



Netherlands Enterprise Agency

Integrated Ground Model

Nederwiek Wind Farm Sites I-A and I-B

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RVO Approval for Publication

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1. This report has not been reviewed by the certifying body yet, this will be done at a later date and a certified version will be published on the RVO website. Therefore the certified report may change and no rights can be deferred from the current report.
2. The investigated area is 'Nederwiek Sites I-A and -B', this is formerly known as 'Nederwiek (zuid) site I' or 'Nederwiek (zuid)'. RVO's publications may still refer to the latter two site names.
3. The digital data associated with this report will be published in due course. The current plan is August 2025.

Approval

Approval for public disclosure	Position
Joep Bronkhorst	Project Manager RVO Offshore Wind Energy
Matté Brijder	Programme Co-ordinator RVO Offshore Wind Energy

Rijksdienst Voor Ondernemend Nederland (RVO)

RVO Nederwiek Wind Farm Zone Site I IGM & GIR

Integrated Ground Model Report

Reference: NWFZ_I_20250627_RPT_Integrated_Ground_Model_V04_F

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Arup International Projects Limited

8 Fitzroy Street
London
W1T 4BJ
United Kingdom
[arup.com](https://www.arup.com)

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		Name	Gareth Nash Stephen Eaton Esben Dalgaard Bruno Stuyts	Stephen Eaton Chris A Smith Chris A Smith
		Signature		Approved by

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Abbreviations

2D	Two dimensional
BGS	British Geological Survey
BH	Borehole
bsf	Below seafloor
cm	Centimetre
CPT	Cone Penetration test
CRP	Common Reflection Point
DMR	Downhole-magnetic resonance
EMODnet	European Marine Observation and Data Network
ETRS	European Terrestrial Reference System
Fs	Sleeve Friction
Fr	Friction Ratio
GGM	Geological ground model
GP	Geophysical
GW	Gigawatt
HKW	Hollandse Kust West
IA	Investigation Area
IGM	Integrated Ground model
IHO	International Hydrographic Organisation
IJV	IJmuiden Ver
LAT	Lowest astronomical tide
m	Meters
m/s	Meters per second
MBES	Multibeam echosounder
m BSF	Meters below seafloor
MIS	Marine Isotope Stage
MPa	Mega Pascal
ms	Milliseconds
MTD	Mass transport deposit
nT	Nanotesla

2D	Two dimensional
PCPT	Piezocone Penetration test
PGM	Preliminary ground model
PP	Pore pressure
P-S logging	Compressional (P-wave) and shear (S-wave) suspension logging
P-wave	Compressional velocity
q _c	Measured cone resistance
QC	Quality control
RVO	Rijksdienst voor Ondernemend Nederland
s	Seconds
S&P	S&P Global
SBP	Sub-bottom profile
SCPT	Seismic cone Penetration test
SGR	Spectral gamma
SNS	Southern North Sea
TCPT	Temperature cone Penetration test
TD	Total depth
T-D	Time-Depth pairs
THU	Total horizontal uncertainty
TNO	Netherlands Organisation for Applied Scientific Research
TNW	Ten noorden van de Waddeneilanden
TVU	Total vertical uncertainty
TWTT	Two-way travel time
UHRs	Ultra-high Resolution Seismic
UK	United Kingdom
UTM	Universal Transverse Mercator
VC	Vibrocore
V _{INT}	Seismic interval velocity
V _p	Compressional wave velocity
V _s	Shear wave velocity
WFZ	Wind Farm Zone
YM	Yarmouth Roads Formation

1. Introduction

1.1 Overview

As part of the Dutch Offshore Wind Energy Roadmap, the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO), appointed an Arup International Projects Ltd (Arup) led consortium (including British Geological Survey (BGS), Inosys, SolidGround, and RockWave) to develop a Geological Ground Model (GGM), Geotechnical Interpretative Report (GIR), and Integrated Ground Model (IGM) for the Nederwiek Wind Farm Zone (NWWFZ), Site I.

The Nederwiek Wind Farm Zone is located approximately 100 kilometres (km) from the west coast of the Netherlands. Hereafter in this report the site is referred to as NW I (Nederwiek Site I). The total capacity of NWWFZ will be 6000MW and NW I aims to have a potential installed capacity of 2000MW.

This work underpins part of a major expansion in the offshore wind capacity in the Netherlands since 2015, with a total target of 21.5GW by 2032 from existing operational windfarms and windfarms under construction, in development, or in the planning phase (Figure 1.1).

After Borselle, Hollandse Kust zuid, noord and west, and Ten noorden van de Waddeneilanden and IJmuiden Ver, this is the seventh WFZ for which site investigations have been undertaken and ground models developed for the Netherlands Offshore Wind Energy Roadmap 2030.

This report represents the IGM. The IGM communicates the spatial distribution of seismostratigraphic units identified as part of the GGM and subsequently geotechnically categorised as part of the GIR.

1.2 Purpose and scope of report

1.2.1 Integrated Ground Model

This IGM report aims to communicate the interpreted ground conditions and all associated data and knowledge in a clear and effective manner that is beneficial to wind farm developers. Specifically, to aid development decision making, risk management, regulatory compliance, cost efficiency and environmental sustainability.

An integrated approach to data acquisition, analysis and validation ensures projects are set-up for success during the development of offshore wind projects.

This IGM report includes the following:

- A discussion of all data incorporated into the IGM, and processes used in the incorporation of the data (e.g. seismic re-processing and interpretation).
- A 3D IGM of the NW I area incorporating bathymetric data, picked seismic horizons, in-situ ground investigation data, and laboratory testing results. This model provides the spatial allocation of geotechnical parameters derived in the GIR.
- Predictions of CPT parameters along all seismic lines using an innovative pre-stack seismic inversion approach.
- A 3D voxel model of interpolated predicted CPT parameters covering the NW I site.
- A comprehensive discussion on uncertainty, propagation of uncertainty through phases of modelling, and how uncertainty should be carried forward by future users.
- Identification of locations within NW I that present opportunities for development, and areas that present potential difficulties for future development.

Some elements stated above are partly covered in either the accompanying GGM (Arup, 2025a) and/or the GIR (Arup, 2025b) reports. Where necessary key elements will be summarised in this report otherwise reference will be made to the relevant report.

Offshore Wind Energy Roadmap 21 GW

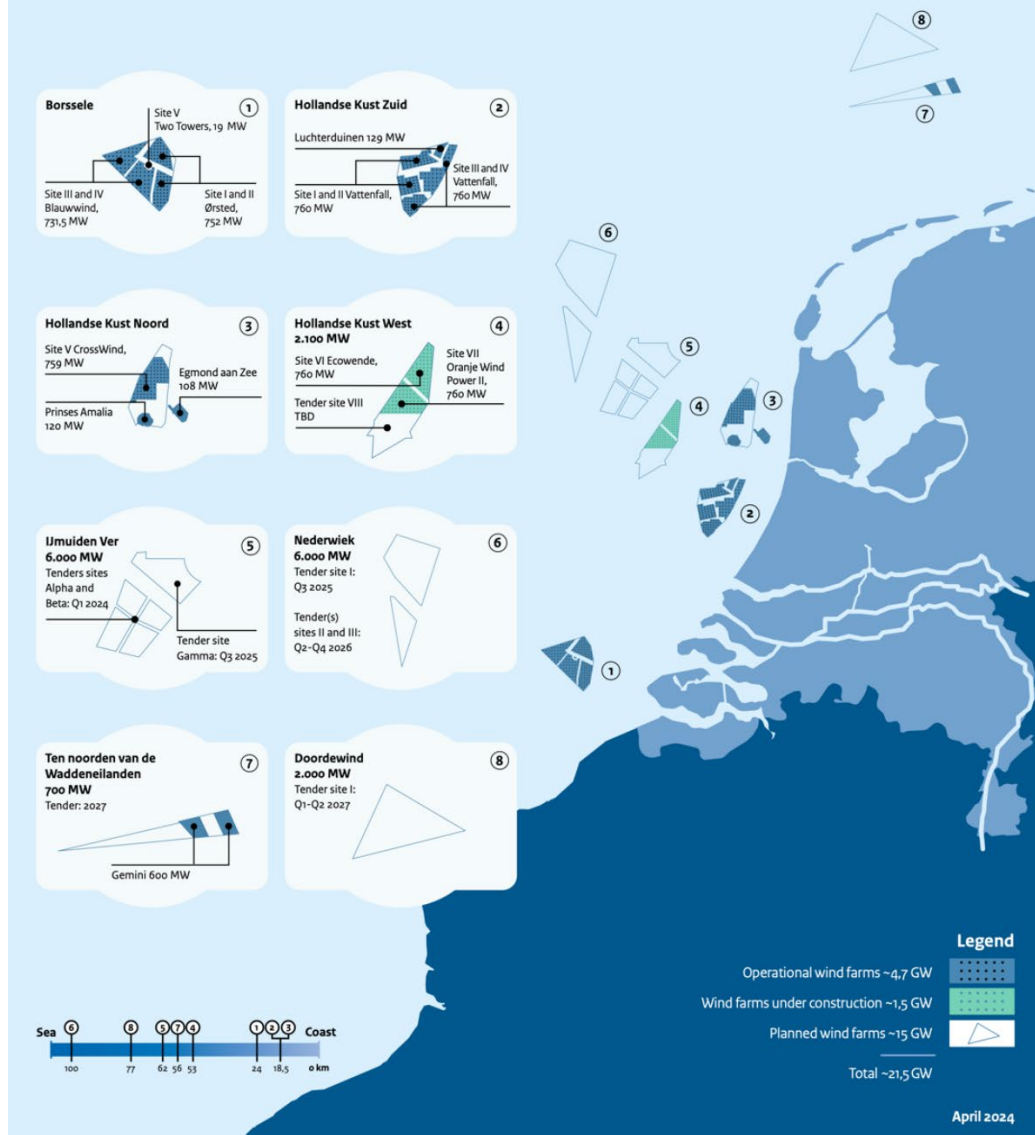


Figure 1.1: NL Wind Energy Roadmap 21GW (RVO, 2024)

1.2.2 Area of interest

NW I covers an area of 273 km² and is situated in the Dutch sector of the southern North Sea, approximately 100 km to 120 km from the Dutch coastline, neighboring IJmuiden Ver wind Farm Zone to the south and Nederwiek Wind Farm Zone Site II and III to the north. Water depths are between 24 m and 34 m below lowest astronomical tide (LAT). Within NW I, a survey area was designated, referred to as the Investigation Area (IA) (Figure 1.2:). The IA limits the maximum or outer extent of the geotechnical and geophysical data acquisition (270 km²). Table 1-1 details the coordinates for the Nederwiek I IA.

Table 1-1: Coordinates used as the boundary definition for the NW I IA.

Coordinates ID	Eastings [m]	Northings [m]
IA 01	504971.7	5901203.0
IA 02	505927.6	5895643.0
IA 03	506396.8	5895669.5
IA 04	511712.1	5861681.0
IA 05	513597.6	5865294.5
IA 06	520477.7	5886811.5
IA 07	506725.3	5901232.5
IA 08	504971.7	5901203.0

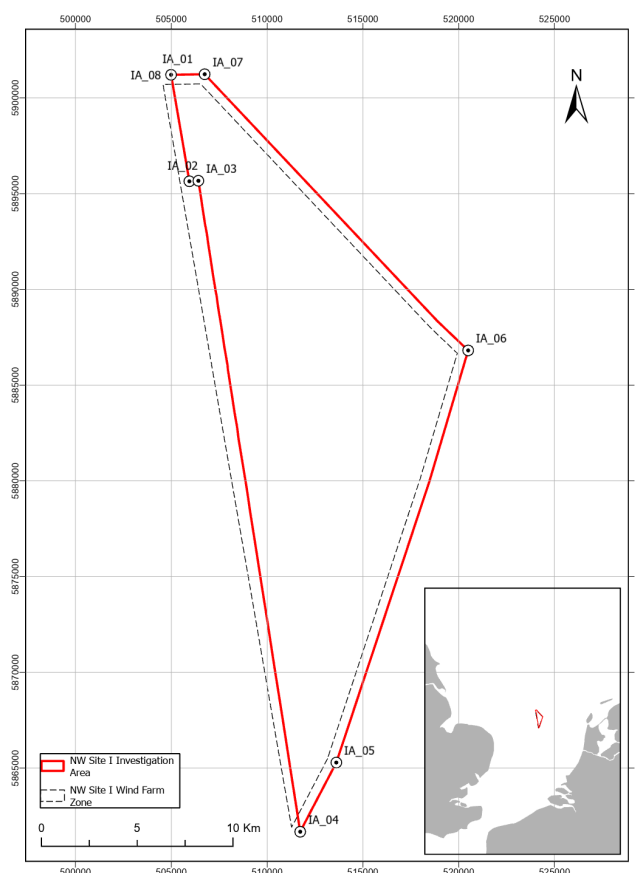


Figure 1.2: NW I Investigation Area with corner coordinates

1.2.3 Geodetic parameters

For the IGM the vertical datums considered are

- Lowest Astronomical Tide (LAT), and
- Seafloor (depth below seafloor (BSF)).

See (Fugro, 2023b) for vertical reference datum.

Table 1-2 provides a summary of the geodetic parameters for horizontal coordinates used in the IGM.

Table 1-2: Geodetic parameters and horizontal coordinates

Local Geodetic Datum Parameters	
Datum	ETRS 1989 UTM Zone 31N
Ellipsoid	GRS 1980
EPSG	25831
Semi major axis	6378137.0
Inverse flattening	298.257222101
Local Projection Parameters	
Projection name	Universal Transverse Mercator
Grid System	UTM Zone 31N
Latitude Origin	00°00'00.000" N
Central Meridian	003°00'00.000" E
Scale factor	0.9996
False Easting	500000 m
False Northing	0 m

1.3 Report Format

The IGM combines geotechnical and geological ground investigation (GI) data with geophysical data to create a comprehensive 3D representation of surface and subsurface conditions, highlighting stratigraphic variability across the site. As part of this project, we evaluated components of the quantitative ground model workflow, exploring methods for integrating geotechnical and geophysical data and assessing their impact on the model's robustness and accuracy (e.g. field based CPT soil behaviour type cross-correlated with geophysical horizons and geotechnical laboratory data).

This report outlines the methodology, results, limitations, and recommendations derived from the work that have produced the IGM.

Table 1-3: Summary of report sections and their contents

Section	Title	Contents
Section 2	Data Sources	Describes the data sources that have been integrated and interpretation of ground conditions
Section 3	Integration Workflow	This section describes the workflow applied to ensure integration of datasets and describes how they have been used in the IGM.
Section 4	GGM Summary	A summary of the Geological Ground Model (GGM), and the seismostratigraphic framework for the site
Section 5	GIR Summary	A summary of the Geotechnical Interpretative Report (GIR), and the geotechnical soil unit classification for the site
Section 6	Soil Provinces & Soil Profiles	Describes the integrated presentation of soil provinces and representative soil profiles pertinent to design
Section 7	Integrated 3D Ground Model	Presents the integrated structural model and represents the 3D representation of the soil unit definition which reconciles the GGM and GIR.
Section 8	Prediction of CPT Parameters at Seismic Trace Locations	This section presents the pre-stack inversion workflow that is used to predict geotechnical parameters at seismic locations. Sources of uncertainty in the predictions are introduced and discussed.
Section 9	Interpolation of Predicted CPT Parameters	This section discusses the methodology used for 3D interpolation of the pre-stack inversion predictions provided, the introduction of interpolation uncertainty, and the propagation of the prediction uncertainty.
Section 10	Digital Deliverables	Details of all digital deliverables that accompany this report
Section 11	References	-
Appendix A	2DUHR Seismic Processing Report	Seismic reprocessing report
Appendix B	Cross Sections	Selected cross sections produced as part of the Leapfrog structural model for the site, integrated with geotechnical data points.
Appendix C	Measured vs Predicted CPTs	Plotted geotechnical parameters per location, including quantitative seismic inversion predictions of cone resistance and sleeve friction
Appendix D	NetCDF User Guide	User guide to accompany the 3D voxel model of interpolated cone resistance parameters across the site.

1.4 Digital deliverables

The digital deliverables outlined in Table 1-4 accompany this report.

Table 1-4: IGM Digital deliverables

Digital Deliverable	Contents	Delivered As
Reprocessed 2D UHRS SEG-Y	- Pre-stack 2D UHRS - Post-stack 2D UHRS	SEG-Y data
IHS Kingdom Package	- All post stack seismic reflection files in time. - Geophysical interpretation of the seismostratigraphic unit boundaries. - Geotechnical investigation locations and CPT profiles.	S&P Global Kingdom Project
ESRI ArcPro	- Interpretative site conditions and all geotechnical data points - Seismostratigraphic unit boundaries, isochores, geological constraints and hazards. - Soil province polygons	- Full package shared as .ppkx - Geospatial data shared as shapefile (.shp)
Quantitative Seismic Inversion & CPT predictions	Data for predicted values of cone resistance, sleeve friction, bulk modulus, and shear modulus	SEG-Y data
	Predicted values of cone resistance, sleeve friction, bulk modulus, and shear modulus at the closest seismic trace to each geotechnical location	AGS data
	Attributes (Absolute Inversion g_k, Prior Model k, Seismic (pre conditioned), Velocities (Vintt, Vrmst)	SEG-Y data
Linear correlation & Interpolated prediction voxel models	- NetCDF voxel models containing interpolated predicted parameters, combined uncertainty, geotechnical soil units, and seismostratigraphic units. - NetCDF voxel models containing linear predicted parameters for coarse grained and fine grained units, geotechnical soil units, and seismostratigraphic units.	Zipped .nc files
Leapfrog 3D visualisation	3D voxel models containing: - Linear and interpolated predictions of cone resistance, sleeve friction, and shear modulus (interpolation only) - Geotechnical soil units - Seismostratigraphic units - Plan sections of the geotechnical soil units at 5m increments 8No. cross sections showing geotechnical soil units and measured CPT profiles showing sleeve friction, cone resistance, and pore pressure ratio - Capability to cut arbitrary sections/slices through the site.	Leapfrog viewer (.lfrview)
Profile extractor tool	- Jupyter notebook that provides capability to extract plots of NetCDF data as .pdf and plot contents as .json. - Capability to take arbitrary profiles through the site.	.ipynb Jupyter notebook

1.5 Project responsibilities, usage, and disclaimers

This report presents data and information to a project specification as outlined and monitored by the client. This report was prepared in accordance with Contract WOZ2230067 between RVO and Arup International Projects Limited, dated 9 June 2023.

This report represents the status of the project based on geotechnical data made available to Arup end November 2024 and is liable to change based on receipt of new data.

2. Data sources

2.1 Overview

This section outlines the data sources which were reviewed to develop the IGM for the NW I IA.

Geophysical and geotechnical data was acquired for the site between 2023-2024. Seabed geotechnical data integrated with surface and subsurface geophysical data was the primary input for the development of the GGM. Borehole geotechnical data was acquired and integrated to provide the complete input ground truthed dataset for development of the GIR and IGM.

2.2 Pre survey desk study

TNO and Deltares (TNO & Deltares, 2023) conducted a pre-site survey desk study for the NWWFZ. This study presented the predicted geology for the NWWFZ using publicly available geological and borehole data. The study utilized data from 219 shallow boreholes (5 m to 102 m BSF) and 130 deep boreholes (510 m to 6200 m BSF) within the NWWFZ. The geological setting described in the desk study, combined with Arup's experience of the local site's geological characteristics, was used early in the project to validate the geophysical contractors interpretations of the NW I IA and to develop the preliminary ground model, which guided the scoping of borehole geotechnical investigation locations.

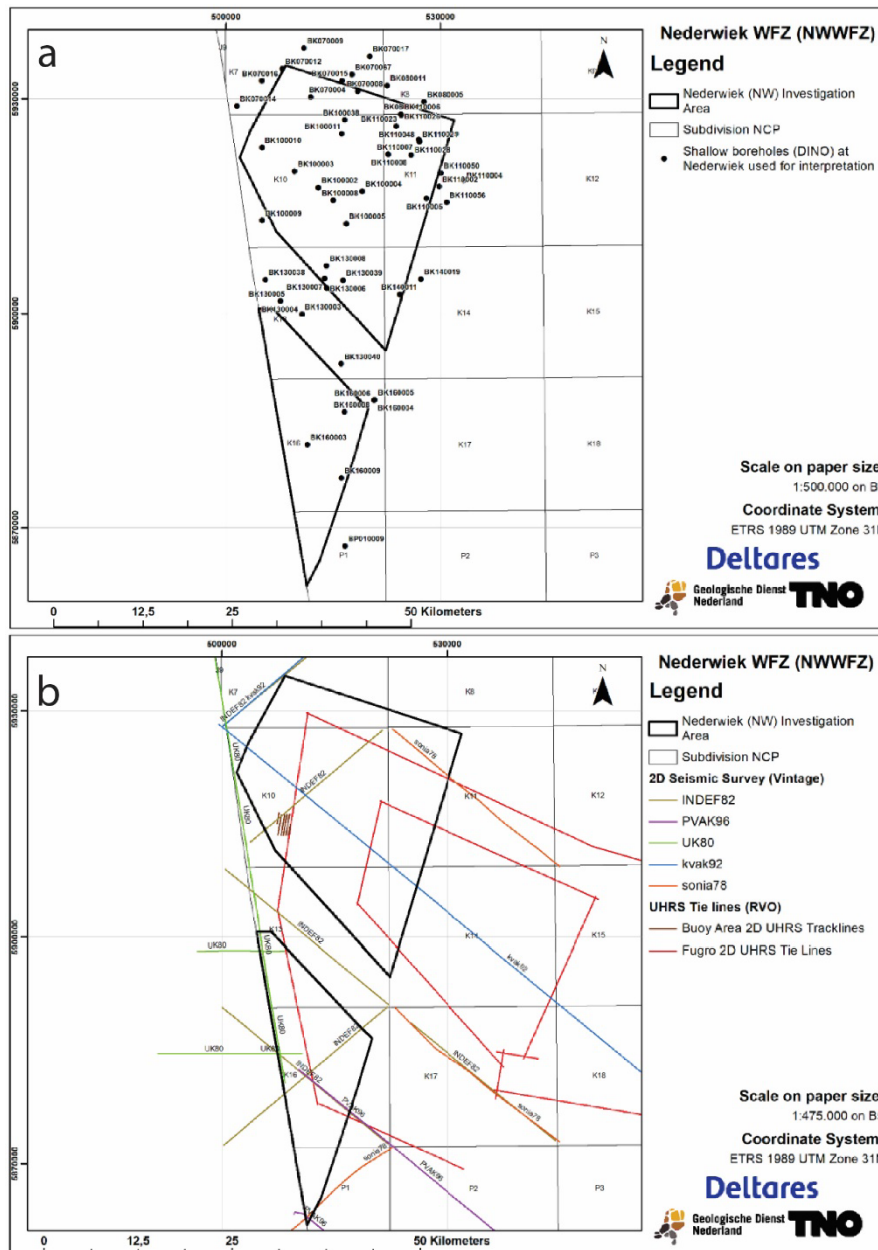


Figure 2.1 Locations of selected shallow cores and boreholes (a) and 2D seismic data (b) used in the desk study.

2.3 Geophysical data

Fugro (Fugro, 2023d) conducted a geophysical survey across the NW I IA in 2023, to provide data that enabled detailed characterisation of both seabed and subsurface conditions. The objectives included:

- Supplying an accurate bathymetric dataset.
- Providing information to characterise all significant seabed features related to wind farm construction including:
- Seafloor morphology and seabed geology.
- Identification of natural features.
- Identification of anthropogenic features.
- Mapping subsurface seismostratigraphic units.

The geophysical survey acquired full coverage of geophysical data at the NW I IA, with the survey mapping bathymetry, the static and dynamic elements of the seabed surface, imaging the seafloor with side-scan sonar, identifying ferrous objects with a gradiometer, and imaging the sub-surface geological soil layers to at least 100 m BSF. The survey results were used for planning environmental investigations, hazard assessment, planning geotechnical investigation, foundation design, cable burial, and installation design. Table 2-1 presents information on the geophysical data acquired.

Table 2-1: Fugro (2023) data received

Data Type	Sensor Specifics	Coverage	Resolution
Multibeam echo sounder & Backscatter	Dual-head Kongsberg EM2040, (200 - 400 kHz)	Entire NW I IA	THU & TVU IHO Special Order compliant
Side-scan sonar	Edgetech HF and LF (230/540 kHz)		> 0.5 m target detection 200% coverage at 75m range
Magnetometer	TVG (x2 magnetometers at 1.52m separation)	~65m in line ~420m cross line	> +/- 2 nT
Sub bottom profiler	Innomar SBP		0.2 m vertical resolution
2D Ultra High Resolution Seismic	Multi-level stacked sparker source with 96 channel Geometrics LH-16 GeoEel streamer		0.5 m vertical resolution to 40 m BSF 1.5 m vertical resolution from 40 m BSF to end of record
Intrusive samples	Dual van Veen Grab Sampler	x16 locations	0.1 m ²

The survey lines for 2D UHRS and SBP were acquired with a nominal main line spacing of 65 m and a nominal crossline spacing of 420 m (Figure 2.2). For detailed specification further to that presented in Table 2-1 on all acquired geophysical data refer to the Operations and Processing Report, (Fugro, 2023d).

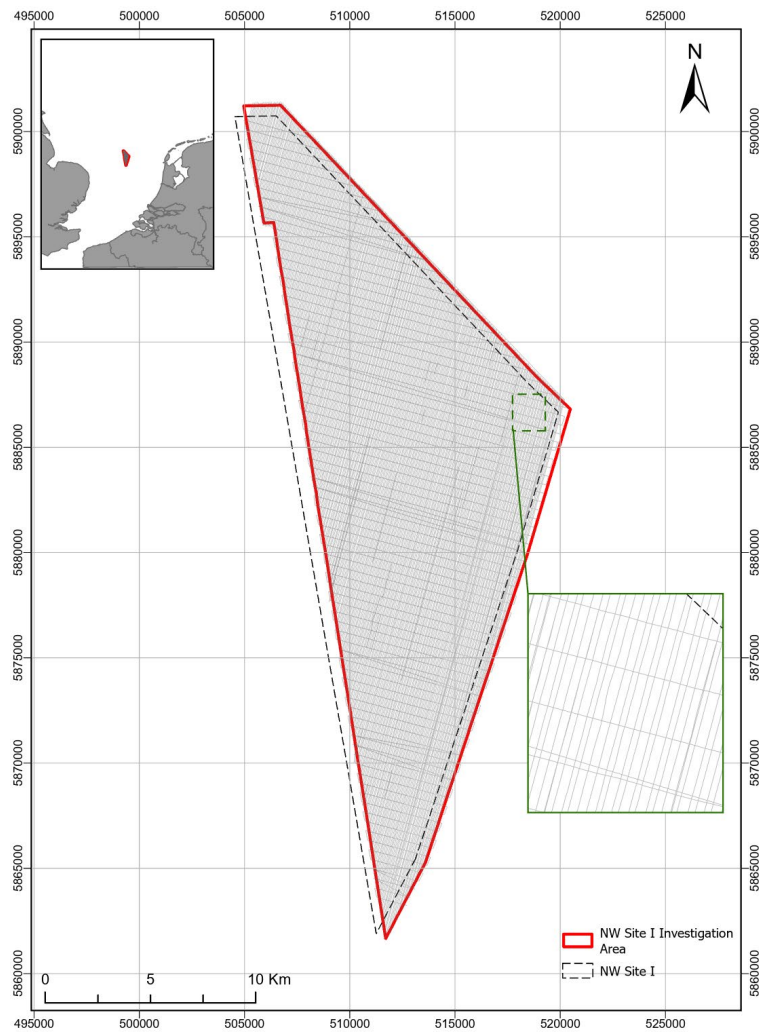


Figure 2.2: Geophysical data, with 2D UHRS line plan, as shown inset

2.4 Reprocessed 2D UHRS

As input to the seismic inversion workflow, reprocessing of Fugro's 2D UHRS data (Fugro, 2023b) was undertaken with the primary objective to deliver amplitude-variation-with-offset (AVO) compliant pre-stack CRP 2D Kirchhoff migrated gathers and an associated velocity model for input to quantitative inversion.

A final stack product was also produced to provide an updated interpretation volume to the legacy processed stack. Although the final stack data was not used directly in interpretation, it was used to provide additional information for features identified which were challenging to interpret due to artefacts in the original data that were removed and/or improved by the reprocessing steps.

The reprocessing consisted of four main stages, summarised below in Table 2-2.

For a detailed overview of the reprocessing and how it has been designed and used in the inversion workflow see Section 8.2, and Appendix A.

Table 2-2: AVO-compliant pre stack 2D UHRS reprocessing stages

Stage	Description
Pre-migration processing	Removal of noise, surface ghosts, source bubble, free-surface multiples, interbed multiples, source and receiver statics.
Velocity model building	An offline 2D Kirchhoff migration on a sparser 25 m CRP grid was carried out using production demultiple data and a smoothed version of the Legacy (Geophysical Contractor acquired dataset, processed to deliver stack volume and reprocessed to deliver pre-stack gathers in this reprocessing – referred to as “Legacy” throughout) manually picked velocity model. The model was then updated with a layer-based RMS velocity tomographic update based on residual moveout picks on the migrated gathers. The raw tomographic update was converted to interval velocity and smoothed to ensure structural stability of the interval velocities.
Migration and post-migration processing	2D pre-stack Kirchhoff time migration using the velocity model updated through tomographic inversion. Time-variant scaling and filtering was applied followed by amplitude-Q (attenuation) compensation, residual demultiple, denoise and redatum from mean-sea-level to lowest astronomical tide which ensured consistency with the Legacy stack volume and interpretations of geophysical horizons.
Stack and post stack processing	Data were stacked with a 0-30° angle mute and mild residual denoise, demultiple, water bottom signature and time variant scaling were applied.

2.5 Preliminary seismostratigraphic interpretation

A preliminary seismostratigraphic interpretation for NW I IA were made by (Fugro, 2023c) using the 2D UHRS data (Figure 2.3). These interpretations consisted of interpretation of five primary horizons: H02, H05, H10, H20 and H25; and notable seismic features (e.g. amplitude anomalies and channel-forms). These interpretations were made on a subset of the post-stack 2D UHRS data (priority lines) and were provided to Arup in an S&P Kingdom workstation project.

These preliminary interpretations were used as inputs to the unitisation alongside the seabed geotechnical data to develop the laboratory testing strategy and plan the borehole investigation campaign.

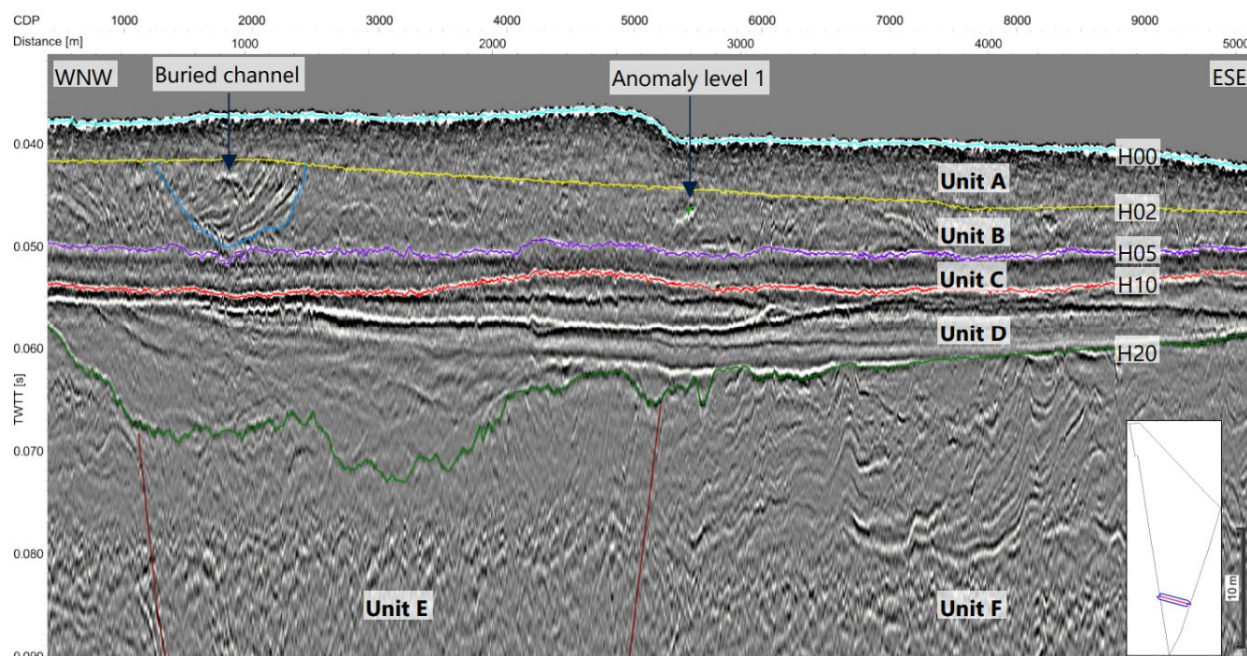


Figure 2.3: Example preliminary seismostratigraphic interpretation made by Fugro (Fugro, 2023c).

2.6 Geotechnical data

Geotechnical data were acquired by Fugro (Fugro, 2025) across the NW I IA. Seabed geotechnical investigation was comprised of seabed CPTs and vibrocores. Borehole geotechnical investigation was comprised of boreholes with downhole sampling, CPTs and borehole geophysical logging.

All investigation locations were planned using interpretations from the geophysical survey, grab samples and available geotechnical data.

2.6.1 Seabed Geotechnical Investigation (Lot 1)

The seabed geotechnical investigation data was composed of 184 investigation locations of insitu piezocone CPT (PCPT), seismic CPT (SCPT), temperature CPT (TCPT) and sampling vibrocores. Details for each of these test types and there location can be found in Table 2-3 and Figure 2.4.

All seabed geotechnical PCPTs and SCPTs were located nearby the crossing of two 2D UHR geophysical lines, and cleared for geotechnical acquisition based on the location, and interpretative results from coincident magnetometry.

All borehole geotechnical investigation locations (Section 2.6.2) were co-located next to a seabed geotechnical location, which either encountered specific units of interest or refused early requiring additional insitu test characterisation.

Table 2-3: Lot 1 Geotechnical Data

Location Type	Number of Locations	Penetration [m BSF]	Objective
PCPT	72 (including 6 blind locations)	12.3 to 54	Understand soil profiles, geotechnical parameters and soil behaviours aimed at developing a GM detailing stratigraphy and soil properties.
SCPT	26	12.3 to 53.7	Understand shear wave velocity, soil stiffness/elasticity and seismic site response, as well as information on stratigraphy and soil properties
TCPT	26	2.1 to 7.0	Understand soil thermal properties
Vibrocore	60	3.2 to 6.2	Sediment profiling

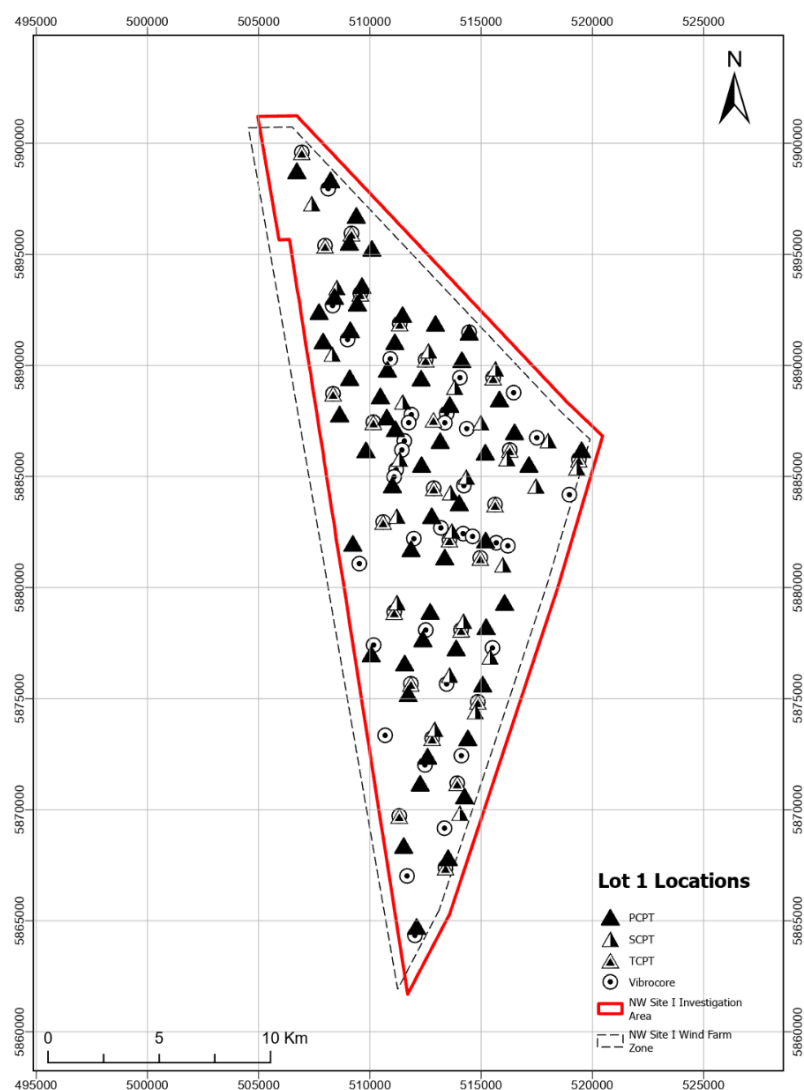


Figure 2.4: Seabed geotechnical investigation locations

2.6.2 Borehole Geotechnical Investigation (Lot 2)

Borehole geotechnical locations were selected to maximise the length of unit specific samples recovered based on a preliminary soil unitisation scheme for the laboratory campaign, and to maximise in-situ testing

coverage (PCPT, SCPT). Five boreholes were selected with representative conditions across the site for borehole geophysical logging, including P-S logging, calliper, natural gamma and DMR.

Details for each of these test types and location can be found in Table 2-4 and Figure 2.5.

Table 2-4: Borehole geotechnical investigation data

Borehole Type	Target Depth (m)	Number of Locations	Sampling/Testing
1a	60	15	Quasi Continuous Sampling >50 m BSF + Combined PCPT/Sample
1b	60	17	Quasi Continuous Sampling <50 m BSF + Quasi Continuous PCPT + Combined PCPT/Sample
1c	80	9	Quasi Continuous Sampling <50 m BSF + Combined PCPT/Sample
2a	60	7	Quasi Continuous Sampling <50 m BSF + Quasi Continuous SCPT + Combined SCPT/Sample
2b + 4	66	5	Quasi Continuous Sampling <50 m BSF + Quasi Continuous SCPT + Combined SCPT/Sample + BGL
Number includes bump-over and retest locations			

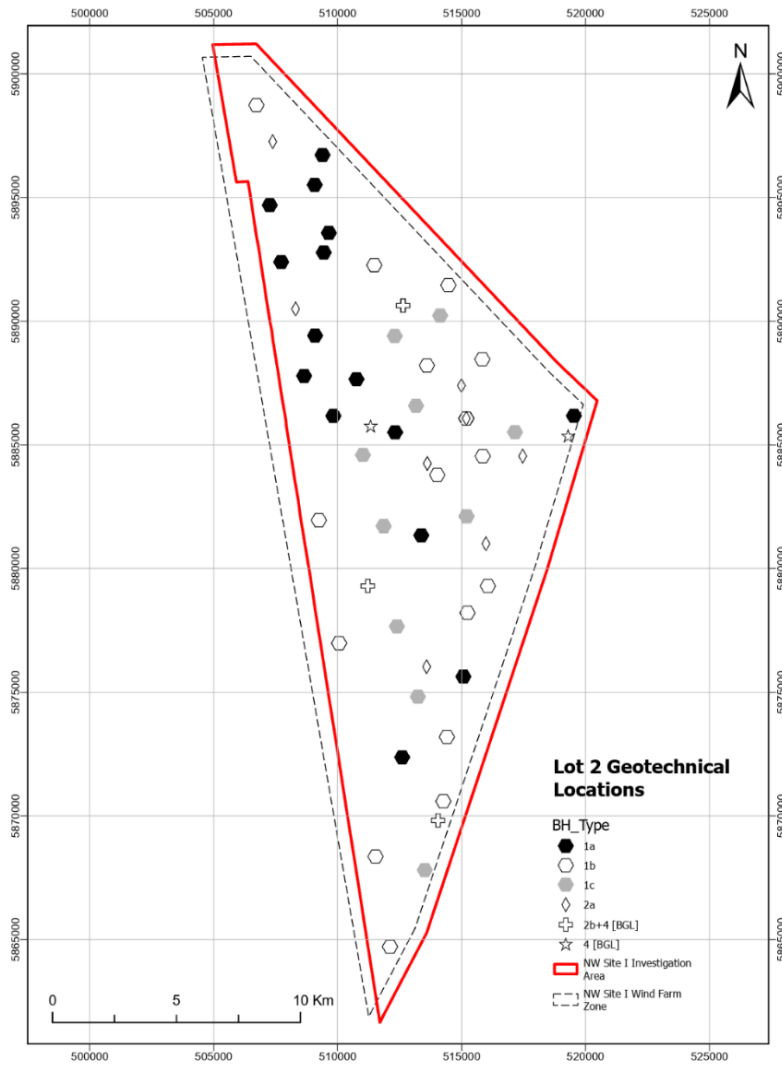


Figure 2.5 Borehole geotechnical investigation locations by type

2.6.3 Seabed Geotechnical and Borehole Geotechnical Data Discrepancy

The data acquired during the Lot 1 campaign was found to have higher-than-expected sleeve friction for the encountered soil at several locations. This, as highlighted by the Geotechnical (GT) Contractor, was believed to be due to wear of the cone tip of specific probes to the extent that it affected the recorded data [4] (Appendix B).

The high friction values became apparent at the stage of comparing overlapping Lot 1 and Lot 2 data acquired at the co-located locations, where down-hole CPT data (Lot 2) were displaying significantly lower sleeve friction than that which was measured during the Lot 1 campaign. A 1m overlap between the Lot 1 and the Lot 2 campaigns was specified for comparison of seabed and down-hole mode test data.

To overcome this artificially high sleeve friction, the GT Contractor proposed an 'Extended Correction Method' ([4] (Appendix B)) which accounts for geometry variation effects during the Lot 1 campaign (i.e. geometry of the cone reducing progressively with the testing metreage increase).

For an extended review of the discrepancy and the methodology used to correct the data refer to the GIR (Arup, 2025b).

2.7 Geological data

To calibrate the geological model for NW I IA, eight boreholes (Fugro, 2024b) were tested for geochronology; including radiocarbon, palynomorphs and microfossil analysis.

The geochronological programme primarily comprised palynomorphological and microfossil analysis. Radiocarbon C¹⁴ age dating was attempted on four samples, however, only one was successful (NWZ-BH-5027) as other borehole samples were not considered appropriate for testing.

BioChron (Fugro, 2025) present the results of the age dating, including assessment of the age, depositional environment and continuity of the soil units at the site. Figure 2.6 shows the geotechnical locations upon which geochronological testing was performed, and Table 2-5 presents the results and stratigraphy inferred at each location based on regional correlations and knowledge of evolutionary geological history.

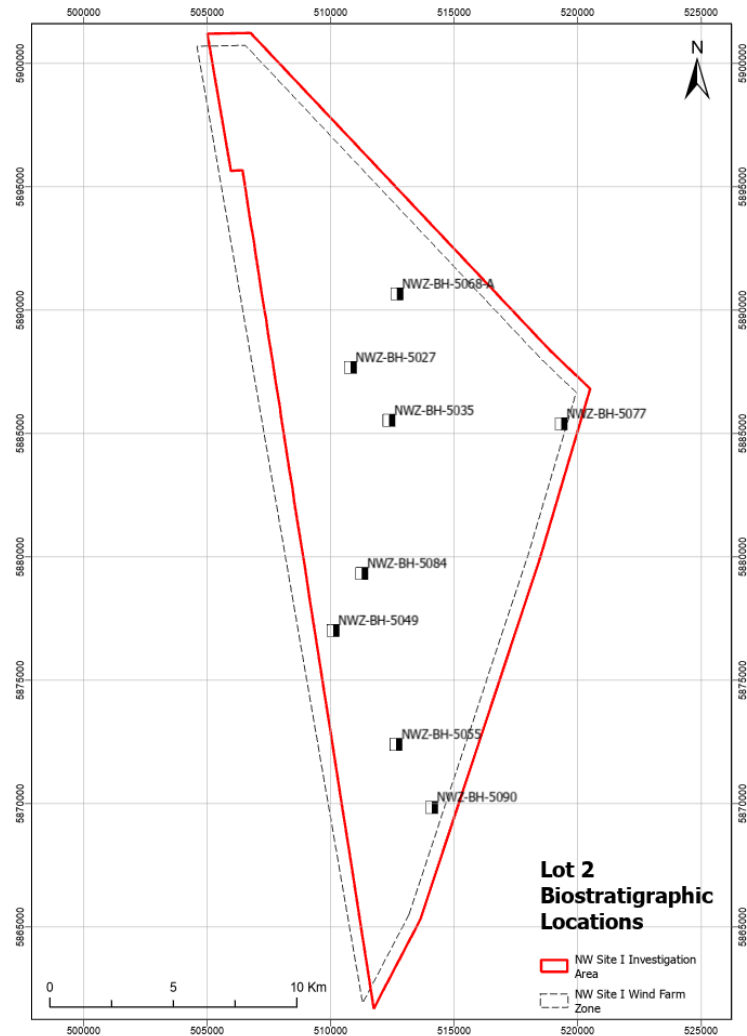


Figure 2.6: Lot 2 boreholes with biostratigraphic testing [locations plotted within NW I IA]

Table 2-5 Boreholes for biostratigraphic analysis and their test profiles

Borehole	Number of Samples	Radiocarbon 14C	Stratigraphic Test Profile
NWZ-BH-5027	48	1 (successful)	Whole stratigraphy to Yarmouth Roads
NWZ-BH-5035	32	1	Whole stratigraphy to Peelø
NWZ-BH-5049	40		Whole stratigraphy to Peelø
NWZ-BH-5055	40	1	Whole stratigraphy to Yarmouth Roads excl. Peelø
NWZ-BH-5068-A	36		Whole stratigraphy to Peelø
NWZ-BH-5077	36	1	Whole stratigraphy to Yarmouth Roads excl. Peelø
NWZ-BH-5084	34		Whole stratigraphy to Peelø
NWZ-BH-5090	44		Whole stratigraphy to Yarmouth Roads excl. Peelø

3. Integration workflow

3.1 Overview

Integration of the datasets listed in Section 2 was split into phases to support an evolution in understanding of site conditions during the project. Fixed outputs of this process are the geological ground model (Arup, 2025a), geotechnical interpretation report (Arup, 2025b) and integrated ground model (*this report*). Figure 3.1 presents a schematic representation of the integration workflow.

Site characterisation for the design of offshore wind structures is focussed on the acquisition of continuous cone penetration test data that can be correlated with geotechnical laboratory results. This information is from individual locations, and representative of a small area across a development of over 250 km². Therefore, integration of geotechnical data points with remote sensed geophysical data is essential to provide site-wide assessment of ground conditions. Table 3-1 presents the primary inputs and outputs of each phase, with increasing complexity in understanding of the site.

This iterative workflow has enabled integration of geophysical and geotechnical data to create a site-wide ground model.

Table 3-1: Phases of data integration and ground model development

Phase	Input	Output	Result
0	Geological desk study Geophysical data (surface & subsurface) Preliminary seismostratigraphic framework	Geological framework Seismostratigraphic Units	Seabed geotechnical investigation scoping
1	Geophysical data (surface & subsurface) Seabed geotechnical data (field) Seabed geotechnical data (laboratory)	Preliminary geotechnical soil units Seismostratigraphic Units A to F	Borehole geotechnical investigation scoping
2	Borehole geotechnical data (field) Borehole geotechnical data (laboratory)	Geotechnical Soil Units 1 to 7	Geological Ground Model Geotechnical Interpretation Report
3	Reprocessed 2D UHRS seismic data Pre-stack quantitative seismic inversion	Soil provinces and profiles 3D linear CPT correlations 3D predicted CPT parameters	Integrated Ground Model

Phase 0

The geological desk study (TNO & Deltares, 2023) integrated with a preliminary seismostratigraphic framework (Fugro, 2023c) of five key structural horizons interpreted by the geophysical contractor, provided the basis for scoping the seabed geotechnical investigation to sample the expected variability in ground conditions across the NW I IA.

Phase 1

Subsequent integration of the preliminary seismostratigraphic framework (Fugro, 2023c) with the seabed geotechnical investigation (Fugro, 2024a), allowed the creation of a set of preliminary geotechnical soil units which were used as the basis for scoping the borehole geotechnical investigation.

This first phase of geotechnical unitisation was an iterative process between geophysical and geotechnical disciplines that enabled the preliminary seismostratigraphic framework to be refined and new interpretation added based on the geotechnical significance of acoustic reflections in the subsurface datasets.

Phase 2

Following acquisition of the borehole geotechnical investigation (Fugro, 2025), ground truthed locations up to 80 m BSF were available at over 230 locations across the NW I IA. This comprehensive dataset provided the means of confirming geotechnical soil units by identifying changes in geotechnical properties (e.g. soil

type, mechanical behaviour) based on insitu and laboratory test data, alongside further chronostratigraphic interpretation.

This second phase of geotechnical unitisation allowed further refinement of the seismostratigraphic interpretations, and depositional and post-depositional understanding made in Phase 1 to conclude the Geological Ground Model (Arup, 2025a).

The geotechnical soil units as confirmed structurally across the site were then used to complete a Geotechnical Interpretation Report (Arup, 2025b), statistically assessing insitu and laboratory test data based on (DNV, 2021). Characteristic geotechnical parameters for CPT data as derived in the GIR (Arup, 2025b) can also be interrogated as 3D voxels across the site based on linear correlations per geotechnical soil unit.

Phase 3

The site-wide geophysical surfaces and geotechnical soil units were used as the basis to delineate soil profiles and provinces across the NW I IA, as presented in the Integrated Ground Model (*this report*). Predictive CPT results (q_t , f_s , and G_{max}) were generated using a pre-stack quantitative seismic inversion along the 5,025 km of 2D UHRS. These predictions were interpolated unconfined between seismic lines and presented as 3D voxels across the site with associated measures of uncertainty per defined seismic interval linked to geotechnical soil unit.

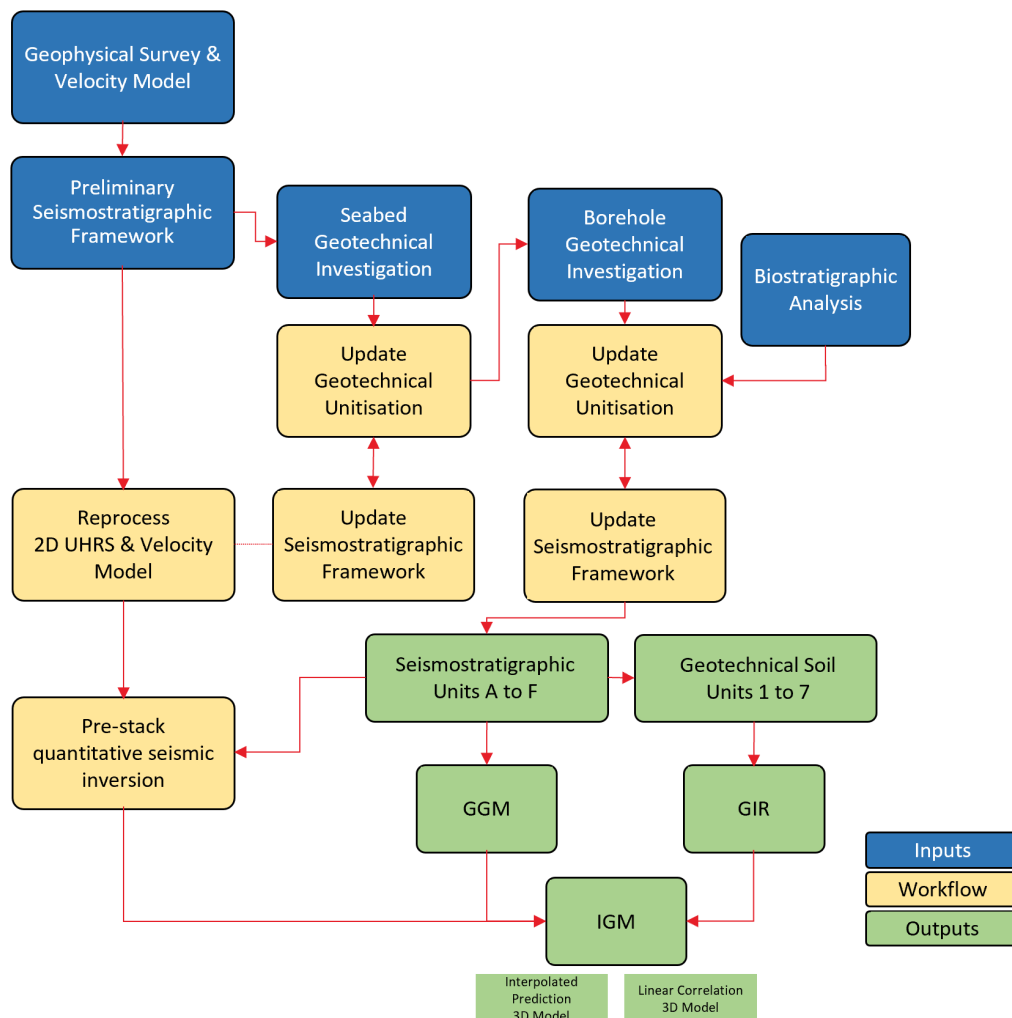


Figure 3.1: Integration workflow

4. Geological Ground Model – Summary

4.1 Overview

The GGM (Arup, 2025a) details the subsurface stratigraphy of the NW IIA. It integrates geophysical and geotechnical data to define fourteen seismostratigraphic units, characterising their seismic architecture, lithology, and chronostratigraphy (Figure 4.1).

The GGM examines the complex geological evolution of NW IIA in the Southern North Sea during the Quaternary, identifying key geological constraints like buried channels and organic soils that could impact wind farm construction. The study uses various data sources, including 2D UHRS geophysical data, boreholes, CPTs, and biostratigraphic analysis to refine the geological model and assess potential geohazards.

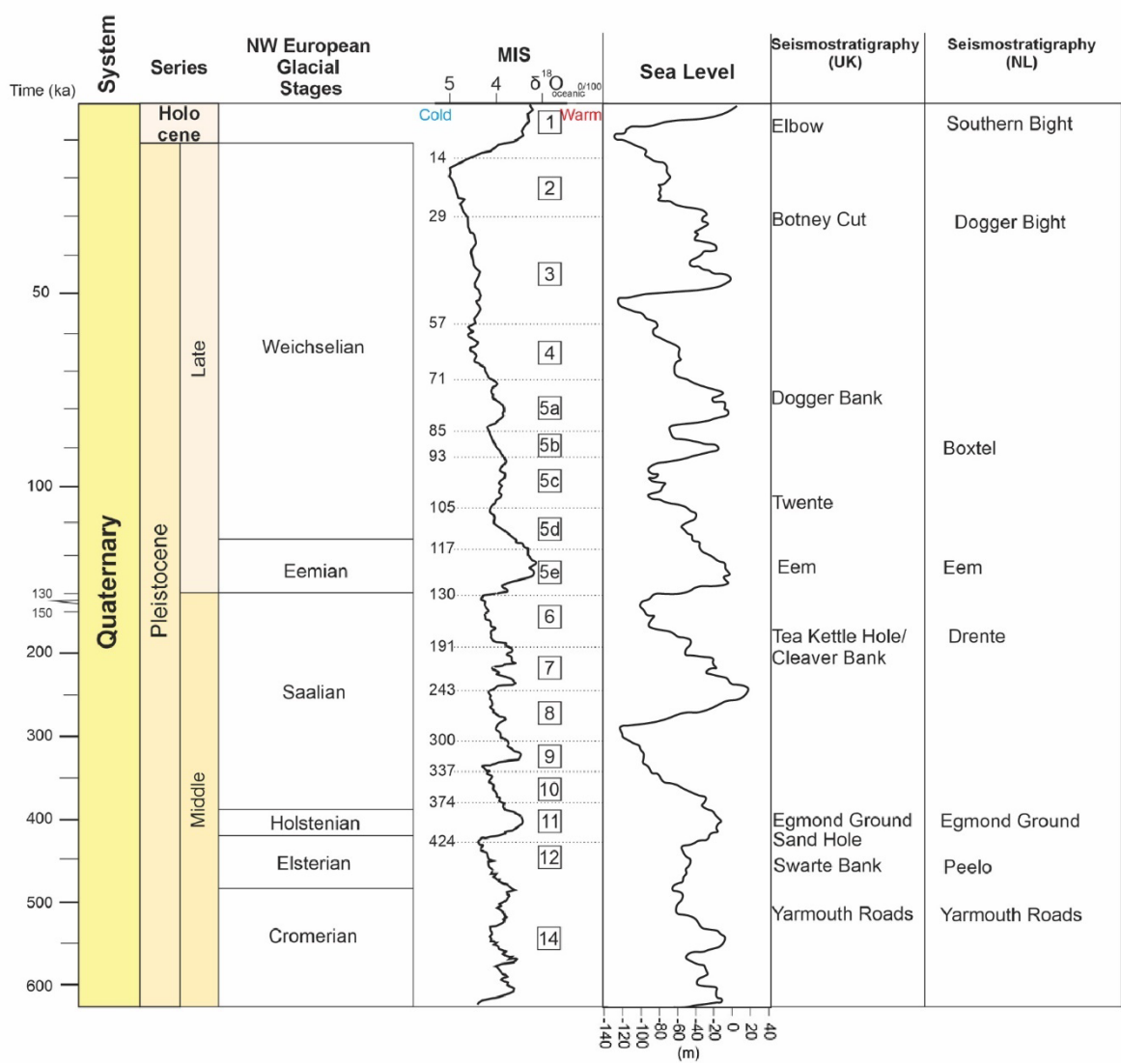


Figure 4.1: Lithostratigraphic framework comparing typical UK and NL lithostratigraphy Marine Isotope Stages (MIS) and sea level curve. Adapted from Figure 13 of Deltares (2017).

4.2 Datasets and workflows

The primary geophysical dataset used for development of the GGM was the final post-stack 2D UHRS (Fugro, 2023c) consisting of 5025 km line length loaded into a S&P Kingdom workstation project with preliminary seismostratigraphic interpretations (five horizons) expanded across the full dataset (Section 2.5).

All detailed interpretation was undertaken on the final stack 2D UHRS dataset with additional key horizons identified during development of the seismostratigraphic unitisation, using the workflow documented in Section 3. Eight additional horizons were interpreted (Table 4-1) in addition to refinement of the five preliminary horizons and seismic features interpreted by Fugro as part of the Preliminary ground Model.

The vertical resolution of the dataset is ~0.4 ms at 50 ms TWTT and ~1.2 ms at 160 ms TWTT, equating to ~0.5 m vertical resolution in the shallow and ~1.5 m deeper in the data. In addition to the 2D UHRS data, Sub bottom profiler (SBP) data, MBES, backscatter, SSS and magnetometer data were available and integrated into the ground modelling process. The SBP and MBES data were primarily used for refinement of the near seabed horizons (R02) and understanding of seabed bedforms and potential mobility. Magnetometer data was not used for geological interpretation but was used during the borehole geotechnical investigation planning process.

The interpretation framework provided by the geophysical contractor (prefix 'H') was superseded by final interpretations (prefix 'R'), see Table 4-1.

In parallel to interpretation of the seismic dataset, the geophysical reprocessing undertaken as part of the seismic inversion workflow was made available for comparison against the final stack 2D UHRS provided by the GP contractor. Uplift identified following reprocessing are outlined in the GGM for comparison purposes only and were not used for interpretation.

In addition to the NW I IA 2D UHRS data, the project was also given access to 2D UHRS tie-lines to neighbouring Dutch offshore wind farm sites.

4.3 Depositional sequence

The seismostratigraphic units record the complex geological evolution during the Quaternary that have resulted in the variability and spatial distribution of sediments deposited at NW I IA through seven primary stages:

- **Pre-Elsterian** (>480 ka): Defined in this report as the Yarmouth Roads Formation. The Yarmouth Roads comprises deltaic and fluvial deposits with few thin peats as identified in one borehole. Soil types typically comprise fine to medium and dense sand with clay or silt beds, often transitioning into interbedded sands, silts, and clays. Can contain variable organic material such as woody fragments or lenses of peat. Characterised by complex multi-channel phases of incision resulting in high lateral and vertical sedimentological variation.
- **Elsterian** (~480-421 ka): Predominantly a cold period resulting in ice-advance from the north and the formation of tunnel valleys that incise into the Pre-Elsterian stratigraphy. The maximum depth of the erosional base can terminate below the seismic record length (>150 m BSF). The seismic architecture and lithology of the tunnel valley fill is different to the surrounding Pre-Elsterian stratigraphy (Yarmouth Roads Formation). The infill of the tunnel valleys comprises five seismostratigraphic units that may span Elsterian, Holstenian to Saalian in age and constitute multiple depositional environments including ice marginal/fluvio-glacial, fluvio-deltaic coastal plain and marine. Although glacial till is not identified from geotechnical sampling, its presence cannot be ruled out.
- **Holsteinian** (~421-395 ka): Predominantly a warm period indicating retreat of ice and sea level rise, associated with the deposition of the Urk and Egmond Ground Formations. These form the dominant part of the seismostratigraphic units that infill the interpreted tunnel valleys. It is also possible that at NW I IA, there are units deposited within the tunnel valley, that are not captured within 'type formation' descriptions (e.g., Egmond Ground Formation). Holstenian-aged sediments that infill the tunnel valley are associated with laterally and vertically heterogeneous soil types, comprising sands, silts and clays.
- **Saalian** (~395-120 ka): Primarily represents a cold period spanning over 300,000 years. Although the ice-margin is not interpreted to have reached the NW I IA, the Saalian likely forms a significant unconformity across the site. Uncertainty remains regarding the deposition/preservation of Saalian-aged stratigraphy, however if present, may form part of the seismostratigraphic units within the northern tunnel valley (e.g. the Drenthe Formation).

- **Eemian** (~120-108 ka): Predominantly a warm period resulting in the retreat of ice and sea level rise (Eemian Formation) and the deposition of interbedded, spatially varying clay-sand intervals. Soil types include dense to very dense calcareous sands containing shells and rare organic matter and medium to stiff calcareous clay containing some subangular gravels. The Brown Bank Member is interpreted as present across the site forming a distinctive stiff clay soil unit containing variable amounts of organic matter.
- **Weichselian** (~108-11.7 ka): Largely a cold period associated with ice advance in the Central North Sea. Although the Weichselian-aged ice-margin did not reach NW I IA, the environmental impact includes the transition to a periglacial terrestrial environment and likely indicates a period of erosion/hiatus. Soil types typically comprise dense to very dense fine to medium sand with occasional interbedded clays/silts and shell fragments.
- **Holocene** (<11.7 ka): Prior to complete marine inundation, a marshy environment prevailed with formation of peat in the north of NW I IA (Nieuwkoop Member). Coastal plain environments likely resulted in deposition of sandy fluvial channels (Naaldwijk Formation), therefore buried channels and organic sediments are also identified in this unit. Marine transgression from ~8.5 ka to the present-day led to deposition of the Southern Bight Formation, dominated by marine sand and the formation of sand waves, as observed on the present day seafloor.

4.4 Seismostratigraphic framework and spatial variability

In this section, the seismostratigraphic framework is presented and includes descriptions of each seismostratigraphic unit, its spatial distribution and lithological properties. Figure 4.2 displays a conceptual section of the site that shows the seismostratigraphic framework, the spatial relationship of the seismostratigraphic units, and relative thickness across the NW I IA.

Figure 4.3 presents interpreted east-west and north-south composite seismic sections with seismostratigraphic units and geotechnical soil units annotated.

Table 4-1 lists the correlation between seismostratigraphic units and geotechnical soil units.

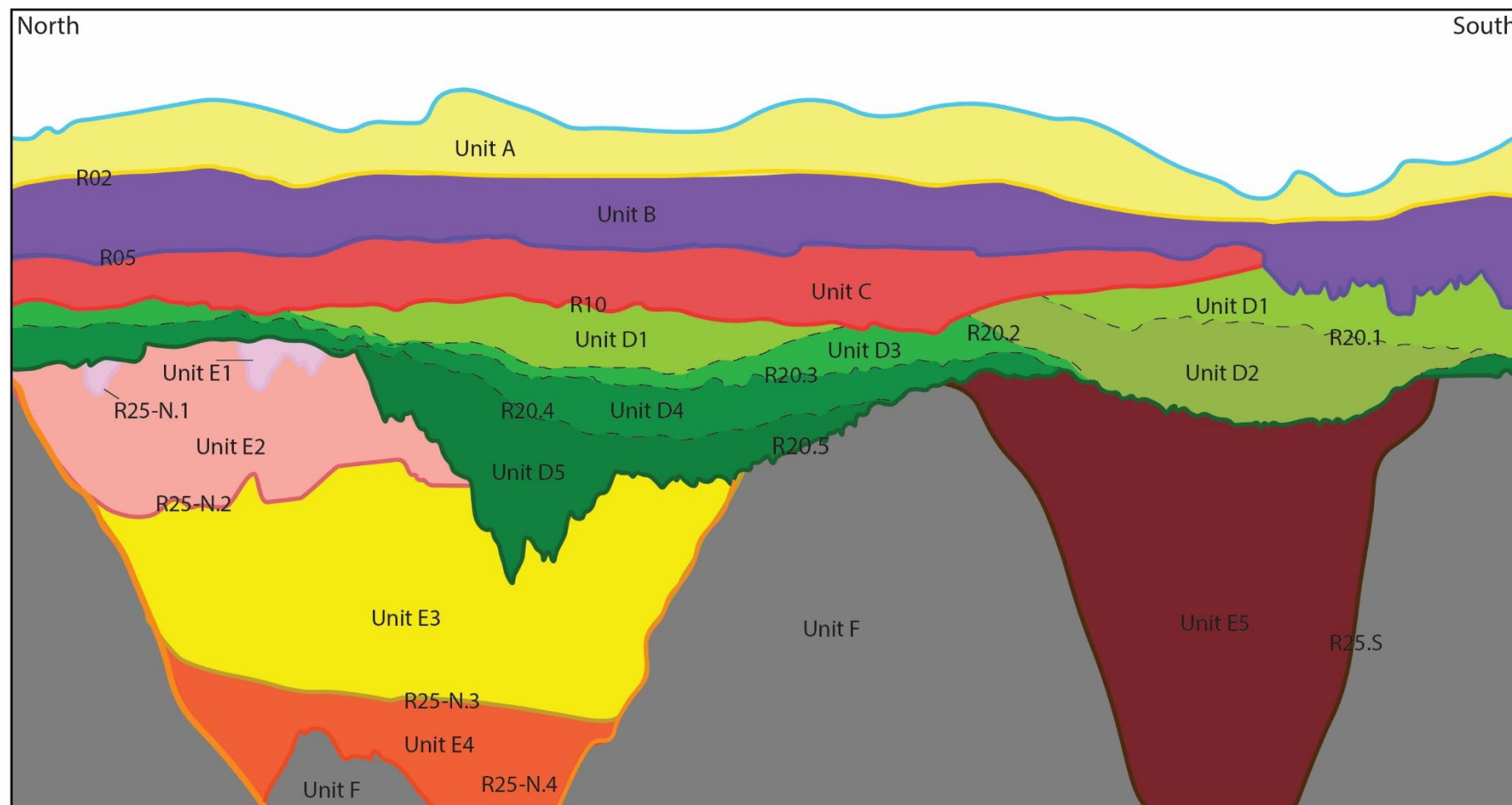


Figure 4.2: Conceptual model showing the relationship between the seismostratigraphic units and interpreted horizons.

