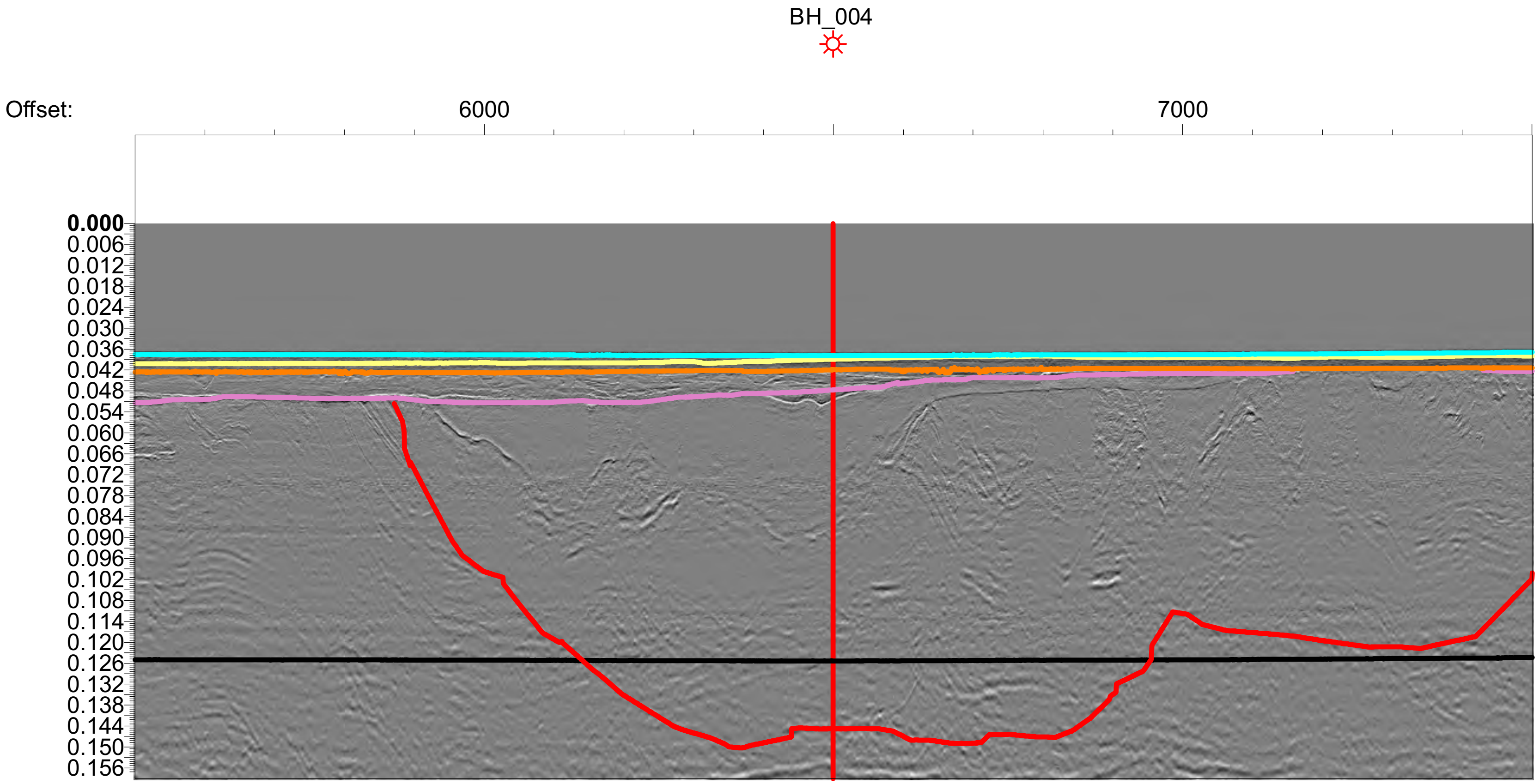
Interpretation	Location Assignment	Review
MvC	DS	CJS



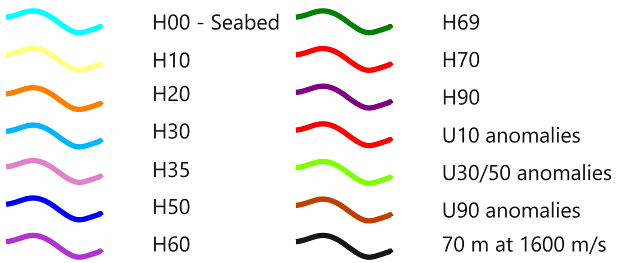
Location Name	Easting [m]	Northing [m]	Rationale
BH_003	405693	6226774	U70 seismic character changes / internal reflector. Location to characterise any geotechnical changes

H00 - Seabed	H69
H10	H70
H20	H90
H30	U10 anomalies
H35	U30/50 anomalies
H50	U90 anomalies
H60	70 m at 1600 m/s

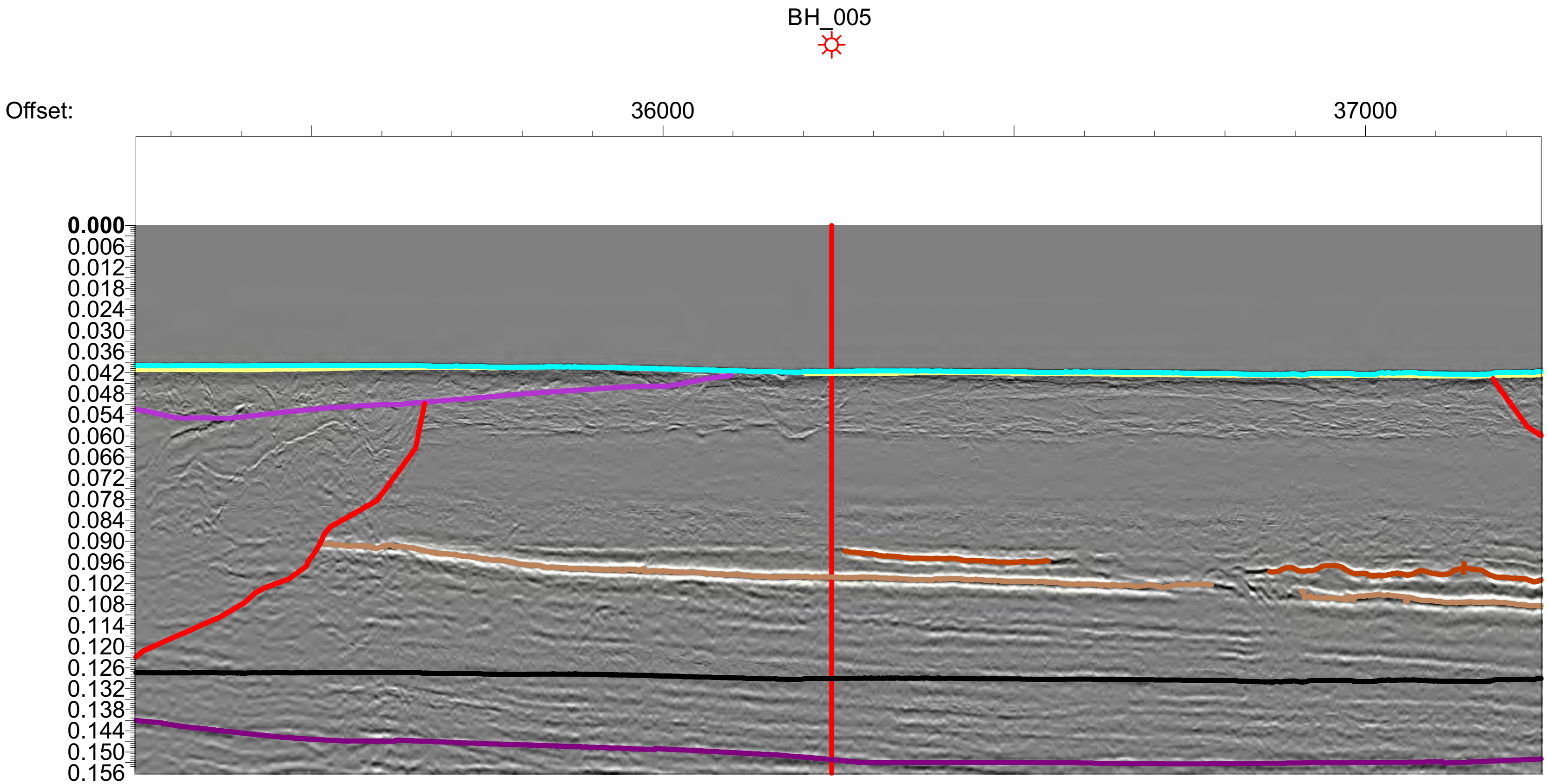
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
BH_004	394835	6216771	U70 seismic character changes / internal reflector. Location to characterise any geotechnical changes



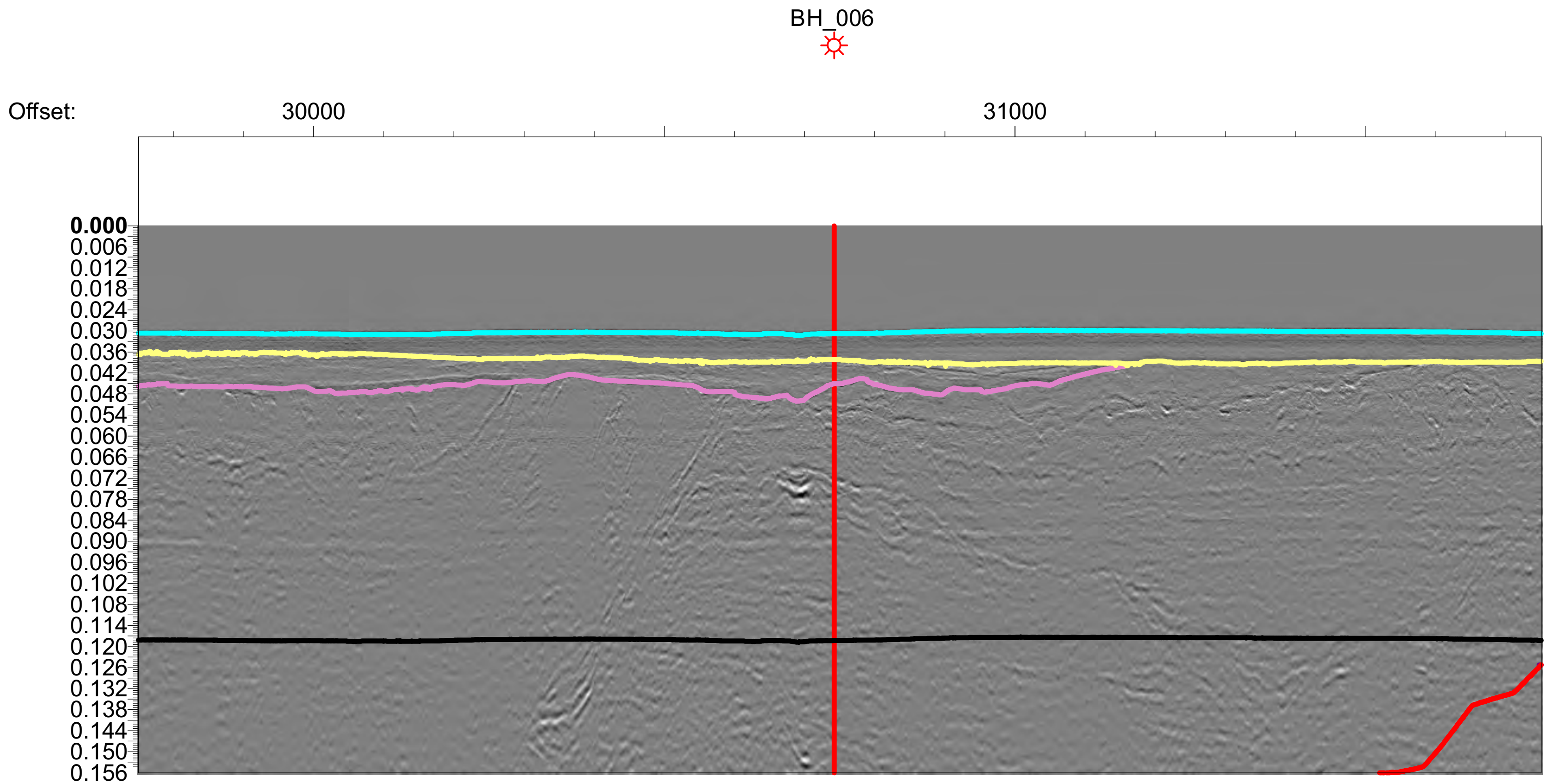
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
BH_005	388756	6196773	U90 Seismic character changes. Location to characterise possible geotechnical changes. Acoustic anomalies within U90 also sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

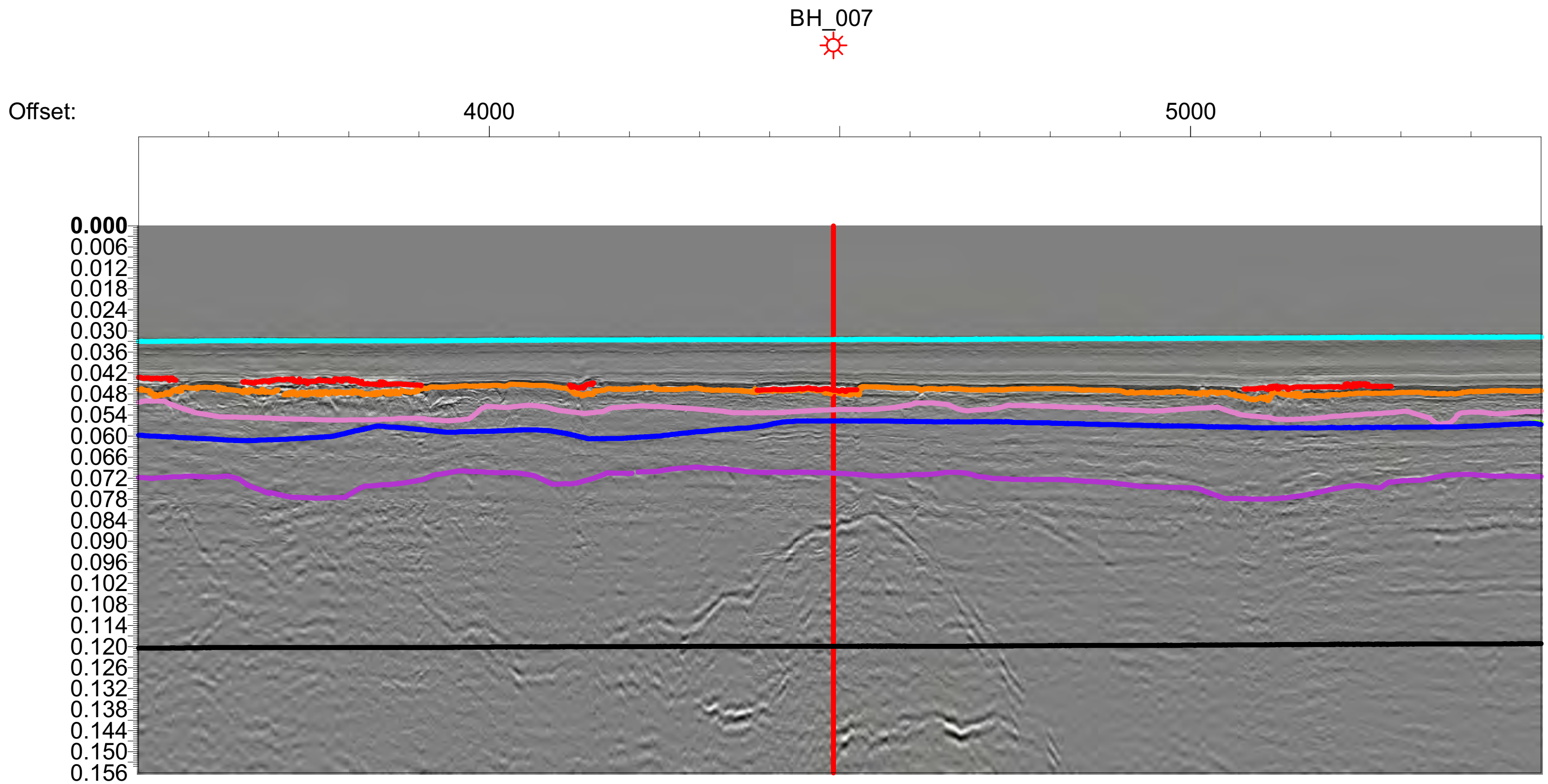
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
BH_006	394190	6196779	U70 channel in the south-west as well as seismic character changes / internal reflector. Location to characterise any geotechnical changes

H00 - Seabed	H69
H10	H70
H20	H90
H30	U10 anomalies
H35	U30/50 anomalies
H50	U90 anomalies
H60	70 m at 1600 m/s

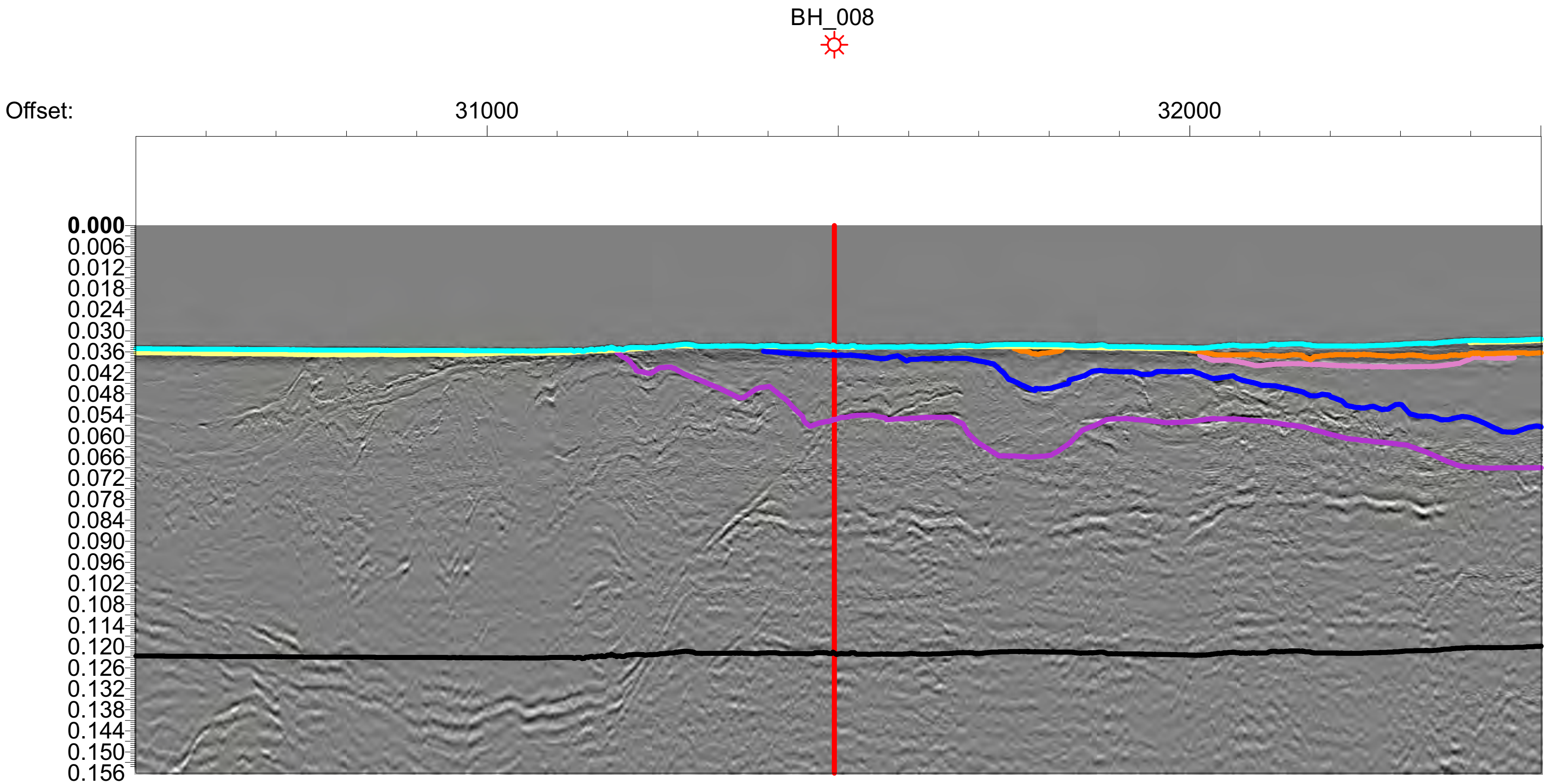
Interpretation	Location Assignment	Review
MvC	DS	CJS



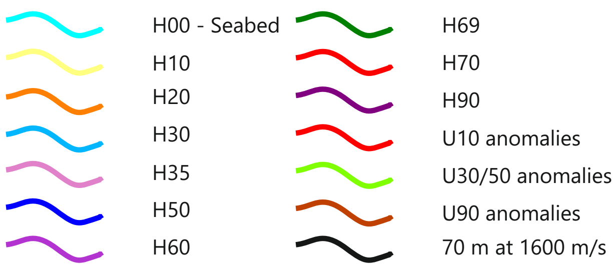
Location Name	Easting [m]	Northing [m]	Rationale
BH_007	420133	6196775	U20 variability and U20 seismic anomaly sampled. U70 seismic character changes also sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

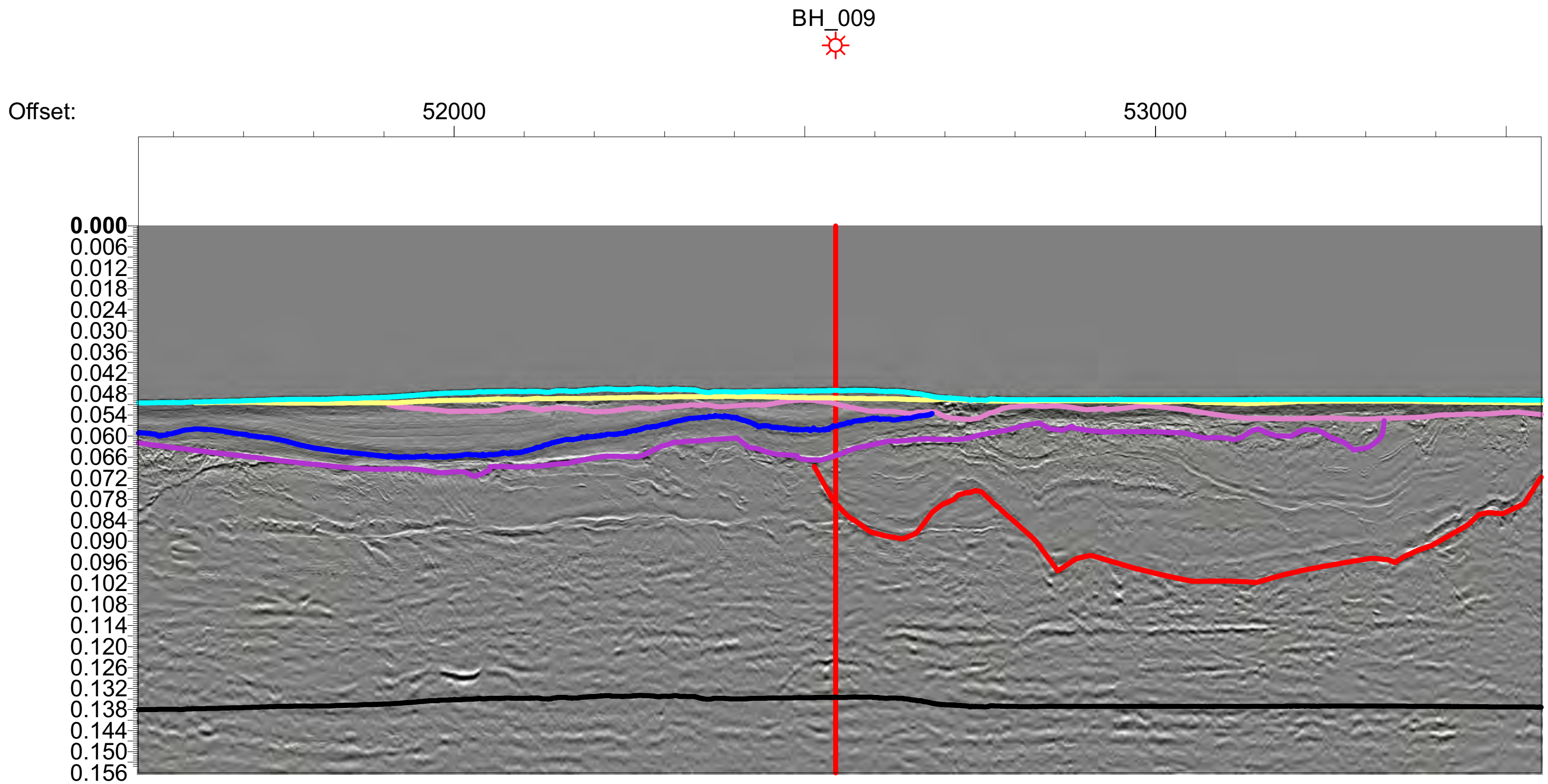
Interpretation	Location Assignment	Review
MvC	DS	CJS



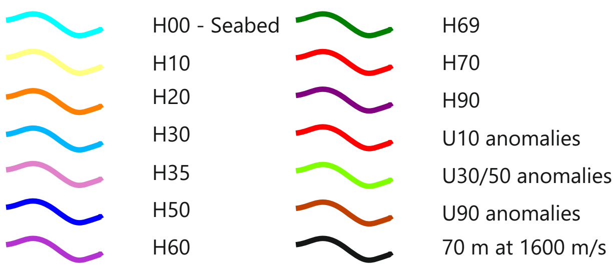
Location Name	Easting [m]	Northing [m]	Rationale
BH_008	402412	6186746	Internal variability within U70 sampled.



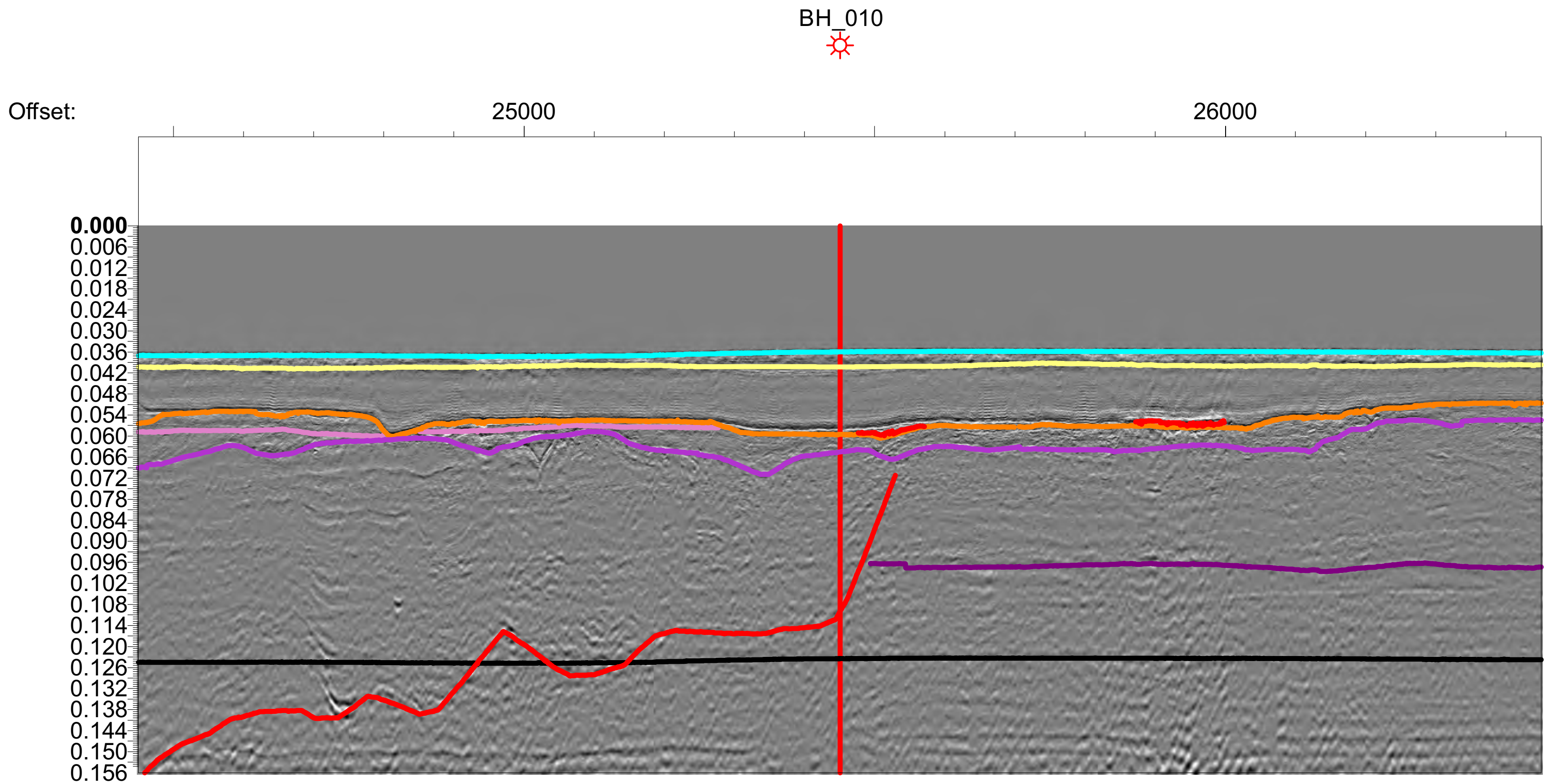
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
BH_009	372645	6196777	Shallow south-west U70 channel sampled



Interpretation	Location Assignment	Review
MvC	DS	CJS

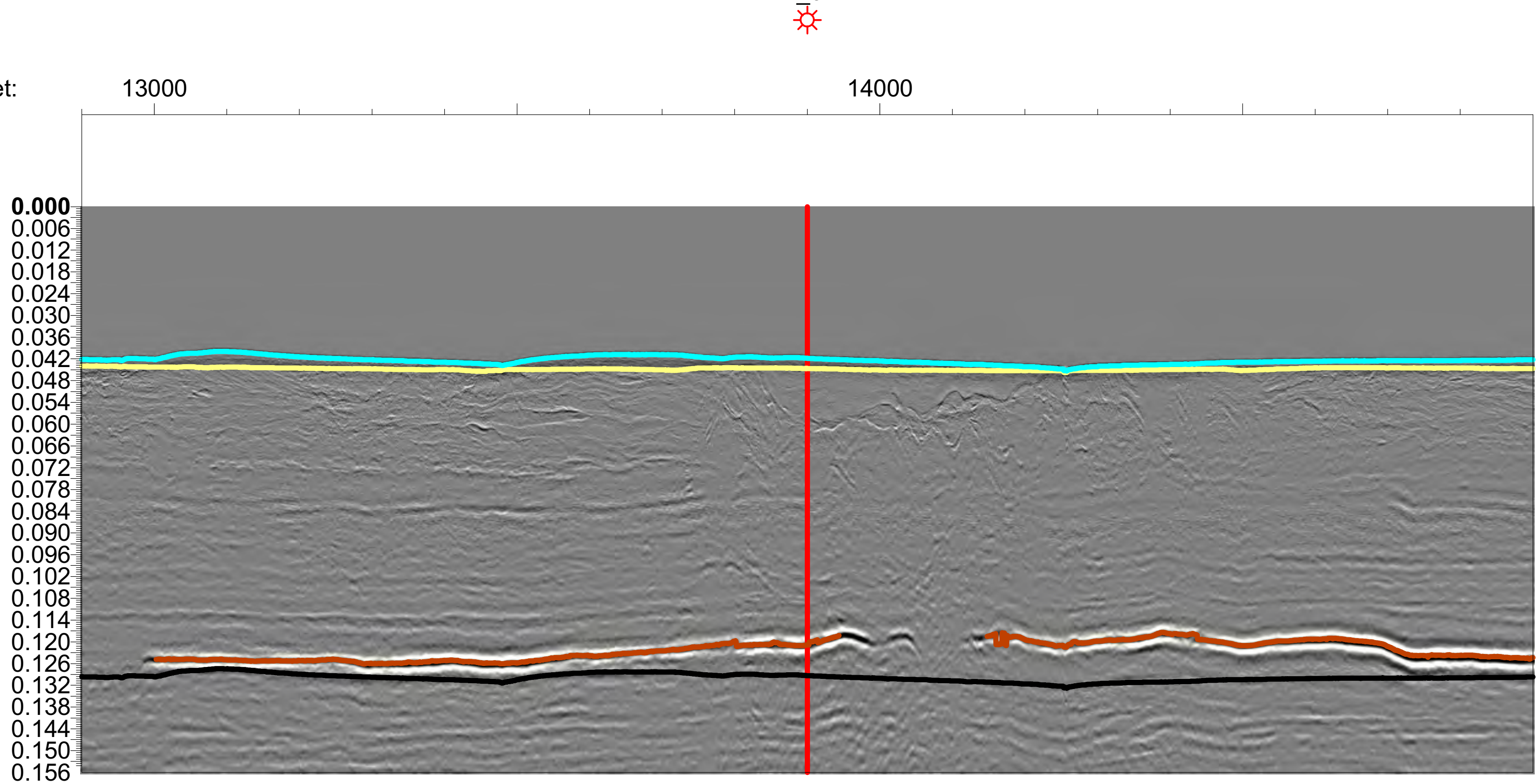


Location Name	Easting [m]	Northing [m]	Rationale
BH_010	389955	6210155.78	Internal changes in U20 sediments in area of thick deposits. U20 channel in west of site

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

Interpretation	Location Assignment	Review
MvC	DS	CJS

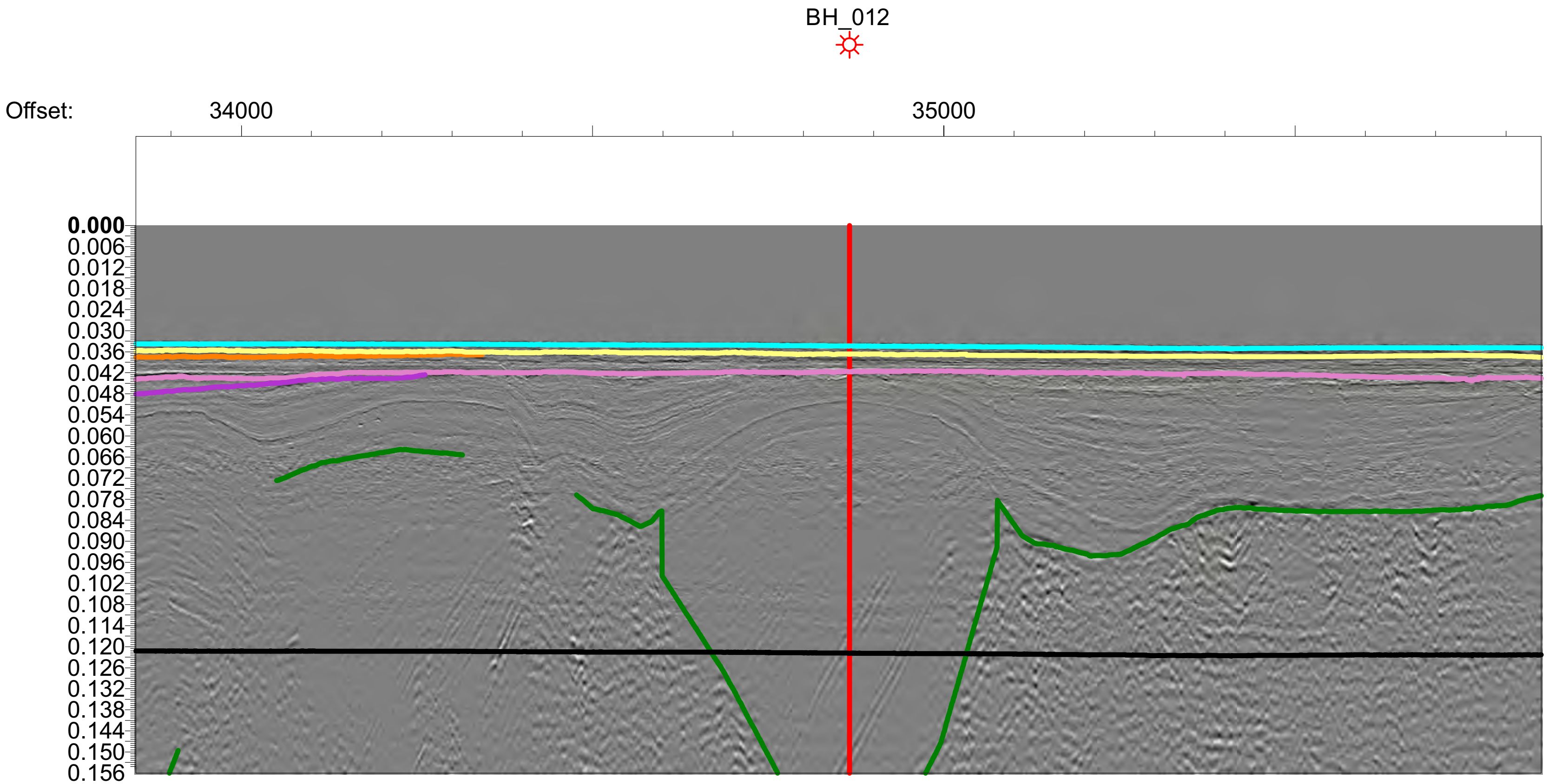
BH_011



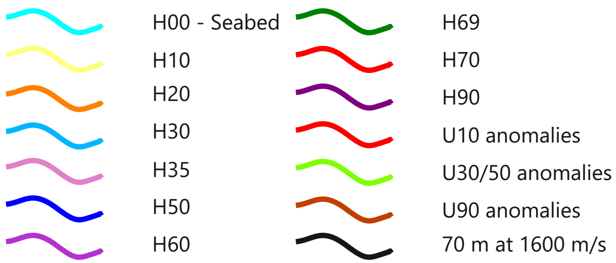
Location Name	Easting [m]	Northing [m]	Rationale
BH_011	379951	6199760	U90 Seismic character changes. Location to characterise possible geotechnical changes. Acoustic anomalies within U90 also sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

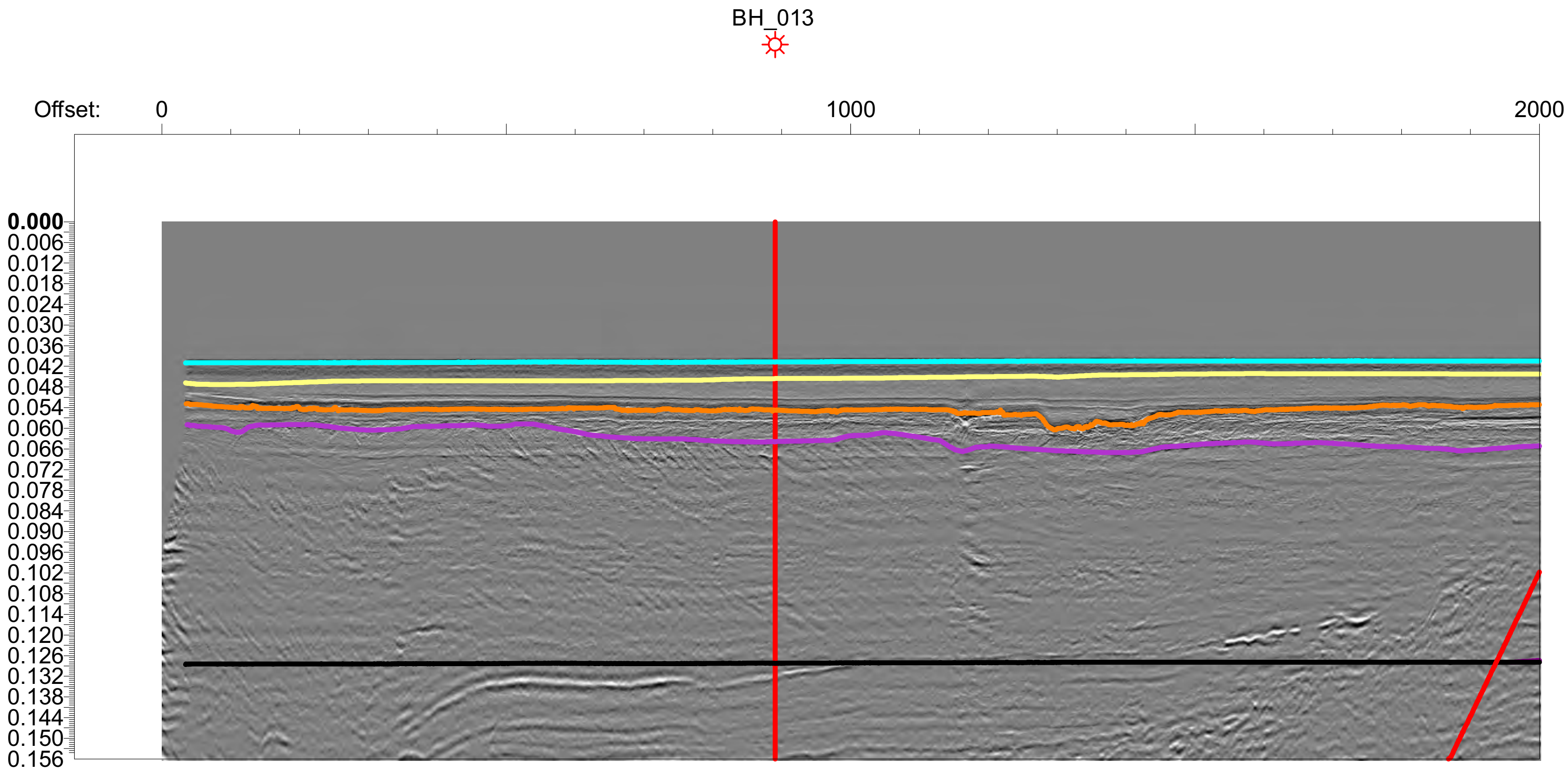
Interpretation	Location Assignment	Review
MvC	DS	CJS



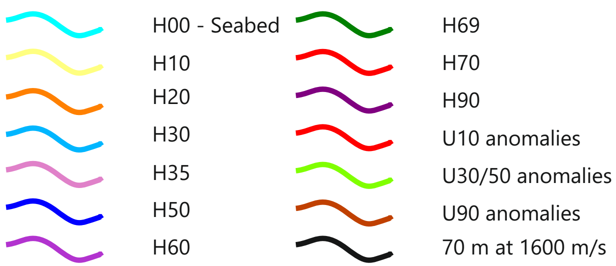
Location Name	Easting [m]	Northing [m]	Rationale
BH_012	399949	6218831	U69 inclined beds in east of site



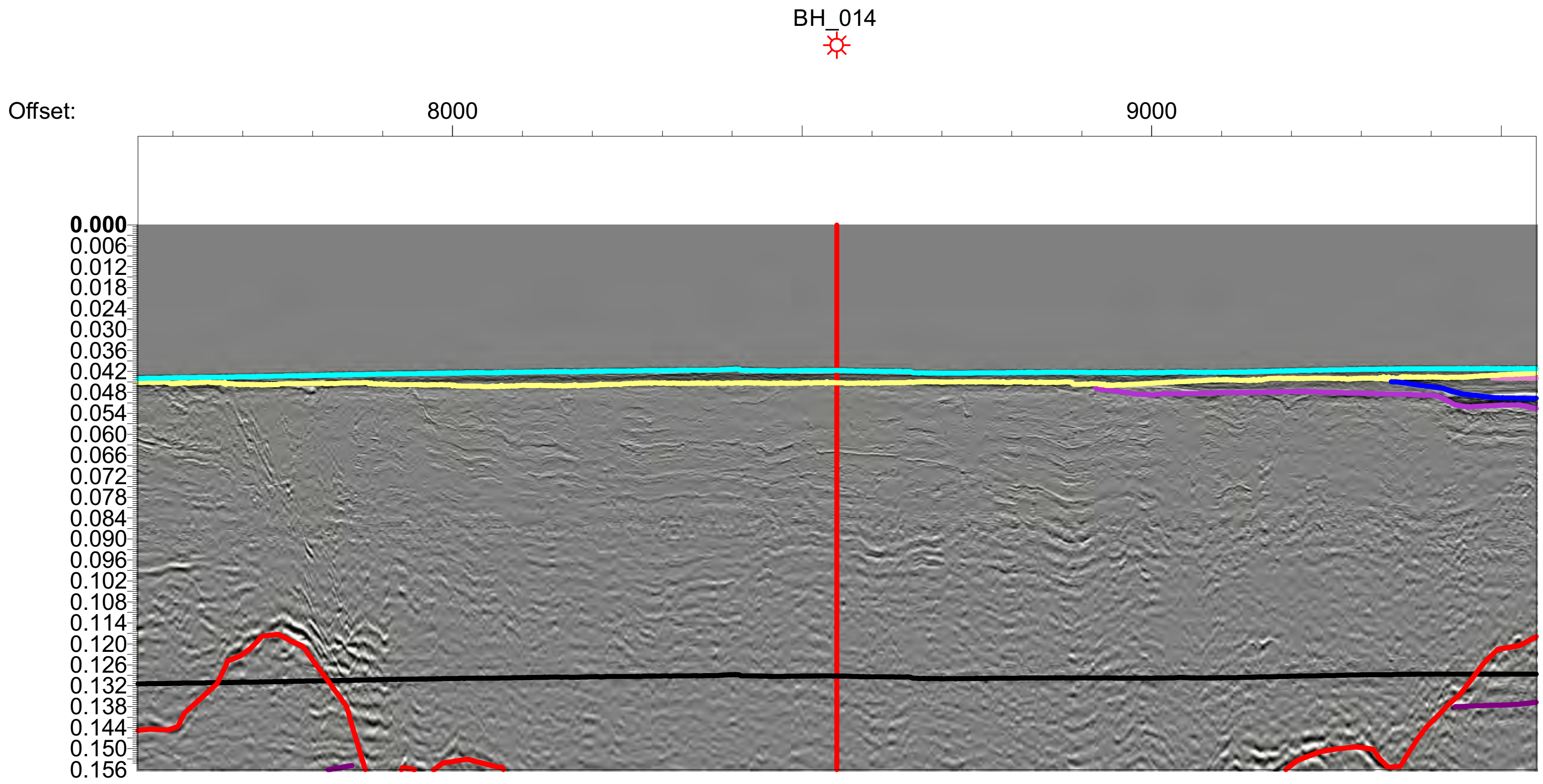
Interpretation	Location Assignment	Review
MvC	DS	CJS



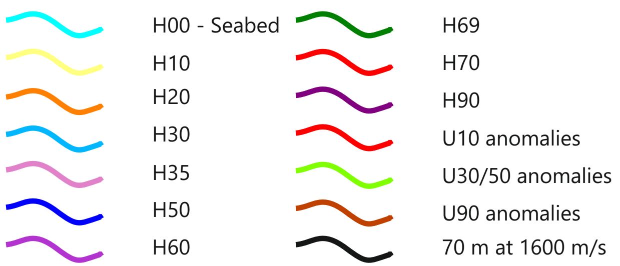
Location Name	Easting [m]	Northing [m]	Rationale
BH_013	381366	6216802	Thick U20 sediments to sample any changes with depth. U70 tunnel valley in west of site to be characterised.



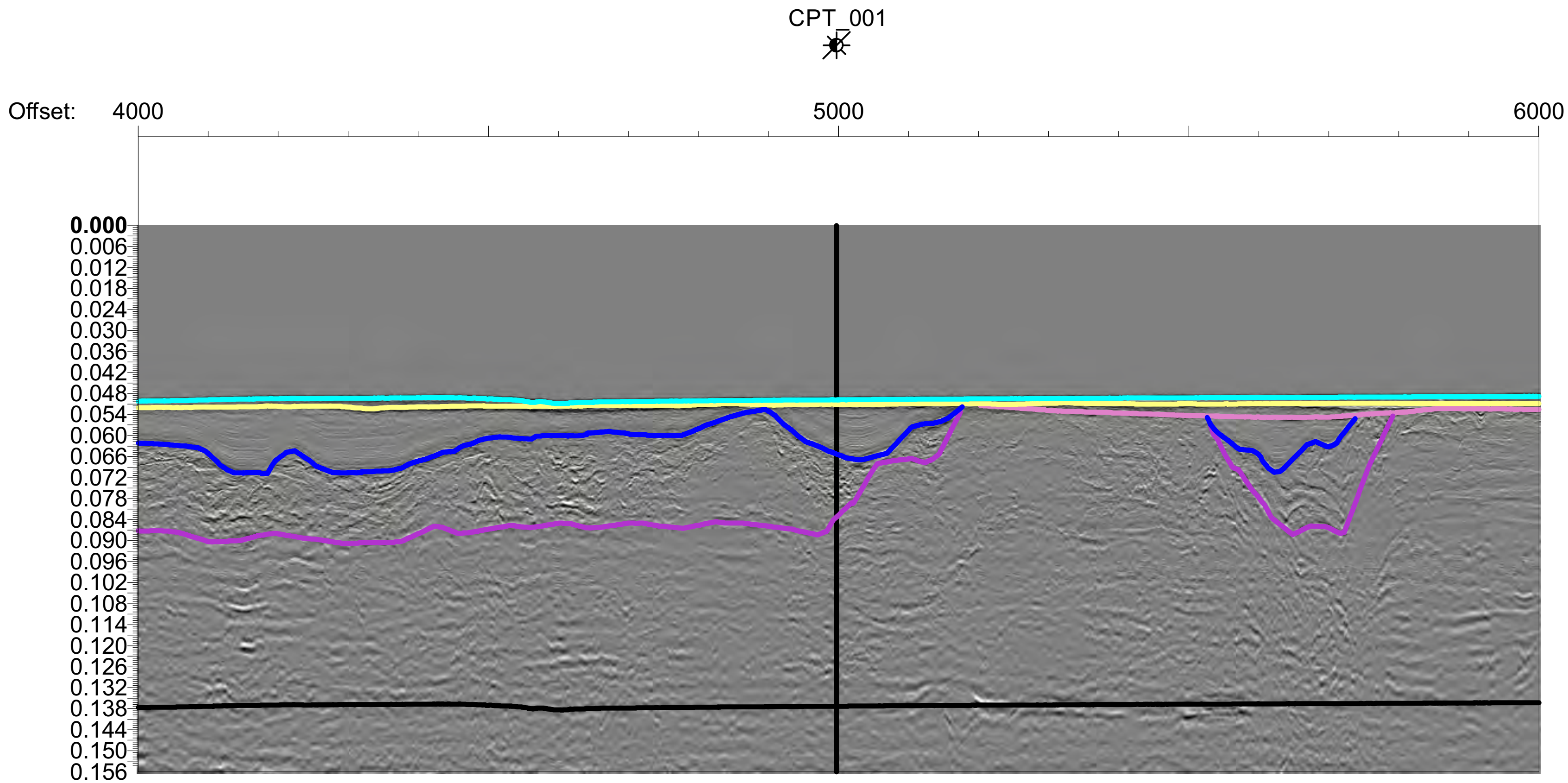
Interpretation	Location Assignment	Review
MvC	DS	CJS



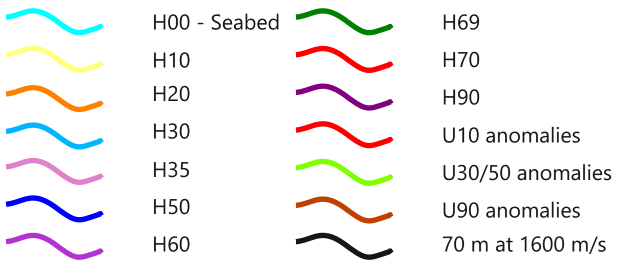
Location Name	Easting [m]	Northing [m]	Rationale
BH_014	382816	6206777	U70 tunnel valley in the west to be characterised. Internal variability sampled



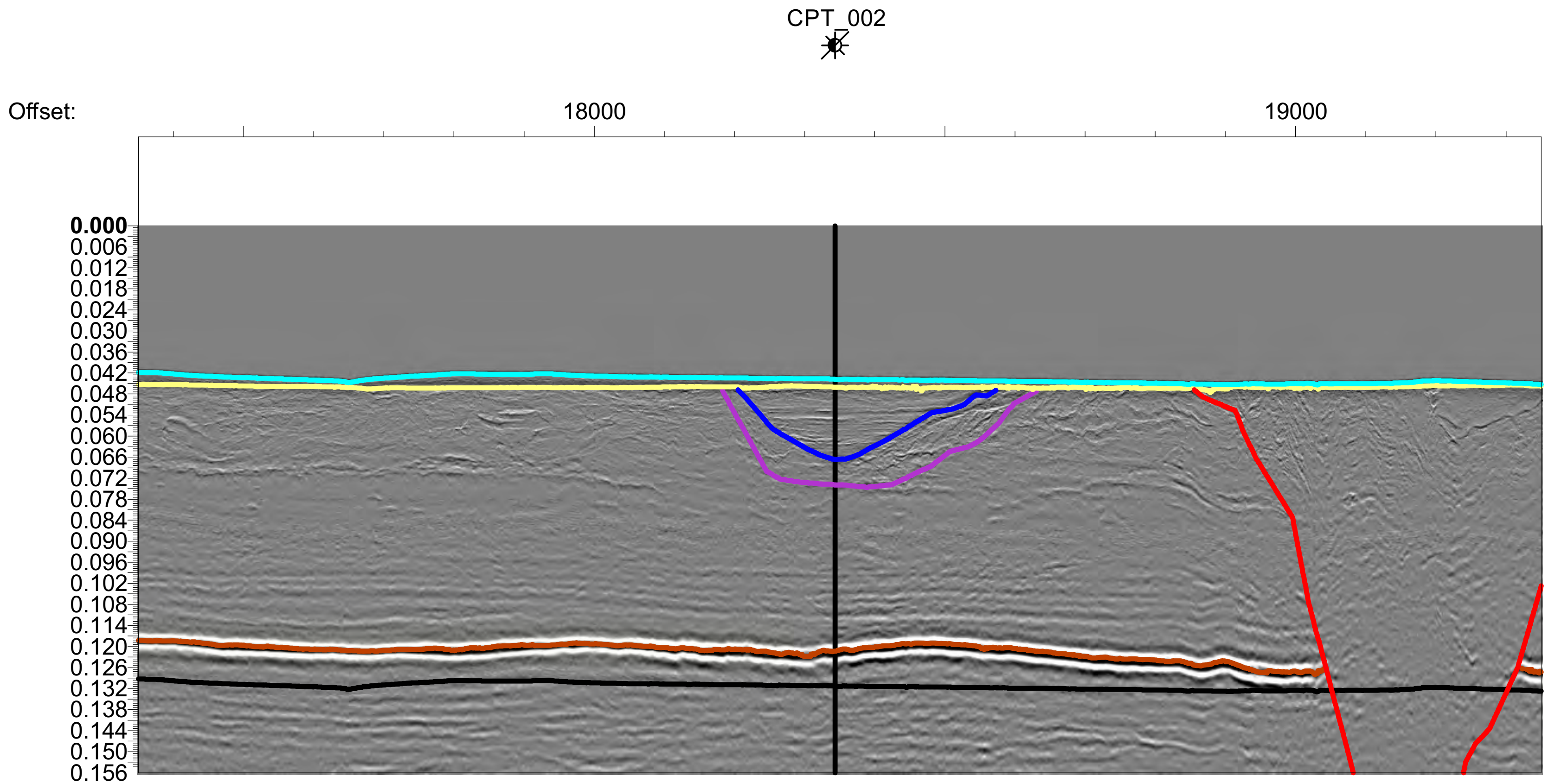
Interpretation	Location Assignment	Review
MvC	DS	CJS



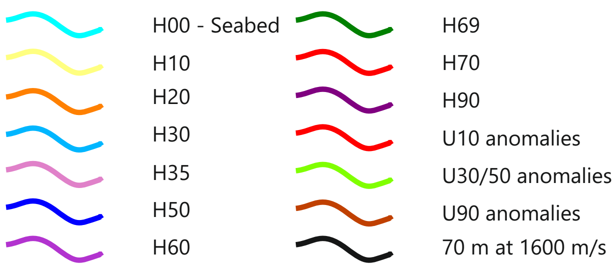
Location Name	Easting [m]	Northing [m]	Rationale
CPT_001	369948	6194485	Channelised area of U50 in the west of the site, U60 seismic character variability to be sampled



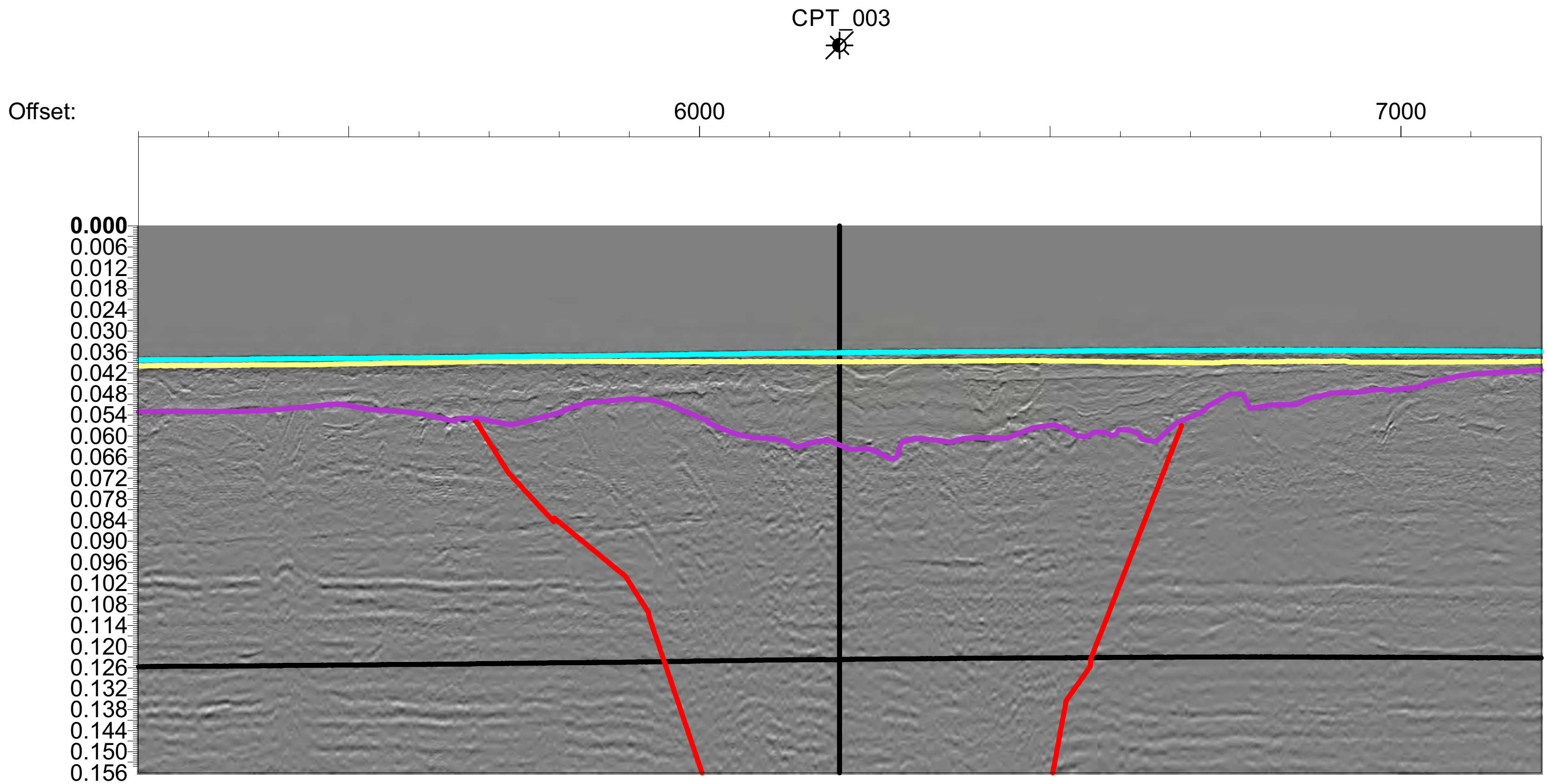
Interpretation	Location Assignment	Review
MvC	DS	CJS



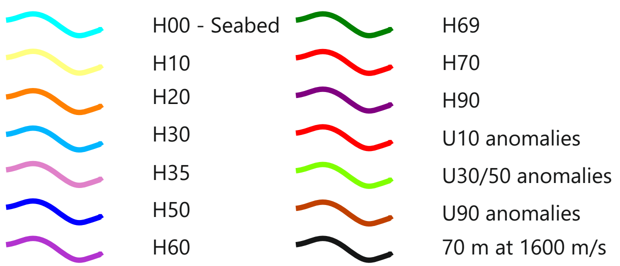
Location Name	Easting [m]	Northing [m]	Rationale
CPT_002	379950	6204168	Channelised area of U50 in the west of the site, U60 seismic character variability to be sampled



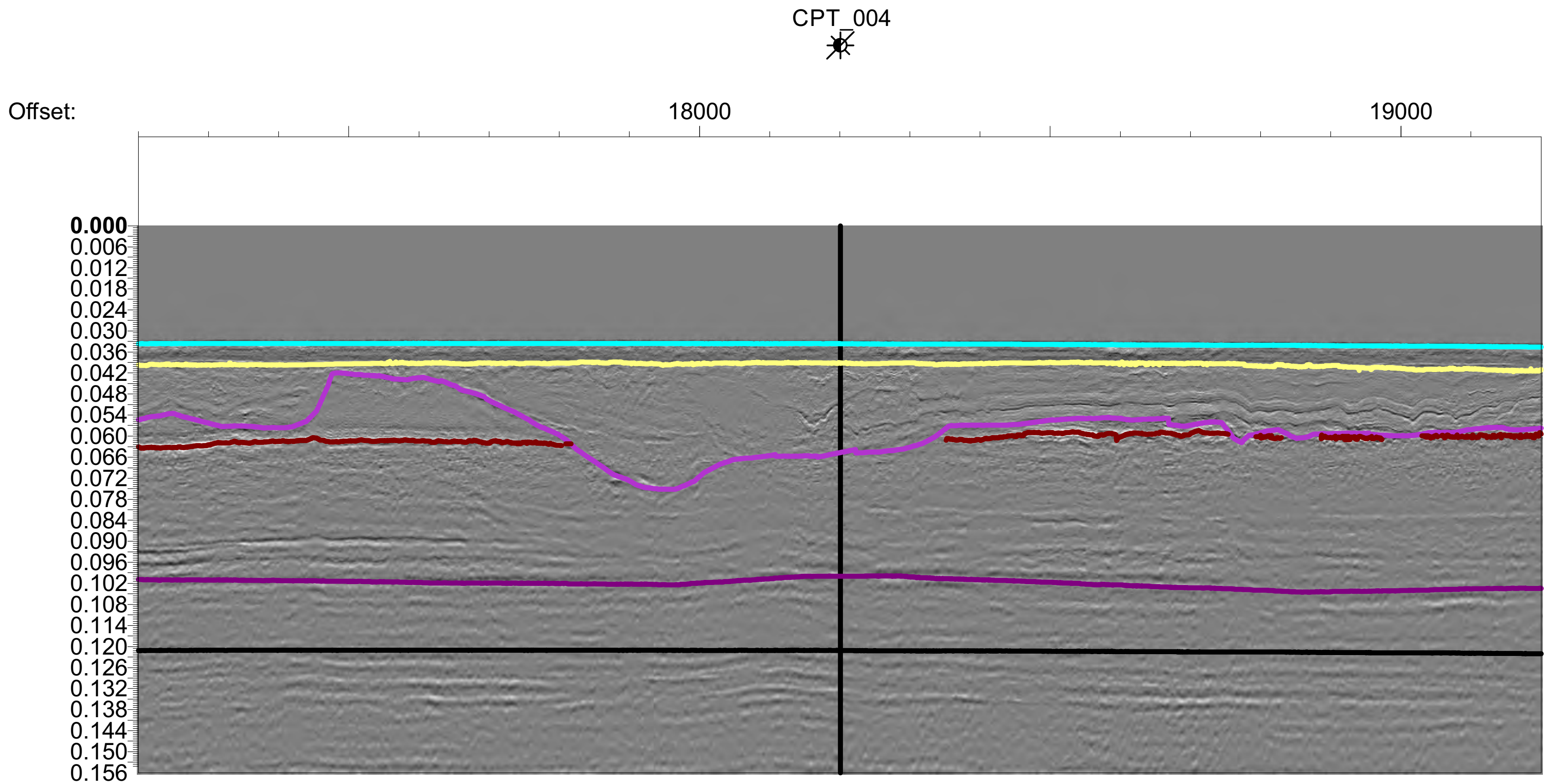
Interpretation	Location Assignment	Review
MvC	DS	CJS



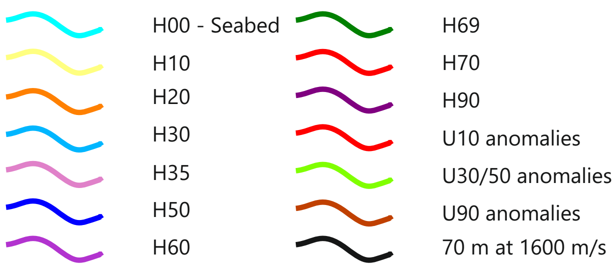
Location Name	Easting [m]	Northing [m]	Rationale
CPT_003	389948	6191219	U60 seismic character changes. Location may also sample U70 if penetrated by CPT



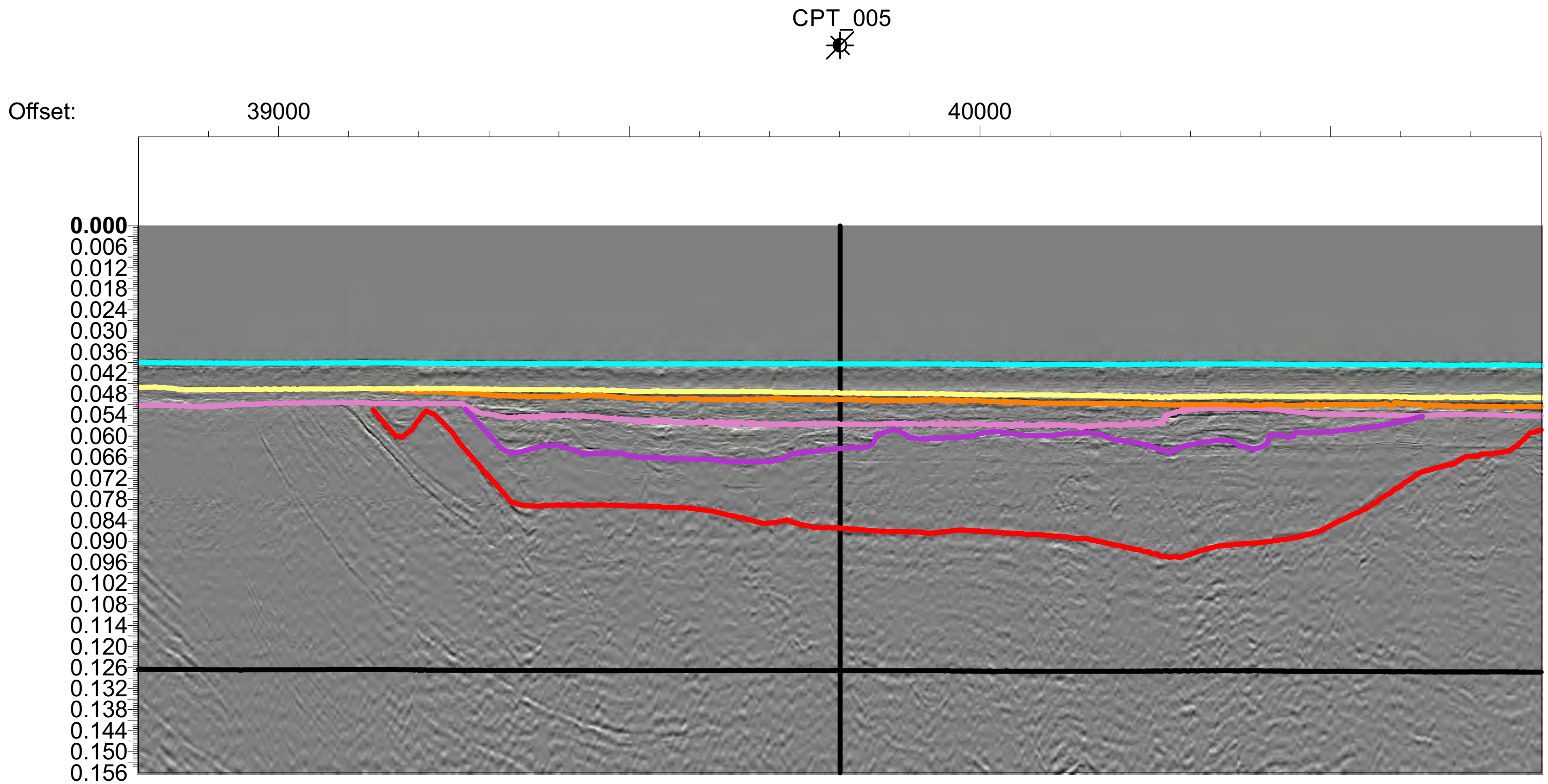
Interpretation	Location Assignment	Review
MvC	DS	CJS



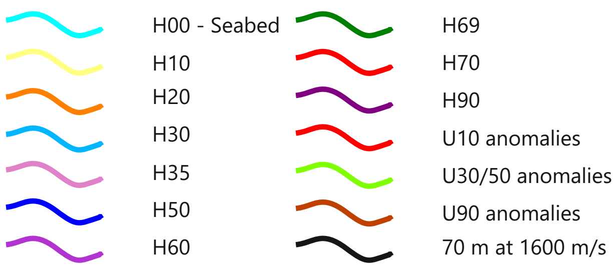
Location Name	Easting [m]	Northing [m]	Rationale
CPT_004	389956	6203023	Internal U60 seismic character changes to be sampled



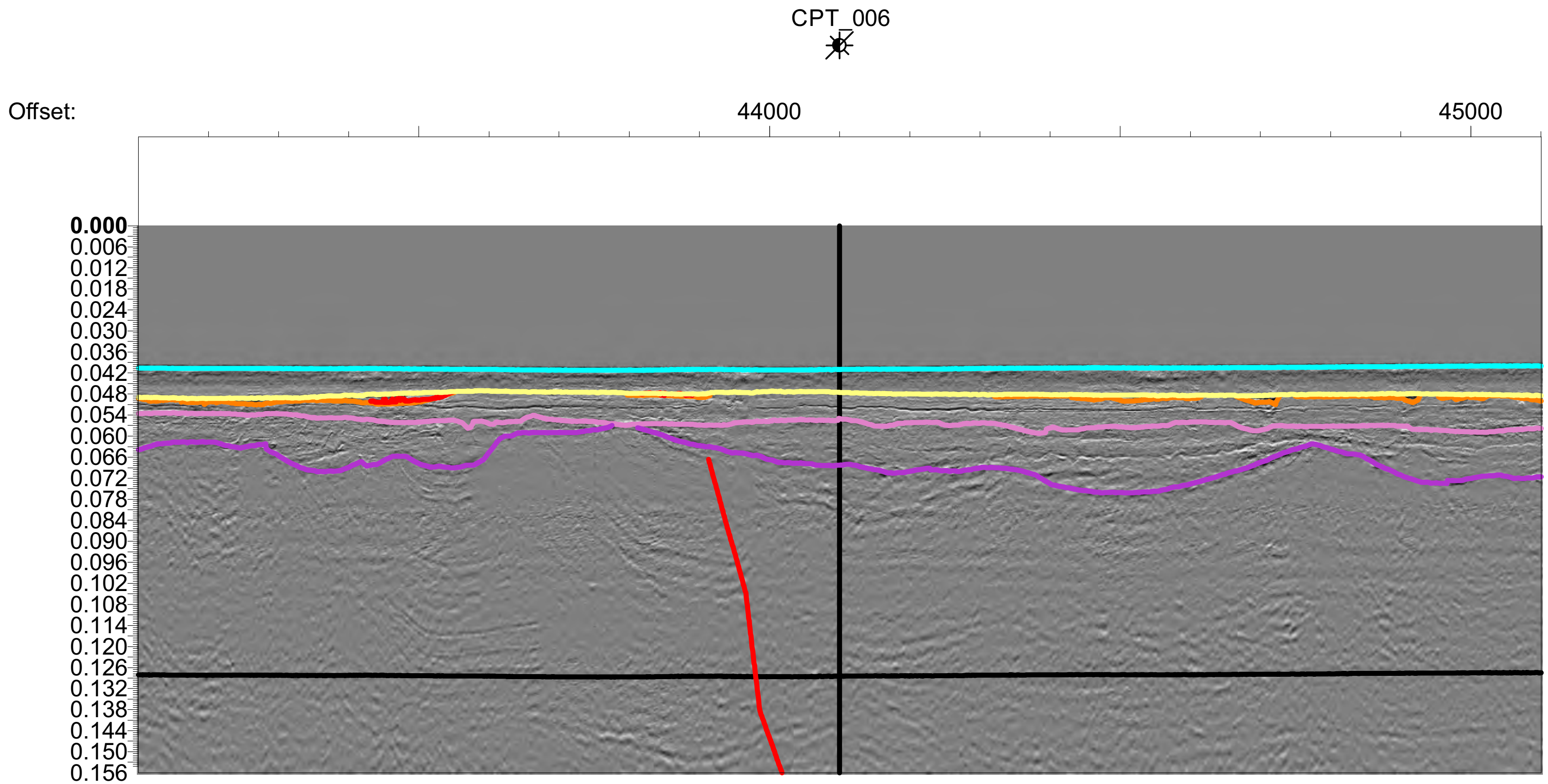
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_005	389953	6224272	Area of thick U10 sediments, area of thicker U35 sediments to be sampled



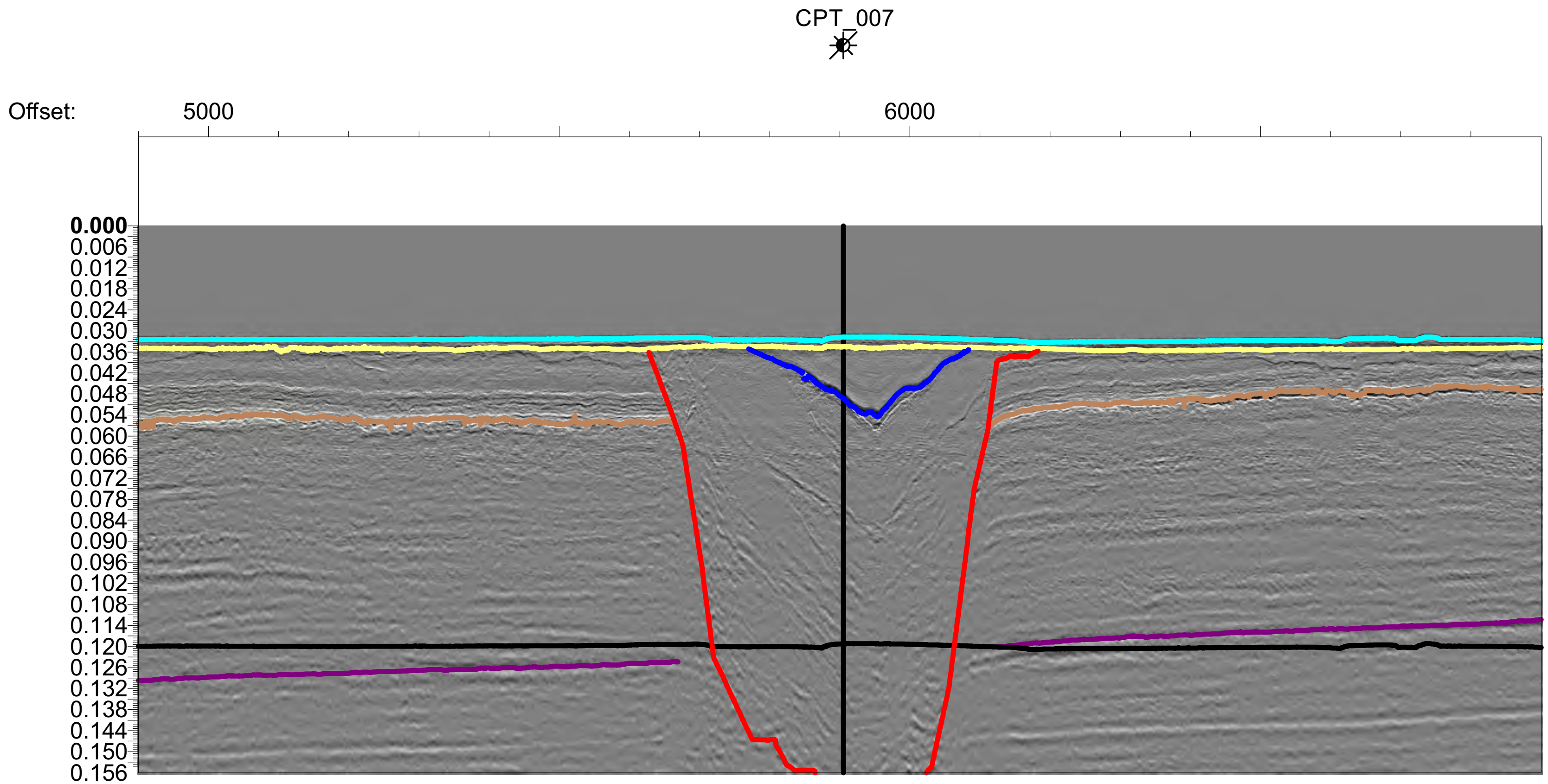
Interpretation	Location Assignment	Review
MvC	DS	CJS



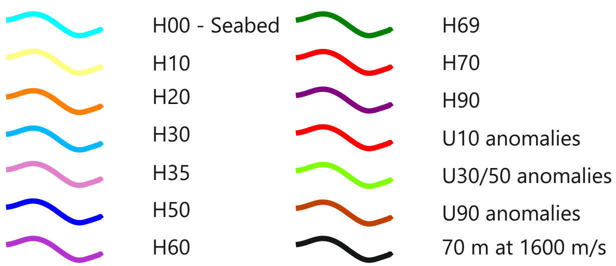
Location Name	Easting [m]	Northing [m]	Rationale
CPT_006	389950	6228502	Area of thick U10 sediments, U35 sediment variations with internal seismic reflector to be sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

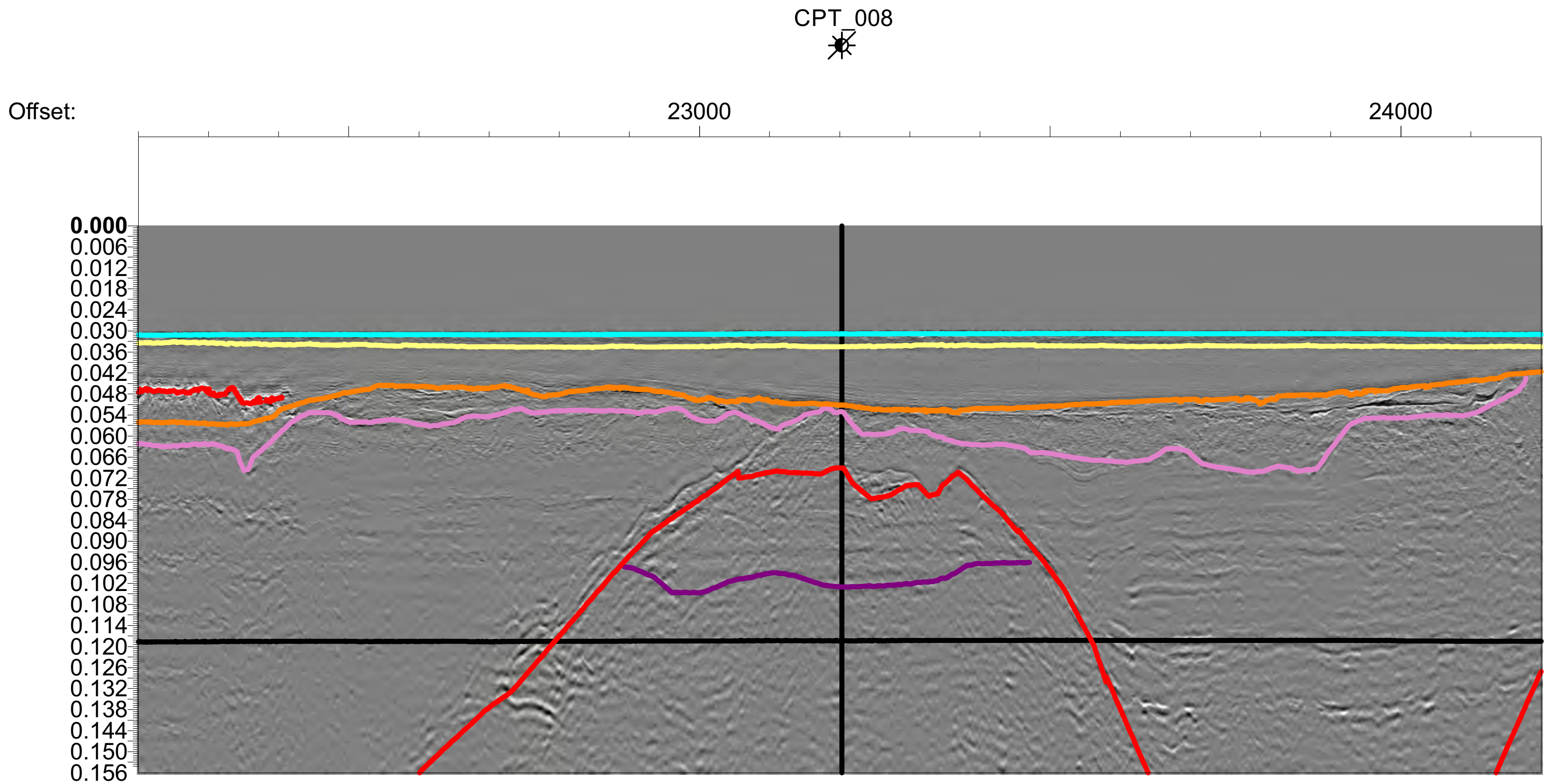
Interpretation	Location Assignment	Review
MvC	DS	CJS



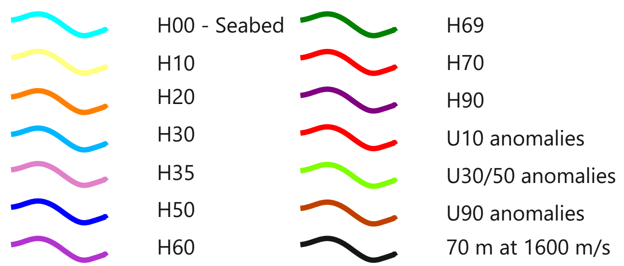
Location Name	Easting [m]	Northing [m]	Rationale
CPT_007	399944	6190076	Localised U50 channel to be sampled.