Table 4-1: Geological ground model summary

Horizon (GP Contractor)	Horizon Upper	Horizon Lower	Seismo- stratigraphic Unit	Geotechnic al Soil Unit		General dominant lithological description	Interpreted depositional environment	Formation/ Member name	Postulated unit age / MIS	Postulated basal surface age / MIS
H02	R00	R02	A	U1		Sand	Marine	Southern Bight Formation	Holocene	Holocene
H05	R02	R05	B	U2		Sand	Fluvial/coastal plain. Periglacial at basal R05	Naaldwijk Fm/ Nieuwkoop Mb	Late Weichselian MIS 3/2	Weichselian MIS 4
H10	R05	R10	C	U3		Clay	Marine	Brown Bank Formation Mb (Eem Fm)	Early Weichselian – Early Glacial. MIS 5a	Weichselian MIS 5a
H20	R05 or R10	R20.1	D-1	U4- CG	U4- FG	Sand and clay sequence	Marine - tidal sand ridges?	Eem Formation	Early Weichselian – Early Glacial. MIS 5b?	MIS 6/5e?
	R20.1	R20.2	D-2				Marine		Early Weichselian – MIS 5c?	
	R20.2	R20.3	D-3				Marine - tidal sand ridges?		Eemian MIS 5d?	
	R20.3	R20.4	D-4				Marine		Eemian MIS 5e?	
	R20.4	R20.5	D-5				Terrestrial to marine		Late Saalian/Eemian MIS 6/5e?	
H25	R20	R25-N.1	E-1	U5- CG	U5- FG	Sand (dominant) and clay	Pro- to periglacial?	Drenthe Formation?	Late Saalian MIS6?	MIS 6?
	R25-N.1	R25-N.2	E-2				Fluvial to marine	Urk/Egmond Ground? (possibly akin to Sand Hole Fm?)	Saalian MIS 9-7?	MIS 9-7?
	R25-N.2	R25-N.3	E-3			Interbedded / variable	Marine	Urk/Egmond Ground? (possibly akin to Sand Hole Fm?)	Holsteinian MIS 11	MIS 11
	R25-N.3	R25-N.4	E-4				Marine	Urk/Egmond Ground? (possibly akin to Sand Hole Fm?)	Holsteinian MIS 11	MIS 11
	R20.5	R25-S	E-5	U6- CG	U6- FG	Interbedded / variable	Sub-glacial to marine	Urk/Egmond Ground or possible Peeloo Formation?	Holsteinian to Elsterian MIS 11	MIS 11
YM	R20.1 to 5, R25-N or R25-S	Horizon not defined (beyond seismic record length)	F	U7		Sand and silt Pocket of thick clay BH	Fluvial / deltaic / shallow marine	Yarmouth Roads Formation	Cromerian	n/a

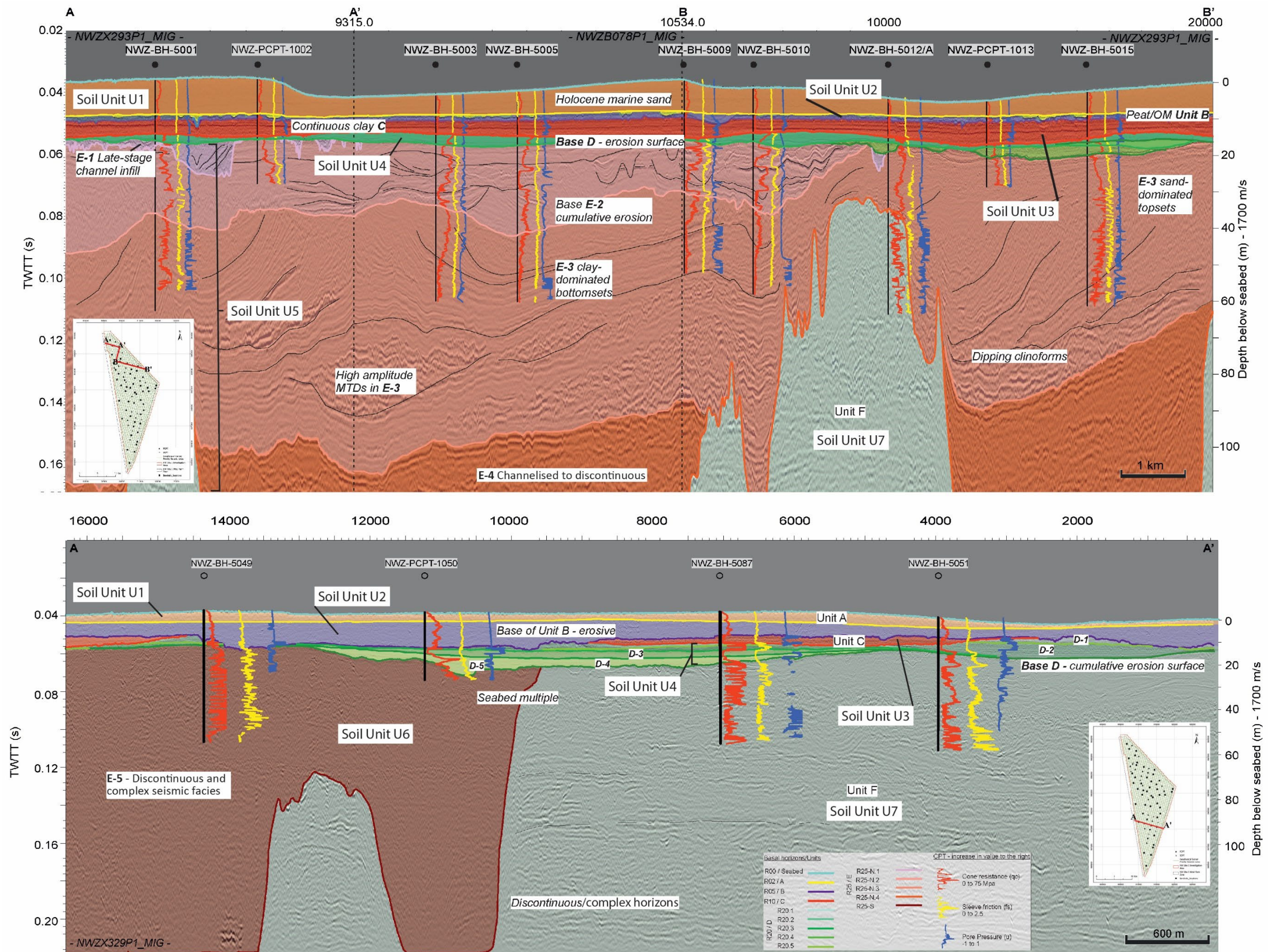


Figure 4.3: Composite E-W (top image) and N-S (bottom image) orientated seismic lines showing the seismostratigraphic framework for the investigation area with soil units.

4.4.1 Seismostratigraphic Unit A

Unit A is the youngest seismostratigraphic unit and is laterally continuous, interpreted across the entire IA. The upper horizon (R00) is defined as the seabed and the basal horizon (R02) represents an unconformity, occurring at the base of the typically seismically transparent unit (Figure 4.4). On occasion, it is possible to observe dipping reflections within Unit A, potentially at the base of relict or present-day mobile sediments. The basal horizon is interpreted between 0.048 and 0.0411 s TWTT and is located stratigraphically above the top of interpreted buried channels associated as part of the Unit B. The basal R02 surface is likely erosional, although there is limited information to suggest how much erosion occurred. The upper surface that forms the seabed is variable, with some parts of NW I IA characterized by an undulous and dipping surface, and other parts are relatively flat-laying. Where the surface becomes undulous and/or dipping, is typically attributed to the presence of sediment waves or ripples. The thickness of Unit A is interpreted as being absent or very thin towards the east of the site to 10.9 m thick in the upper northwest

Unit A represents the Southern Bight Formation and corresponds to a rapid sea-level rise across the North Sea during the Middle Holocene (~8.5 ka). The seismic facies are typically transparent, however dipping laterally continuous reflectors in cross-section and the presence of sand waves and dunes on the present-day seabed suggest the presence of mobile sediment within the IA. The seismic character is typically transparent and featureless, geotechnical characterisation is consistently very dense, very dark greyish brown, slightly calcareous fine- and medium sand with rare black organic matter and rare coarse sand-sized shells and shell fragments.

The depositional environment of the Southern Bight Formation is consistent with high-energy and sandy open marine deposits, supported by the biostratigraphic analysis (Fugro, 2024b).

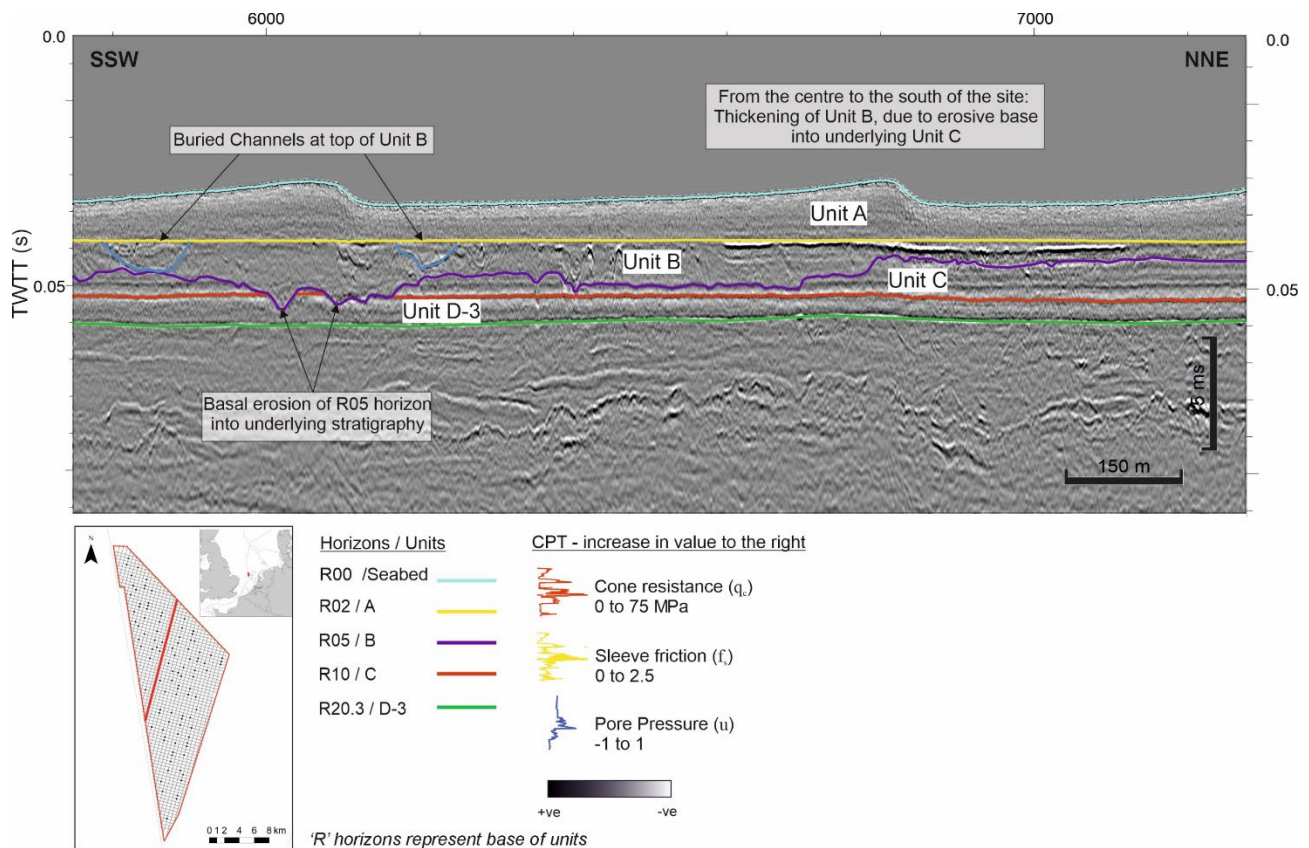


Figure 4.4: NNE-SSW orientated 2D seismic line (NWZD143R1) showing seismostratigraphic horizons R02 to R20.3 and associated seismic character.

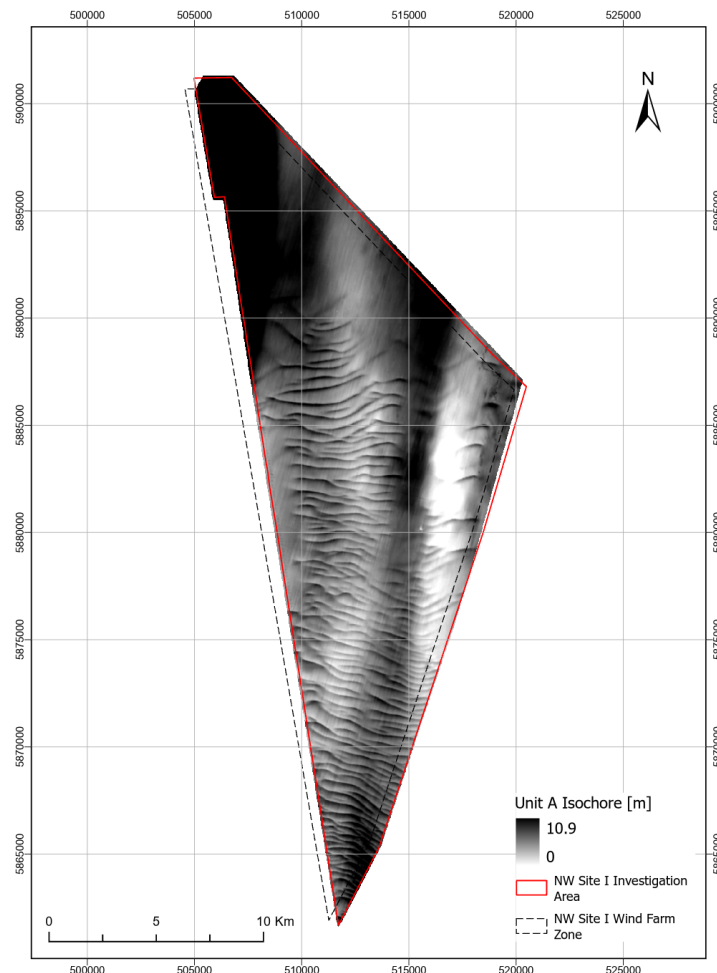


Figure 4.5: Isochore maps for seismostratigraphic unit A showing variation in thickness and spatial distribution.

4.4.2 Seismostratigraphic Unit B

The base of Unit B (R05), as shown in (Figure 4.4), is undulating and laterally continuous across the IA. The horizon represents the base of a variable, chaotic to transparent seismic unit containing numerous high-amplitude anomalies, internal erosion surfaces, internal channel-like features, and dipping reflections. Unit B is typically bound by R02 at the top, and R05 at the base, although locally it may incise into the deeper stratigraphy as shown in Figure 4.4. The maximum thickness is ~25 m in a small area of an interpreted channel, however this is not representative of the whole unit, which has an average thickness of ~3.8 m.

The top surface (i.e. R02) is generally marked by a low amplitude negative reflector, however in places it is difficult to distinguish from the overlying sand-dominated Holocene sediments (A Unit). The basal surface of R05 is semi-horizontal in the north, becoming increasingly irregular in the centre and to the south of the IA. Locally, R05 erodes into the underlying Seismostratigraphic Units C and D. The erosive contact is attributed to channelisation at the top, within, or at the base of the unit.

The thickness of Unit B varies across the site, ranging from a minimum of around 0.045-0.047 s TWTT (approximately 1.5 m BSF) in the north and deepening towards the south of the site. The typical thickness observed to the central eastern margin of the site where the base of R05 erodes into the underlying units is ~5-9 m. However, in the north, where the base is not as erosive, the unit is 1 to 4 m thick. The acoustic character of Unit B is mainly chaotic to acoustically transparent, with no continuity of internal regional reflectors and variable amplitude distribution from low to high. Locally inclined, and horizontal reflections were observed within this unit. The internal channels at the base of the R02 horizon, or within Unit B often display high amplitude reflections and a clear layered internal architecture. The erosional channels at the base of Unit B typically show lower amplitude reflections and are typically less distinguishable from the surrounding unit. In addition, high amplitude seismic anomalies are mapped throughout Unit B and often occur at the top of one of the incisional channel features particularly in the north of the site. The anomalies

are in the form of high-amplitude reflections typically associated with reverse polarity and/or pulse broadening. The identified seismic anomalies may relate to laminae or beds of peat, or deposits of organic clay.

Imaging of the sub-bottom profiler data penetrates up to ~10 m BSF, imaging the upper section of the ground model. Unit B appears as a homogenous unit that contains a few internal discontinuous reflections and may be coincident with organic bearing layers (Figure 4-23), however it is noted that vibrocore sediment descriptions of a vibrocore (VC-4138) that is close to bright amplitude response does not contain descriptions of organic soils or peats.

Unit B is penetrated in every borehole, reflecting the lateral continuity of this unit across the IA. The composition is predominantly described from boreholes as dense to very dense fine to medium sand with occasional interbedded clays/silts and shell fragments. This typically homogenous nature is reflected in the chaotic to acoustically transparent nature of the unit.

The basal horizon of the Unit B (R05) is an erosional surface representing significant channelisation and is reflected from north to south across the IA, where the basal surface of R05 erodes into the underlying stratigraphy. A map view showing the basal R05 horizon identifies a distinct northwest-southeast trending boundary where there is a marked increase in incision, eroding up to 25 m into the underlying stratigraphy, Seismostratigraphic Units C and D (Figure 4-24:). North of this boundary is a series of cross-cutting N-S trending sinuous features, interpreted as channels and typically belong to the 'buried channel' unit, associated with the upper stratigraphy of R05. To the south of the boundary more NW-SE trending lineations are present, coincident with marked incision near the major change in erosion.

The R05 horizon represents the base of a variable, chaotic seismic unit interpreted as the Base of the Naaldwijk Formation and is consistent with observations and interpretations made in other Dutch windfarm sites (IJV) and is supported by the biostratigraphy report (Fugro, 2024b). Unit B is also interpreted as the Naaldwijk Formation, with the environment of deposition thought to be mainly coastal to tidal flat and lagoonal with a possible glaciofluvial influence in the channel-like deposits. It is noted that sediments deposited at the base of the unit may correspond to older Formations, such as the Well Ground Member (a member of the Dogger Bight Formation), however this remains an uncertainty.

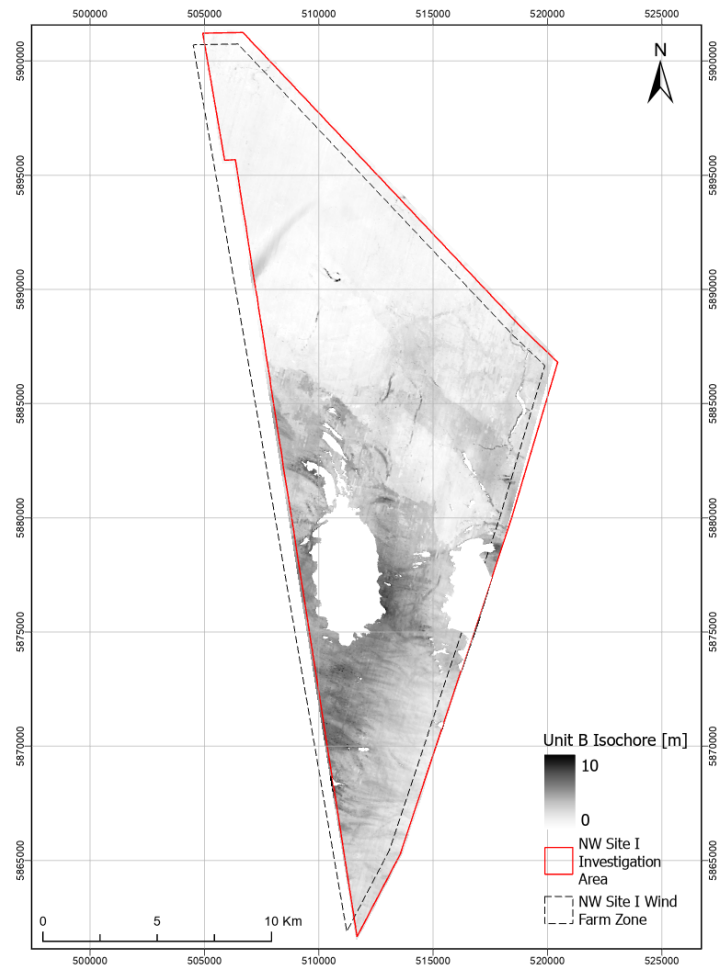


Figure 4.6: Isochore maps for seismostratigraphic unit B showing variation in thickness and spatial distribution.

4.4.3 Seismostratigraphic Unit C

Unit C is stratigraphically younger than Units D-1 to 5. Unit C is present across almost the entire IA, apart from a combined area of $\sim 40 \text{ km}^2$ in the central-southern sector that is eroded out by the overlying Unit B, and by channels on the eastern margin of the IA. The thickness of the Unit C is interpreted from being absent to $\sim 9.3 \text{ m}$ thick (Figure 4.7), showing moderate variability in the thickness anticipated across the IA. The upper surface of the Unit C is mapped as the base of the overlying Unit B, which is highly erosional. The basal surface of the Unit C (R10) is mapped from 0.0482 to 0.0588 s TWTT and is conformable with the underlying stratigraphy. The acoustic character of the C unit comprises dominantly low amplitude horizontal and laterally continuous reflections that appear to onlap antecedent topography from the underlying D units and, like the clay-dominant Units D-2 and 4, does not form a constructional morphology. It is possible to divide the Unit C into two discrete seismic packages as the unit is often characterised by a moderate to high amplitude negative reflector within the middle of the seismic unit. However, based on integration with geotechnical data, it was found to have minimal geotechnical significance (Section 5). Based on the distinct seismic facies, combined with geotechnical data, there is low uncertainty with the interpretation of Unit C.

Unit C is consistently described across the IA as a high-strength calcareous silty clay containing rare pockets to thinly laminated black organic matter. Where laminated, the black organic matter is identified as very or extremely-closely spaced thin laminae in units that vary between decimetres (e.g., BH-5069, 5087-A) to multiple meters in thickness (e.g., BH-5003, BH-5030, BH-5077). The unit is typically fissured, with fissures described as platy, sub-horizontal (0° to 10°) and extremely closely spaced together. In places slightly sandy to gravelly sections are described.

Unit C is interpreted as the Brown Bank Member, part of the Eem Formation and supported by biostratigraphic analysis (Fugro, 2024b). The distinct seismic boundary within the Unit C is also identified in a study located $\sim 60 \text{ km}$ to the south of Nederwiek I (Wajeen et al. 2024). At this location, the Brown Bank Fm is a clay-rich unit sub-divided into two (BB1 and BB2) relating to decreasing energy in the North Sea

water during later MIS5a, a temperate interstadial towards the transition into MIS4, a cold stadial (i.e., Weichselian ice) (Waaen et al., 2024). On seismic, BB1 (the lower unit) displays high amplitude seismic unit and BB2 (the upper unit) is more transparent. These seismic facies change is also observed on the UHRS seismic dataset in Nederwiek I (Figure 4-22), however lithological similarities throughout the C Unit did not warrant further geotechnical sub-division.

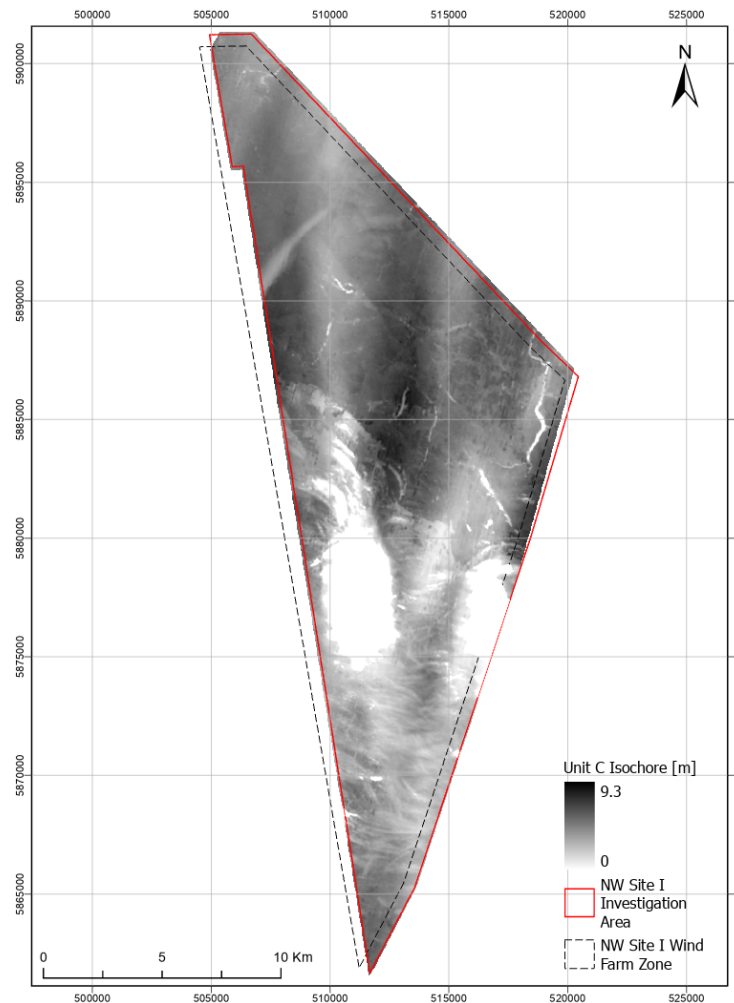


Figure 4.7: Isochore maps for seismostratigraphic unit C showing variation in thickness and spatial distribution.

4.4.4 Seismostratigraphic Unit D

Seismostratigraphic Unit D is divided into five subunits, each with distinct seismic facies and upper and lower bounding surfaces. The spatial distribution and thickness are shown in (Figure 4.8) Figure 4.8.

D-1

Unit D-1 is the upper and youngest subunit of the R20 sequence deposited above the Units D-2 and 3 subunits. It is preserved from the centre to the east of the IA, forming N-S linear features interrupted by potential faulting towards the northern sector. The overall width of the unit is mapped around 5.5 km, however, likely extends beyond the eastern margin of the site. It ranges in thickness from 0 to ~6.9 m (Figure 4.8). The basal surface (horizon R20.1) appears as dominantly conformable with the underlying stratigraphy, interpreted between 0.0588 and 0.0520 s TWTT. The horizon is typically interpreted on a negative reflector, however, is not consistent across the area. The upper boundary of the unit, mapped as the base of the R10 horizon (Unit C), can appear as flat-topped with shallow dipping margins. The flat-topped features are up to 3 km in width and ~10 km length and have margins that dip ~4 m over ~1km distance. The principal seismic facies are broadly transparent, however in places there is some evidence of internal interval bedding down lapping onto the basal R20.1 surface and appears to form a constructional morphology. The unit appears

typically well-preserved in the stratigraphy, however, occasionally is eroded by 1-2 m thick broad 'U'-shape scours that have a channel-form geometries, part of the stratigraphically younger Unit B.

Unit D-1 forms the upper subunit that comprise units D-1 to D-5. There are 27 geotechnical locations that penetrate Unit D-1. The unit is typically characterised by dense to very dense olive- to dark greyish brown calcareous medium and coarse-grained sand. Rare black organic matter and coarse sand-sized to fine-gravel-sized shell fragments are also identified in some boreholes (e.g., BH-5055). The descriptive sedimentology of D-1 is similar to D-3, and therefore may have similar geotechnical characteristics, however some differences in q_c exist. For example, in BH-5043 and BH-5038, R20.1 is interpreted as immediately above Unit D-3. Although lithologically the soil descriptions are similar, the sands of different units appear to be distinct in terms of their q_c value. In BH-5043, the q_c value of Unit D-1 is up to 40 MPa and Unit D-3 is up to 90 MPa. In BH-5038, the q_c of Unit D-1 is up to 60 MPa and Unit D-3 is up to 75 MPa. Like Unit D3, this unit also appears to be structureless in borehole cores (e.g. BH-5083, 7.5-10 m BSF), suggesting bioturbation, consistent with deposition in a marine environment.

D-2

Unit D-2 is the next subunit in the D-Unit sequence, deposited above the D-3, 4, and 5 subunits and partly over Unit F. The D-2 Unit forms a linear, broadly N-S trending feature that thickens to a maximum of ~6.8 m towards the eastern-central sector of the IA (Figure 4.8). Part of the subunit is truncated by the overlying D-1 sub unit, and interpreted as absent, towards the south of the IA. D-2 also likely extends south and northwards, beyond the IA boundary. The principal seismic facies are dominantly low amplitude and homogenous with occasional sub-horizontal internal bedded reflectors. The basal reflector typically appears to be conformable with the underlying units, suggesting passive infill onto the antecedent topography. The base of unit is mapped between 0.0625 to 0.0529 s TWTT. The upper surface is typically observed as sub-horizontal.

There are 21 geotechnical locations that penetrate D-2. This unit is typically characterised as closely fissured medium to high strength clay with rare mica crystals and thin laminae of black organic matter. The fissures are platy, sub-horizontal (0° to 10°) and extremely closely spaced and undulating (e.g., BH-5044). In places, the clay has a dark grey mottled appearance and can also contain thin to thick laminae of light brown sand. This subunit infills the underlying constructional geomorphological features associated with the underlying D-3 subunit. This subunit is reflection poor, with the lack of layered acoustic facies in the seismic data supporting the unit as dominantly comprising a homogeneous clay. A marine environment is also interpreted for this unit, given its stratigraphic relationship with the underlying and overlying sand ridges and its lithological similarity to Unit C.

D-3

The D-3 subunit is the next subunit in the D-Unit sequence, typically deposited above the D-4, E and F Units. The distribution of D-3 is located across the majority of the IA, apart from three isolated N-S oriented linear areas to the east, west and south of the IA (up to ~11 km length and 3 km wide). Where D-3 is interpreted as absent, the base of the horizon appears to pinch out, however there may also be some minor erosion from overlying units. Towards the western margin of the site, the interpretation is patchy with absent areas (up to 1 km width) where the younger Unit B completely erodes D-3. The upper surface of Unit D-3 can show an undulating surface, with waveform amplitudes up to ~500 m length and ~1.5 m in height. Unit D-3 is 0 m to 7 m thick (Figure 4.8) and where over 5 m thickness, the principal seismic facies typically exhibit low amplitude internal dipping reflectors. At these locations, Unit D-3 forms mounded geomorphological features up to 7 m thick, with internal interval bedding that downlaps onto the basal reflector, suggesting a constructional morphology. Where the unit is thinner, such internal structure is not present. The basal surface (R20.3) appears to be conformable and is typically interpreted on a high amplitude negative impedance reflector, between 0.063 to 0.052 s TWTT.

There are 65 geotechnical locations that penetrate Unit D-3, highlighting the widespread deposition of this unit across much of the IA. The subunit is typically characterised as dense dark greyish-brown calcareous fine to medium sand and can contain gravelly sections containing sand- to gravel-sized shell fragments. Gravel clasts are flat, elongate and sub-angular and are composed of various lithologies including sandstone

(e.g., BH-5010, 5020). Rare brown to black organic matter is also identified in some boreholes (e.g., BH-5090).

Unit D-3 sand is the first sub-unit that extends beyond the confined N-S trending channel-like troughs created by the antecedent Unit D-5. Unit D-3 forms a sand-dominated layer, typically <1 m to 2 m thickness deposited across the entire site. Unit D-3 is thickest in the west of the IA, where asymmetrical convex to flat-topped landforms are mapped. Within these, eastward dipping seismic events are identified, suggesting that they are constructional geomorphological features. These are interpreted as sand ridges deposited in a marine or subaerial environment. Based on biostratigraphical, palynological and paleoenvironmental evidence from offset publications (e.g. Wajeen et al., 2024), and the presence of marine shells, it is suggested that this sand was deposited in a marine environment. A comparison to present-day tidal ridges across the North Sea could suggest that these sands were influenced by tidal currents with material redeposited from fluvial or deltaic sediments. Unit D-3 may therefore represent sand ridges, formed by tidal currents, resulting from rising sea levels across the area. In borehole core (e.g., BH-5087, 15.5 m BSF), this unit appears to be structureless, which could suggest it has been bioturbated, further lending support to a marine interpretation, and is supported by the biostratigraphy data (Fugro, 2024b).

D-4

Unit D-4 is the next sub-unit in the sequence, deposited above Seismostratigraphic Unit D-5, F, and E. Unit D-4 is dominantly mapped towards the south and centre of the site and forms a broad ~27.5 km N-S trending linear feature that can be broadly subdivided into three vertical sub-sections based on the thickness of the unit. The main N-S trending depocentre in the centre of the site is mapped up to 4.7 m thickness, located where the lower erosive Unit D-5 incises deepest into the antecedent stratigraphy (Figure 4.8). To the west of the main depocentre, the stratigraphy is thinner (<1 m), and deepens further west before the western boundary of NW I IA. The minimum width of Unit D-4 is ~6 km to 8 km mapped within the IA, however the unit continues east and south beyond the site boundary. The upper surface of Unit D-4 may be partially eroded in places by the overlying Unit D subunits and in places it is eroded by Seismostratigraphic Unit B. Therefore, the preserved present-day spatial extent is likely impacted by erosion.

The basal surface of Unit D-4 (R20.4) typically appears to be conformable, however is gently undulating and is typically mapped on a low-amplitude positive reflector. The base of unit is mapped between 0.0533 s to 0.0639 s TWTT and the maximum thickness of the unit is 4.7 m. The upper surface is typically horizontal to sub-horizontal. The principal seismic facies of Unit D-4 typically show a low-amplitude unit with well-bedded internal reflections across the site that appears to onlap onto the channel-margins formed by the underlying Unit D-5. In places, the Unit D-4 is interpreted as being deposited beyond the boundary of underlying Unit D-5 channel-like feature forming a more laterally continuous deposit across the site.

There are 34 geotechnical locations that penetrate the Unit D-4. Geotechnical samples typically describe this unit as medium strength, slightly calcareous clay that can contain fine-to coarse subrounded to subangular gravel of various lithologies. Rare coarse gravel-size shell fragments are also documented in this unit (e.g., BH-5042 and 5047). In places, the clay is extremely closely fissured containing slightly sandy slightly calcareous clay with rare black organic matter with platy, sub-horizontal fissures (0° to 10°) extremely closely spaced and planar smooth (e.g., BH-5042). Unit D-4 typically infills the troughs and onlaps the topography created by the antecedent D-5 Unit. The presence of occasional shell fragments could suggest that Unit D-4 was deposited in a marine environment, indicating that sea-levels had risen sufficiently across the area to a shallow marine environment.

D-5

Unit D-5 is the deepest and oldest seismostratigraphic subunit and is dominantly mapped in an NNE-SSW orientation across the IA, deposited above Seismostratigraphic Unit F and E-1 to 5 Units. The basal surface of Unit D-5 (R20.5) forms two discrete incisional channel-like features. The base of the larger western erosional unit is mapped between ~2.6 km and ~5.2 km width and is ~31 km long, with the channel feature continuing north and south beyond the IA boundary. The smaller eastern erosional unit is mapped as ~2.5 km and ~10 km long, continuing to the south of the IA boundary. The present-day plan view of Unit D-5 is stepped in nature, with the upper surface potentially eroded by overlying Unit D-4 to 1, and influencing the present-day distribution of Unit D-5, Figure 4-19E.

The basal horizon of R20.5 erodes up to ~14 m into the underlying stratigraphy, including into the Seismostratigraphic Units E and F. The upper surface typically gently dips down (<1 degree), up to 8 m, into the depocentres formed by the R20.5 basal surface. The base of the unit is mapped between 0.0537 s to 0.0755 s TWTT and the maximum thickness of the unit is ~14.10 m (Figure 4.8). The lower bounding undulating surface of the R20.5 varies between exhibiting a low impedance variable reflector in the troughs of the main channel-like features, to a high impedance negative reflector on the margins of channel-like features. The upper surface may be partially eroded in places by the overlying Seismostratigraphic Unit D, however in a few areas, it is fully eroded from channel-like features associated with the younger stratigraphy associated with the younger Unit B.

The principal seismic facies of Unit D-5 typically show low-amplitudes with poorly-to well-imaged internal reflections across the site. Where imaged, the margins of the channel-feature exhibits downlap of the reflectors into the depocenter towards the western erosional channel-like feature. A discrete internal, positive impedance surface that mirrors the base of the channel-like unit acts as a boundary that may indicate a subtle change in lithology. The acoustic character above the internal surface is variable, comprising acoustically transparent to subtly dipping reflectors (typically observed in a west to east orientation) to more chaotic or undulating horizons with internal bedding (typically observed in a north to south orientation).

There are 33 geotechnical locations that penetrate Unit D-5; however boreholes (with core descriptions) do not penetrate the axis of the two N-S trending major channel features. As such, the prediction of lithologies within the axis is not documented from core data. However, where penetrated off-centre and on the margins of the channel-like features, this unit is typically dominated by dense to very dense dark grey to dark greenish grey silty fine sand and can contain rare mica crystals and rare black organic matter (e.g., BH-5055 and 5058). In BH-5020 towards the north of the site, at 17.3 m to 17.4 m BSF a thin (10 cm) gravel layer containing flint was present within the sandy unit, present near the base of the channel.

Interpretation of the depositional environment corresponds to a change in climatic conditions between the Saalian glacial to Eemian interglacial period. The unconformity at the base of the R20 horizon suggests a hiatus/erosion and one suggestion is that this cumulative erosion surface could represent the at least part of the Saalian period (~300,000 years). There is a high degree of ambiguity relating to the limits and morphology of the Saalian ice margin, however existing models suggest that the present-day location of Nederwiek I is ~100-200 km from the Saalian curved ice-front. The channel-like incision associated with R20.5 could potentially be attributed to the latest part of the Saalian period as the area transitioned from a pro-to periglacial and finally terrestrial environment before eventually being flooded. One interpretation is that the base of the channel-like features could have been eroded during the latest Saalian in a terrestrial environment and infilled from the deposition from terrestrially derived sediments (e.g., fluvial). If the age assignment is correct, Unit D-5 could possibly be assigned to the Eem Formation, however possibly incising during the latest Saalian (MIS 6/5e). The sedimentology of this sand unit is most dissimilar to the upper Unit D-3 and D-1 and therefore may have some differences in geotechnical characteristics.

To the west in the Ijmuiden Ver windfarm site, the cumulative basal erosion (Seismostratigraphic Units D* to C, equivalent of the 'D' Units in Nederwiek I) is present above Unit F (interpreted as Yarmouth Roads), however such channel-like features, as associated with Unit D-5, are not interpreted.

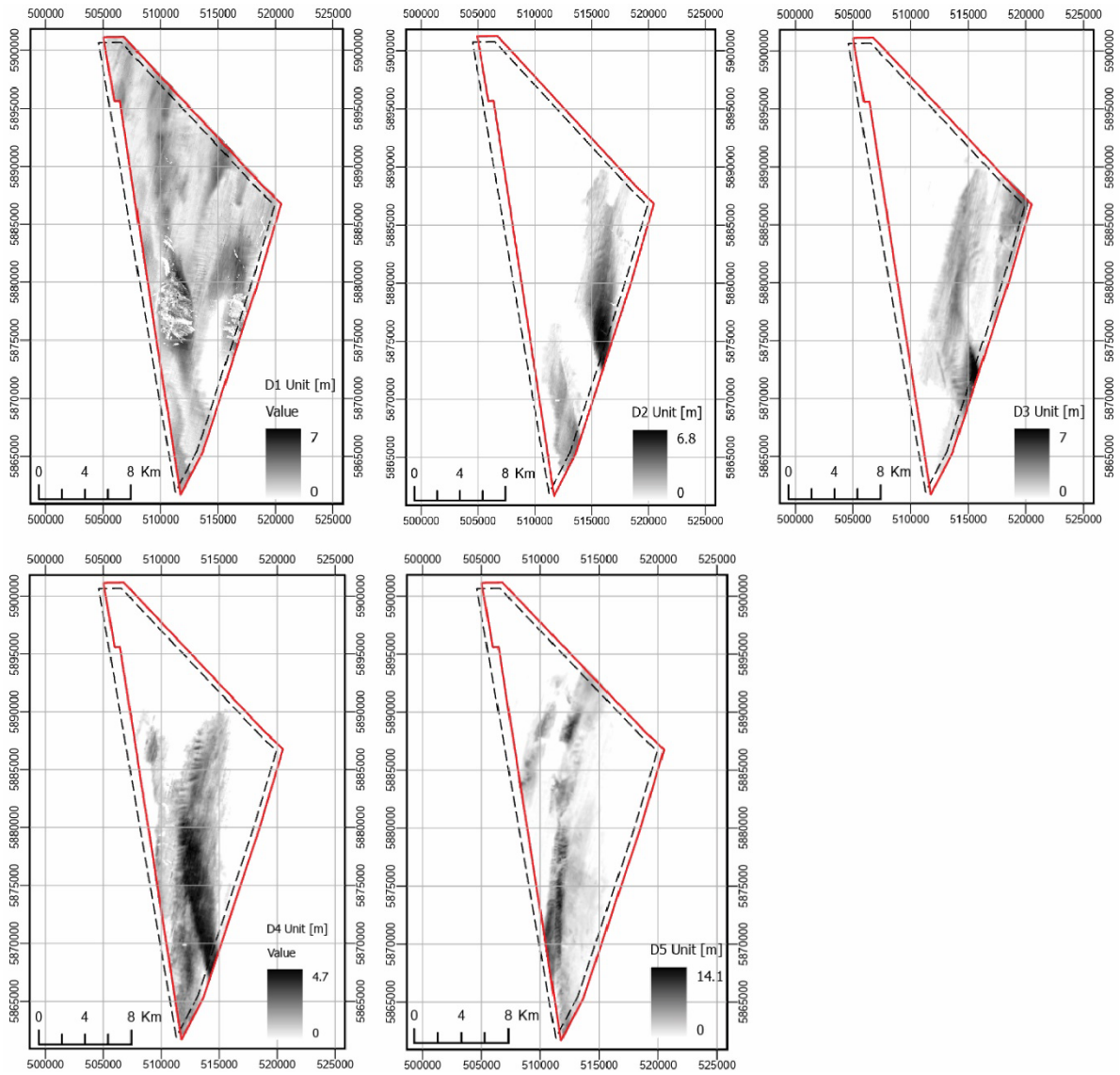


Figure 4.8: Isochore maps for seismostratigraphic units D-1, D-2, D-3, D-4 and D-5 showing variation in thickness and spatial distribution

4.4.5 Seismostratigraphic Unit E

Unit E is divided into five subunits based on distinct seismic facies and spatial trends (E-1 to 5) and constitutes the fill of two tunnel valleys, one in the north and one in the south of the IA (Figure 4.9). Units E-1 to 4 (youngest to oldest, respectively) are interpreted in the north of the study area, whereas Unit E-5 is interpreted in the central and southern sectors of the study area. The associated common basal horizon of subunits E-1 to 4 units are denoted by ‘R25-N’ showing its northern NE-SW spatial distribution (‘-N’). The basal horizon of Unit E-5 is denoted by ‘R25-S’ showing its more southerly N-S distribution (‘-S’).

The rationale for differentiating the northern and southern Seismostratigraphic Unit E subunits was based on differences in seismic character and geotechnical conditions sampled. Unit E-1 to E-4 have a more complex layered seismic character, with distinct seismic facies. In contrast, Unit E-5’s seismic character is typically characterised by discontinuous, chaotic seismic reflectors with little internal organisation. The conceptual model shown in Figure 4.2 shows the relationships between the subunits of Seismostratigraphic Unit E. Table 4-1 shows the relationship between the lower bounding horizons, specific to either the north or south of the IA (R25-N and R25-S) and Unit E subunits.

Equivalents of Units E-1 to 5 are not interpreted in the nearby wind farm zones (IJmuiden Ver Alpha & Beta and Hollandse Kust West). However, over 180 km north, Ten noorden van de Waddeneilanden (TNW) is interpreted to contain similar seismostratigraphy, formed by consistent geological processes, in this region the basal horizons are named “R51, R52, R53 and R54”.

The southern erosive feature (R25-S) covers an area of ~60 km² and trends north-south. The erosive features cover an area of ~ 92 km² and trend northeast to southwest (horizon R25-N). In TNW, the interpreted erosive features are Elsterian-aged tunnel valleys with the Peel Formation infilling the channel-like features. In Nederwiek I, the R25-S and -N basal horizons are interpreted to also represent the erosional margins of subglacial tunnel valleys, with both horizons incising into the underlying Unit F.

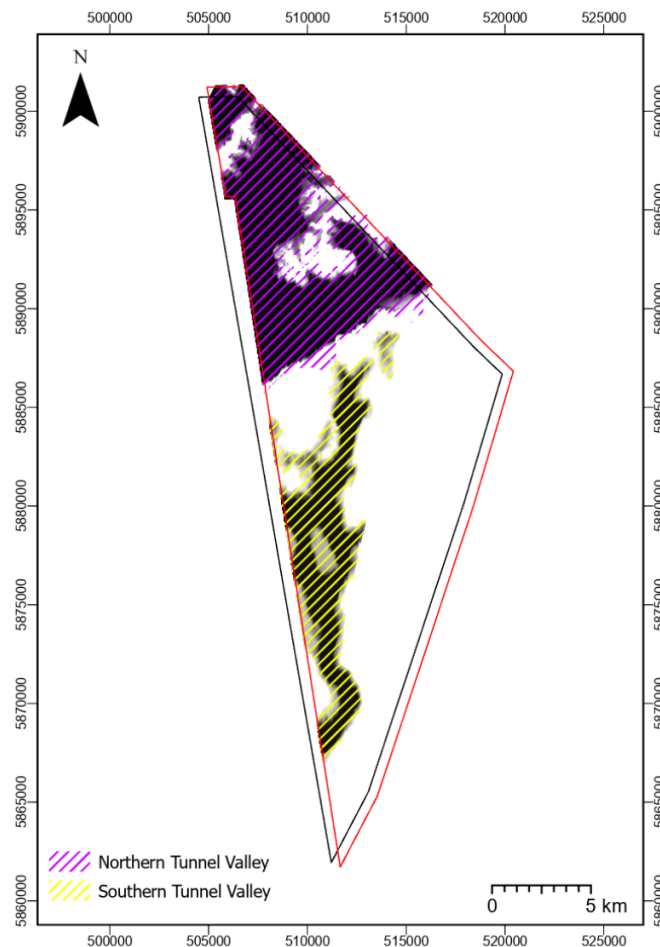


Figure 4.9: Northern and southern tunnel valleys infilled by Seismostratigraphic Unit E

E-1

Unit E-1 is the shallowest and youngest subunit within the northern tunnel valley. In cross section, it has an undulating, erosive base which cuts down into the underlying E-2 subunit. Unit E-1 has a relatively flat upper surface formed by the R20 horizon and is typically erosive, truncating this unit. In plan view, these features appear as distinct channel features, likely different in formation from the underlying Unit E-2. The base of the subunit is mapped between 0.052 s and 0.067 s TWTT and the top between 0.052 s and 0.062 s TWTT. The maximum thickness of the unit is 0.021 seconds (~17.8 m); however, this thickness is limited to small areas in the centre of the channel features, and is typically much thinner (i.e., <10 m), Figure 4.10.

The subunit is discontinuous in nature, with several deeply-incising areas in the northwest and one to the southeast. Between these areas, the unit is highly discontinuous, with individual channels not traceable across more than one seismic line. Seismic facies are identified as low to high amplitude and are generally discontinuous, with some locally dipping reflectors. Where mapped, the subunit is well-imaged with clear top and basal contacts, reducing uncertainty in the seismic interpretation. There is however some uncertainty in the overall extent of the unit. Across the northern tunnel valley, it is possible that the unit may be locally very thin and therefore not seismically resolvable. It is also possible that the unit extends to the south into the area where Seismostratigraphic Unit F underlies Unit D. Here it is not possible to distinguish the incisive features from those in Unit F, and therefore Unit E-1 is not extended into this area.

Only one borehole has penetrated Unit E-1 (BH-5066), and as such has limited calibration of the seismic mapping. Those that do sample the unit, show a varied mix of lithologies with interbedded sands, silts and clays. The limited number of penetrations through this unit make prediction of lithology away from the data points difficult, and as such a wide range of possible lithologies could be found where this unit is present.

This subunit is interpreted as a series of incisive, channel complexes that trend from northwest to southeast. The mapping shows preservation of this unit is patchy, and it is possible that only the deepest erosive sections of the channel system are preserved. Other, less incisive areas may have been eroded away during exposure at the unconformity mapped at the R20 horizon. The absolute age of these channels is uncertain; however, Unit E-1 is bound by chronostratigraphic dating of borehole data. After inferring the age of the underlying tunnel valley fill as Elsterian to Holsteinian, and the overlying marine intervals of Seismostratigraphic Unit D as Eemian, a large time gap is apparent. This time gap spans around 270,000 years and includes glaciations associated with the Saalian period. The Fennoscandian and British Ice Sheets are thought to have merged, with the IA sitting in a proglacial setting just south of this merge point. Given, the proximity to this ice front, it is possible that the channels are related to this glacial activity could be interpreted as meltwater channels.

Saalian-aged tunnel valleys, moraines and glaciotectionic ridges have been recognised onshore Netherlands, and to the west in the Hollandse Kust South and Hollandse Kust West windfarm sites. A thick, incisive package, named 'Unit E', is mapped at HKW and is interpreted as the furthest west of the Fennoscandian ice sheet extent at this time (Cartelle, et al., 2021). The extent of the British Ice Sheet to the northwest of the site is more uncertain, with fewer Saalian glacial features report in literature. A northwest to southeast meltwater flow direction is assumed, given that the ice sheets were broadly north of the site, and the majority of meltwater ultimately flowed southward into the Atlantic during glaciations associated with the Saalian period. In onshore Netherlands, glacial deposits of Saalian age grouped into the Drenthe Formation, and so this unit is tentatively assigned this formation name. Unit E-1 is the youngest infill of the northern tunnel valley, but if the age assignment above is correct, would coincide with a different glacial period than the underlying sediments.

E-2

Unit E-2 is the next unit in the northern tunnel valley sequence. It forms a continuous seismic package that is mapped in the north of the IA. The subunit directly overlies Unit E-3 and has a highly erosive base. The base of the subunit is mapped between 0.055 s and 0.1 s TWTT and the top between 0.05 s and 0.07 s TWTT. The maximum thickness of the unit is ~38 m and average thickness is 0.025 s (15m). The unit is capped by the laterally continuous basal R20 horizon. The nature of this contact is erosive with truncation of the underlying sediments being evident. Locally the Unit E-2 is overlain and eroded into by Unit E-1.

Within Unit E-2 there are *four distinct seismic facies*:

- (1) Low amplitude, erosive features commonly containing dipping reflectors, interpreted as fluvial channels;
- (2) Discontinuous packages which thicken towards the channels, interpreted as overbank deposits;
- (3) Isolated sequences of continuous high amplitude reflectors interpreted as floodplain deposits, and;
- (4) At the top of the unit there is an interval which is distinct from the above seismic facies. Its base is marked by an unconformity, which is then overlapped by moderate amplitude, continuous and horizontal reflectors.

Each of the four seismic facies packages are distributed across the unit, creating a complex internal architecture. This interval is up to ~38 m and is limited to the northern part of Unit E-2. The seismic definition of this unit is generally clear with the greatest uncertainty in the position of its basal horizon. For a consistent approach, the basal horizon has been mapped as the basal unconformity surface, comprising composite erosion from multiple surfaces. This horizon overlies the top of the clinoforms of Unit E-3 and due to its erosive nature, its position can be locally uncertain. This is particularly true in the far northwest of the unit, where seismic image quality is reduced, and the seabed multiple coincides with the expected location of the horizon.

A variety of different seismic facies are identified within this subunit and interpreted as elements of a terrigenous fluvial plain setting. These elements are reasonably well sampled by the borehole dataset, which show that lithology can be predicted by seismic facies to some extent. The interpreted erosive channels, with dipping reflectors are commonly sand-dominated. They are interpreted as fluvial channels containing migrating point bar deposits. The adjacent floodplain facies are heterogenous and shows a broader range of lithologies including interbedded clay, silt and sand. These facies are generally finer than the channel facies, and contains some thick, isolated clay units such as in BH-5005 and 5010. BH-5005 intersects a 5 m thick medium to high strength dark grey slightly calcareous silty clay interval (22 to 27 m BSF). BH-5010 intersects a 2.1 m thick medium strength dark grey sandy calcareous silty clay interval (19.2 to 21.3 m BSF). Both clay units contain rare organic matter. Such overbank deposits are sparsely sampled but where intersected are heterogenous with interbedded sand, silt and clay. The uppermost interval within Unit E-2 is sand-dominated with rare silt and clay interbeds. The depositional environment of this interval is difficult to describe from seismic alone. The samples that intersect the unit commonly contain shell fragments and so a marine interpretation is tempting. However, other units which are interpreted as non-marine also contain shell fragments, possibly due to short-lived marine influence or reworking of the shells. Therefore, this cannot be used as a diagnostic feature in isolation.

The bulk of this unit is interpreted as deposited on a fluvial plain that had formed over the site of the mostly filled northern tunnel valley. The orientation of the mapped fluvial channels is approximately northwest to southeast, but it is not clear what the direction of flow would have been. If flow was from the northwest, these unit would be formed by continued melting of the ice sheets during the latter part of the Elsterian or early Holsteinian. Deltas could have delivered sediments down through the network of tunnel valleys, filling in subaqueous environments as they migrated southwards. The underlying clinoforms from Unit E-3 are not clearly joined or related to the fluvial system interpreted as part of the Unit E-2. However, it is possible that the fluvial system is part of one of the rivers draining the continent to the south. If the underlying tunnel valleys had now been mostly filled, one of these rivers could have migrated over this area and drained to the north or south eventually. If true, this unit would be more accurately described as part of the Urk Formation, which is described in onshore Netherlands.

The uppermost interval within this unit marks a probable change in depositional environment. The continuous, onlapping seismic facies, and presence of shell fragments in cores could point to increasing marine influence at this time. Comparison with sediments in the United Kingdom sector shows a similar late infill of the Elsterian-aged carved tunnel valleys corresponding to the Egmond Ground Formation. The dominance of a more fluvial-like seismic architecture in NW I IA may suggest the Urk Formation that occurred during the Holsteinian interglacial.

E-3

Unit E-3 is typically identified as a semi-continuous seismic package mapped exclusively within the northern tunnel valley over an area of ~70 km². It overlies the Unit E-4 with a basal contact (R25-N.3). In places, this horizon can be relatively poorly imaged and difficult to characterise as purely conformable or unconformable. It is overlain by Unit E-2, bound by an erosive contact between the two units. The base of Unit E-3 is mapped between 0.06 s and 0.17 s TWTT and the top between 0.055 s and 0.1 s TWTT. The maximum thickness of the unit is 0.09 s (77 m), and the average thickness is 0.06 s TWTT (53 m).

Within Unit E-3, several seismic facies types are identified which have an ordered structure reflecting a major change in the depositional infill of the tunnel valley. The base of the unit typically contains continuous, low to high amplitude (positive and negative) reflectors. Above this, laterally migrating, large-scale, continuous, dipping reflectors develop and are interpreted as prograding clinoforms. The bottomsets of these clinoforms contain high-amplitude, discontinuous and moderately chaotic seismic bodies, typical of mass-transport deposits/complexes (MTDs/MTCs), and turbidites derived from the clinoforms.

There is some uncertainty in the placement and nature of the basal surface of this unit (R25-N.3), notably around areas of mapped highs of Seismostratigraphic Unit F in the northern tunnel valley, and to the southwest margin of the northern tunnel valley fill. At these locations the package is poorly imaged, and there is uncertainty over the presence of the unit where the clinoform features become difficult to distinguish, particularly where chaotic, disrupted reflectors and multiples make interpretation of the R25-N.3 horizon challenging.

Fourteen boreholes penetrate Unit E-3. Boreholes penetrating the base of the unit show a clay dominated section, with interbedded sands and silts. Above this the section becomes more silt and sand rich with interbeds of clay. This corresponds to the foresets of the clinoforms that are observed (Arup, 2025a). Towards the top of the unit, the section becomes sand-dominated, with rare interbedded silt and clay. In borehole BH-5012A, a 20 cm thick section of sand also includes gravels. This uppermost interval corresponds to the topsets of the clinoforms. The chaotic deposits observed in the seismic data are typically below 60 m BSF, however one large ~7 m-thick deposit is penetrated by BH-5011. This unit is identified as very dense, slightly silty, slightly calcareous fine sand (and rare organic matter). The subunit also comprises higher q_c (around 60-80 MPa) in comparison to the medium to high-strength clays above and below this unit (<20 MPa), Figure 5-6. Towards the upper part of Unit E-3, the topsets of the clinoforms are observed with a sub-horizontal, continuous to discontinuous seismic character, locally eroded by chaotic seismic features. The seismic packages observed suggest that antecedent topographic expression of the tunnel valley was present in the landscape after its incision, before being infilled by the clinoform units associated with Unit E-3.

The depositional evolution of Unit E-3 is interpreted using information from the seismic, boreholes, CPTs and regional context. Prograding facies are typical of a subaqueous environment. Initial deposition may have been in an open lake, marginal marine to marine environment, supported by the biostratigraphy data (Fugro, 2024b). Accommodation space was available, created by the underfilled nature of the northern tunnel valley. A minimum water depth of ~50 m can be estimated by measuring the initial vertical height of the overlying clinoforms and converting this value from time to depth. This water body was filled by the clinoforms, which locally prograde locally from the northeast, east and southeast. A large influx of sediment would have rapidly deposited this sedimentary sequence, although uncertainty remains regarding the provenance of these sediments. One interpretation is that a large volume of sediment would be expected to be transported from the rapidly retreating ice front to the north as time passed from the Elsterian glacial into the Holstenian interglacial period, creating high-energy meltwater flows. A second interpretation would be that these clinoforms correspond to deltas that were sourced from short rivers eroding sub-aerial exposures of Yarmouth Roads into the tunnel valley. The two interpretations would place this interval between the Elsterian into the Holstenian interval. Biostratigraphy data assigns this unit to the Egmond Ground Formation, defined as a marine fine-grained, sparsely shelly sand up to 10 m thickness (Rijsdijk et al. 2005), however as outlined earlier, the seismic facies sequence at Nederwiek is much thicker than what is normally described as the Egmond Ground sequences. The biostratigraphy suggests deposition within a hypersaline marginal to marine depositional environment suggesting similar environments.

Such uncertainties could possibly be relating to the physical location of NW I IA situated at a highly dynamic ice-margin and as retreat of the Elsterian ice ensued, it underwent rapid sea-level rise, not only

preserving the undulating landscape of the tunnel valleys, it deposited thick sedimentary sequences within topographically controlled features resulting from the presence of the tunnel valleys. The volume of sediment available must have been sufficient to infill and outpace the rising sea-level. An alternative hypothesis would be that the clinoforms were sourced by the paleo-Rhine or Meuse rivers that would have flowed from east to west south of this area but may have periodically drained northward into glacial meltwater lakes. Regardless of the provenance of the clinoforms, the interpretation of the unit as a shallowing upward sequence, becoming more sand-dominated towards the top as the environment evolved into a widespread fluvio-deltaic coastal plain.

E-4

Unit E-4 is the oldest seismostratigraphic subunit in the northern tunnel valley sequence. The margin of the channel feature (R25-N) extends from 0.055 s TWTT (~ 46 m BSF) at its edge, to beyond the base of the seismic data at 0.22 s TWTT (~130 m BSF). Similar to R25-S, the basal R25-N horizon appears to show a flat-bottomed channel as the channel is beyond the depth limit of the seismic data; however, the actual base of the channel is likely more morphologically complex and extends deeper beyond the seismic record length. In parts of the northern tunnel valley, Unit E-4 is overlain by Unit E-3, which is characterised in the seismic data by clinoform features. Where Unit E-3 is not mapped, Unit E-4 is overlain by Seismostratigraphic Units D-1 to 4.

Mapping the base of the northern tunnel valley captures only a small part of the much larger geomorphological feature, which crosses the IA. However, the morphology observed is consistent with tunnel valleys previously studied near to- and within the survey area e.g., (Moreau et al., 2014), in the North Sea region (Van Der Vegt et al., 2012); (Ottesen et al., 2020); (Kirkham et al., 2024)) and globally (e.g., Storm et al. 2012). The northern tunnel valley shows a complex internal geometry with two distinct internal highs as shown in Figure 4.10. Though most of northern tunnel valley infill (Unit E-4) lies beneath the NW I IA foundation zone, parts of the southeast tunnel valley margin and fill are present within the upper 100 m of the zone of interest, as well as in locations where internal highs show significant buried topography.

Only four boreholes penetrate Unit E-4, all located towards the southeast margin of the northern tunnel valley where the unit is closest to surface (BH-5018, BH-5020, BH-5026 and BH-5027). Of these, borehole data describe fine to medium sands in boreholes BH-5018, BH-5026 and BH-5027, and calcareous clay in BH-5020. Shells are described in Unit E-4 within sandy sediments in boreholes BH-5018 and BH-5027 and rare dark organic material in BH-5018, BH-5026 and 5027.

Only one borehole (BH-5027) penetrates through the Unit E-4 into the underlying Seismostratigraphic Unit F, and there is little apparent variation in lithology at the boundary of the two units (around 54 m BSF); both being described as fine sands with a calcareous component which extends to 52 m in the borehole. CPT measurements show a general increase in cone resistance (q_c) at the boundary (PCPT-1027 and BH-5027), although it remains variable into Unit F.

Seismostratigraphic interpretation interprets the Unit E-4 as the deepest part of the fill of a large incised glacial tunnel valley within the zone of interest. The paucity of borehole data for this unit, which lies largely beneath the foundation zone of interest, means that a confident interpretation of its lithological characteristics based on borehole information cannot be made. Based on the seismic character of the unit, and comparison to similar tunnel valleys nearby, it is suggested that Unit E-4 comprises heterogeneous material deposited during and after tunnel valley formation; this could include glacial tills and glaciofluvial sediments, all of which may have been further modified by fluvio-glacial processes. It is likely that much of these sediments were eroded and re-deposited from the underlying Seismostratigraphic Unit F. Although glacial till was not identified in boreholes, its presence cannot be ruled out.

E-5

The southern tunnel valley margin extends from 0.055 s TWTT (~ 46 m BSF) at its edge, to beyond the base of the seismic data at 0.22 s TWTT (~ 147 m BSF). The R25-S basal horizon appears to show a flat-bottomed channel when the actual base of the channel is likely more morphologically complex and extends deeper beyond the seismic record length. Unit E-5 infills the southern tunnel valley and is overlain by Seismostratigraphic Unit D. Although most of Unit E-5 is typically >100 m BSF, parts of the tunnel valley

margin and fill are closer to surface, especially on the margins of the tunnel valley, and where internal highs show significant buried topography.

The maximum ‘thickness’ of the Unit E-5 is at 178 ms (~ 147 m), with the caveat that the base of the unit extends beyond the extent of the seismic data. The length of the southern tunnel valley (within IA) is around 20 km, however it extends beyond the boundaries of the available seismic data to the south. The maximum width is around 4 km, narrowing to 1.5 km in the south, and displays an anastomosing morphology, with internal structural highs. Such features are also observed in other studies of tunnel valleys in the nearby area (Van Der Vegt et al., 2012); (Moreau et al., 2014). The dip of the margins is variable, from ~10 to 48 degrees with a locally maximum dip in the southern tunnel valley of 60 degrees and in the northern tunnel valley a locally maximum dip of 74 degrees, and the geometry of the internal highs are complex.

The seismic character of the Unit E-5 is highly variable, and it is not possible to consistently interpret any subunits within the tunnel valley fill. Generally, Unit E-5 comprises discontinuous, chaotic seismic reflectors and sometimes steeply northward dipping discontinuous reflectors, without any apparent internal organisation. There is some evidence for small internal channel features within the Unit E-5 but are not seen consistently throughout the unit fill. There is also no clear evidence for clinoforms within the upper part the tunnel valley fill, as observed in the northern tunnel valley (Unit E-3).

In some places towards the west of the Unit E-5, a set of high amplitude undulating continuous triple reflectors are present. The high amplitude reflectors generally shallow towards the south and west, and may represent a large internal channel feature, but are either not present or not imaged consistently across the unit. A lack of clear seismic character is reported elsewhere in tunnel valley fill in the North Sea (Stewart et al., 2012); (Van Der Vegt et al., 2012), making it difficult to interpret depositional environment for Unit E-5 from seismic facies alone. Interpreting the basal R25-S horizon along dipping margins can also cause some uncertainty, especially when these coincide with the steeply dipping reflectors. However, the generally chaotic/transparent nature of Unit E-5 fill, in contrast to the discontinuous sub-horizontal reflections of the underlying Unit F, allows for consistent picking of the R25-S horizon.