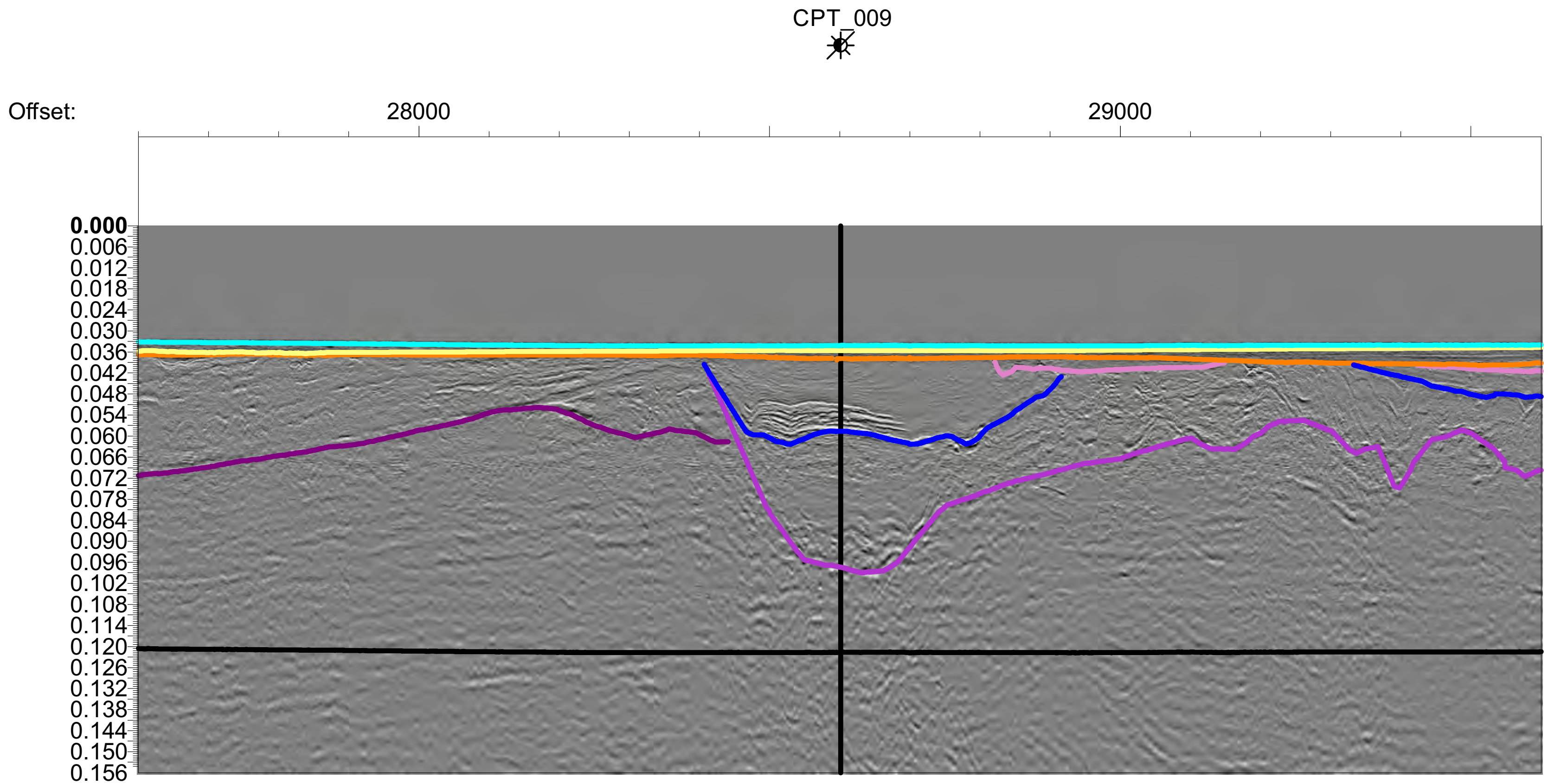
Interpretation	Location Assignment	Review
MvC	DS	CJS



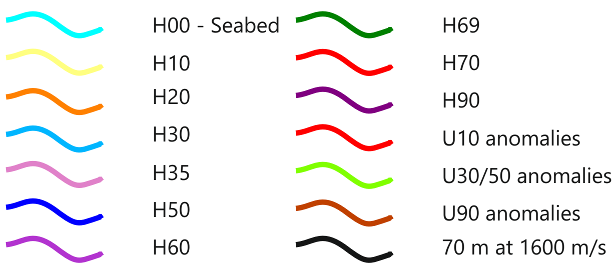
Location Name	Easting [m]	Northing [m]	Rationale
CPT_008	399944	6207251	Thick U20 sediments to be sampled to identify changes with depth



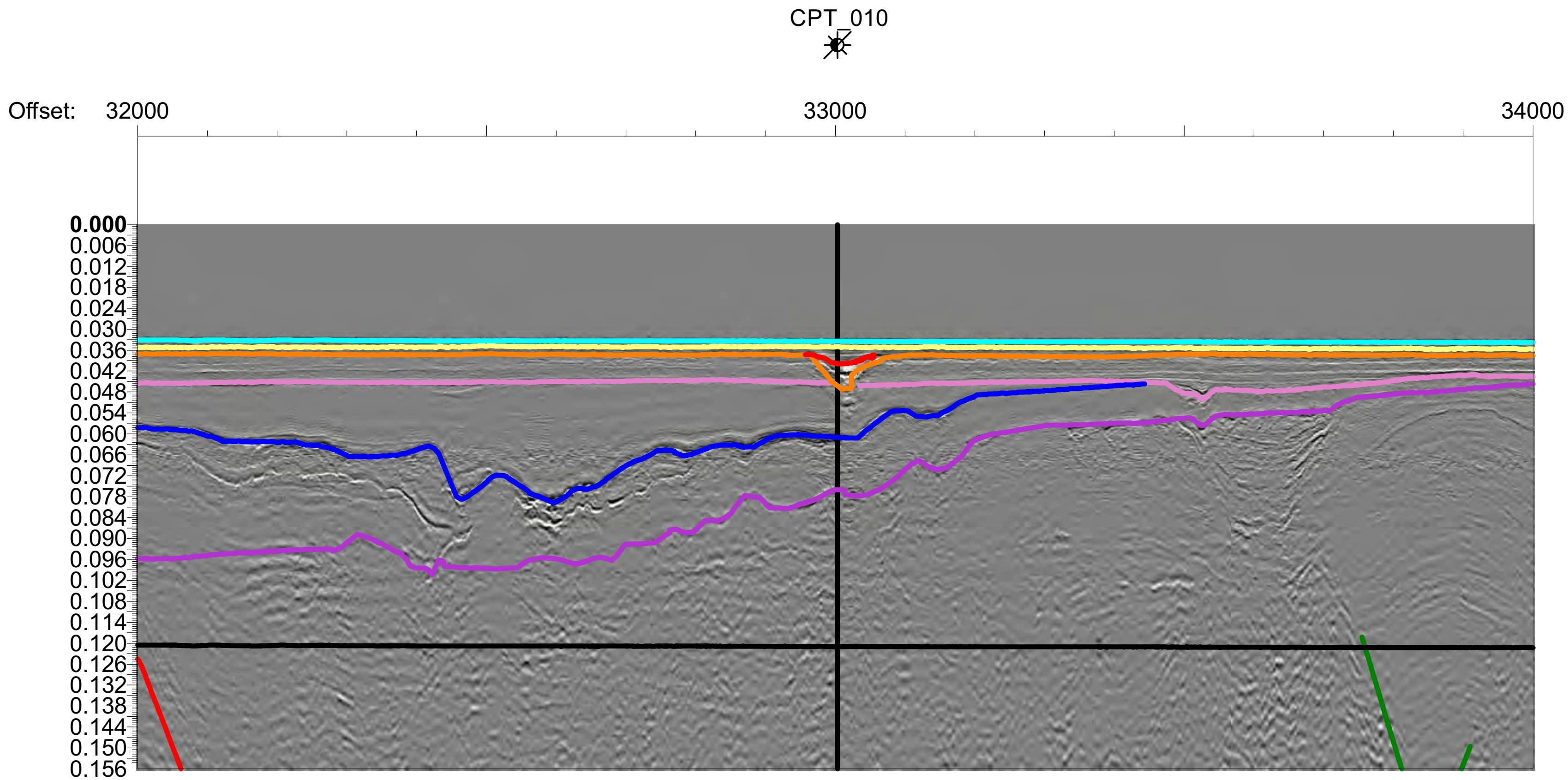
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_009	399966	6212610	U50 channel to be sampled. Change in seismic character within unit to be sampled



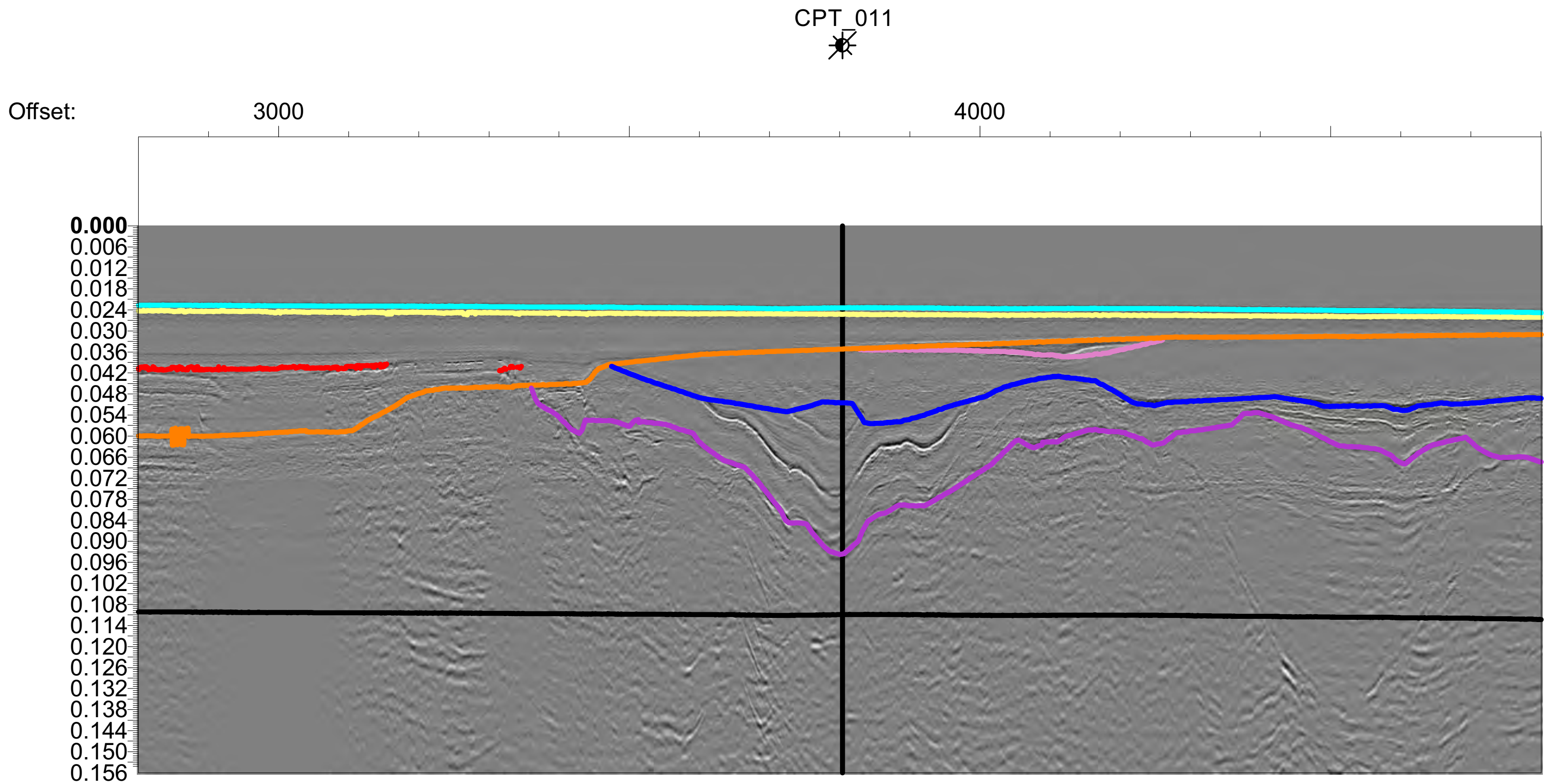
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_010	399955	6216981	U20 and associated seismic anomaly to be sampled

H00 - Seabed	H69
H10	H70
H20	H90
H30	U10 anomalies
H35	U30/50 anomalies
H50	U90 anomalies
H60	70 m at 1600 m/s

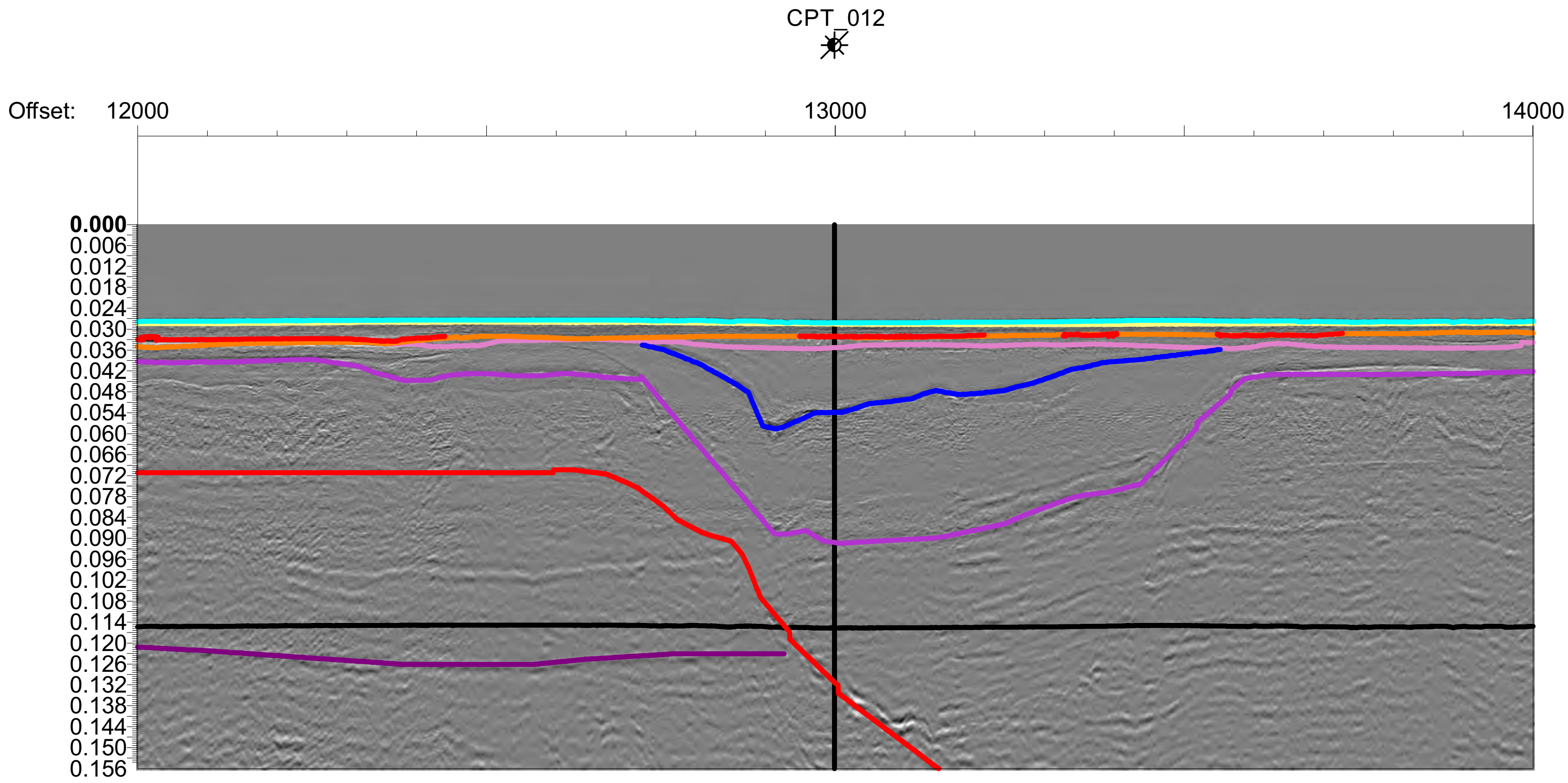
Interpretation	Location Assignment	Review
MvC	DS	CJS



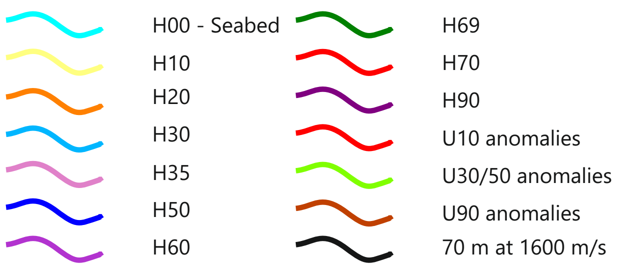
Location Name	Easting [m]	Northing [m]	Rationale
CPT_011	409950	6187083	U50 channel and U60 channel with more stratified seismic to be sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

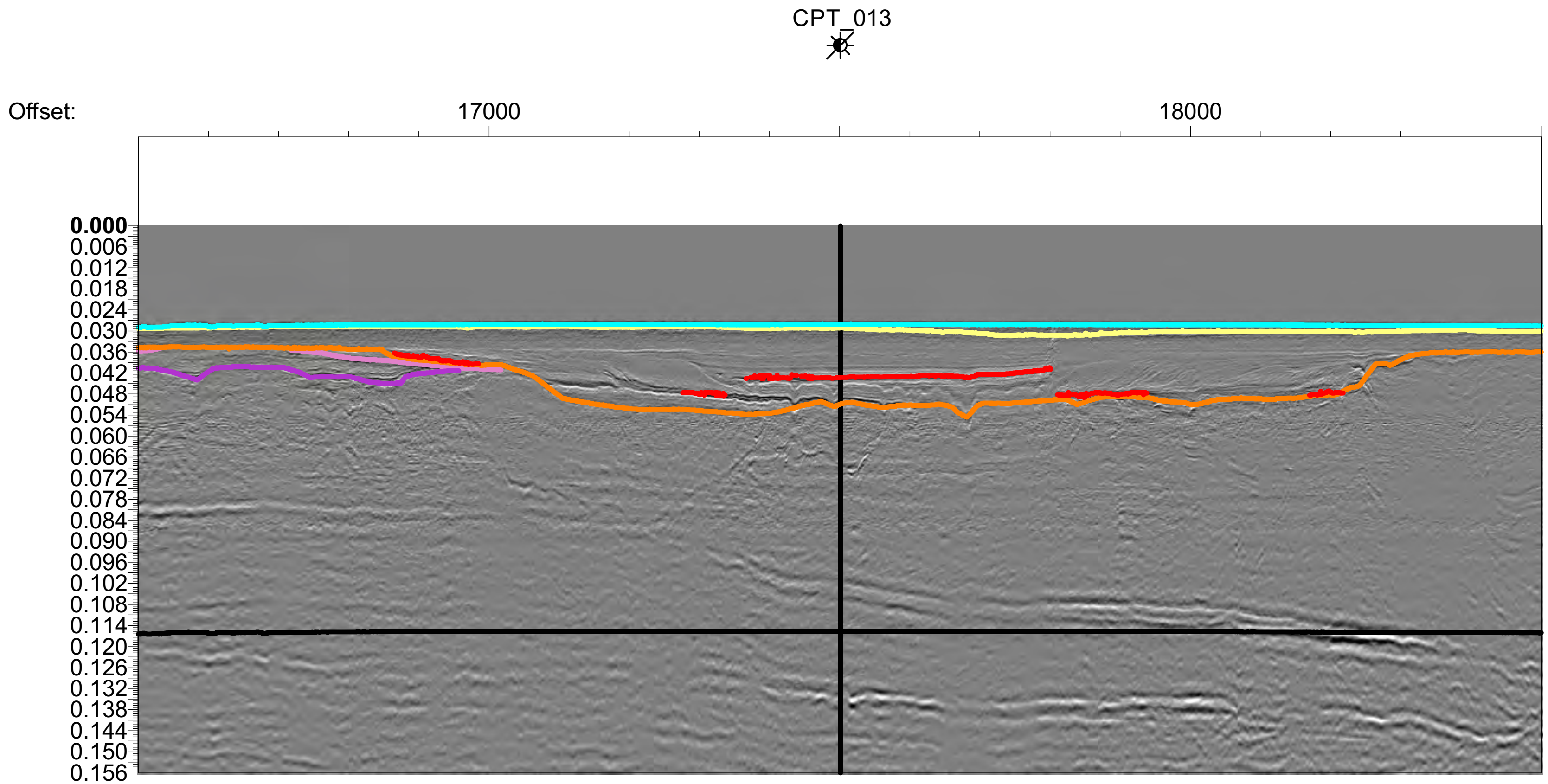
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_012	409953	6196205	U20 seismic anomaly, U50 channel area to be sampled



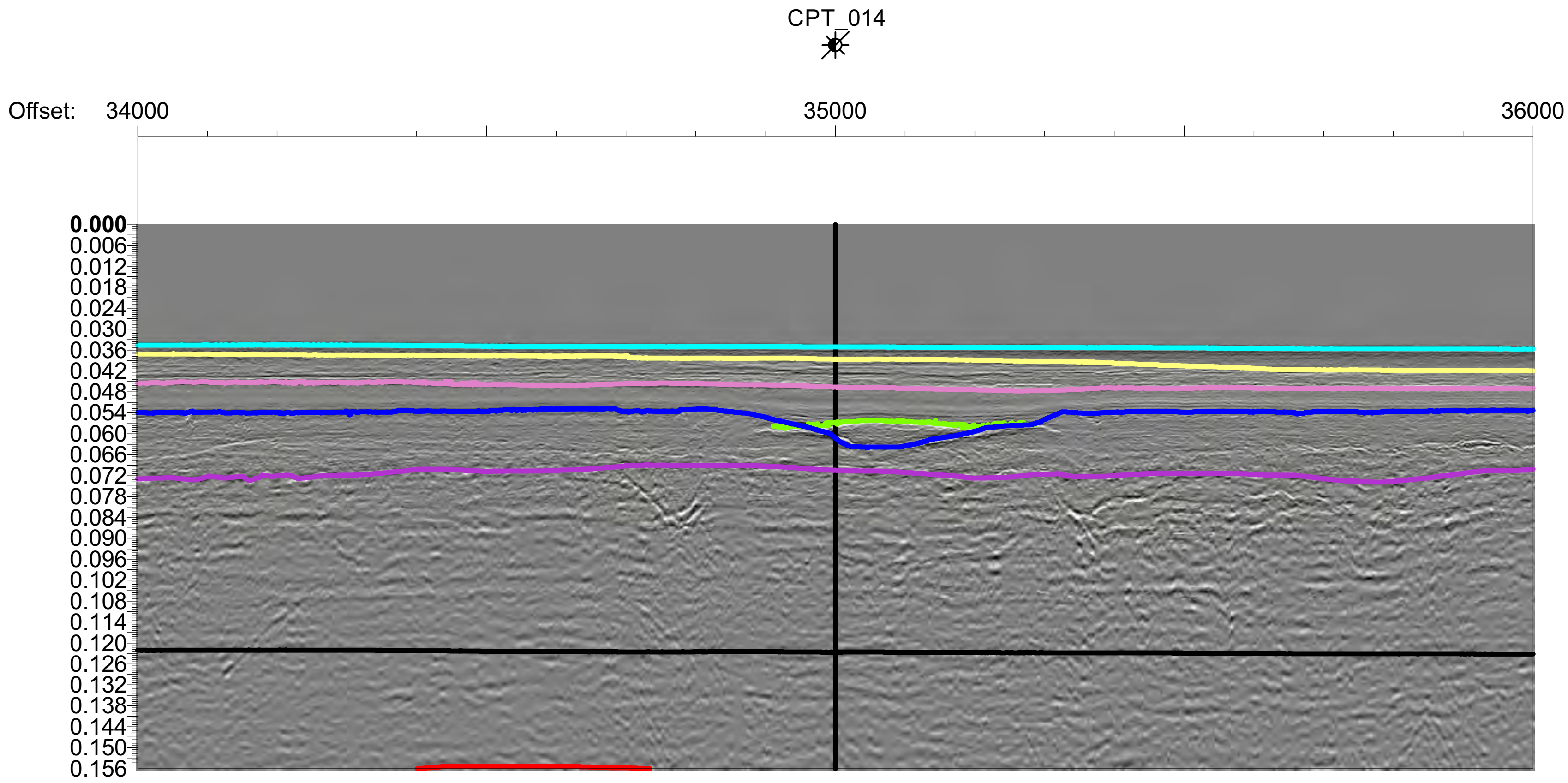
Interpretation	Location Assignment	Review
MvC	DS	CJS



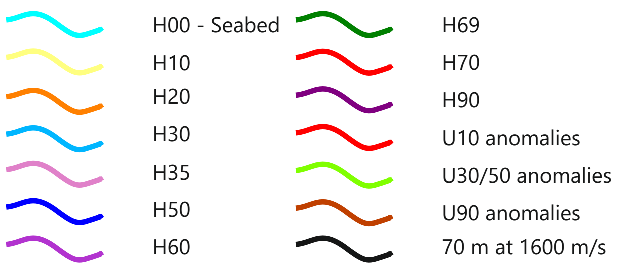
Location Name	Easting [m]	Northing [m]	Rationale
CPT_013	409955	6200673	Thick U20 sediments and seismic anomaly to be sampled

- H00 - Seabed
- H10
- H20
- H30
- H35
- H50
- H60
- H69
- H70
- H90
- U10 anomalies
- U30/50 anomalies
- U90 anomalies
- 70 m at 1600 m/s

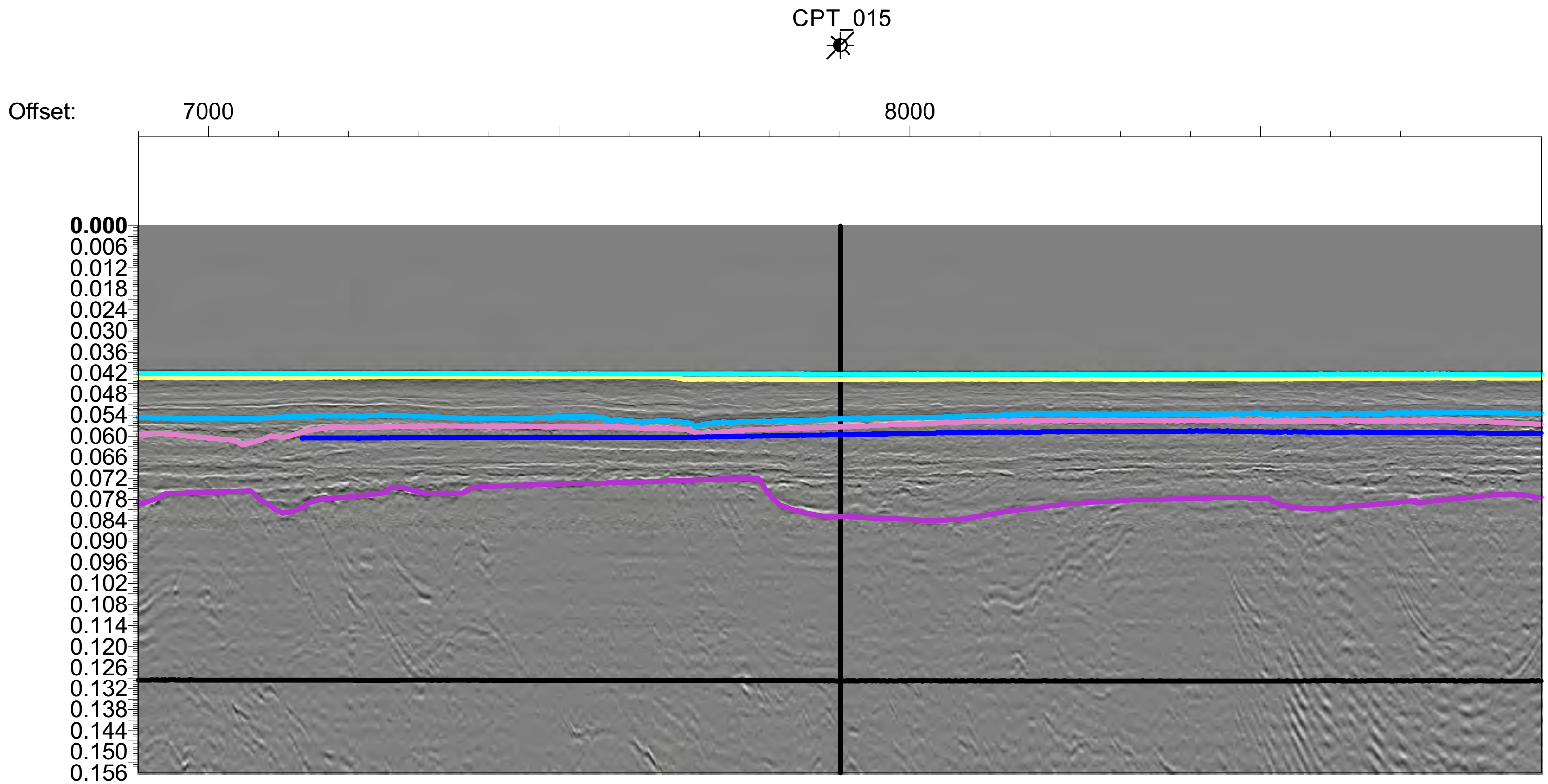
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_014	409955	6218035	U50 seismic anomaly to be sampled



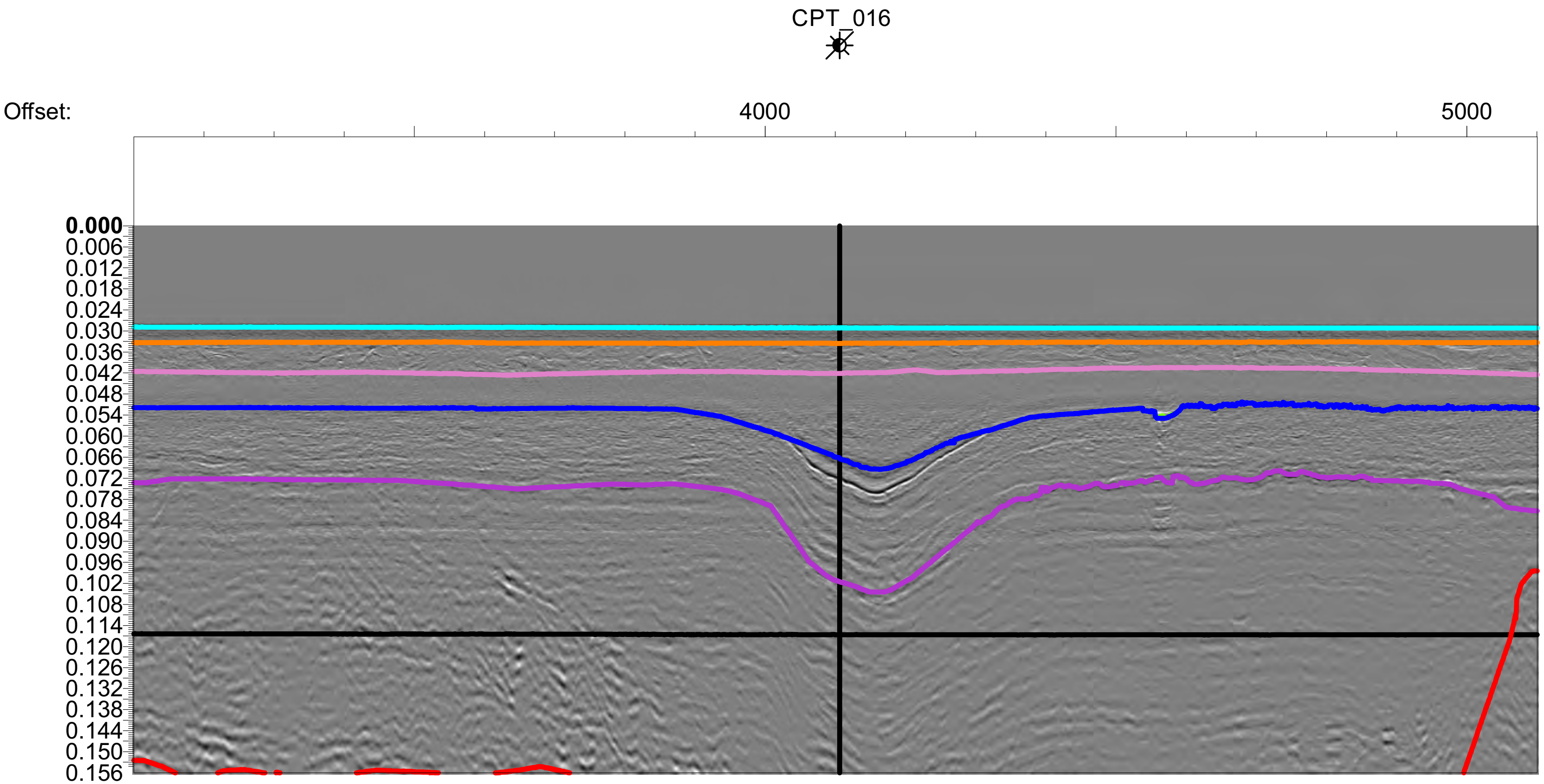
Interpretation	Location Assignment	Review
MvC	DS	CJS



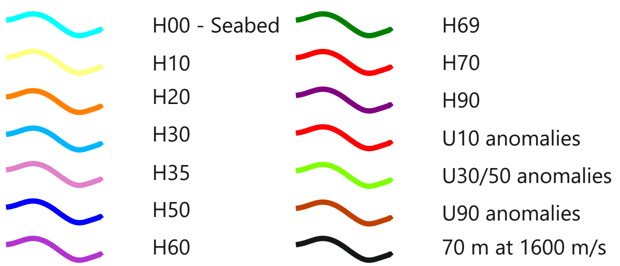
Location Name	Easting [m]	Northing [m]	Rationale
CPT_015	396827	6236790	Spatially limited U30 sediments to be sampled

- H00 - Seabed
- H10
- H20
- H30
- H35
- H50
- H60
- H69
- H70
- H90
- U10 anomalies
- U30/50 anomalies
- U90 anomalies
- 70 m at 1600 m/s

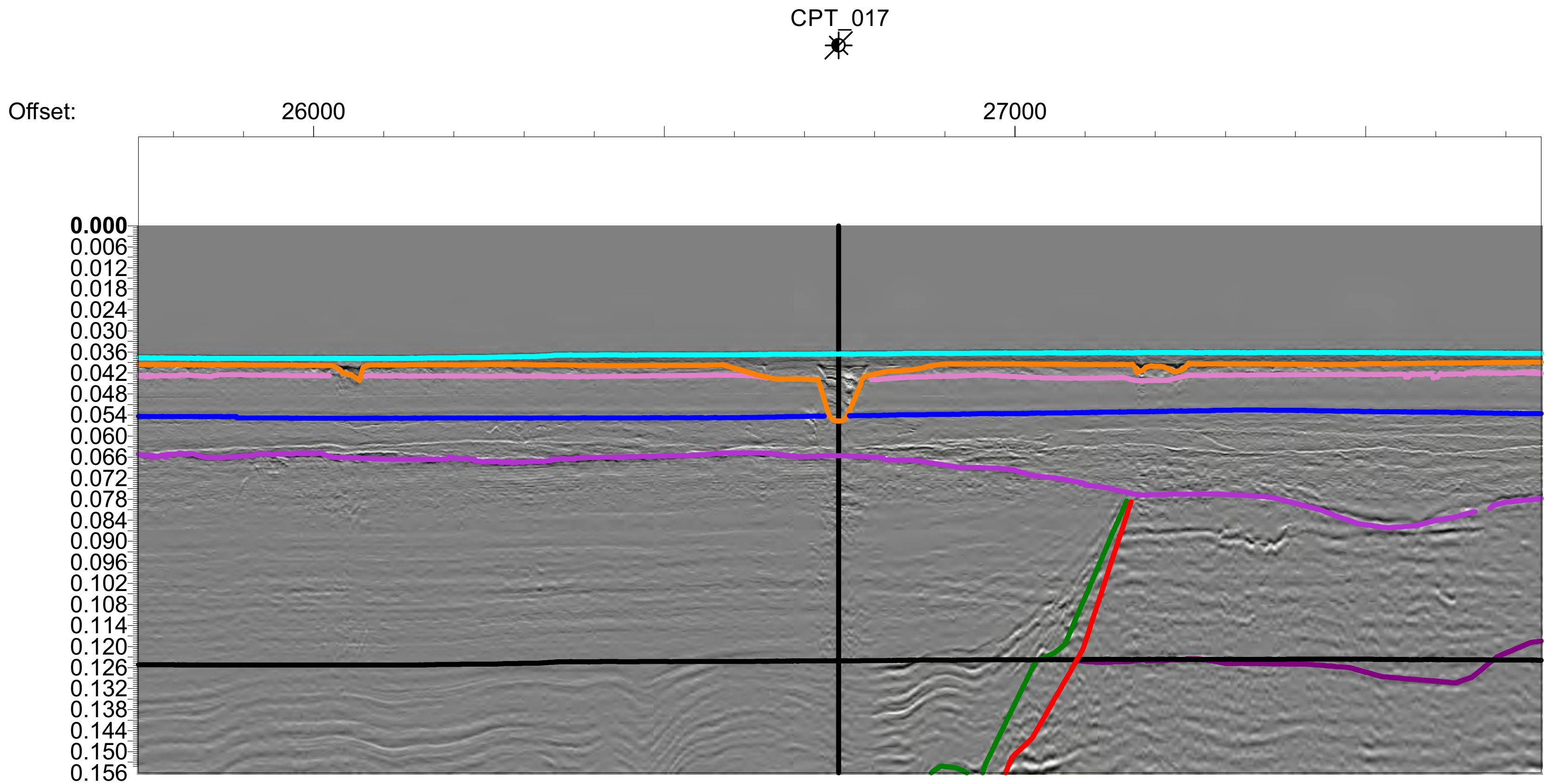
Interpretation	Location Assignment	Review
MvC	DS	CJS



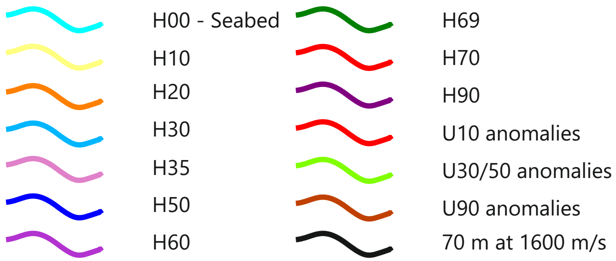
Location Name	Easting [m]	Northing [m]	Rationale
CPT_016	419913	6187222	U50 channel and seismic character change in U60 to be sampled



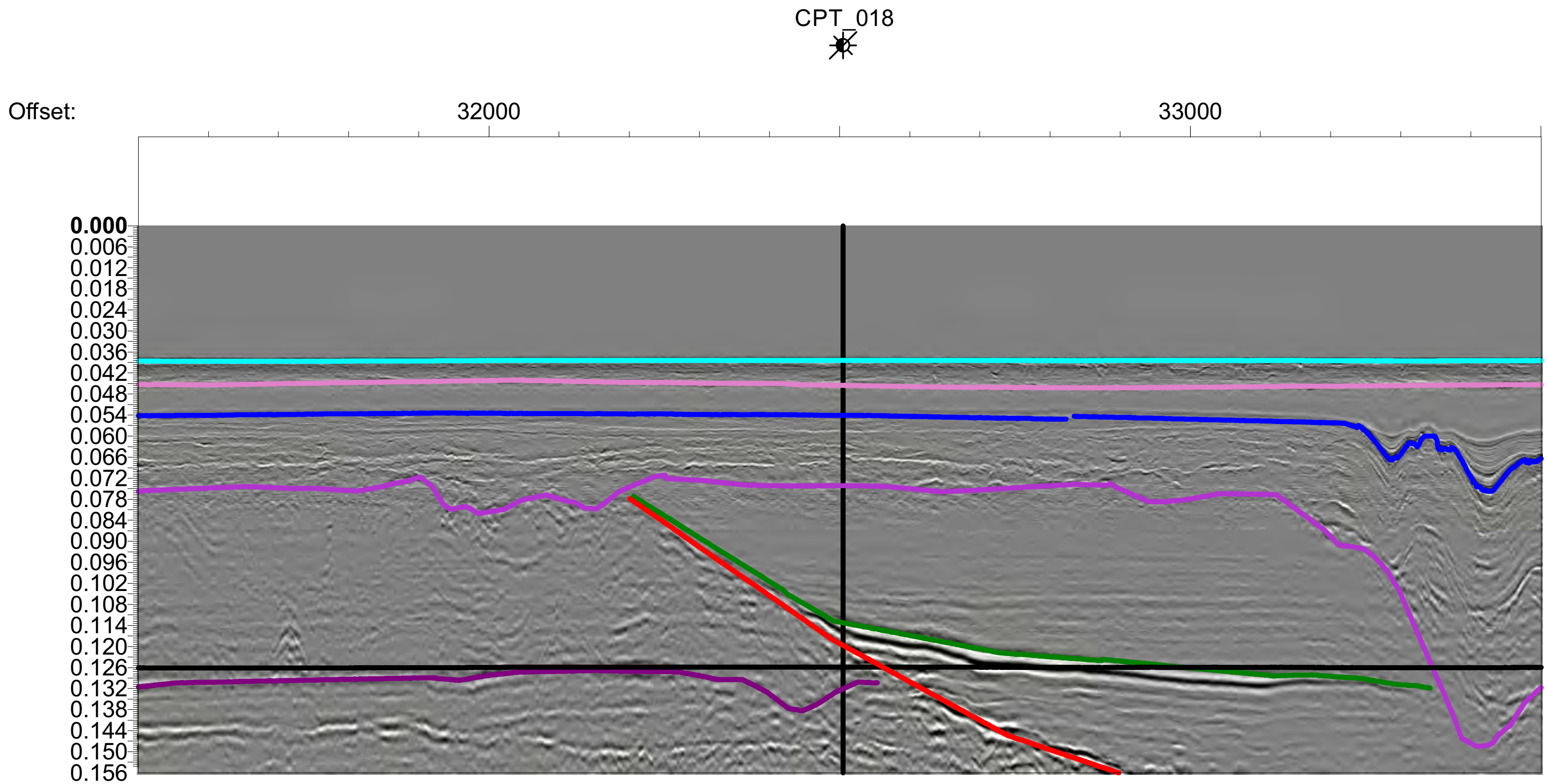
Interpretation	Location Assignment	Review
MvC	DS	CJS



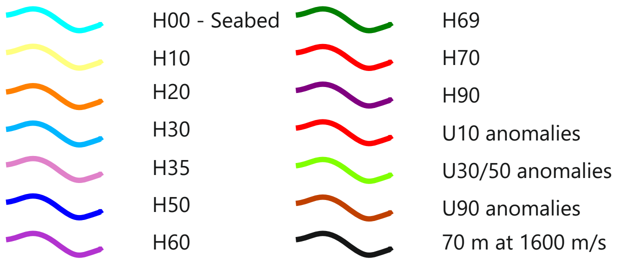
Location Name	Easting [m]	Northing [m]	Rationale
CPT_017	419962	6209718	Localised U20 channel area to be sampled, U69 sediments may also be sampled if location penetrates to sufficient depth



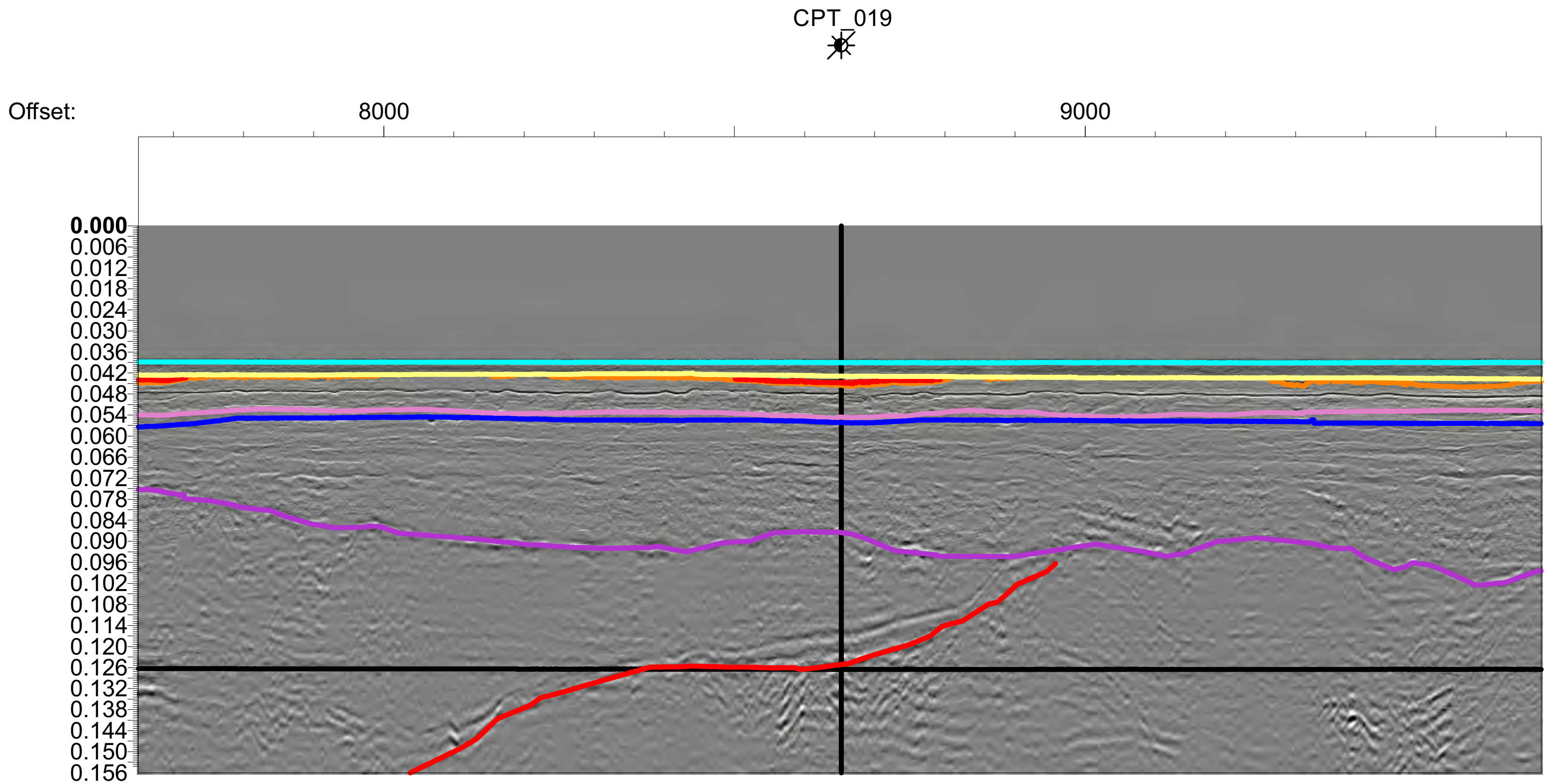
Interpretation	Location Assignment	Review
MvC	DS	CJS



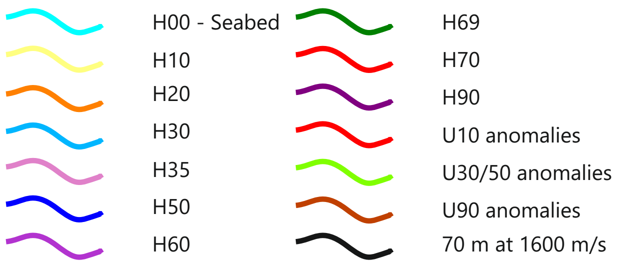
Location Name	Easting [m]	Northing [m]	Rationale
CPT_018	419963	6215439	Possible U69 sediments if location penetrates sufficient depth. Internal variability within U60 to be sampled



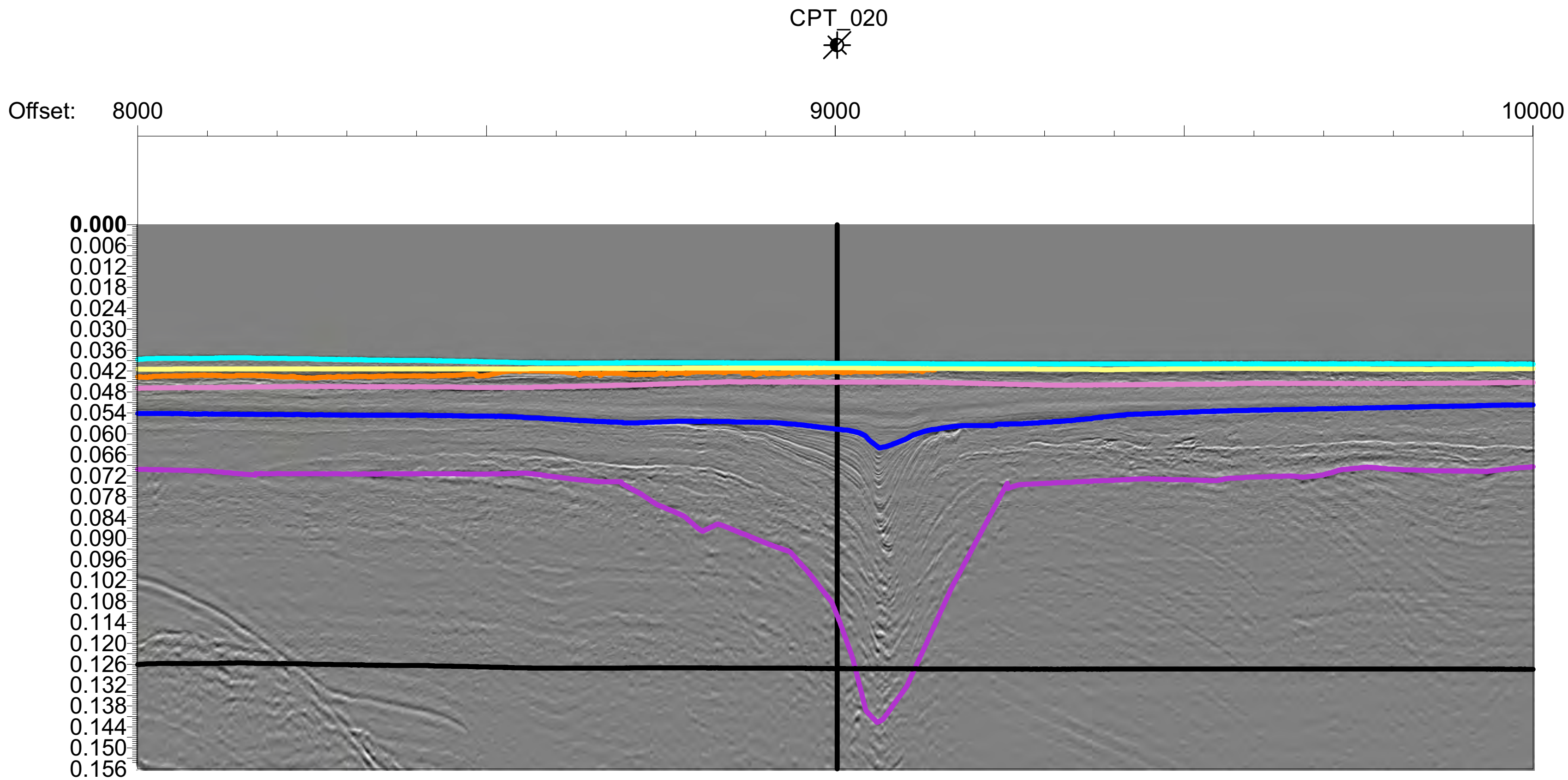
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_019	401350	6226783	U20 seismic anomaly (in area where may interact with U10) to be sampled. H25 seismic character change observed to be sampled if sufficient penetration is acheived



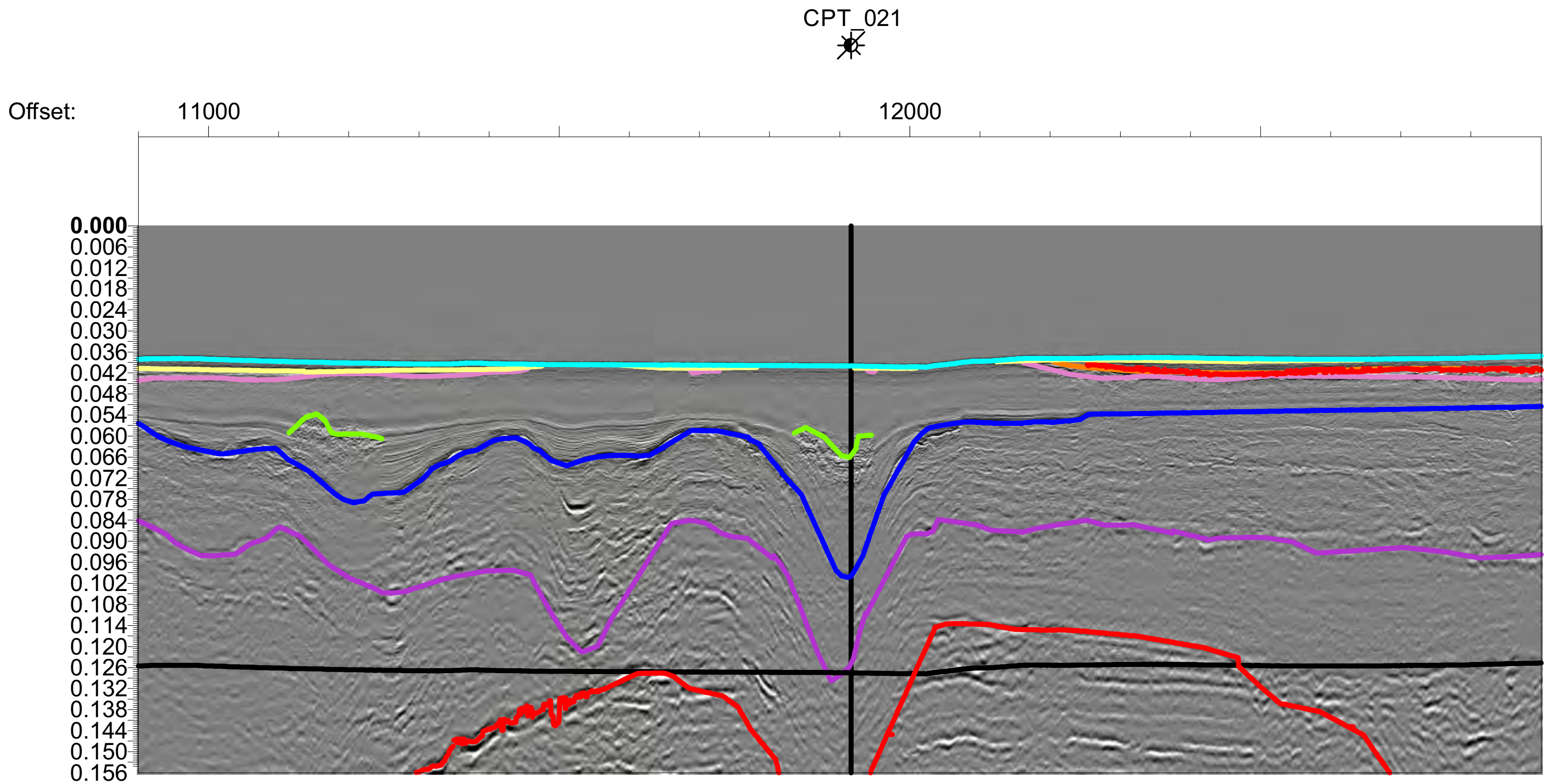
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_020	417706	6226746	Deep U60 channel to be sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

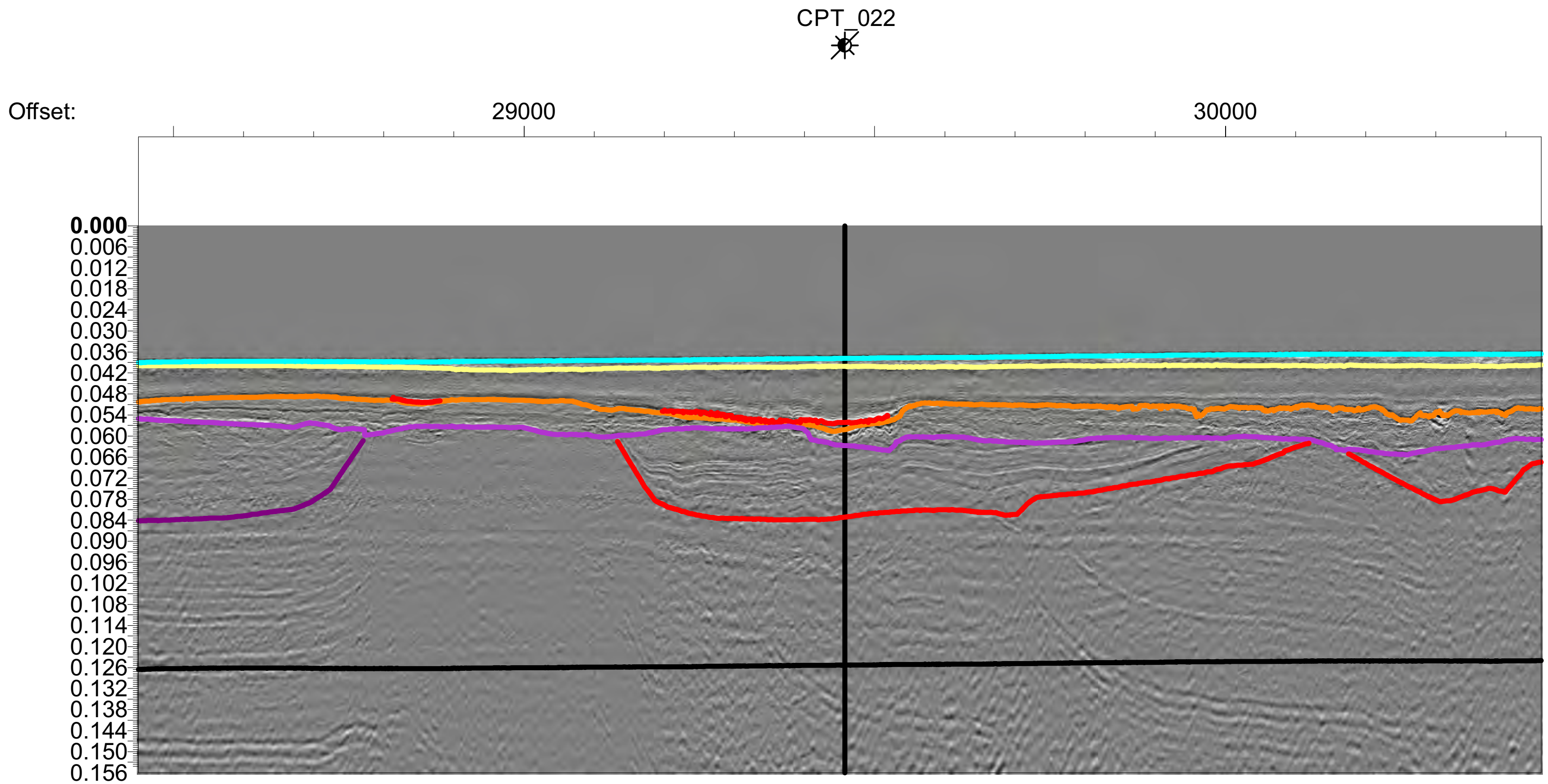
Interpretation	Location Assignment	Review
MvC	DS	CJS



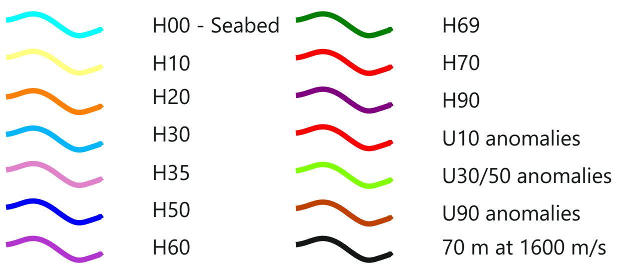
Location Name	Easting [m]	Northing [m]	Rationale
CPT_021	420598	6226768	Deep U50 and U50 seismic anomaly to be sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

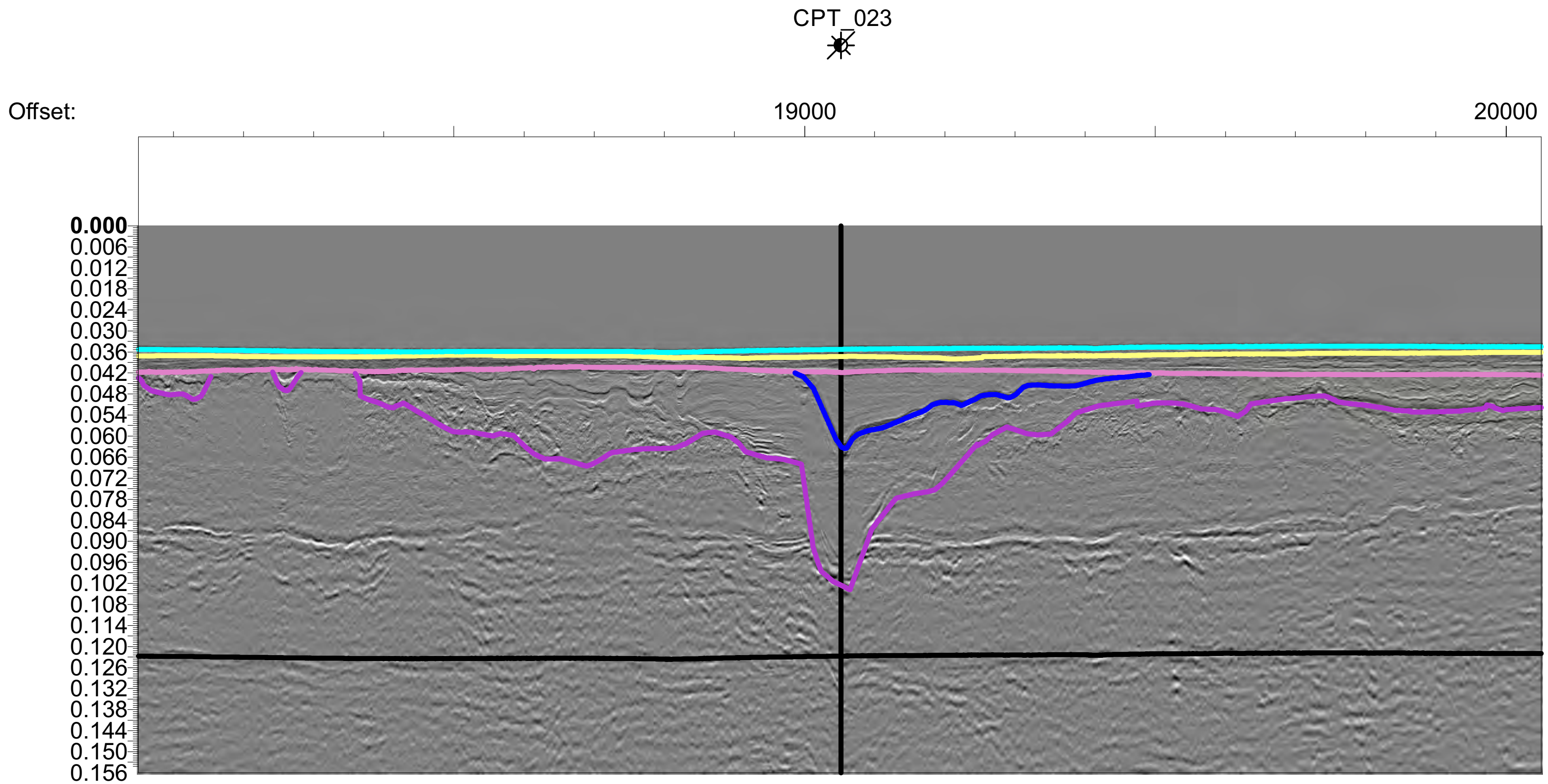
Interpretation	Location Assignment	Review
MvC	DS	CJS



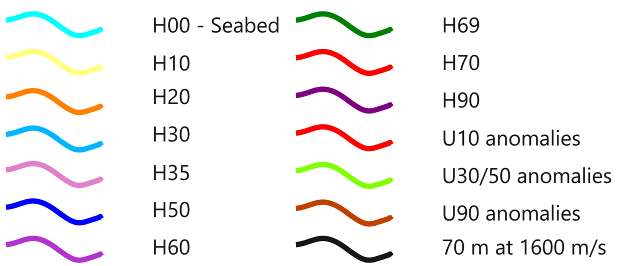
Location Name	Easting [m]	Northing [m]	Rationale
CPT_022	389953	6214097	Deep U20 channel and anomaly to be sampled. Small U70 channel may also be sampled if sufficient penetration is achieved



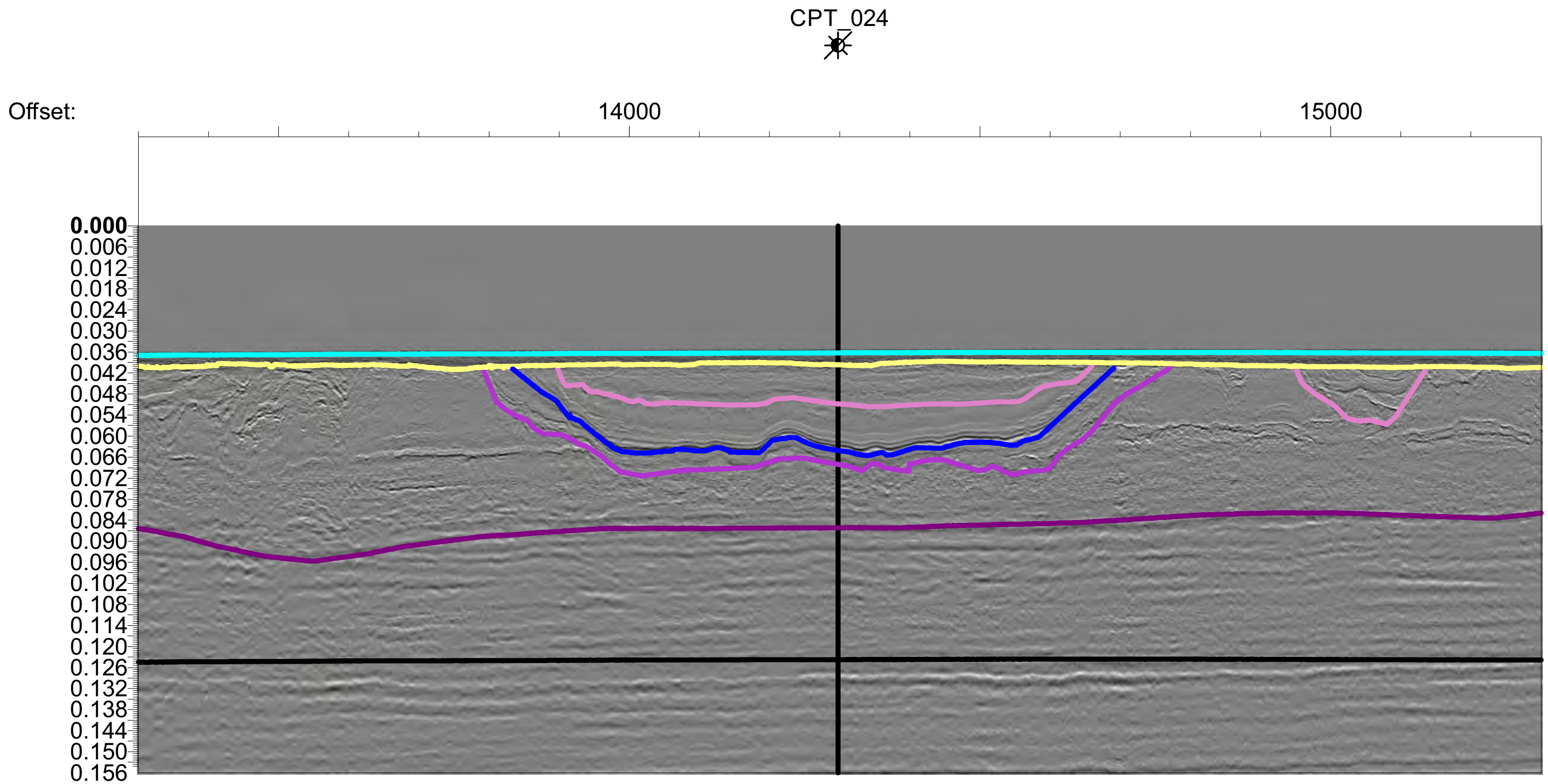
Interpretation	Location Assignment	Review
MvC	DS	CJS



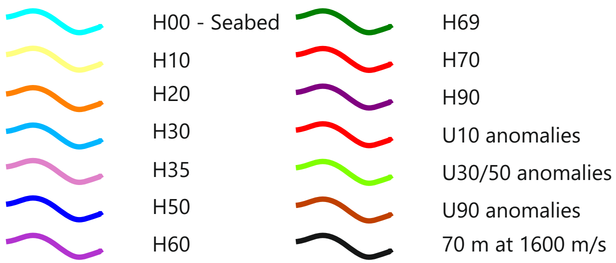
Location Name	Easting [m]	Northing [m]	Rationale
CPT_023	407244	6216787	Localised U50 and U60 channel area to be sampled



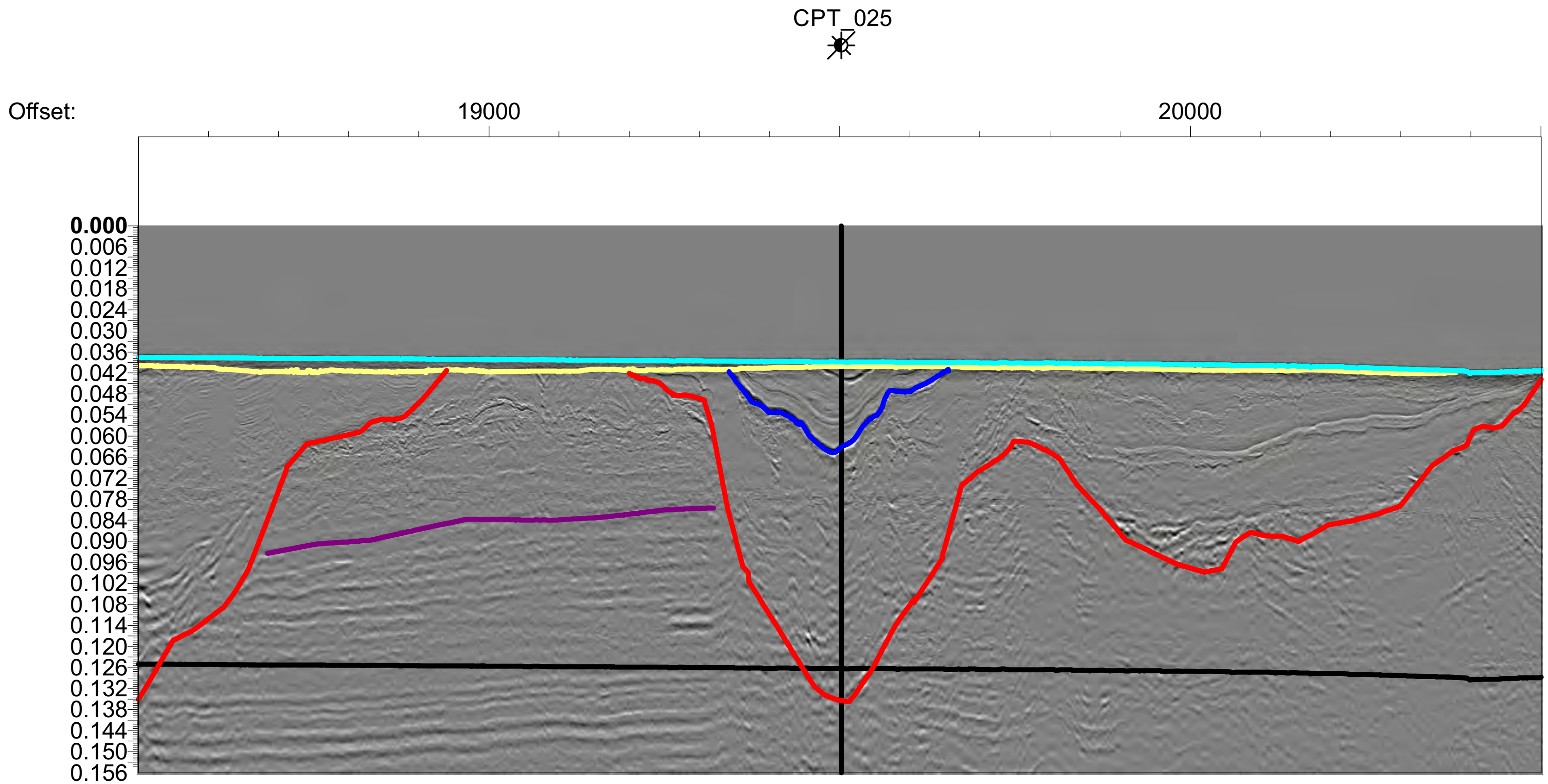
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_024	388495	6206804	U35 channel above U50 channel with seismic character change at base to be sampled



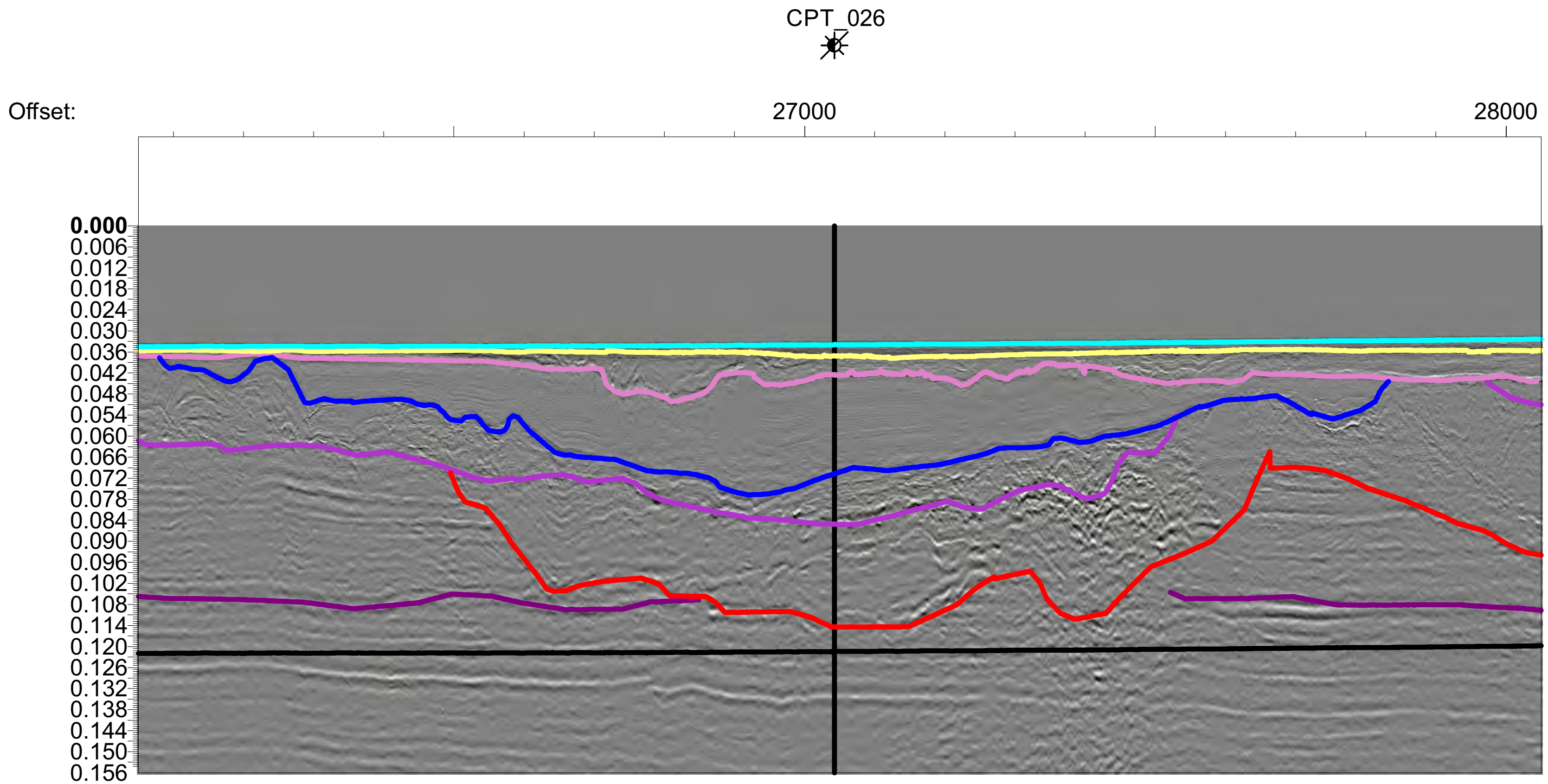
Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_025	393637	6206777	U50 channel and small U70 valley feature to be sampled