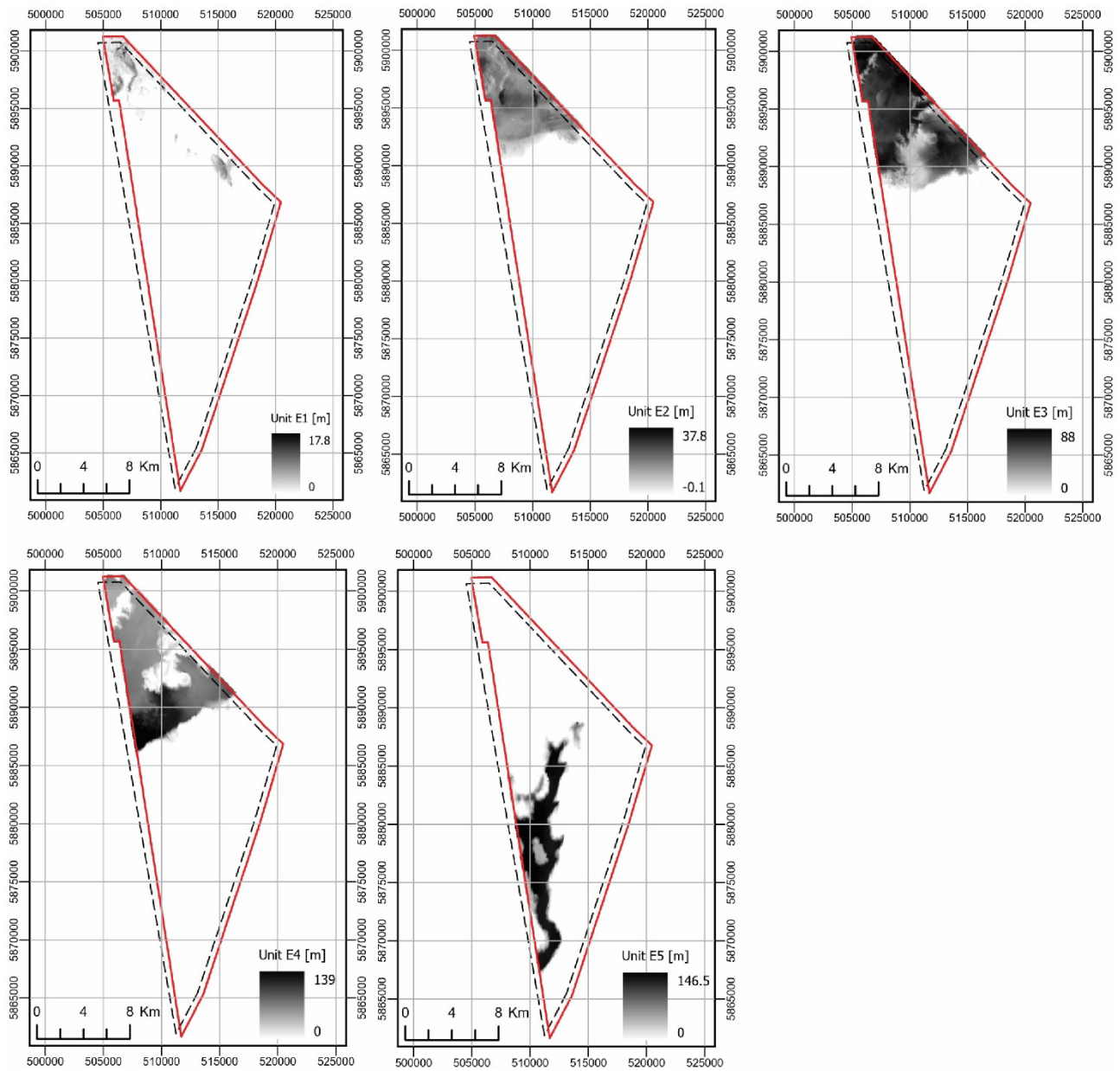


Figure 4.10: Isochore maps for seismostratigraphic units E-1, E-2, E-3, E-4 and E-5 showing variation in thickness and spatial distribution

4.4.6 Seismostratigraphic Unit F

Unit F is anticipated across the entire IA, where not eroded by the overlying subunits (E-1 to 5). This unit is expected to contain the oldest sediments within the depth of interest of the foundation zone. The base of the unit can extend beyond the vertical extent of the ground model (i.e., 100 m), and therefore the maximum thickness is undefined and cannot be determined at Nederwiek I. The maximum seismically defined thickness of this unit is 89 m, in areas not incised by units E1 to 5. However, the unit thickness relative to the base of the borehole (i.e. from the top of the unit to the base of the borehole) is described below.

Unit F is typically thickest where it directly underlies subunits D-1 to 5. Here, the top of the unit ranges from 0.056 s TWTT (13.1 m BSF, BH-5037) to 0.064 s TWTT (22.8 m BSF, BH-5060) depth and extends to the base of the borehole (i.e. between 60 m to 80 m depth). The maximum penetrated thickness occurs at BH-5037 where Unit F ranges from 13.1 m to 60.3 m (64.7 m thick) beneath the R20.5 horizon. The unit is typically thinner (or absent) when it occurs beneath subunits E1-5, ranging from 0.077 s TWTT (31.3 m BSF, BH-5012-A) to 0.101 s TWTT (43 m BSF, BH-5027). The minimum penetrated thickness relative to the base of the borehole occurs at BH-5027 where Unit F ranges from 43m to 60.5m (17.5m thick), Figure 4-3. Unit F is laterally continuous, bound at the top by Units E1-5 or Unit D1-5, Figure 4-4. The chronostratigraphic framework suggests there could be ~300,000 years between deposition of Units F and D subunits (where E subunits are absent), and therefore the top of Unit F (R20.5) likely represents an unconformity across the IA. The extent of erosion at the top (meter to deci-meter scale) is unknown.

The principal seismic facies of Unit F feature a chaotic acoustic character with horizontal to sub-horizontal continuous to semi-continuous reflectors towards the base, and more discontinuous (incisional) reflectors towards the top of the unit, likely representing significant channelisation. The seabed multiple typically intersects this unit, and in most of the site impacts the interpretation across the IA. Consistent or continuous seismostratigraphic boundaries are not present within Unit F and there is often no clear lithological division that can be made from boreholes. It is noted that the biostratigraphic analysis data suggests that only the Yarmouth Roads Formation is present (BH-5090 and 5055). The discontinuous to chaotic acoustic nature of Unit F reflects the heterogenous nature of the primary depositional environment that it was deposited.

Seismostratigraphic Unit F features horizontal to sub-horizontal continuous to semi-continuous reflectors at the base and more discontinuous (incisional) reflectors at the top. It was deposited in brackish to hyposaline marine conditions within a predominantly shallow subtidal environment (Fugro, 2024b), ranging from coastal plain to deltaic and shallow marine settings.

The lithostratigraphy of Unit F is heterogeneous, mainly consisting of sand with clay or silt beds, transitioning to interbedded sands, silts, and clays (as seen in CPT data). The sands are typically fine to medium and dense, containing variable organic material such as woody fragments, peat lenses/beds (up to 16 cm thick in NWZ-BH-5037), or shelly material. The presence of peats/organic within borehole did not correlate with a clear seismic response (e.g. amplitude anomaly) or a specific seismic character that could be laterally interpreted.

These sands often transition to interbedded sands, silts, or clays, as observed in NWZ-BH-5038, likely due to rapidly changing depositional environments like channel fill, overbank, flood plain, or marine settings. Biostratigraphy data (NWZ-BH-5055, NWZ-BH-5090) suggests Unit F belongs to the Yarmouth Roads Formation.

Unit F is seismically challenging to interpret, and a dominant lithology cannot be correlated across the site due to inconsistent transitions between soil types and seismic amplitude. This is consistent with other wind farms in the Dutch sector, where the internal complexity of the Yarmouth Roads made it difficult to correlate geotechnical changes within the unit. At other wind farm sites (IJV and HKW), an intra-unit horizon was identified on seismic data and correlated with biochronology/palynological analyses. However, no intra-unit horizon is apparent at Nederwiek I, and biostratigraphy data does not suggest deeper stratigraphy. It is possible that, as Nederwiek I is located further west towards the centre of the SNS, the overall Unit associated with the Yarmouth Roads is thicker here compared to other wind farm sites closer to the shoreline.

Unit F is a predominant formation within the target foundation depth across the IA. Its complexity is often attributed to a fluvial to deltaic (subtidal to brackish) depositional setting and later phases of erosion or possible deformation due to glacial periods

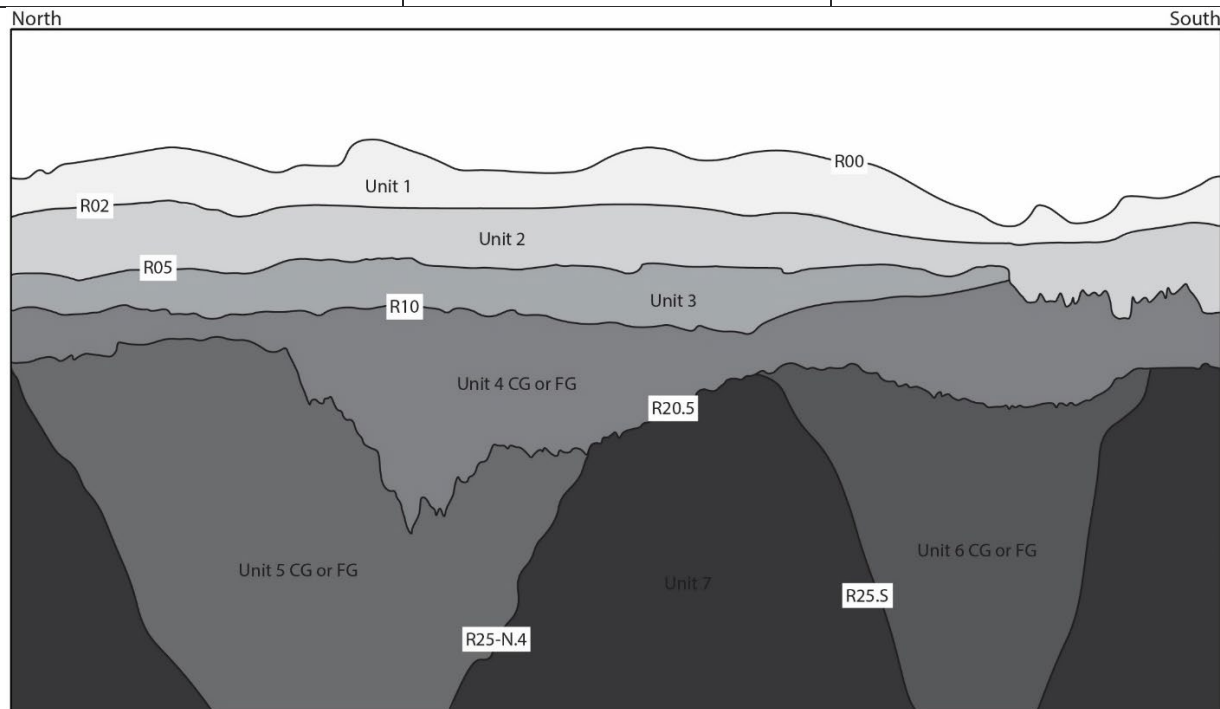
4.5 Seismostratigraphic units and geotechnical soil units

Each seismostratigraphic unit will be composed of either fine grained (FG) or coarse grained (CG) components. The varied nature of the depositional and post depositional conditions of the geological formations encountered (Section 4.4) means that not every seismostratigraphic unit can be exclusively defined as a geotechnical soil unit with consistent soil granulometry. Section 5 provides geotechnical rationale for the grouping of soil units, and the decision making regarding the quantity of geotechnical data available.

Table 4-2 and the accompanying image show the relationship between Seismostratigraphic Units and Geotechnical Soil Units. In the GIR (Arup, 2025b), the soil layering model provided in the GGM are used with some minor adjustment of the geological unit boundaries ($\pm 0.5\text{m}$) to match observations seen in geotechnical insitu locations and boreholes.

Table 4-2: Correlation between seismostratigraphic units and soil units

Basal Horizon	Seismostratigraphic Unit	Geotechnical Soil Unit
R02	A	U1
R05	B	U2
R10	C	U3
R20.1 to R20.5	D-1 to D-5	U4-CG/FG
R25-N.1 to R25-N.4	E-1 to E-4	U5-CG/FG
R25-S	E-5	U6-CG/FG
Horizon not defined (beyond seismic record length)	F	U7-CG/FG



4.6 Time to Depth Conversion

Time- to depth conversion enables translation of seismic data in the time domain into depth measurements. This is a critical step in enabling integration of seismic with geotechnical data and the development of a comprehensive ground model. A carefully considered time to depth conversion with uncertainties considered will allow for the accurate mapping of geotechnical soil units and geological features across the site, ultimately leading to more robust design and placement of foundations.

A time to depth converted model, converting the zone of interest (up to 100 m BSF) was devised. A two-layer model was used, with 1480 m/s down to seabed and 1700 m/s constant velocity for the sediments. This model was considered the ‘best technical’ case, with low and high cases also run to capture uncertainty of depth conversion in the model. Three data sources providing information about the sediment velocity were utilised, with P-S logging available from direct borehole measurements. However, to understand the possible data range (e.g. minimum and maximum) of velocities beyond the measured values, the mean V_p from CPTs (down to TD) and the V_{INT} data were also derived. The integration of the measured and empirical data helped to refine the data range across a wider area. The data types, measured and empirically derived, are described below:

1. P-wave data from borehole wireline P-S logging at five borehole locations (BH-5068, BH-5076, BH-5077, BH-5084, BH-5090), down to a depth of ~60 m BSF. The average sediment velocity from the five boreholes with P-S logging is 1700m/s, which was selected as the velocity for the best technical case. The range of velocities varies across the five logged locations, from 1550m/s to 1835m/s, with the average at each specific location between 1672m/s and 1733m/s.
2. Derived V_p data for all CPTs, with a maximum depth of this data was 80 m BSF. As P-wave measurements are only available from P-S logging results, empirical correlations are sought between V_p and V_s (Stuyts et al., 2024; Section 8.3). Variability in the data is from 1537 to 1743m/s.
3. Seismic interval velocities (V_{INT}) outputted from the seismic reprocessing work, covering the entire depth of interest (down to 100 m BSF). This data captured the deeper values beyond the CPT TD at each location. Variability in this dataset is from 1717 to 1816m/s. It was desirable to use CPTs that penetrated as much of the 100 m zone of interest as possible, and given that the TCPTs penetrate 6 m BSF, these were removed from the calculation to avoid biasing the result.

The calculated velocities vary across the site, with each CPT location showing different values reflecting lateral changes consistent with variations in the geology (as observed in Figure 4.11). The interval velocities in the V_{INT} dataset are low resolution and do not correlate with the high-resolution seismic interpretation in places. The data do however show background velocity trends and are therefore a valuable source of information.

From these three datasets (P-S logging, CPTs and V_{INT} data), a minimum, best technical and maximum range of velocities was selected that cover the variation in mean velocity calculated (1550 – 1700 – 1850 m/s). Depth conversion on the horizons was run using this velocity data range. The impact of the depth conversion is provided in the depth horizons (Elevation Surface m LAT,). Table 4-3 provides an overview of the maximum and minimum depth velocities for each of the depth-converted surfaces in the ground model. These were calculated by running the low case and high case depth conversion (1550 and 1850m/s, respectively) and then subtracting the resulting surfaces from the best technical surfaces (1700m/s). The maximum possible upward or downward shift in the surfaces is then reported.

The CPT and borehole time-depth curves in the accompanying GGM S&P Kingdom project use the best technical velocity model (1480 m/s for water depth and 1700 m/s from seabed to TD of the geophysical logs). Prominent lithostratigraphic markers tied the ground model with the velocity model at the top and base of the C Unit and at the base of the D Unit. Such boundaries provided a key visual assessment of the accuracy of the CPTs/boreholes observed at unit boundaries.

Table 4-3: Depth uncertainty table of each subsurface grid utilising the maximum (1850 m/s) and minimum velocity (1550 m/s) derived from CPT and V_{INT} data.

Depth (m BSF)	Depth m +/- from 1700m/s
5	0.4
10	0.9
20	1.8
30	2.6
40	3.5
50	4.4
60	5.3
70	6.2
80	7.1
90	7.9
100	8.8

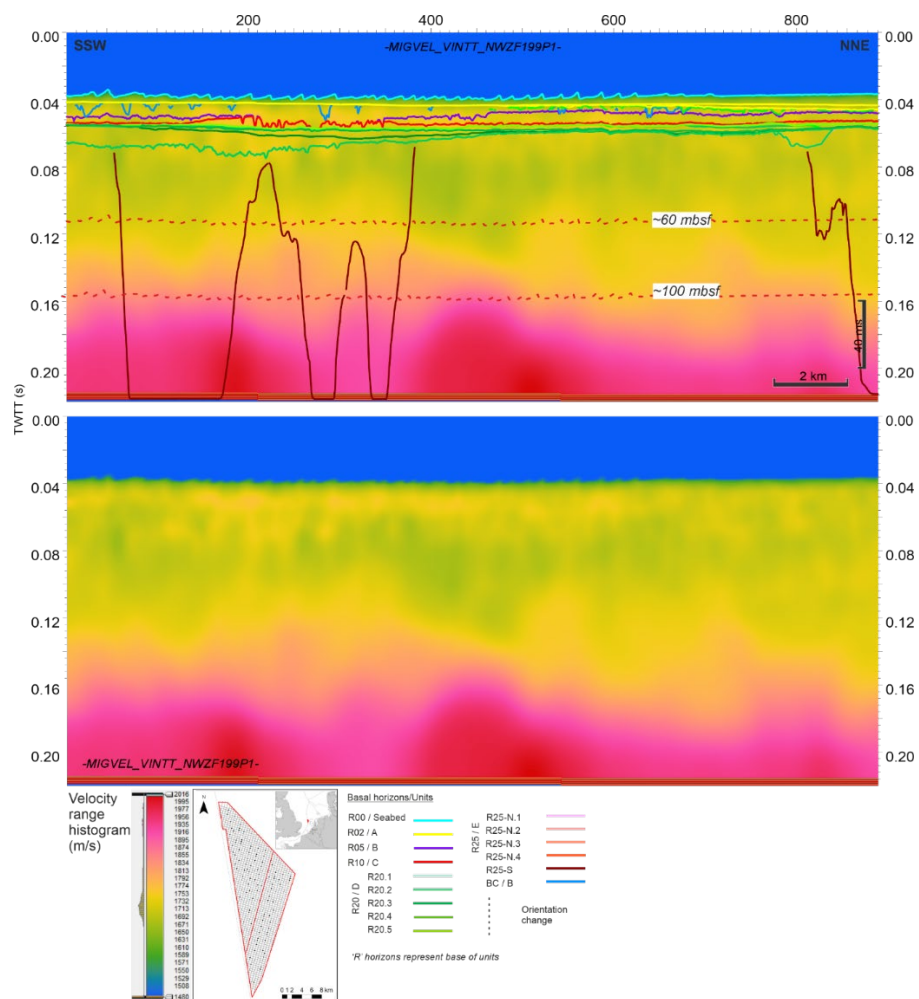


Figure 4.11 Example of V_{INT} seismic from reprocessing. Seismic line NWZF199P1, SP 1 to 881. The horizons in the upper figure indicate where the interpretation sits on the V_{INT} data.

5. Geotechnical Interpretative Report – Summary

5.1 Overview

The specific objectives of the Geotechnical Interpretative Report (Arup, 2025b) for NW I IA include:

1. Update geotechnical soil units and layering from the GGM based on geotechnical observations;
2. Determine representative soil parameters for each soil unit;
3. Calibrate CPT correlations for soil parameters based on in situ and laboratory testing;
4. Calibrate CPT linear models for q_t and f_s predictions.

This section presents a summary of the characteristic description for the geotechnical soil units across NW I IA, and their split in coarse grained and fine-grained fractions. Characteristic linear correlations for CPT data are introduced herein and are adopted for the 3D interpolated models in Section 9.

5.2 Geotechnical soil units

The seismostratigraphic framework from the GGM were used to guide definition of geotechnical soil units by considering the description of recovered material, in-situ testing and laboratory data within the defined geological understanding of the site. The geotechnical units were divided based on their primary fraction, with detailed characterisation completed for each of the two members. The subdivision between CG and FG was done based on available in-situ CPT using I_B based SBT (Robertson, 2016); descriptions of recovered material and PSD test results. $I_B=32$ was used to distinguish FG and CG.

Geotechnical Soil Units 1 to 7 are:

- U1: Very dense sand with minor organic matter and shell fragments.
- U2: Dense to very dense sand with occasional clays/silts and organic matter.
- U3: High-strength silty clay with organic matter.
- U4: Alternating sand and clay layers with gravel and shell fragments.
- U5: Varied lithologies with interbedded sands, silts, and clays, primarily in the northern tunnel valley.
- U6: Sand and clay with organic material and shell fragments, primarily in the southern tunnel valley.
- U7: Heterogeneous sand, silt, and clay, representing the Yarmouth Roads Formation.

In Figure 5.1, Robertson charts of geotechnical soil units are reported, noting that the primary interpretation and evaluation of geotechnical parameters is presented in the GIR (Arup, 2025b).

Geotechnical Soil Units U1 and U2 are coarse grained, Unit U3 is fine-grained, the remaining units presents both CG and FG fractions and characterisation for both fractions are reported in the GIR.

Each fraction, CG or FG, is generally well grouped and fits within one of the areas highlighted by Robertson (2016) (TD, TC, CC, CD etc.) in the last plot of Figure 5.1), with the exception of Geotechnical Soil Unit U5. This is expected due to the diverse range of depositional environments that led to the infilling of the tunnel valley (Section 4.4.5). In this case, bi-linear correlations are required both for characterisation of the material (unit weight, moisture content, etc.) and of its mechanical properties, examples can be found in Figure 5.2.

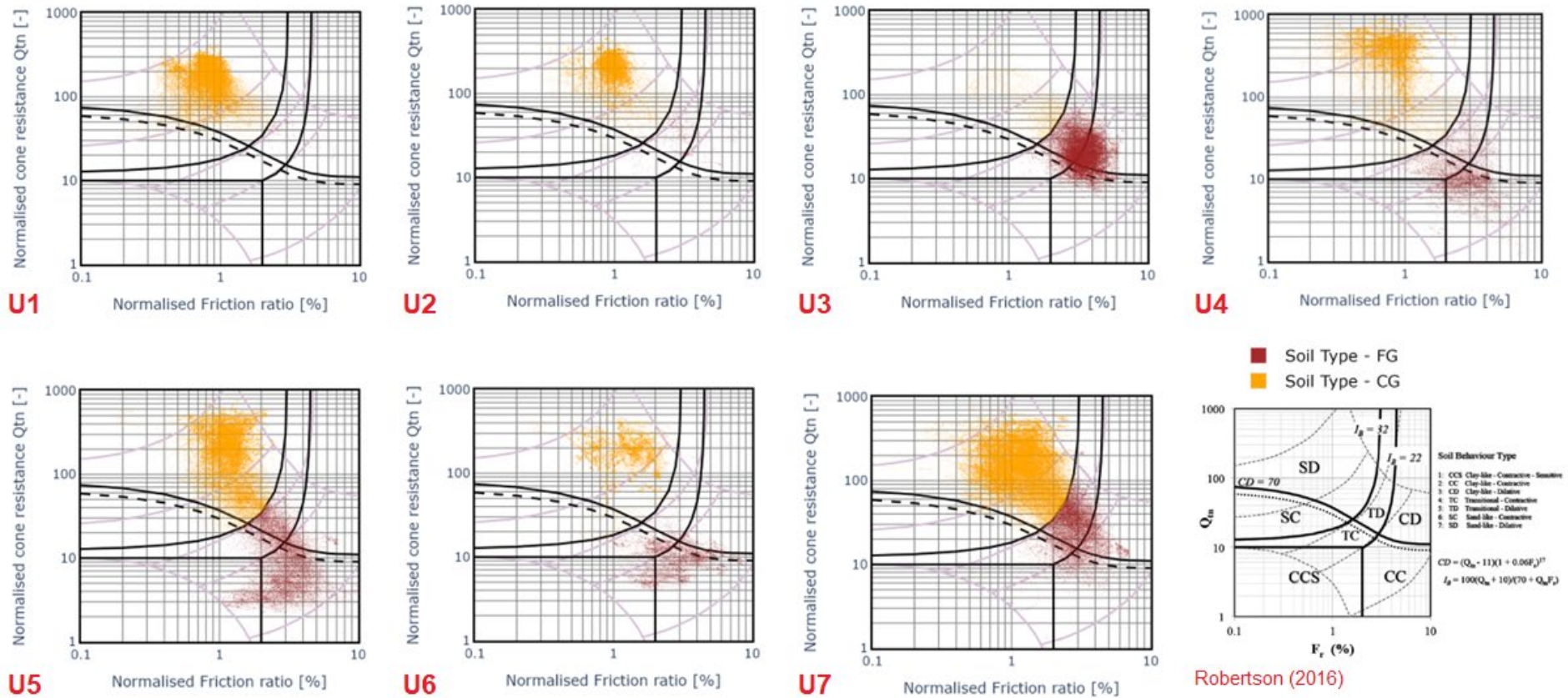
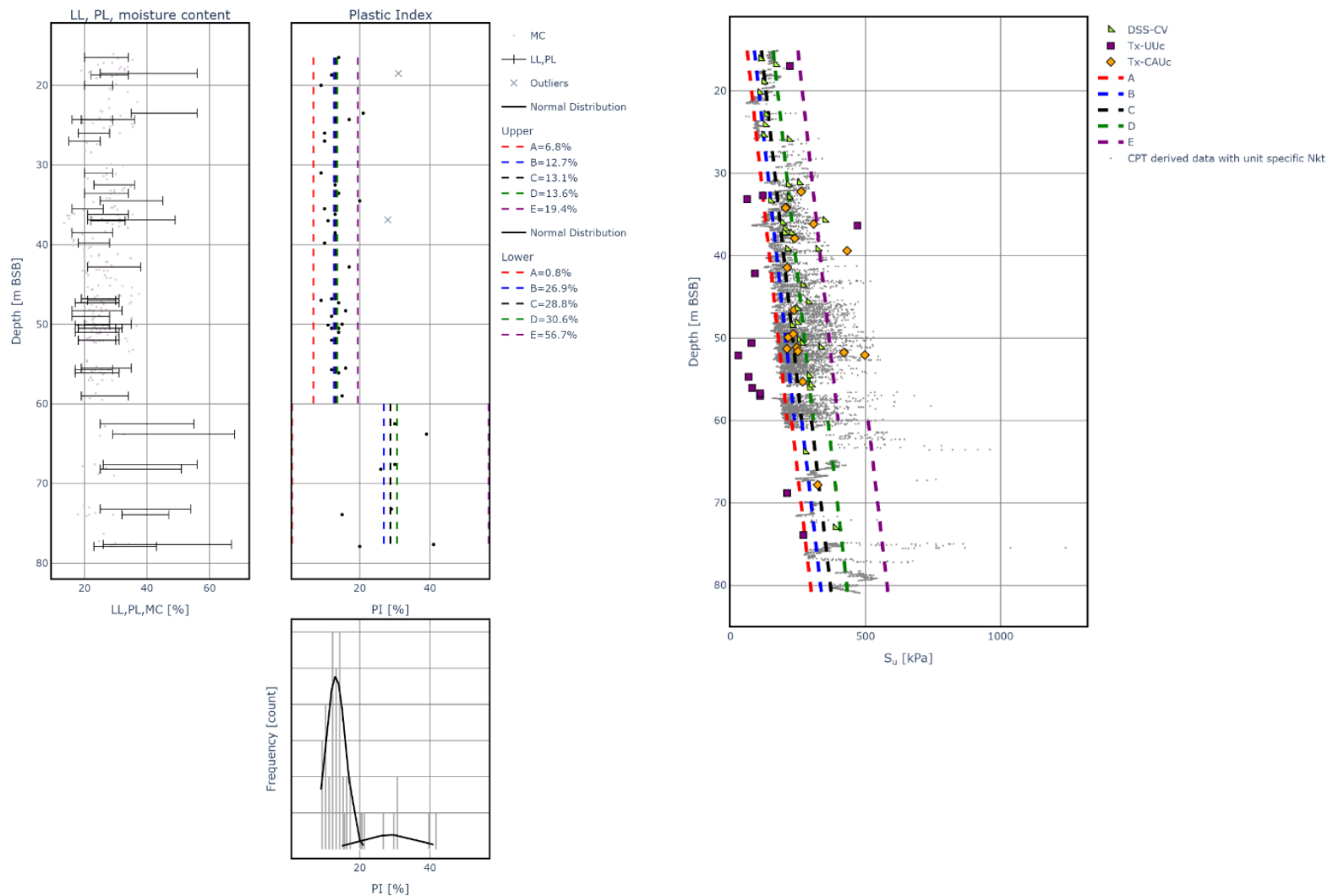


Figure 5.1: Units' Robertson plots, picturing the CG (yellow) and FG (brown) fractions in different colours



a)

b)

Figure 5.2: Example of bilinear correlations for U5 a) U5-FG Atterberg Limits, b) undrained shear strength. Images reformatted form GIR

The variability of geotechnical soil units with a mixed CG and FG fraction was quantified over the total investigated length of the unit, this was completed for insitu testing and recovered soil samples. Tested and sampled data agree well, and the percentages are reported in Table 5-1.

Site wide visual presentation of the geotechnical soil units as stick plots is presented Figure 5.3 to 5.10.

Table 5-1: Comparison of primary fraction of each geotechnical soil unit

Geotechnical Soil Unit	Samples Recovered		CPT behaviour from Robertson Charts		Inferred primary fraction
	CG	FG	CG	FG	
U1	100%	0%	99%	1%	CG
U2	88%	12%	93%	7%	CG
U3	4%	96%	4%	96%	FG
U4	64%	36%	59%	41%	CG/FG
U5	73%	27%	59%	41%	CG/FG
U6	56%	44%	52%	48%	CG/FG
U7	92%	8%	83%	17%	CG/FG

As an illustrative example, Figure 5.9 and Figure 5.10 present plots depicting the CG and FG distribution of U6 and U7 respectively from the GIR (Arup, 2025b). It can be noted that while U7 FG fraction is spread throughout the site. U6 FG material was encountered primarily in the central part of the site. In contrast, the southern end of the site is identified as primarily CG with limited FG bands.

These observations are coherent with the knowledge of the depositional environment of Seismostratigraphic Units E-5 and F (Section 4) which correspond to U6 and U7, although none of these features could be confidently extrapolated laterally.

To provide further context into the primary fraction variability, i.e. trends of CG and FG splits across the site, reported is a further characterisation of seismostratigraphic subunits via geotechnical descriptions. This was done considering both sample description and CPT data. The primary focus is to analyse subunits that otherwise had been amalgamated (D-1 to D-5 (U4) and E-1 to E-4 (U5), Table 4-2), although all the seismostratigraphic units are characterised in the table below. The CG/FG split per seismostratigraphic unit and subunit are reported in Table 5-2. It can be observed that Seismostratigraphic Units D-1 to D-5, have a defined primary fraction, whereas Seismostratigraphic Units E-1 to E-5 are not as clearly defined.

Spatially mapped sub-units can be extrapolated into predicted CG or FG allocations that have a marked predominant primary fraction throughout the site, even at locations that were not directly investigated.

This allows engineers to utilise correlations provided for CG or FG fractions of specific geotechnical soil units in a more focused way, through correlation with the spatial distribution of the seismostratigraphic framework (Section 6 & 7) together with data in Table 5-2. Despite this added use of the data, it is believed that adequate sensitivity checks for FG and CG material properties for the different design scenarios should be performed for each unit.

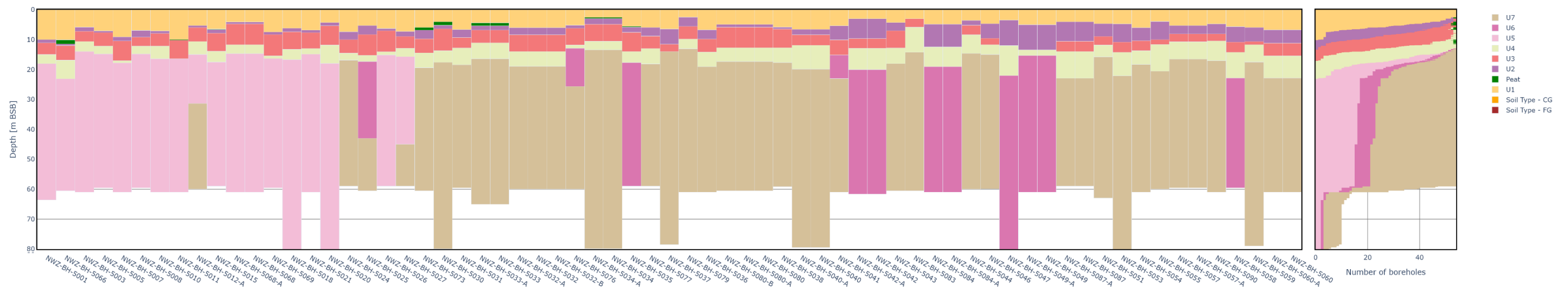


Figure 5.3: Cross section across site for geotechnical units (North to South) with corresponding soil behaviour types for each unit for (a) U1, (b) U2, (c) U3, (d) U4, (e) U5, (f) U6 and (g) U7.

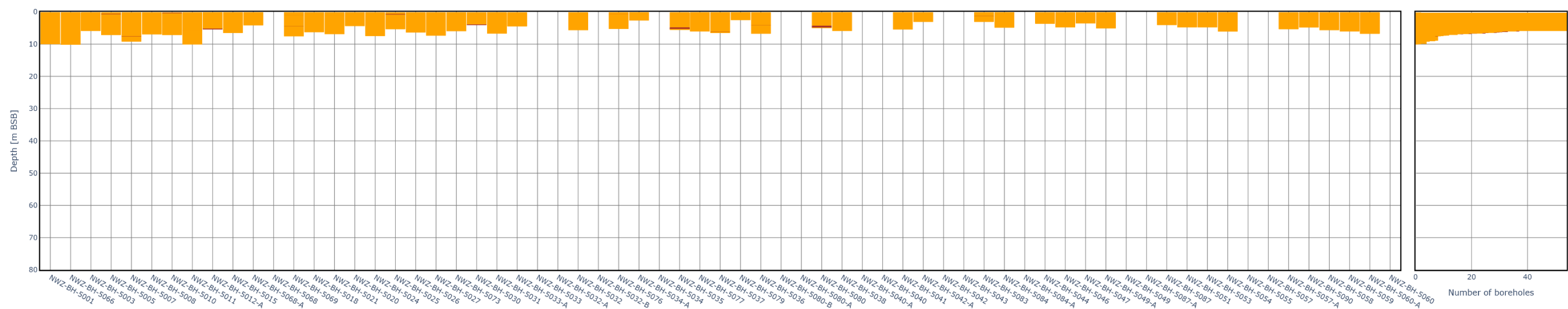


Figure 5.4 (a) U1 presence across the site with split CG (orange) and FG (red) material plotted north to south

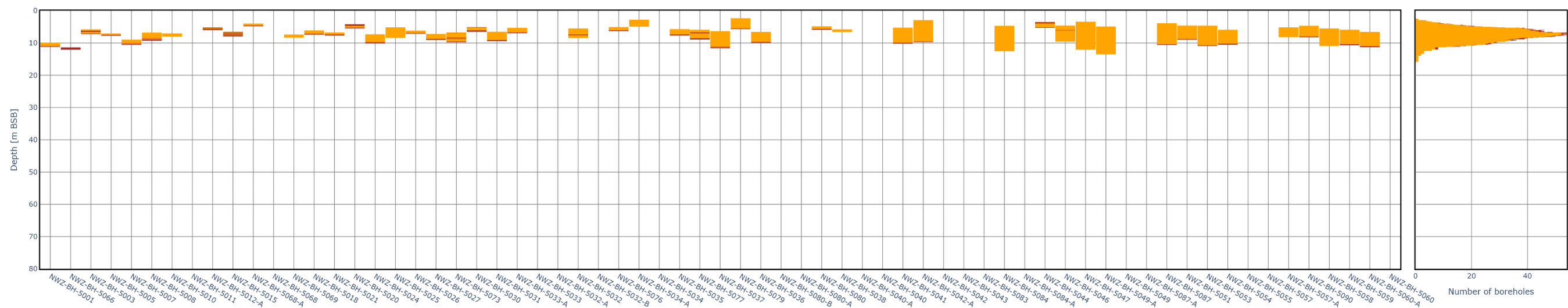


Figure 5.5: (b) U2 presence across the site with split CG (orange) and FG (red) material plotted north to south

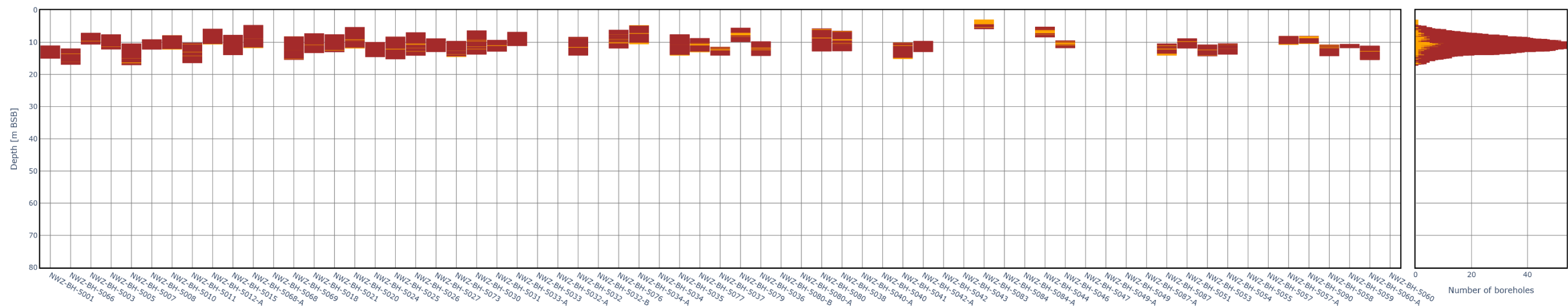


Figure 5.6 (c): U3 presence across the site with split of CG (orange) and FG (red) material plotted north to south

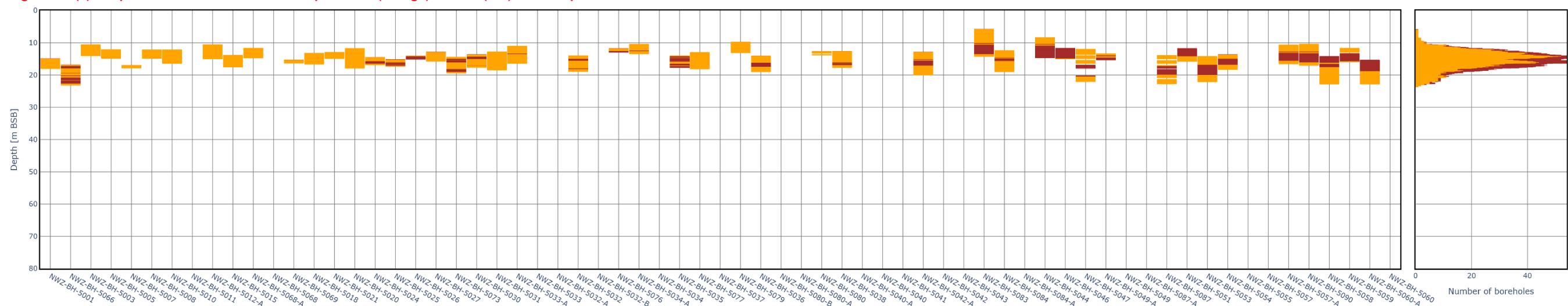


Figure 5.7 (d): U4 presence across the site with split of CG (orange) and FG (red) material plotted north to south

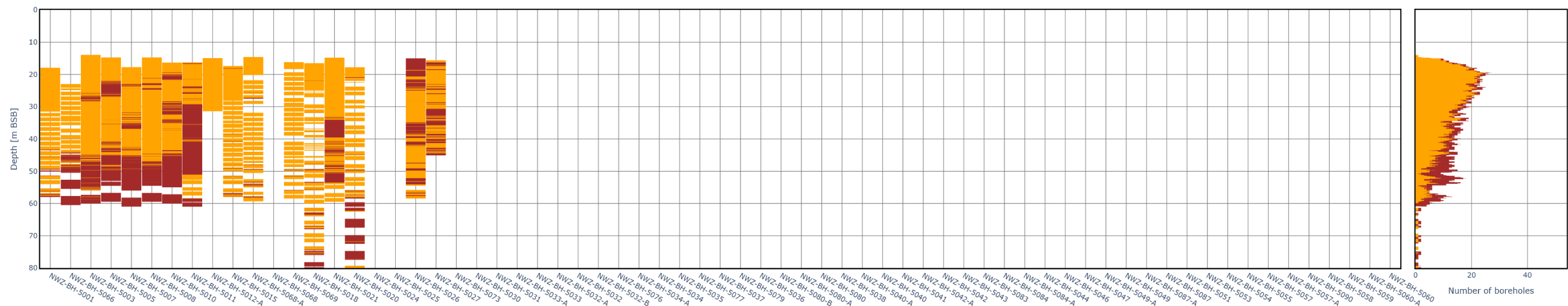


Figure 5.8 (e): U5 presence across the site with split of CG (orange) and FG (red) material plotted north to south

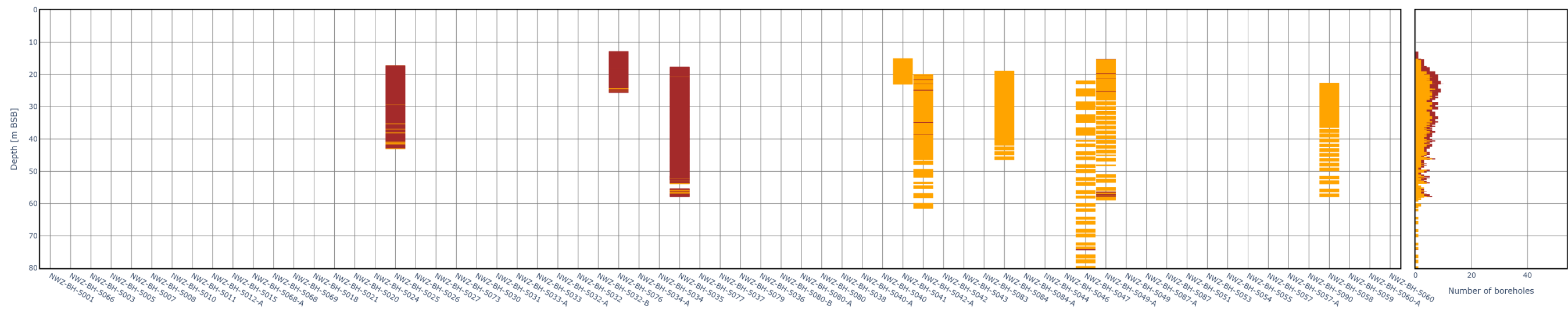


Figure 5.9 (f): U6 presence across the site with split of CG (orange) and FG (red) material plotted north to south

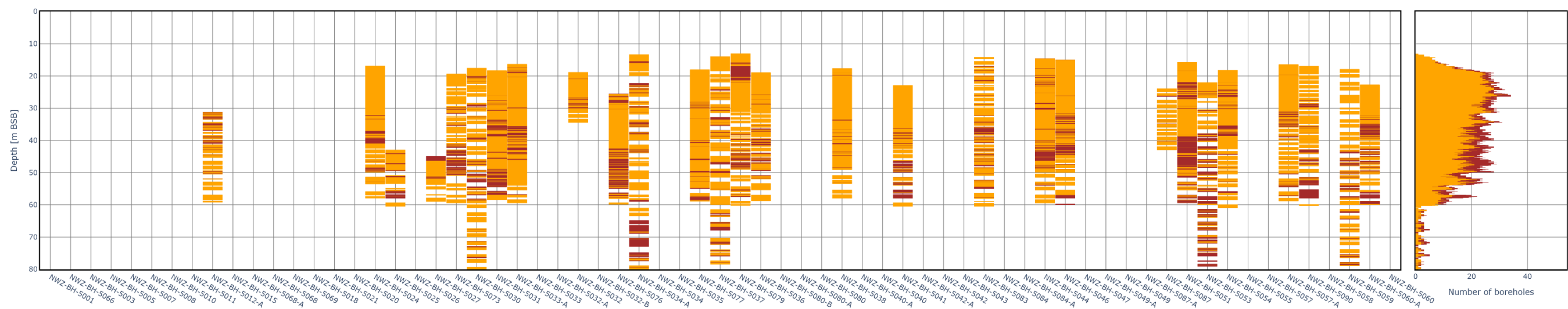


Figure 5.10 (g): U7 presence across the site with split of CG (orange) and FG (red) material plotted north to south

Table 5-2: Comparison of primary fraction of each seismostratigraphic unit

Seismostratigraphic Unit/Sub-Unit	Geotechnical Soil Unit	Samples Recovered CG FG split [%]		CPT behaviour from Robertson Charts split [%]		Inferred Primary Fraction
		CG	FG	CG	FG	
A	U1	100%	0%	99%	1%	CG
B	U2	88%	12%	93%	7%	CG
C	U3	4%	96%	4%	96%	FG
D-1	U4 CG/FG	88%	12%	95%	5%	CG
D-2		4%	96%	11%	89%	FG
D-3		92%	8%	81%	19%	CG
D-4		13%	87%	13%	87%	FG
D-5		96%	4%	90%	10%	CG
E-1	U5 CG/FG	64%	36%	57%	43%	CG/FG
E-2		90%	10%	78%	22%	CG
E-3		68%	32%	55%	45%	CG/FG
E-4		64%	36%	65%	35%	CG/FG
E-5	U6 CG/FG	56%	44%	52%	48%	CG/FG
F	U7 CG/FG	92%	8%	83%	17%	CG/FG

5.3 Characteristic geotechnical parameters

The main purpose of a quantitative ground model is to reliably predict information across the entire development area that can be used for additional survey planning for the concept design of foundation options. Therefore, the prediction of geotechnical parameters relevant for engineering purposes can be approximated by using CPT linear correlations, or through prediction of CPT parameters with seismic data (Section 8).

The linear correlations derived are considered simplistic, but also robust and intuitive as they are based on ground truthed data points. The linear model is a simplified approach and does not provide information about the parameter's spatial variation away from sampled locations. However, it provides a good understanding of the site wide CPT response per unit.

The CPT data used to calibrate the model is partial, due to the presence of data from tests that refused due to maximum thrust of the CPT being reached. The linear correlations best estimate values might be biased toward the lower bound of the q_t and f_s values, as the upper bound of the data may not be fully represented by the data that has been acquired. This bias is expected to be more prevalent for deeper geotechnical soil units, specifically U5 to U7.

For this reason, engineering judgement is required to select the correct line to be applied for different design scenarios when using results of the linear correlation, and it is recommended to use the best estimate, the lower bound and the upper bound correlations provided in the GIR (Arup, 2025b). The appropriate correlation to be used would depend on the specific use case being assessed.

5.3.1 CPT linear correlations

The linear model consists of a linear best fit to all data for a given geotechnical soil unit both for q_t and f_s data. For each geotechnical soil unit, the model has a constant slope and intercept and thereby allows for a CPT prediction based on unit and depth below seabed m BSF.

Results of best fit correlations are provided in Section 5.3.2.

The split between CG and FG is applied to the data prior to linear regression to minimize the influence of the interbedded sand and clays, and correlations are provided distinctly for both the primary fractions for U4 to U7, CG correlations are provided for U1, and U2 and FG correlations are provided for U3.

The selection factors of the linear correlation were completed on CPT data acquired offshore applying similar methodology as reported for soil properties characterisation in the GIR (Arup, 2025b). , and hence reader should refer to Appendix A of the GIR for detailed explanation of the statistical treatment of the data.

In summary five correlations were derived as reported in Table 5-3, low estimate is based on the 5% quantile and, a high estimate is based on the 95% quantile, in accordance with DNV-RP-C207. To acknowledge the uncertainty in the estimates of 5%, 95% quantile and mean values, these are estimated with a confidence level of 95%, as it is recommended by EN1997-1:2024. As reported in Table 5-3, Low Estimates (A lines) are presented with an upper confidence interval (meaning lower values are presented), whereas High Estimates (E lines) are presented with a lower confidence interval (meaning higher values are presented). For Best Estimate values (C lines) both the Cautious Low Best Estimate, i.e. best estimate evaluated with high confidence (B line) and the Cautious High Best Estimate, i.e. best estimate evaluated with low confidence (C line) are reported.

Some additional observation can be made on the definitions in Table 5-3 for the linear CPT model:

1. B and D lines lose relevance when derived with strict “confidence level” methodology using a statistical t-test, when the number of statistical degrees of freedom becomes high, i.e. when using CPT derived data to derive trends. For this reason, the definition of the B and D lines is given herein, is the Best Estimate value plus or minus 0.5 times the standard deviation.
2. In this case for the CPT data is considered not to be well represented by a normal distribution and lognormal distribution is used instead. Definitions in Table 5-3, are used even for the lognormal distribution. For this type of distribution, the Best Estimate is evaluated as the mode of the data, i.e. the most frequent value, rather than the mean value.

3. For Lines A, B, D and E for lognormal distribution, the same definitions given in DNV-RP-C207 section 2.5 (“soil parameters with confidence intervals”) are applied to the transformed normal distribution and carried over to the lognormal space with a monotonic transformation (using an exponential function), as quantiles are preserved under monotonic transformations.

Based on these recommendations, five characteristic design conditions as detailed in Table 5-3, based on the guidance provided in DNV-RP-C207.

Engineering judgement is used to adjust best estimates or associated uncertainties. This is done to develop models that are consistent with physical reality.

Table 5-3: Representative values definition, reported from GIR

Line Name	Representative value	Interpretation
A	Low Estimate	5% quantile in the distribution of the soil property with an upper confidence interval of 95%.
B	Cautious Low Best Estimate	Best Estimate minus 0.5 times the standard deviation.
C	Best Estimate	This is the mean if a data set is normally distributed and the mode (highest frequency value) for datasets of other distributions
D	Cautious High Best Estimate	Best Estimate plus 0.5 times the standard deviation.
E	High Estimate	95% quantile in the distribution of the soil property with a lower confidence interval of 95%.

5.3.2 Global CPT linear correlations formulation

As discussed above and in the GIR, the design choice to use either of the A, B, C, D or E lines is determined by the associated soil mobilisation, by the geometry of the structure under consideration and by type of assessment being performed. Any parameter selection should be done by competent engineers after an evaluation of the adequate level of risk associated with the specific design/assessment stage.

The use of the linear correlations needs to consider at least lines A, C and E. For brevity in Table 5-4, line C (best estimate) are reported.

The remaining correlations are reported in the GIR (Arup, 2025b).

Figure 5.14 to Figure 5.22 plot the correlations against source CPT data. Appendix C presents results per geotechnical location with Lines A, C and E annotated.

Line C from the linear correlations, both for CG and FG, is then implemented in the Voxel model described in Section 9.5.

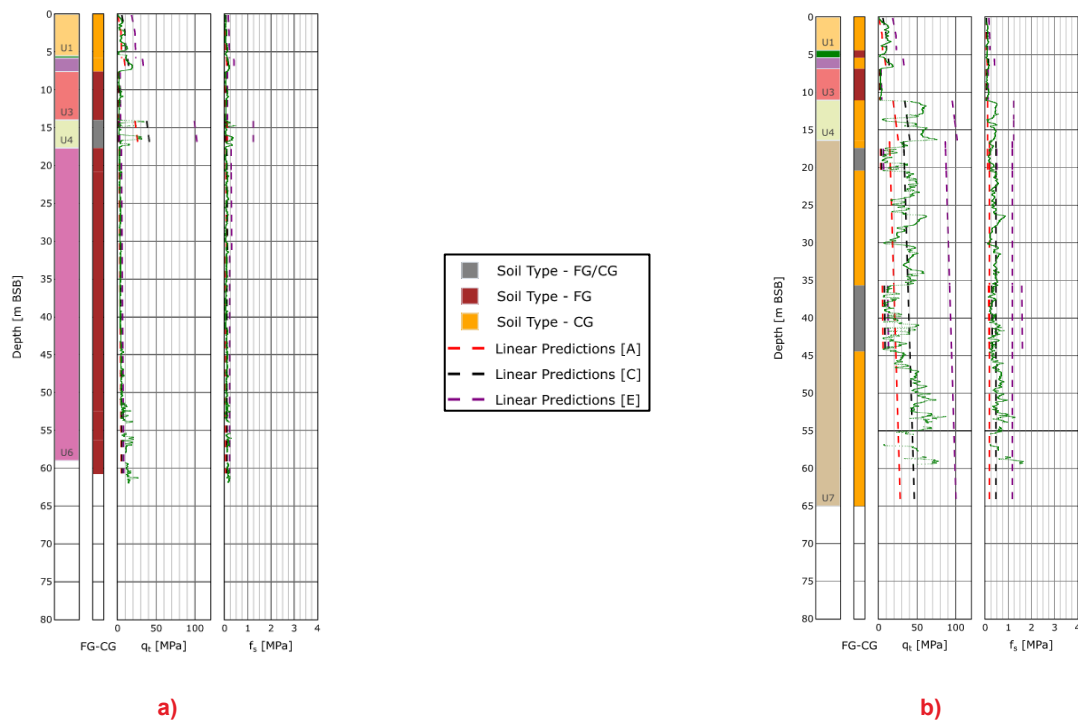
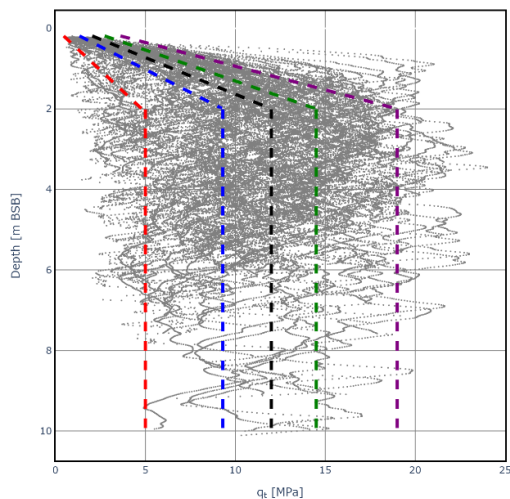


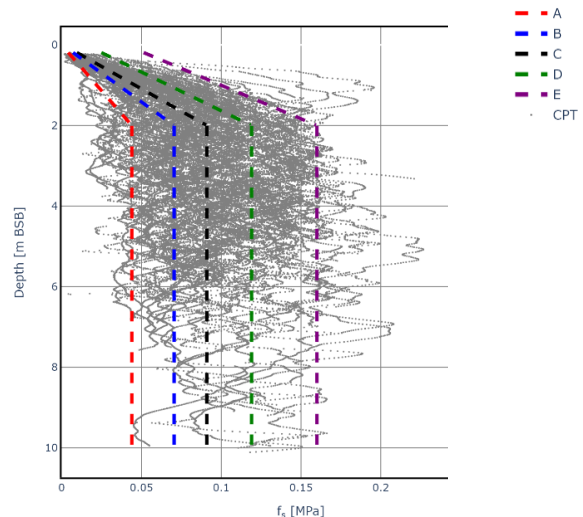
Figure 5.11: Example of linear correlation application for primarily FG and CG locations: a) FG location NWZ-PCPT-1035 b) CG location NWZ-PCPT-1033

Table 5-4: CPT linear model, different units and primary fractions C lines equations

Unit	Linear predictions q_t [MPa]	Linear predictions f_s [MPa]
U1	$q_{t-C} = 1.0 + 5.50 * depth$, valid for depth < 2.0 m BSF $q_{t-C} = 12.0 + 0.00 * depth$, valid for depth > 2.0 m BSF	$f_{s-C} = 0.0010 + 0.045 * depth$, valid for depth < 2.0 m BSF $f_{s-C} = 0.0910 + 0.0 * depth$, valid for depth > 2.0 m BSF
U2	$q_{t-C} = 12.0 + 0.60 * depth$	$f_{s-C} = 0.0744 + 0.0117 * depth$
U3	$q_{t-C} = 1.00 + 0.10 * depth$ valid for depth < 10.0 m BSF $q_{t-C} = 2.01 + 0.00 * depth$, valid for depth > 10.0 m BSF	$f_{s-C} = 0.0600$ valid for depth < 10.0 m BSF $f_{s-C} = 0.0640 + 0.0 * depth$, valid for depth > 10.0 m BSF
U4-CG	$q_{t-C} = 40.0 + 0.0 * depth$	$f_{s-C} = 0.3570 + 0.0 * depth$
U4-FG	$q_{t-C} = 1.65 + 0.0 * depth$	$f_{s-C} = 0.0500 + 0.0 * depth$
U5-CG	$q_{t-C} = 30.0 + 0.30 * depth$	$f_{s-C} = 0.4921 + 0.0 * depth$
U5-FG	$q_{t-C} = 1.24 + 0.065 * depth$, valid for depth < 60.0 m BSF $q_{t-C} = 1.79 + 0.07 * depth$, valid for depth > 60.0 m BSF	$f_{s-C} = 0.1200 + 0.0 * depth$, valid for depth < 60.0 m BSF $f_{s-C} = -0.1440 + 0.0044 * depth$, valid for depth > 60.0 m BSF
U6-CG	$q_{t-C} = 28.57 + 0.50 * depth$	$f_{s-C} = 0.5517 + 0.0004 * depth$
U6-FG	$q_{t-C} = 1.57 + 0.07 * depth$	$f_{s-C} = 0.0599 + 0.0022 * depth$, valid for depth < 32.0 m BSF $f_{s-C} = 0.1000$, valid for depth > 32.0 m BSF
U7-CG	$q_{t-C} = 33.0 + 0.15 * depth$	$f_{s-C} = 0.4656 + 0.0 * depth$
U7-FG	$q_{t-C} = 1.36 + 0.12 * depth$, valid for depth < 30.0 m BSF $q_{t-C} = 3.12 + 0.12 * depth$, valid for depth > 30.0 m BSF	$f_{s-C} = 0.1200 + 0.0036 * depth$, valid for depth < 30.0 m BSF $f_{s-C} = 0.1531 + 0.0036 * depth$, valid for depth > 30.0 m BSF

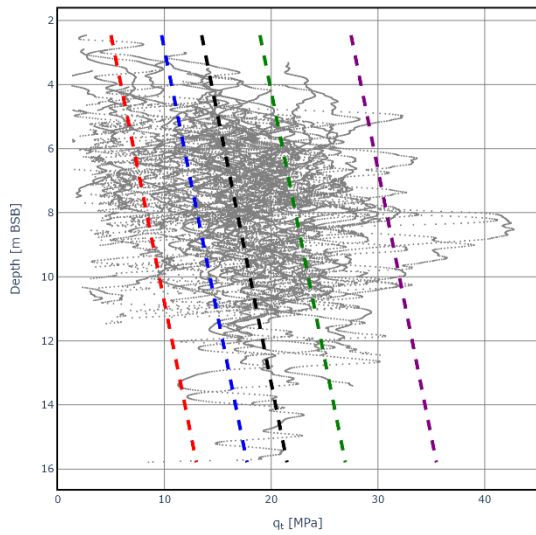


a)

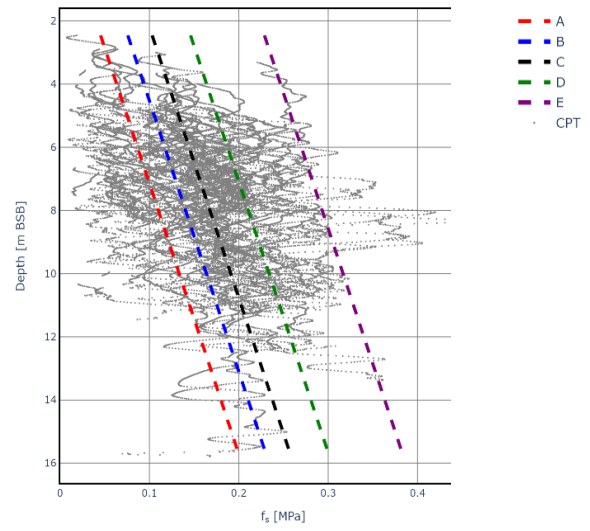


b)

Figure 5.12: U1 linear correlations a) q_t ; b) f_s

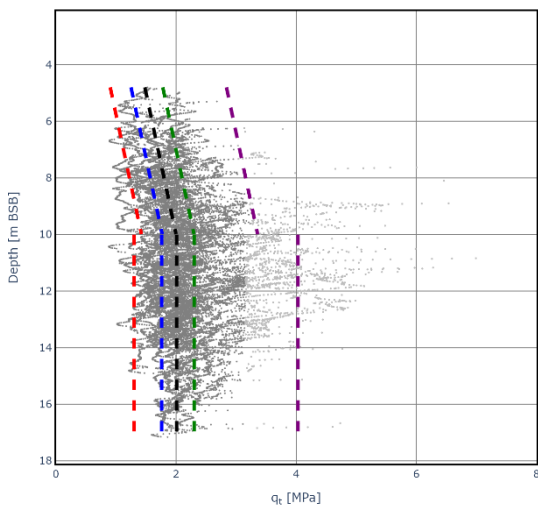


a)

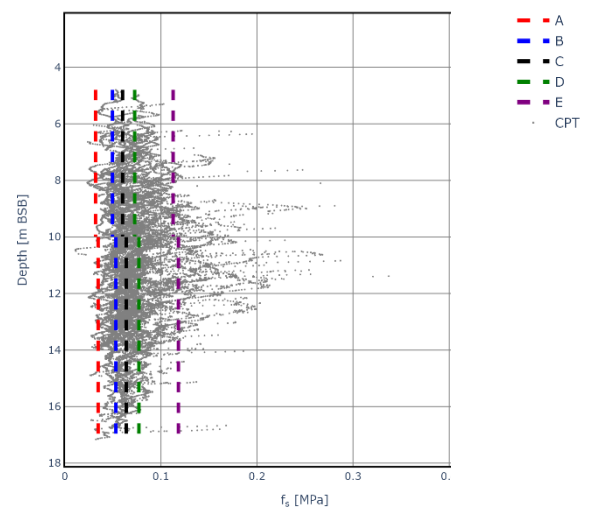


b)

Figure 5.13: U2 linear correlations a) qt; b) fs

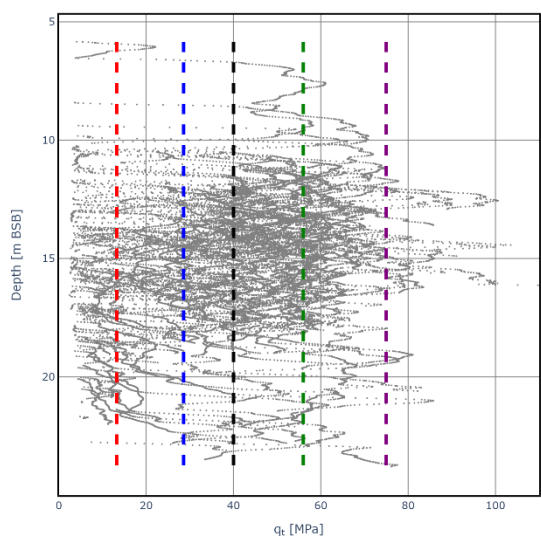


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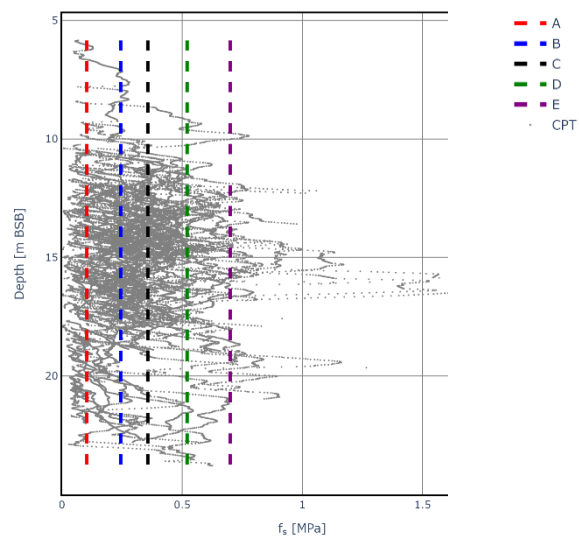


b)

Figure 5.14: U3 linear correlations a) qt; b) fs

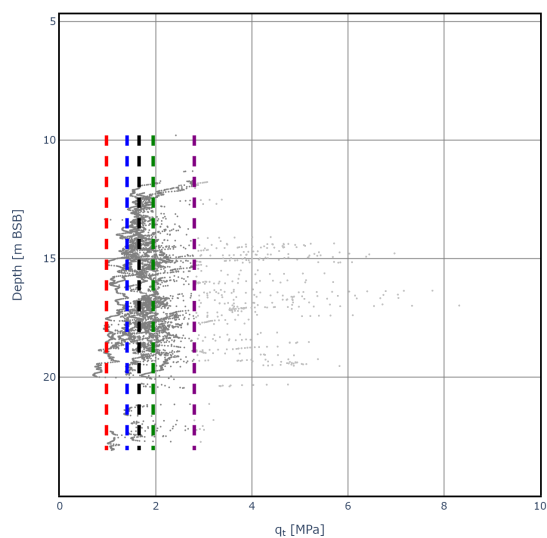


a)

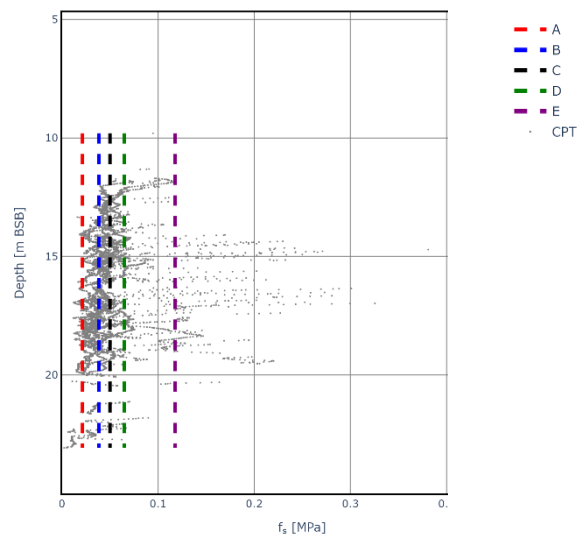


b)

Figure 5.15: U4-CG linear correlations a) qt; b) fs

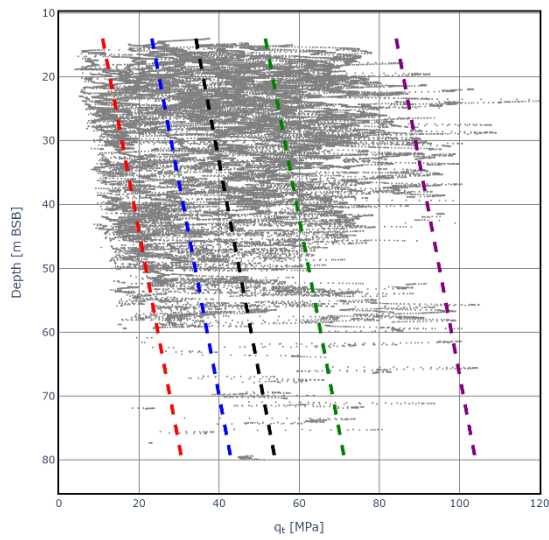


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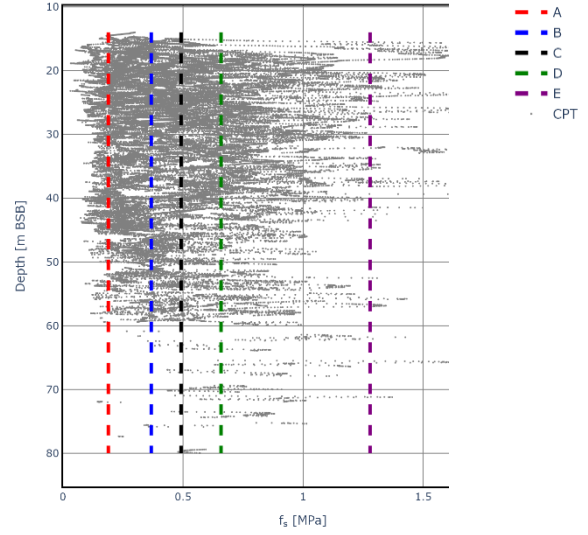


b)