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

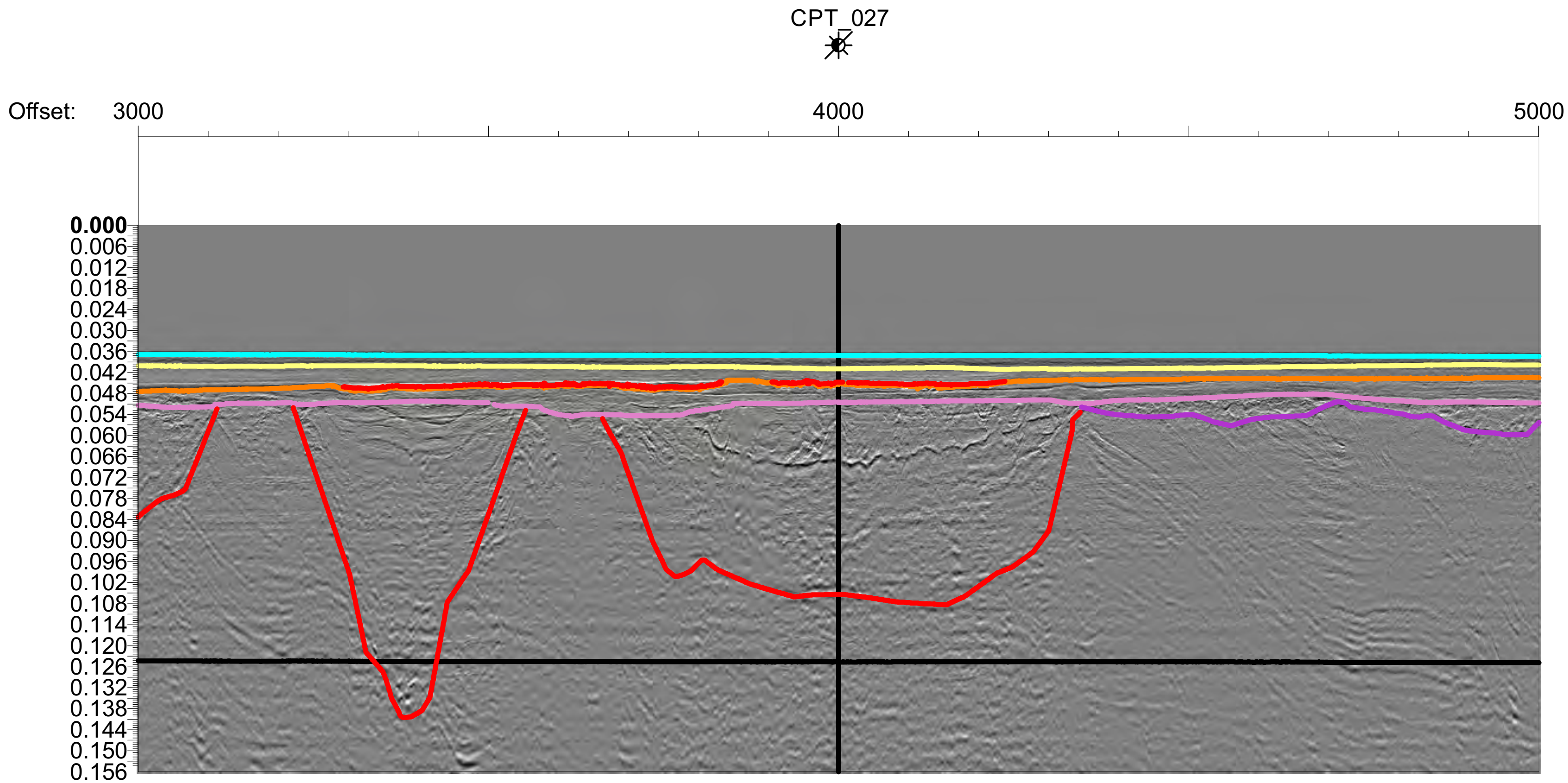
Interpretation	Location Assignment	Review
MvC	DS	CJS



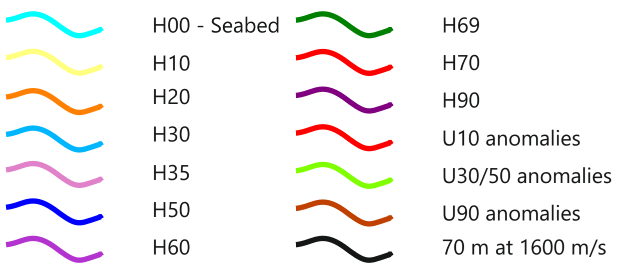
Location Name	Easting [m]	Northing [m]	Rationale
CPT_026	397845	6196773	Deep U50 and U60 channel to be samped to establish strength with depth

H00 - Seabed
H10
H20
H30
H35
H50
H60
H69
H70
H90
U10 anomalies
U30/50 anomalies
U90 anomalies
70 m at 1600 m/s

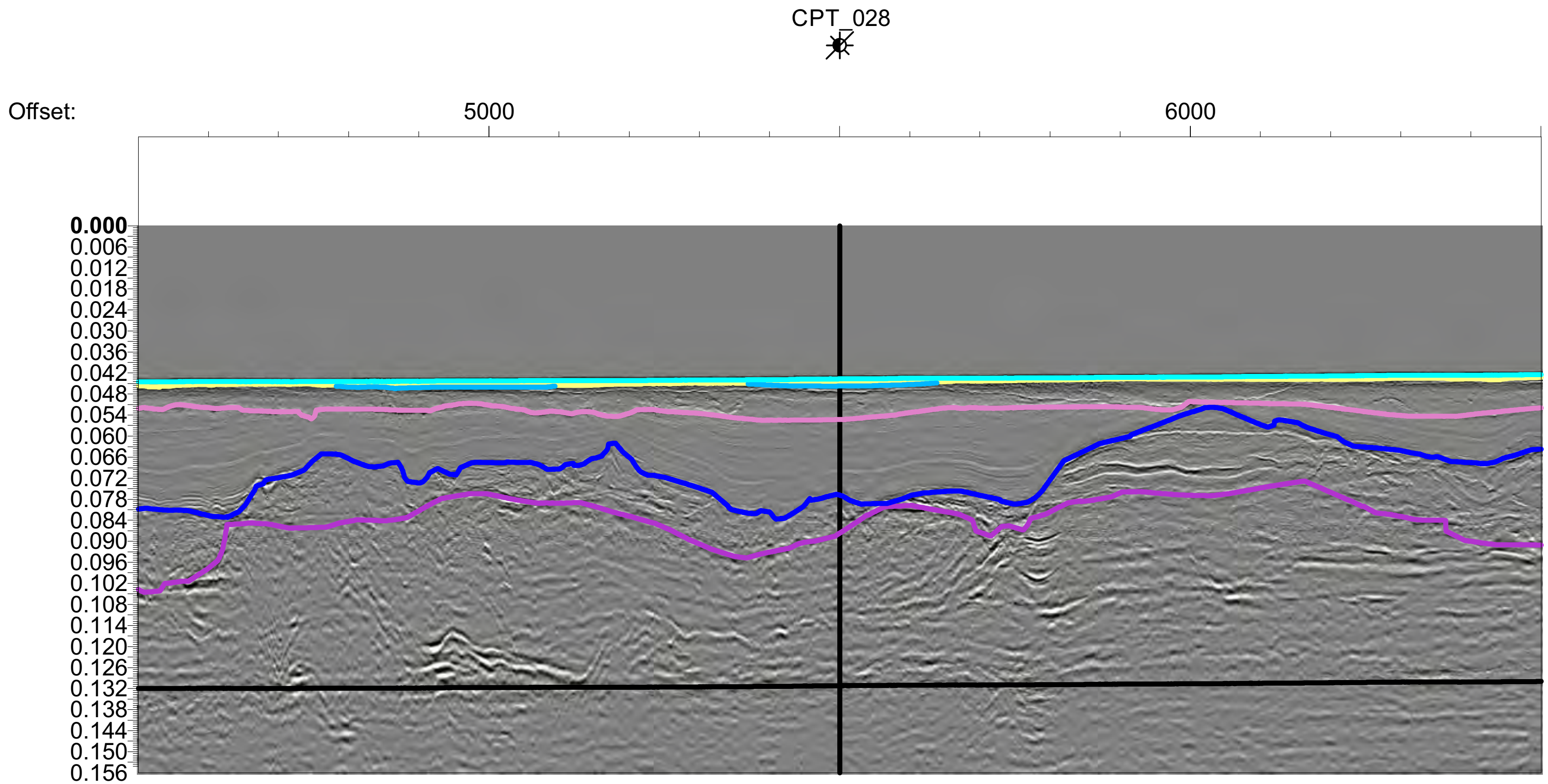
Interpretation	Location Assignment	Review
MvC	DS	CJS



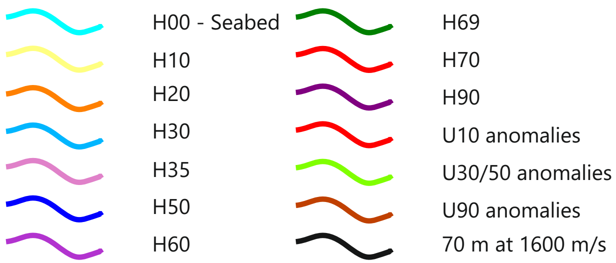
Location Name	Easting [m]	Northing [m]	Rationale
CPT_027	392365	6216779	U20 and seismic anomaly to be sampled. Internal reflector within U70 to be sampled if penetration sufficient



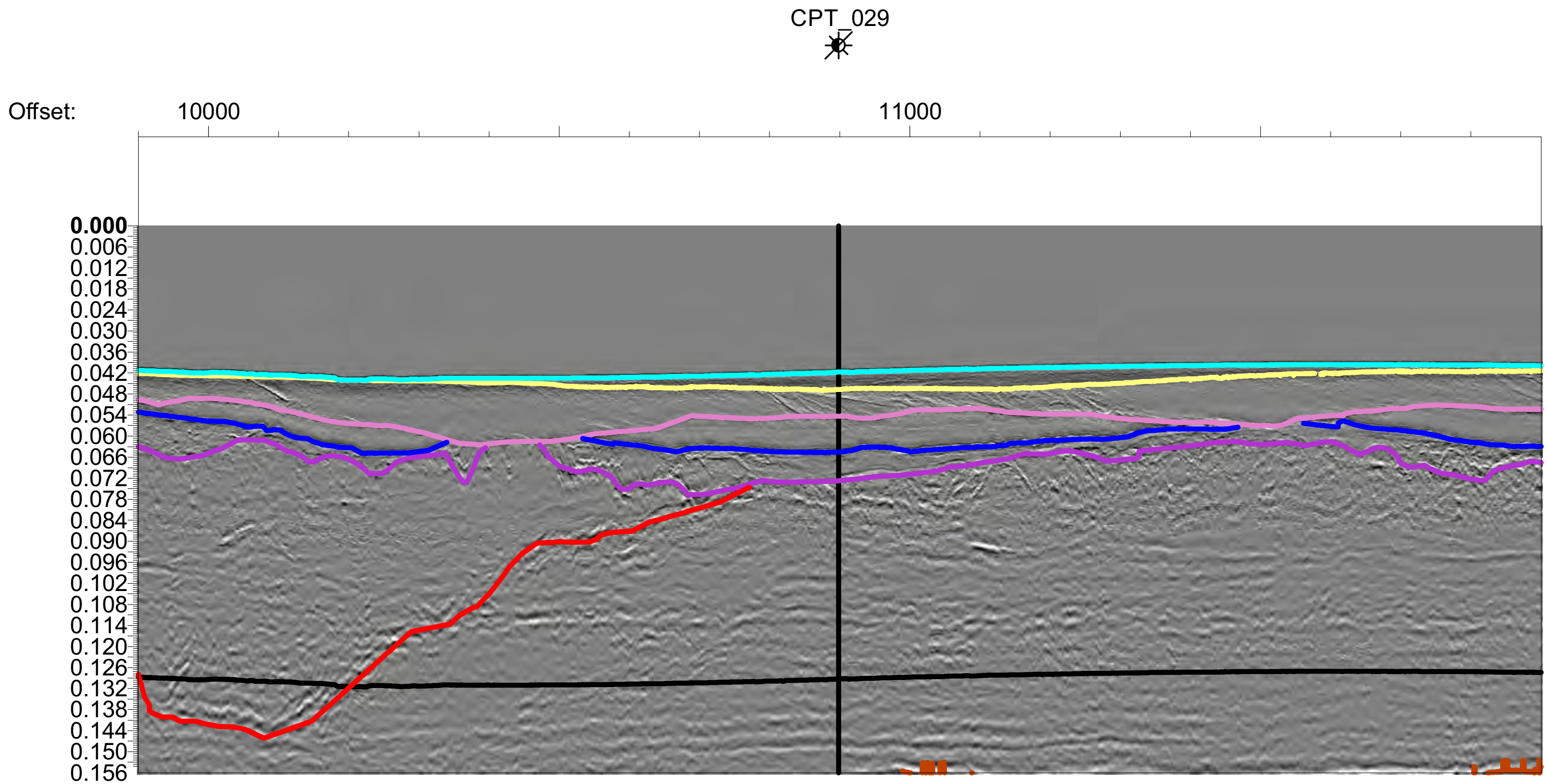
Interpretation	Location Assignment	Review
MvC	DS	CJS



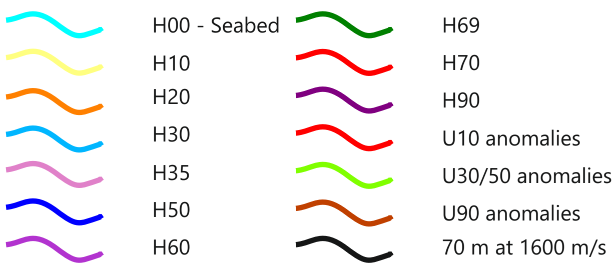
Location Name	Easting [m]	Northing [m]	Rationale
CPT_028	376767	6186726	Thick U50 channel to be sampled. Seismic character change in U35 sediments may also be captured



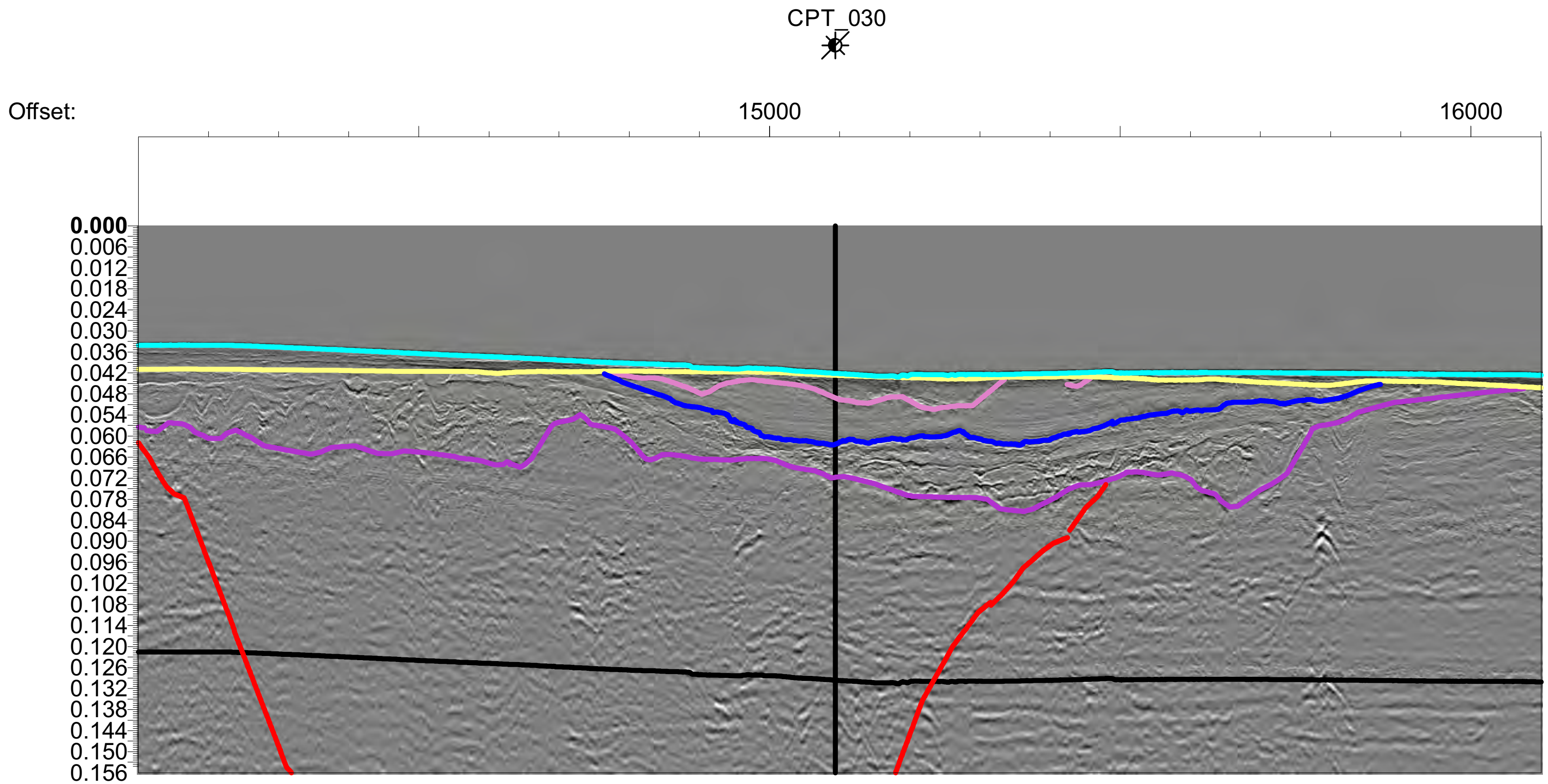
Interpretation	Location Assignment	Review
MvC	DS	CJS



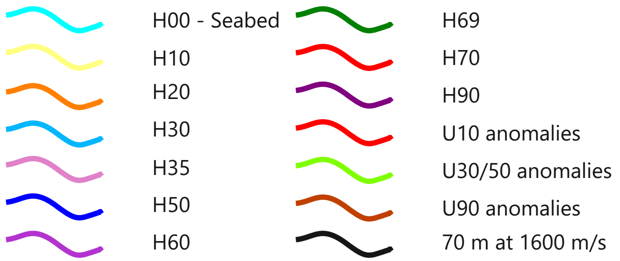
Location Name	Easting [m]	Northing [m]	Rationale
CPT_029	382093	6186771	Inclined reflectors within U35 to be sampled. U50 channel sediments will also be captured



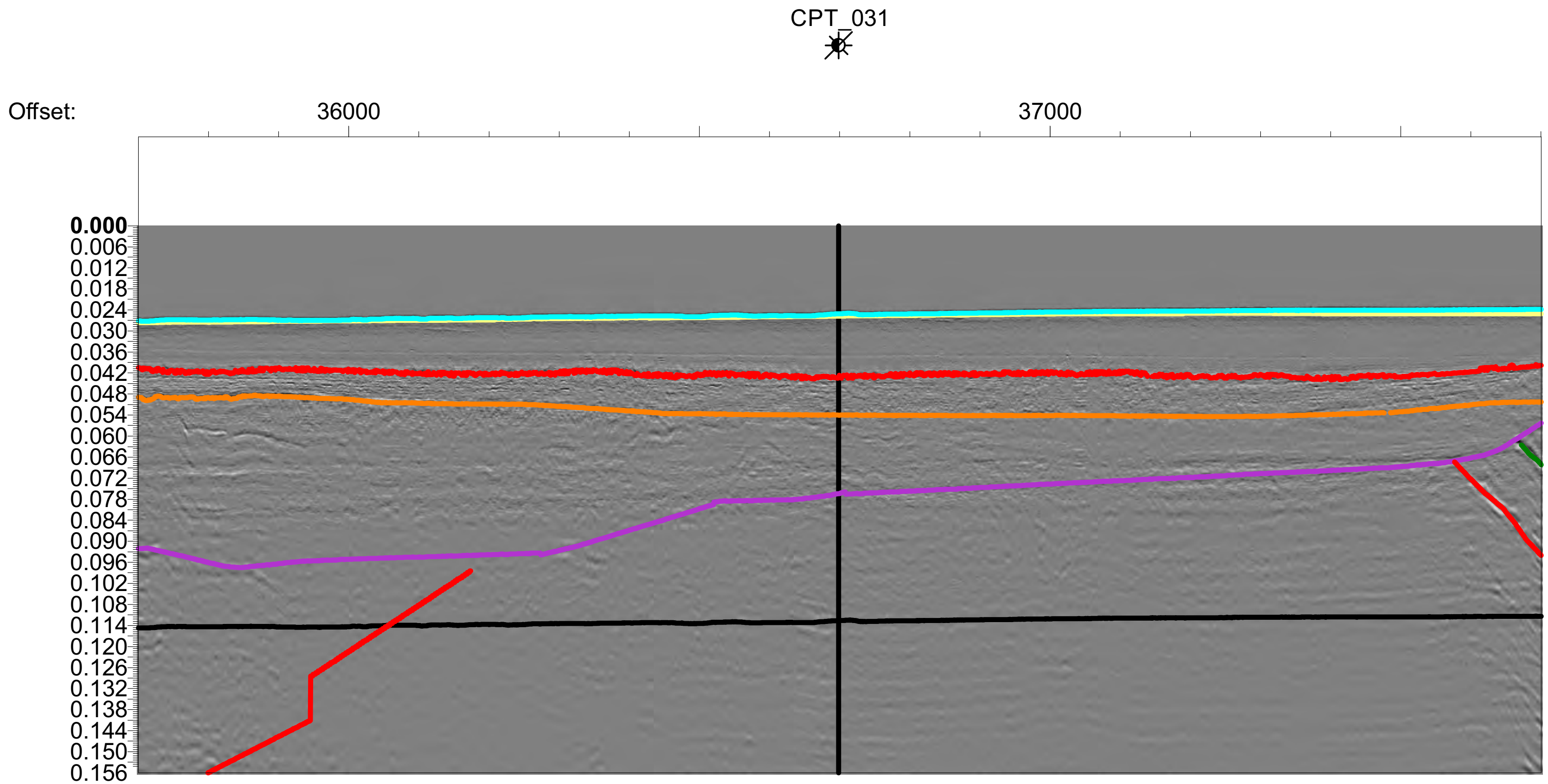
Interpretation	Location Assignment	Review
MvC	DS	CJS



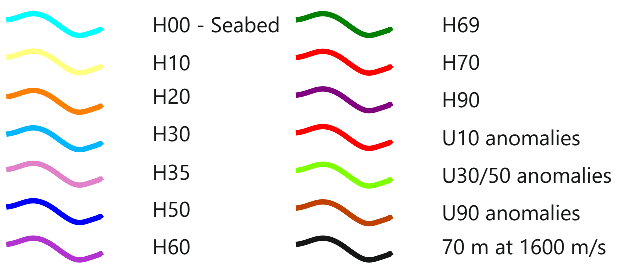
Location Name	Easting [m]	Northing [m]	Rationale
CPT_030	386233	6186789	U35 and U50 channel sediments to be sampled



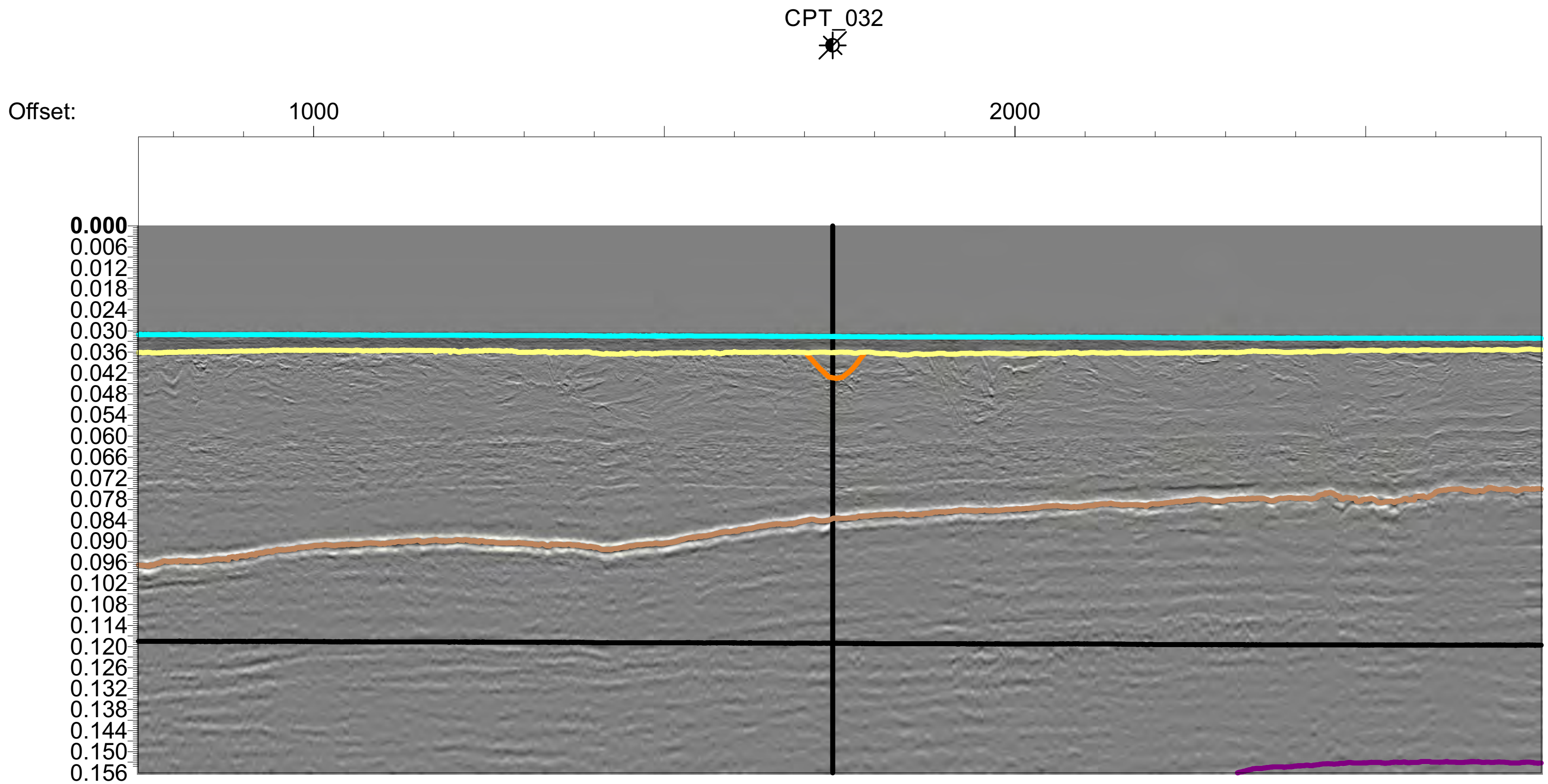
Interpretation	Location Assignment	Review
MvC	DS	CJS



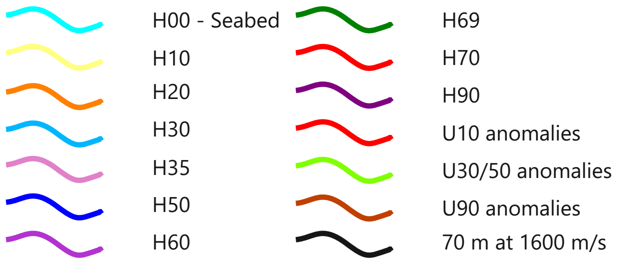
Location Name	Easting [m]	Northing [m]	Rationale
CPT_031	407546	6186777	U20 seismic anomaly in area of thick deposit of this unit to be sampled



Interpretation	Location Assignment	Review
MvC	DS	CJS



Location Name	Easting [m]	Northing [m]	Rationale
CPT_032	4399957	6185941	Small U20 channel observed in south to be sampled. U90 sediments and anomaly if penetration depth sufficient



Interpretation	Location Assignment	Review
MvC	DS	CJS

Appendix A

2D UUHR Seismic Processing Report

2D UUHR Baseline Processing Report

Danish Offshore Wind 2030 | North Sea 1, Denmark

F217715-REP-PROC-001 (01) | 1 July 2023

Complete

Energinet Eltransmission A/S

Document Control

Document Information

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Document Title	2D UUHR Processing Report
Fugro Project No.	F217715
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Client Information

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Client Document No.	22/02940-12

Revision History

Issue	Date	Status	Comments on Content	Prepared By	Checked By	Approved By
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Abbreviations

2D UUHR	Two Dimensional Ultra Ultra High Resolution
CDP	Common Depth-point
CMP	Common Mid-Point
DGPS	Differential Global Positioning System
FTP	File Transfer Protocol
F-K	Frequency - wave number
F-X	Frequency - space domain
GPS	Global Positioning System
LNA	Linear Noise Attenuation
MLSS	Multi-Level Stacked Sparker
MSL	Mean Sea Level
NMO	Normal Move Out
PoSTM	Post-Stack Time Migration
QC	Quality Control
SFT	Secure File Transfer
SRME	Surface Related Multiple Elimination
TWTT	Two-Way Travel Time
UTM	Universal Transverse Mercator
WB_ZO	Water Bottom Zero Offset Time
X-T	Space – Time Domain
.csv	Comma Separated Values

1. Introduction

Energinet has contracted Fugro to perform the Offshore Geological Site Survey for the Danish Offshore Wind 2030 campaign at the North Sea 1 site (Part 5).

The seismic processing report aims to detail the step by step processes used to get the best imaging of the seismic data. The techniques involved aim to reduce the noise in the datasets, improve signal to noise ratios, and improve upon the acquisition brute bandwidth of the data.

1.1 Scope of Work

Fugro acquired 2D Ultra Ultra High Resolution (2D UUHR) seismic data for Energinet utilising the MV Arctic. This was the baseline survey covering just over 500 km of UUHR seismic data, with further work planned on the Pioneer for the remained of the survey.

The data were QC'd offshore and processed onshore, using Fugro *Uniseis* software.

The aim of this survey was to acquire and provide high quality and high resolution data of the work locations. The objective of the geologic survey is to map the upper part of the subsurface in sufficient level of detail to:

- Map all major geological layers and structures to at least 100m below seabed.
- Locate structural complexities or geohazards within the shallow geological succession such as faulting, accumulations of shallow gas, buried channels, soft sediments, hard sediments, mobile sediments etc.

In general data was of high quality. Lines were assessed onboard between the QC and client to determine if a client concession could be issued for lines that were technically out of spec. A couple of lines were reshot in areas due to poor weather.

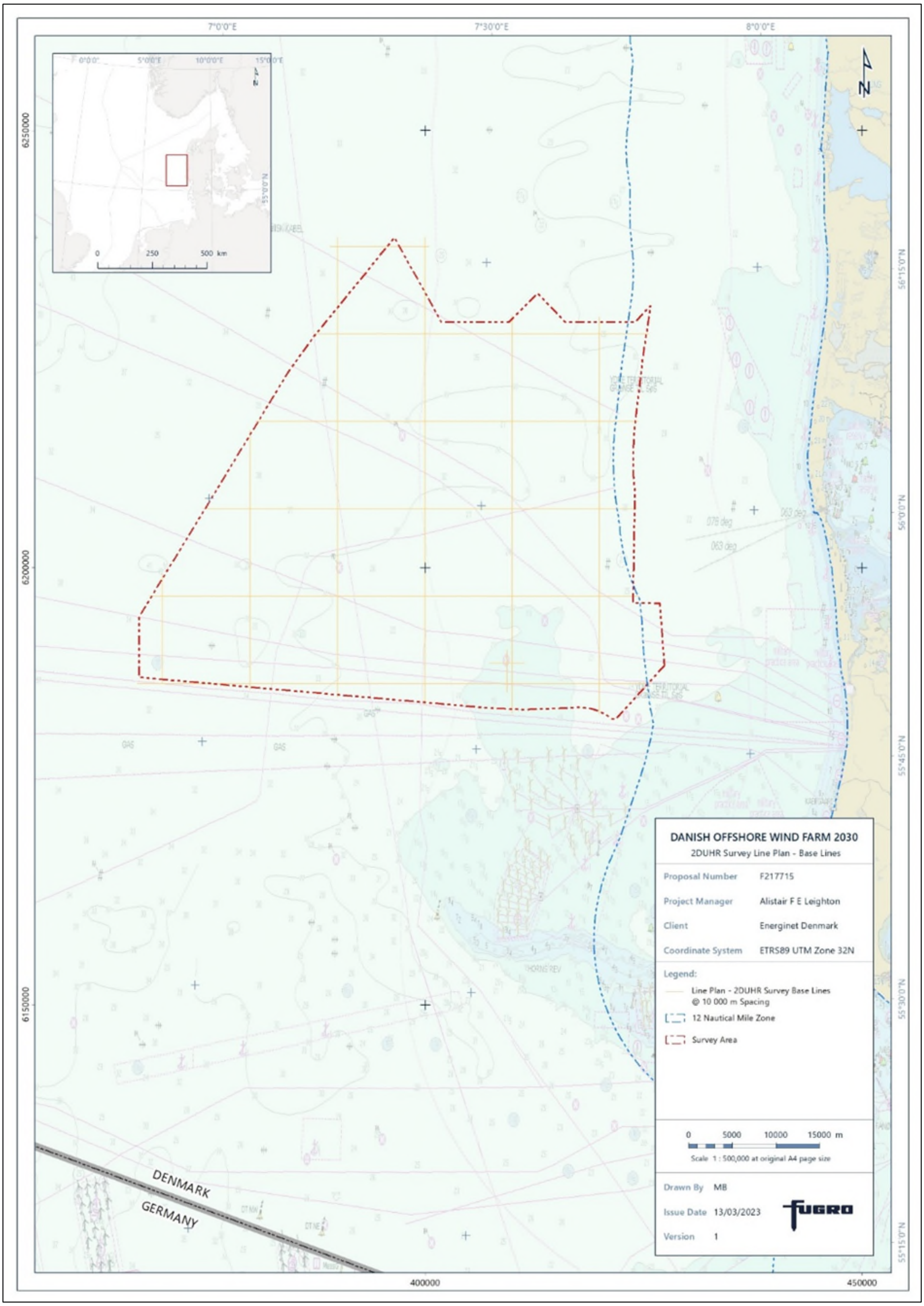

Figure 1.1: 2D UUHR Survey Area

1.2 Acquisition Configuration

Table 1.1: 2D UUHR Acquisition parameters

Acquisition	
Source	
Type	DuraSpark 400 Sparker
Power	800 Joules
Shot Interval	1 m
Depth	0.38 m
Streamer	
Model	GeoEel LH-16
Groups	96
Group Interval	1 m
Active Length	96 m
Near Offset	~6 m
Depth	1.4 m
Recording System	
Model	CNT-2
Sample interval	0.125 ms
Record length	219.875 ms
Format	SEG-D

2. Processing 2D UUHR

2.1 2D UUHR Processing Summary

The processing flow was applied to all the lines as follows:

- Reformat from SEG-D
- Apply recording delay correction static: 0 ms (No delay on recording system)
- Apply low-cut filter: 20Hz / 18 dB/Oct
- Apply T^2 spherical divergence
- Merge seismic with source & receiver navigation, update offsets, assign 2D geometry
- Pick zero offset seabed – assign hyperbolic seabed time per channel
- Edit out bad shots / channels identified from offshore QC
- Shot domain swell noise attenuation
- Temporary statics application (to aid QC – statics reassessed after final velocities)
- Channel domain swell noise attenuation
- Linear noise attenuation
- 2D SRME
- Deghosting
- Additional remnant demultiple
- Velocity analysis in Pegasus: 500 m pick intervals
- Sort to CMP domain
- NMO using picked velocity
- Final statics application
- Outer trace final mute
- Stack using 1/N trace normalisation – 48 fold max
- Zero phase filter application using data derived wavelet (positive seabed)
- Post stack pre migration processing
- Post stack Kirchhoff time migration
- Post stack surface wave noise attenuation
- Time variant bandpass filter
- Inverse "Amplitude only" Q compensation
- Apply source and receiver datum correction
- Apply tidal static correction and bathy correction
- Cosmetic seabed mute
- Output to SEG-Y

2.2 Reformatting and Navigation Merge

For each sequence, raw field data in SEG-D format was reformatted into *Uniseis* internal processing format. As part of the reformatting process a bulk shift is applied to the data to compensate for the delay in the recording system. This recording system has zero start of data delay, so the resulting trace data had the original acquired 219.875 ms record length and a sample rate of 0.125 ms. A de-bias low-cut filter of 20 Hz / 18 dB/Octave was applied to the data in order to remove low frequency noise and instrument DC bias prior to processing. A spherical divergence correction (time squared) was applied to the data to aid in QC and further processing.

A QC of the data was conducted on the vessel so that any missing shots, bad channels and noisy records that may have an adverse effect on data quality could be identified.

Geometry was assigned in order to give each trace a CMP number and source / receiver positions were merged into the seismic dataset in order to get accurate offsets and locations for the data prior to velocity picking. Correct CMP locations enabled trends from nearby lines to be used in order to help with consistency and accuracy of velocity picks.

Finally, at this stage, near trace gathers were used to interactively pick a zero offset water bottom time (near trace seabed time with normal moveout applied) for use in later processing.

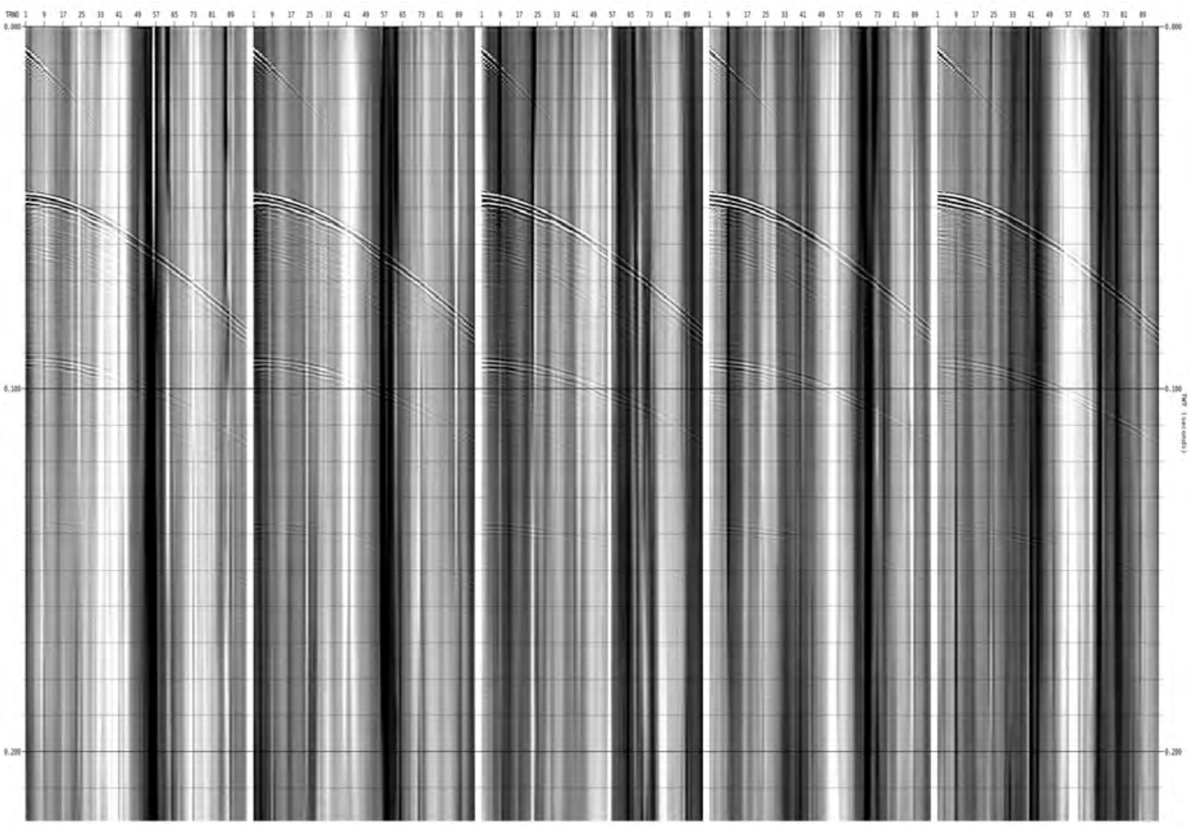

Figure 2.1: Reformat: Raw shots

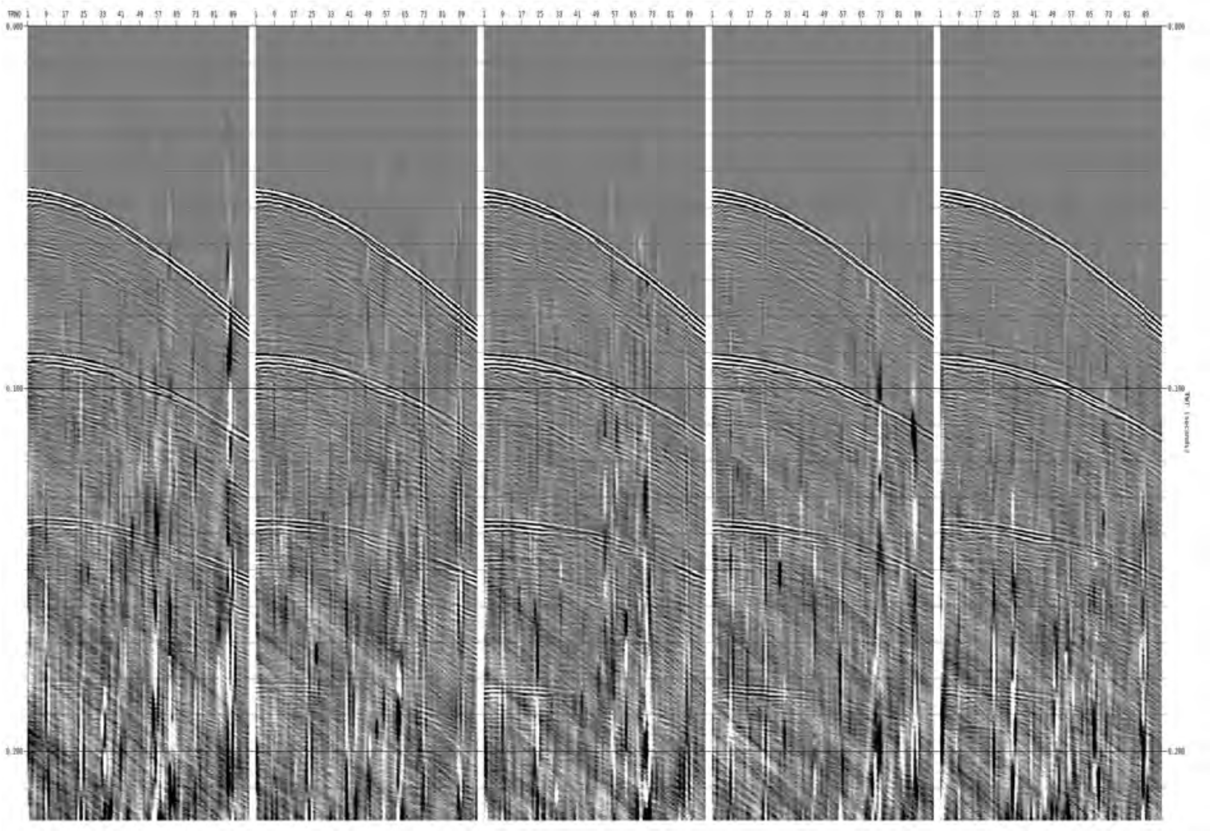

Figure 2.2: Reformat: Low cut and geometrical spreading

2.3 Swell Noise Attenuation

Swell noise was effectively attenuated using the *Uniseis 'SWNA'* and *'TFDN'* tools. The *'TFDN'* algorithm makes use of the fact that, unlike an impulsive source such as a shot, the amplitude of the swell noise will not decay with time since it is being continuously generated during recording. The process decomposes the trace data into signal and noise components, down-weighting or removing the noise to leave a clean trace.