Figure 5.16: U4-FG linear correlations a) qt; b) fs

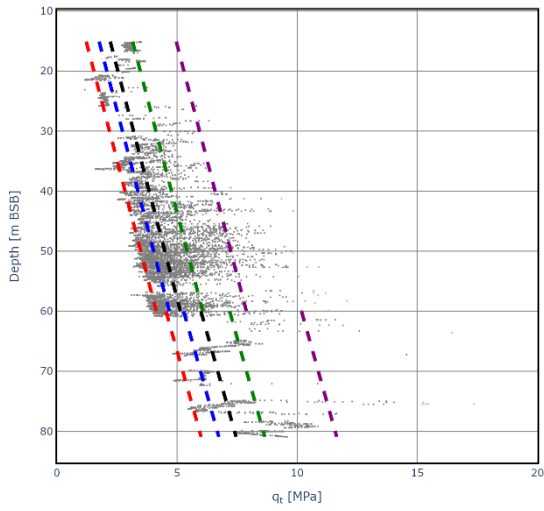


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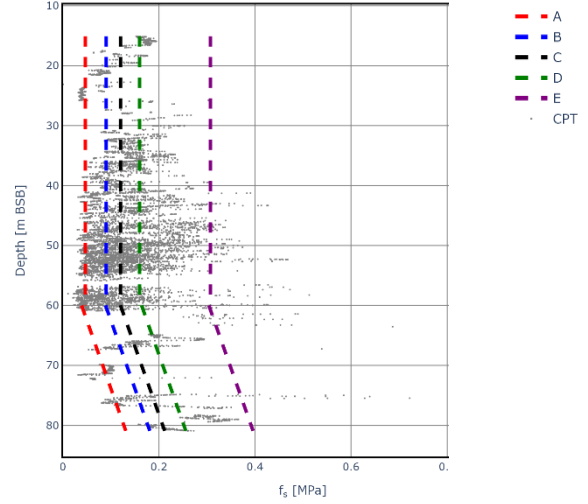


b)

Figure 5.17: U5-CG linear correlations a) qt; b) fs

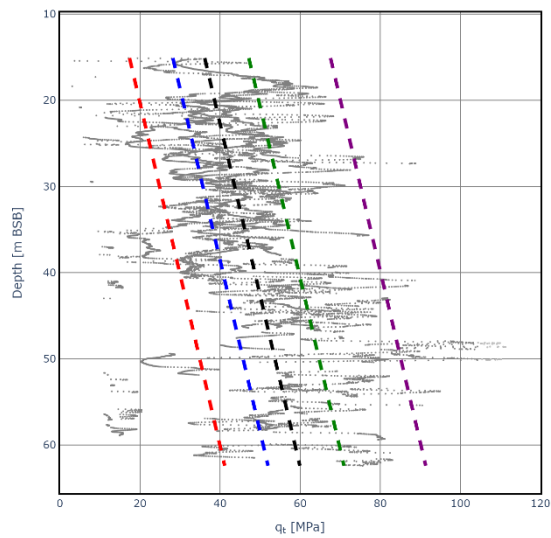


a)

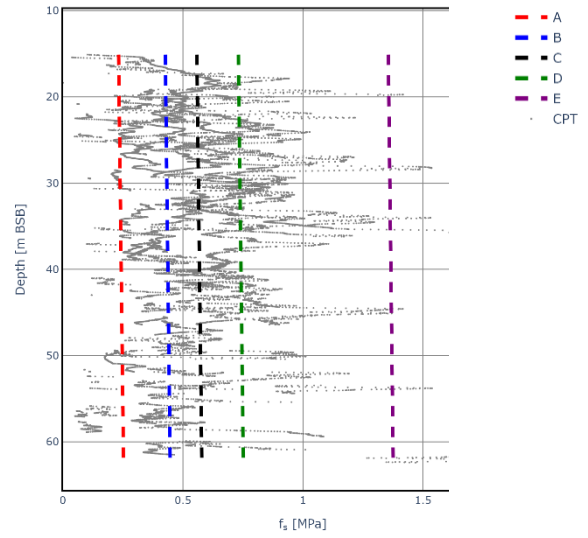


b)

Figure 5.18: U5-FG linear correlations a) qt; b) fs

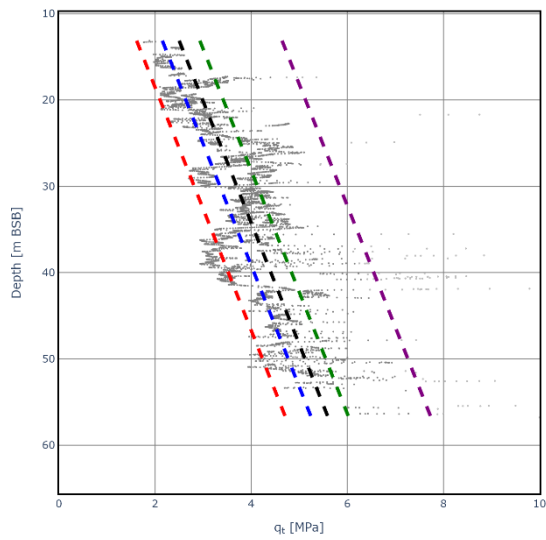


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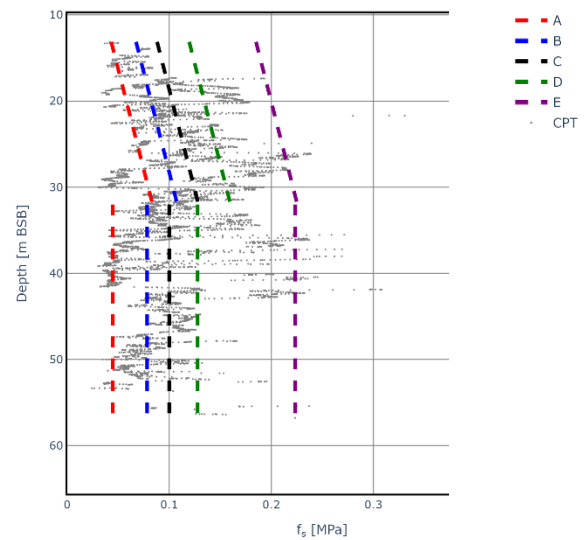


b)

Figure 5.19: U6-CG linear correlations a) q_t ; b) f_s

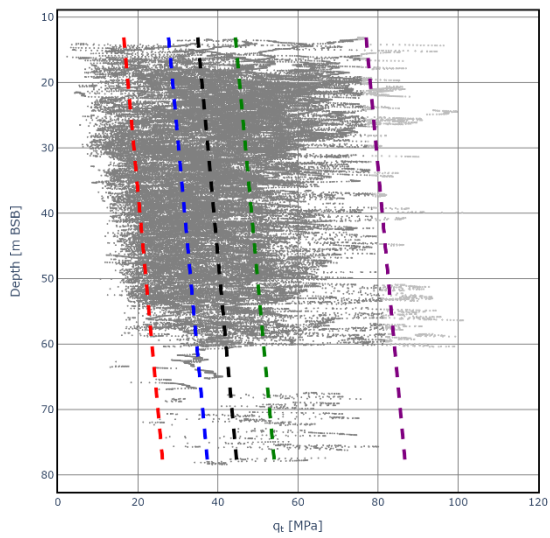


a)

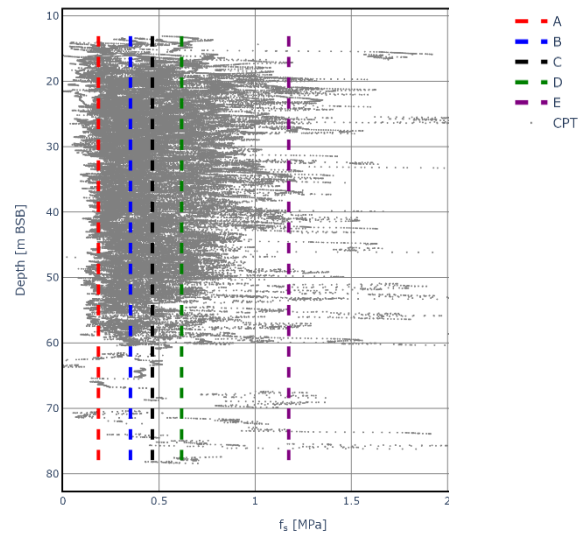


b)

Figure 5.20: U6-FG linear correlations a) q_t ; b) f_s

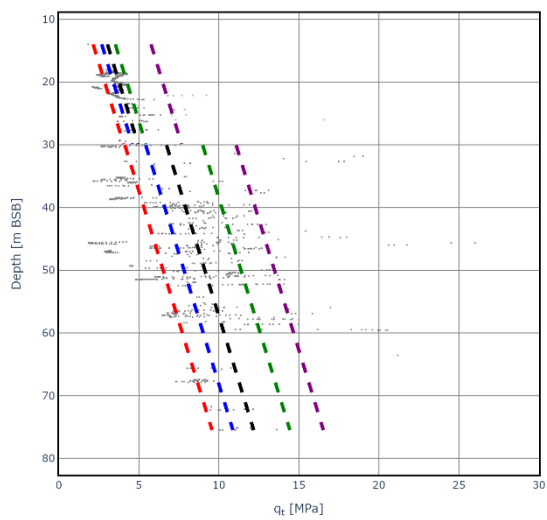


a)

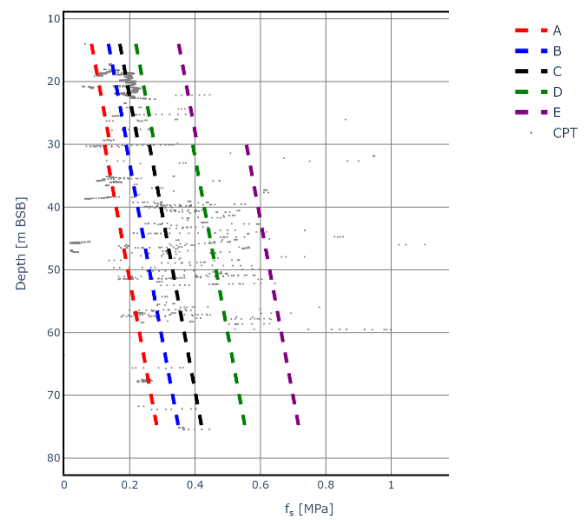


b)

Figure 5.21: U7-CG linear correlations a) q_t ; b) f_s



a)



b)

Figure 5.22: U7-FG linear correlations a) q_t ; b) f_s

6. Soil provinces and profiles

6.1 Overview

This section presents soil province mapping and representative soil profiles across the NW I IA. Understanding soil provinces can assist the user with identifying areas of similar soil characteristics for future engineering development.

6.2 Soil provinces and profiles

The soil provinces and profiles were determined by the spatial distribution and extent of seismostratigraphic units, that are considered significant based on their geotechnical properties and chronostratigraphic history (Section 4 and 5). The soil province cut-offs were selected to offer representative soil profiles with a relevance to engineering, when integrated with the companion GIR (Arup, 2025b).

Six distinct soil provinces were defined within the NW I IA. Figure 6.1 illustrates a conceptual cross-section overlain with the geometries and rationale for each soil province. The numbers at the top of the diagram correspond to the adopted soil province numbering.

Definition of soil provinces was primarily controlled by three key site-specific features:

1. Depth of interest (100 m BSF),
2. Tunnel valley distribution, and
3. Naaldwijk channel erosion.

Where Soil Unit F (Yarmouth Roads Formation) extended below 100 m BSF and was overlain by Soil Unit E (Tunnel Valleys), a soil province was defined. Soil Units E-1 to E-4 (northern Tunnel Valley) were treated separately to Soil Unit E-5 (southern Tunnel Valley) based on soil characteristics and age relationships.

Soil Unit B (Naaldwijk Formation) is present over most of the IA, however in places it directly overlies Soil Unit D (Eem Formation), with Soil Unit C (Brown Bank Formation Member) missing due to erosion and is defined as a separate soil province.

Figure 6.2 presents the soil provinces in the NW I IA. Sections 6.2.1 to 6.2.6 provide additional details for each individual province.

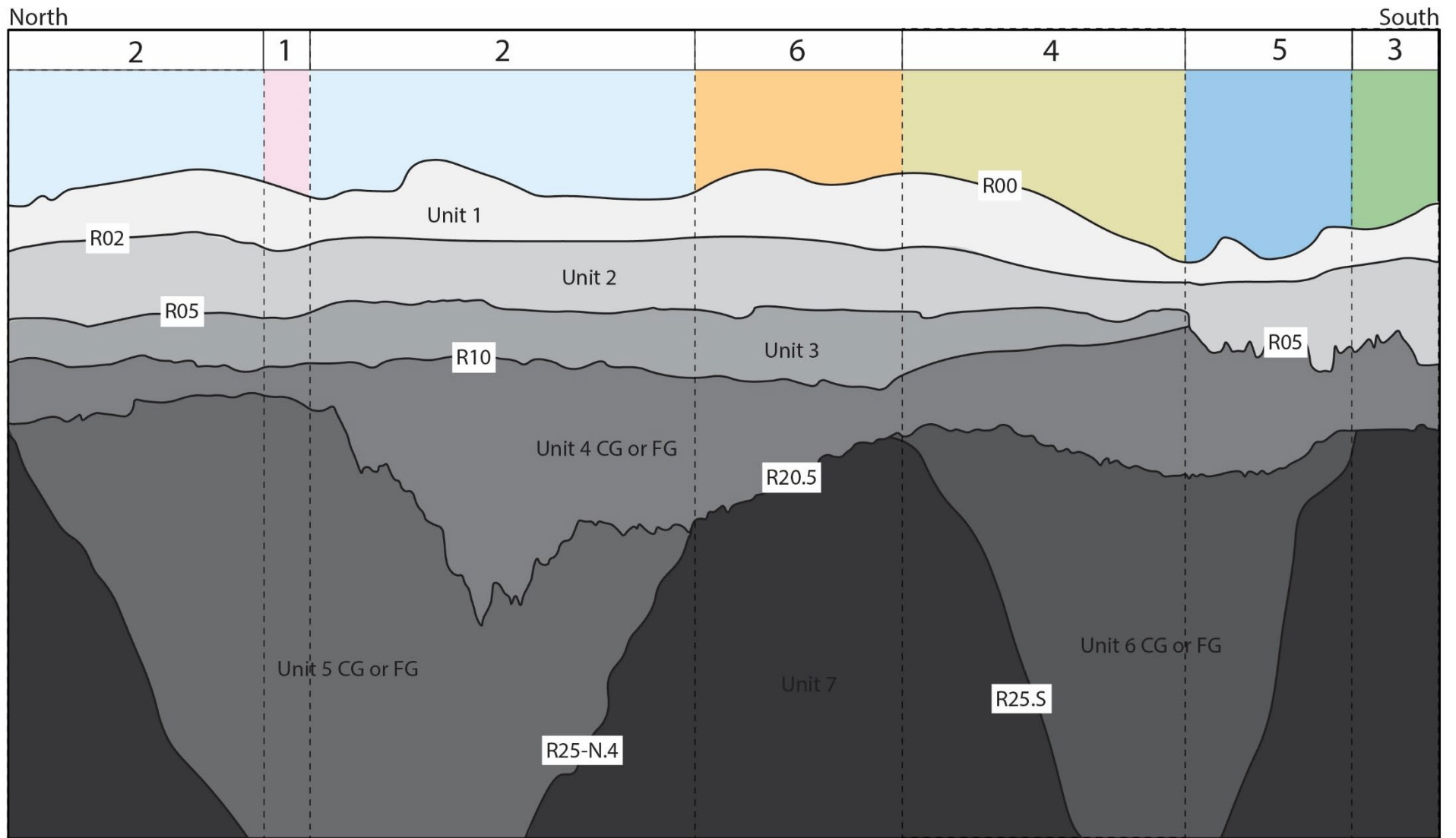


Figure 6.1: Displays of the spatial extent of each soil province and provides summary profiles for each indicative soil profile. These soil profiles are derived by calculating the minimum, average, and maximum depth below the seafloor at which each soil unit boundary is observed within each province, offering an indicative estimate of expected soil conditions.

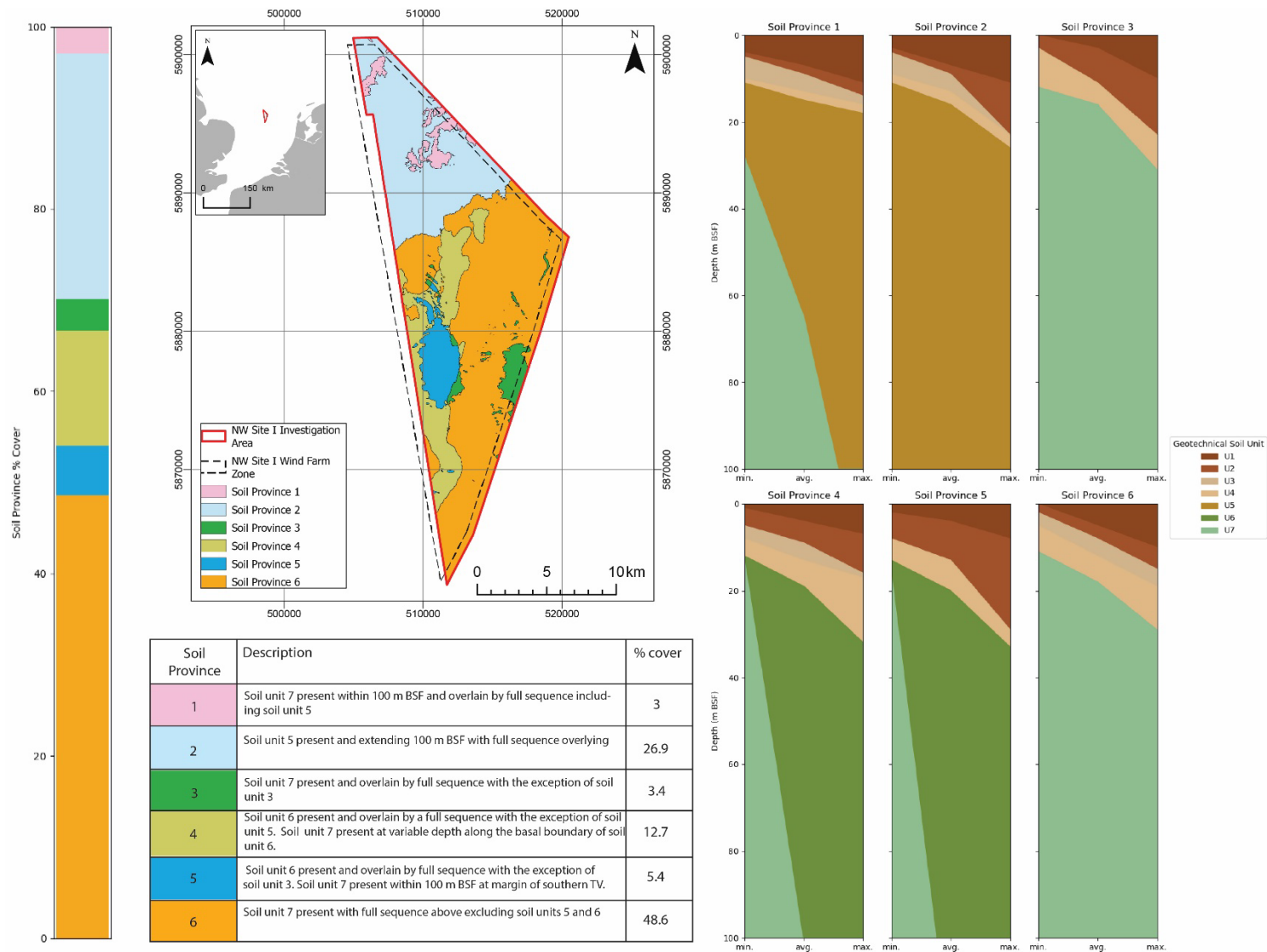


Figure 6.2: Displays of the spatial extent of each soil province and provides summary profiles for each indicative soil profile. These soil profiles are derived by calculating the minimum, average, and maximum depth below the seafloor at which each soil unit boundary is observed within each province, offering an indicative estimate of expected soil conditions.

6.2.1 Soil Province 1

Soil Province 1 occurs where Soil Unit 7 (Yarmouth Roads Fm) is present within 100 m BSF and directly overlain by Soil Unit 5. The top of Soil Unit 7 has an average depth of ~65 m BSF. The overlying sediments (U1 to 4) in this province are typically thinner than seen elsewhere. Soil Unit 7 also occurs within 100 m BSF along the southern boundary along Soil Unit 5's basal boundary.

Soil Province 1 occurs only in the north of the investigation area and occupies 3% of the site.

6.2.2 Soil Province 2

Soil Province 2 occurs where Soil Unit 5 (Urk/Egmond Fm's) extends 100 m BSF and soil unit 7 does not occur within 100 m BSF. The overlying sediments in this province are typically thinner than seen elsewhere. It should be noted that on the margins of Soil Unit 5 (Tunnel valley margins), Soil Unit 7 does occur within 100 m BSF but due to uncertainty associated with interpreting these features have not been considered when defining Soil Province 2.

Soil Province 2 occurs only in the north of the investigation area and occupies 26.9% of the site.

6.2.3 Soil Province 3

Soil Province 3 occurs where Soil Unit 3 (Naaldwijk Fm.) is absent. Here Soil Units 1, 2 and 4 (Southern Bight, Brown Bank, Eem Fm's) are present and are underlain by Soil Unit 7.

Soil Province 3 is located only in the mid-eastern areas of the investigation area and occupies only 3.4% of the investigation area.

6.2.4 Soil Province 4

Soil Province 4 occurs where Soil Unit 6 (Urk/Egmond Fm's) extends 100 m BSF and is overlain by the full sequence excluding Soil Unit 5. Soil Unit 7 does occur above 100 m BSF in Soil Province 4, but is associated with the steep margins Seismostratigraphic Unit E-5. The interpretation of these margins is uncertain and therefore not included within the sequence defining Soil Province 4.

Soil Province 4 is located in the western areas of the investigation area as a linear geometry and occupies 12.7% of the investigation area.

6.2.5 Soil Province 5

Soil Province 5 is present where Soil Unit 3 is absent. Here Soil Units 1, 2 and 4 are present and are underlain by Soil Unit 6.

Soil Province 5 is located only in the middle-western areas of the investigation area and occupies 5.4% of the investigation area.

6.2.6 Soil Province 6

Soil Province 6 occurs where Soil Unit 7 is present and overlain by the full sequence (Soil Unit 1, 2, 3 and 4) excluding Soil Unit 5 and 6.

Soil Province 6 is the largest soil province and occupies 48.6% of the investigation area and is distributed southern and middle portions of the site.

6.3 Spatial distribution of Seismostratigraphic Units D1 to 5 and E1 to 5

Soil provinces were generated using geotechnical soil units as defined in Table 4-1. As presented in Section 5, decisions were taken to amalgamate seismostratigraphic sub-units for the purpose of improving sample quantity and geotechnical test data significance, therefore seismostratigraphic subunits D1 to D5 and E1 to E4 were combined into U4 and U5, respectively.

In order to capture the fine grained and coarse grained components of the individual seismostratigraphic subunits in relation to the defined soil provinces, additional maps of seismostratigraphic sub-unit extent are presented for each in Figure 6.3 and Figure 6.4.

The 3D structural model (Section 7) enables visualisation of both the spatial extent and variability of the seismostratigraphic subunit thicknesses across the IA.

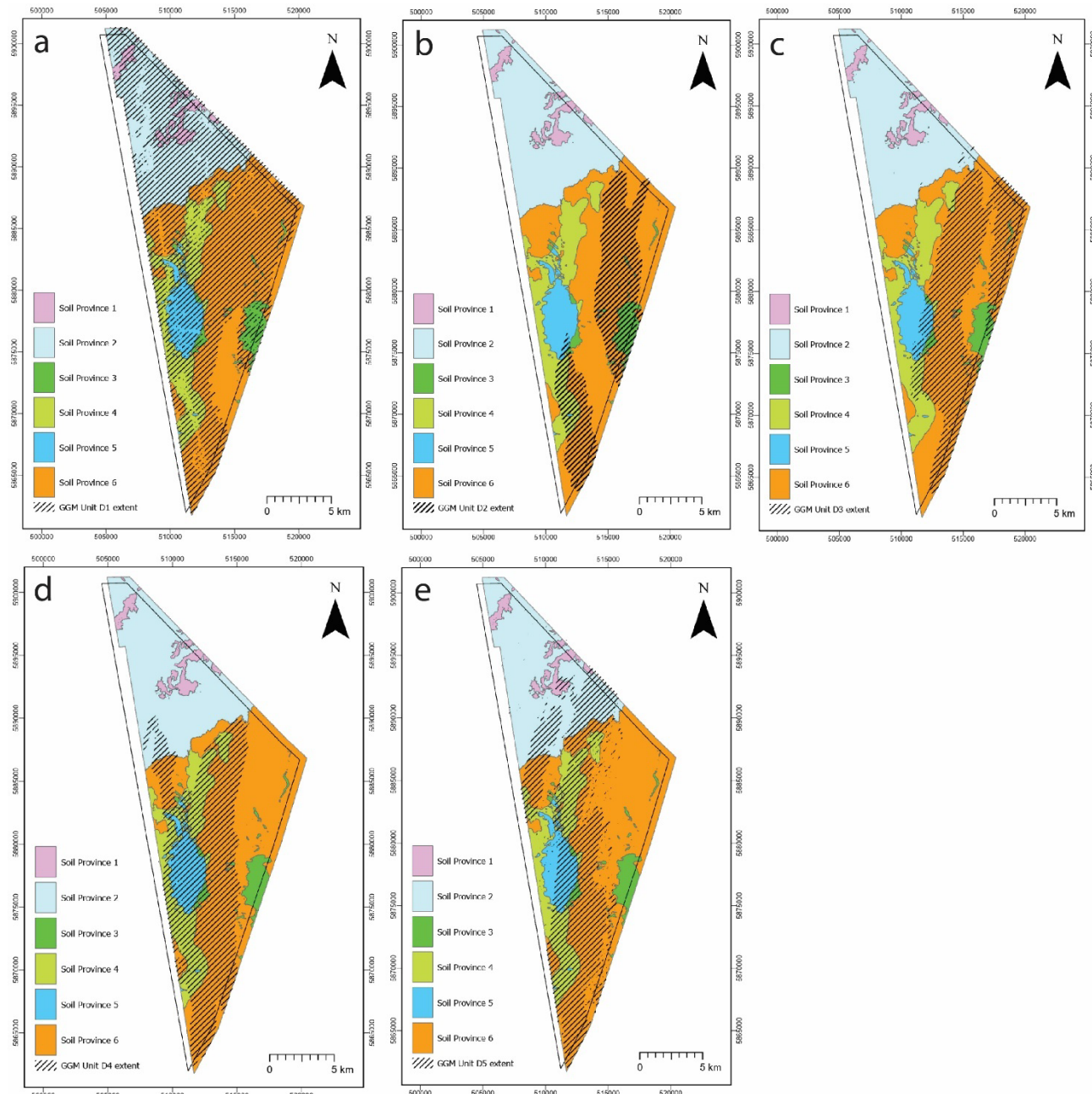


Figure 6.3 Soil provinces overlain with spatial extent of Seismostratigraphic Units D1 (a), D2 (b), D3 (c), D4 (d), D5 (e).

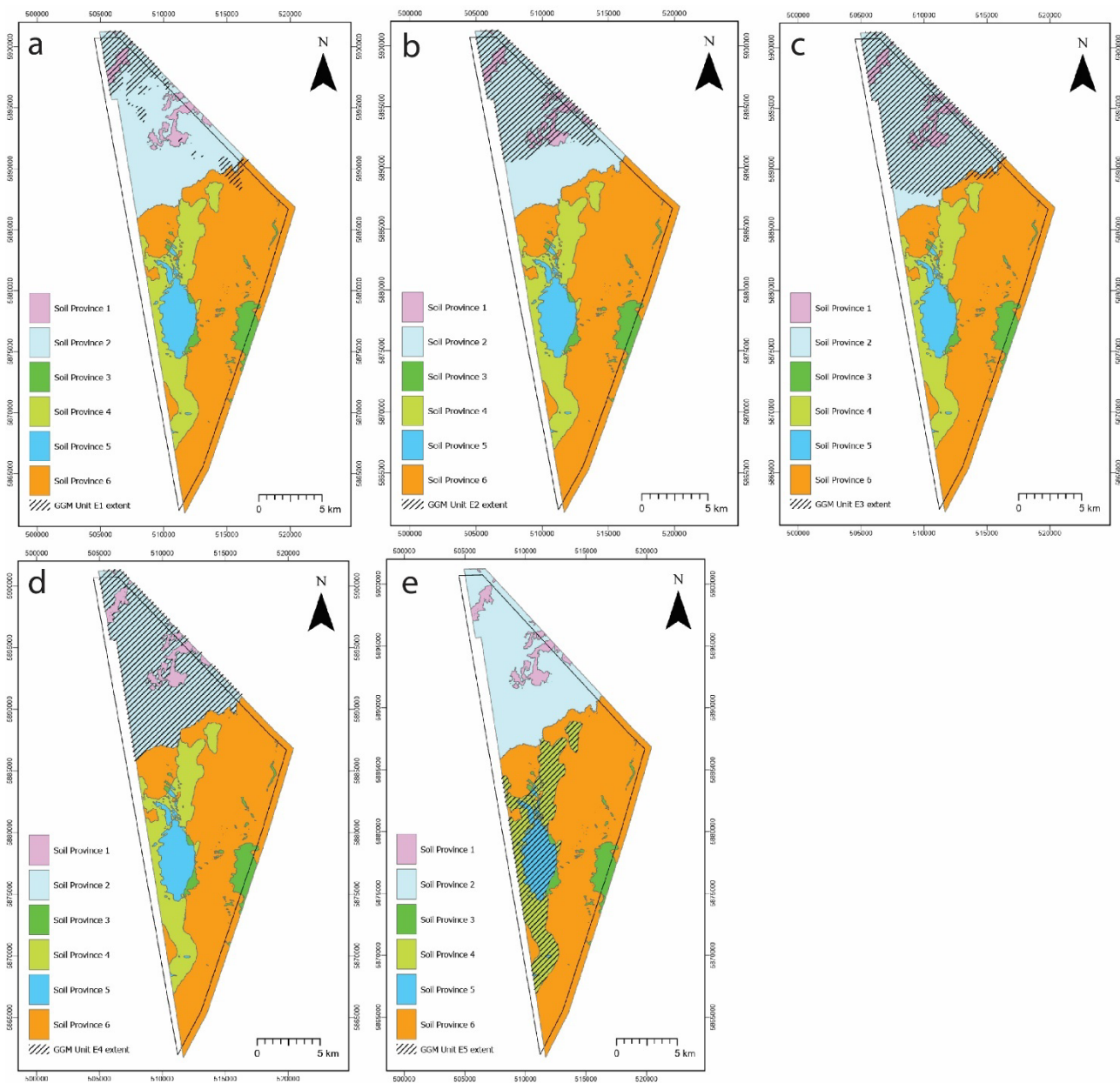


Figure 6.4 Soil provinces overlain with spatial extent of Seismostratigraphic Units E1 (a), E2 (b), E3 (c), E4 (d), E5 (e).

7. Integrated 3D Ground Model

7.1 Overview

A 3D voxel ground model was produced as part of this IGM. The 3D voxel ground model is composed of geotechnical soil units (U1 – U7), themselves aggregated from the seismostratigraphic framework (A – F) as established earlier in this report. The voxels that make up the 3D ground model are based on the seismostratigraphic surfaces created and delivered as part of the GGM.

The 3D voxel ground model represents a visualisation of the geological interpretation carried out in the GGM and the consolidation of those seismostratigraphic units into geotechnical soil units carried out as part of the GIR.

The 3D voxel ground model provides the spatial context required to use the geotechnical parameters defined in the GIR.

Sections cut from the 3D voxel ground model represent our best understanding of the ground conditions within the NW I IA based on information available to us at the time of writing.

The 3D voxel ground model is visualised in Leapfrog. No further geological interpretation is contained within the 3D voxel ground model than that already completed in the GGM.

The 3D voxel ground model extends from seabed to a depth of -100mLAT. The lowest unit boundary that was modelled is the top of Seismostratigraphic Unit F/Geotechnical Soil Unit 7 across the site, beneath this everything is treated as Unit F to a depth of -100mLAT. As the geophysical investigation extended to a depth of ~-150mLAT we can be confident that there are no other units below U7 within the model extents.

7.2 Outputs

The following outputs are available for the 3D voxel ground model.

7.2.1 3D ground model

Within the leapfrog viewer file the 3D voxel ground model is provided, the ground model can be visualized both in terms of the Geotechnical Soil unitisation (U1-U7), and the Seismostratigraphic unitisation.

The 3D ground model is provided at the resolution of the voxel model which is 20x20x0.5m, discussed later in Section 9.5.

Figure 7.1 shows the discrete geotechnical soil units within the voxel model and how these layers appear in the 3D ground model.

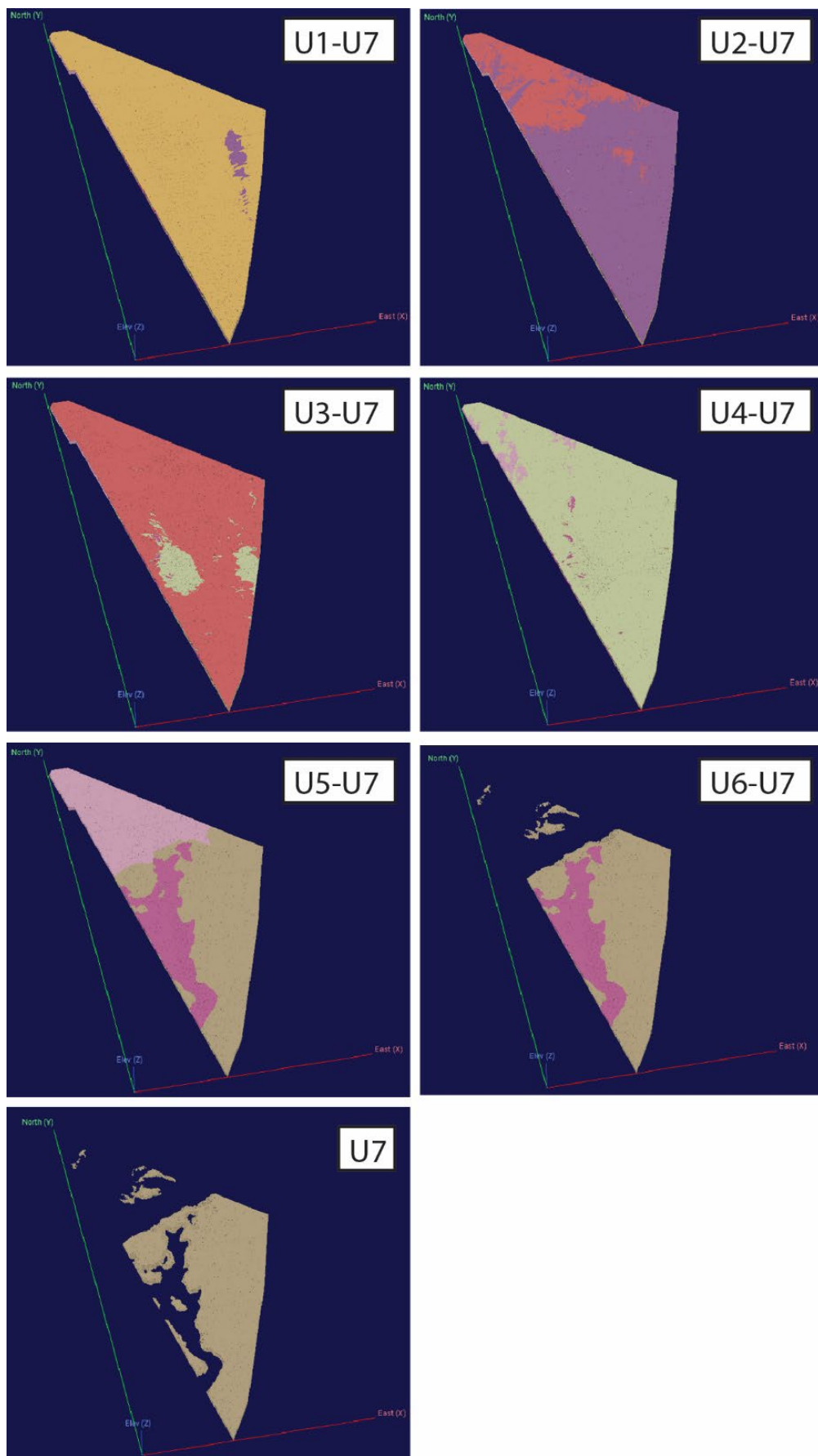


Figure 7.1: Voxel model of Geotechnical Soil Units, from top left: U1-U7; U2-U7; U3-U7; U4-U7; U5-U7; U6-U7; U7

7.2.2 Cross sections

A series of cross sections were taken through the 3D voxel ground model across the site. These sections are presented in Appendix B.

The cross sections show geotechnical soil units, overlaid with seismostratigraphic horizons and CPT data displaying sleeve friction, cone resistance, and pore pressure ratio.

Whilst the cross sections provided in Appendix B are static, the Leapfrog viewer file provides the capability to cut arbitrary sections throughout the site.

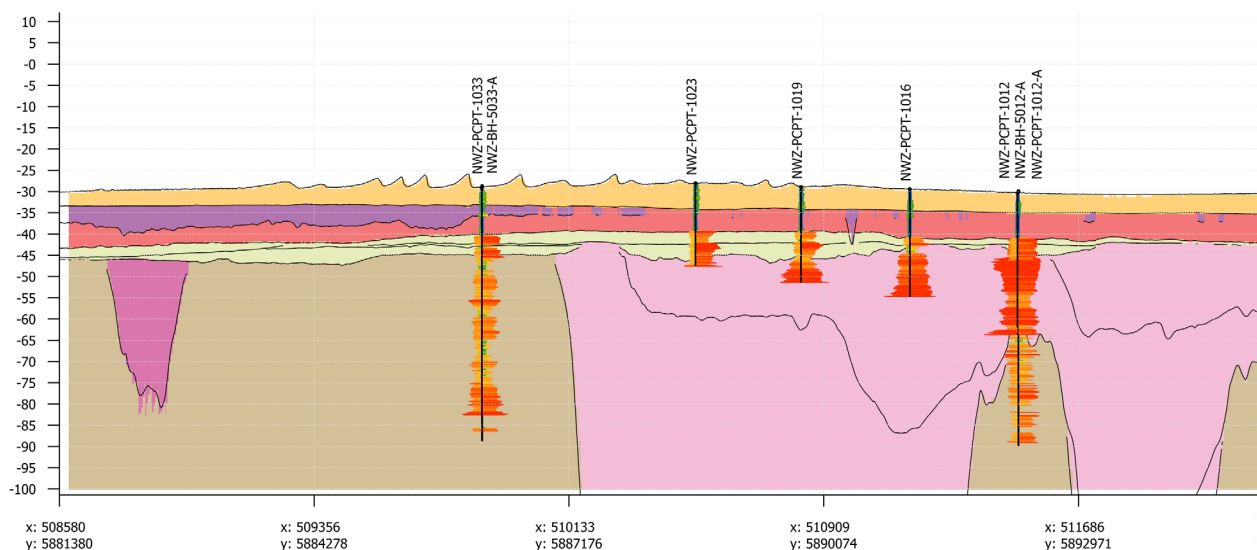


Figure 7.2: Example of cross section showing geotechnical soil units (coloured), seismostratigraphic horizons (black lines), and CPT results

Occasionally on the cross sections it appears as if the voxels are ‘spilling’ over the geophysical horizons, this can be seen on the example in Figure 7.2 where the tunnel valley fill spills over the geophysical horizon defining the top of the Yarmouth Roads. This has been investigated as is a visualisation quirk only, the data contained within the voxels is correct. The quirk is caused by the resolution difference between the geophysical horizon (10m^2) and the voxels (20m^2) where there is a relatively steep geological boundary.

7.2.3 Plan sections

A series of plan sections at 5m depth intervals were taken through the 3D voxel ground model. These sections are presented in Appendix B. The plan sections show the development of geotechnical soil units. These plan sections can be reviewed in conjunction with the soil provinces to understand how the unitization changes vertically throughout the site.

Figure 7.3 provides two examples of the plan sections at -40 m LAT and -75 m LAT.

7.2.4 Linear estimates and interpolation predictions

The 3D voxel model within Leapfrog Viewer also contains the linear correlations of cone resistance and sleeve friction for coarse grained and fine-grained soils, and the interpolated predictions of cone resistance, sleeve friction, and shear modulus based on pre-stack qualitative seismic inversion.

The methodology used in the creation of the linear estimates is provided in Section 5.3, and the methodology for the interpolated predictions is provided in Section 9.

Figure 7.4 shows an example of a cross section taken through the voxel model displaying interpolated predictions of cone resistance overlain with seismostratigraphic horizons.

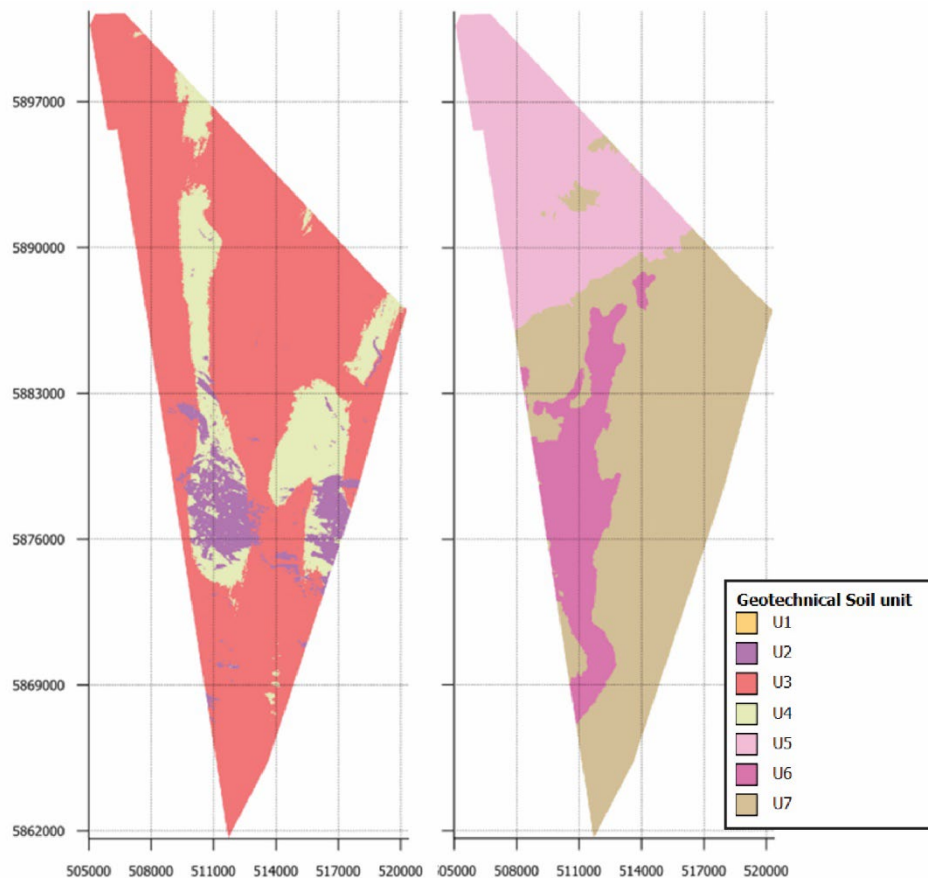


Figure 7.3 Example of plan section of geotechnical soil units at -40 m LAT (left) and -75 m LAT (right)

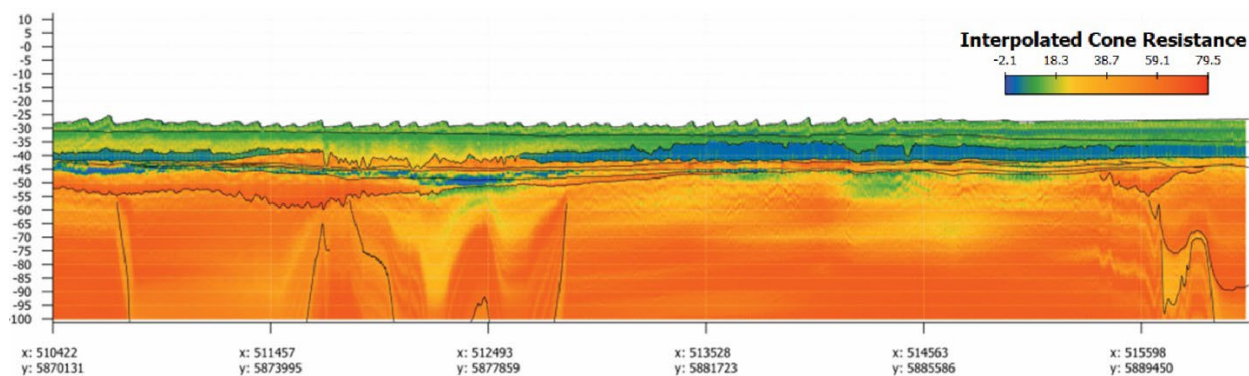


Figure 7.4 Example of cross section showing interpolated predictions of cone resistance [MPa] (coloured), and seismostratigraphic horizons (black lines)

8. Prediction of CPT parameters at seismic trace locations

8.1 Overview

This section describes the methodologies and results for prediction of geotechnical parameters across the NW I IA based on pre-stack quantitative seismic inversion.

A summary of the reprocessing workflow and results is given, leading to the production of a reprocessed prestack 2D UHRS dataset and its application in the inversion and geotechnical prediction workflows. The integration, interpretation and modelling of prestack seismic data and geotechnical data are documented, as well as the application of conditioned data in the inversion workflow. Finally, the geotechnical parameter prediction and uncertainty quantification methodologies and results are presented.

8.2 Reprocessing seismic data

As part of the IGM workflow, 5,025 km of 2D UHRS data from the NW I IA was reprocessed. The reprocessing aimed to produce amplitude-variation-with-offset (AVO)-compliant data for quantitative seismic inversion, involving several innovative processing stages including a novel deghosting workflow and directional designature. The process was iterative, incorporating feedback from various project disciplines through various stages of data integration (Section 3) to optimise data quality.

Final deliverables included pre-stack common reflection point gathers, a final stack, and an updated velocity model. Improvements in resolution and multiple attenuation are highlighted below in comparison with legacy data.

The processing steps undertaken are shown in Figure 8.1 and for a full overview of the reprocessing methodology and results see Appendix A.

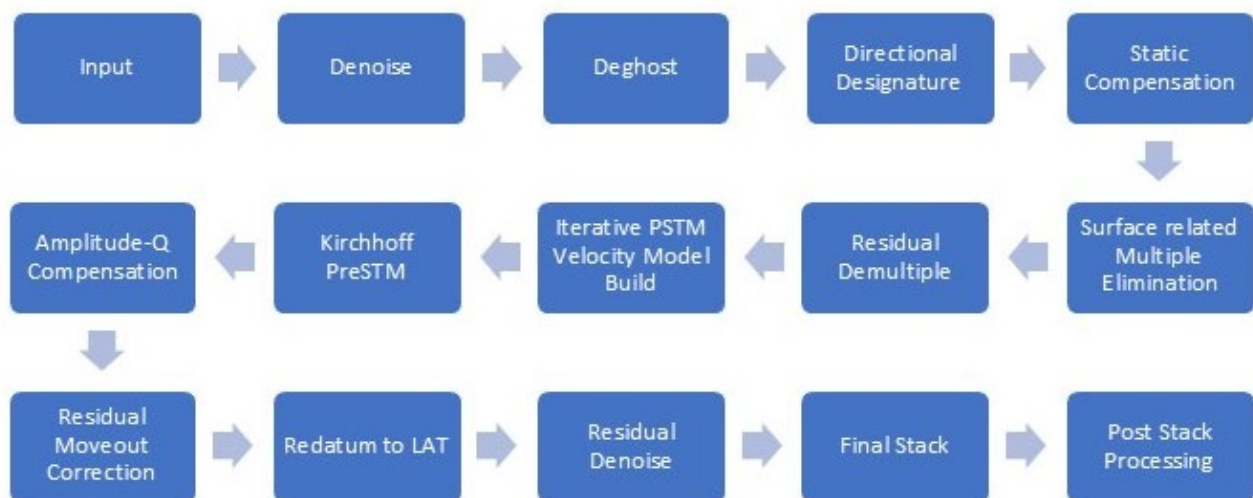


Figure 8.1: Processing flow schematic

8.3 CPT parameter prediction at seismic trace locations

The workflow for the CPT parameter prediction was iterative as illustrated in Figure 8.2:.

The workflow consisted of several stages, including importing and preparing geotechnical and geophysical data, geostatistical modelling to create an elastic prior model, wavelet estimation and 2D UHRS pre-stack inversion, accompanied by uncertainty estimation for all derived parameters. The CPT prediction results were validated and compared to the ground truthed data, this comparison helped to validate and refine parameter settings in preceding workflows, improving overall performance.

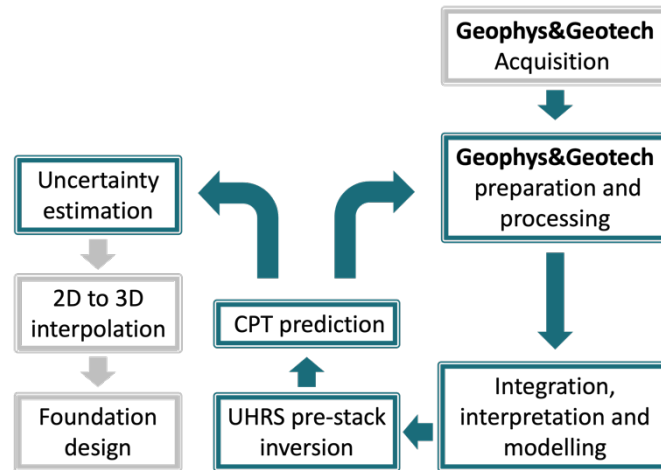


Figure 8.2: Flowchart for the CPT parameter prediction process. Highlighted in green are the workflows that are applied for the CPT prediction. Grey boxes represent input to, and workflows following, the CPT prediction illustrated.

8.3.1 Geotechnical data import and preparation

Factual geotechnical data from the seabed and borehole geotechnical campaigns were reviewed and imported into a geotechnical database for quantitative seismic inversion. This geotechnical database was used in subsequent workflows to retrieve the geotechnical parameters as part of the inversion workflow. The following data was imported:

- 114 seabed CPTs
- 59 downhole CPTs
- 42 SCPTs
- 5 borehole geophysical logging (P-S data)

During the geotechnical data processing task, concerns were highlighted on the reliability of the sleeve friction measurements at selected locations (Section 2.6.3). The post processed, ‘corrected’ data was used for x16 locations following the procedure advised by the geotechnical contractor (Fugro, 2025).

Elastic soil properties were not available for all investigation locations. For the seismic inversion, these elastic properties are needed at all investigation locations. At locations where in-situ SCPTs and P-S logging tests were available, CPT-based correlations for shear wave velocity V_s and compression wave velocity V_p were used to estimate the elastic properties.

The correlation by (Stuyts, et al., 2024) shown in Equation 8-1 was used to derive V_s from the CPT data. This is a physics-based semi-empirical correlation based on the vertical effective stress (σ'_{v0}) and Robertson’s soil behaviour type index I_c , with two calibration parameters (α and β).

For this project, the first calibration coefficient was slightly modified (2.1 instead of 2.075) to better fit the data present at the NW I IA. The correlation is reported to have a neutral bias and a coefficient of variation of 0.2 for the ratio of calculated to measured V_s .

$$V_s = \alpha \cdot \left(\frac{\sigma'_{v0}}{1kPa} \right)^\beta = 10^{2.1-0.213 \cdot I_c} \left(\frac{\sigma'_{v0}}{1kPa} \right)^{0.77-0.25 \cdot \log_{10}(\alpha)} \quad \text{Equation 8-1}$$

A location-specific V_p profile was derived from an empirical relation between V_s and V_p from previous projects where both V_s and V_p measurements from P-S logging were available. It should be noted that this is a relatively crude and purely data-driven correlation, and the coefficients cannot directly be related to physically meaningful values. For example, Robertson (2009) proposed a minimum V_p of 1500 m/s for saturated soil, which is higher than the intercept of the correlation for $V_s=0$. The correlation was therefore used with caution and because of the limited data on which the correlation was calibrated, its applicability should be re-evaluated when more data becomes available.

Direct correlations between V_p and CPT parameters were not identified in the literature. Therefore, V_s was first estimated based on the CPT-based correlation and the result was then used to apply the correlation between V_s and V_p .

$$V_p = 1200 + 6.5 \cdot V_s^{0.75} \quad \text{Equation 8-2}$$

Bulk unit weight (γ) was derived from the CPT data using the correlation by Mayne et al., (2010), with γ_w being the unit weight of water and f_t being corrected sleeve friction. The correlation was first recalibrated to provide a slightly better fit to North Sea data.

$$\gamma = 1.857 \cdot \gamma_w \cdot \left(\frac{\sigma'_{v0}}{P_a} \right)^{0.06} \cdot \left(\frac{f_t}{P_a} \right)^{0.06} \quad \text{Equation 8-3}$$

The accuracy of the CPT-based correlations was assessed, both in graphical and numerical terms. For the V_s correlation, the V_s measurements with the SCPT were compared to the CPT-based estimate.

Figure 8.3 shows the performance for three datasets. The calculated values of V_s with the CPT-based correlation are compared to the direct measurement with the SCPT. The black dashed line in the figure represents perfect predictions.

The three datasets are:

- Background data from other projects in the Southern North Sea (SolidGround, 2023);
- The IJmuiden Ver Alpha and Beta (Fugro, 2023a) dataset (which contains substantially more SCPT test locations than NW I);
- NW I IA datasets (Fugro, 2025).

Figure 8.3 shows that the correlation has a nearly neutral bias for all datasets and similar scatter. NW I IA has a small negative bias (mean of the ratio of calculated to measured $V_s < 1$) but a smaller coefficient of variation. The residuals for each of the datasets are shown in Figure 8.4 in terms of the ratio of calculated to measured V_s . The nearly neutral bias and similar coefficients of variation for each of the datasets can be observed from the histograms.

Compared to other correlations from the literature (Stuyts, et al., 2024), the selected correlation shows excellent predictive power.

Table 8-1: Summary statistics for the ratio of calculated to measured V_s

Project	Number of V_s measurements with the seismic CPT	Mean of $\frac{V_{s,calculated}}{V_{s,measured}}$	Coefficient of Variation for $\frac{V_{s,calculated}}{V_{s,measured}}$
Background data	2373	1.024	0.200
IJmuiden Ver	1148	1.019	0.220
Nederwiek	362	0.948	0.188

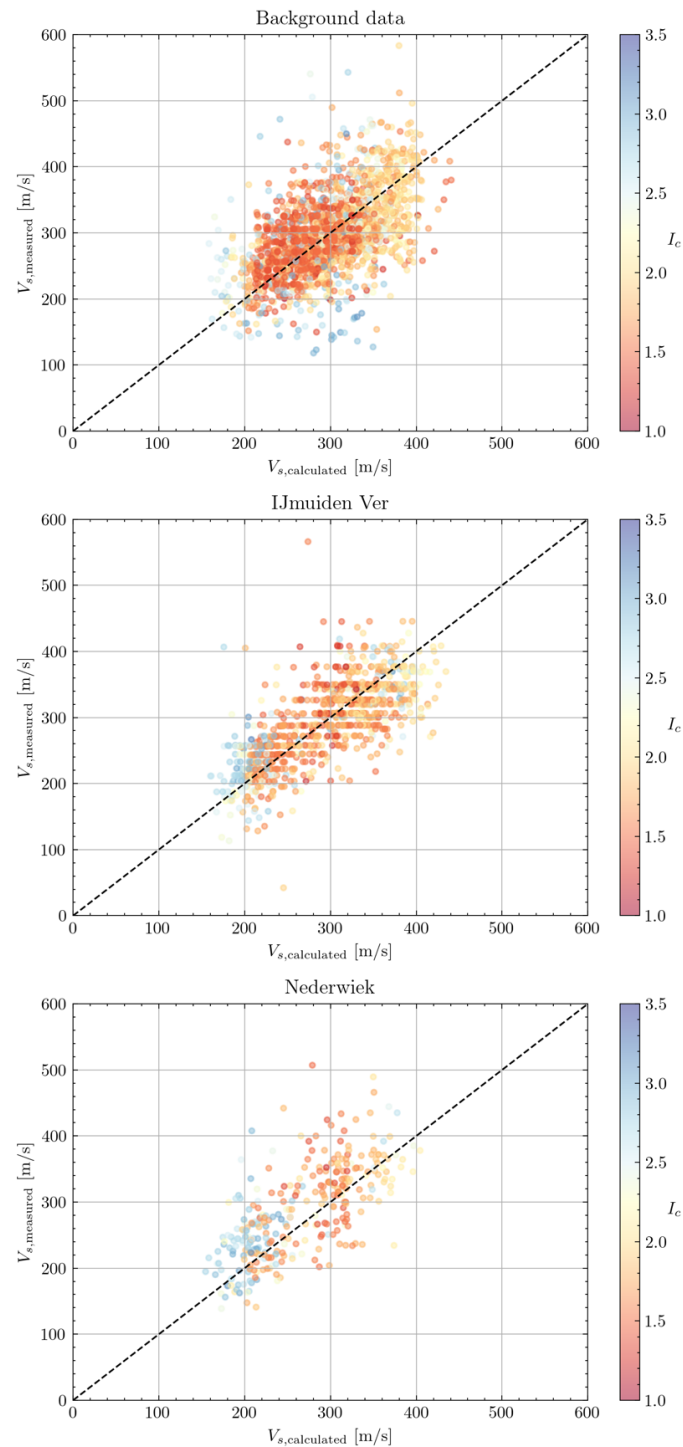


Figure 8.3 Graphical evaluation of the CPT-based correlation for V_s

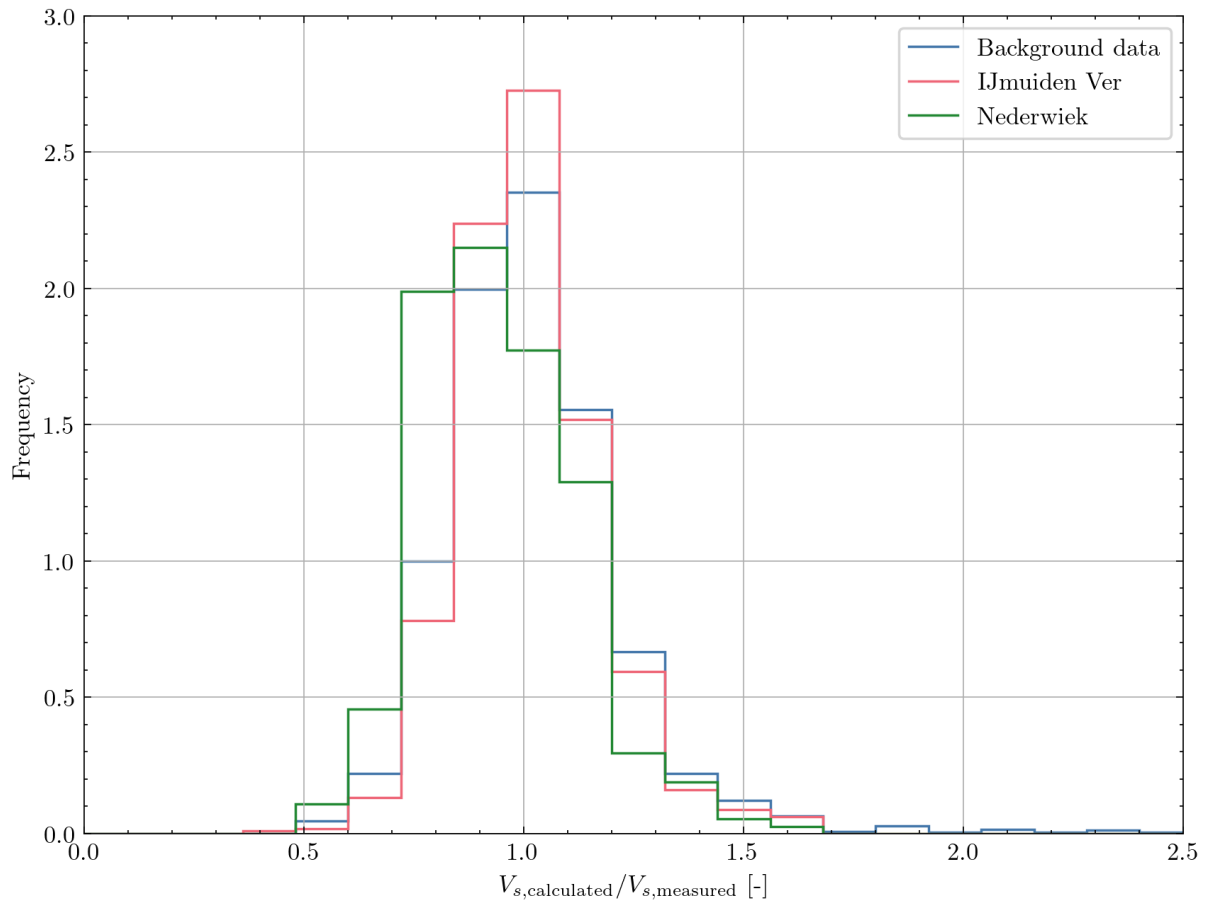


Figure 8.4: Graphical evaluation of the residuals for the CPT-based correlation for V_s . The selected correlation for V_p can also be evaluated based on the available P-S logging data.

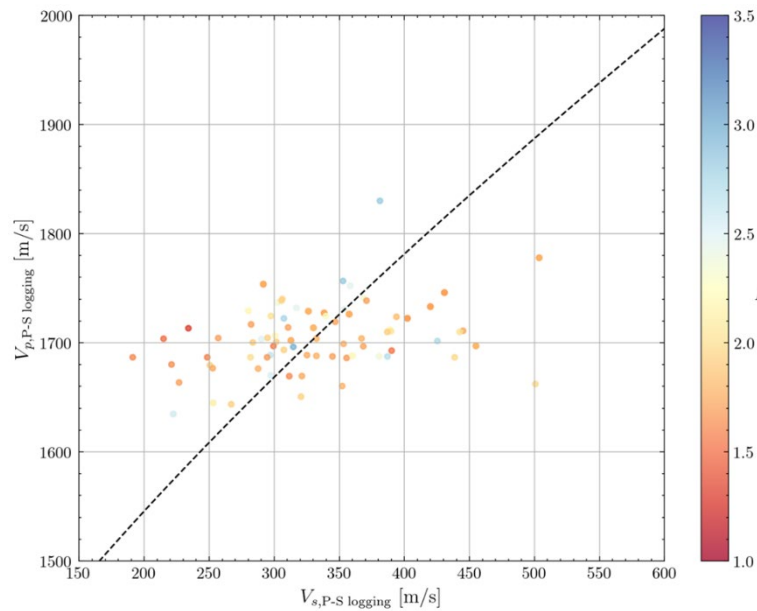


Figure 8.5: Graphical evaluation of the correlation between V_s and V_p from P-S logging

Figure 8.5 shows the performance of the correlation. Although the correlation passes through the centre of the cloud of data, the data do not capture the underlying trend. The relation between V_p and V_s is not well described by Equation 8-2, therefore the V_p results need to be treated with caution.

The correlation performance (combining Equation 8-1 and Equation 8-2) can also be assessed by comparing the indirect V_p estimate from CPT data with the measured V_p with P-S logging. Figure 8.7 shows that the

correlation predicts higher V_p values compared to the measurements. One possible explanation is that during P-S logging in sand, the borehole will relax to a certain degree. Although a limited amount of relaxation was observed in sands from the caliper values during P-S logging, limited wall displacements can lead to significant stress relaxation in sand.

The effects of borehole relaxation can also be observed by comparing the V_s measurements with the seismic CPT to V_s measurements with P-S logging at corresponding locations and depths as shown in Figure 8.6. The markers in Figure 8.6 are color-coded based on Robertson's soil behaviour type index I_c . The figure shows that a higher shear wave velocity is nearly always measured in cohesionless soils ($I_c < 2$) with the seismic CPT than with P-S logging. The difference between the V_s values from S-PCPT and P-S logging becomes greater for lower values of V_s , which correspond to shallow depths. Due to the lower confining stress, more relaxation is expected at these shallower depths.

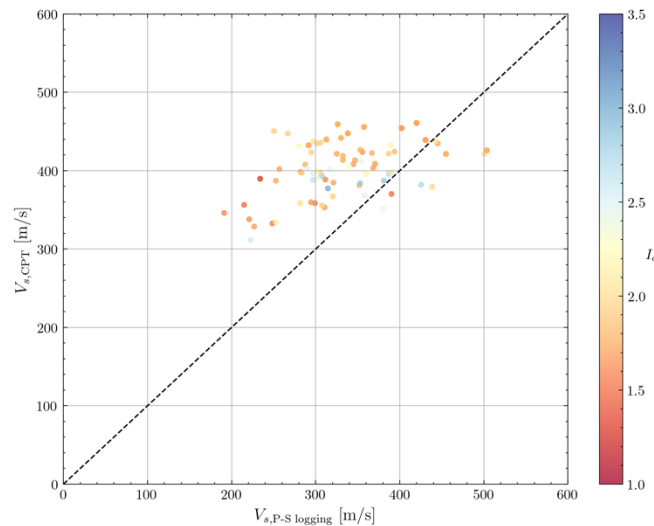


Figure 8.6: Comparison of V_s measured with SCPT and P-S logging

Based on the comparison of V_s obtained with seismic CPT and P-S logging, a hypothesis can be formulated on the bias of V_p estimates obtained with Equation 8-2. The markers in Figure 8.5 are color-coded based on Robertson's soil behaviour type index I_c and points with I_c lower than 2 (cohesionless behaviour) show a wider scatter around the mean trend which would indicate more variable amounts of borehole relaxation in sand. The correlation passes through the centre of these points with $I_c < 2$. The correlation therefore captures an unbiased relation between V_s and V_p based on P-S logging data only. Borehole relaxation is then inherently included in the correlation. Because of disturbance by drilling, the true compression wave velocity of the undisturbed soil may be higher than the value measured with P-S logging.

Figure 8.7 shows the effect of the difference between the CPT-based estimate and the P-S logging measurement. The estimate of V_p from the CPT data is based on the V_s from SCPT and is therefore expected to be higher than the measurement with P-S logging. This is confirmed in the figure, with calculated V_p values being higher than measured ones. The calculated V_p would then be more representative for the true state of the soil (without borehole relaxation effects).

The mean of the ratio of calculated to measured V_p is 1.048. The coefficient of variation is 0.021 based on 100 datapoints where both the V_p measurement from P-S logging and the CPT-based estimate are available. For the inversion, the calculated V_p values were used without adjusting for the bias of the correlation.

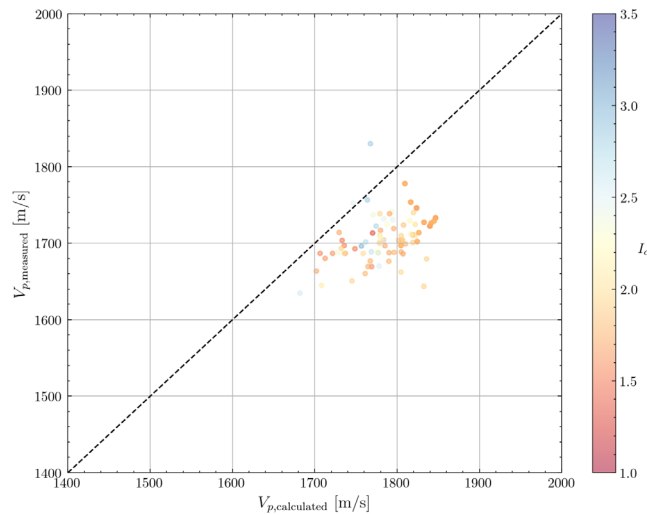


Figure 8.7: Graphical evaluation of the accuracy of the V_p correlation

Finally, the predictive power of the bulk unit weight (γ) correlation was assessed. Figure 8.8 shows that the correlation has very limited predictive power. Therefore, a constant value of unit weight of 20.3 kN/m^3 was considered a better estimate with a neutral bias and a coefficient of variation for the ratio of predicted to measured unit weight of 0.023. This estimate is based on 88 datapoints.

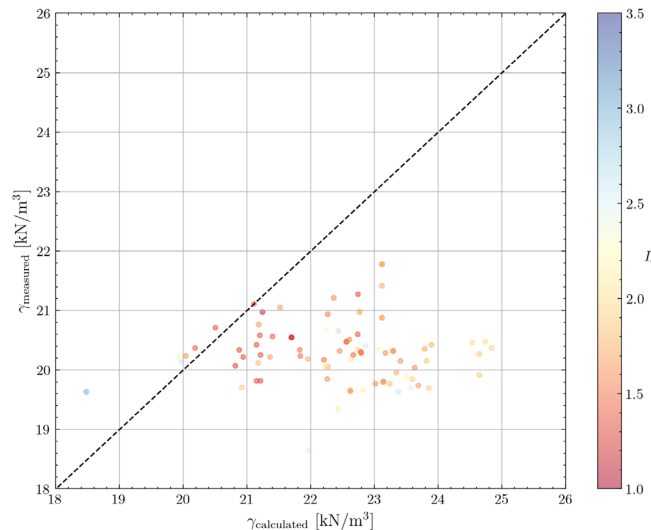


Figure 8.8: Graphical evaluation of the accuracy of the bulk unit weight correlation according to Mayne et al (2010)

At locations where CPT data and data on V_s , V_p or bulk density is available, the CPT-based estimates and the direct measurements were summarised using a constant unit weight. Figure 8.9: shows an example of location NWZ-SCPT-2077.

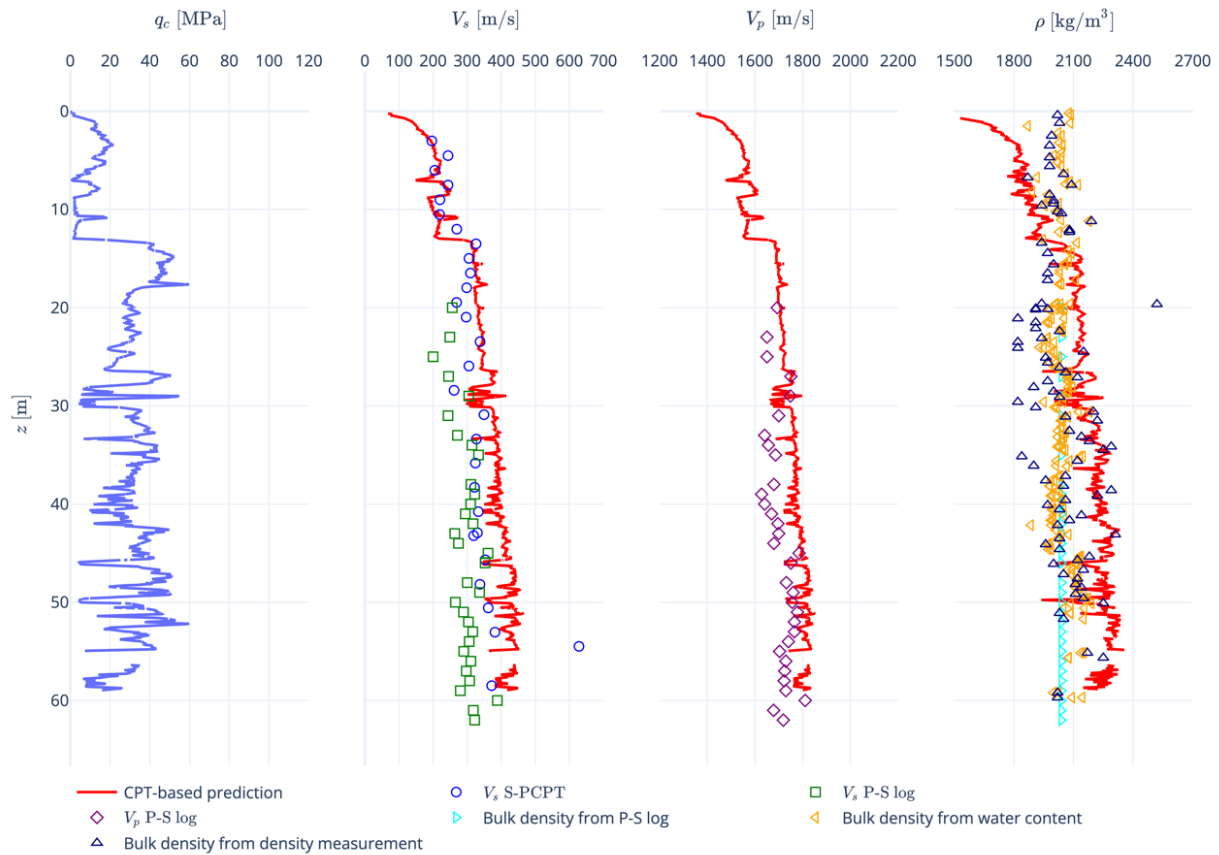


Figure 8.9: Comparison of CPT-based predictions of V_s , V_p and bulk density with direct measurements at location NWZ-SCPT-2077

The nearly constant measured bulk density is immediately apparent from Figure 8.9. The V_s estimates from the CPT follow the SCPT data well above 30m, after which the CPT-based estimates overestimate V_s for this particular location. The overestimation is even more severe when comparing the V_s measurements from P-S logging to the CPT-based correlation. This can be attributed to borehole stress relaxation. The CPT-based V_p estimate is also somewhat higher than the measured V_p from P-S logging which would also account for borehole stress relaxation. Interestingly, in the layers with low cone resistance around 30 m depth, V_p is not overestimated. This could be because these layers are cohesive, and the borehole wall does not relax as much in those layers. Overall, the estimates of V_s and V_p appear to be suitable for use in the inversion. The proposed correlations are thought to provide V_s and V_p estimate which are close to the true in-situ values.

8.3.2 Geophysical data import and preparation

The reprocessed 2D UHRS data described in Section 8.1 was imported then pre-conditioned and stacked into angle bands prior to the inversion. The velocity field used for stacking should ideally be a smooth representation of actual in-situ velocities. Figure 8.10 presents the reprocessed velocity field (Appendix A) alongside the CPT-derived velocity at a representative location. This comparison demonstrates that the velocity field is both smooth and closely aligned with expected in-situ velocities to sufficient degree. Based on this assessment, the reprocessed velocity field was selected for stacking seismic gathers into angle stacks. Figure 8.12 illustrates the 2D UHRS data in the gather domain and the calculation into angle bands. We see that the angle coverage of the seismic data, extends up to 50° for two-way travel-time (TWTT) down to 70 ms and narrowing to 25° for TWTT values down to 150 ms. Enhanced angle coverage generally supports better resolution of AVO components, which are critical for seismic inversion.

Experience from analogous sites in the North Sea suggests that angle ranges up to 30° provide sufficient resolution for parameters associated with AVO terms. The seismic angle gather reveals consistent seismic events across offsets. However, the angle range between 0 and 10° exhibits low fold and reduced correlation

with the remainder of the seismic data. Inversion tests demonstrated that excluding data below 10° of incidence produces better results. Consequently, seismic data below 10° were omitted from further analysis to optimize the resolution and reliability of the inversion process.

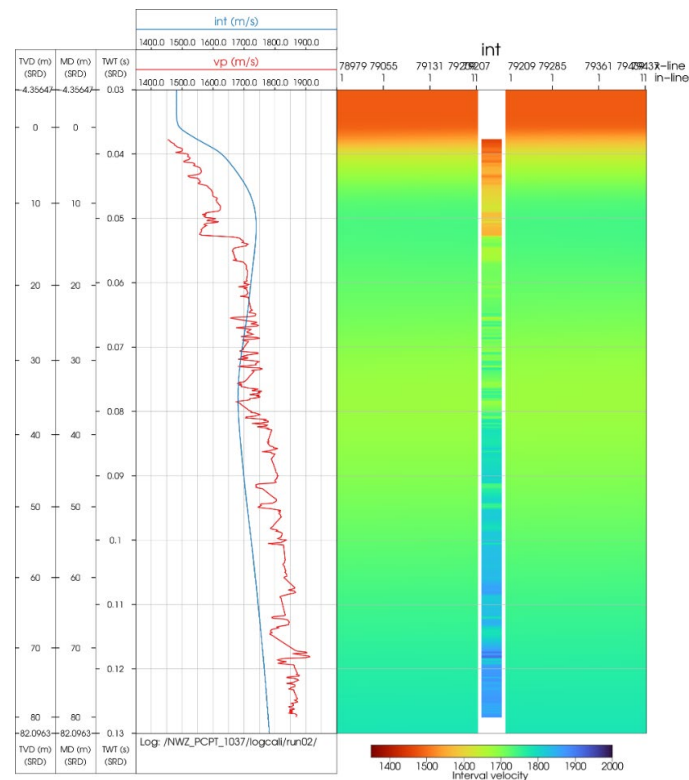


Figure 8.10: Seismic velocities (blue curve) plotted together with velocities modelled from the CPT (red curve) at NWZ-PCPT-1037 together with a short section of the seismic velocities crossing the CPT location plotted at the right side of the figure.

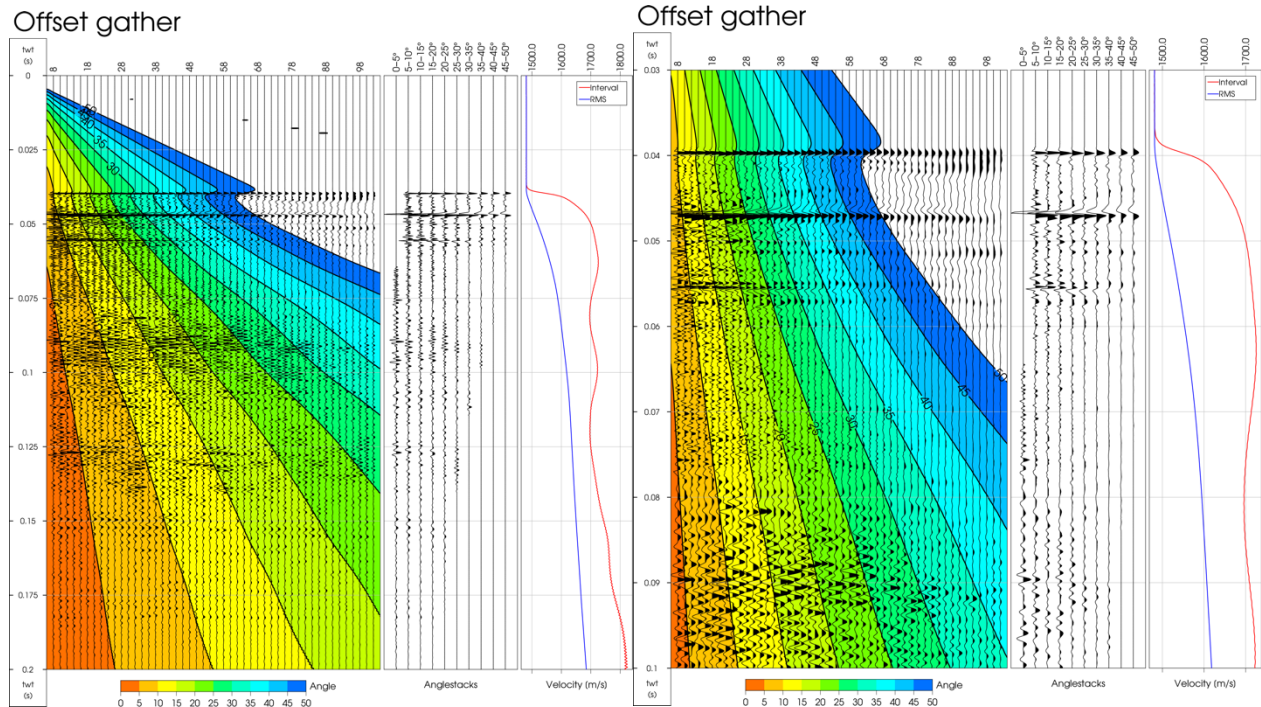


Figure 8.11: Example of input offset gathers around NWZ-PCPT-1016 overlaid with constant angle bands. Left plot going from 0 s to 0.2 s TWT below seabed, and the right plot is zoomed in between 0.03 s and 0.1 s TWTT. For each plot: left panel are showing offset gather overlain by calculated angle ranges, mid panel is showing the stacked seismic for each angle band, and right panel is showing the seismic interval and rms velocities used for angle band calculations.

For pre-stack quantitative inversion, pre-conditioning flows were applied based on preliminary assessment using geotechnical datasets. These, further to the AVO reprocessing provide the ability to increase usability of the data for assessment:

1. **FK Filter:**

The FK filter operates in the frequency-wavenumber (f-k) domain to separate seismic energy based on its velocity or direction of propagation. It is commonly used to suppress unwanted coherent noise, such as ground roll or linear events, and to enhance specific components of the seismic signal by filtering out undesirable frequencies and wavenumbers.

2. **Cadzow Filtering:**

Cadzow filtering is a denoising technique based on singular value decomposition (SVD). It enhances seismic data by reconstructing the signal with only the most significant singular values, effectively removing random noise. This method is widely used in seismic processing to improve signal-to-noise ratio while preserving important geological features.

3. **Seismic Alignment:**

This process aligns seismic traces to correct for static or dynamic time shifts caused by variations in acquisition geometry, near-surface effects, or incorrect velocity models. By ensuring that reflectors and wavelets are temporally coherent across traces, seismic alignment improves data quality for stacking and interpretation.

4. **Bandpass Filter:**

A bandpass filter retains seismic frequencies within a specified range while attenuating frequencies outside this range. Low frequencies (e.g., ground noise) and high frequencies (e.g., acquisition noise) are removed, preserving the signal components most relevant to seismic interpretation. It is an essential tool for enhancing resolution and clarity in seismic data.

Following extensive testing and analysis, we opted to apply a combination of seismic pre-conditioning techniques to enhance the quality and interpretability of the seismic data for subsequent processing steps. Specifically, we employed the FK filter to suppress noise and separate coherent signal patterns in the frequency-wavenumber domain. Additionally, we utilized the Cadzow filter to reduce random noise and improve the continuity of seismic reflections through singular value decomposition. Finally, a bandpass filter was applied to isolate the frequency range of interest, removing low-frequency noise and high-frequency artifacts. These combined methods ensured that the seismic data were optimally conditioned for further analysis and interpretation. Figure 8.12 shows the angle gathers before and after the pre-conditioning flow is applied.

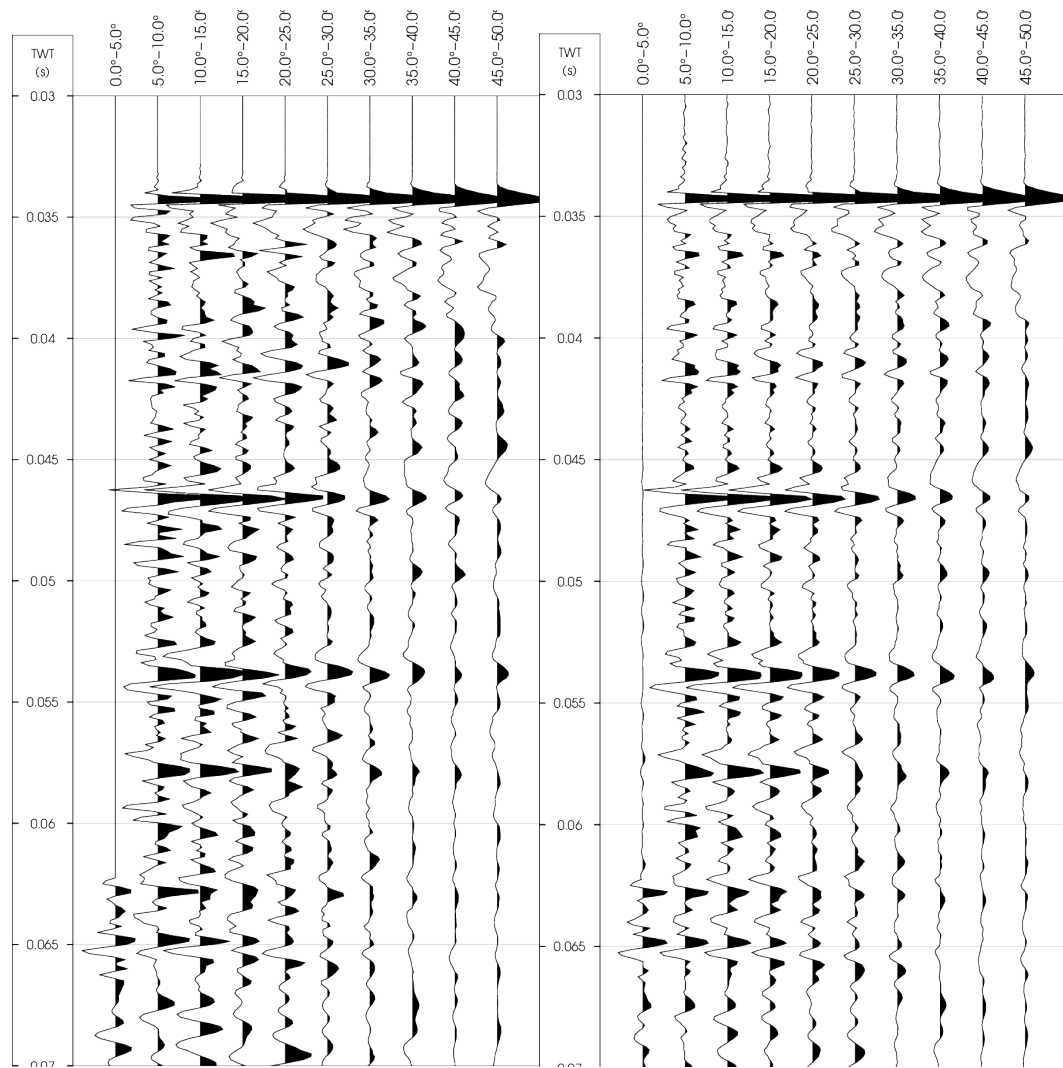


Figure 8.12: Seismic stacked gathers in 5° angle bands. Left plot is before pre-conditioning and right plot is after pre-conditioning applied.

8.3.3 2D UHRS pre-stack inversion

The inversion of bulk modulus (K), shear modulus (G_{max}) and in-situ bulk density (ρ) were carried out through a simultaneous seismic inversion of the pre-conditioned partial angle stacks through the three term Aki & Richards (1980) reflectivity model. From this the reflection coefficient $R(\theta)$ can be described as:

$$R(\theta) \approx A + B \sin^2 \theta + C \tan^2 \theta \sin^2 \theta \quad \text{Equation 8-4}$$

where:

- A (Intercept) represents zero-offset reflectivity, mainly influenced by P-wave velocity and density contrasts.
- B (Gradient) represents P-wave and S-wave velocity contrasts and is crucial for Amplitude Versus Offset (AVO) analysis.
- C (Curvature) accounts for higher-order effects, including density contrasts.

The coefficients are given by:

$$A = \frac{1}{2} \left(\frac{\Delta \rho}{\rho} + \frac{\Delta V_p}{V_p} \right) \quad \text{Equation 8-5}$$

$$B = \frac{1}{2} \frac{\Delta V_p}{V_p} - 2 \left(\frac{V_s^2}{V_p^2} \right) \frac{\Delta V_s}{V_s} \quad \text{Equation 8-6}$$

$$C = \frac{1}{2} \frac{\Delta V_p}{V_p} \quad \text{Equation 8-7}$$

where:

- V_p and V_s are the P-wave and S-wave velocities,
- ΔV_p , ΔV_s and $\Delta \rho$ their respective contrasts across the interface.

P-wave and S-wave velocities in an isotropic medium are related to the bulk modulus and shear modulus by:

$$V_p = \sqrt{\frac{K + \frac{4}{3}G_{max}}{\rho}} \quad \text{Equation 8-8}$$

$$V_s = \sqrt{\frac{G_{max}}{\rho}} \quad \text{Equation 8-9}$$

Using these relationships, the velocity contrasts can be rewritten as:

$$\frac{\Delta V_p}{V_p} = \frac{1}{2} \left(\frac{\Delta K}{K + \frac{4}{3}G_{max}} + \frac{4}{3} \frac{\Delta G_{max}}{K + \frac{4}{3}G_{max}} - \frac{\Delta \rho}{\rho} \right) \quad \text{Equation 8-10}$$

$$\frac{\Delta V_s}{V_s} = \frac{1}{2} \left(\frac{\Delta G_{max}}{G_{max}} - \frac{\Delta \rho}{\rho} \right) \quad \text{Equation 8-11}$$

By substituting these expressions into the Aki & Richards equations, we obtain reflectivity terms in terms of bulk modulus and shear modulus.

Through prior models for each inverted parameter an absolute inversion was achieved. Inversion trials were conducted with the aim of evaluating seismic data processing, optimizing pre-conditioning steps, and fine-tuning inversion parameter settings for improved outcomes.

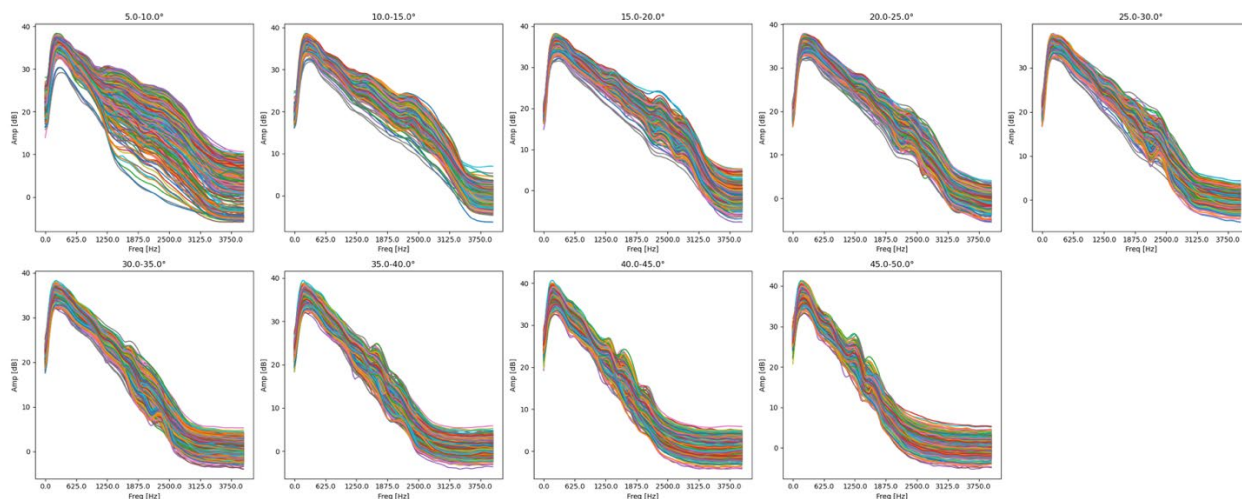


Figure 8.13: Amplitude spectra plotted for all seismic lines within each angle-stacks.

Semi-statistical zero-phase global wavelets were estimated for each sub-stack as shown in Figure 8.14. From the seismic amplitude spectra shown in Figure 8.13 we observe stability from 10 degrees and up across all seismic lines, providing confidence in applying a single global wavelet for the inversion process. This consistency in wavelet characteristics significantly reduced uncertainties and contribute to robust inversion results. Our statistical wavelets have constant phase information derived from seabed reflectivity and the spectral content estimated from the seismic data. The wavelets are not considered stable with depth, primarily evident at the seabed transition. Focus was on inversion parameterization and pre-conditioning to limit this effect, any residual seabed transition effects are evident in the bulk modulus results having higher than expected values just below seabed, this effect is minimal. The wavelet is non-stationarity with time, this does not impact the results to a degree where a depth varying wavelet was considered.

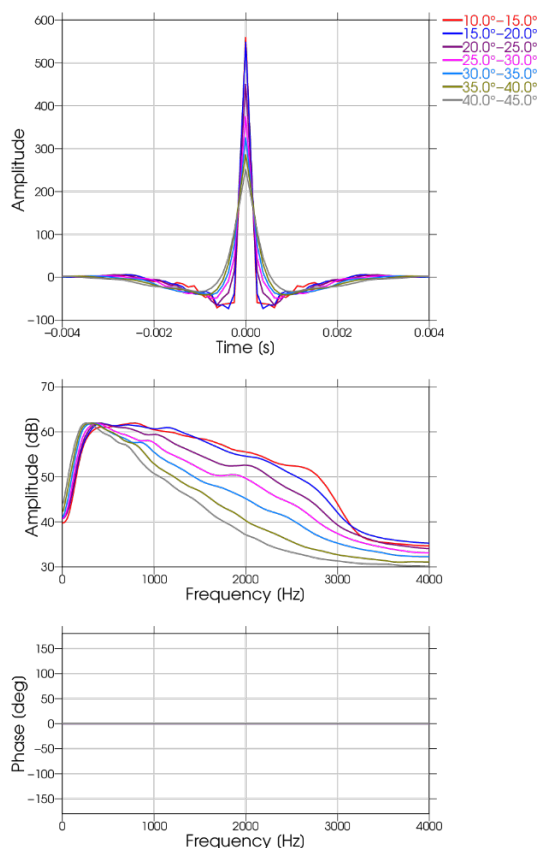


Figure 8.14: Top panel is showing wavelet amplitude in time domain, middle panel is showing the amplitude spectra for the wavelets and the lower panel is showing the phase of the wavelets as a function of frequency. In the figure are wavelets plotted from 10 to 45° corresponding to wavelets used for the inversion.

The elastic prior modelling applied used geotechnical data and seismic interpretations. The elastic derived parameters from the CPTs were low pass filtered and interpolated across the site guided by the seismic interpretation from the structural model. The interpolation of ground truth data was based on a multiquadric radial basis function interpolation in 3D.

Examples of the prior model for K , G_{max} , and ρ can be seen in Figure 8.15, Figure 8.16, and Figure 8.17 respectively.

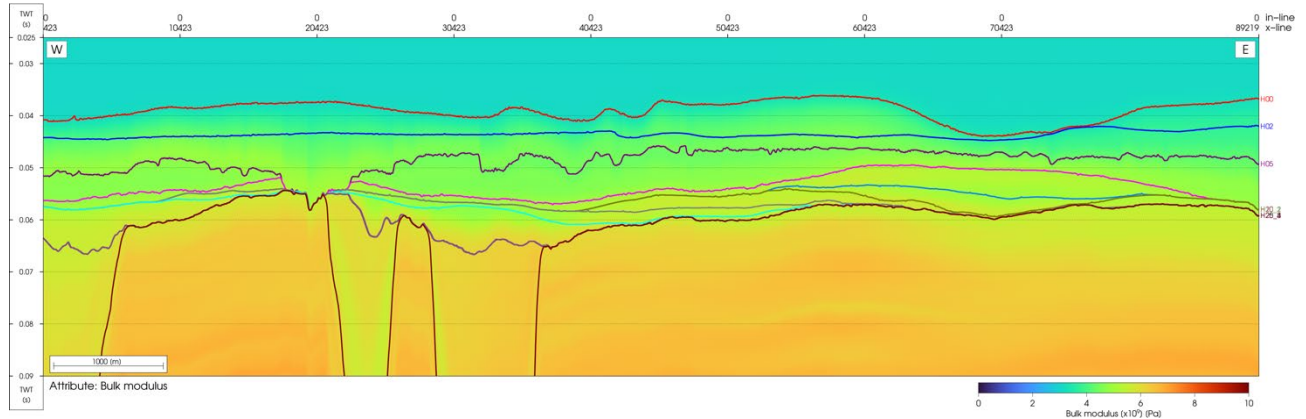


Figure 8.15 Prior model for bulk modulus along line X314-P1

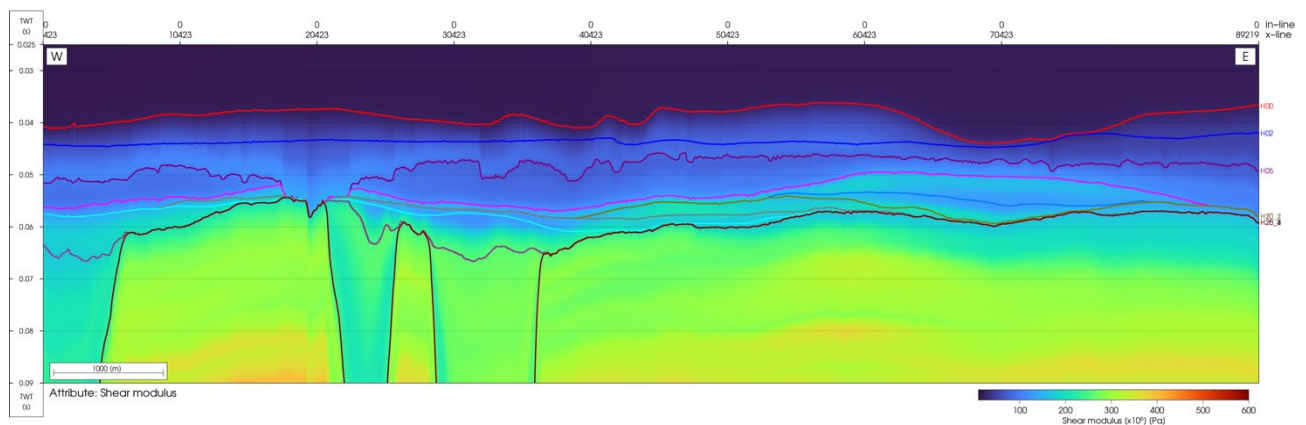


Figure 8.16 Prior model for shear modulus along line X314-P1

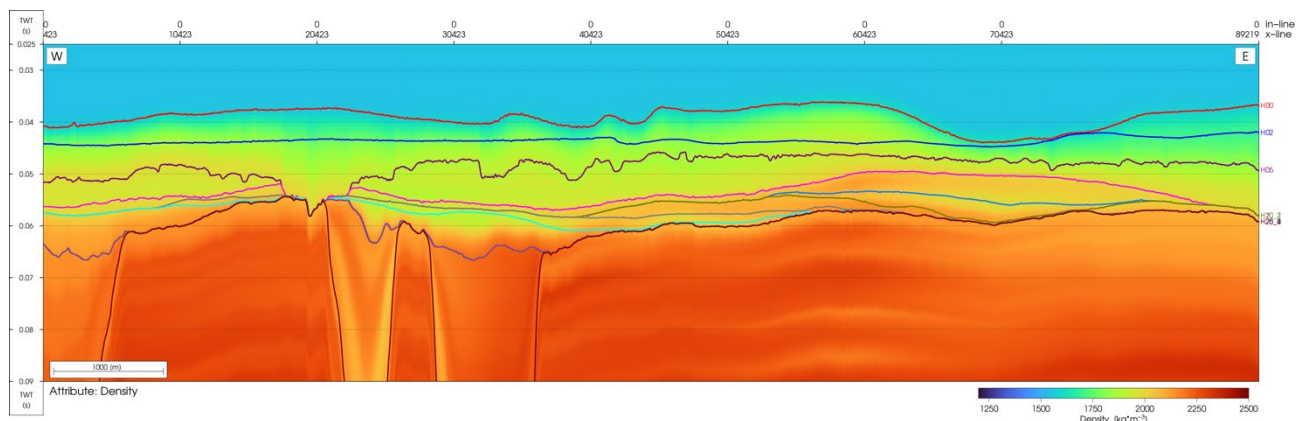


Figure 8.17: Prior model for density along line X314-P1

8.3.4 CPT parameter prediction (cone resistance and sleeve friction)

The CPT prediction is formulated within a Bayesian framework, allowing for a probabilistic assessment and prediction of any CPT property. This approach accounts for the fact that multiple soil types may exhibit similar elastic responses by assigning equal probabilities to such cases. For instance, this occurs when soil mineral compositions are similar or when there is a relatively high level of noise in the seismic data.

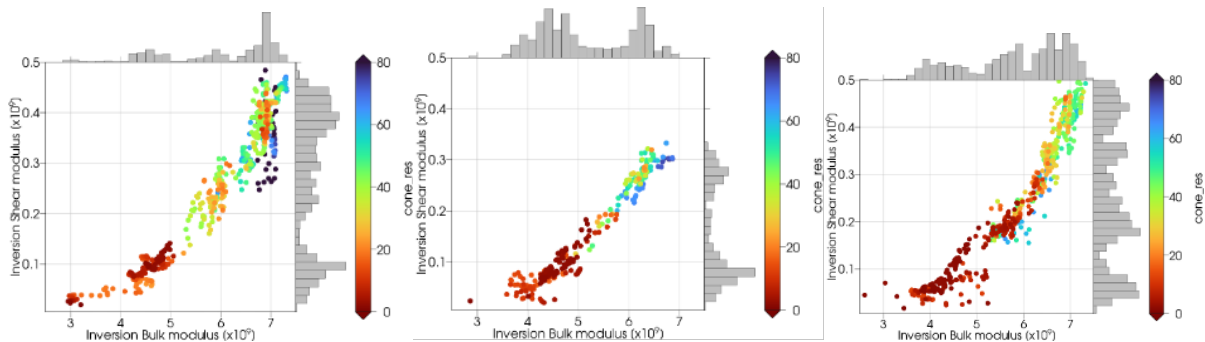


Figure 8.18: Cross-plot analysis from three selected CPT locations (NWZ-PCPT-1001, NWZ-PCPT-1039 and NWZ-SCPT-2080). Cross-plot analysis is the basis of the definition of the non-Gaussian probability density functions used for classifying the soil units. The cross-plots display the inverted bulk modulus on the x-axis and the inversion shear modulus on the y-axis color-coded with the measured cone resistance. The entire CPT measured interval at the locations is shown.

This CPT prediction process takes the absolute seismic elastic inversion results as input to estimate the following geotechnical properties:

1. Cone resistance;
2. Sleeve friction.

The prediction makes use of non-Gaussian probability density functions (PDFs), which are generated using Gaussian kernel-density estimation. These probability density functions are derived from polygons that encapsulate the relevant points for the CPT property of interest from the inversion results (as illustrated in Figure 8.18).

To differentiate soil types that exhibit distinct elastic behaviours (different areas in the elastic domain cross-plots), polygons are carefully defined. By applying the computed PDFs to the elastic inversion results, the likelihood of encountering specific soil types (e.g., Type A, Type B, etc.) is calculated. Characteristic geotechnical properties are subsequently assigned to each classified soil type. This information, combined with the probability of encountering each soil type, generates predicted CPT values. In this way, elastic property information from seismic AVO data is mapped into relevant CPT properties. The approach is global in nature, implying that the same defined PDFs and soil characteristics have been consistently applied across all seismic traces for the site.

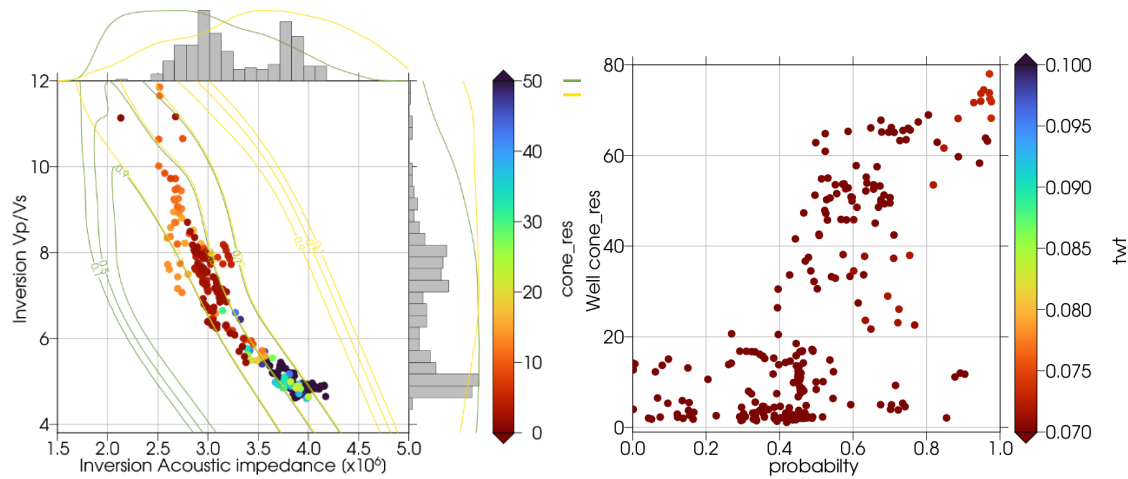


Figure 8.19: Left: Example of soil type classification of soil type “green” and soil type “yellow”, here defined in the acoustic impedance and Vp/Vs inversion domain. Right: Likelihood of encountering soil type “yellow” on the x-axis and measured cone resistance on the y-axis. The entire CPT measured interval at location NWZ-PCPT-1039 is shown.

Figure 8.19 provides an example of the process used to derive predicted cone resistance values by classifying soil types. This example focuses on two distinct soil types and demonstrates how PDFs are defined to calculate the probabilities of encountering each type. The figure furthermore illustrates the level of correlation between measured cone resistance and soil probability when translating elastic properties into soil classifications.

For this project, a set of 8 PDFs were developed and applied to capture the various soil behaviors present at the site. Figure 8.20 showcases an example of a predicted cone resistance at a CPT location where Figure 8.21 and Figure 8.22 show the results of predicted cone resistance and predicted sleeve friction along a seismic line.

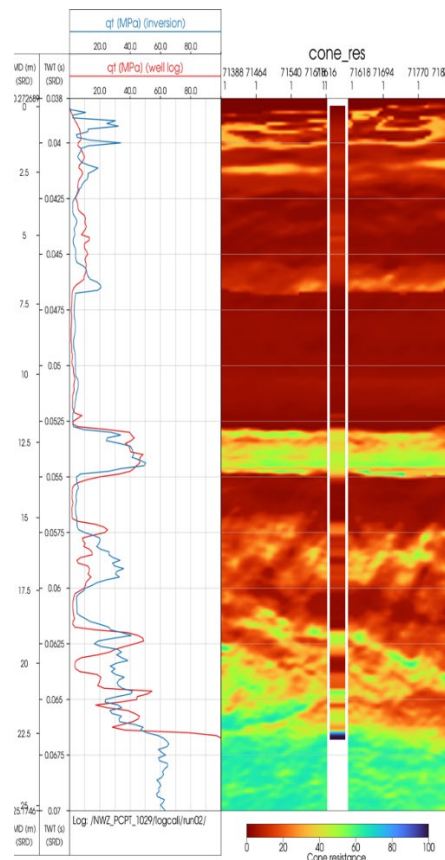


Figure 8.20: Example of CPT prediction at PCPT-1029. Blue curve is the predicted cone resistance, and the red curve is the measured cone resistance. Right part of the figure is a small cross section along the seismic line with the measured CPT in the centre.

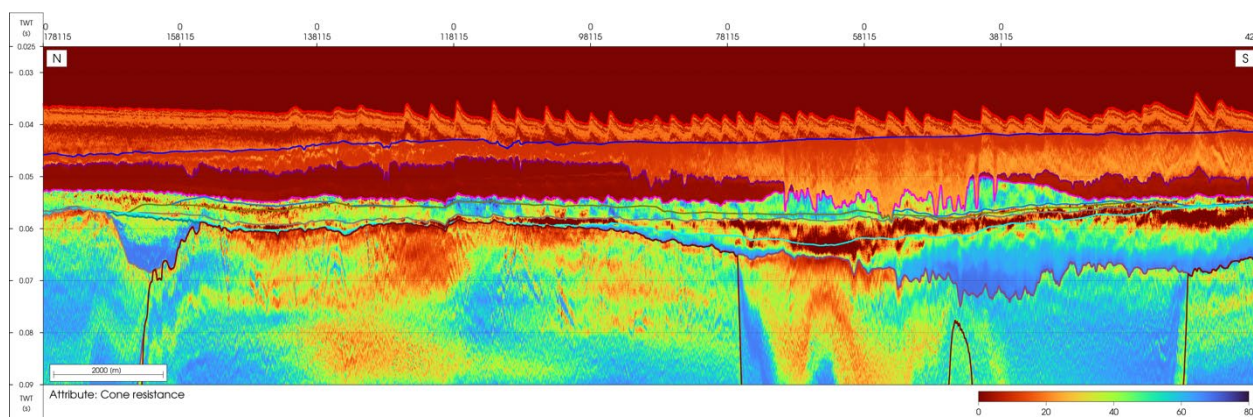


Figure 8.21: Predicted cone resistance along seismic line F199-P1, units in MPa.

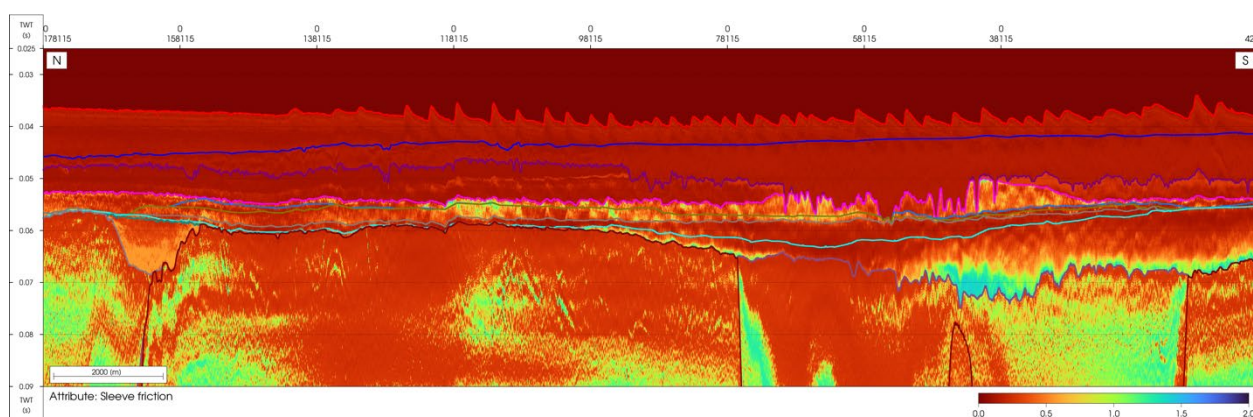


Figure 8.22: Predicted sleeve friction along seismic line F199-P1, units in MPa.

8.4 Uncertainty quantification

Geophysical data is remote sensed, and as such, has various sources of uncertainty built into acquisition, processing and handling prior to analysis. Quantitative inversion processes also introduce further uncertainty, undertaken in preceding inversion steps. Therefore, the predicted result(s) need to take into account all sources of uncertainty and provide an aggregated view.

Sections 8.4.1 to 8.4.4 present five key sources of uncertainty.

8.4.1 Positioning errors

A mismatch can occur between the positioning of seismic measurements and geotechnical measurements, which can lead to additional errors and uncertainties in the results.

As the geotechnical data in most cases are not exactly co-located with the seismic data, the geotechnical data are projected to the nearest trace at the seismic lines. This projection distance will, especially in heterogeneous geology, introduce a natural difference between measured and predicted properties. This is exemplified in Figure 8.24: and Figure 8.25:, where the results from two perpendicular seismic lines are projected to NWZ-PCPT-1009, which is located at the intersection of the two lines.

In addition to projection-related uncertainties, several positioning factors contribute to the overall error. Seismic positioning errors, include uncertainties in the location of reflection points at depth, surface positioning variations, and cable feathering. These all can introduce discrepancies in data interpretation. Furthermore, the scale of the Fresnel zone affects spatial resolution, adding another layer of uncertainty. The assumption of verticality in geotechnical measurements also introduces potential inaccuracies in determining the true subsurface location.

These uncertainties are difficult to quantify precisely and are embedded within the overall uncertainty, often leading to higher perceived uncertainties in the results.

8.4.2 Time-Depth Conversion

The process of converting time measurements to depth is inherently associated with uncertainty, due to potential discrepancies in velocity models or interpretation errors.

Uncertainties arising from time-depth conversion are detailed in Section 4.6 and the GGM (Arup, 2025a).

Errors from here are in part handled through tying CPT data with the seismic, however residual noise will be embedded within the overall uncertainty, resulting in higher perceived uncertainties that may exist.

Quantitative inversion results were converted to depth using a consistent velocity model as applied throughout the project.

8.4.3 Seismic noise

Seismic noise refers to seismic energy that does not follow conventional seismic wave equations which can lead to uncertainty in the final product. This energy was mapped and analysed to optimize seismic data processing and pre-conditioning.

The pre-conditioning steps are aiming at lowering the overall seismic noise, see Section 8.3.2

8.4.4 Prior model

The prior model serves as an initial approximation and, by nature, will contain some inaccuracies. The aim is to make the model as unbiased yet as useful as possible, striking a balance between the two.

Inputs for this model come from geotechnical data and seismic geological interpretation.

The uncertainty contribution from the prior model is evaluated and quantified using the leave-one-out exercise, which provides insight into biased uncertainty.

8.4.5 Uncertainties in CPT prediction

Several sources contribute to uncertainties in the CPT prediction:

- Uncertainty in geotechnical data
- Uncertainty arising from seismic data and inversion processes
- Interpretation of seismostratigraphic units and integration of geotechnical data (see Section 4.6)
- Interpretative challenges in data analysis, which are linked to the understanding of soil physical properties

With a large dataset of CPT points, we can conduct robust statistical analysis, allowing us to accurately quantify uncertainties originating from the data input, focusing on unbiased uncertainty.

8.4.6 Uncertainty calculations

Uncertainty quantification is conducted based on the difference between measured and predicted parameters (q_c , f_s , K and G_{max}) at surveyed locations. The predicted parameter in this exercise is determined using a leave-one-out cross-validation approach. This means the predicted value for a given CPT is derived without any influence from the specific CPT being analysed. In this way, all CPT measurements are treated as blind tests to estimate unbiased errors.

Table 8-2: Uncertainty terms

Designation	Term	Description
C	Predicted Value	Mean predicted value in each soil unit
SD	Standard Deviation	($\pm$) Standard deviation on the prediction error in each soil unit
A, E	Prediction Interval	($\pm$) 95% prediction intervals of the data in each soil unit
B, D	Confidence Interval	($\pm$) 95% confidence intervals on the mean prediction in each soil unit

Within each defined time interval (i) and for each CPT location, the difference ($\Delta p_{i,j}$) between the measured and the leave-one-out predicted values of the parameter, p , is calculated for each TWT depth (z_j) as:

$$\Delta p_{i,j} = p_{measured,i}(z_j) - p_{predicted,i}(z_j) \quad \text{Equation 8-12}$$

The distribution of $\Delta p_{i,j}$ in each defined time interval across all locations is plotted for each parameter in Figure 8.23. Assuming that the error distributions are Gaussian, the following metrics are derived per defined time interval following DNV-RP-C207 (DNV, 2021):

- Mean error: $\hat{\mu}_{\Delta p_i}$
- Standard deviation on error: s_{p_i} :

$$s_{p_i} = \sqrt{\frac{1}{n_i - 1} \sum_{j=1}^{n_i} (\Delta p_{i,j} - \hat{\mu}_{\Delta p_i})^2} \quad \text{Equation 8-13}$$

Where: n_i = the number of samples within the per seismic interval corresponding to a geotechnical soil unit (i).

95% prediction interval (A and E) per property are defined as:

$$p_A = p_{predicted} + \hat{\mu}_{\Delta p_i} - 1.96 \cdot s_{p_i} \quad \text{Equation 8-14}$$

$$p_E = p_{predicted} + \hat{\mu}_{\Delta p_i} + 1.96 \cdot s_{p_i} \quad \text{Equation 8-15}$$

95% confidence interval for the mean prediction (B and D) are calculated based on based on Student's t-distribution following Equation 2.5.1.1 from DNV-RP-C207 (DNV, 2021), with N_i being the number of CPTs penetrating the specific soil unit zone. $1 - \alpha$ being the confidence level (95% in this case corresponding to $\alpha = 0.05$).

$$p_B = p_{predicted} + \hat{\mu}_{\Delta p_i} - \frac{t_{N_i-1}(\alpha) \cdot s_{p_i}}{\sqrt{N_i}} \quad \text{Equation 8-16}$$

$$p_D = p_{predicted} + \hat{\mu}_{\Delta p_i} + \frac{t_{N_i-1}(\alpha) \cdot s_{p_i}}{\sqrt{N_i}} \quad \text{Equation 8-17}$$

The values for the prediction intervals denoted as the A and E bounds for each defined time interval are written in Table 8-3. For the confidence interval on the mean prediction (B and D bounds) the values are written in Table 8-4.

The uncertainty metrics assumes a Gaussian distribution on the error distributions. To assess the goodness-of-fit of the estimated Gaussian distribution to the observed data, we compute the coefficient of determination (R^2), which measures how well the theoretical distribution explains the observed data.

The R^2 statistic is defined as:

$$R^2 = 1 - \frac{\sum(O_i - E_i)^2}{\sum(O_i - \bar{O})^2} \quad \text{Equation 8-18}$$

where:

- O_i is the observed frequency in bin i
- E_i is the expected frequency in bin i (from the fitted Gaussian distribution)
- $\bar{O}$ is the mean of observed frequencies

With an $R^2 \approx 1$ the fitted Gaussian distribution closely matches the observed data, with $R^2 > 0.9$ we have a very good fit, $R^2 \approx 0.5$ a moderate fit and $R^2 \approx 0$ the fitted distribution does not match the observed data. The R^2 for each estimated distribution are also plotted in Figure 8.23.

Out of the 20 distributions presented in Figure 8.23 Eight have an R^2 value between 0.8 and 0.9, indicating a good fit to the Gaussian distribution. Additionally, eleven distributions have an R^2 above 0.9, representing a very good fit.

One distribution has an R^2 below 0.3, specifically the prediction of cone resistance between R05 and R10 (Geotechnical Unit 3), resulting in a poor fit to the Gaussian approximation. However, it should be noted that the cone resistance prediction in this interval performs well overall, as most of the misfit values are very close to zero. Consequently, in this case, the Gaussian approximation leads to conservative uncertainty estimates.

Table 8-3: Estimated prediction interval per seismic interval corresponding to a geotechnical soil unit (A and E bounds)

Base horizon	Seismostratigraphic Units	Geotechnical Soil Units	Sleeve Friction [MPa]	Cone Resistance [MPa]	K [MPa]	Gmax [MPa]
R02/R05	A/B	U1/U2	±0.047	±4.90	±441.90	±19.99
R10	C	U3	±0.042	±3.61	±347.38	±25.72
R20.5	D-1 to 5	U4	±0.177	±17.16	±607.80	±60.33
R25-N.1	E-1	U5-CG or U5-FG	±0.213	±18.41	±683.19	±68.98
R25-N.2	E-2		±0.232	±18.60	±602.31	±73.64
R25-N.3	E-3		±0.286	±21.15	±673.12	±103.72
R25-N.4	E-4		±0.298	±17.95	±719.86	±113.42
R25-S	E-5	U6-CG or U6-FG	±0.298	±17.95	±719.86	±113.42
Below R25_4	F	U7	±0.304	±16.84	±544.85	±96.80

Table 8-4: Estimated confidence interval on the mean prediction per seismic interval corresponding to a geotechnical soil unit (B and D bounds)

Base horizon	Seismostratigraphic Units	Geotechnical Soil Units	Sleeve Friction (MPa)	Cone Resistance (MPa)	K (MPa)	Gmax (MPa)
R02/R05	A/B	U1/U2	±0.0053	±0.549	±49.54	±2.24
R10	C	U3	±0.0047	±0.405	±38.94	±2.88
R20.5	D-1 to 5	U4	±0.0198	±1.924	±68.14	±6.76
R25-N.1	E-1	U5-CG or U5-FG	±0.0239	±2.063	±76.59	±7.73
R25-N.2	E-2		±0.0260	±2.086	±67.52	±8.26
R25-N.3	E-3		±0.0320	±2.371	±75.46	±11.63
R25-N.4	E-4		±0.0334	±2.012	±80.70	±12.72
R25-S	E-5	U6-CG or U6-FG	±0.0334	±2.012	±80.70	±12.72
Below R25_4	F	U7	±0.0341	±1.888	±61.08	±10.85

Table 8-5: Estimated standard deviation on the error (s_{p_i})

Soil Unit	Seismostratigraphic Units	Geotechnical Soil Units	Sleeve Friction (MPa)	Cone Resistance (MPa)	K (MPa)	Gmax (MPa)
R02/R05	A/B	U1/U2	±0.024	±2.50	±225.46	±10.20
R10	C	U3	±0.021	±1.84	±177.24	±13.12
R20.5	D-1 to 5	U4	±0.090	±8.75	±310.10	±30.78
R25-N.1	E-1	U5-CG or U5-FG	±0.109	±9.39	±348.57	±35.19
R25-N.2	E-2		±0.118	±9.49	±307.30	±37.57
R25-N.3	E-3		±0.146	±10.79	±343.43	±52.92
R25-N.4	E-4		±0.152	±9.16	±267.28	±57.87
R25-S	E-5	U6-CG or U6-FG	±0.152	±9.16	±267.28	±57.87
Below R25_4	F	U7	±0.155	±8.59	±277.99	±49.39

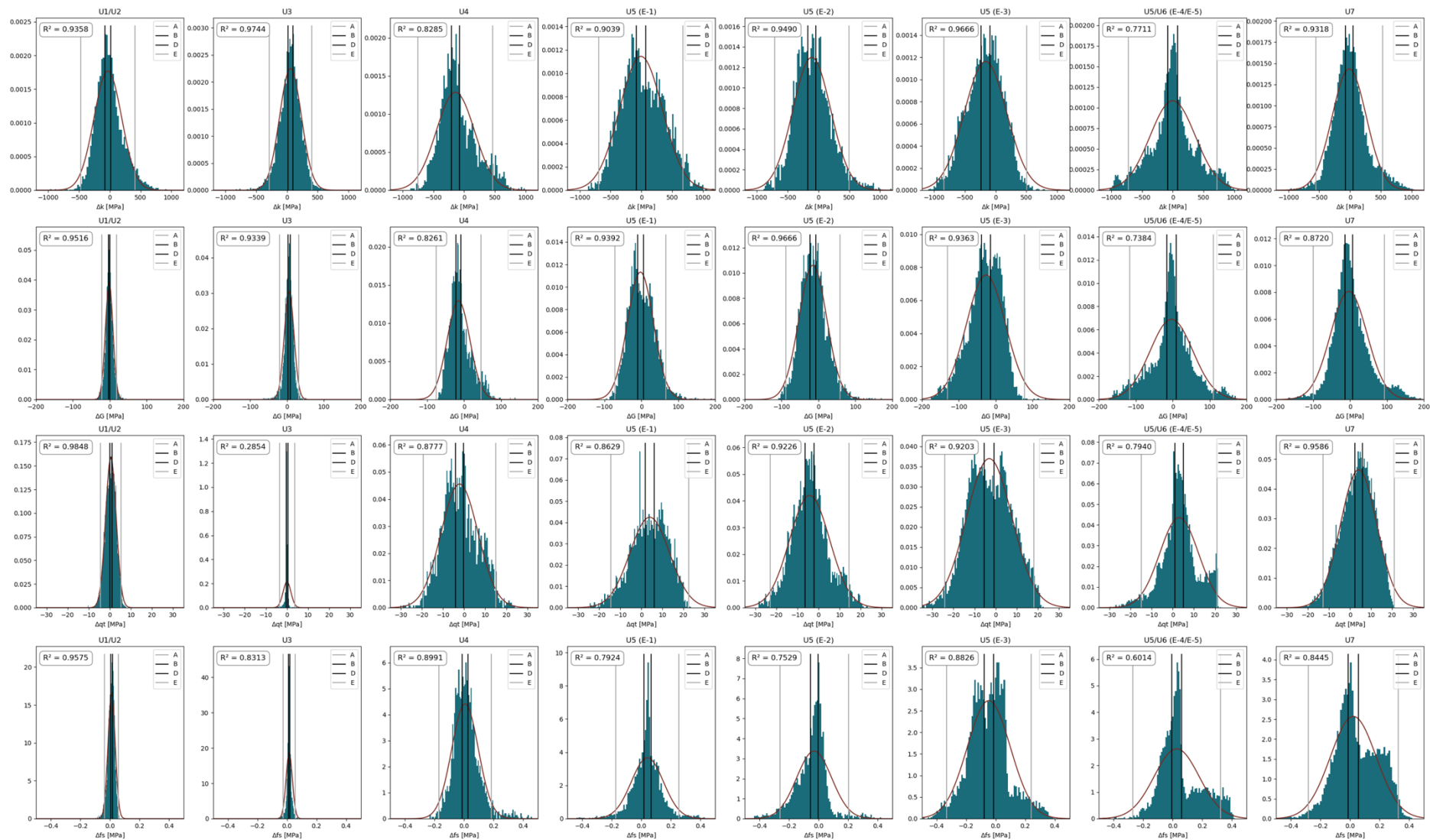


Figure 8.23 Distribution of the unbiased error for different geotechnical soil units. From the top to the bottom, we see the error of Bulk Modulus, Shear modulus, Cone resistance and Sleeve friction plotted. In green we see the distribution plotted with the red curve representing the Gauss curve describing the distribution. The A, B, D and E intervals are plotted on top of at each interval and each property.

8.5 Results discussion

The results of the seismic inversion and the CPT prediction, along with the associated prediction interval (A and E bounds), are presented for four locations in Figure 8.24:, Figure 8.25:, Figure 8.26: and Figure 8.27:.

The analysis involves comparing the bulk modulus and shear modulus from absolute inversion results with elastic properties derived from the individual CPTs. For cone resistance and sleeve friction, the comparison focuses on the seismic-predicted CPT values versus the actual measured CPT values. For validation with measured properties, where no additional modelling is applied, the comparison remains independent of further modelling, thereby reducing uncertainties in this domain. Results of predicted cone resistance and sleeve friction along seismic line F199-P1 are shown in Figure 8.21: and Figure 8.22. Along the seismic line we can follow the spatial distribution of the parameters. Evaluation of the results along the seismic line focuses more on how well the results align with the expected behaviour of cone resistance and sleeve friction and how the imprint, if any, of the prior model is affecting the results.

In general, there is a strong fit between the observed geotechnical data and the results derived from seismic inversion:

Dynamic behaviour:

- The overall dynamics of the seismic inversion results align closely with observations from the geotechnical data.

Event correlation:

- Events demonstrate strong correlation between seismic inversion data and geotechnical data. This is especially evident for the stronger events, which show a consistently high level of alignment.

Seabed definition:

- The seabed is clearly delineated in the seismic inversion results. This indicates a phase relationship between the seismic data and the wavelet.

Side lobe behaviour:

- Side lobes are generally minimal, indicating a consistent phase relationship between the seismic data and the wavelet.

Uncertainty quantification

- Uncertainties presented are unbiased by considering the CPTs measurements as blind evaluation points. Uncertainties are in general increasing with depth.

Predicted CPTs

- Overall, a good match between the predicted and the measured CPTs is observed both in the lower frequency domain and the higher frequency domain. Cone resistance is in general better resolved compared to sleeve friction. Comparison between predicted CPTs and measured CPTs can be observed in Appendix C.

Interpretation of SBT based on predicted CPTs

- Despite the good agreement between the predicted and measured CPTs, in Appendix C, soil characterisation using Robertson (2016) on predicted CPTs is challenging due to the range of uncertainty quantified, especially at depth. The source of the difficulty, in trying to characterise the SBT via predicted CPT data, is the requirement of using several CPT parameters in combination. This will compound the level of uncertainty on the final Robertson (2016) SBT values. The uncertainty on the soil assignment requires only one of the parameters to be overestimated or underestimated and the soils might be mischaracterised by the SBT method. Sensitivity checks should be performed when attempting this exercise for any practical use, please refer to Section 5 for linear correlations of geotechnical data acquired.

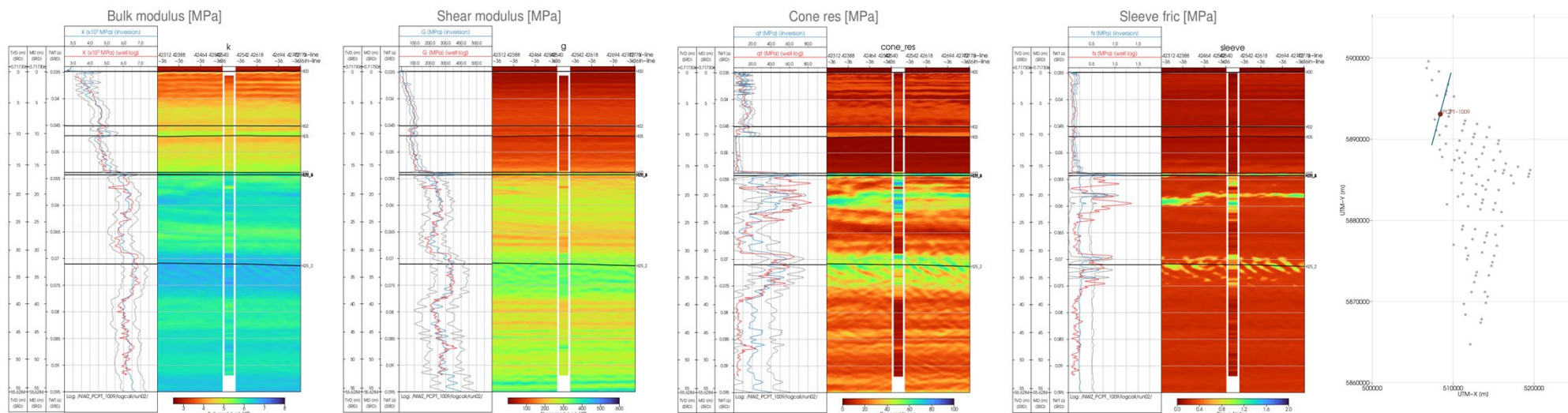


Figure 8.24: Bulk modulus, shear modulus, cone resistance and sleeve friction at PCPT-1009 projected to seismic line B078-P1. Blue curve is the predicted parameter, and the red curve is the measured. Grey curves represent the prediction interval (A and E bounds). Right part of each plot is a cross section along the seismic line with the CPT in the centre.

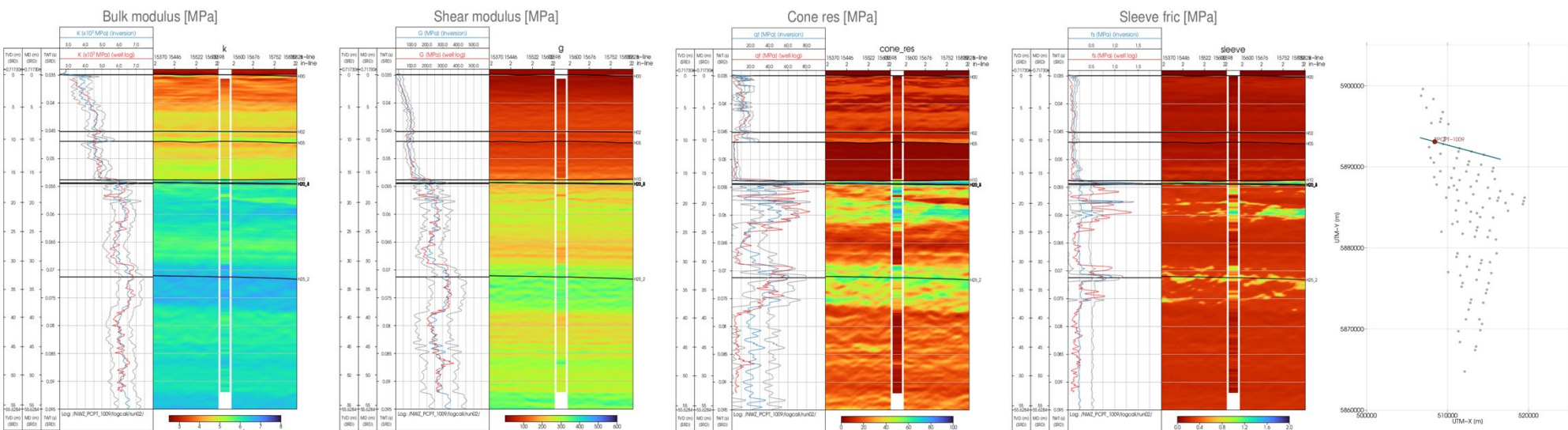


Figure 8.25: Bulk modulus, shear modulus, cone resistance and sleeve friction at PCPT-1009 projected to seismic line X293-P1. Blue curve is the predicted parameter, and the red curve is the measured. Grey curves represent the prediction interval (A and E bounds). Right part of each plot is a cross section along the seismic line with the CPT in the centre.