An initial pass of de-swell (TFDN) was applied to frequencies up to 150Hz in the shot domain. Dip attenuation (SWNA) was then applied to attenuate any non-physical dips up to 200Hz below 1000 m/s apparent velocity. This was followed by a second pass of TFDN / SWNA performed in the channel domain up to 250 / 150 Hz respectively.

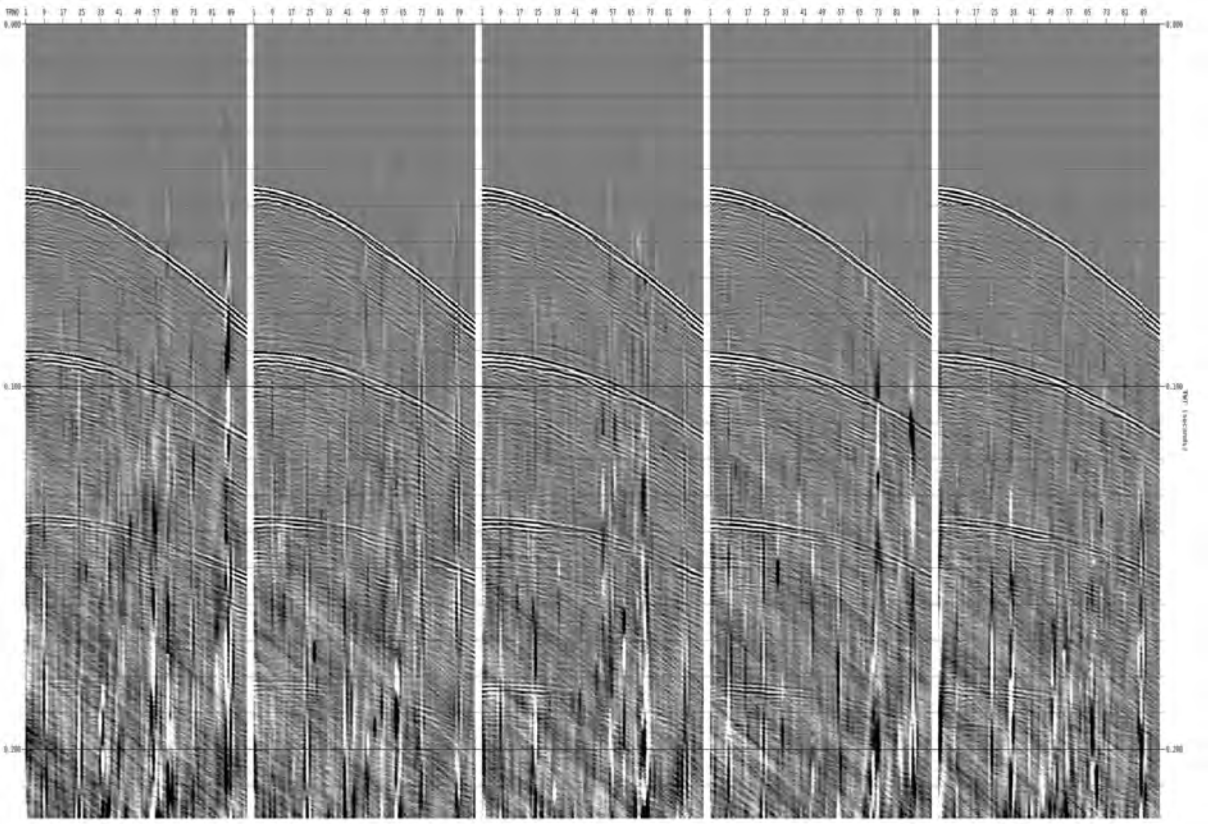

Figure 2.3: Denoise: Input shots

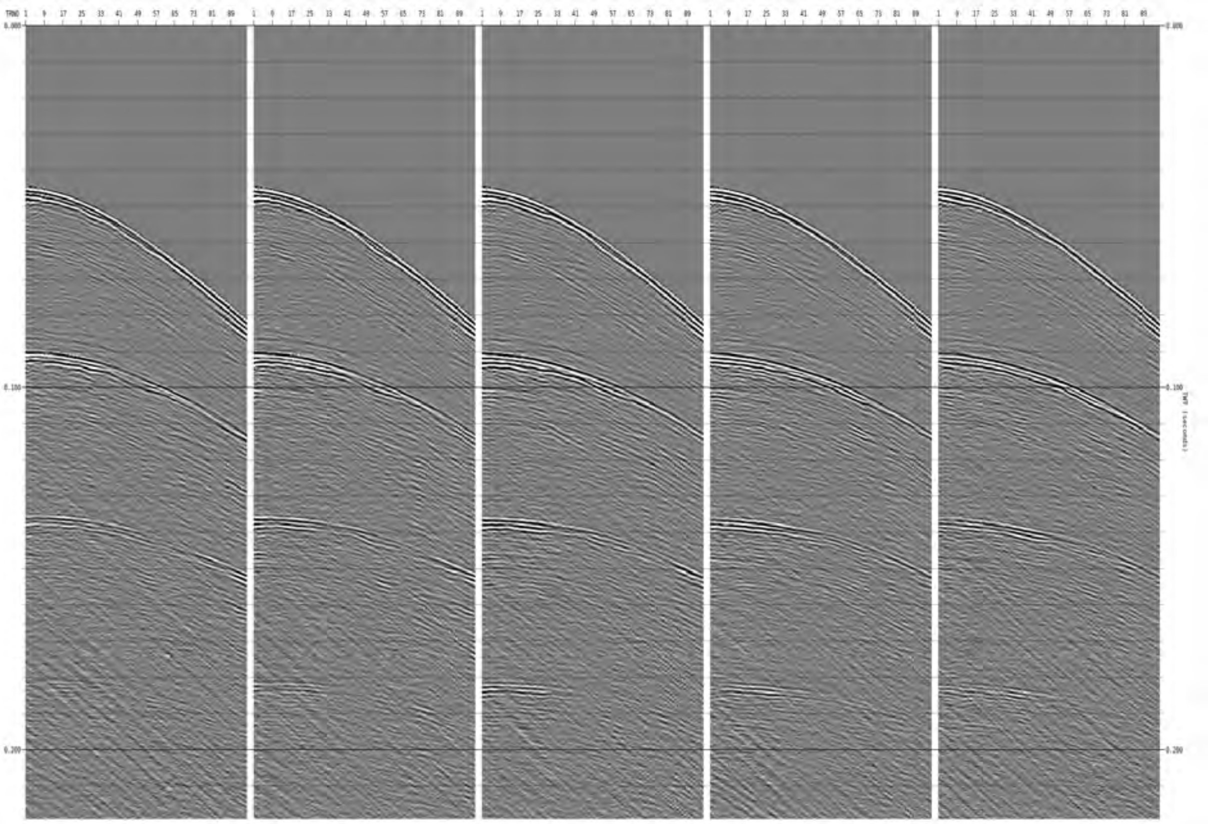

Figure 2.4: Denoise: Output shots

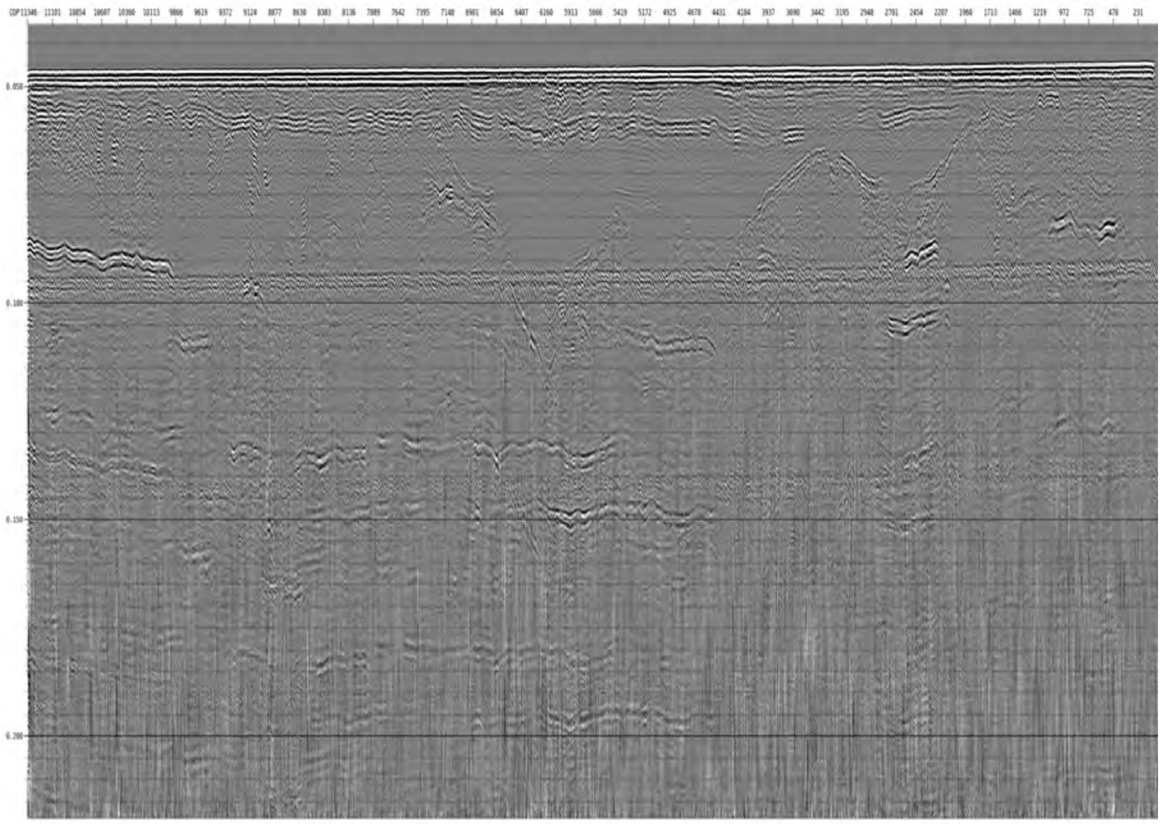

Figure 2.5: Denoise: Input stack

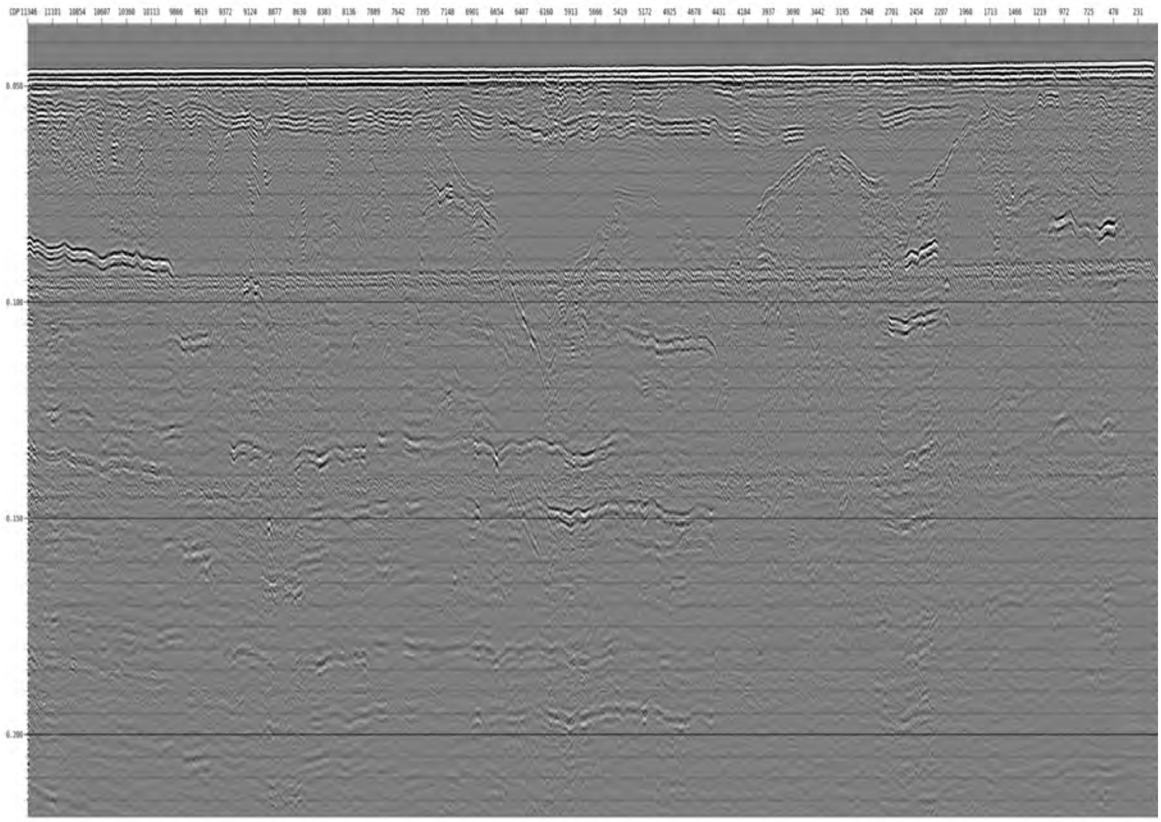

Figure 2.6: Denoise: Output stack

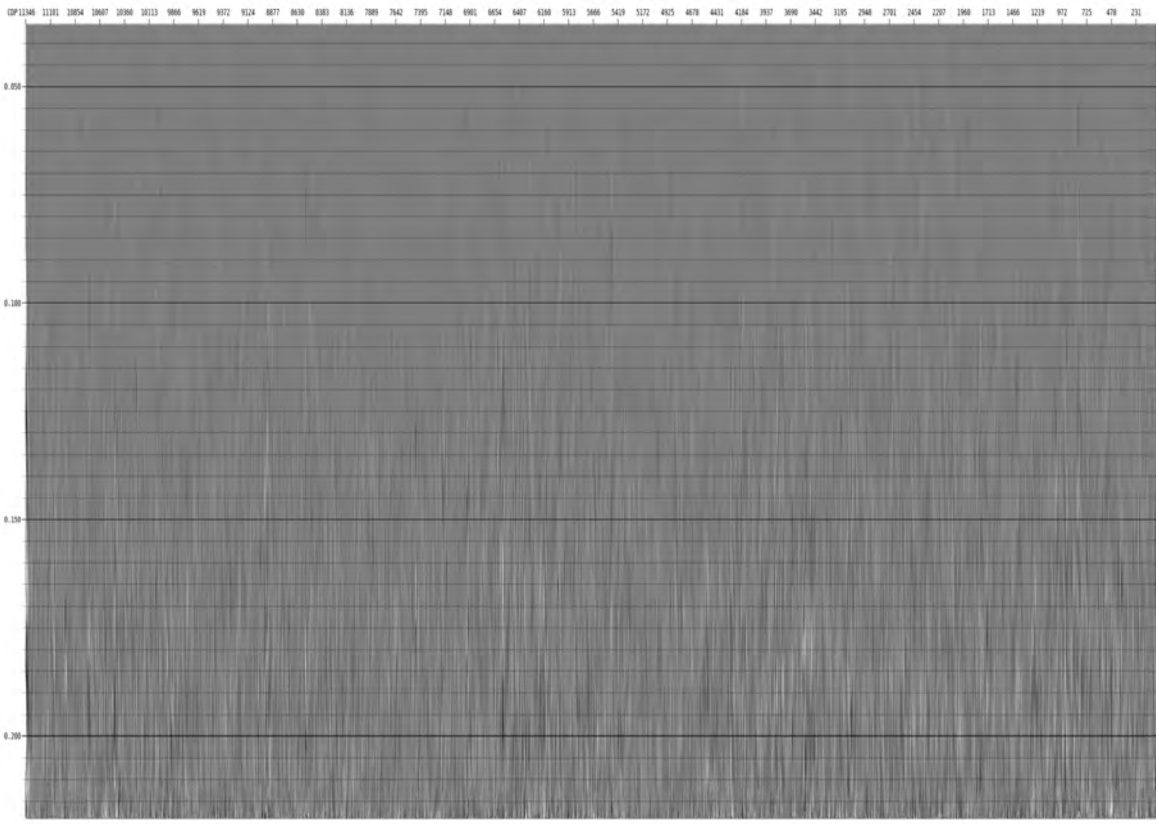

Figure 2.7: Denoise: Difference stack

2.4 Preliminary Shot Statics

Due to the fine sampling rate, shot statics were a large factor in the resolution of the shallow section of the data. It was important at this stage, once data was relatively free of low frequency swell noise, to apply some preliminary shot statics to aid the QC of some of these further processes. It is particularly useful to have shot statics applied prior to deghosting as it is difficult with this high resolution of data to identify what the process is doing if shot statics are still predominant.

To achieve this, a provisional shot statics computation was ran using the *Uniseis* module *'NEPTUNE'*. This is ran on NMO corrected CMPs, creating a pilot trace for each CMP using a weighted mix of local stacked traces. Cross-correlations of the pilot trace with the traces in its respective CMP gather are used to assess the static, and this is ran in multiple iterations. With each iteration, the static computed is applied and the pilot trace is correspondingly updated. This run focused solely on the shot static which is a short period effect that locally damages the stack. 5 iterations were chosen, as there was a slight uplift from 3 iterations. Any more than 5 iterations were where the static had already converged to the accepted value and would only unnecessarily increase the runtime.

Later in the processing, once the data is deghosted and velocities are picked, we rerun this computation and add in a component to correct for the streamer depth static using the module *'PASTA'*.

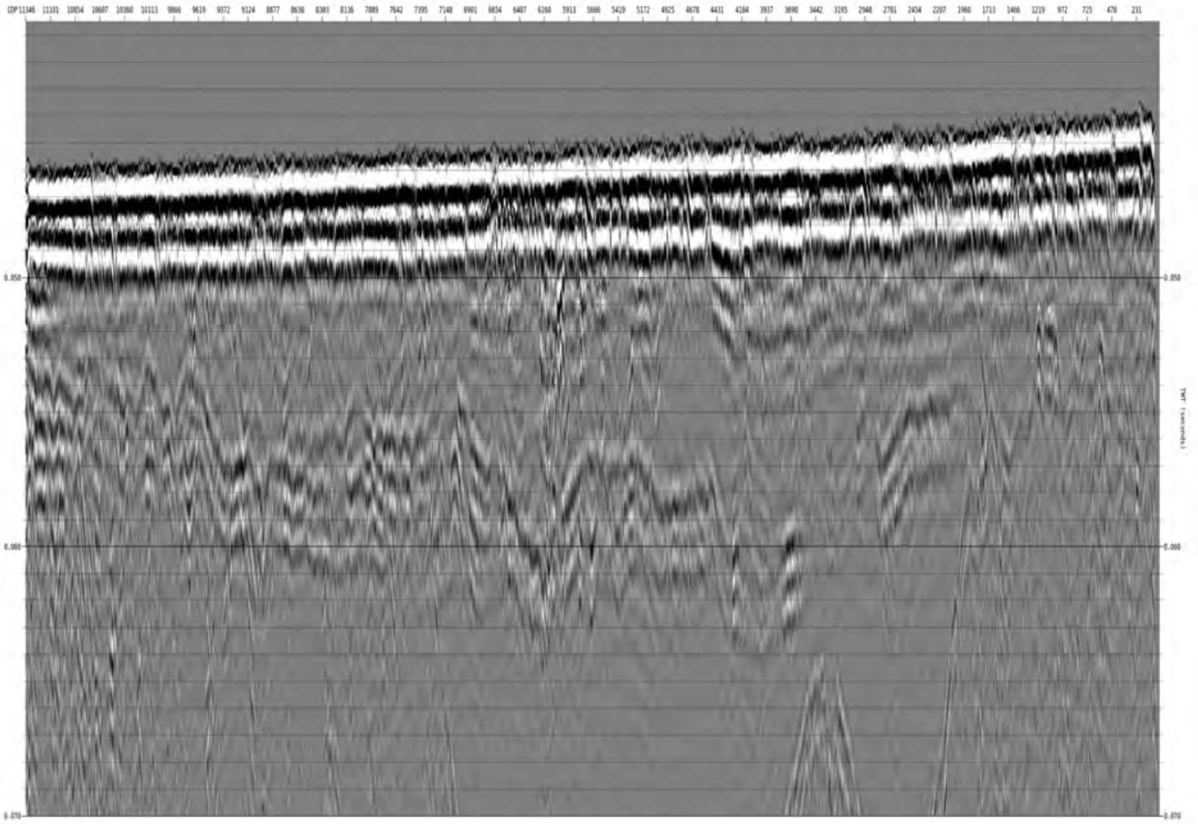

Figure 2.8: Preliminary shot statics: Input stack (zoomed)

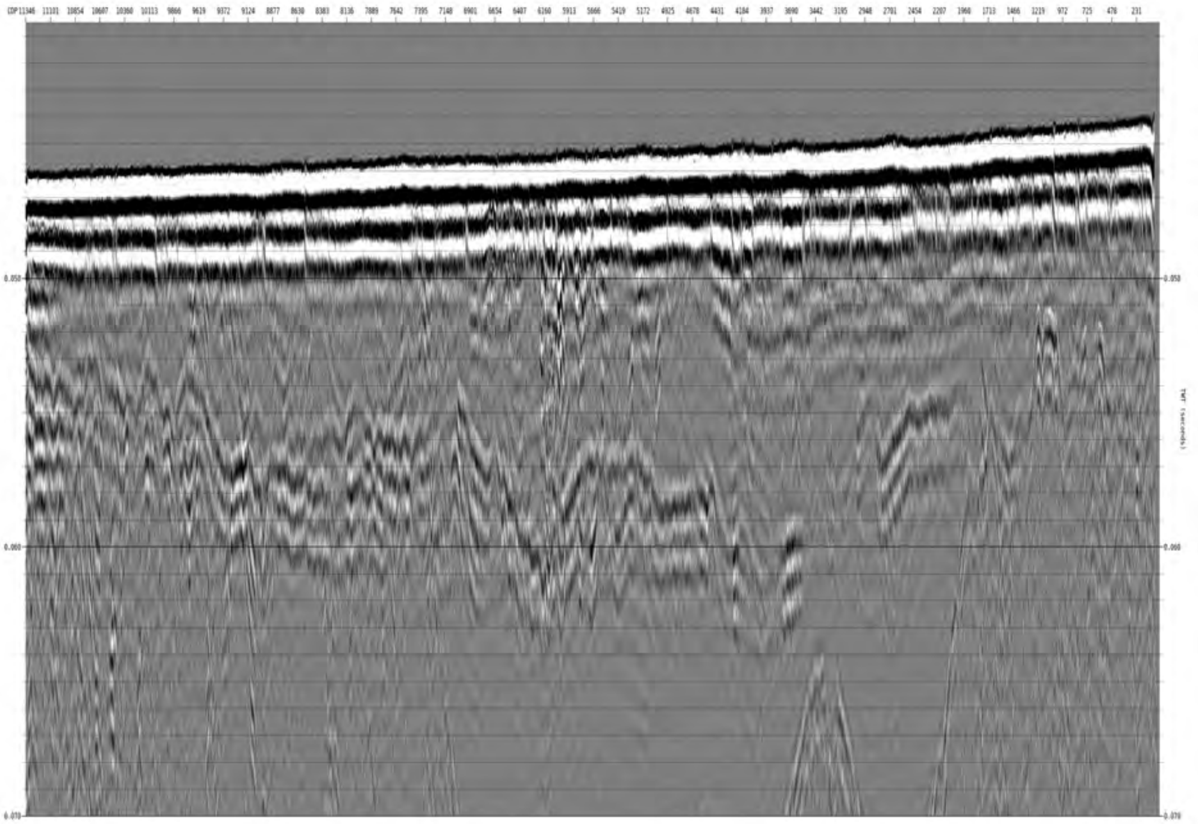

Figure 2.9: Preliminary shot statics: Output stack (zoomed)

2.5 Linear Noise Attenuation

Linear noise was observed to some extent on all lines in this survey. A Tau-P linear transform was applied to the data to effectively attenuate this noise. Data was transformed into the Tau-P domain with a range of -100 ms to +100 ms at the far offset. This was then muted to create a noise model of data with dip greater then 50 ms at reference offset in the shallow, tapering tighter to 20 ms at the end of record. This model was then muted below the seabed to avoid any noise modelling in the very shallow. This final noise model was then subtracted from the input data.

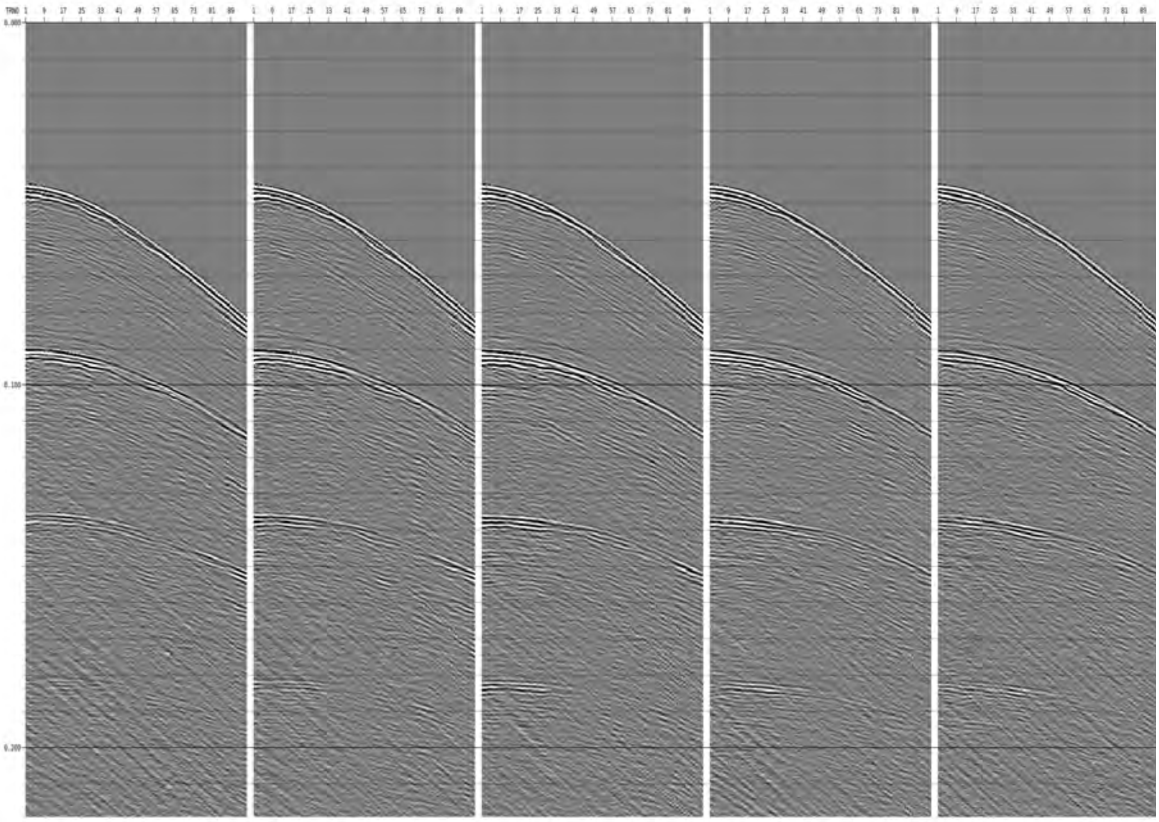

Figure 2.10: LNA: Input shots

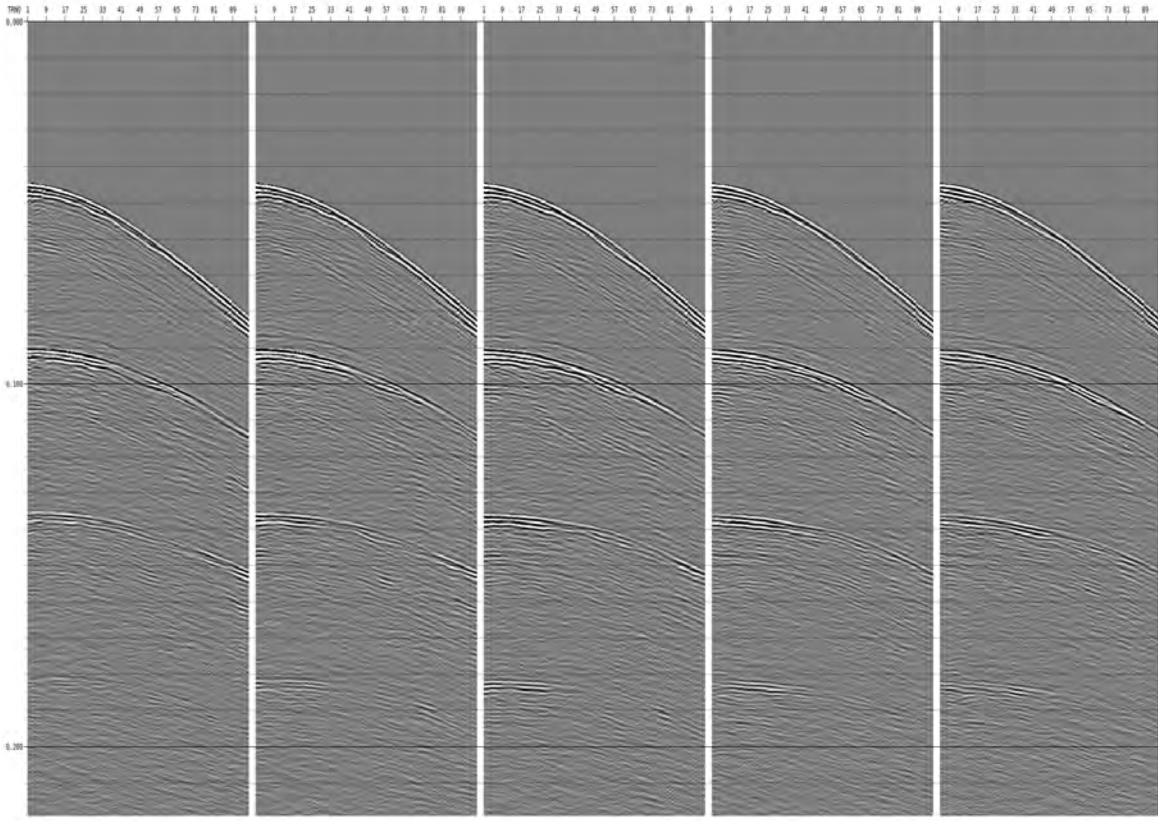

Figure 2.11: LNA: Output shots

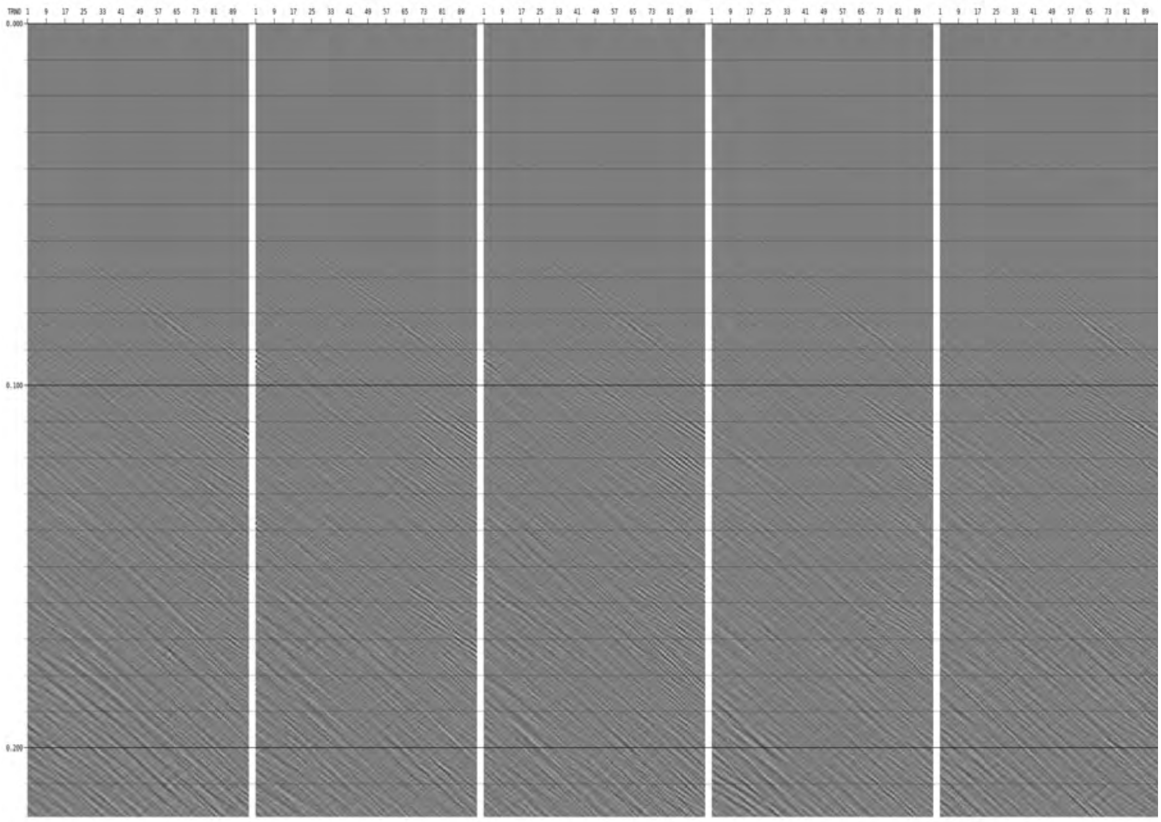

Figure 2.12: LNA: Difference

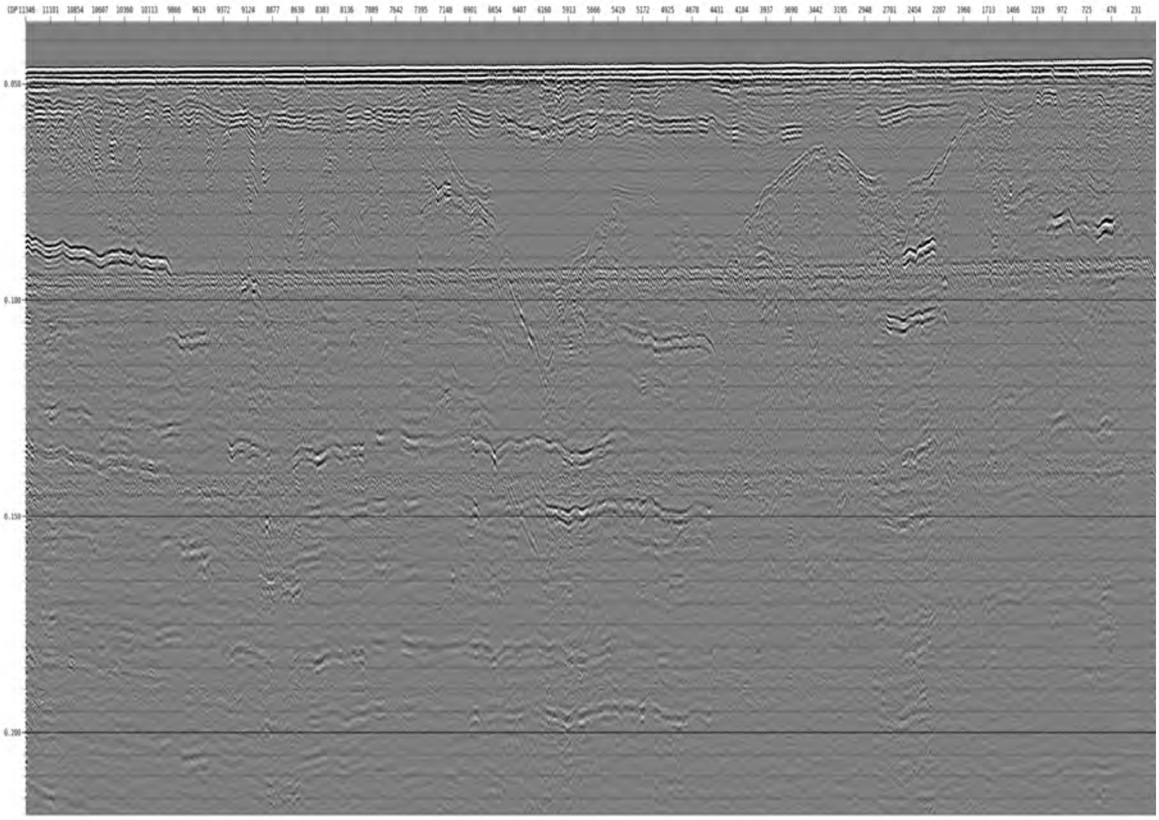

Figure 2.13: LNA: Input Stack

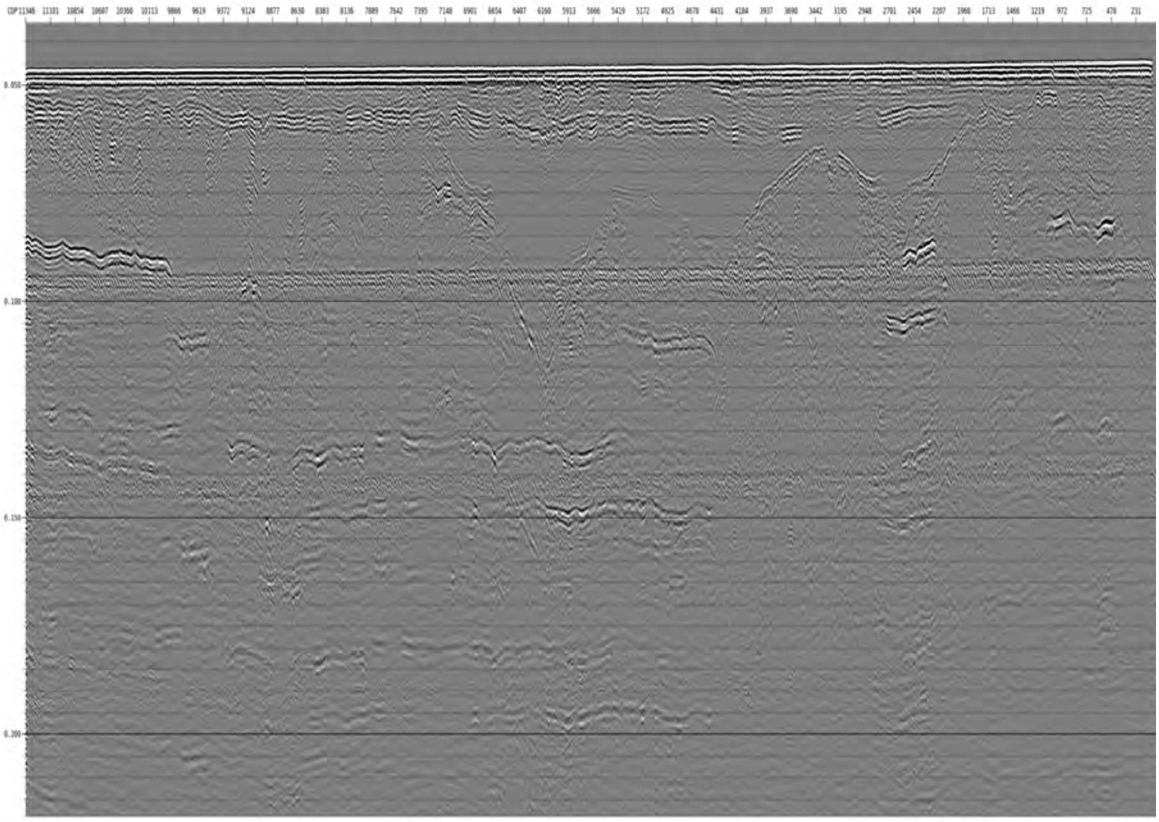

Figure 2.14: LNA: Output Stack

2.6 Surface Related Multiple Elimination (SRME)

There was significant multiple energy within the data, mainly associated with the water bottom. To attenuate multiple energy, SRME (Surface Related Multiple Elimination) was carried out. SRME uses the geometry of shot recording to estimate all possible multiples that can be generated by the surface. Before evaluating the multiple model, the recorded data was extrapolated to zero offset and a mute was applied to the input shot records to remove direct arrival and guided wave energy. The predicted multiple energy was removed from the input gathers with a double adaptive matching algorithm, the first done in the common channel domain and the second in the shot domain. The adaption in the common offset domain was computed over 211 neighbouring shots, with a filter length of 15ms and an operator of 50ms. Less traces than 211 can cause the SRME to be too harsh (with a small SP interval of 1 m this is just over 200 m), and conversely a higher number of traces can often lead to a degraded model where there is steeply dipping and variable multiple. Before adaptive subtraction, the modelled multiples were muted above the first seafloor multiple. SRME was found to be effective in attenuating multiple energy whilst preserving primary events.