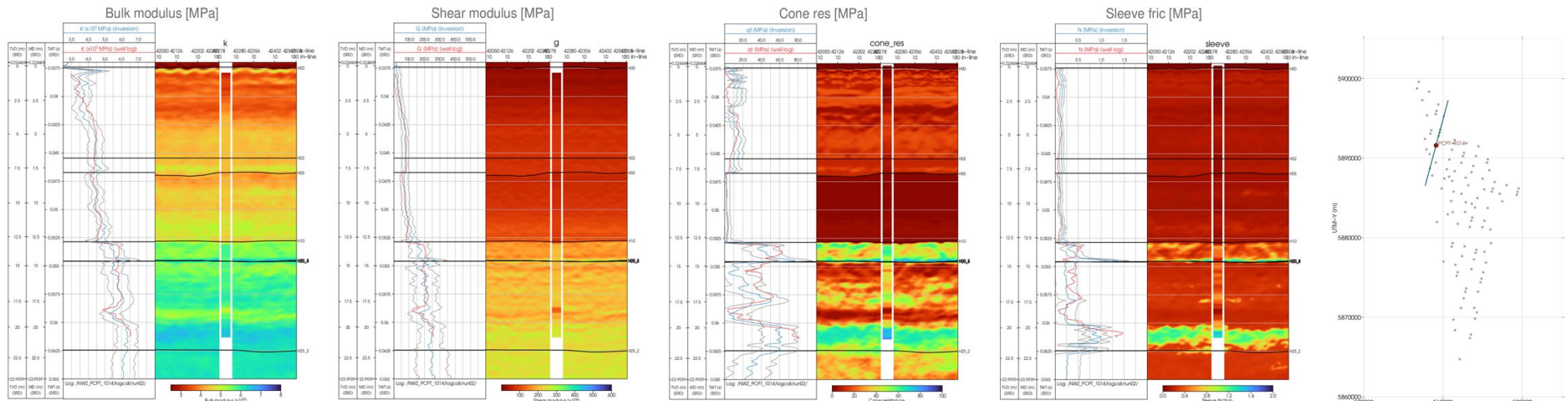


Figure 8.26: Bulk modulus, shear modulus, cone resistance and sleeve friction at PCPT-1014 projected to seismic line B095-P1. Blue curve is the predicted parameter, and the red curve is the measured. Grey curves represent the prediction interval (A and E bounds). Right part of each plot is a cross section along the seismic line with the CPT in the centre.

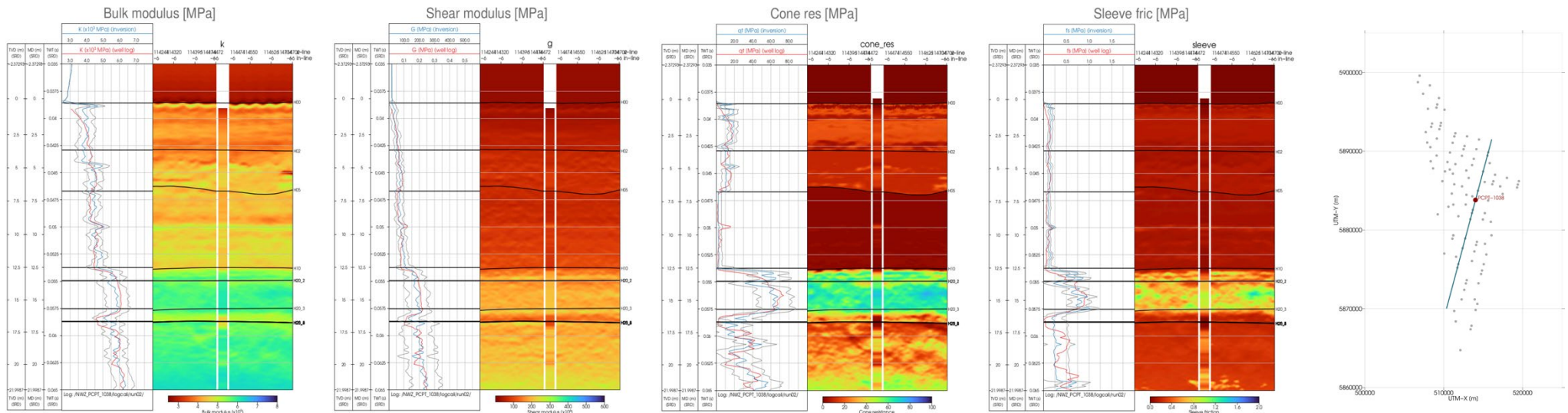


Figure 8.27: Bulk modulus, shear modulus, cone resistance and sleeve friction at PCPT-1038 projected to seismic line F199-P1. Blue curve is the predicted parameter, and the red curve is the measured. Grey curves represent the prediction interval (A and E bounds). Right part of each plot is a cross section along the seismic line with the CPT in the centre.

9. Interpolation of predicted CPT parameters

9.1 Overview

Following the creation of predicted CPT parameters at seismic trace locations in Section 8, this section discusses the methodology and outcome of producing a continuous 3D voxel model of interpolated, predicted seismic inversion (shear modulus) and CPT parameters (cone resistance and sleeve friction).

The purpose of the continuous 3D volume of interpolated predicted parameters (herein referred to as the 3D parameter model) is to maximise the value of intrusive and non-intrusive surveys and provide developers with a preliminary method of assessing the ground conditions for any given location within the NW IIA.

The 3D parameter model should be used by engineering geologists and geotechnical engineers for the purpose of preliminary engineering assessment, for example, in foundation optioneering studies which would be confirmed by further non-intrusive and intrusive surveys.

Note that there is another continuous 3D voxel model which contains the linear correlations discussed in Section 5.3. This model is not discussed further here but is clearly differentiated in the digital deliverables as the ‘linear’ model.

Figure 9.1 provides an overview of the workflow used with a comprehensive methodology outlined in the remainder of this section.

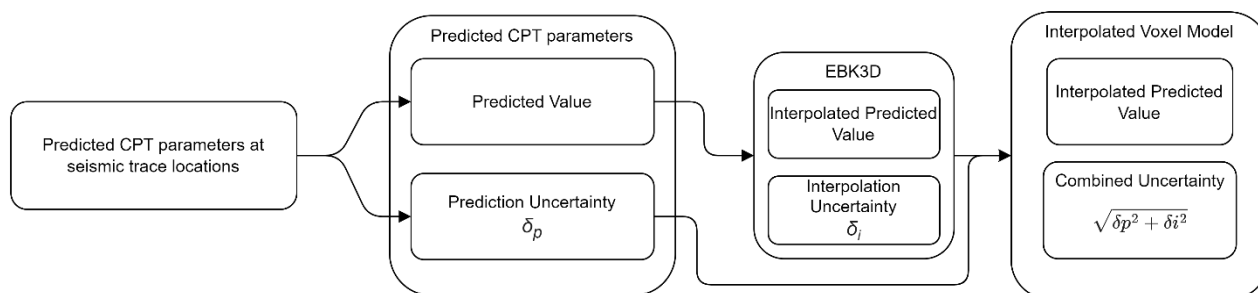


Figure 9.1: Process diagram for creation of a continuous voxel model of interpolated parameters

Uncertainty metrics for predicted parameters generated from seismic inversion (Section 8) were calculated per groups of geotechnical soil unit (see Table 8-1 and Table 8-2:), therefore the uncertainty metrics have not been interpolated as they can be assumed to be constant across the site for each soil unit.

Unlike the prediction uncertainty the interpolation uncertainty is unconfined by soil units and there is one value of interpolation uncertainty per voxel (i.e., each prediction location (voxel centroid) has one value of interpolation uncertainty). This variable interpolation uncertainty is combined with the constant soil unit prediction uncertainty to create a cumulative uncertainty metric, referred to in the model as the ‘combined uncertainty’.

9.2 3D interpolation methodology

9.2.1 Data manipulation

The outputs of Section 8 comprise predicted seismic inversion and CPT parameter values (cone resistance, sleeve friction, shear modulus, and bulk modulus) in 2D SEG-Y format:

The 3D interpolation methodology requires the input to be in 3D point format. To create the 3D point dataset we developed an Extract, Transform, Load (ETL) pipeline on the Databricks platform which followed the following process:

- Unpack SEG-Y data using the SEG-YIO (Equinor ASA, 2025) python library and store the data as parquet files.
- Transform the data in the parquet files by performing down-sampling on the data.
 - This was required to make the data manageable for the interpolation process. More information is provided in the down-sampling strategy below.
- Store the predicted data in a table which can be queried or downloaded.
- Download the tabular data from Databricks and transform to geospatial 3D point data.

9.2.2 Data down sampling

Once transformed, the prediction data provides an incredibly dense network of 3D points. Theoretically any interpolation process will produce more accurate results with a higher resolution of input data however a trade-off needs to be made between computational resources, processing time, and accuracy of the interpolation output.

Therefore, a “down sampling” strategy was devised to strike a balance between accuracy and speed of the interpolation. The down sampling involved a reduction in the number of traces along a seismic line and the number of samples within a trace. These were reduced by a constant factor across the full dataset.

Figure 9.2 provides a schematic visualisation of the down sampling strategy in plan view. The original SEG-Y data provided a trace every 0.50 m along the seismic line. We have down-sampled by a factor of 5 to leave a trace every 2.5 m, in the diagram the larger red points are the points retained following down-sampling.

Similarly, the sampling rate down each trace has been down sampled by a constant rate of 5. The original sampling rate was 0.05 m over the range 0 – 100 m. The down sampled rate is 0.25 m, shown in Figure 9.3.

Statistical outliers have not been removed from the prediction dataset that is used in interpolation. This is because we cannot be confident that any outliers in the prediction dataset do not reflect real site conditions, e.g., a lens of stiff material in a soft soil may appear as an outlier statistically but geologically is valid. On a dataset of this size the removal of outliers may incorrectly remove valid data.

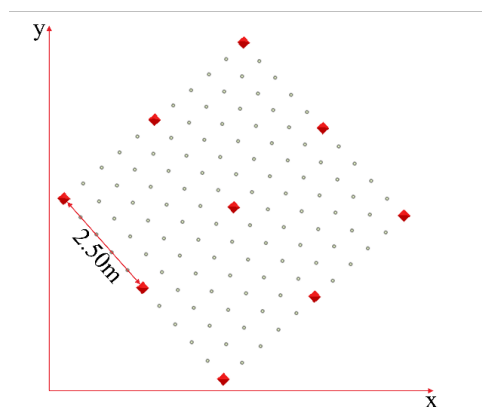


Figure 9.2: Visualisation of data down sampling in plan view

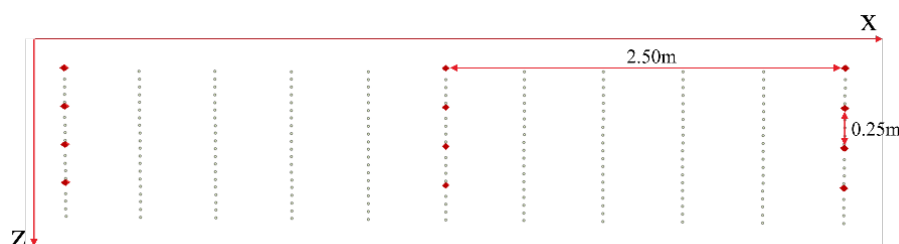


Figure 9.3 Visualisation of data down sampling in cross section

The down sampled data maintains a high resolution in the context of the full investigation area and provides a suitably dense grid of data on which to perform interpolation.

9.2.3 Interpolation method selection process

A review of 3D interpolation methods was carried out to determine the most suitable interpolation methodology to use and which software to conduct the interpolation in. As quantification of uncertainty is a key requirement in the development of the IGM it was decided to use kriging interpolation, as opposed to techniques such as Inverse Distance Weighting, which do not provide uncertainty measures. Kriging methods provide both an interpolated value and an associated uncertainty.

This interpolation uncertainty is combined with the prediction uncertainty developed as part of Section 8. Further detail on the combination and propagation of uncertainty quantification is provided in Section 9.3.

Following a literature review of kriging methods the decision was made to use a proprietary ESRI method of 3D kriging called 'Empirical Bayesian Kriging 3D' (herein referred to as EBK3D). This method was selected over traditional kriging methods (ordinary kriging, simple kriging etc.) because it divides the data into subsets and empirically creates the optimum semi-variogram for that subset.

Given the size of the investigation area and the quantity of data being used in the interpolation it was not deemed suitable to determine one semivariogram model and use it for the whole site.

We considered EBK3D to be preferable to traditional kriging methods because:

- One semi-variogram is not being used to perform predictions over the full NW I IA, instead semivariograms are produced empirically for smaller subsets of the data and the user can determine the subset size and overlaps between subsets; and
- Minimal subjective input is required for the semi-variogram modelling meaning there is less chance of cognitive bias.

Confined or unconfined interpolation

Aligned to the decision of interpolation method is the decision of whether to run the interpolation unconfined or confined by the geotechnical soil units.

Confining the interpolation by the geotechnical soil units (i.e., subsetting the data into a 3D point layer per unit) may provide a quicker and less computationally demanding interpolation, however there is concern about how the interpolation will perform at the boundaries of soil units especially in thin units that are non-laterally continuous or relatively steep sided units such as the vertical boundary of tunnel valleys.

Allowing the interpolation to run unconfined by geotechnical soil unit is considered to provide a better interpolation of the predicted parameter data.

Once the interpolation is completed and the resultant geostatistical layer was converted to a voxel model, the geotechnical soil units can be evaluated against the voxel model meaning that although the interpolation has run unconfined by geotechnical soil unit boundaries, the geotechnical soil units can be included in the output voxel model.

9.2.4 EBK3D interpolation variable selection

Within EBK3D the user can manipulate several variables that inform the speed and accuracy of the interpolation.

Some interpolation variables were set as fixed values based on our understanding of the interpolation methodology and the regularly gridded nature of the input data whereas others were determined based on sensitivity analyses.

Three 15km² trial areas were defined and the purpose of these trial areas was to run interpolations on smaller sections of the data as this reduces the processing time required for sensitivity analyses.

The three trial areas were the Northern Tunnel Valley (NTV), Southern Tunnel Valley (STV), and General (GEN), shown in Figure 9.4. The trial areas were selected as they are geographically separate and provide a suitable representation of the geological variability of the NW I IA:

- NTV – A section of a tunnel valley with a sedimentary fill subdivided into seismostratigraphic subunits E1 to E5 that together comprise geotechnical soil units U5-CG/FG and U6-CG/FG. The tunnel valley is overlain by seismostratigraphic units A, B, C and all subunits of D, correlating to geotechnical soil units U1, U2, U3, and U4-CG/FG. Where the base of the tunnel valley is within the depth of interest it is underlain by seismostratigraphic unit F, correlating to geotechnical soil unit U7.
- STV – A section of a tunnel valley with a generally homogenous sedimentary infill, seismostratigraphic subunit E5, geotechnical soil unit U6-CG/FG. The tunnel valley is overlain by seismostratigraphic units A, B, C and all subunits of D, correlating to geotechnical soil units U1, U2, U3, and U4-CG/FG. Where the base of the tunnel valley is within the depth of interest, or beyond the lateral margins of the tunnel valley seismostratigraphic unit F is present, correlating to geotechnical soil unit U7.
- GEN – A section of the site where seismostratigraphic subunits A, B, C, and all subunits of D sit directly above seismostratigraphic unit F, correlation to a geotechnical soil unit sequence of U1, U2, U3, U4-CF/FG, U7.

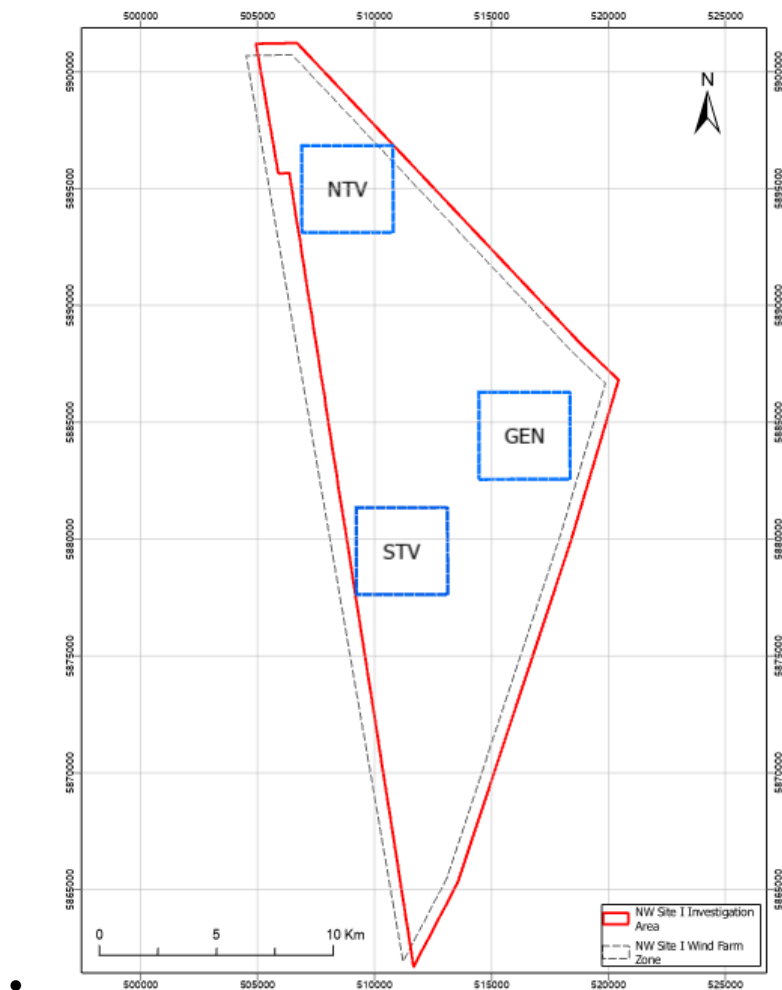


Figure 9.4: Interpolation trial locations

The following sections discuss the variables which can be set in the EBK3D process and those selected.

Semivariogram model & data transformation

EBK3D employs an automated, iterative process to model semivariograms, minimizing the need for subjective input. While many traditional geostatistical interpolation methods and software can automatically estimate parameters, EBK3D enhances this process by simulating multiple semivariograms and averaging them. This approach reduces the potential for human error and provides a more objective, data-driven method for building the semivariogram used in interpolation, inherently accounting for uncertainty in the subset data.

The process begins with a subset of the full dataset, from which a semivariogram is calculated based on the selected semivariogram model. This semivariogram is then used to perform unconditional simulations, generating new data at the input locations within the subset. These simulations create a series of semivariograms, each based on a different realisation of the data. The number of semivariograms generated depends on the number of simulations specified by the user.

Each new semivariogram is incorporated into the Bayesian framework. This iterative process allows for a continuous refinement of the model. Once all simulations are completed, the tool takes a weighted average of the generated semivariograms. When required, this averaged semivariogram is then used to predict a value at an unknown location, ensuring that the final model incorporates the range of possible behaviours in the data.

By using multiple simulations and averaging the results, EBK3D effectively incorporates uncertainty into the interpolation process. Each simulation represents a plausible scenario of how the data might behave, and by averaging the results, the tool ensures that the semivariogram used for interpolation is more robust. This approach helps provide a more reliable and comprehensive understanding of the spatial variability in the data.

Based on the information above, the user must select a semivariogram model. The tool provides a choice of several models (esri, 2024); we have chosen to use an exponential semivariogram model. Exponential semivariogram models are commonly used in interpolation of geological phenomena as they are well suited to modelling data that has a strong short-range spatial correlation (i.e. data points which are close to each other in space tend to have similar values).

In the context of EBK3D, data transformation can be used to stabilise variance and make the data more closely follow a normal (Gaussian) distribution. However, in this analysis, data transformation was deemed unnecessary. Although the dataset does not strictly follow a Gaussian distribution, EBK3D is capable of handling moderate non-Gaussian distributions by simulating multiple semivariograms and averaging them. The decision not to transform the data was based on an assessment that the existing data characteristics are adequate for producing reliable interpolation results.

Maintaining the original data distribution can be advantageous as it preserves the inherent characteristics and relationships within the data. EBK3D is robust enough to handle data that may not perfectly adhere to a Gaussian distribution, allowing for effective modelling and interpolation without the need for transformation.

By not transforming the data, we avoid introducing potential biases or distortions that could arise from the transformation process. This approach aligns with the objective of maintaining data integrity and leveraging the strengths of EBK3D in modelling and interpolating spatial data.

Subset Size, overlap factor, and number of simulations

The subset size determines how many data points to group together when empirically calculating the semivariogram models, as explained above. The subset size, as with other variables, strikes a balance between accuracy and computational efficiency.

Theoretically smaller subset sizes can capture local variations in the data (and thus geology) which would be lost with a larger subset size. However, the opposite is true in that if your subset size is too small you risk missing macro trends in your data.

We have used a subset size of 1000 data points. Given the density of the down-sampled data and after the elevation inflation factor is introduced, (see below), this subset is deemed an appropriate size to capture a suitable amount of resolution.

The overlap factor controls the degree of overlap between subsets. For the final process an overlap factor of 1.5 was used, meaning each point falls into an average of 1.5 subsets. This was chosen as a lower overlap factor reduces processing time and the overlap factor has increased importance when you have sporadic data. As we have consistent and plentiful data it was deemed that only a low overlap factor was required.

The number of simulations refers to the numbers of semivariograms that are created per subset. The number of simulations increases processing time so as with other variables a balance needs to be struck whereby you create enough simulations to accurately represent the data; producing too many simulations will increase processing time for minimal added benefit. 30 simulations per subset has been found to be a suitable number.

Elevation inflation factor

EBK3D multiplies the elevation value of a dataset (i.e., data in the z direction) by a constant inflation factor prior to performing subsetting and interpolation and reverses this process once the interpolation is complete.

The purpose of this is to account for the fact that most geographical and geological data varies quicker vertically than horizontally. Geology is a good example of this, where typically formations are laterally continuous but vertically heterogeneous.

Left unset the EBK3D algorithm will calculate an elevation inflation factor on the behalf of the user. Inputting an elevation inflation factor reduces processing time and for the purposes of this study it was considered suitable to use an elevation inflation factor of 20.

Neighbourhood search

The neighbourhood search variables determine, at each prediction location, how many neighbouring data points should be used for interpolation, how far away these data points can be, and how to search for them. The neighbouring data points represent the averaged semivariograms created during the subset/simulation process. The search radius is a linear distance, usually provided in meters, beyond which the tool will not select data points for use in interpolation. The maximum and minimum number of neighbouring points to be used in interpolation can be set, and the tool will stop searching for points to use in interpolation once the maximum has been reached.

The number of sectors within the search radius can also be set. The tool will attempt to balance where it takes neighboring points from to achieve an even distribution between sectors, ensuring that the interpolation is not too heavily skewed by data from one direction. We have used a four-sector spherical search, as shown in Figure 9.5. A four-sector search is deemed suitable for this purpose as the data is gridded.

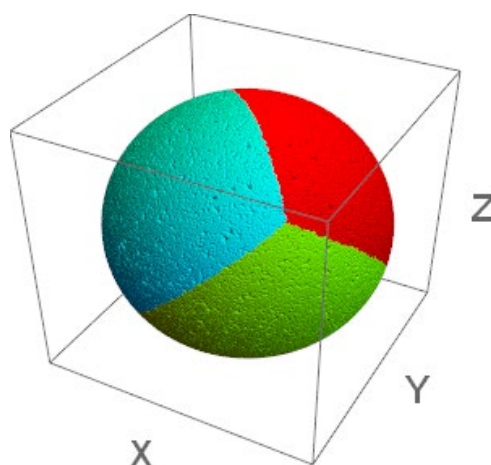


Figure 9.5: Example of a 3D spherical search area divided into 4 sectors (Tetrahedron) – © ESRI

9.2.5 EBK3D interpolation trial results

Traditionally, the success of geostatistical interpolation is assessed using a leave-one-out cross-validation method. Cross validation takes the full input dataset, hides one point at a time, and uses the semivariogram model to predict the value of the hidden point. For each point you can then perform a direct comparison of the predicted value vs. the known, or measured, value.

This cross-validation approach works well for most use cases in 3D interpolation where the data points are sporadically located, as it effectively mimics a prediction at a new location within the spatial extent of the dataset. However, with the regularly gridded nature of the predicted CPT data, this method does not provide a complete picture, only telling us how successful the interpolation is along the grid lines and not in the space within grid lines.

Figure 9.6 shows results from cross validation for interpolation of cone resistance data in the three trial areas. For each trial area approximately 31 million data points were used in the interpolation.

The cross validation produces a number of metrics that quantify the success of the interpolation. The primary metric for comparing the accuracy of interpolation models produced from EBK3D is Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{z}(s_i) - z(s_i))^2}{n}} \quad \text{Equation 9-1}$$

Where:

- $\hat{z}(s_i)$ = predicted value at location s_i
- $z(s_i)$ = measured value at location s_i
- n is the number of measured points

The value of RMSE is given in the units of the interpolated value, in this case MPa for q_c . The RMSE indicates the average error between predicted and measured data across your entire dataset. The interpolation trials returned the following RMSE values:

- STV – 2.87MPa
- NTV – 2.87MPa
- GEN – 3.16MPa

A histogram of normalized prediction error (i.e., (predicted – measured) / measured) is provided for each trial area in Figure 9.6. For each trial area the mean normalized prediction error is 0.00 and the standard deviation of the normalized errors is <1. This is after having removed the top and bottom 1% of data.

The combination of these cross-validation outputs indicate that the interpolation performs extremely well along the seismic gridlines as would be expected due to the density and regularity of the data. This is visualised on the scatter plots in Figure 9.6 where the $\pm 95\%$ CI (BD lines) are so close to the mean prediction that they obscure the 1:1 line.

Interpolation between the gridlines will provide a good level of accuracy however this can only truly be assessed by comparison against future intrusive investigation that is carried out ‘off-grid’.

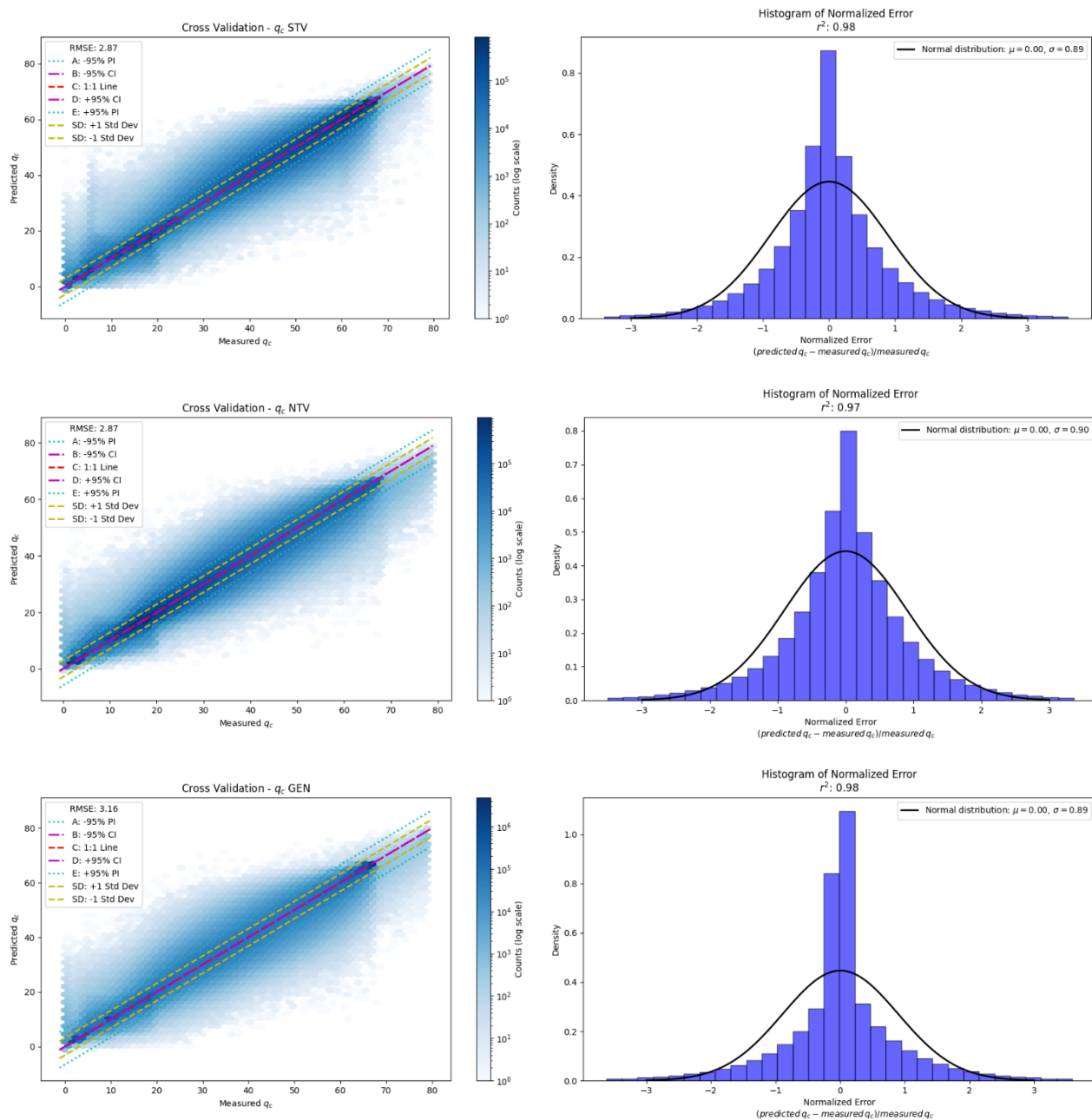


Figure 9.6: Cone resistance (q_c) cross validation results for trial areas.

9.3 Interpolation regions

Due to the size of the site and limits on how much data can be interpolated at a single time it was decided to divide the NW I IA into five overlapping regions, A-E. Prediction data within each region was interpolated separately from the other regions.

Due to the parameters set in the EBK 3D workflow and the localised approach of the methodology this is considered to be an appropriate technique.

Following the interpolation the interpolated predictions and interpolation error for each voxel centroid was accumulated back into one data source, effectively removing the regions. Where a voxel centroid was located with an overlapping region the mean of the interpolated prediction and the interpolation error was taken and these values were used in the voxel model to prevent duplication.

To reduce the size of the final voxel models it was decided to deliver the NetCDF voxel models in regions however these voxel models do not overlap. Refer to Section 10.3 for more information on the division of the final voxel models. Combined, these regional voxel models produce a continuous 3D volume of the site.

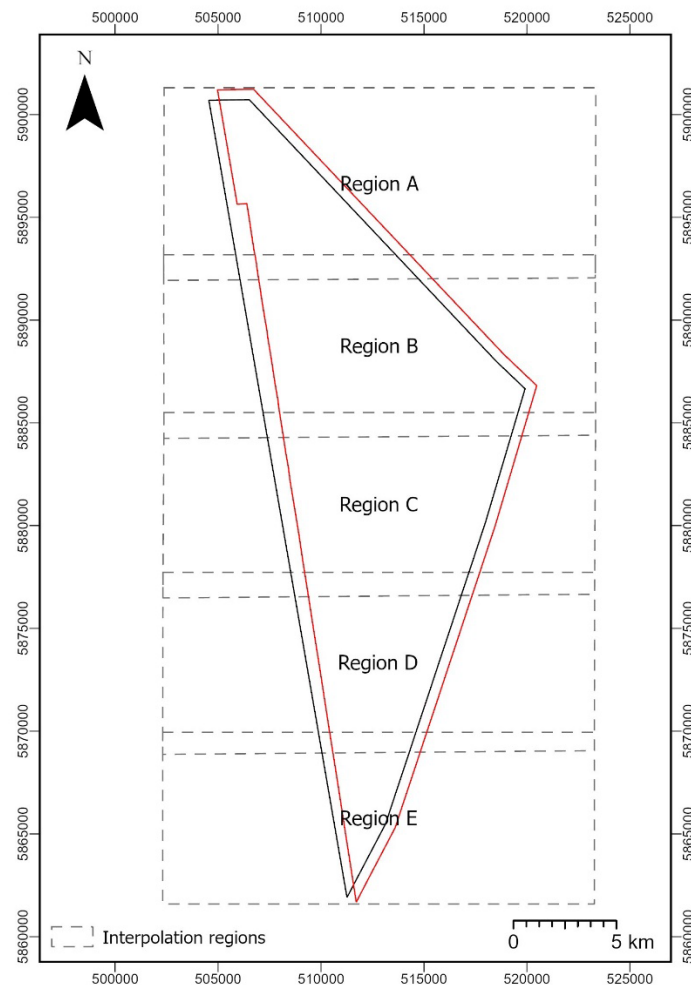


Figure 9.7: Interpolation Regions

9.4 Propagation of uncertainty

The measurement and statistical uncertainty derived in Section 8 is an independent variable calculated externally to the 3D interpolation process.

This means that the prediction uncertainty metric is statistically independent from the interpolation uncertainty and therefore, in line with DNV guidance (DNV, 2021) the squares of the two uncertainty values can be summed to calculate a final level of uncertainty as per the following equation:

$$\delta_{combined} = \sqrt{\delta_p^2 + \delta_i^2} \quad \text{Equation 9-2}$$

Where:

- δ_p = *prediction uncertainty*
- δ_i = *interpolation uncertainty*

In the 3D voxel model that contains the interpolated predicted data per geotechnical soil unit the prediction standard deviation is the uncertainty metric that was used when calculating the combined uncertainty value, refer to Section 8.4 for the values of standard deviation.

Figure 9.8 is an indicative representation of how the uncertainties appear before they are summed on a plot of cone resistance vs elevation.

The graph on the left shows the interpolated predicted parameter, in this case cone resistance, as a solid blue line and this is the same in each graph. The orange envelope surrounding the blue line represents the prediction uncertainty, δ_p . As previously explained the prediction uncertainty is a constant value per geotechnical soil unit hence the width of the uncertainty bounds changes between soil units (grey dash horizontal lines).

The middle graph shows the interpolation uncertainty, δ_i , as a green envelope combined with the prediction uncertainty by simply combining the values $\delta_p + \delta_i$. This graph is for visualization purposes only to show the differences in the two uncertainties.

The graph on the right shows the combined uncertainties, $\delta_{combined}$, calculated as per Equation 9-2 in line with DNV guidance (DNV, 2021). This combined uncertainty is the value that is taken forward to the voxel model.

The expected behaviour of the uncertainty is that the interpolation uncertainty should increase between the gridlines of predicted parameters as the predicted location is farther from the source data. Given that the prediction uncertainty remains constant per soil unit, the variability in the interpolation uncertainty will provide the required variation to communicate that the uncertainty increases away from the gridlines.

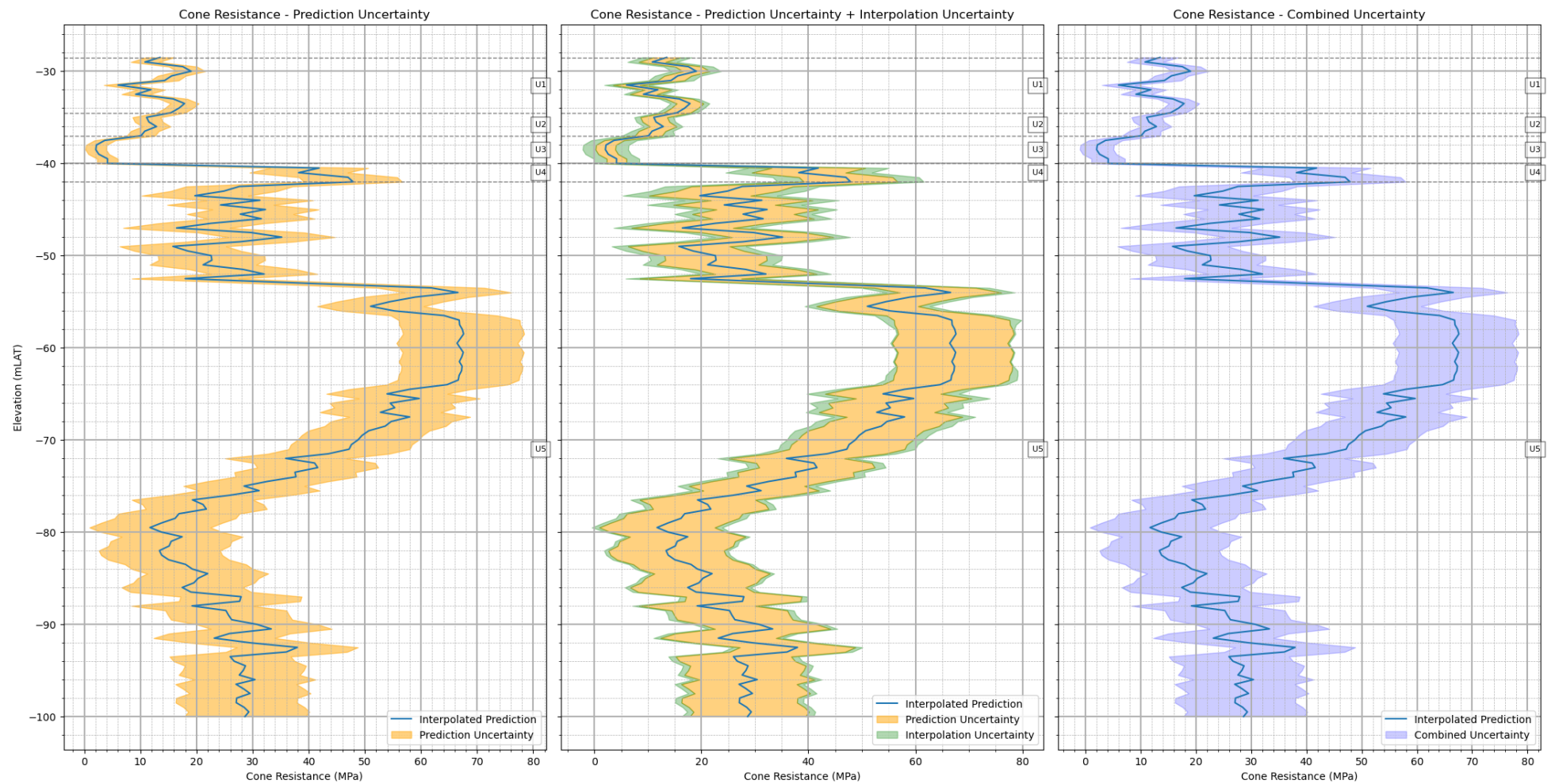


Figure 9.8: Graphical representation of uncertainty propagation

9.5 Conversion to NetCDF voxel model

9.5.1 Interpolated Prediction Voxel Model

The output from EBK3D is an ESRI proprietary 3D geostatistical layer that contains the interpolated predicted values and the interpolation uncertainty.

As this is a proprietary format, we have opted to transform the geostatistical layers to an open format NetCDF voxel model.

The dimensions of the voxel are 20m x 20m x 0.5m. This was chosen as this strikes a balance between providing a useful output for engineering assessment without losing too much resolution during the consolidation of data into voxels.

The technique to extract the interpolation values and the interpolation error is to create a 3D cubic volume of points at the resolution of the desired voxel model, in this case 20 x 20 x 0.5m. One volume of points was created for each region (A - E). Esri provide a tool (GA Layer 3D to NetCDF) to extract the interpolation values and errors to each point location. These points represent the voxel centroids of the finished voxel model.

Each voxel in the interpolated prediction NetCDF model contains the following data:

- Geotechnical Soil Unit
- Seismostratigraphic Soil Unit
- Cone Resistance Interpolation
- Cone Resistance Combined Uncertainty
- Sleeve Friction Interpolation
- Sleeve Friction Combined Uncertainty
- Shear Modulus Interpolation
- Shear Modulus Combined Uncertainty

Whilst NetCDF files can handle strings they work better with, and have a smaller file size when, numerical data is used. Therefore, we have decided to provide a numerical key for the geotechnical and seismostratigraphic soil units, provided in Table 9-1 and Table 9-2.

Users of the NetCDF data in software without pre-processing (e.g., ArcGIS Pro) will need to be cognisant of the numerical lookup and make use of it.

Users extracting information from the NetCDF data using the provided Jupyter Notebook will not need the numerical lookup as the lookup is reversed in the code so the output contains the correct string type unitisation.

Where values are outside of the NW I IA the value of the voxels has been set to NaN or null. This is the case for voxels within the water column as well. In certain software the user may need to filter out NaN values however this is done automatically in Leapfrog Viewer and done on behalf of the user in the Jupyter Notebook used for extracting profiles from the voxel model.

Table 9-1: Numerical key for geotechnical soil units

Soil Unit	Numerical Key
U1	1
U2	2
U3	3
U4	4
U5	5
U6	6
U7	7

Table 9-2: Numerical key for seismostratigraphic units

Seismostratigraphic Unit	Numerical Key
A	1
B	2
C	3
D1	4
D2	5
D3	6
D4	7
D5	8
E1	9
E2	10
E3	11
E4	12
E5	13
F	14

9.5.2 Linear Prediction Voxel Model

The linear prediction voxel model has the exact same dimensions as the interpolated prediction voxel model. Each voxel in the linear prediction NetCDF model contains the following data:

- Geotechnical Soil Unit
- Seismostratigraphic Soil Unit
- Cone Resistance Linear Prediction Fine Grained
- Cone Resistance Linear Prediction Coarse Grained

- Sleeve Friction Linear Prediction Fine Grained
- Sleeve Friction Linear Prediction Coarse Grained

This voxel model does not contain any uncertainty. The linear predictions contained in the voxels are based on the ‘C’ line (i.e., best estimate). Refer to Section 5.3.2 for an explanation of the linear correlations.

Where a geotechnical soil unit has been deemed to be either coarse grained or fine grained then the voxel will not contain a predicted value; where a geotechnical unit is expected to have a balance of coarse- and fine-grained material then a prediction for both coarse and fine grained is provided.

As an example – U1 is considered predominantly coarse grained therefore the voxels for U1 have a prediction for Cone Resistance Coarse Grained but not for Cone Resistance Fine Grained whereas U7 is considered to have a balance of fine and coarse material so a prediction is provided for Cone Resistance Coarse Grained and Fine grained. Table 9-3 below shows which geotechnical soil units are included in the fine and coarse prediction models.

Table 9-3: Linear Prediction Voxel Model Fine/Coarse Grained Split

Soil Unit	Coarse Grained	Fine Grained
U1	✓	
U2	✓	
U3		✓
U4	✓	✓
U5	✓	✓
U6	✓	✓
U7	✓	✓

10. Digital deliverables

10.1 Leapfrog Viewer

A Leapfrog Viewer file is provided with the report. This contains the following data:

Bathymetry.

Borehole data:

- CPT data from the geotechnical campaign.

- CPT data from the AGS data containing predictions of cone resistance, sleeve friction, and shear modulus created at the seismic trace closest to each geotechnical location.

A selection of SEG-Y files containing cone resistance, sleeve friction, and shear modulus predictions created in Section 8.

Meshes of the seismostratigraphic horizons.

Voxel models:

- Interpolated prediction voxel models (Region A – E).

- Linear prediction voxel models (Region A-E).

Cross sections and plan sections as discussed in Section 7.

10.2 AGS

AGS data was produced for the predicted parameters at seismic trace locations as derived in Section 8. Note that the AGS represents the predicted data at seismic trace locations prior to 3D interpolation.

The scope requires that AGS data is provided at each geotechnical location. As the geotechnical locations sit marginally off the seismic lines a Euclidean distance calculation has been carried out to find the seismic trace closest to each geotechnical location and this trace is then represented in AGS format.

For the purposes of easy identification, the trace has been given the name of the geotechnical location it is closest to followed by a suffix of ‘-Prediction’. Therefore, the LOCA_ID for the trace closest to NWZ-BH-5055 will be NWZ-BH-5055-Prediction.

Due to this workflow there is some duplication in the data where one trace is the nearest trace to two geotechnical locations for example.

The following AGS groups have been included in the output:

- PROJ
- ABBR
- DICT
- TRAN
- TYPE
- UNIT
- LOCA
- GEOL
- SCPG
- SCPT

The tables below outline the pertinent or non-standard contents of LOCA, GEOL, and SCPT, and how we intend for these to be used.

Table 10-1 AGS Group: LOCA

Heading	Comments
LOCA_ID	As above, each LOCA_ID carries the name of the closest geotechnical location followed by the suffix ‘-Prediction’ . Prediction AGS has not been created for vibrocore or TCPT locations.
LOCA_GREF	EPSG: 25831 ETRS89 / UTM zone 31N
LOCA_GL	The elevation at which cone resistance prediction values are non-zero (i.e., seabed).
LOCA_REM	A statement containing the relevant seismic line and CDP of the trace to allow users to cross-reference with SEG-Y files.

Table 10-2 AGS Group: GEOL

Heading	Comments
GEOL_TOP	Top depth of soil unit below ground level (LOCA_GL).
GEOL_BASE	Base depth of soil unit below ground level (LOCA_GL).
GEOL_GEOL	Geotechnical soil unit which can be referenced against Section 8 to assign prediction uncertainty metrics to the predictions provided in SCPT.

Table 10-3 AGS Group: SCPT

Heading	Comments
SCPT_DPTH	Depth below ground level (LOCA_GL).
SCPT_RES	Cone resistance predictions.
SCPT_FRES	Sleeve friction predictions.
SCPT_BM	* Note – non-standard field, refer to DICT group. Bulk modulus predictions.
SCPT_SM	* Note – non-standard field, refer to DICT group. Shear modulus predictions.

10.3 NetCDF voxel model

As discussed in Section 8 the interpolated predicted parameters (q_c , f_s , and G_{max}) and linear predictions of cone resistance and sleeve friction are delivered in a series of NetCDF voxel models.

The voxel models are delivered as standalone .nc files, and are included in the Leapfrog viewer file as block models (Seequent terminology for voxel model).

Neither ArcGIS Pro or Leapfrog provide functionality to produce a graph or series of graphs from a voxel model, therefore we have made the decision to build a free to use tool to extract data and/or graphs from the voxel model(s). This tool is written in Python using open-source libraries is provided as a Jupyter notebook.

The tool takes either a single easting and northing, or a series of eastings and northings via a csv file as inputs and returns a graph/series of graphs in the style of Figure 9.8, as well as a JSON file containing all data used in the production of the graphs.

A user guide is provided in Appendix D explaining how to use the tool.

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Appendix A: 2D UHRS Reprocessing Report



A photograph of a young child with dark hair, seen from the side, looking out towards a landscape with several large white wind turbines under a cloudy sky. The image is framed by a blue border.

Report prepared by: CB
Reviewed by: RW
Approved by: PC

Geophysicist
Operations Director
Geophysics Director

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1. Introduction

1.1 Project Background

As part of the Dutch Offshore Wind Energy Roadmap, the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO) appointed the Arup International Projects Ltd (Arup) led consortium (including BGS, Inosys, RockWave and SolidGround) to develop a Geological Ground Model (GGM) as part of the Geotechnical Interpretation Report (GIR) and Integrated Ground Model (IGM) for the Nederwiek Wind Farm Zone I (Nederwiek I). Nederwiek I is located approximately 100 kilometres (km) from the west coast of the Netherlands. The total capacity of the Nederwiek Wind Farm Zone will be 6000 MW and Nederwiek I aims to have a potential installed capacity of 2000 MW.

This seismic processing report documents the reprocessing undertaken by RockWave with the primary objective to deliver amplitude-variation-with-offset (AVO) compliant pre-stack CRP (Common Reflection Point) 2D Kirchhoff migrated gathers, and associated velocity model, to SolidGround as input for elastic pre-stack inversion. A final stack product was also produced to provide an updated interpretation volume to the “Legacy” processed stack. The seismic data volume consisted of 386 2D lines of ultra-high resolution seismic (UHRS) data, covering 4958 kilometres.

The main body of the report focusses on the final processing workflow but this project involved iterative testing via a Feasibility study (two weeks proof of concept testing on test-lines), Fast Track (delivery of full survey migrated gathers based on Feasibility Study work with improvements), and then the Final Processing which improved on the Fast Track guided by feedback from all project disciplines and based directly on early inversion results from the Fast Track. This iterative and integrated nature of the project significantly helped to achieve the excellent final data quality and ensured that the data would be suitable for inversion ahead of the final delivery.



Figure 1: Nederwiek Wind Farm Zone

1.2 Executive Summary

The reprocessing consisted of four main stages as described below:

1. **Pre-migration processing:** Removal of noise, surface ghosts, source bubble, free-surface multiples, interbed multiples, source and receiver statics.
2. **Velocity model building:** An offline 2D Kirchhoff migration on a sparser 25 m CRP grid was carried out using production demultiple data and a smoothed version of the Legacy (Geophysical Contractor acquired dataset, processed to deliver stack volume and reprocessed to deliver pre-stack gathers in this reprocessing – referred to as “Legacy” throughout) manually picked velocity model. The model was then updated with a layer-based RMS velocity tomographic update based on residual moveout picks on the migrated gathers. The raw tomographic update was converted to interval velocity and smoothed to ensure structural stability of the interval velocities.
3. **Migration and post-migration processing:** 2D pre-stack Kirchhoff time migration using the velocity model updated through tomographic inversion. Time-variant scaling and filtering was applied followed by amplitude-Q (attenuation) compensation, residual demultiple, denoise and redatum from mean-sea-level to lowest astronomical tide which ensured consistency with the Legacy stack volume and interpretations of geophysical horizons.
4. **Stack and post stack processing:** Data were stacked with a 0-30 degree angle mute and mild residual denoise, demultiple, water bottom designation and time variant scaling were applied.

1.3 Key Innovations and Processes

Within the processing sequence, stages that had a significant impact on the final data quality or which required the development of new workflows to optimise the results, are highlighted below:

- **Deghosting:** A novel UHRS deghosting workflow was developed which applied an offline amplitude preconditioning to the data prior to receiver deghosting; this helped to mitigate artefacts observed around very high amplitude (organic) layers.

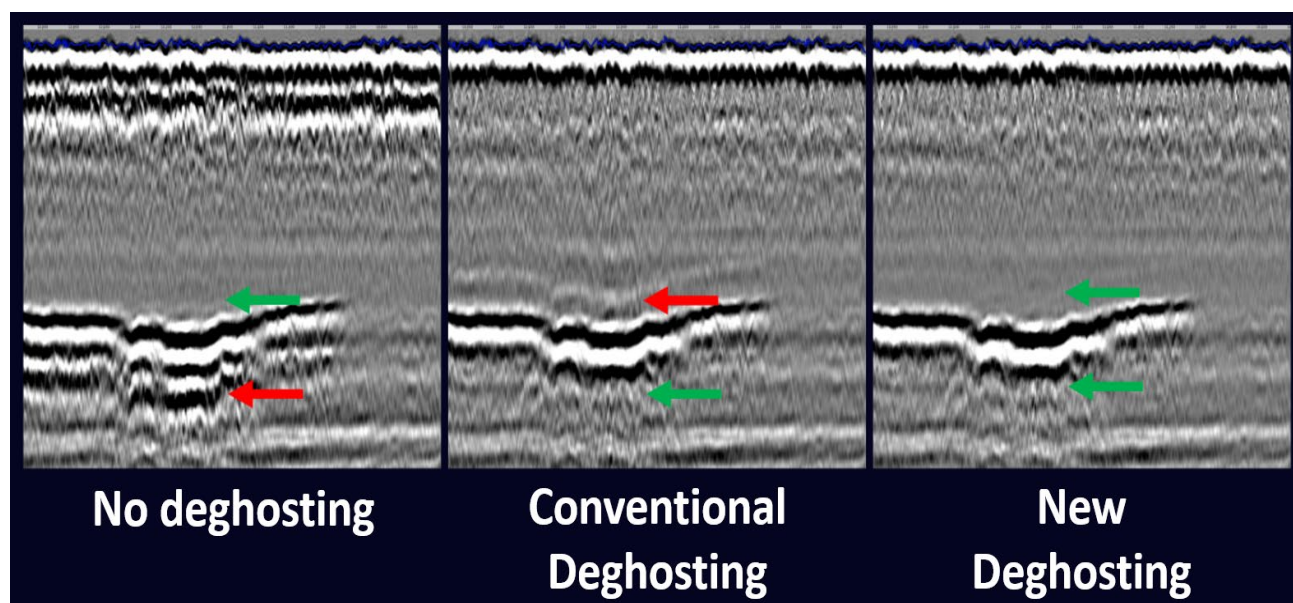


Figure 2: Deghosting around high amplitude organic layers shown on QC stacks

- **Interbed Multiple Attenuation:** Interbed Multiple Attenuation - absent from the Legacy processing sequence – was utilised in the reprocessing. A combination of approaches were used to target multiples in an iterative manner, the most significant of which taking the manually interpreted intermediate horizons provided by the geophysical/geological discipline – at that time named H00, H10 and H20. This integrated approach across disciplines helped to target internal multiple energy, survey wide, in a surgical manner which would not have been possible without interpreted horizons.
- **Directional designature:** Efforts were taken to preserve, improve and monitor amplitude-versus-offset integrity through all processing stages. A novel, UHRS directional designature approach was developed to derive global designature operators in the tau-p domain to account for source signature variation as a function of incidence angle.
- **Amplitude-Q compensation:** Absorption losses led to a relative reduction of higher frequencies with TWT. These were recovered via amplitude-Q compensation which balanced the full bandwidth of the data and maximised resolution.

The below images compare the Legacy GP Contractor stack on which the interpretation was carried out, with the raw stack of the reprocessed gathers for inversion.

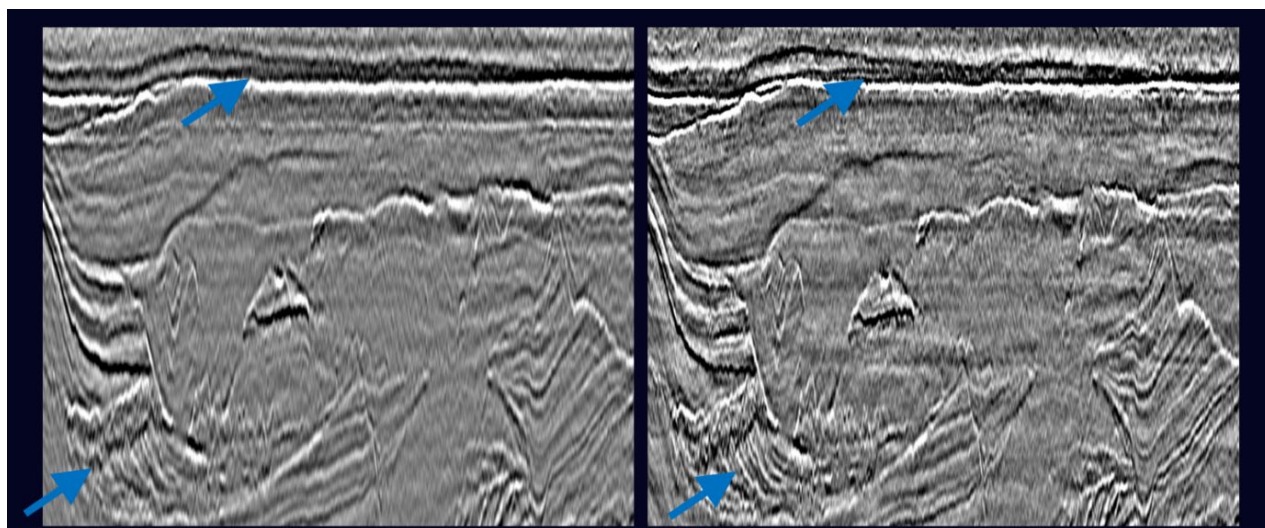


Figure 3: Resolution improvements seen on migrated Full Stacks. Legacy (left), Reprocessing (right)

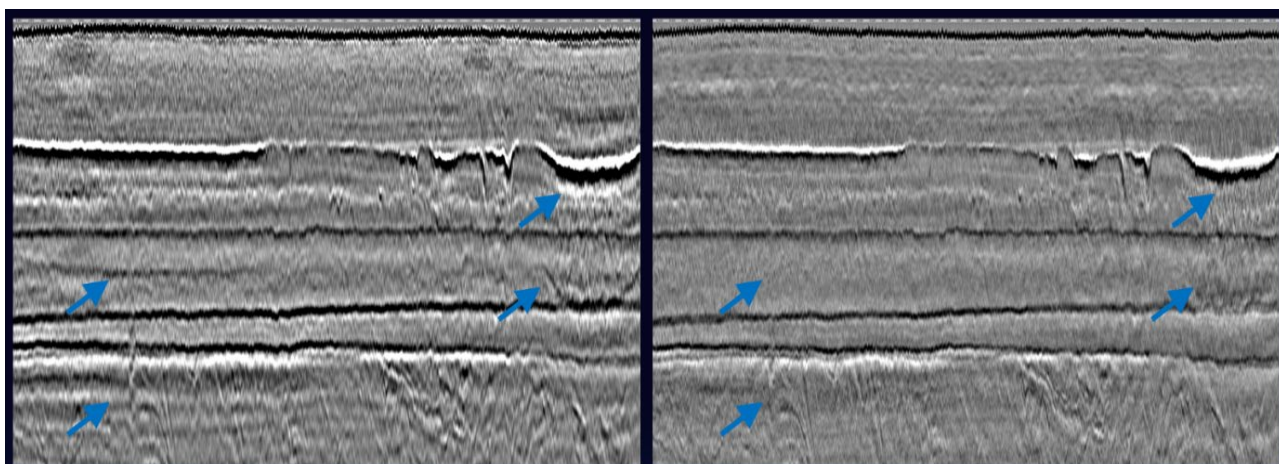


Figure 4: Peat interbed and ringing improvements on migrated Full Stacks. Legacy (left), Reprocessing (right)

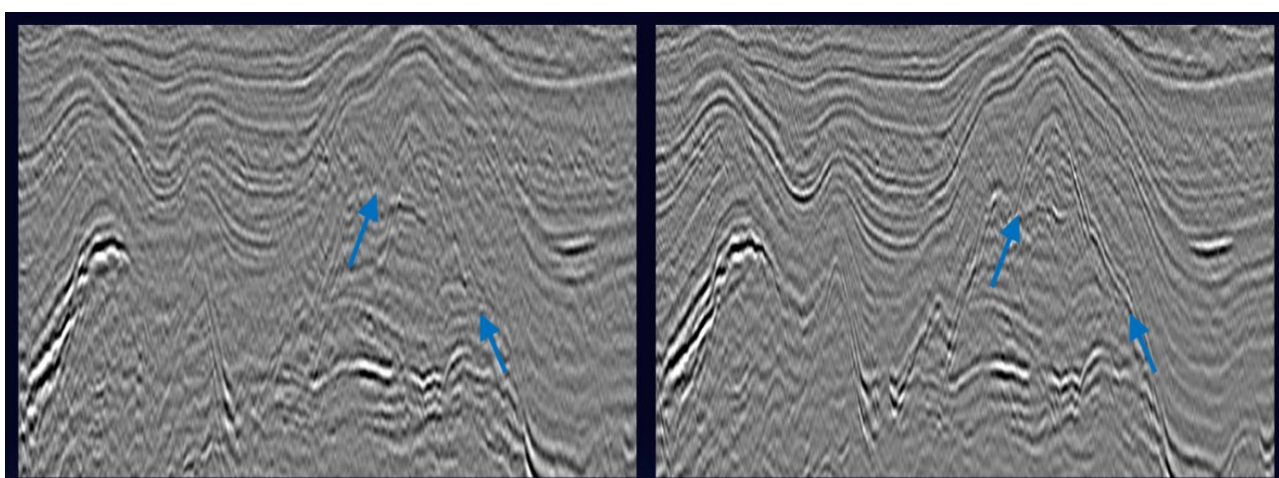


Figure 5: Steep dip imaging improvements on migrated Full Stacks. Legacy (left), Reprocessing (right)

2. Processing

2.1 Introduction

In total, 386 lines of UHRS data were processed equating to 4958 km. The data were acquired in 2023, with a sample rate of 0.125 ms and a maximum record length of 218.75 ms. Shots were fired every 1 m and the receiver spread consisted of a 96-channel streamer with a 1 m hydrophone interval. The line spacing was 65 m for inlines and 420 m for crosslines. A summary of the UHR acquisition parameters can be found in Table 1 and a map of acquired UHR seismic lines is shown in figure 6, along with a map of the picked seabed TWT in figure 7.

Acquisition Parameters	
Vessel	Fugro Discovery
Date of acquisition	January 2023
RECORDING SYSTEM	CNT-2
Sample rate	0.125 ms
Record length	218.75 ms
Recording format	SEG-D 8058 rev 1
SOURCE	MLSS 900J
Number of sources	1 x 3 tip arrays
Power	900 J
Nominal source depth	0.72 m, 0.90 m, 1.12 m
Shot point interval	1 m
STREAMER	GeoEel LH-16
Number of channels	96
Channel spacing	1 m
Inline offset from source	8 m
Lateral offset from source	4 m
Nominal receiver depth	1.4 m

Table 1: UHR acquisition summary.

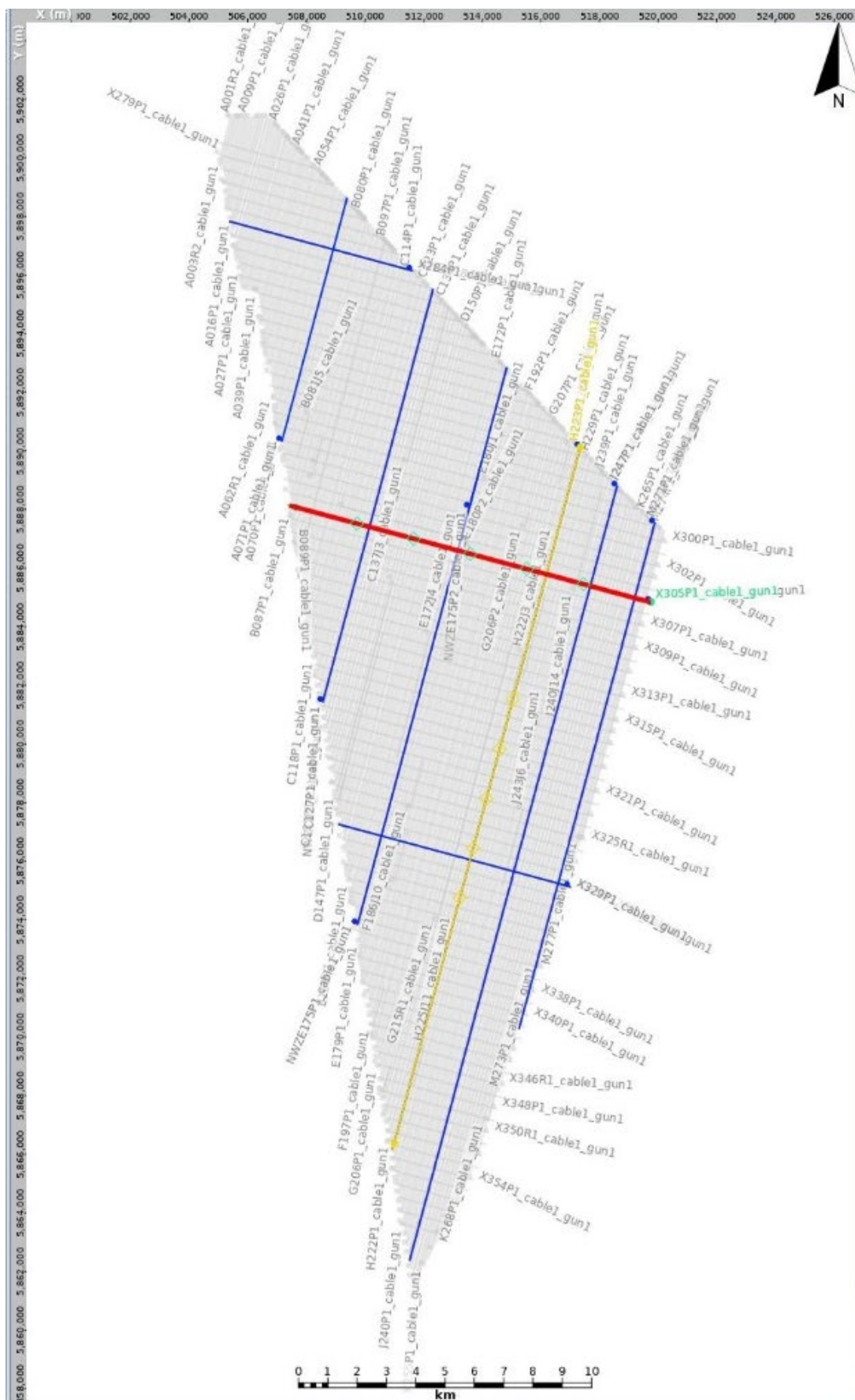


Figure 6: UHR Line Map

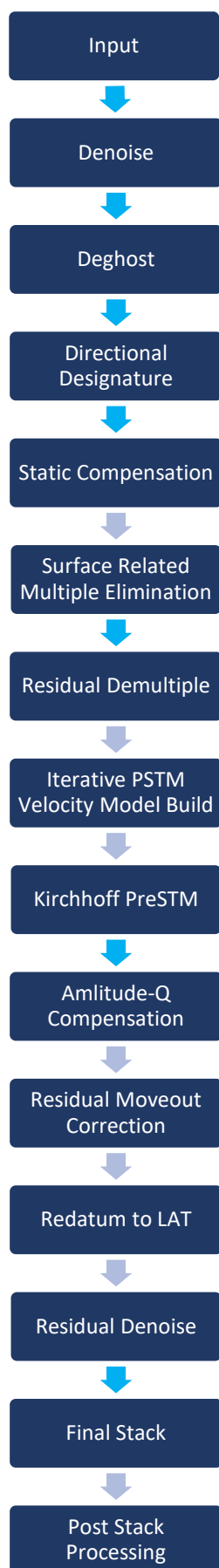


Figure 8: Processing Flow Schematic

2.2 Processing Details

2.2.1 Input

The data were provided in SEG-Y format with trace headers having already been merged with navigation. A thorough QC was undertaken to assess the data, signal quality and noise levels across the survey. This highlighted linear noise, noise spikes, and a small number of erroneous shots and channels.