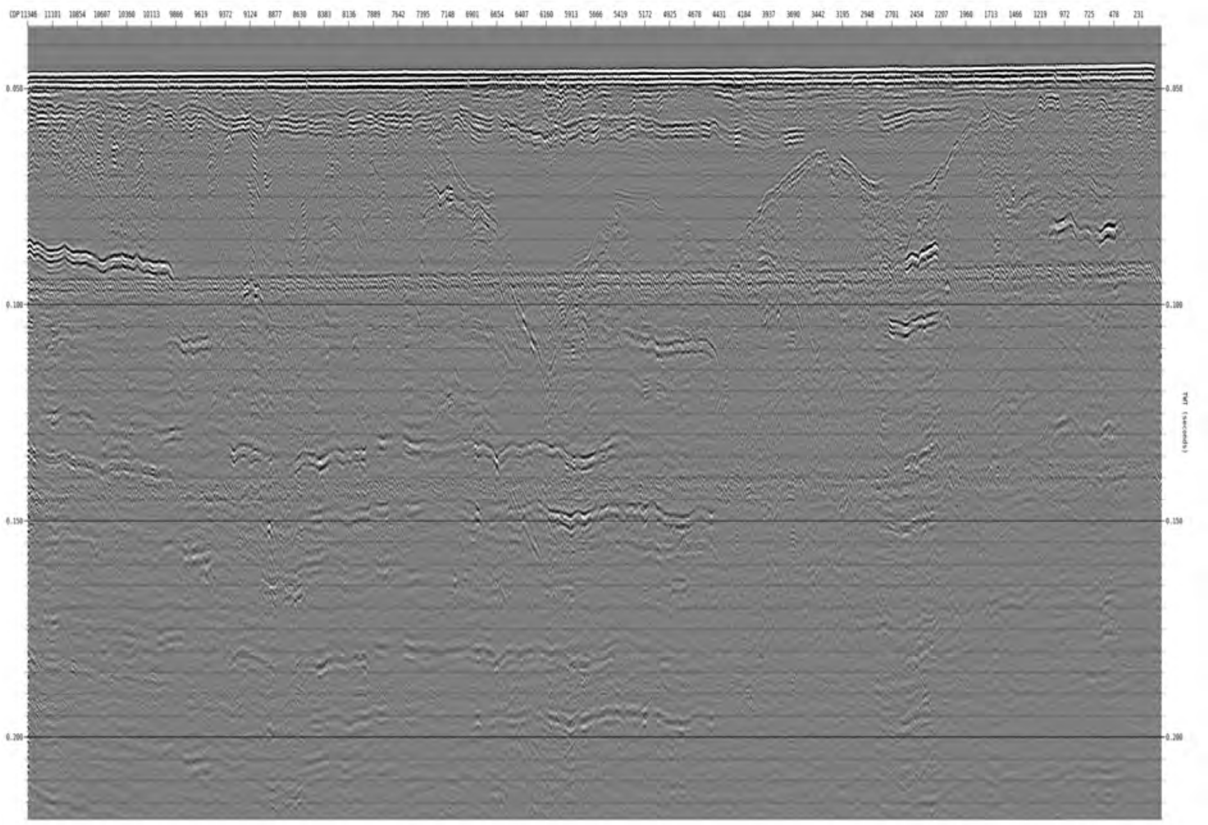

Figure 2.15: SRME: Input stack

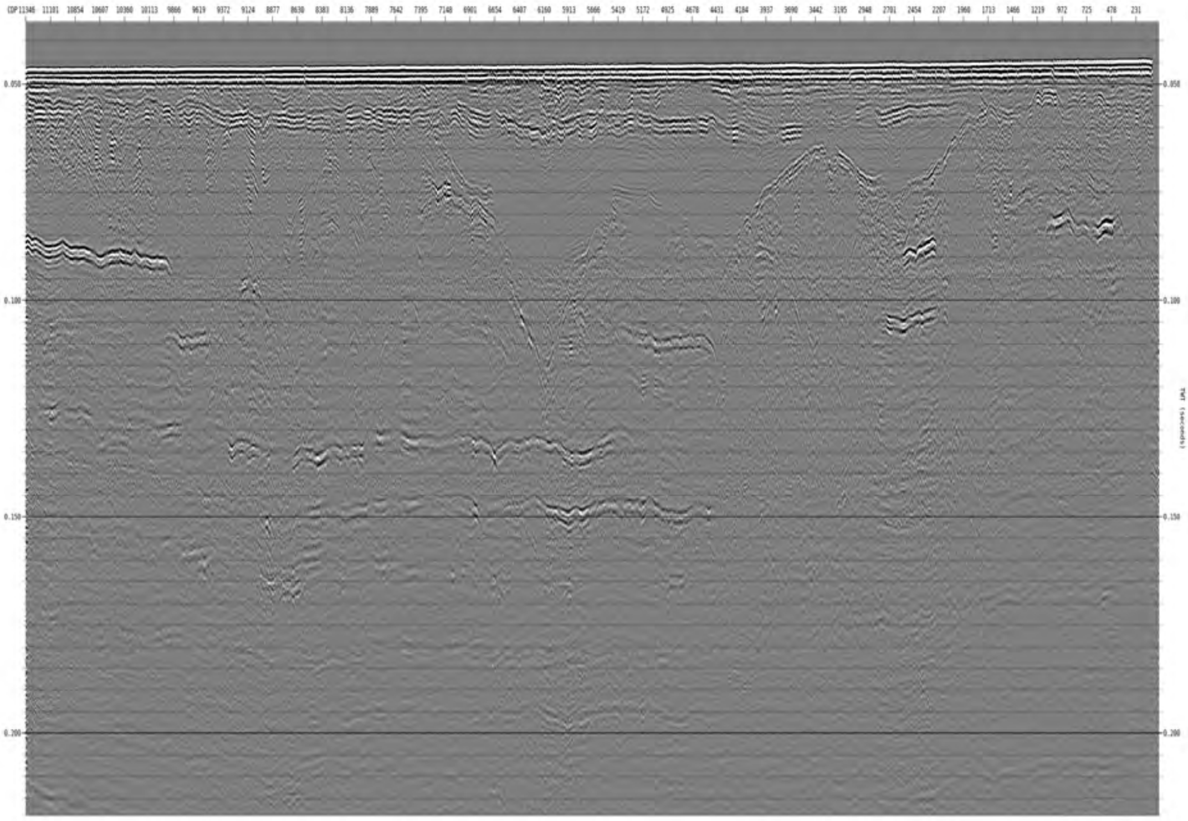

Figure 2.16: SRME: Output stack

2.7 Source and Receiver Deghosting

The high acoustic impedance contrast between the water column and the sea surface causes the latter to act as a near perfect reflector of acoustic energy. Consequently, some of the acoustic energy from a seismic source reflects at this interface before being recorded at the receivers and this is referred to as (source/receiver) ghost, thereby limiting the wavefield spectral band.

To attenuate source, receiver and combined source / receiver ghosts, the *Uniseis 'DEGHOST'* module was applied. *'DEGHOST'* attempts to separate the primary energy from the secondary ghosted wavefield. The primary upcoming wavefield should be more representative of the subsurface reflectivity required for interpretation & well-log matching. Reflections should become shorter, less complex wavelets and be more representative of their characteristic reflectivity in magnitude and polarity. The consequence of this is that we improve the resolution and achieve a broader spectrum. Various tests showed the standard reflection coefficient of -1 for the source and receiver deghosting worked well to attenuate the ghost. A 0.5 m wave height allowance for the frequency dependent scattering model was applied to the source deghosting (none for receiver side), and this helped to reduce ringing from the deghosting process.

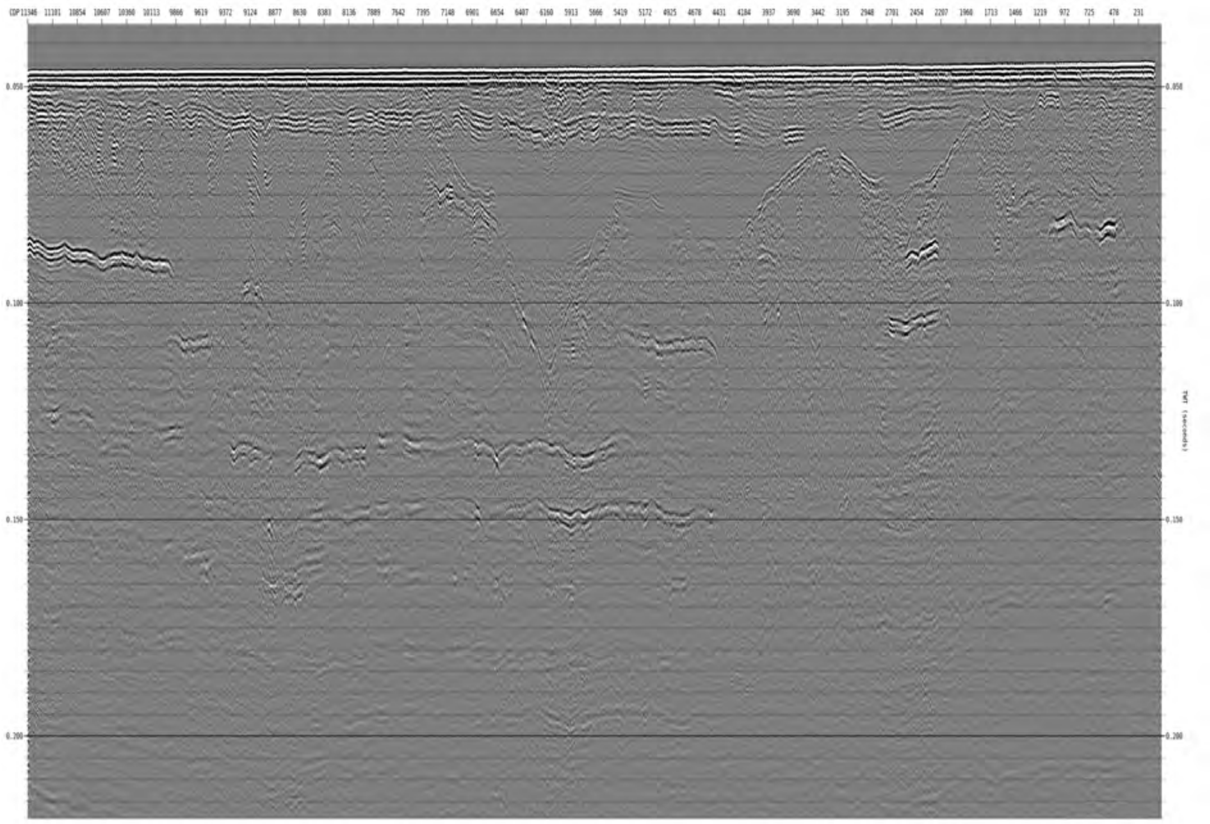

Figure 2.17: Deghost: Input stack

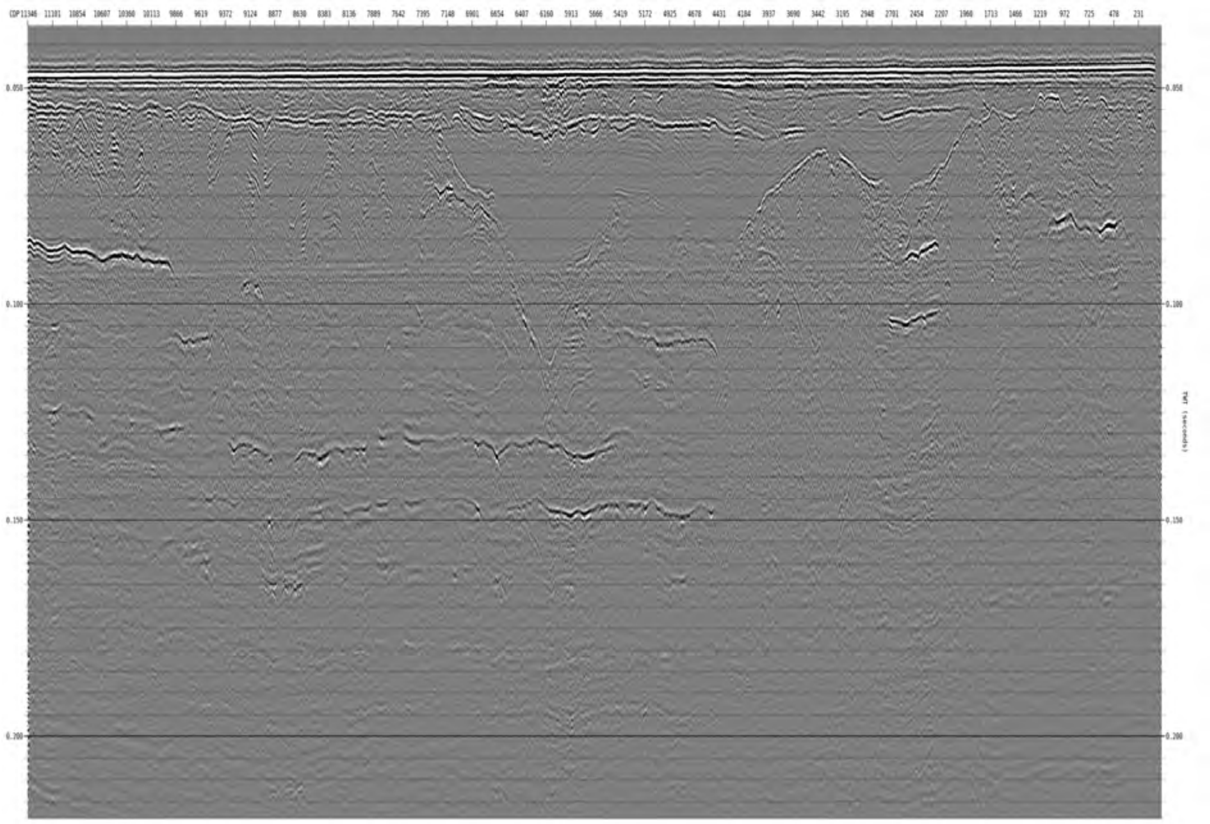

Figure 2.18: Deghost: Output stack

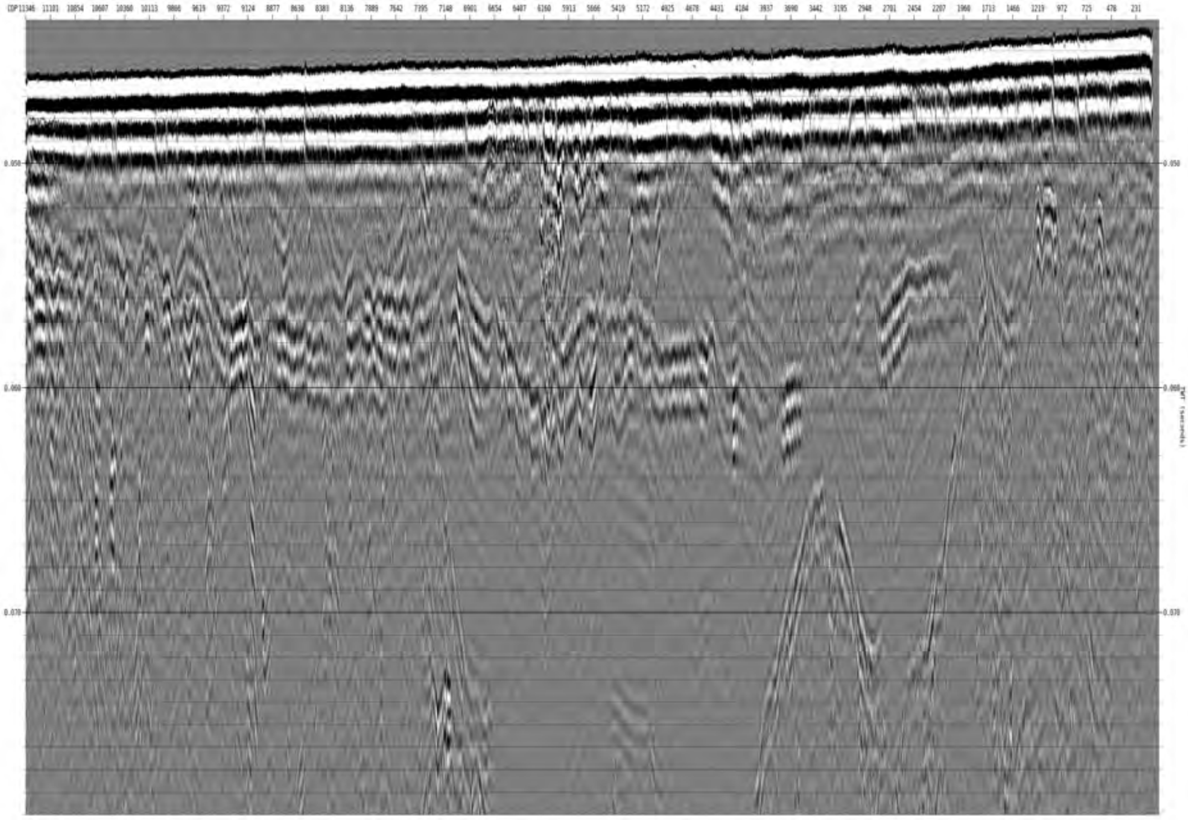

Figure 2.19: Deghost: Input stack (zoomed)

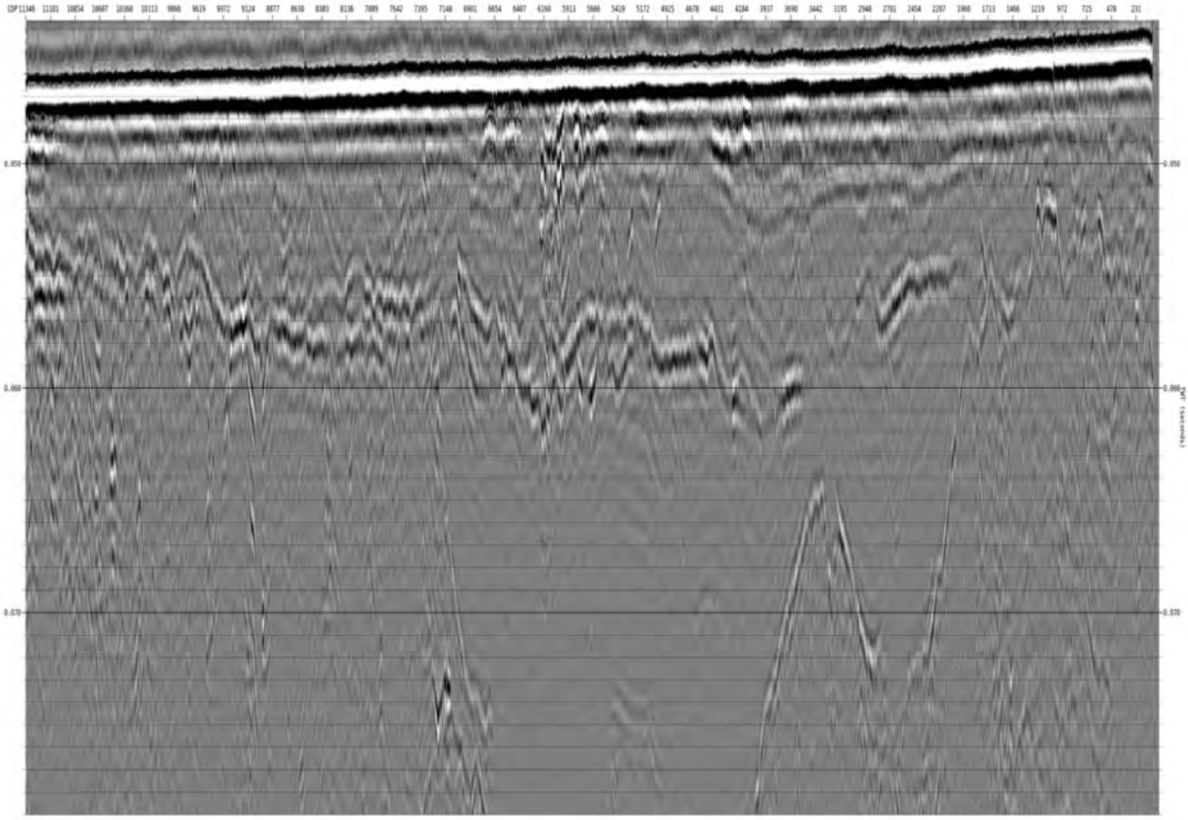

Figure 2.20: Deghost: Output stack (zoomed)

2.8 Additional Demultiple

An additional adaption of the multiple model was performed after deghosting in order to further attenuate any remnant multiple. This proved of benefit to this data after the data was free from ghost, hence making the data much less complex to adaptively match.

Note that the earlier initial stage of demultiple is useful to reduce any potential artefacts during deghosting coming from the strong amplitude of the first bounce multiple.

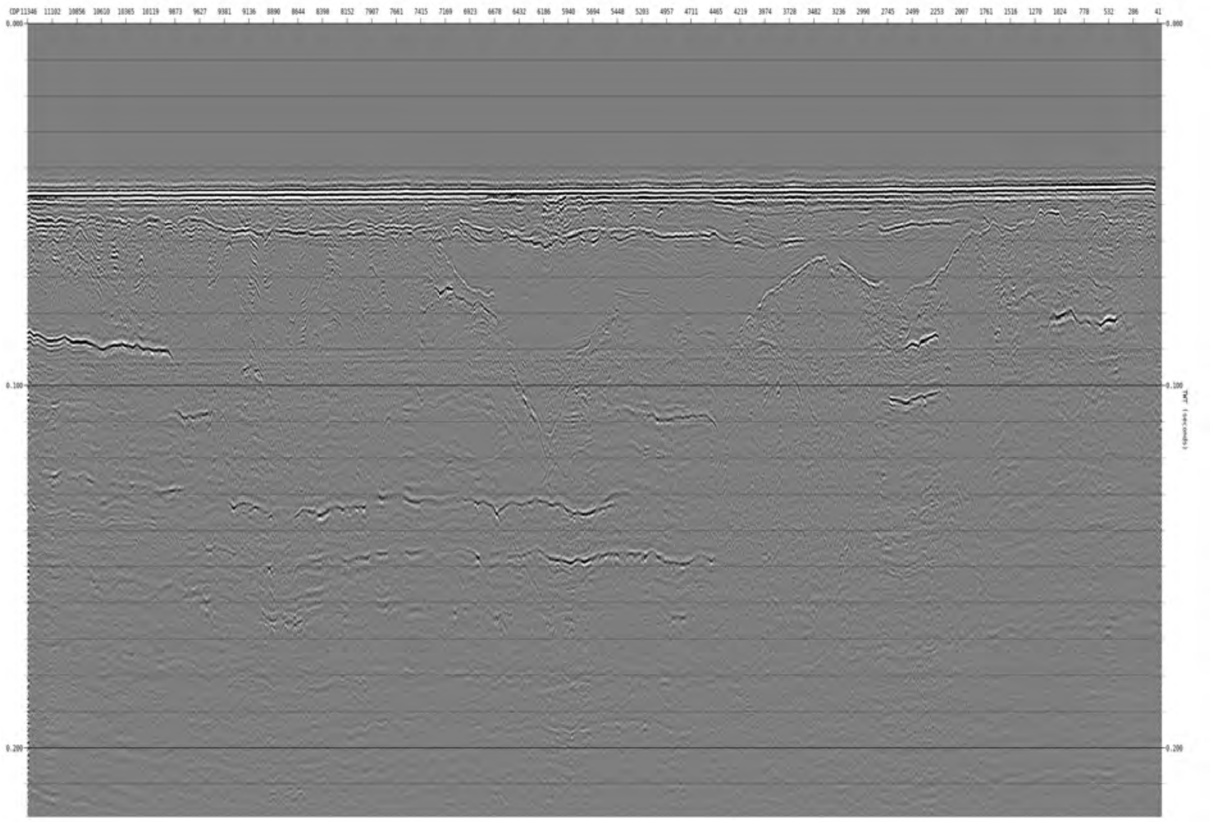

Figure 2.21: Additional demultiple: Input stack

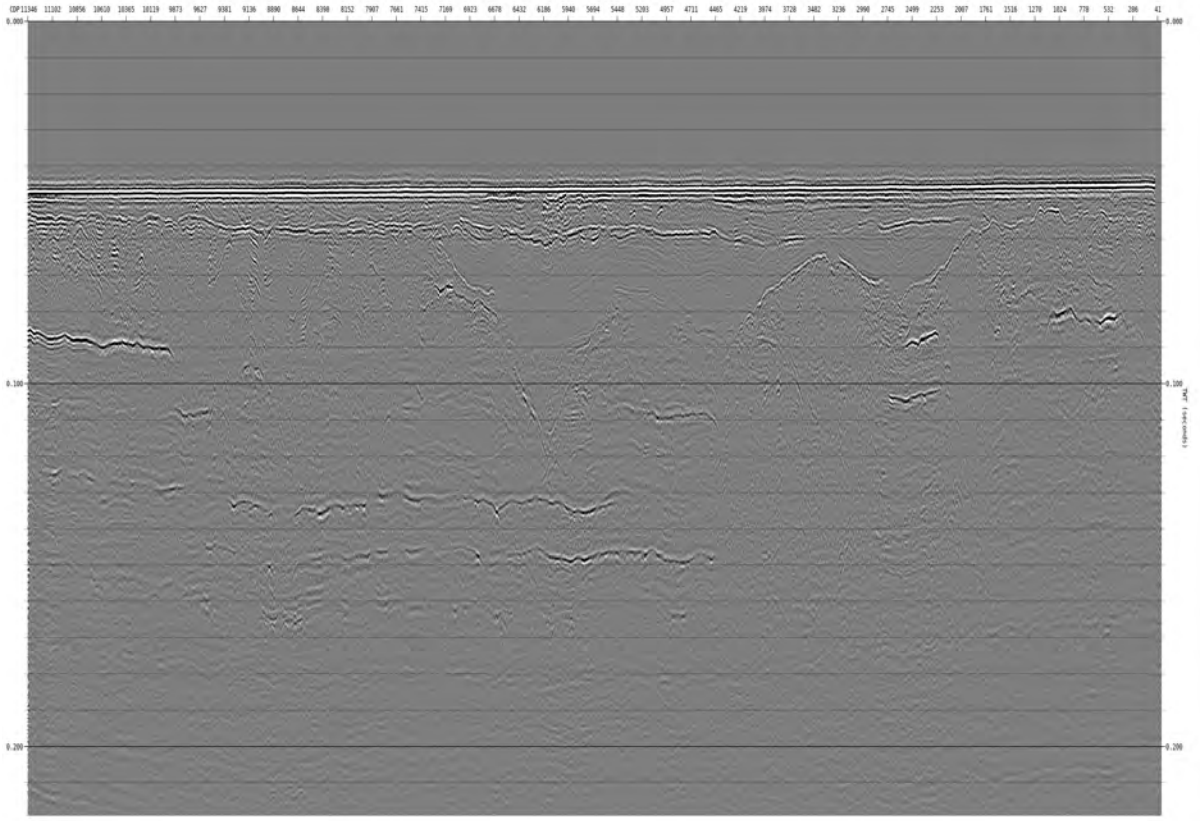

Figure 2.22: Additional demultiple: Output stack

2.9 Velocity Analysis

A high-resolution velocity analysis using 2nd order NMO correction was conducted for each line using the interactive velocity analysis software *Pegasus*. The analysis was performed at 500 m intervals with each location being compared to and constrained by neighbouring locations. This ensured that consistency was maintained between adjacent lines and velocity locations. Examples below show the displays generated by *Pegasus* for the purposes of velocity analysis. This image shows the semblance, NMO corrected gather, constant velocity stacks and real time stack.

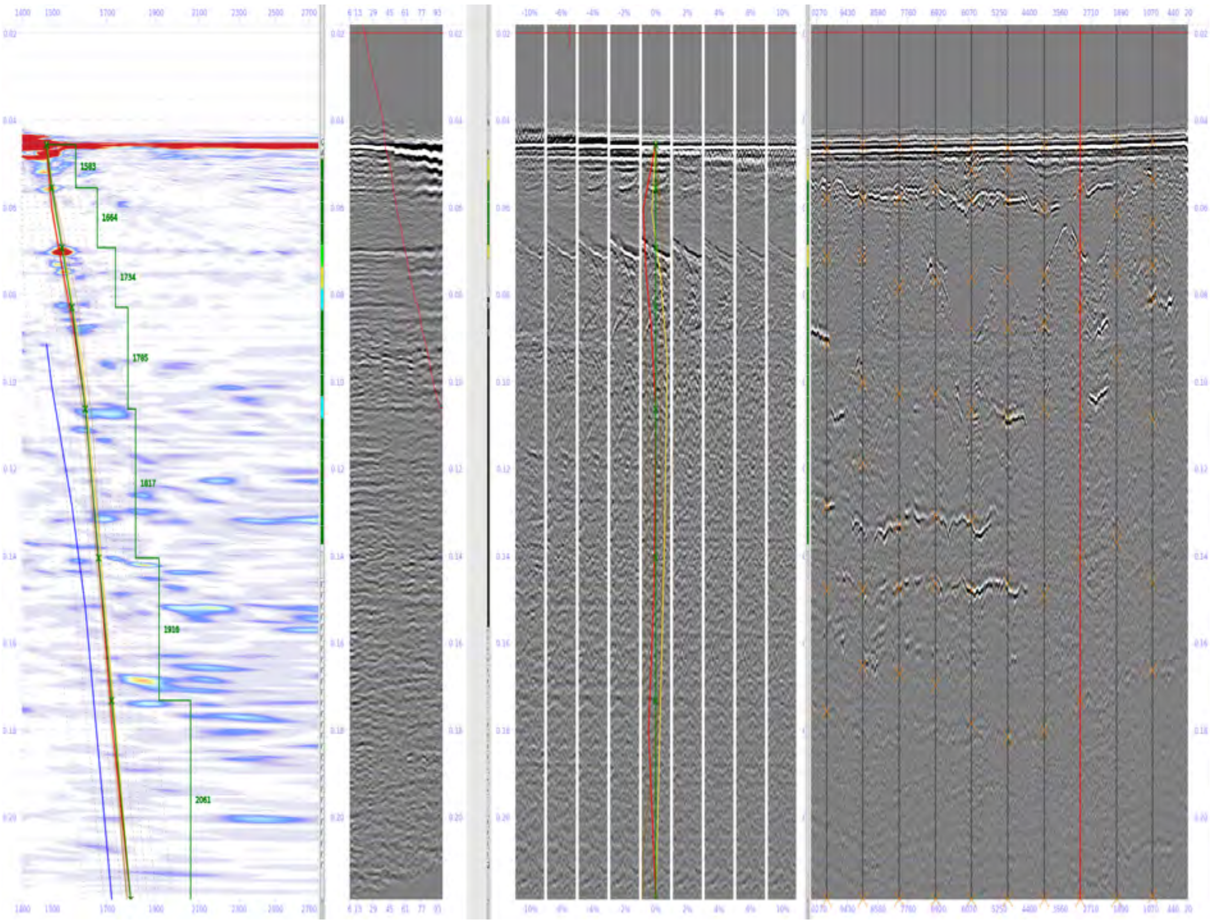

Figure 2.23: Pegasus Velocity: 2D velocity picking example on EAAA001P1

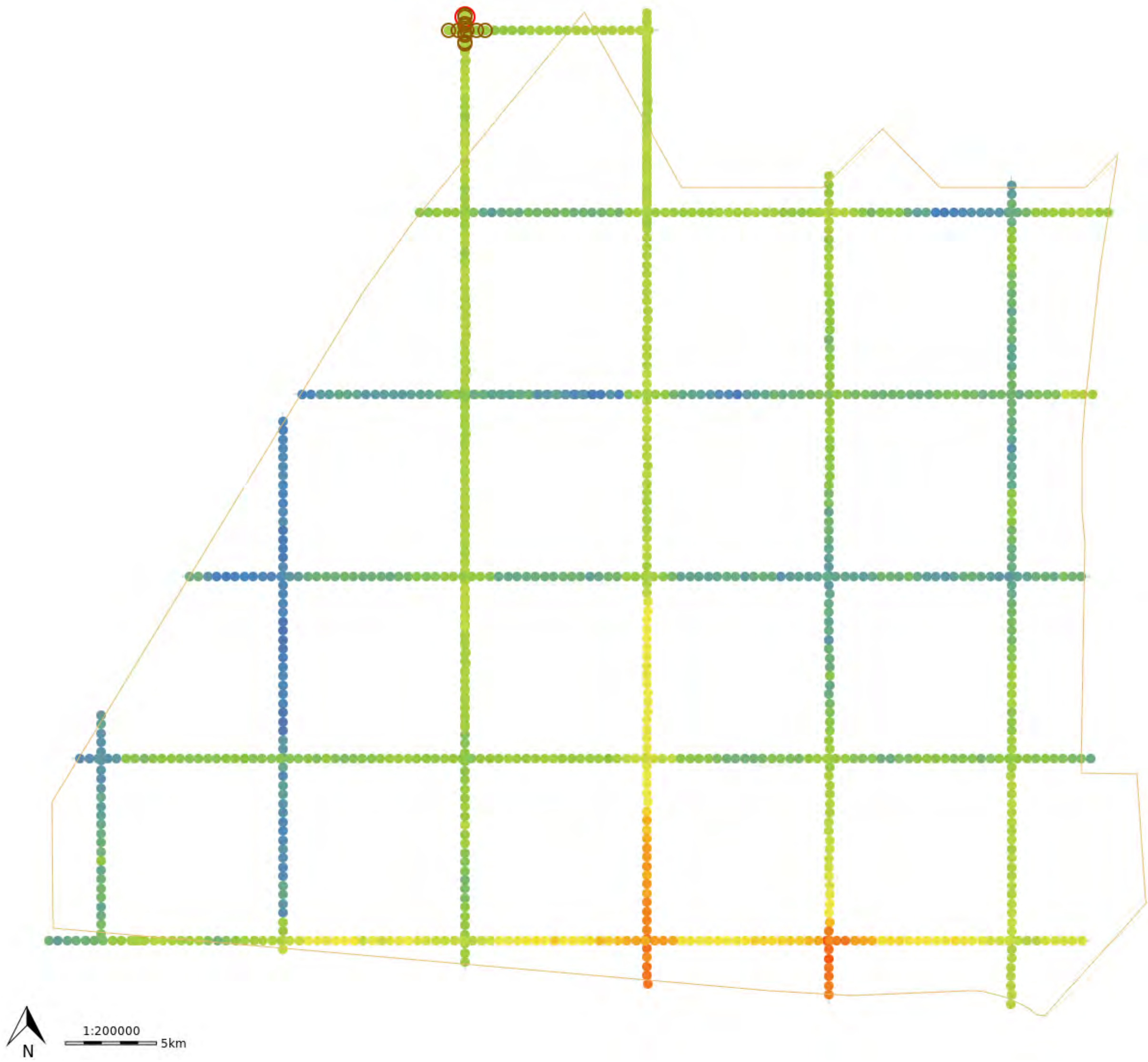

Figure 2.24: Pegasus Velocity: Map of RMS variations at 100 ms

2.10 Final Statics

Similar to the section on preliminary shot statics, we now recompute the shot statics using the same *'NEPTUNE'* process, but now the data has a significantly attenuated ghost along with picked velocities. This allowed for a slightly improved shot static computation. Again 5 iterations were used to converge the static to an acceptable value; 3 being too little, and any more iterations being unnecessary.

Once this was calculated and applied to the shots, an additional pass of *'PASTA'* was applied to NMO corrected CMPs to correct for residual streamer depth statics. This is achieved in a similar manner, by cross correlating the traces in the CMP with a pilot trace which is a weighted trace mix of the stack. We achieve a better result by isolating the shot statics independently first with *'NEPTUNE'* rather that attempting to correct for both at the same time.

The data were now ready to be stacked. An outer trace mute was applied to remove NMO stretch on the far offsets. After various testing of tight and more open mutes than the QC mute so far, a slightly tighter mute was used at the seabed as an improvement to the higher frequencies was shown in the top 10ms. A more open mute was shown to introduce stretch in the shallow regions, a consequence of the rather shallow conditions. Trace normalization of 1 / N was used when stacking. See below for an example of the gathers with the tighter final mute overlaid.