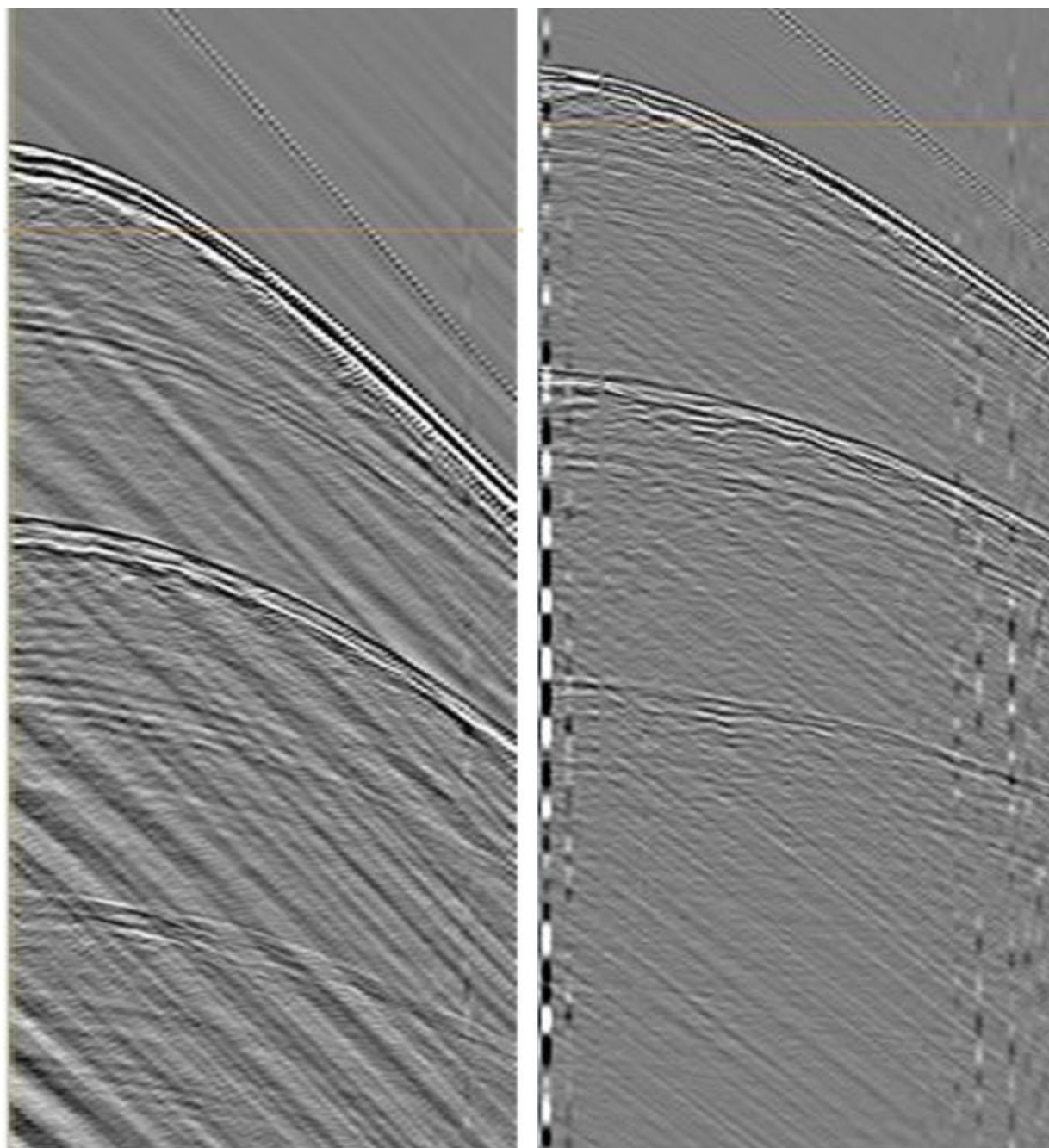


Figure 8: Example of shots with linear noise or spiky swell noise

2.2.2 Denoise

Prior to denoise processing, a t^2 divergence correction was applied to compensate for spherical divergence and transmission losses to better balance amplitudes for processing (this was backed off pre-migration). Acquisition shot and channel edit traces were muted, as were additional edits detected by amplitude thresholding; edited traces were then interpolated in the channel and shot domain respectively.

The main noise types observed within the data were coherent, linear noise and more random, anomalous noise (see Figure 8). Linear noise was attenuated from the data via modelling in the tau-p (slowness) domain, whilst high amplitude, anomalous noise was attenuated through the use of a time-frequency domain median filter algorithm.

2.2.3 Deghost

Ghosts are reflections of the up-going wavefield at the sea surface which are redirected downwards and recorded by the receivers. They cause an extra lobe or “ghost” to trail behind the primary wavelet and are generated on both the source and receiver side of the wavefield, although in practice the receiver ghost is more prominent on UHRS data. The delay time of ghost reflections is determined by the apparent instrumentation depth beneath the sea surface (which is a combination of actual instrumentation depth and sea state) and the water velocity.

Deghosting was performed using *DUG Broad*, which formulates the forward ghost model using the wave equation in the f-p domain, fully incorporating non-linear receiver and/or source depth profiles, and a directional expression of stochastic free-surface reflectivity. *DUG Broad* deghosts all events, offsets, and dips. The algorithm has no dependency on the earth model, other than knowledge of the water velocity.

For receiver-side deghosting, accurate receiver depths for every trace within the survey were calculated from the data through an automated detection of the seabed receiver ghost event on autocorrelations. This delay time was then converted into a vertical receiver depth using a water velocity of 1540 ms^{-1} .

The presence of shallow organic layers exhibiting a very high impedance contrast represented a challenge for deghosting. The very large amplitude contrast observed at these layers resulted in deghosting results with undesirable ghost attenuation and/or acausal artefacts – an effect which is also observed on the legacy processing and feasibility products. To overcome this, an innovative solution was developed to condition the dynamic range of the amplitudes prior to ghost modelling, simultaneously optimising ghost attenuation whilst preventing acausal artefacts (see Figure 9).

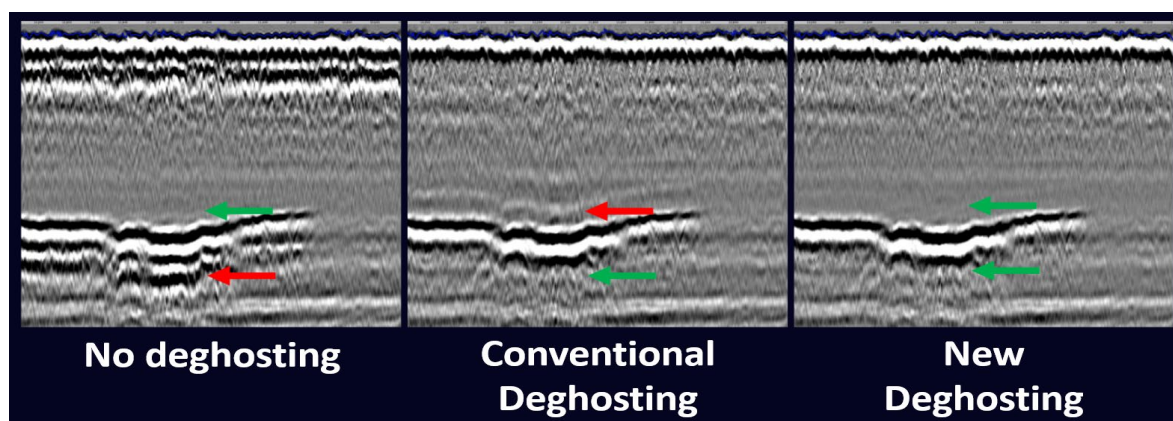


Figure 9: Deghosting around bright organic layers shown on QC stacks

2.2.4 Directional designature

Due to the inherent directivity effect of sparker sources and the AVO-compliant requirements of the processing at the Nederwiek I site, a typical 1D (uniform wavefield assumption) designature operation was not sufficient. To acknowledge the observed variation in the emitted wavefield with angle of incidence, a novel, data-derived directional designature approach was developed whereby designature operators were computed in the tau-p (slowness) domain, where the data are inherently decomposed into unique incidence angles (see Figure 10 for comparison of 1D versus directional designature application).

The directional designature operators were designed in two steps, prior to their application to the data in the tau-p domain;

1. Bubble pulse attenuation operators were computed through a predictive gapped deconvolution, with a gap of 0.375 ms, an operator length of 30 ms and a design window of 200 ms from 0 to 200 ms. Autocorrelations were spatially averaged in the common-p domain over 2001 shots to stack out geology and ensure only elements of the source signature were deconvolved.
2. Zero-phase conversion operators were computed on directional wavelets derived from the global stacking of common-p traces. Following zero-phase conversion of all frequencies, the data is "SEG Normal" polarity, where a central peak represents an increase in acoustic impedance.

Directional Designature

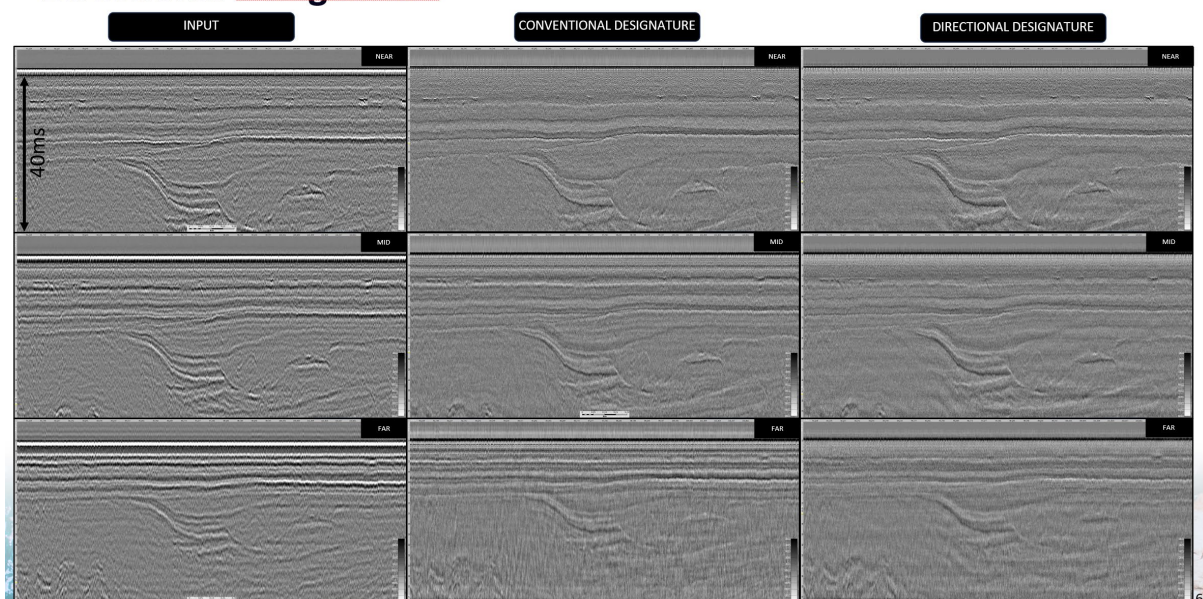


Figure 10: Novel Directional Designature reviewed on near, mid and far

2.2.5 Static Compensation

At ultra-high resolutions, movement of the source and/or receiver instrumentation due to wave motion can have a large impact on the timing of the recorded data, causing static effects which manifest themselves as timing shifts between adjacent traces. These were compensated for by a series of multidimensional cross-correlation analyses which derived static timing shifts for each trace. After application of the timing shifts, alignment of primary energy was significantly improved. This was particularly important on lines acquired during bad weather conditions; for example the testline M271P1.

2.2.6 Surface-related multiple elimination (SRME)

Free surface multiple energy was attenuated through the generation of a data driven, 2D SRME multiple model created using an offset varying half-aperture increasing from 10 m at zero offset to approximately 75 m at far offset (approximately 100 m). Prior to adaptive matching, timing mismatches between the data and SRME model due to sea state dynamics were corrected for through cross correlation analyses. Following alignment, least-squares adaptive matching - performed in a frequency split fashion in the common in channel domain – was applied to the model prior to subtraction.

2.2.7 Residual demultiple

Following SRME, both residual free-surface, and internal multiple was attenuated in a targeted, horizon constrained approach using interpreted horizons supplied by the geophysical/geological discipline. Residual multiple energy was modelled using frequency and dip discrimination from underlying primary energy using the following multiple generators;

- 2 x seabed
- 3 x seabed
- Seabed – H10 interbed
- Seabed – H20 interbed
- Seabed – Shallow organic layer interbed

Note that the geophysical/geological discipline did not interpret the shallow organic layer and so this was automatically detected during processing through amplitude thresholding between the seabed at H10 horizon.

Following this, a time varying high-cut filter was applied to remove residual, high frequency multiple deeper in the section, prior to the removal of the spherical divergence correction (applied in Section 2.2.2 Denoise stage) in preparation for Kirchhoff migration.

The images below show the pre-migration processing flow at different stages on shot gathers.

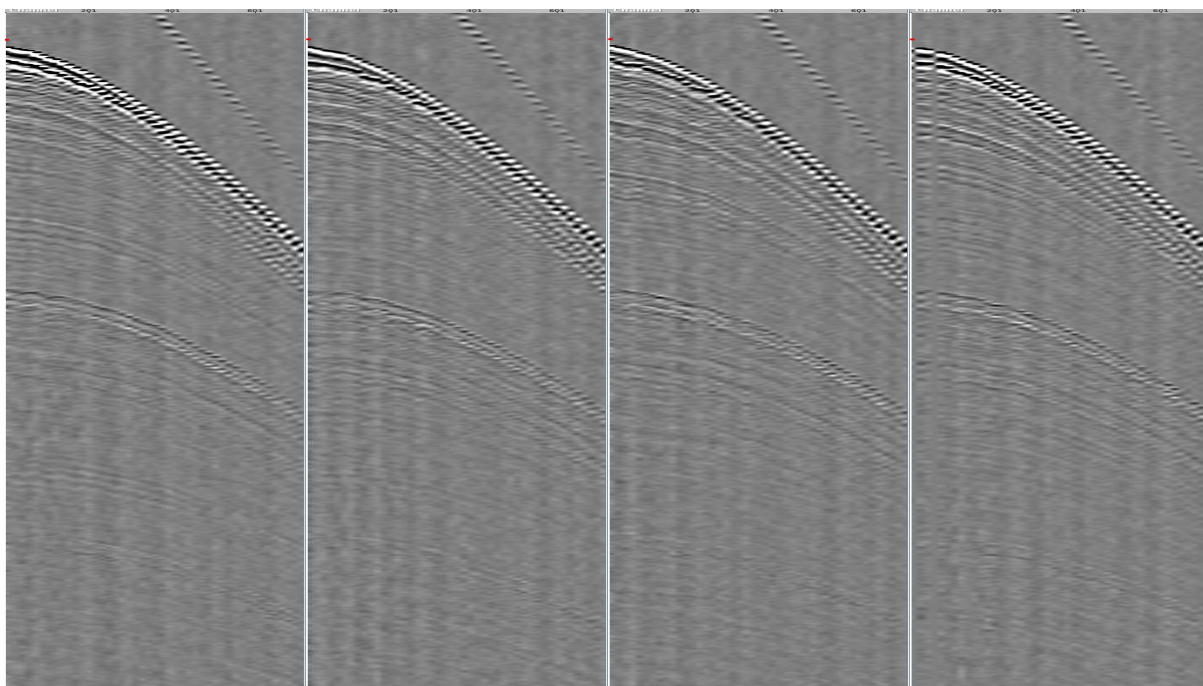


Figure 11: Dataload

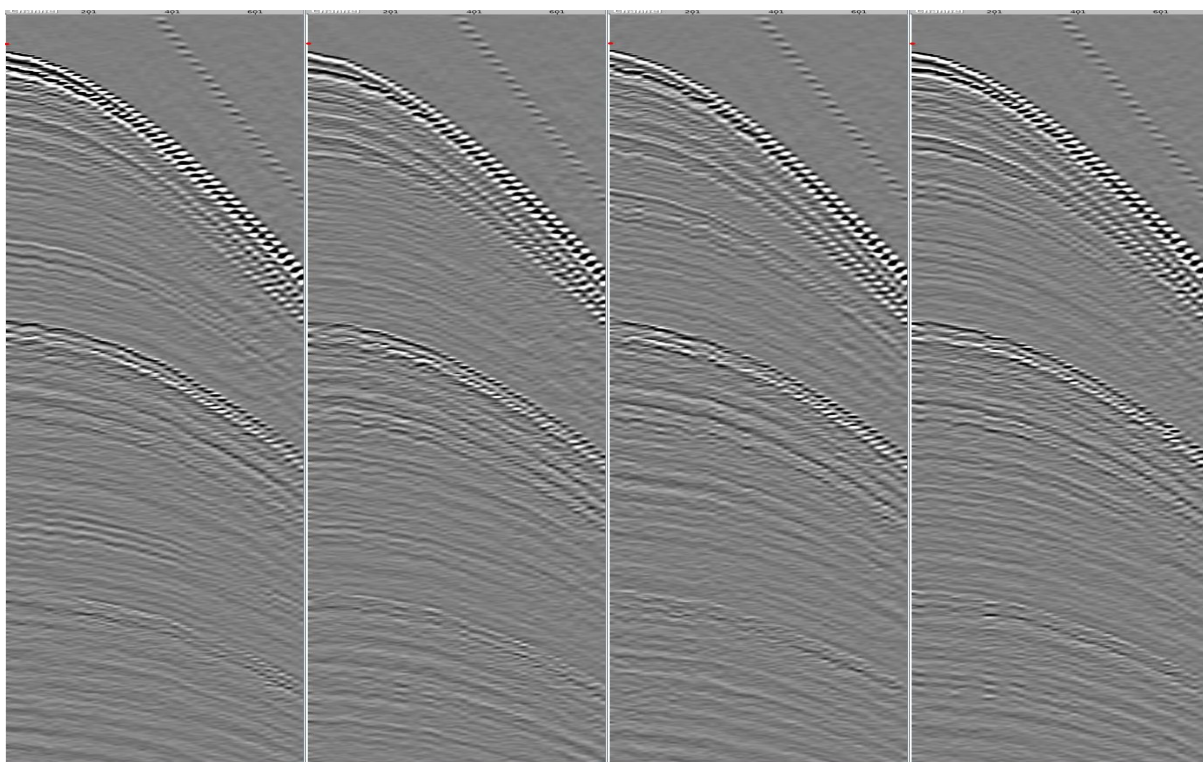


Figure 12: Denoise

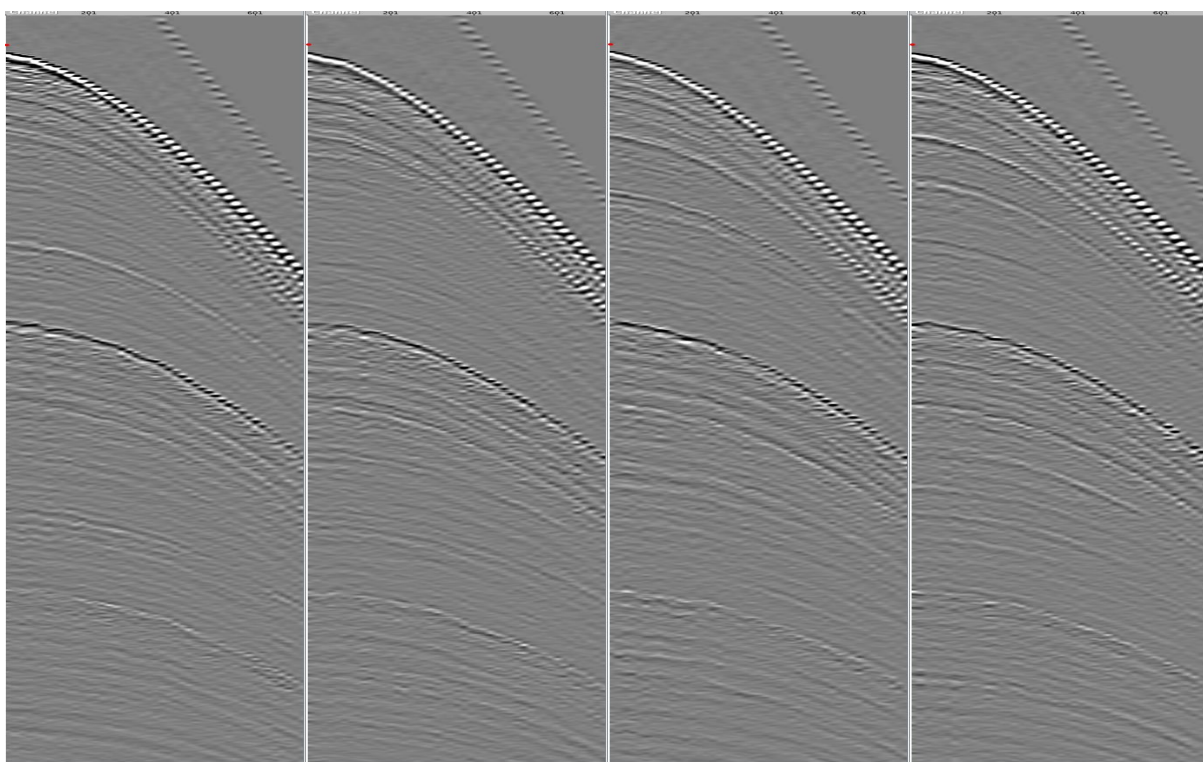


Figure 13: Deghost

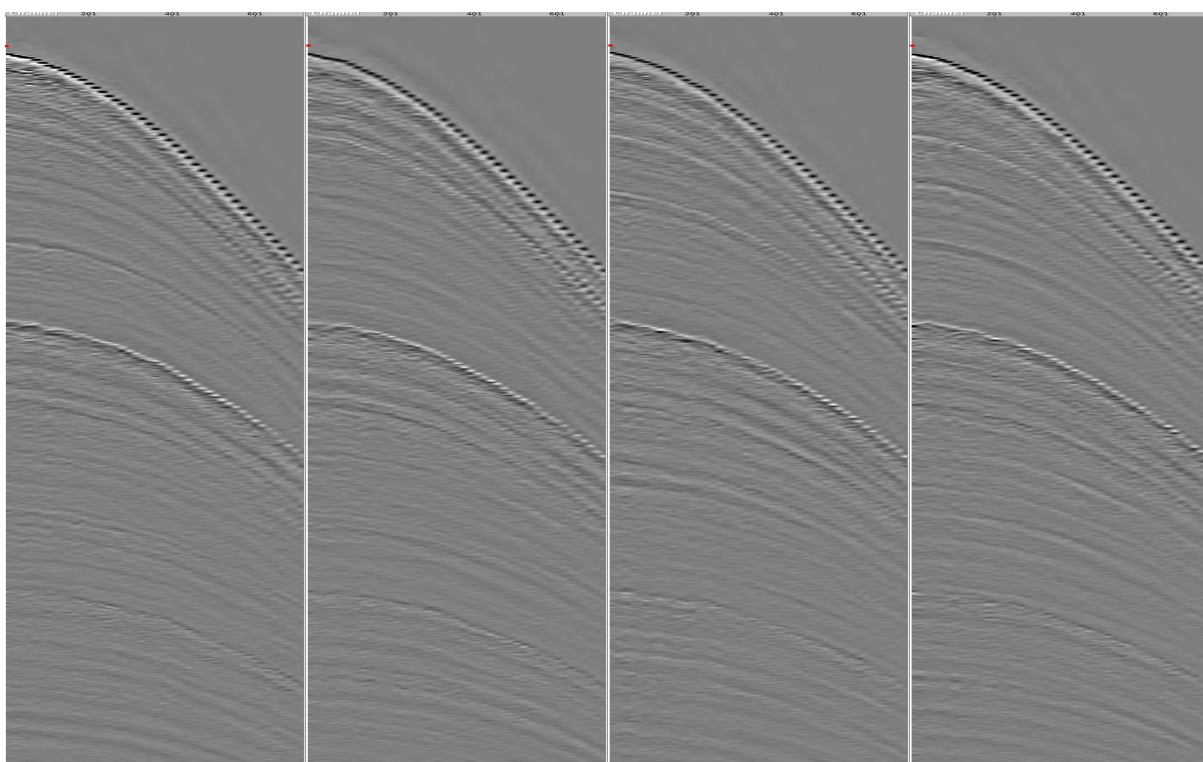


Figure 14: Directional signature

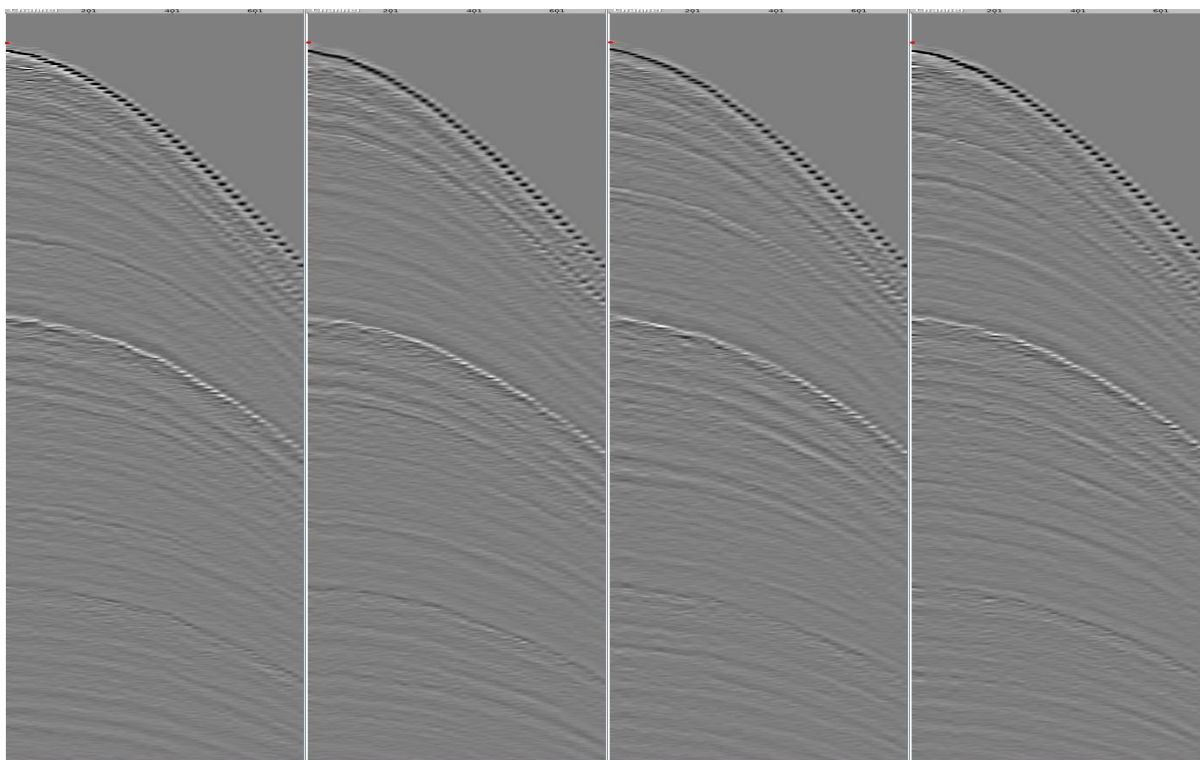


Figure 15: Zerophase

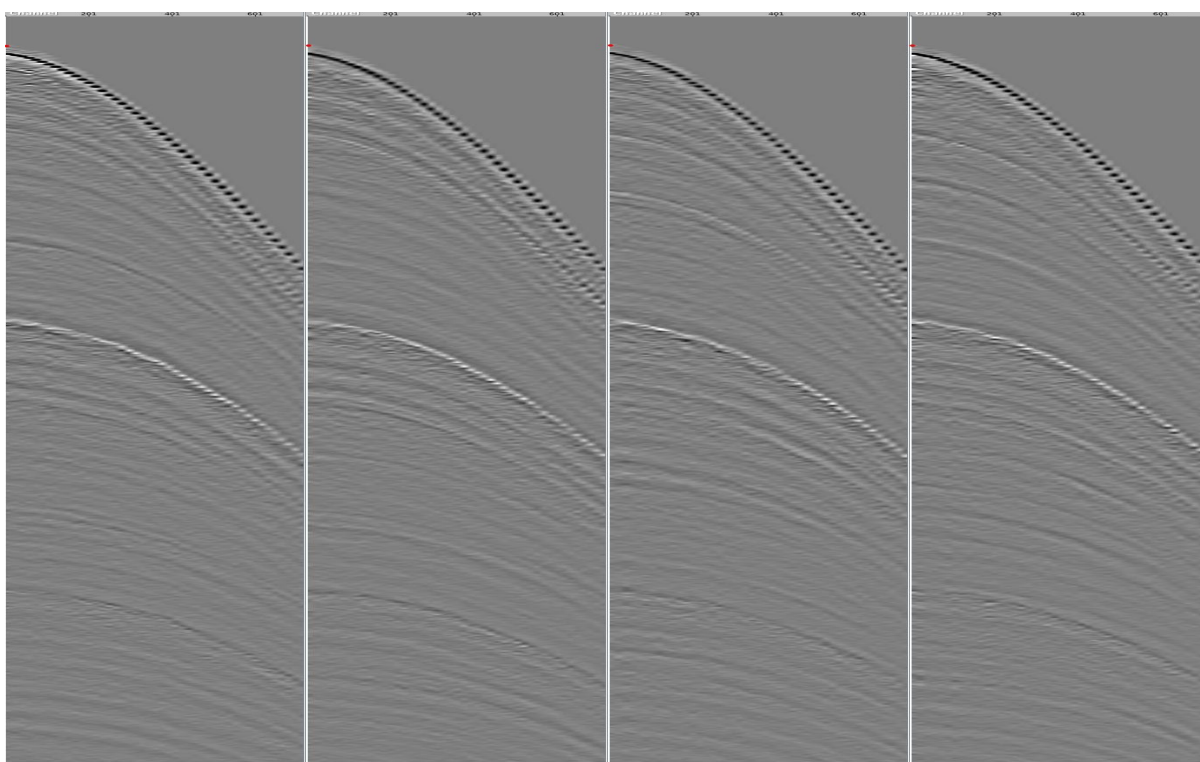


Figure 16: Wave-height static corrections

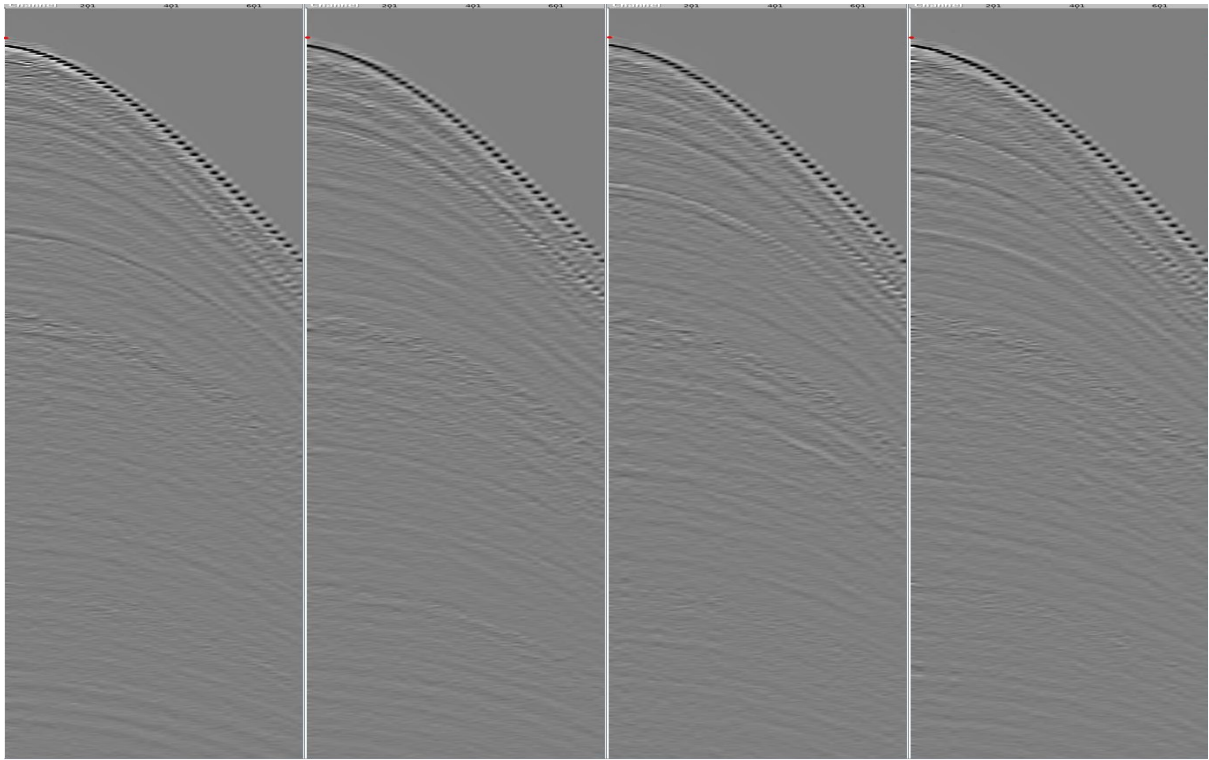


Figure 17: SRME

2.2.8 Velocity model generation

Velocity model building was carried out in parallel with the data processing. The testing progressed together and ultimately the input seismic data for the velocity model building was the residual demultiple production data. The workflow was:

- Input legacy velocity model > shift to MSL > convert to V_INT > smooth > convert to V_RMS
- Sparse offline pre-stack Kirchhoff time migration with above V_RMS velocity model
- Conditioning of gathers followed by Residual MoveOut (RMO) picking
- Two layer time tomography based on RMO picks to obtain updated V_RMS velocity model
- Conversion to V_INT, structural smoothing, conversion to V_RMS

The above workflow resulted in a velocity model that provided flat gathers through migration, while simultaneously ensuring stable interval velocities.

DELIVERABLE: RMS and interval velocities

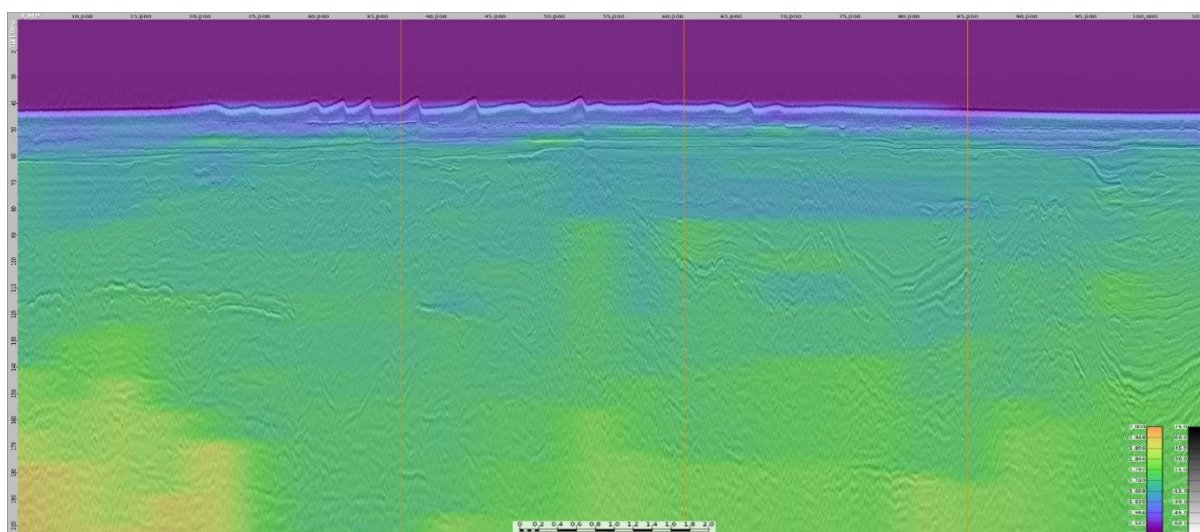


Figure 18: Legacy velocity converted to interval velocity

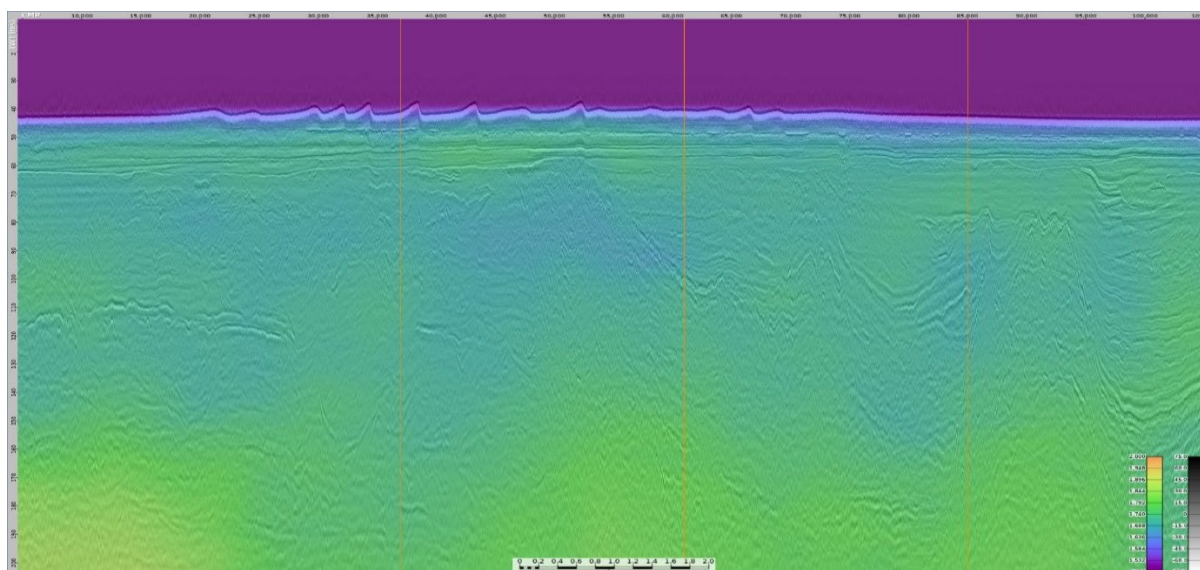


Figure 19: Interval velocity model updated through tomographic inversion

2.2.9 Kirchhoff pre-stack time migration (PSTM)

The data were migrated using a 2D Kirchhoff pre-stack time migration algorithm with a half-aperture of 100 m, a dip limit of 45° and driven by the velocity model detailed in Section 2.2.8.

2.2.10 Amplitude-Q Compensation

Time variant scaling and amplitude-Q compensation were applied to the data to ensure good amplitude consistency from top to bottom and to maximise the bandwidth and resolution. Amplitude-only Q compensation was applied from seabed and below using a constant Q value of 75, a 16 dB limit and a reference frequency of 200 Hz.

2.2.11 Residual Moveout Correction

Following the earlier migration velocity model building (Section 2.2.8), no further velocity update was performed. Instead, final gather flattening was achieved by conditioning CRP gathers, auto-picking parabolic and non-parabolic Residual Moveout (RMO) events based on amplitude and coherency, and then calculating a pre-stack time-shifts volume. The time-shifts volume was smoothed prior to application to the migrated gathers in order to prevent short-wavelength artefacts. The RMO correction resulted in flatter gathers, improved resolution, and stronger stacking power.

2.2.12 Redatum to LAT

Redatum of the CRP gathers and final velocity model to Lowest Astronomical Tide (LAT) was performed to ensure that the reprocessed seismic was located at the same datum as the geophysical/geological discipline interpretation (and legacy processing). This was achieved by calculating a trace shift for every CRP to align the data to the H00 interpreted horizon, with thorough QC performed alongside all project disciplines to ensure consistency between the reprocessed data and the geophysical horizons interpreted from the legacy seismic volume.

2.2.13 Residual Denoise

Final post-migration processing was applied to CRP gathers to improve the signal to noise ratio of the data and enhance resolution, including the following:

- Residual designation was applied on a line by line basis to target residual low frequency lobe in a window beneath the seabed. This was achieved using a short gapped, large spatially average deconvolution operation.
- Residual high frequency noise and multiple in the deeper section was further attenuated through the application of a time-variant filter.
- Residual internal multiple was attenuated using the same method as the pre-migration application: a targeted, horizon constrained approach using geophysical/ geological discipline interpreted horizons.

DELIVERABLE: Final gathers

2.2.14 Final Stack

Migration aperture traces located outside of the acquisition coverage area (“migration swing”) were discarded prior to the application of a 30° outer angle mute. Following muting, the CRP gather were stacked using a mean stack algorithm.

2.2.15 Post Stack Processing

The final stack image was further improved through the following processes:

1. Targeted residual high-frequency demultiple was applied at 2x seabed via Cadzow filtering

2. On selected lines which still showed residual bubble beneath the seabed another pass of targeted debubbling was applied
3. On lines which still showed residual internal multiple another pass of internal demultiple was applied.

2.2.16 SEG-Y Output

The processed full stack was then written to SEG-Y and delivered.

DELIVERABLE: Final stack

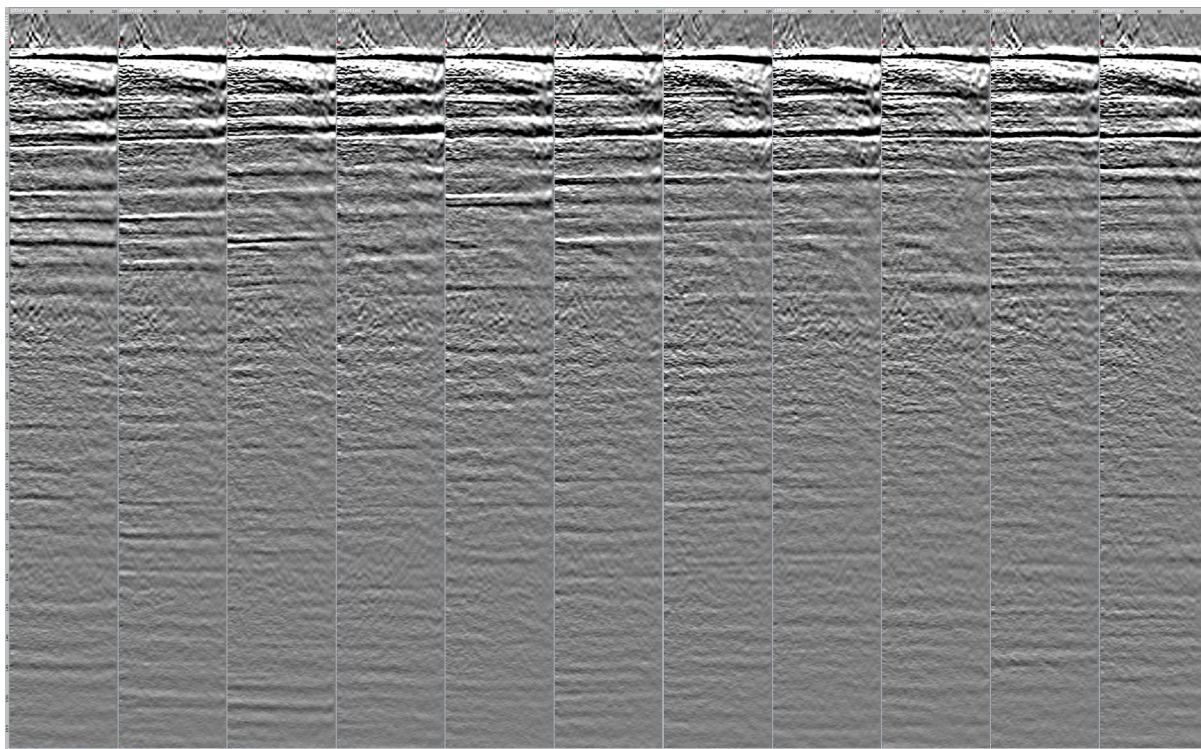


Figure 20: Raw migrated Common Reflection Point gathers

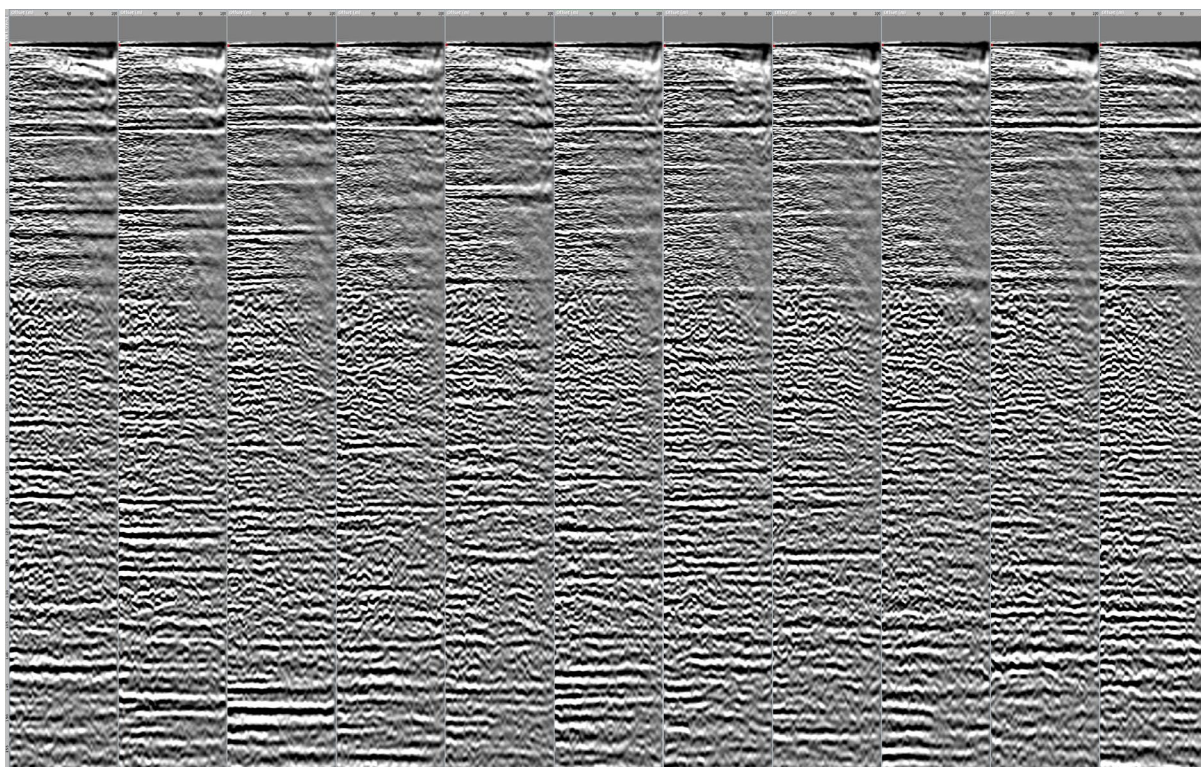


Figure 21: Final processed Common Reflection Point gathers

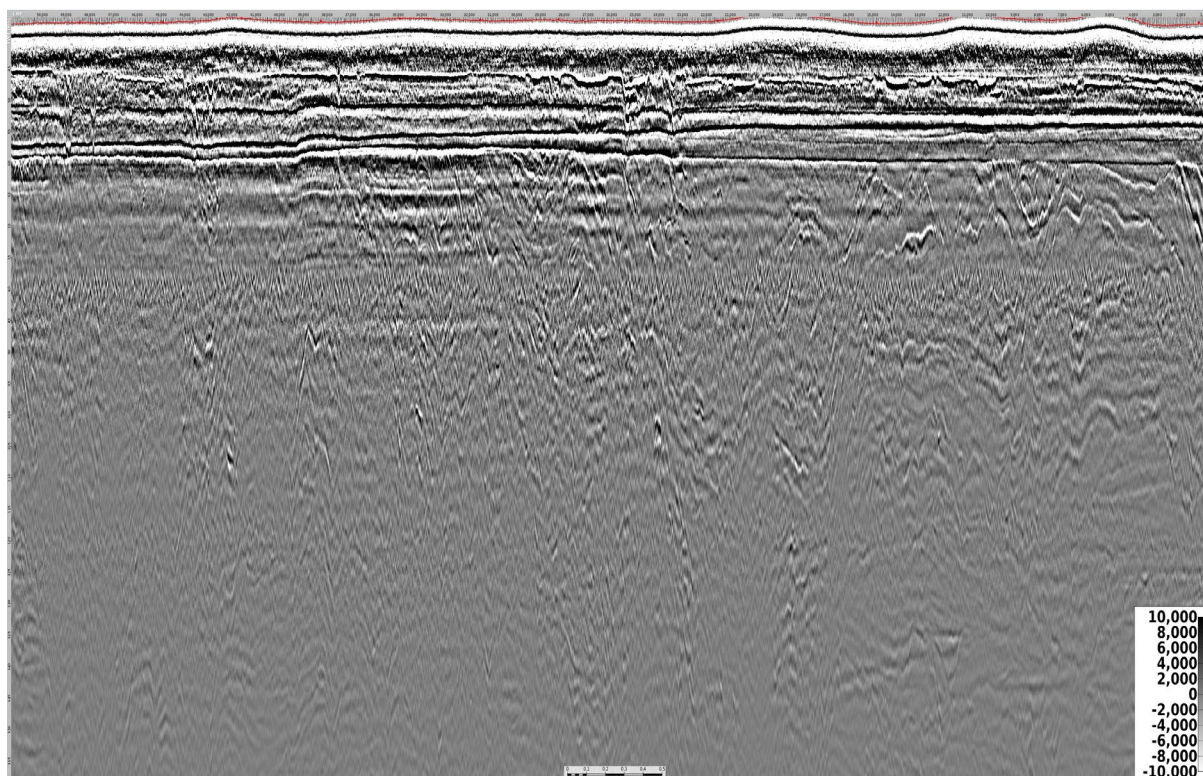


Figure 22: Raw migration stack

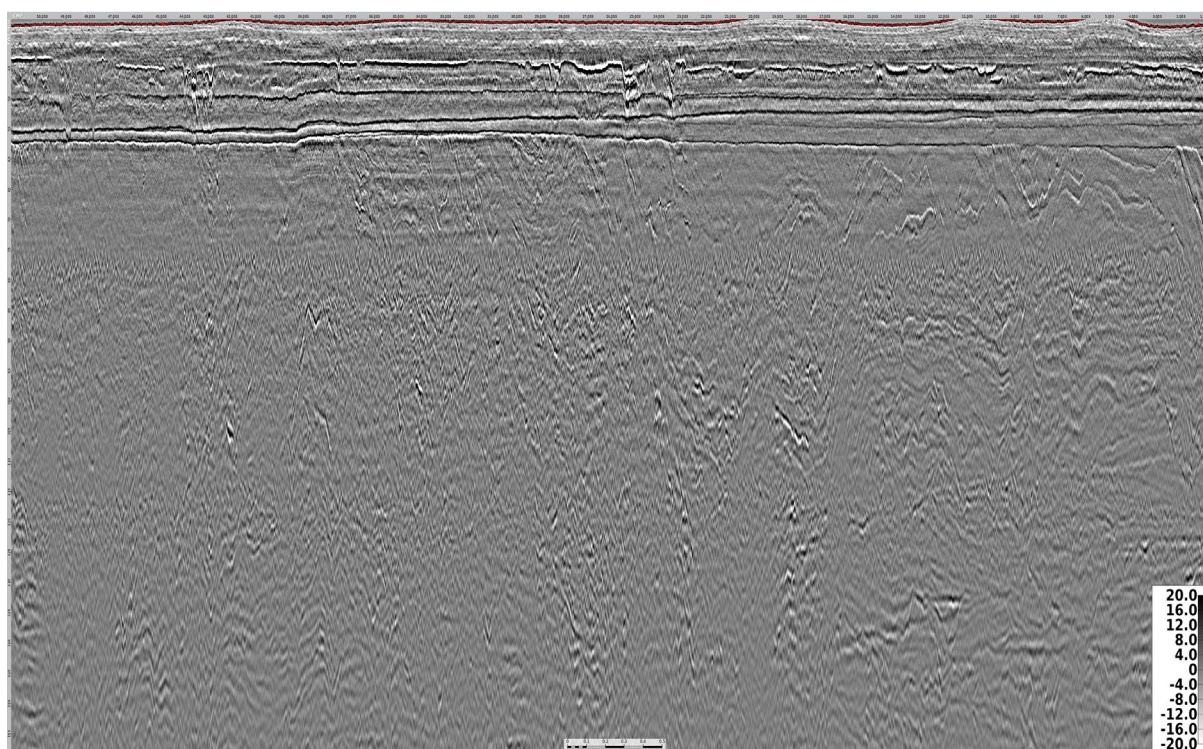


Figure 23: After post migration gather processing

2.3 AVO QC

The AVO-compliance of the processing across offsets and angles was assessed firstly during the testing of each stage on 2D test lines, and then in a survey-wide manner after each production run.

The following were reviewed regularly to ensure AVO-compliance and suitability of the seismic for elastic pre-stack inversion:

- Shots and CRP gathers with and without NMO correction
- Near, mid, and far channels
- Angle stacks (0°-10°, 10°-20, 20°-30, 30°-40°)
- Cross correlation coefficient and time shift attributes (2D lines and as survey wide maps)
- 2-term Shuey AVO intercept and gradient fitting

These QC's showed no unexpected change in the AVO character of the signal through the processing, while simultaneously demonstrating quantitative improvements in the AVO signal through the sequence. Examples of this global improvement in AVO signal can be seen in:

- Figure 24, where the data histogram of correlation coefficient between near and ultra-far angle stack focusses towards a value of 1000 through processing (indicating improved correlation between near and ultra-far angles)
- Figure 25, where the data histogram of time shift between near and ultra-far angle stack focusses towards a value of zero through processing (indicating improved gather flattening between near and ultra-far angles)

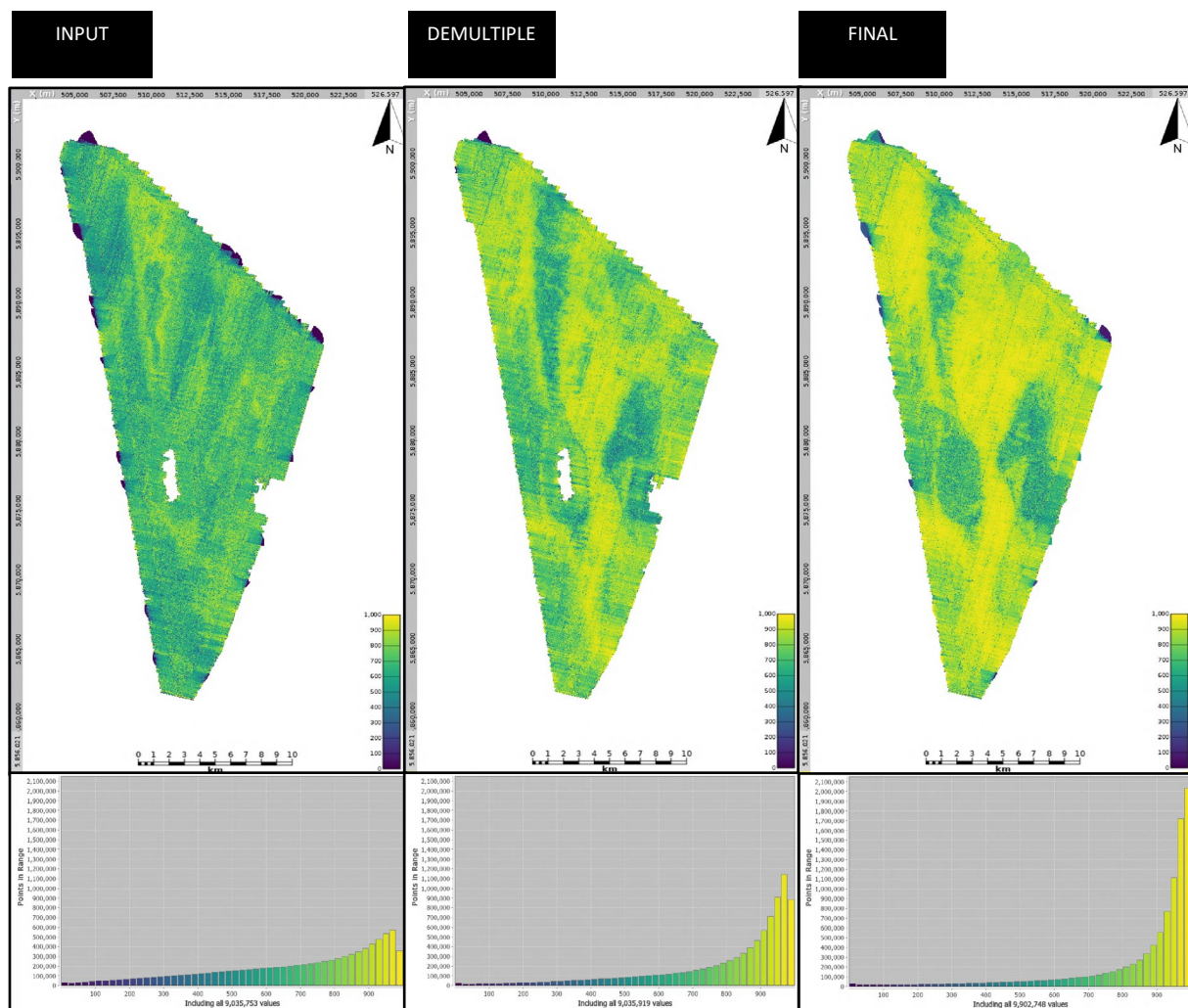


Figure 24: Correlation value of near stack to ultra far stack (normalised to 1000). Map illustrates value per CRP with histogram at bottom.

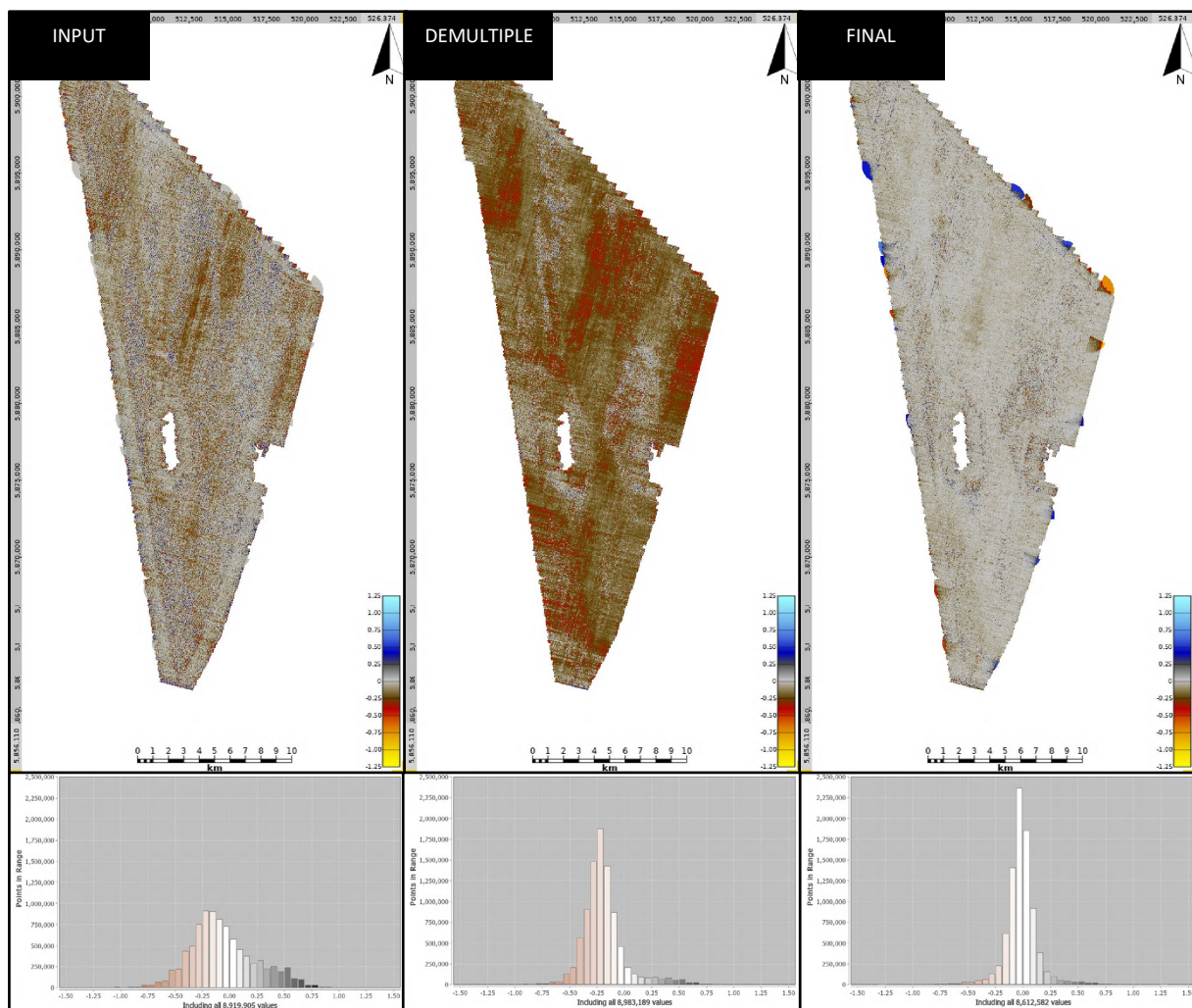


Figure 25: Correlation time shift of near stack to ultra far stack (ms). Map illustrates value per CRP with histogram at bottom.

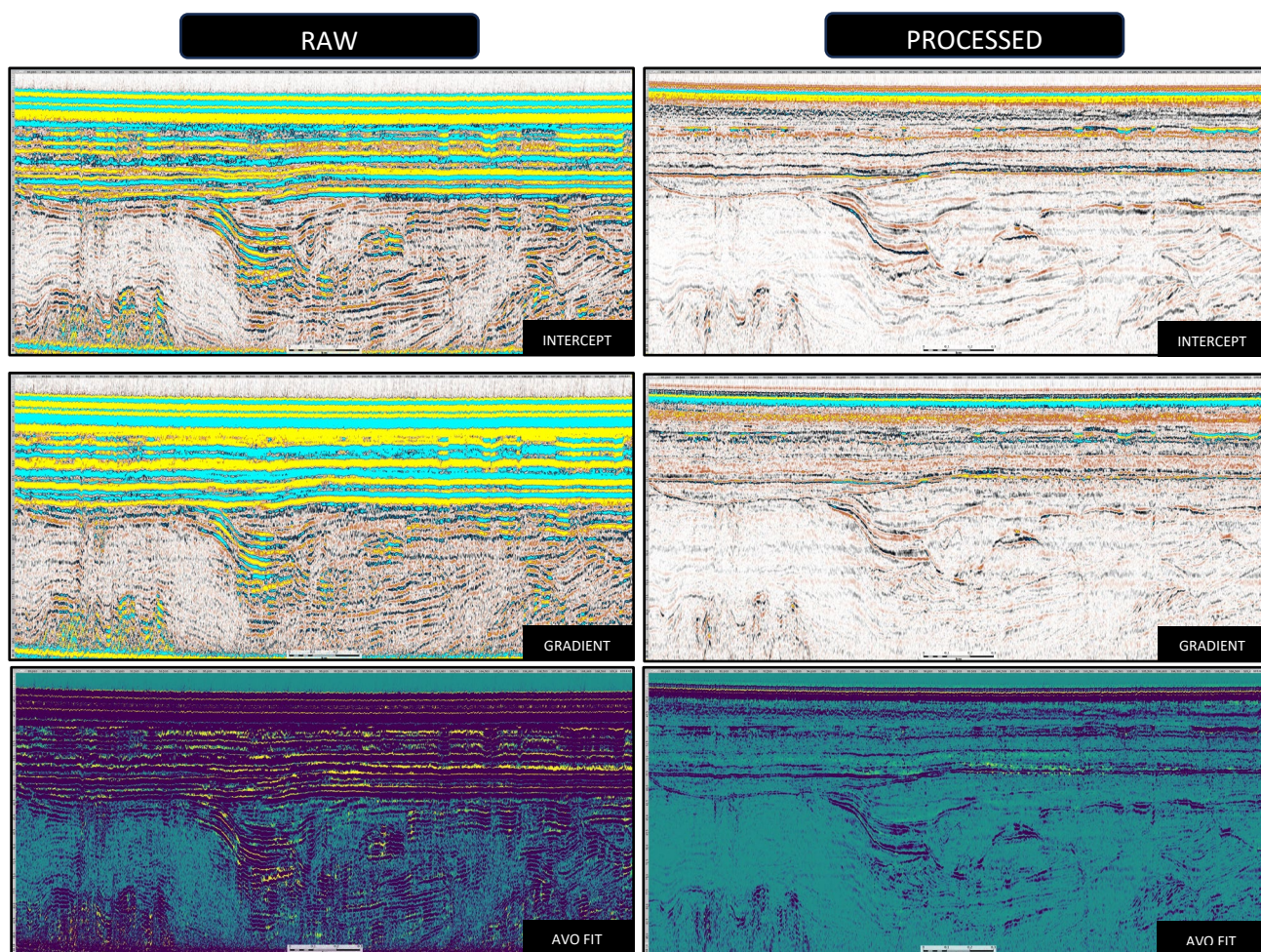


Figure 26: Intercept, Gradient and Goodness of Fit from 2-term Shuey AVO fitting

3. Conclusions

This reprocessing project successfully delivered AVO-compliant final gathers and a suitable velocity model for input to elastic pre-stack inversion. The integration across all disciplines helped to shape the processing flow via regular weekly meetings as well as a thorough workshop review after the delivery of the Fast Track data.

The quality of the gathers is seen to be very good, and despite the primary objective of this reprocessing being to generate gathers for inversion (rather than create a stack product for interpretation), comparison of the final reprocessed stack versus the legacy stack shows improvements in image quality (Figure 27). This is particularly evident in terms of shallow resolution, clarity of the bright organic layers, lack of interbed multiples and deeper steep imaging.

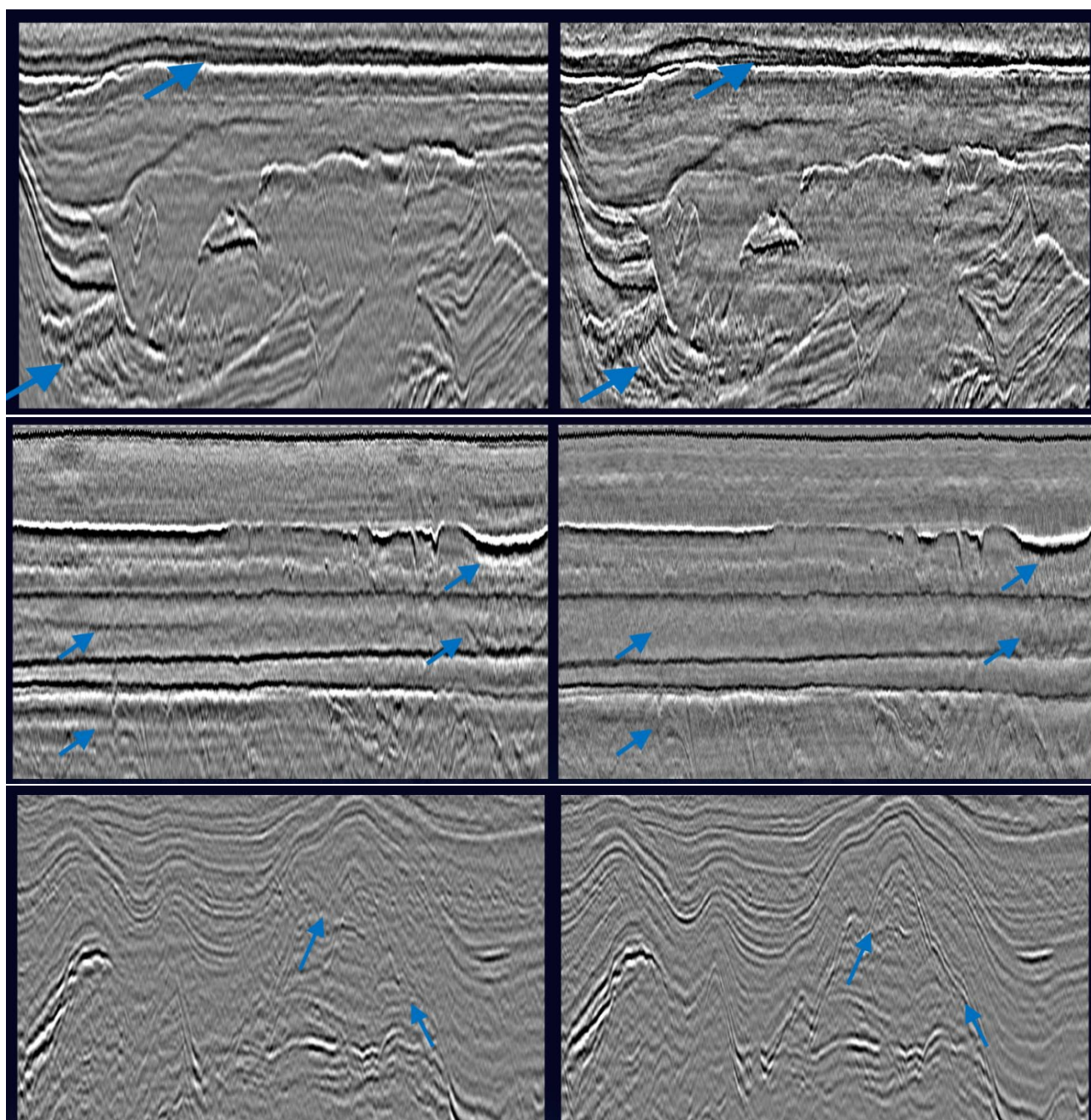


Figure 27: Imaging highlights. Legacy (left), Reprocessing (right)

4 Appendices

4.1 Appendix I: Evolution of Processing and Inter-Discipline Review

This section summarises the earlier iterations of processing flows applied to the data. Namely:

- **Feasibility study: 2 weeks** of testing on 10 testlines as proof of concept
- **Fast track: 2 months** of testing and production to provide SolidGround with all 386 lines through an intermediate flow for initial inversion studies. This flow was based on the Feasibility Study but had no post-migration processing applied. Included a large focus on improving the stability of deghosting.
- **Final Flow: 6 months:** As documented within this report.