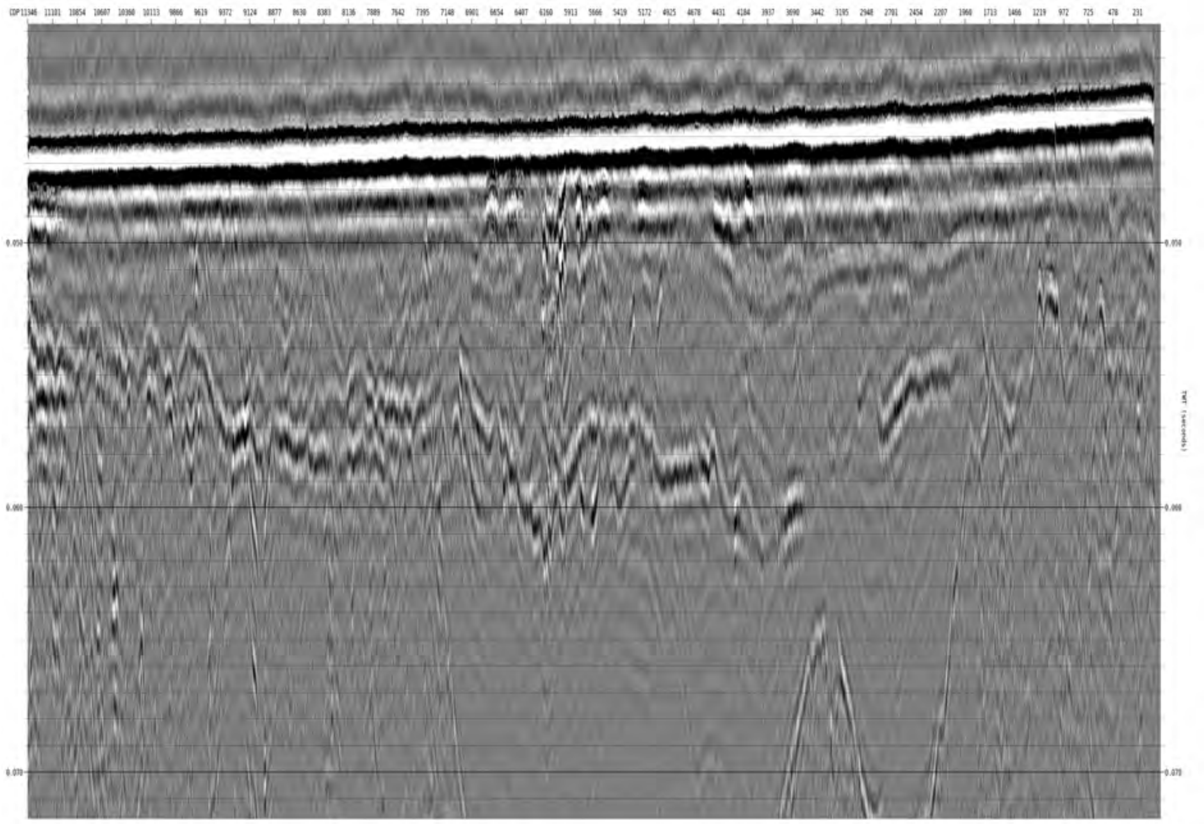

Figure 2.25: Stack with preliminary shot statics (zoomed)

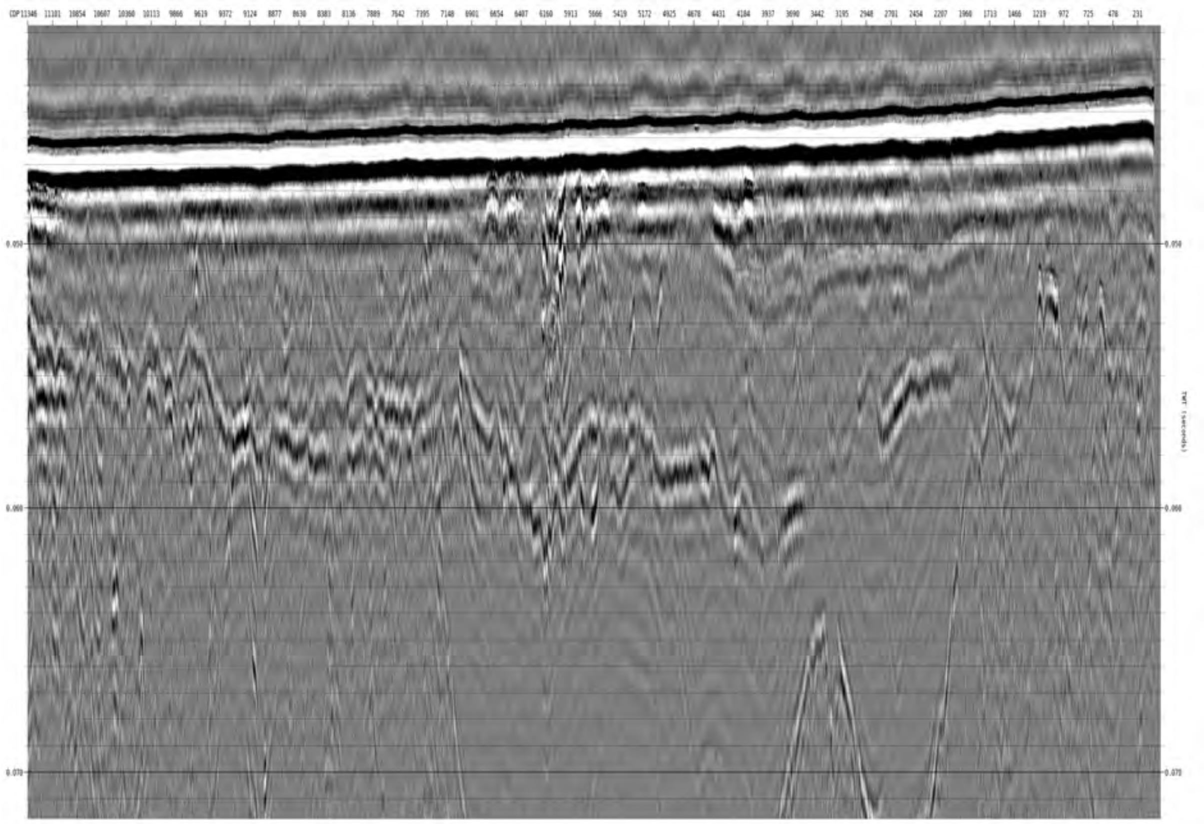

Figure 2.26: Stack with final vel and statics (zoomed)

Table 2.1: Final mute parameters

Time [ms]	Offset [m]
Seabed - 2 ms	25
Seabed + 10 ms	37
Seabed + 65 ms	Full offset range

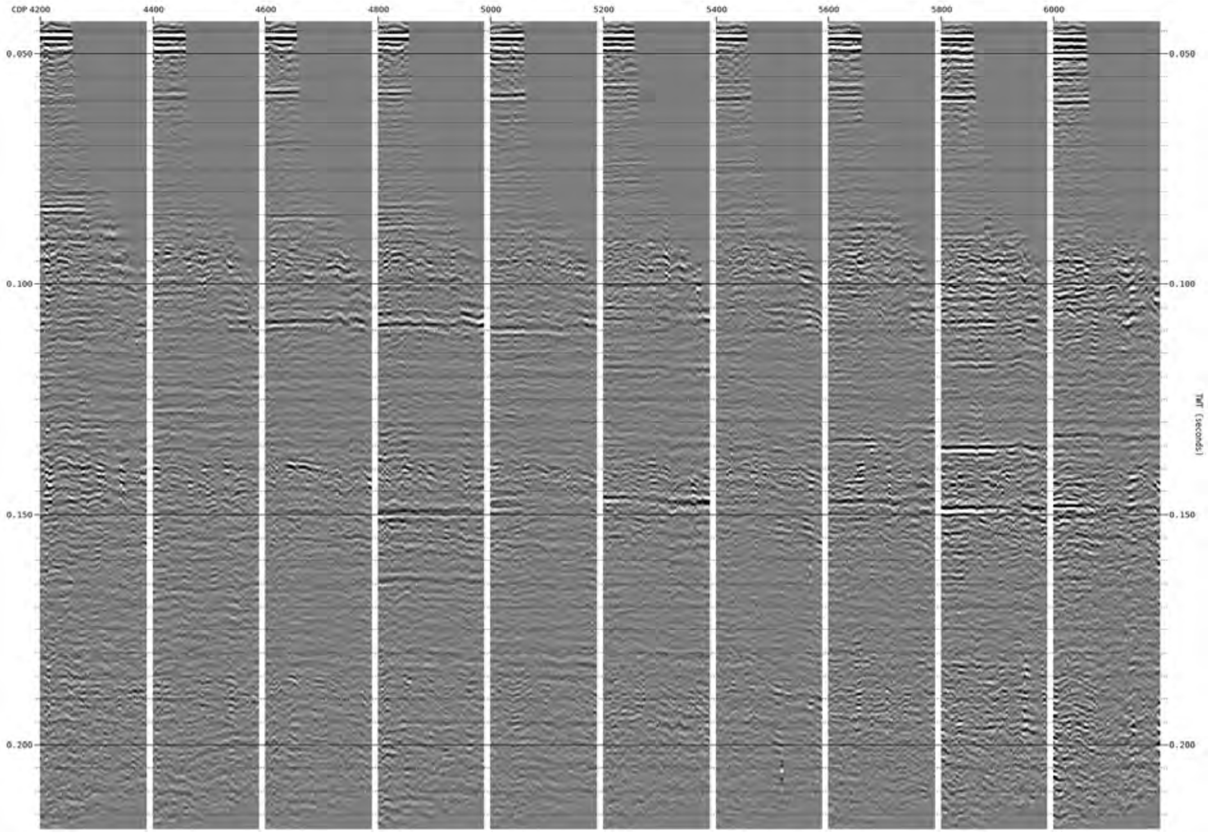

Figure 2.27: CMP gathers with final tighter stacking mute applied

2.11 Zero Phase

A zero-phase filter was designed using a data derived source signature wavelet, itself obtained by super stacking the stack. The water bottom was flattened, and traces shifted to 30 ms prior to the CMPs being super stacked. The onset of the super stacked wavelet was then shifted to 0 ms and the filter calculated. A debubble of gap 0.5 ms was also applied to this at the same time. See below for an example of the zero-phase filter applied to the stack.

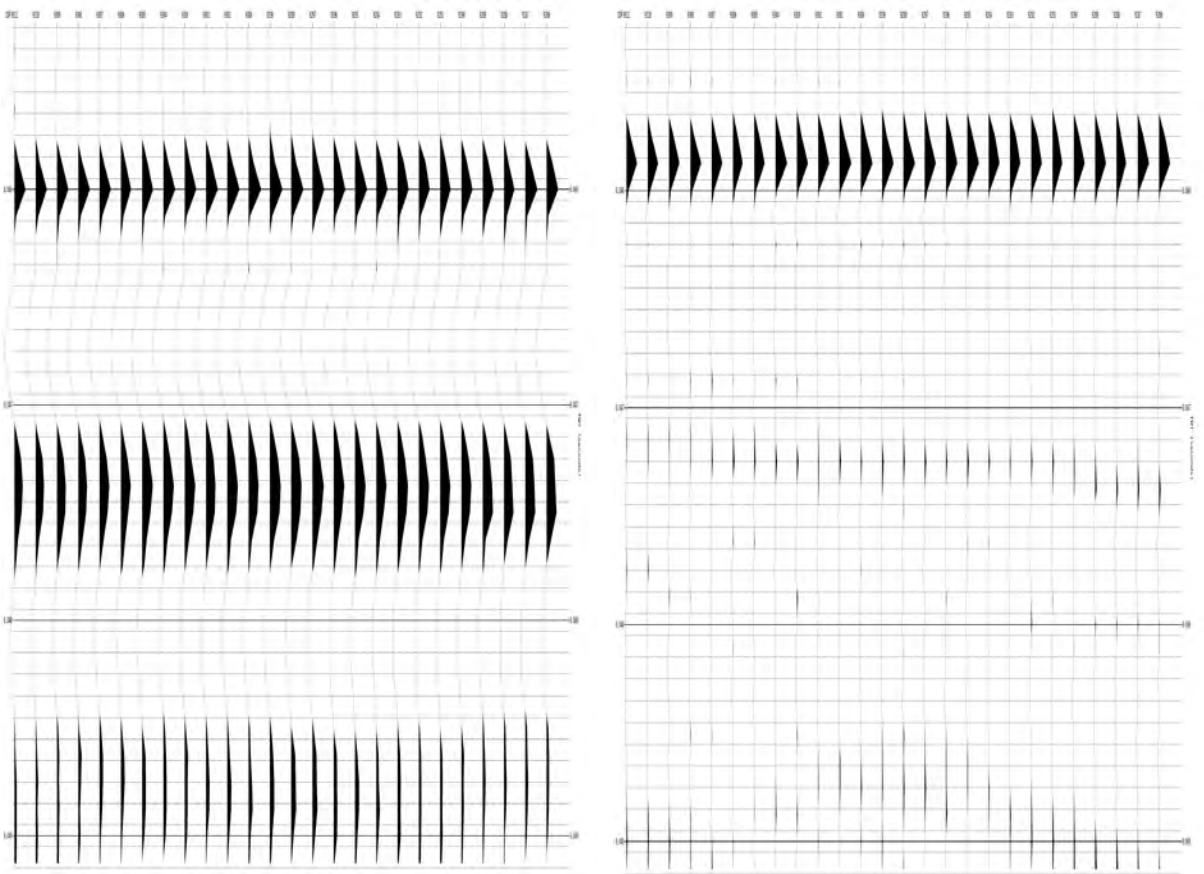

Figure 2.28: Zero Phase: Seabed before and after (zoomed)

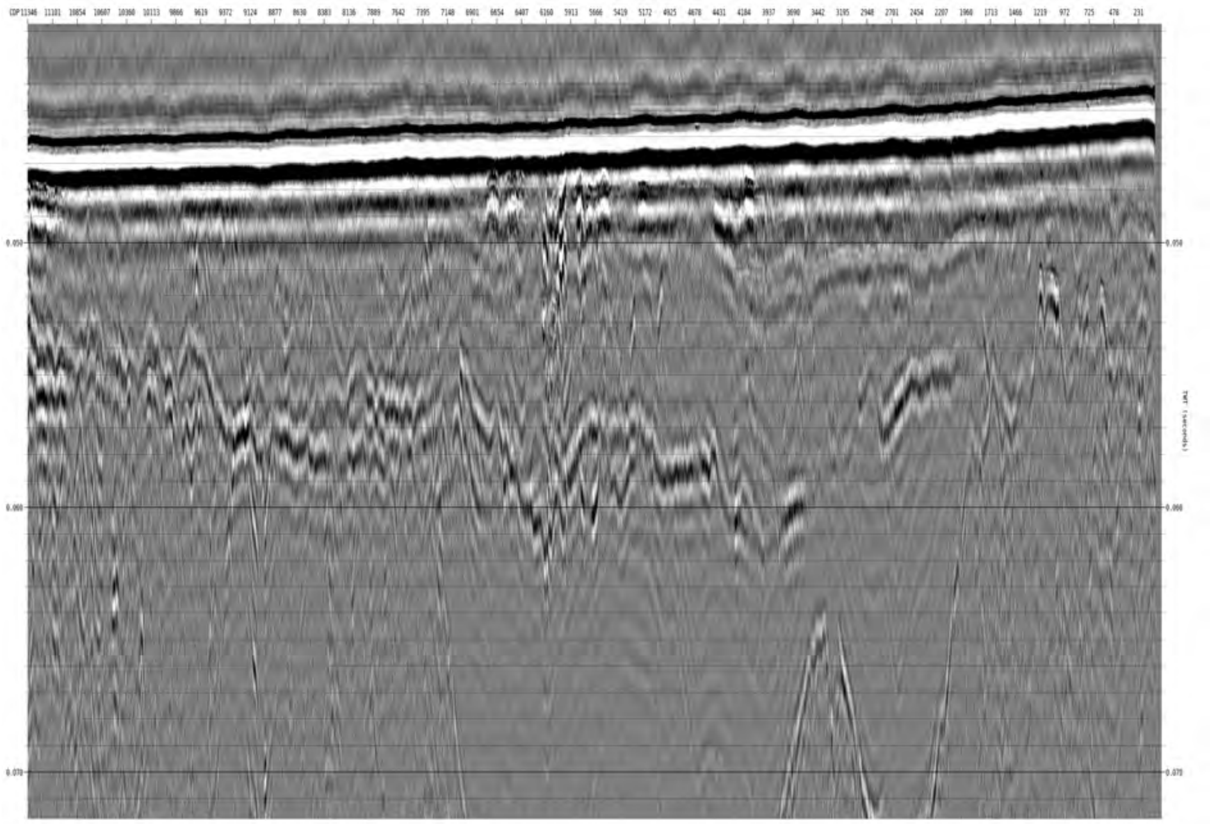

Figure 2.29: Zero Phase: Input stack (zoomed)

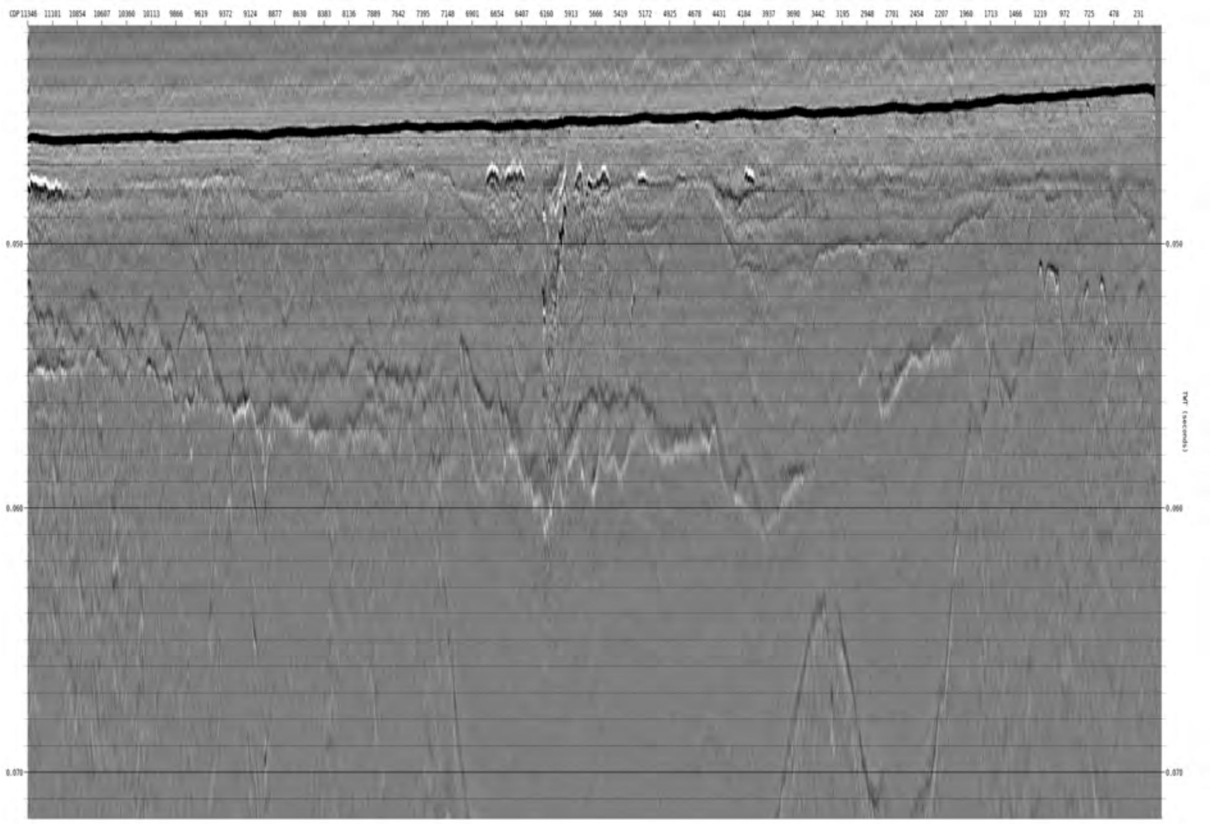

Figure 2.30: Zero Phase: Output stack (zoomed)

2.12 Post Stack Processing Step One

The low frequency noise, mainly boosted by the deghosting process, was attenuated at this stage using the *Uniseis 'SWELL'* module. This decomposed each seismic trace into signal and noise components by filtering the data with a user specified Butterworth filter, which in this case was over the range 0 - 80 Hz only.

A post stack deconvolution followed this to remove further multiple, hitting the remnant second seabed bounce rather effectively. This was a very mild application with averaging of the deconvolution operator over a very large 2001 traces/CDPs, computed with a gap 4ms shorter than the seabed, and operator 10ms longer than the seabed.

A cosmetic mute above the seabed was also applied at this stage.

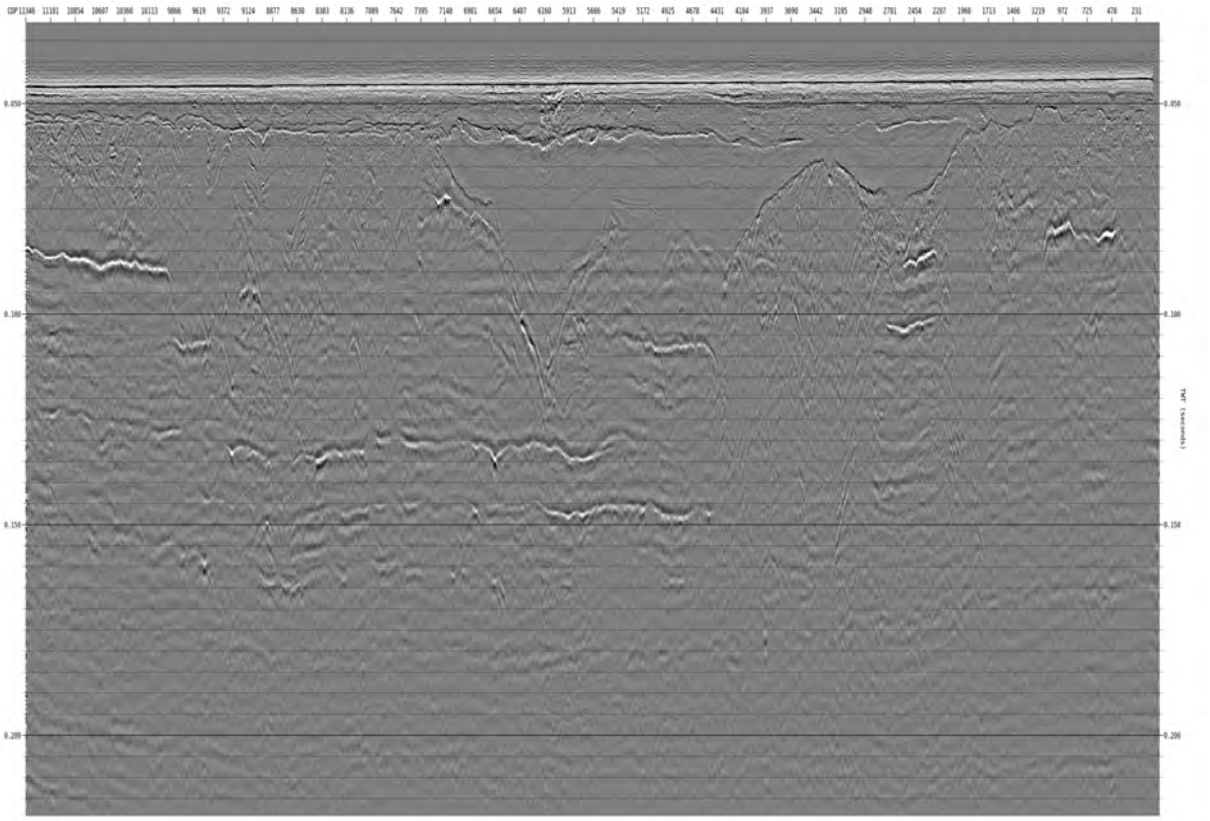

Figure 2.31: Post Stack Processing 1: Input stack

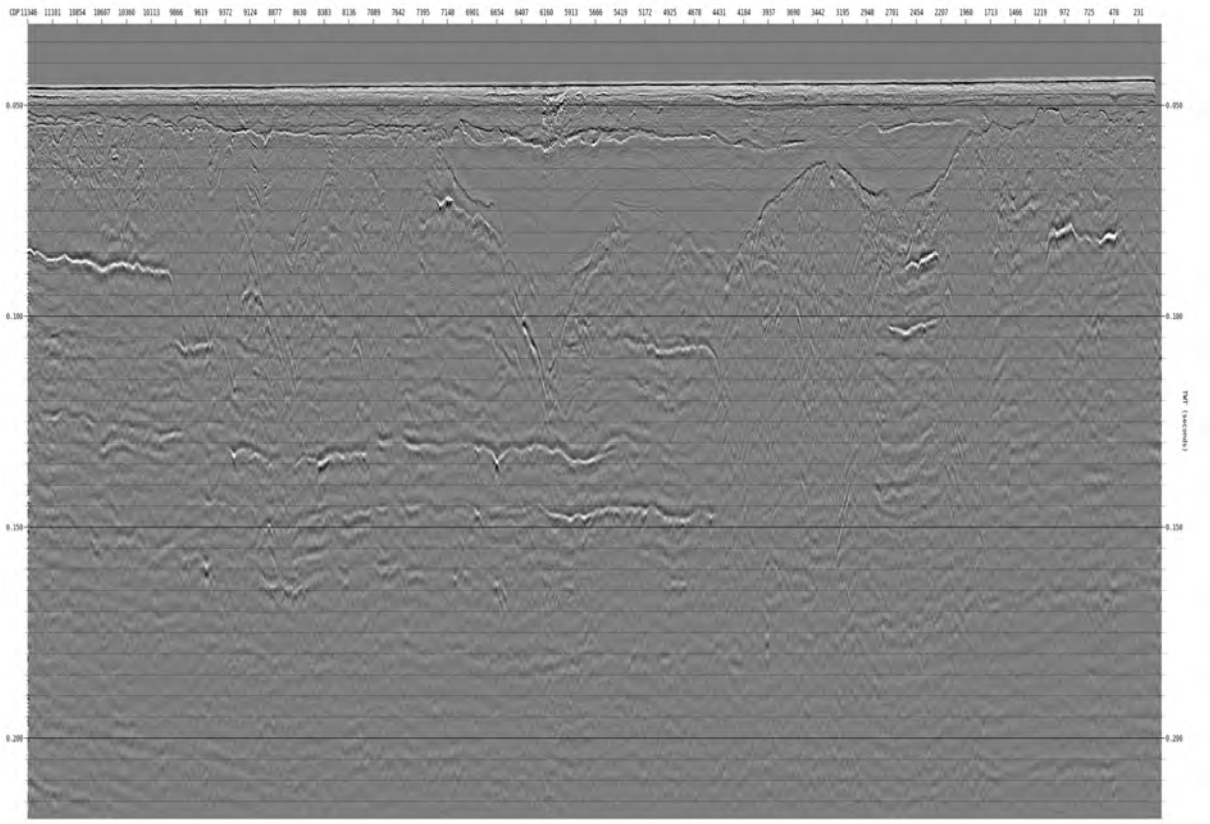

Figure 2.32: Post Stack Processing 1: Output stack

2.13 Post Stack Kirchhoff Time Migration (PoSTM)

As velocity control was good, 2D Post-Stack Kirchhoff Time Migration was performed using 100% of the picked velocity. A migration aperture of radius 80 m was used. Anti-aliasing of 50% was applied by pre-filtering the data within the migration scan depending upon the local migration operator dip. Anti-aliasing protection prevents any undesirable data being included, so aperture muting is unnecessary. No anti-aliasing gave a slightly noisier result, and 80-100% anti-aliasing began to slightly attenuate higher frequency dipping structure in the shallow region, therefore 50% was used as is standard on much of the UUHR data.

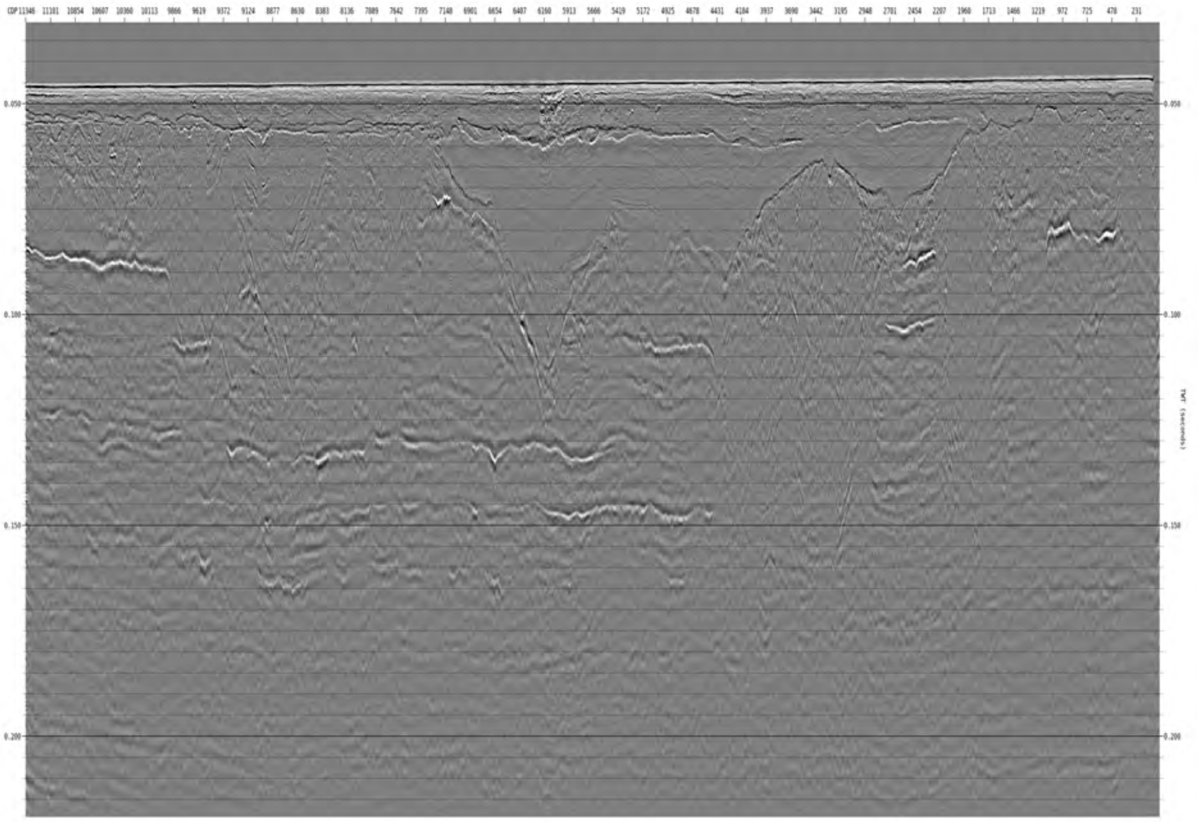

Figure 2.33: PoSTM: Output stack

2.14 Post Stack Processing Step Two

After migration, the final processing steps were to filter the stack before being output as a final product. Various filters were tested with the aim of enhancing signal, preserving resolution and reducing noise. The following set of processes was arrived at:

- Surface wave noise attenuation up to 180 Hz
- Time varying bandpass filter – ref. Table 2.2
- Q compensation from seabed, amplitude only: Q = 100
- 12 dB / second scaling
- Apply source / receiver / tidal static shift
- Cosmetic mute above seabed
- Tie to bathymetry

Table 2.2: 2D UUHR Time varying bandpass filter

Start Time	Low Cut [Hz]	Slope [dB Oct]	High Cut [Hz]	Slope [dB Oct]
Seabed -5ms	80	18	3200	32
Linear taper between				
Seabed + 60ms	60	18	2400	32
Linear taper between				
Seabed + 120ms	40	18	1100	32

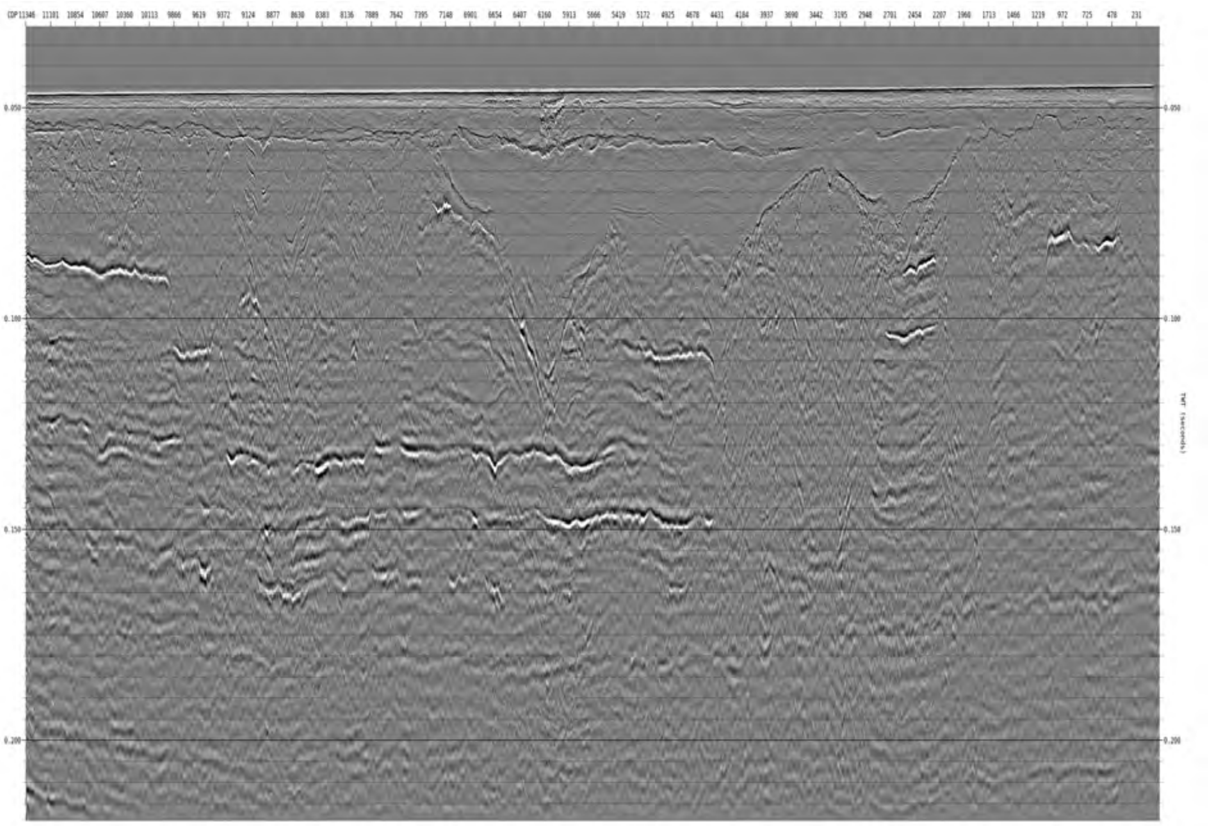

Figure 2.34: Final stack

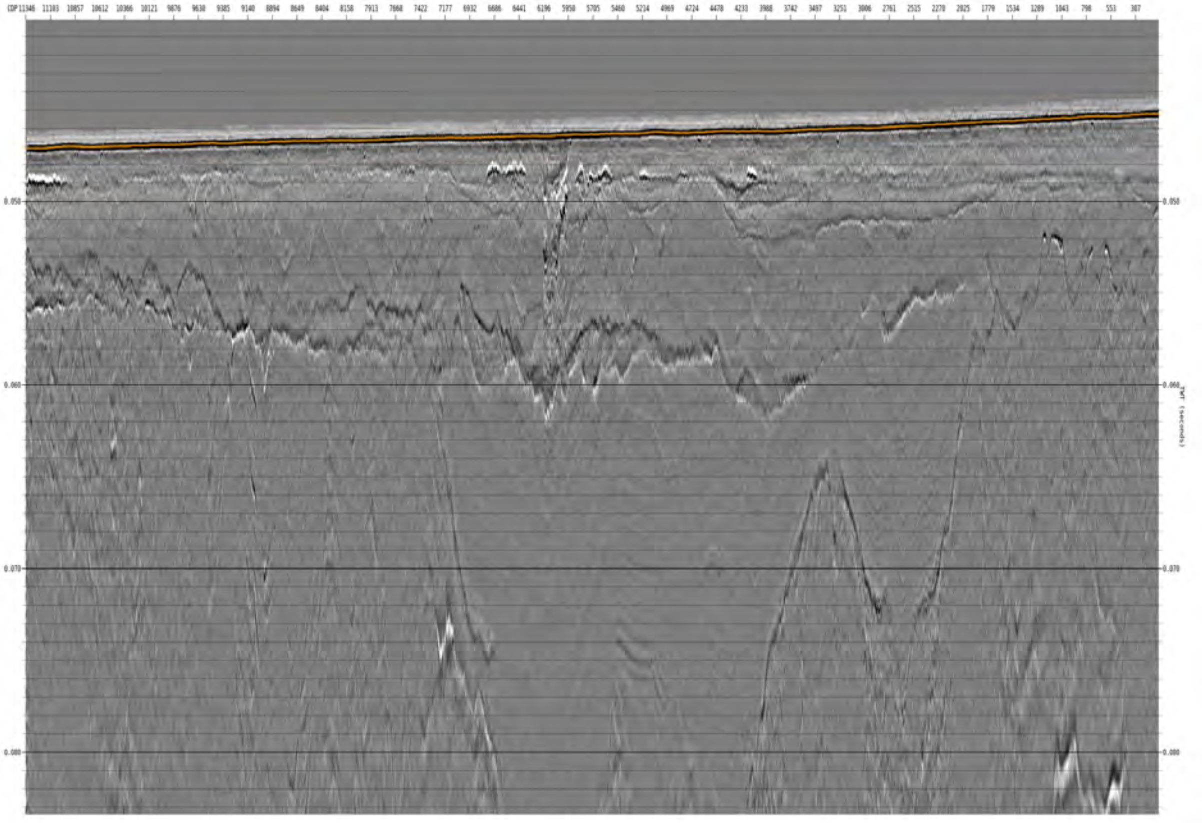

Figure 2.35: Final stack with bathymetry overlay (zoomed)

2.15 Output to SEG-Y

The final stacks were output in SEG-Y format with the CMP positions from the NG exported p190 files. These files were electronically transferred internally to the geophysicists for interpretation via *Media Shuttle*. An example of the migrated time segy EBCDIC header is displayed below.

```
C01 CLIENT: ENERGINET           RECORDED BY: FUGRO
C02 LINE: EAAA001P1             PROJECT: ENN_DOW30
C03 AREA: LOT2A BASELINE
C04 ============= ACQUISITION AND RECORDING PARAMETERS =========================
C05 VESSEL: MV ARCTIC
C06 FORMAT: SEGY REV1
C07 REC LENGTH: 219.875 MS              SAMPLE RATE: 0.125 MS
C08 FILTERS LOW CUT: N/A                HIGH CUT: N/A
C09 SOURCE: DURASPARK 400               SOURCE DEPTH: 0.38 M
C10 VOLUME/LEVEL: 800 J                 SP INTERVAL: 1 M
C11 CABLE TYPE: SERCEL                  CABLE DEPTH: 1.4 M
C12 NUM CHANNELS: 96                    GP INTERVAL: 1 M
C13 NAVIGATION PRIMARY: STARFIX NG
C14
C15 ========================= PROCESSING ========================================
C16 PROCESSING BY: FUGRO  PROCESSING SYSTEM: UNISEIS 2108.2
C17 1)TRANSCRIPTION TO 219.875 MS AT 0.125 MS NO. CHANNELS: 96
C18 2)MERGE SRC/REC NAV 3)APPLY 2D GEOMETRY 4)EDIT BAD TRACES
C19 5)CHANNEL DENOISE 6)PRELIMINARY STATICS 7)SHOT DENOISE
C20 8)LNA 9)2D SRME 10)DEGHOSTING 11)REMNANT DEMULTIPLE
C21 12)500M VELOCITY PICKS 13)FINAL STATICS
C22 14)SORT TO CMP 15)NMO 16)MUTE 17)STACK 18)ZERO PHASE
C23 19)DENOISE 20)KIRCHHOFF MIGRATION
C24 21)POST STACK PROCESSING 22)FINAL ZERO SEA LEVEL STATIC
C25 23)BATHY SHIFT USING 1481 M/S 24)OUTPUT TO SEGY
C26
C27 ================ TRACE HEADER BYTE INFORMATION ==============================
C28 HEADER      BYTES
C29 SHOT        17-20   SRC_X   73-76   REC_X   81-84   CMP_X   181-184
C30 CMP         21-24   SRC_Y   77-80   REC_Y   85-88   CMP_Y   185-188
C31
C32 ELEVATION SCALAR    69-70
C33 COORDINATE SCALAR   71-72
C34 ===================== DATA INFORMATION =====================================
C35 LINE: EAAA001P1
C36 CDP RANGE: 1-11346, SHOTPOINT RANGE: 10001-15626
C37 DATA TYPE: FINAL MIGRATED STACK
C38 ========================= POLARITY ==========================================
C39 INCREASE IN ACOUSTIC IMPEDANCE = POSITIVE NUMBER
C40 END OF EBCDIC
```

Figure 2.36: 2D UUHR: Final migrated time stack EBCDIC example

Appendix A

Line Listings

A.1 2D UUHR Lines M/V Arctic

Table A.1: 2D UUHR M/V Arctic - Accepted lines processed

Line Name				
EAAA001P1	EAAA004P1	EAAA006R1	EAAA009R1	EAAA012P1
EAAA001P2	EAAA004P2	EAAA007P1	EAAA010P1	EAAA012P2
EAAA002P1	EAAA005P1	EAAA008P1	EAAA010R1	
EAAA003P1	EAAA005P2	EAAA009P1	EAAA011P1	18 total

Appendix B

Deliverables

B.1 2D UUHR Deliverables

- Offshore
  - Seg-Y : Raw navigation merged shot gathers
  - Seg-Y : Brute stacks
  - PDF : End of line QC

- Onshore
  - Seg-Y : Migrated time stacks
  - Seg-Y : Migrated depth stacks
  - Seg-Y : 2D picked RMS stacking velocities
  - Seg-Y : 2D picked RMS stacking velocities (smoothed)
  - ASCII : 2D picked RMS stacking velocities

Appendix B

Guidelines for Use of Report

This report (the "Report") was prepared as part of the services (the "Services") provided by Fugro for its client (the "Client") and in accordance with the terms of the relevant contract between the two parties (the Contract") and to the extent to which Fugro relied on Client or third-party information as was set out in the Contract.

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