The integrated nature of this project - with regular communication and data sharing between project disciplines - helped to shape the processing flow and improve the final data quality.

After the delivery of the Fast Track, the quantitative seismic inversion discipline ran a relative inversion of the data and this, along with the seismic gathers and stacks, were thoroughly reviewed and discussed at an inter-disciplinary workshop with RVO and the quality expert support (QES) team in February 2024. From this workshop, key focus areas for testing for the final flow were identified as resolving wave-height statics on very high wave height lines, and the resolution of fine scale bedding. The images below show the significant improvement of both of these items between the Fast Track and the final product, and that the reprocessed final stack volume compares very well with the legacy stack volume.

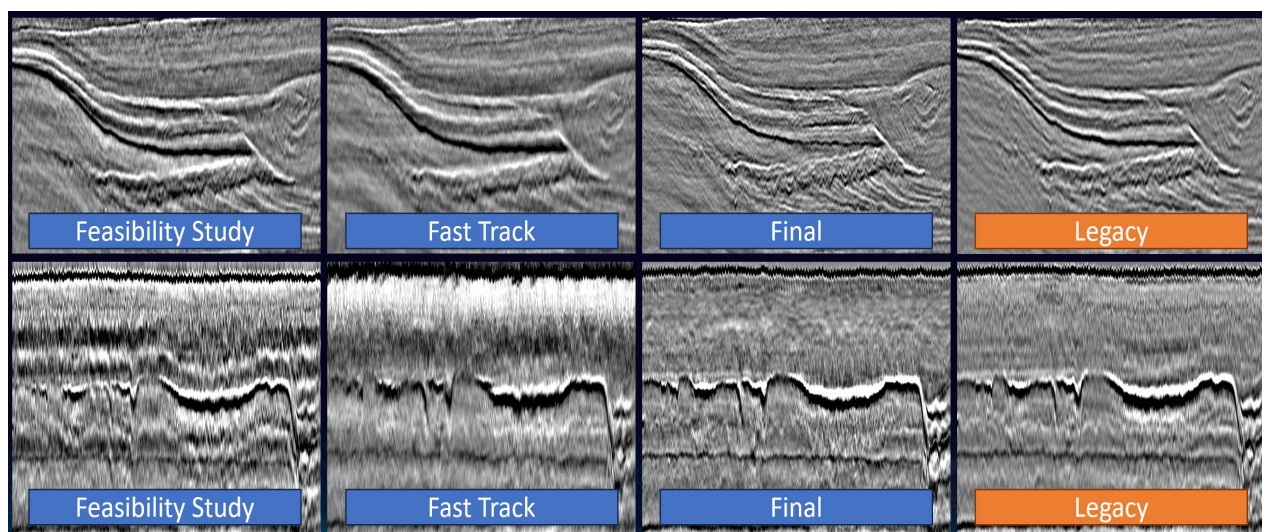


Figure 28: Evolution of processing

4.2 Appendix II: Deliverables

Deliverable	Format	Media	Filename
Final Gathers	SEGY	FTP	PROCESSED TIME MIGRATED FULL OFFSET GATHERS
Final Stack	SEGY	FTP	PROCESSED TIME MIGRATED 0-30 DEGREE STACK
RMS and interval velocities	SEGY	FTP	MIGRATION VELOCITY TIME VRMS/VINT
Processing report	PDF	FTP	20240704_RVO_NWZ_UHRS_Final_Report

4.3 Appendix III: Example EBCDIC Header

```

C 1 CONTRACTOR: ROCKWAVE LTD          CLIENT: RVO (NETHERLANDS ENTERPRISE AGENCY)
C 2 PROJECT: RVO NEDERWIEK INTEGRATED GROUND MODEL
C 3 AREA: NEDERWIEK WIND FARM ZONE
C 4 DATA: 2D ULTRA HIGH RESOLUTION SEISMIC - OFFSHORE
C 5 PRODUCT: PROCESSED TIME MIGRATED FULL OFFSET GATHERS
C 6 2D LINE [LINE                      ]
C 7
C 8 ----- ACQUISITION INFORMATION -----
C 9 ACQUIRED 2023
C10 VESSEL - FUGRO DISCOVERY; 65 x 420 m IL x XL LINE SPACING;
C11 96 CHANNELS AT 1M INTERVAL; 1.4 M FLAT STREAMER
C12 SOURCE - FUGRO MLSS-360 SPARKER; 1M SHOT INTERVAL
C13
C14
C15 ----- NAVIGATION INFORMATION -----
C16 WGS84; UTM31N; ESPG CODE 16031; UNITS - METRES
C17
C18
C19
C20 ----- DATA PROCESSING -----
C21 SHOT AND CHANNEL EDITS AND INTERPOLATION: SWELL, SPIKE AND LINEAR DENOISE;
C22 RECEIVER DEGHOSTING; SOURCE SIGNATURE; ZERO-PHASING;
C23 SOURCE HEAVE CORRECTION; 2D SRME MODELLING AND ADAPTIVE SUBTRACTION;
C24 ADDITIONAL DEMULT INLC INTERBED; 2D PRE STACK KIRCHHOFF MIG WITH TOMO VEL;
C25 RMO CORRECTION; RESIDUAL DESIG; RESIDUAL DEMULT; AMP Q COMPENSATION;
C26 REDATUM TO BATHYMETRY; RESIDUAL DEBUBBLE; SEG Y OUTPUT
C27
C28 POLARTIY; POSITIVE NUMBER = INCREASE IN ACOUSTIC IMPEDANCE
C29
C30 -----TRACE HEADER INFORMATION -----
C31 HEADER VALUE          BYTE LOCATIONS
C32 TRACE NUMBER          5-8
C33 CMP                   21-24
C34 WB TWT                61-64
C35 CMP X                 181-184
C36 CMP Y                 185-188
C37
C38 MAY 2024 WWW.ROCKWAVE.XYZ
C39 SEG Y REV1
C40 END TEXTUAL HEADER

```

4.4 Appendix III: Line List (UHR)

Line	CRP_First	CRP_Last	Line_Length		Line	CRP_First	CRP_Last	Line_Length
A001R2	423	10491	1.26km	...	E184J6	423	19851	2.43km
A002R2	423	11763	1.42km	...	E184P1	423	165195	20.60km
A003R2	423	13051	1.58km	...	E185P1	423	166059	20.71km
A004R3	423	14331	1.74km	...	F186J10	423	13891	1.68km
A005P1	423	15595	1.90km	...	F186P1	423	166915	20.81km
A006P1	423	16867	2.06km	...	F187P1	423	167787	20.92km
A007P1	423	18115	2.21km	...	F188J19	423	14851	1.80km
A008R3	423	19427	2.38km	...	F188P1	423	168643	21.03km
A009P1	423	20691	2.53km	...	F189P1	423	169499	21.13km
A010P1	423	21971	2.69km	...	F190P1	423	170363	21.25km
A011P1	423	23243	2.85km	...	F191P1	423	171219	21.35km
A012P1	423	24531	3.01km	...	F192P1	423	172107	21.46km
A013P1	423	25811	3.17km	...	F193P1	423	172955	21.57km
A014P1	423	27091	3.33km	...	F194P1	423	173811	21.67km
A015P1	423	28363	3.49km	...	F195P1	423	174691	21.79km
A016P1	423	29635	3.65km	...	F196P1	423	175547	21.89km
A017P1	423	30907	3.81km	...	F197J2	423	13819	1.67km
A018P1	423	32195	3.97km	...	F197P1	423	176011	21.95km
A019P1	423	33459	4.13km	...	F198P1	423	177275	22.11km
A020P1	423	34739	4.29km	...	F199P1	423	178115	22.21km
A021P1	423	35987	4.45km	...	F200P1	423	178971	22.32km
A022P1	423	36795	4.55km	...	F201P1	423	179803	22.42km
A023P1	423	37563	4.64km	...	F202P1	423	180243	22.48km
A024R1	423	38411	4.75km	...	F203P1	423	181491	22.64km
A025P1	423	39219	4.85km	...	F204P1	423	182339	22.74km
A026P1	423	40027	4.95km	...	G205P1	423	183187	22.84km
A027P1	423	40827	5.05km	...	G206P1	423	137915	17.19km
A028P1	423	41635	5.15km	...	G206P2	423	31307	3.86km
A029P1	423	42443	5.25km	...	G206P4	423	23891	2.93km
A030P1	423	43235	5.35km	...	G207P1	423	184883	23.05km
A031P1	423	44051	5.45km	...	G208P1	423	185715	23.17km
A032P1	423	44003	5.44km	...	G209P1	423	186555	23.26km
A033P1	423	43507	5.38km	...	G210P1	423	187395	23.37km
A034P1	423	43011	5.32km	...	G211J11	423	8643	1.03km
A035R2	423	42523	5.26km	...	G211P1	423	188235	23.48km
A036R1	423	42035	5.20km	...	G212P1	423	189091	23.58km
A037P1	423	41147	5.09km	...	G213P1	423	189931	23.69km
A038P1	423	41043	5.08km	...	G214P1	423	190779	23.79km
A039P1	423	41611	5.15km	...	G215P1	423	191651	23.90km
A040P1	423	42443	5.25km	...	G215R1	423	84291	10.48km
A041P1	423	43291	5.36km	...	G216P1	423	192491	24.01km
A042P1	423	44155	5.47km	...	G217J16	423	11163	1.34km
A043P1	423	45019	5.57km	...	G217P1	423	193371	24.11km
A044R1	423	45883	5.68km	...	G218P1	423	194211	24.22km
A045R1	423	46755	5.79km	...	G219P1	423	195051	24.33km

A046P1	423	47643	5.90km	...	G220P1	423	195931	24.44km
A047P1	423	48531	6.01km	...	G221P1	423	196771	24.54km
A048P1	423	49403	6.12km	...	H222J3	423	17403	2.12km
A049P1	423	50283	6.23km	...	H222P1	423	196699	24.54km
A050P1	423	51123	6.34km	...	H223P1	423	198499	24.77km
A051P1	423	51963	6.44km	...	H224P1	423	199347	24.87km
A052P1	423	52851	6.55km	...	H225J11	423	11115	1.34km
A053P1	423	53635	6.65km	...	H225J5	423	24099	2.96km
A054P1	423	54387	6.74km	...	H225P1	423	200219	24.98km
A055P1	423	55147	6.84km	...	H226P1	423	201083	25.08km
A056P1	423	55955	6.94km	...	H227P1	423	201931	25.19km
A057P1	423	56763	7.04km	...	H228P1	423	202795	25.30km
A058R1	423	57771	7.17km	...	H229P1	423	203659	25.40km
A059P1	423	58675	7.28km	...	H230P1	423	204115	25.46km
A060P1	423	59563	7.39km	...	H231P1	423	205387	25.62km
A061P1	423	60403	7.50km	...	H232P1	423	206251	25.74km
A062R1	423	61251	7.60km	...	H233P1	423	207115	25.83km
A063P1	423	62083	7.71km	...	H234P2	423	207947	25.94km
A064P1	423	62931	7.81km	...	H235P1	423	208811	26.05km
A065P1	423	63819	7.92km	...	H236P1	423	209659	26.16km
A066P1	423	64707	8.03km	...	H237P1	423	210515	26.26km
A067R1	423	65587	8.14km	...	J238P1	423	211355	26.37km
A068P1	423	66459	8.26km	...	J239P1	423	212195	26.47km
A069P1	423	67307	8.36km	...	J240J14	423	28619	3.52km
A070P1	423	68163	8.47km	...	J240P1	423	213051	26.58km
A071P1	423	68987	8.57km	...	J241P1	423	213907	26.68km
A072P1	423	69803	8.67km	...	J242P1	423	214747	26.79km
A073P1	423	70627	8.77km	...	J243J6	423	21539	2.64km
A074R2	423	71483	8.88km	...	J243P1	423	215611	26.90km
A075P1	423	72235	8.97km	...	J244P1	423	216467	27.00km
A076P1	423	72987	9.07km	...	J245P1	423	217315	27.12km
B077P1	423	73443	9.13km	...	J246P1	423	218163	27.22km
B078P1	423	74395	9.25km	...	J247P1	423	219043	27.32km
B079P1	423	75763	9.42km	...	J248P1	423	219899	27.43km
B080P1	423	76219	9.48km	...	J249P1	423	220739	27.54km
B081J5	423	12651	1.53km	...	J250P2	423	221595	27.65km
B081P1	423	77075	9.58km	...	J251P1	423	222459	27.76km
B082P1	423	77883	9.68km	...	J252P1	423	223315	27.86km
B083P1	423	79043	9.83km	...	K253R1	423	222507	27.76km
B084P1	423	79907	9.93km	...	K254P1	423	219843	27.43km
B085P1	423	80747	10.04km	...	K255P1	423	217179	27.10km
B086P1	423	81211	10.10km	...	K256P1	423	214515	26.76km
B087P1	423	82443	10.26km	...	K257P1	423	211907	26.44km
B088P1	423	82891	10.30km	...	K258P1	423	209291	26.11km
B089P1	423	83771	10.42km	...	K259P1	423	206691	25.78km
B090P1	423	84659	10.53km	...	K260P1	423	204091	25.46km
B091J11	423	12851	1.55km	...	K261P1	423	201483	25.13km
B091J9	423	4571	0.52km	...	K262P1	423	198875	24.81km

B091P1	423	85539	10.64km	...	K263P1	423	196291	24.48km
B092P1	423	86819	10.80km	...	K264P1	423	193683	24.16km
B093P1	423	87691	10.91km	...	K265P1	423	191083	23.83km
B094P1	423	88483	11.01km	...	K266P1	423	188475	23.50km
B095P1	423	89291	11.10km	...	K267P1	423	180275	22.48km
B096J1	423	90083	11.21km	...	K268P1	423	170995	21.32km
B096R1	423	90091	11.21km	...	M269P1	423	161715	20.16km
B097P1	423	90899	11.31km	...	M270P1	423	152427	19.00km
B098P1	423	91699	11.41km	...	M271P1	423	143131	17.84km
B099P1	423	92499	11.50km	...	M272P1	423	133851	16.68km
B100P1	423	93563	11.64km	...	M273P1	423	124579	15.52km
B101P1	423	94523	11.76km	...	M274P1	423	115283	14.36km
B102P1	423	95363	11.87km	...	M275P1	423	106003	13.20km
B103P1	423	96227	11.98km	...	M276P1	423	96715	12.04km
B104P1	423	97075	12.08km	...	M277P1	423	87435	10.88km
B105P1	423	97915	12.19km	...	X278P1	423	28099	3.46km
B106P1	423	98779	12.29km	...	X279P1	423	32379	3.99km
B107P1	423	99635	12.40km	...	X280P1	423	36267	4.48km
B108P1	423	100483	12.51km	...	X281P1	423	40163	4.97km
B109P1	423	101323	12.61km	...	X282P1	423	44043	5.45km
B110P1	423	102195	12.72km	...	X283P1	423	47931	5.94km
B111P1	423	103059	12.83km	...	X284P1	423	51835	6.43km
B112P1	423	103939	12.94km	...	X285P1	423	55715	6.91km
B113P1	423	104787	13.05km	...	X286R1	423	59627	7.40km
C114P1	423	105547	13.14km	...	X287R1	423	63499	7.88km
C115R1	423	106515	13.26km	...	X288P1	423	67387	8.37km
C116P1	423	107299	13.36km	...	X289P1	423	67203	8.34km
C117P1	423	108107	13.46km	...	X290R1	423	71155	8.84km
C118P1	423	108891	13.56km	...	X291R1	423	75147	9.34km
C119P1	423	109683	13.65km	...	X292R1	423	79123	9.83km
C120P1	423	110563	13.77km	...	X293P1	423	83083	10.33km
C121P1	423	111547	13.89km	...	X294P1	423	86931	10.82km
C122P1	423	112515	14.01km	...	X295R1	423	90867	11.30km
C123P1	423	113363	14.12km	...	X296P1	423	94891	11.80km
C124P1	423	114283	14.23km	...	X297P1	423	98827	12.30km
C125P1	423	115099	14.34km	...	X298R1	423	103219	12.85km
C126P1	423	115939	14.44km	...	X299P1	423	107843	13.43km
C127P1	423	116747	14.54km	...	X300P1	423	110051	13.71km
C128R1	423	117587	14.65km	...	X301R1	423	108531	13.51km
C129P1	423	118419	14.75km	...	X302P1	423	106995	13.32km
C130P1	423	119243	14.85km	...	X303R1	423	105571	13.14km
C131P1	423	120067	14.95km	...	X304P1	423	50507	6.26km
C132P1	423	120891	15.06km	...	X304P2	423	88411	10.99km
C133P1	423	121739	15.16km	...	X305P1	423	102531	12.76km
C134P1	423	122563	15.27km	...	X306R1	423	101059	12.58km
C135P1	423	123379	15.37km	...	X307P1	423	99603	12.40km
C136P1	423	124219	15.47km	...	X308P1	423	98099	12.21km
C137J3	423	44515	5.52km	...	X309P1	423	96547	12.01km

C137P1	423	125051	15.58km	...	X310P1	423	95123	11.84km
C138P1	423	125891	15.68km	...	X311P1	423	93667	11.65km
C139P1	423	126691	15.78km	...	X312P1	423	92179	11.47km
C140P1	423	127539	15.89km	...	X313P1	423	90683	11.29km
C141P1	423	128419	16.00km	...	X314P1	423	89219	11.09km
D142P1	423	129307	16.11km	...	X315P1	423	87739	10.91km
D143R1	423	130187	16.22km	...	X316R1	423	86171	10.72km
D144P1	423	131075	16.33km	...	X317P1	423	84675	10.53km
D145P1	423	131963	16.44km	...	X318P1	423	82923	10.31km
D146J1	423	59867	7.43km	...	X319P1	423	81795	10.17km
D146P1	423	132835	16.55km	...	X320R1	423	80283	9.98km
D147P1	423	133715	16.66km	...	X321P1	423	78763	9.79km
D148J6	423	47059	5.83km	...	X322P1	423	77235	9.60km
D148P1	423	134611	16.78km	...	X323P1	423	75267	9.35km
D149J5	423	10083	1.21km	...	X324P1	423	73947	9.19km
D149P1	423	135955	16.94km	...	X325R1	423	72315	8.98km
D150P1	423	136307	16.98km	...	X326R2	423	70667	8.78km
D151P1	423	137131	17.08km	...	X327P1	423	69003	8.57km
D152P1	423	137979	17.19km	...	X328P1	423	67315	8.36km
D153P1	423	138835	17.30km	...	X329P1	423	65627	8.15km
D154P1	423	139675	17.41km	...	X330P1	423	63931	7.94km
D155P1	423	140507	17.51km	...	X331P1	423	62251	7.73km
D156P1	423	141355	17.62km	...	X332P1	423	60571	7.52km
D157P1	423	142195	17.72km	...	X333P1	423	58491	7.26km
D158P1	423	143059	17.83km	...	X334P1	423	57219	7.10km
D159P1	423	143899	17.93km	...	X335P1	423	55531	6.89km
D160P1	423	144771	18.04km	...	X336P1	423	53843	6.68km
D161P1	423	145619	18.15km	...	X337P1	423	52147	6.46km
D162P1	423	146483	18.26km	...	X338P1	423	50451	6.25km
D163P1	423	147339	18.36km	...	X339P1	423	48771	6.04km
D164P1	423	148203	18.47km	...	X340P1	423	47091	5.83km
E165P1	423	149067	18.58km	...	X341P1	423	45427	5.62km
E166P1	423	149915	18.69km	...	X342R1	423	43747	5.41km
E167P1	423	150763	18.80km	...	X343R1	423	42075	5.21km
E168P1	423	151635	18.90km	...	X344P1	423	40419	5.00km
E169P1	423	152483	19.01km	...	X345R2	423	38723	4.79km
E170P1	423	153355	19.11km	...	X346R1	423	37027	4.57km
E171P1	423	154195	19.22km	...	X347R1	423	35347	4.36km
E172J4	423	35131	4.34km	...	X348P1	423	33643	4.15km
E172P1	423	155043	19.33km	...	X349P2	423	31947	3.94km
E173P1	423	155891	19.43km	...	X350R1	423	30267	3.73km
E174P1	423	156723	19.54km	...	X351R1	423	28595	3.52km
E175P1	423	126787	15.79km	...	X352P1	423	26907	3.31km
E175P2	423	39787	4.92km	...	X353R1	423	25243	3.10km
E176P1	423	158411	19.75km	...	X354P1	423	23411	2.87km
E177P1	423	159275	19.86km	...	X355P1	423	21195	2.60km
E178P1	423	160099	19.96km	...	X356P1	423	18563	2.27km
E179P1	423	160947	20.07km	...	X357P1	423	16723	2.04km

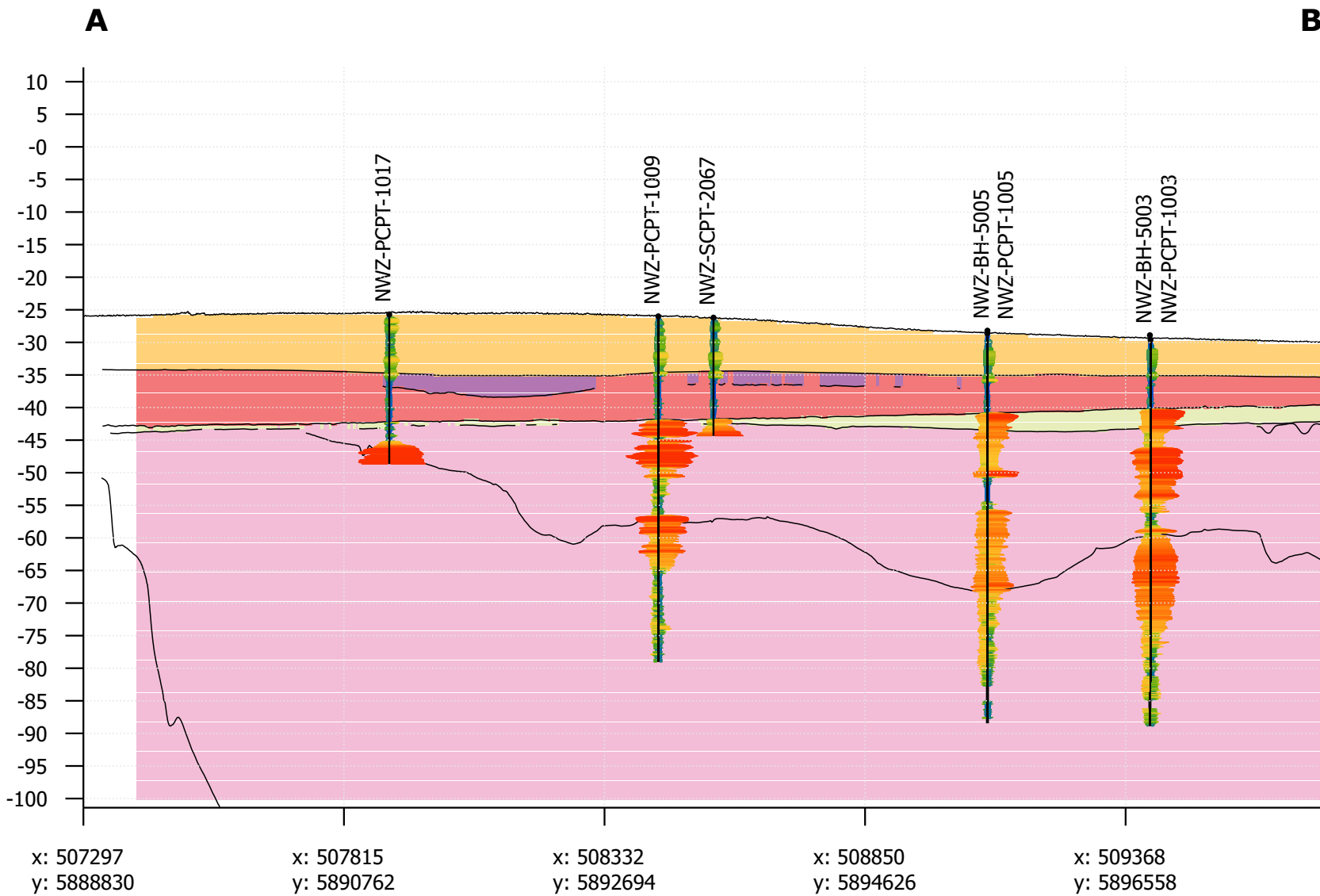
E180J1	423	23179	2.85km	...	X358R2	423	14475	1.76km
E180P1	423	33915	4.19km	...	X359P1	423	12235	1.47km
E180P2	423	114419	14.25km	...	X357P1	423	16723	2.04km
E181P1	423	162635	20.27km	...	X358R2	423	14475	1.76km
E182P1	423	163475	20.38km	...	X359P1	423	12235	1.47km
E183P1	423	164339	20.49km					

Appendix B: Cross Sections

Section AB

Location

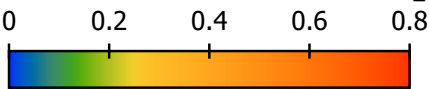
A: 507297, 5888830
B: 509754, 5898001



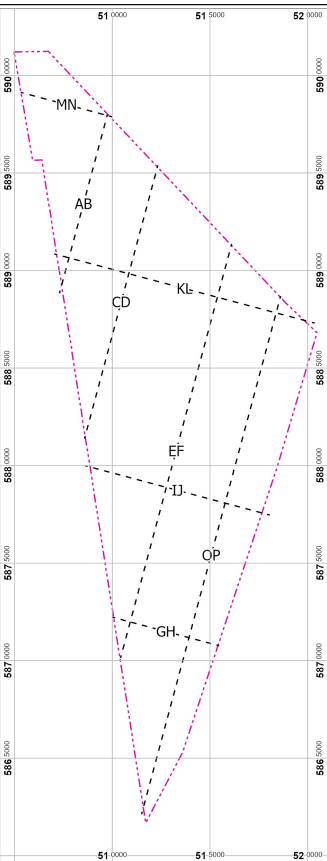
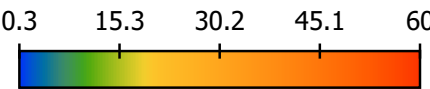
Soil Units

- U1 U4 U7
- U2 U5
- U3 U6

Corrected Sleeve Friction [MPa]



Corrected Cone Resistance [MPa]



Vertical Exaggeration: 50x

Scale: 1:46,000



V03	06/25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP



Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

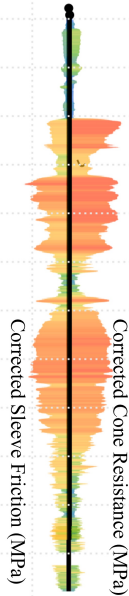
Discipline Geotechnical

Job No 295809

Drawing Status Final

Drawing No

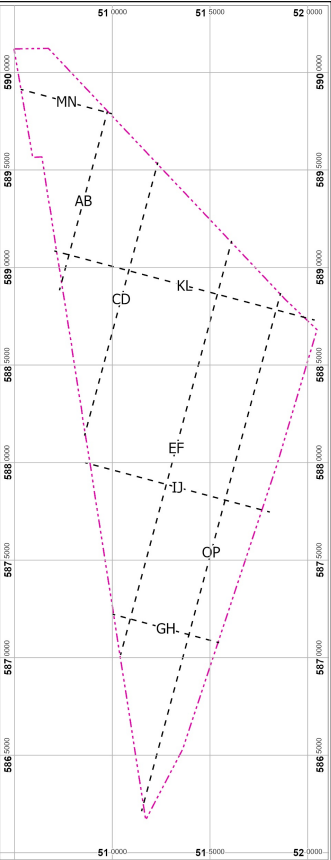
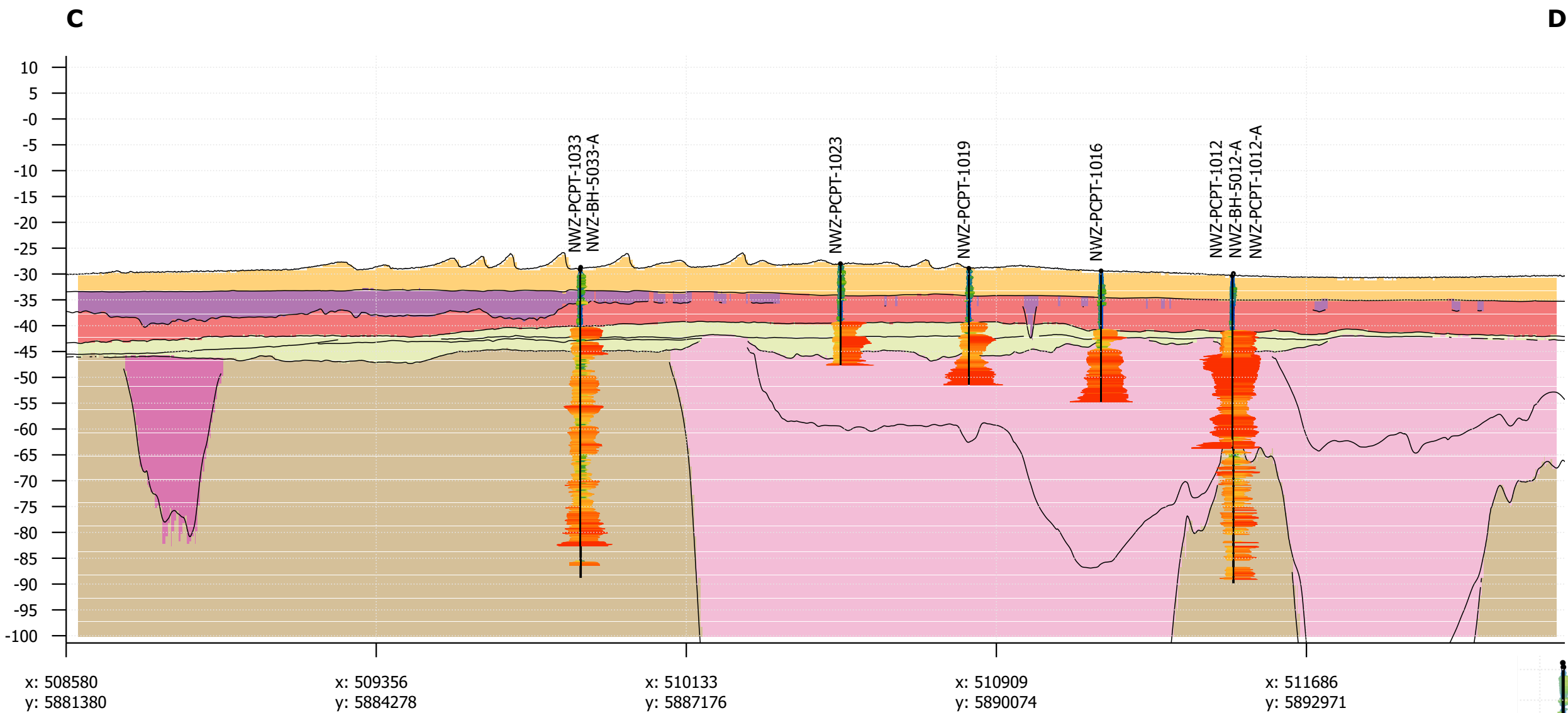
Issue V03



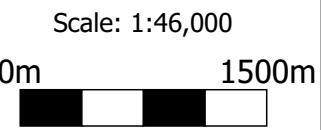
Section CD

Location

C: 508580, 5881380
D: 512333, 5895386



Vertical Exaggeration: 50x



V03	06/25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP

Client
Rijksdienst voor Ondernemend
Nederland

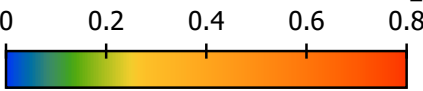
Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

Discipline	Geotechnical
Job No	295809
Drawing Status	Final
Drawing No	Issue V03

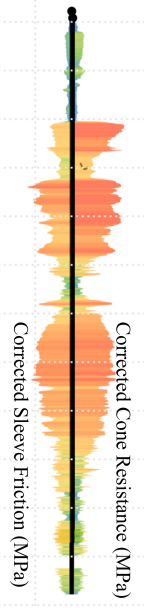
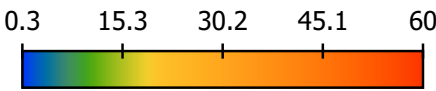
Soil Units

- U1 U4 U7
- U2 U5
- U3 U6

Corrected Sleeve Friction [MPa]



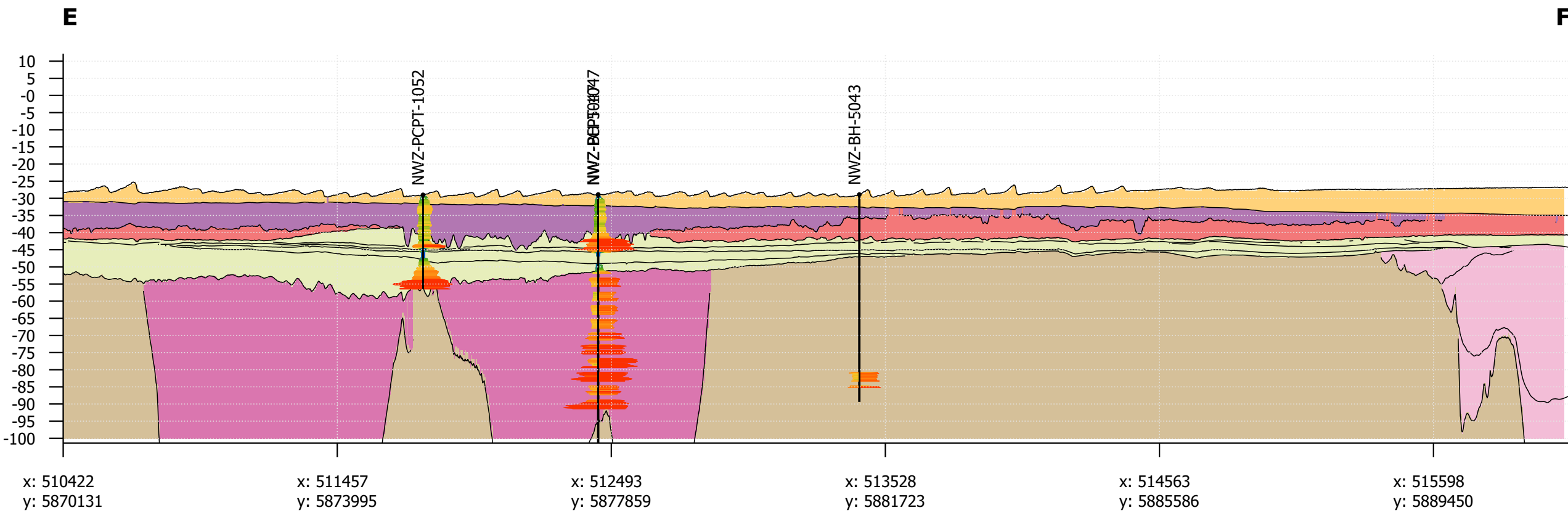
Corrected Cone Resistance [MPa]



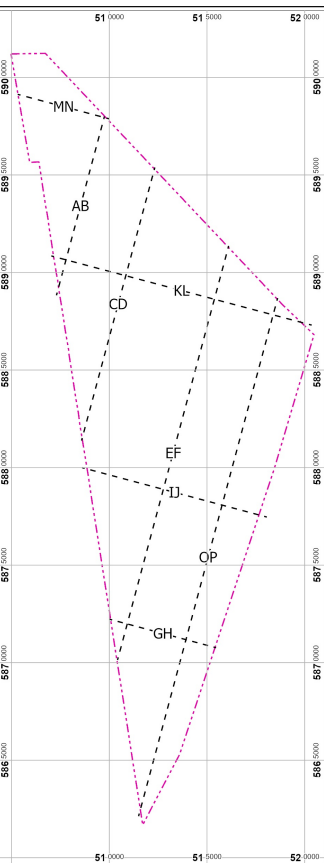
Section EF

Location

E: 510422, 5870131
F: 516111, 5891364

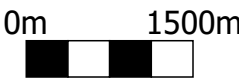


F



Vertical Exaggeration: 50x

Scale: 1:68,000



V03	06/25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP

Client
Rijksdienst voor Ondernemend
Nederland

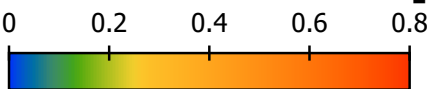
Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

Discipline	Geotechnical
Job No	295809
Drawing Status	Final
Drawing No	Issue V03

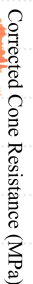
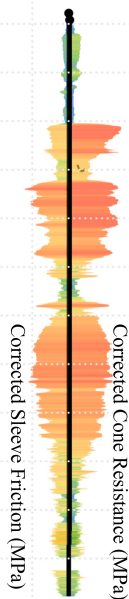
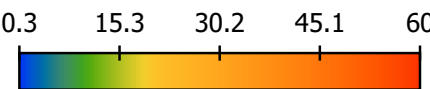
Soil Units

U1	U4	U7
U2	U5	
U3	U6	

Corrected Sleeve Friction [MPa]



Corrected Cone Resistance [MPa]

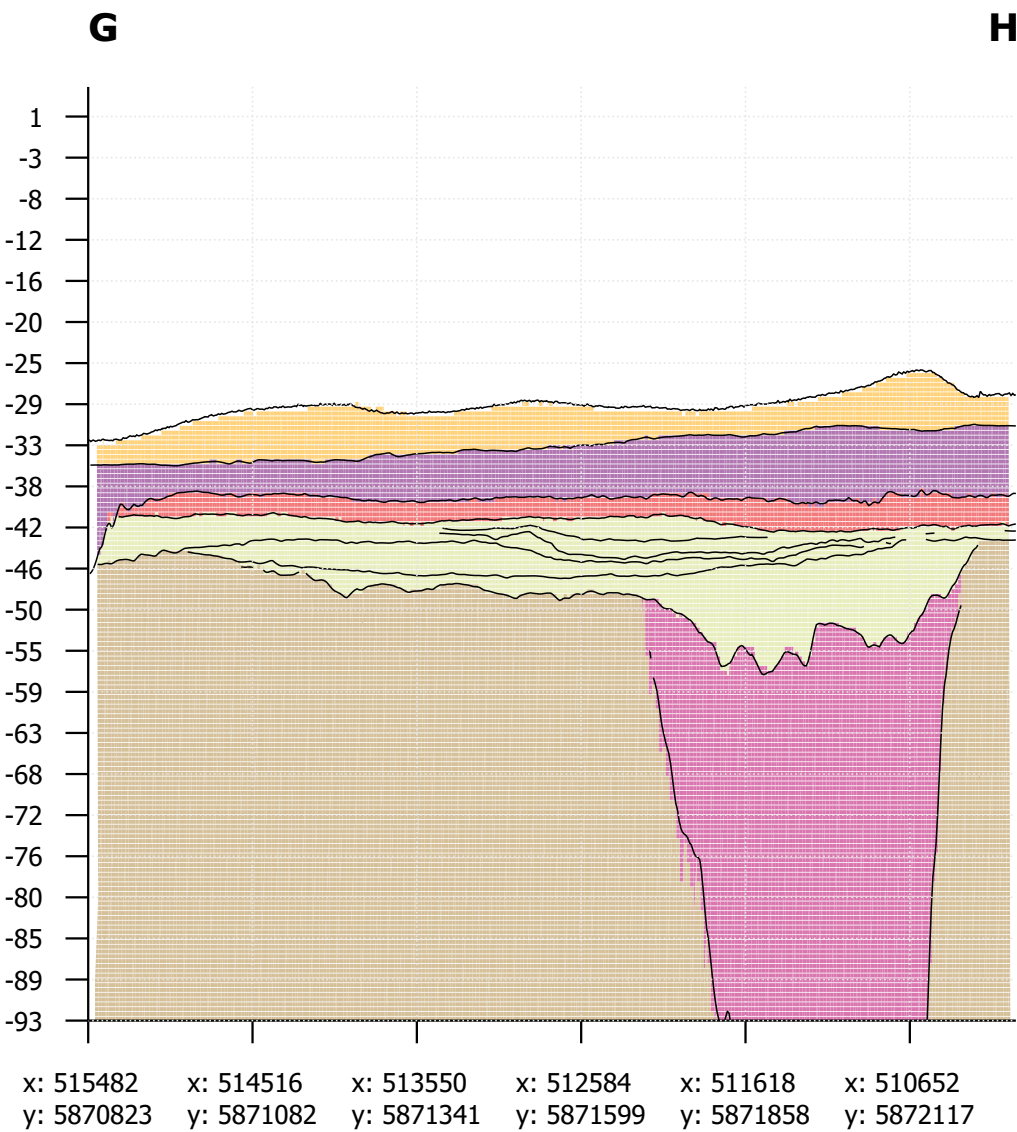


Section GH

Location

G: 515467, 5870766

H: 510014, 5872227



Soil Units

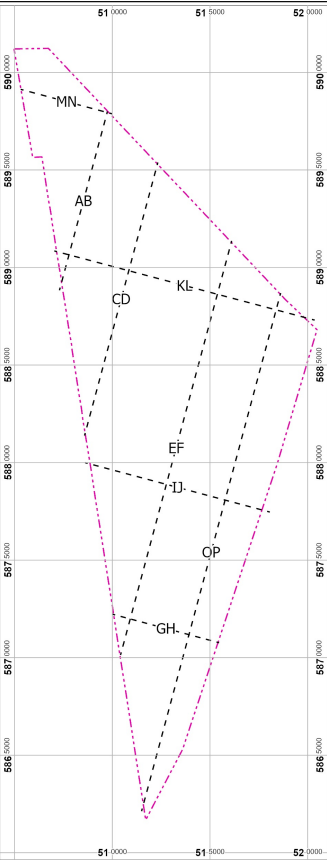
- U1

U2

U3
- U4

U6

U7



Vertical Exaggeration: 50x

Scale: 1:46,000



V03	06/25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP

Client

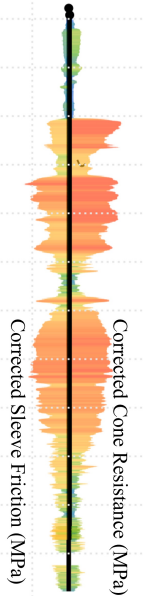


Rijksdienst voor Ondernemend Nederland

Job Title

Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

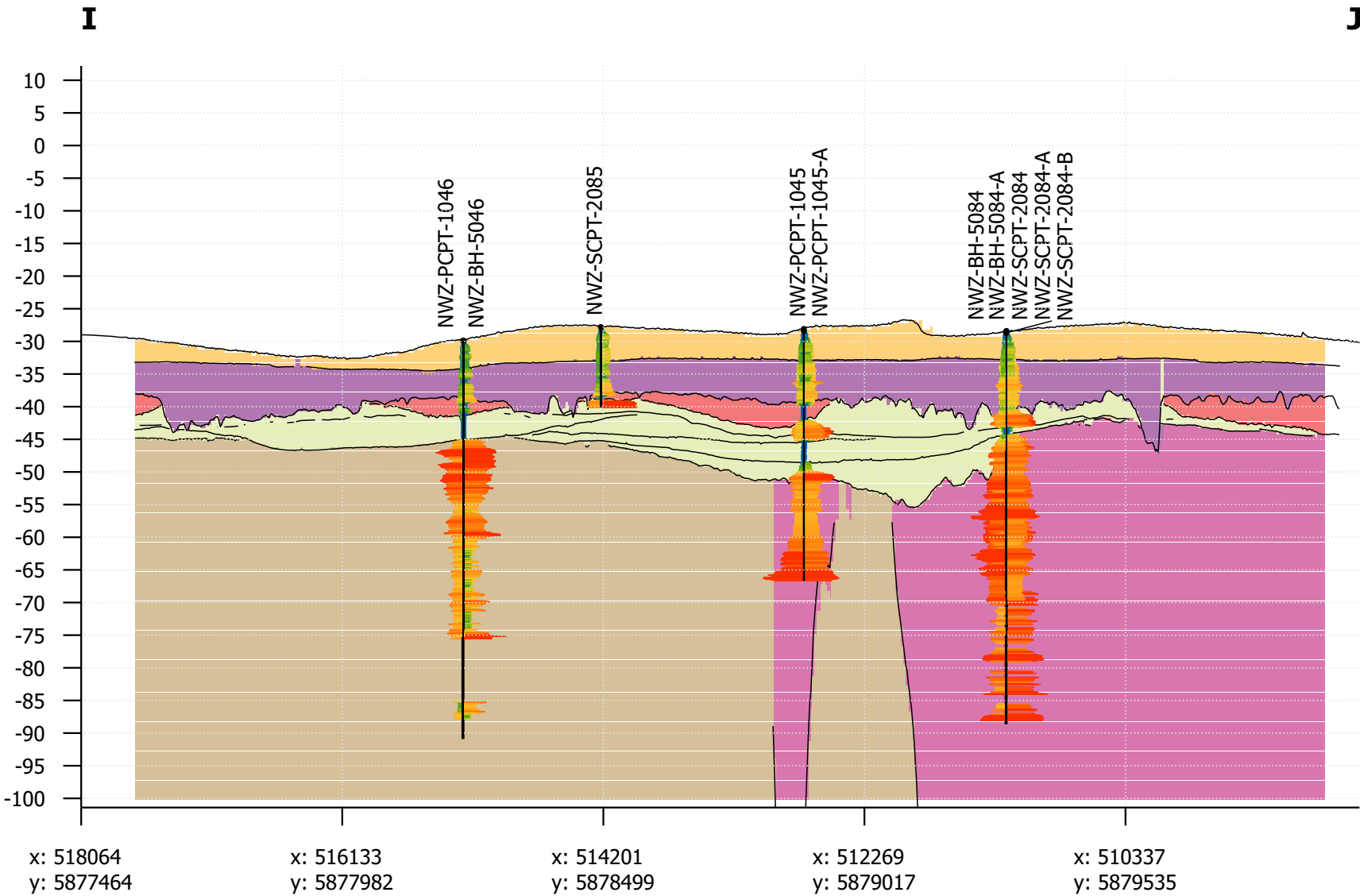
Discipline Geotechnical	
Job No 295809	Drawing Status Final
Drawing No	Issue V03



Section IJ

Location

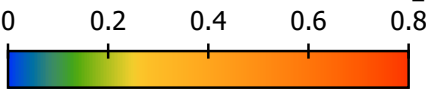
I: 518064, 5877464
J: 508606, 5879998



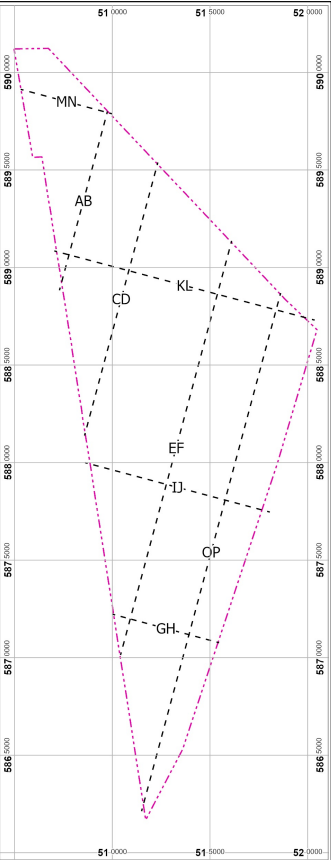
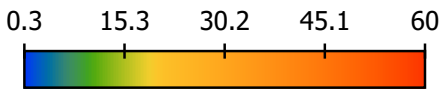
Soil Units

- U1
- U2
- U3
- U4
- U6
- U7

Corrected Sleeve Friction [MPa]



Corrected Cone Resistance [MPa]



Vertical Exaggeration: 50x

Scale: 1:46,000



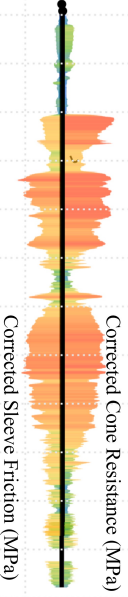
V03	06/25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP

Client
Rijksdienst voor Ondernemend Nederland

Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

Discipline	Geotechnical
Job No	295809
Drawing Status	Final
Drawing No	Issue V03

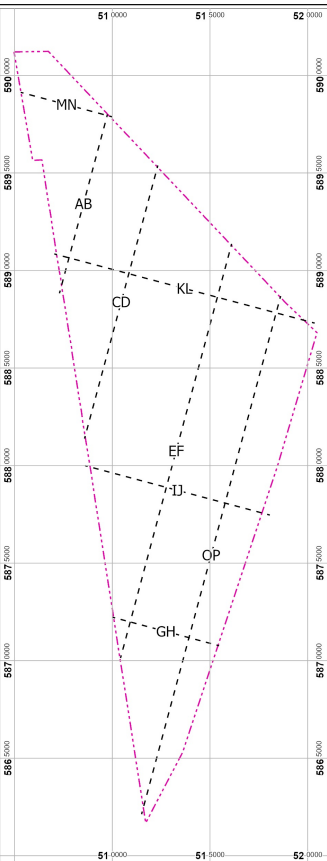
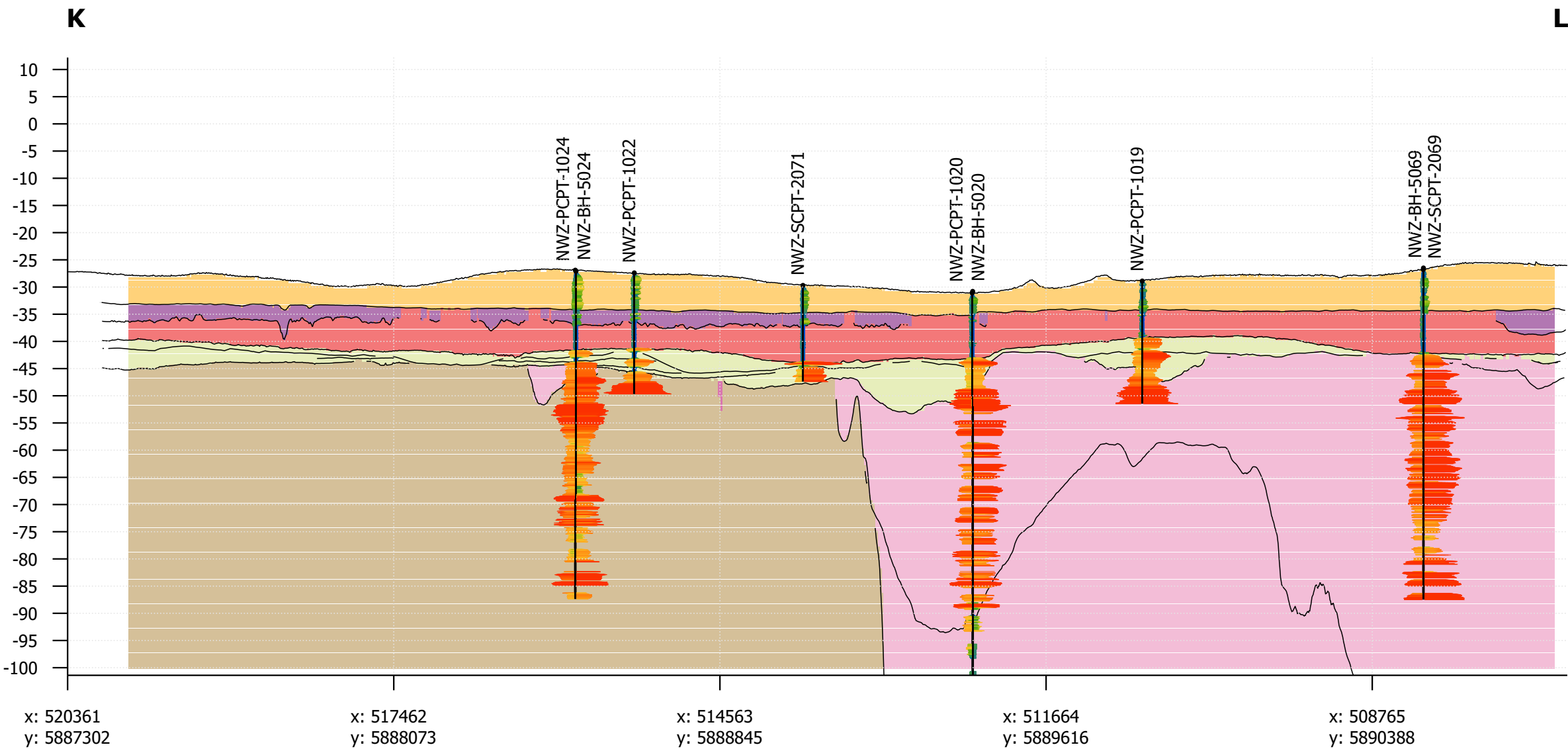


Section KL

Location

K: 520361, 5887302

L: 507031, 5890849



Vertical Exaggeration: 50x

Scale: 1:46,000



V03	06 / 25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP

Client
Rijksdienst voor Ondernemend
Nederland

Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

Discipline Geotechnical

Job No 295809

Drawing Status Final

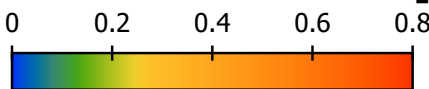
Drawing No

Issue V03

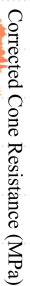
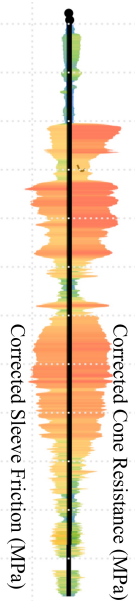
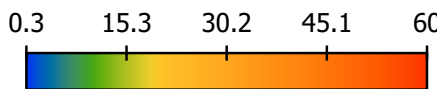
Soil Units

U1	U4	U7
U2	U5	
U3	U6	

Corrected Sleeve Friction [MPa]



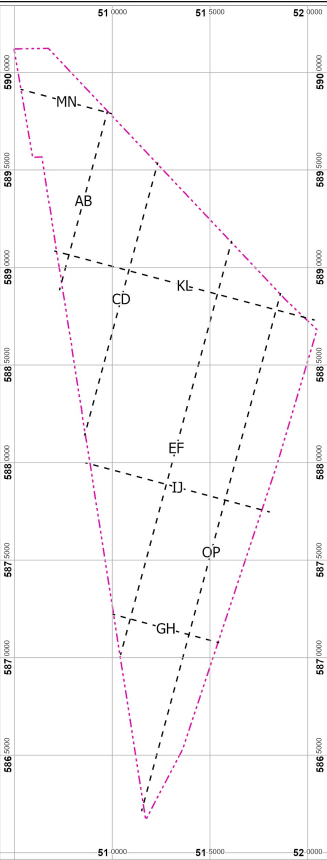
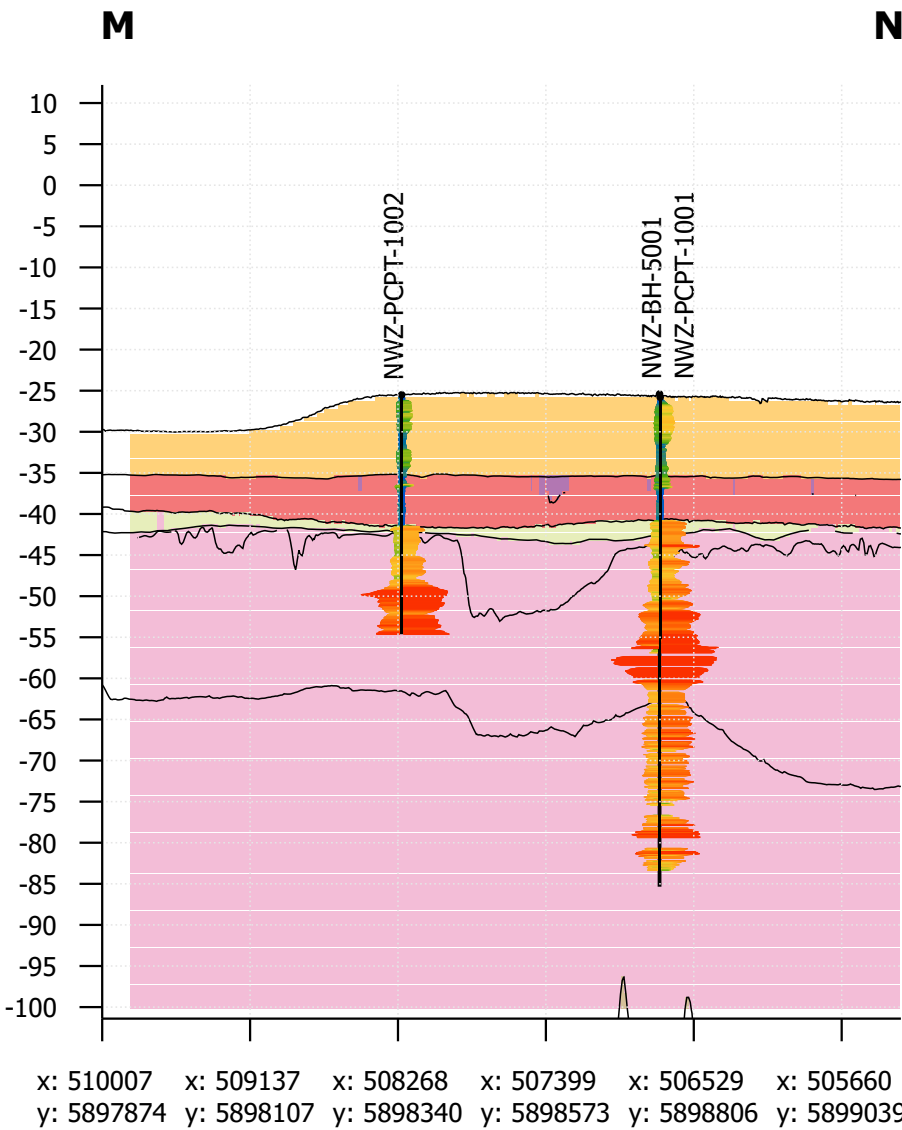
Corrected Cone Resistance [MPa]



Section MN

Location

M: 510007, 5897874
N: 505312, 5899132



Vertical Exaggeration: 50x

Scale: 1:46,000



V03	06 /25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

ARUP

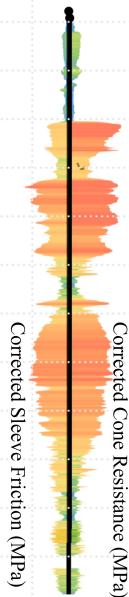
Client
Rijksdienst voor Ondernemend
Nederland

Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

Discipline Geotechnical

Job No 295809 Drawing Status Final

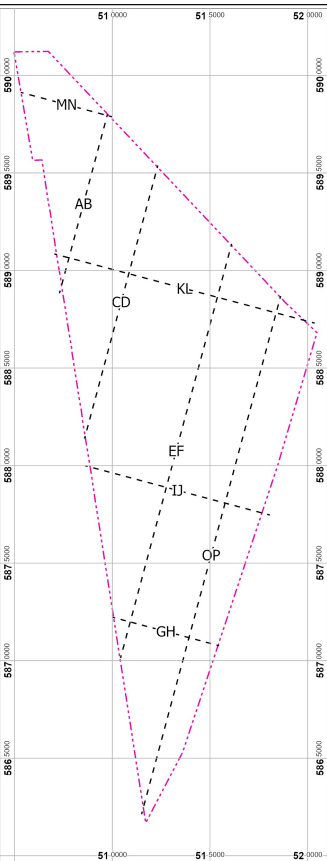
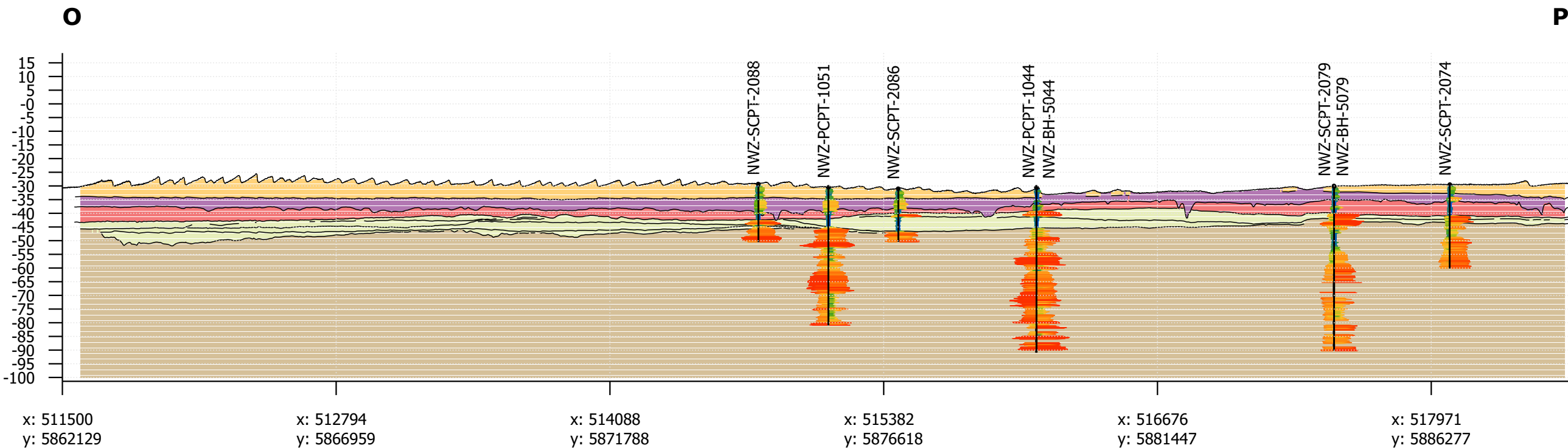
Drawing No Issue V03



Section OP

Location

O: 511500, 5862129
P: 518617, 5888690



Vertical Exaggeration: 50x

Scale: 1:84,000



V03	06/25	GN	CAS	CM
Issue	Date	By	Chkd	Appd

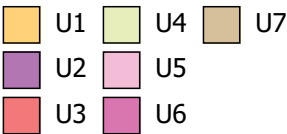
ARUP

Client
Rijksdienst voor Ondernemend Nederland

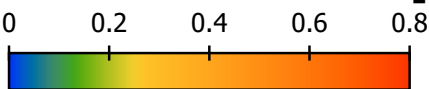
Job Title
Nederwiek Zuid Wind Farm Zone
Integrated Ground Model

Discipline Geotechnical	
Job No 295809	Drawing Status Final
Drawing No	Issue V03

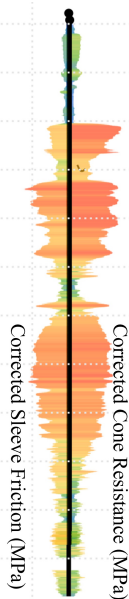
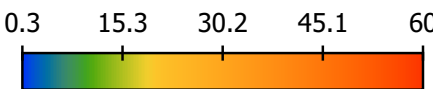
Soil Units



Corrected Sleeve Friction [MPa]



Corrected Cone Resistance [MPa]



Appendix C: Measured versus Predicted CPTs

Appendix D: NetCDF User Guide

Ten NetCDF files are provided as part of this deliverable. They are:

- Interpolated predictions models Region A-E
- Linear prediction models Region A-E

D.1.1 The voxel stack

The voxel stack refers to the stack of 0.5m voxel centroids for a given easting/northing.

The provided Jupyter notebook takes an easting/northing (or series of eastings/northings) as input and decides which is the appropriate 20x20m voxel to query. The query then returns all the vertical data for that 20x20m area which is referred to as the stack.

This is the data that is plotted on the graphs and exported in the JSON files. Two easting/northings within the same 20x20m plan area will return the same stack. Eastings/northings outside the NW IIA will return an empty stack or an error in the notebook.

D.1.2 Querying the NetCDF Models

A Jupyter notebook has been provided that queries the NetCDF models.

A decision has been taken to use python because the functionality provided by working with NetCDF data with python surpasses any freely available software.

Users may interact with the NetCDF model with python in any way they choose however a standard approach is provided in the Jupyter notebook.

The outputs from each query are:

- A tripartite graph showing interpolated parameters and the combined uncertainty envelope (default output).
- A PDF file containing the default output (optional).
- A JSON file containing the voxel data used to plot the graphs (optional) .

As mentioned previously the site is split into five regions and there is a voxel model for each region. The provided code selects the appropriate voxel model to extract the stack from on behalf of the user.

If users are using the NetCDF models for other purposes they should be aware of the divisions between the regions. The divisions are along northing values as follows:

5891934 – southern border of region a, northern border of region b.
5884246 – southern border of region b, northern border of region c.
5876481 – southern border of region c, northern border of region d.
5868869 – southern border of region d, northern border of region e.

The Jupyter notebook approach requires basic literacy in python but contains a ‘how to’ user guide. The user is only required to create a csv, provide two filepaths and toggle whether they want the optional outputs or not.

All libraries used in the notebook are standard open-source python libraries that can be downloaded via pip or conda.



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This investigation was carried out by Arup, commissioned by RVO, an agency of the Ministry Economic Affairs.

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Contacts
Netherlands Enterprise Agency (RVO)
Graadt van Roggenweg 200 | 3531 AH | Utrecht
P.O. Box 8242 | 3503 RE | Utrecht
www.rvo.nl / <https://english.rvo.nl>

Netherlands Enterprise Agency (RVO) | July 2025