Netherlands Enterprise Agency

Site Studies Wind Farm Zone Borssele

Geophysical survey wind farm site II

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Zone Borssele Site Data

The following geophysical reports produced by DEEP Offshore have been reviewed by DNV GL:

- Geophysical Site Investigation Survey / Borssele Wind Farm Development Zone Wind Farm Site 1 / Final Report / Doc. # 20150403_SBD_DEEP_Final report WFS1_V02_F / Version: V02 / 03-04-2015
- Geophysical Site Investigation Survey / Borssele Wind Farm Development Zone Wind Farm Site 2 / Final Report / Doc. # 20150403_SBD_DEEP_Final report WFS2_V02_F / Version: V02 / 03-04-2015

DNV GL has found that the above referenced reports provide sufficient geophysical detail to establish a preliminary design geological model. Such a model can be relied upon to establish general geologic conditions, including discussions on site variability, in order to establish future geotechnical investigation campaigns.

The preliminary geotechnical investigation currently underway will, together with the referenced geophysical reports, form a complete basis to begin preliminary design of future wind farms. Please note that detailed geotechnical investigations will need to be performed in order to address potential data gaps in the preliminary investigations, in particular the lack of a specific wind farm layout.

Sincerely
for Det Norske Veritas, Danmark A/S

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GEOPHYSICAL SITE INVESTIGATION SURVEY

BORSSELE WIND FARM DEVELOPMENT ZONE
WIND FARM SITE 2
DUTCH ECONOMIC EXCLUSIVE ZONE

FINAL REPORT

Netherlands Enterprise Agency

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MANAGEMENT SAMENVATTING

De Rijksdienst voor Ondernemend Nederland (RVO) heeft Deep BV het contract toegekend om vroeg in 2015 geofysische bodemonderzoeken uit te voeren in twee gebieden van het windenergiegebied Borssele (BWFZ) aan de zuidzijde van de Nederlandse Exclusieve Economische Zone (EEZ). Het BWFZ beslaat vier kavels waarin elk een windpark kan komen. De totale verwachte capaciteit bedraagt 1400 MW. Dit rapport presenteert de onderzoeksresultaten van kavel II.

Het doel van het geofysisch bodemonderzoek is om de huidige situatie van het kavel vast te leggen in relatie tot het hydrodynamische milieu in het windparkgebied, en het geven van informatie naar mogelijke gevaren geassocieerd met materiaal, infrastructuur en geologische risico's. De resultaten van dit geofysisch bodemonderzoek zullen gebruikt worden om de eerder gedane geologische- en morphodynamische bureaustudies te herzien zodat één informatiepakket geleverd kan worden ten behoeve van de marktpartijen die willen inschrijven op de SDE+ tender. Voorts zullen de resultaten van deze geofysische surveys, vooral van de sub-bottom profiling surveys ook gebruikt worden voor de planning van het geotechnische onderzoek van kavel II van het BWFZ en zal uiteindelijk dienen als input voor een aangepast geotechnisch model dat door de geotechnische contractor wordt samengesteld.

Om aan alle eisen van het geofysisch bodemonderzoek te kunnen voldoen is een uitgebreide geofysische en bathymetrische survey uitgevoerd met de volgende technieken:

- Volledige bathymetrische meting van de zeebodem in het survey gebied met multibeam echolood;
- Volledige meting van de zeebodem met side-scan sonar om objecten en natuurlijke fenomenen op de zeebodem in kaart te brengen;
- Magnetometer metingen om ferro-metalen objecten te detecteren ($\geq$ 5 nanoTesla (nT)). Deze survey is niet bedoeld voor de detectie van Conventionele Explosieven (CE);
- Sub-bottom profiling met twee technieken: een parametrisch echolood met hoge resolutie om het bovenste deel van de zeebodem in kaart te brengen en een multi-channel sparker seismische survey voor diepere informatie.

De metingen zijn uitgevoerd in twee operationele fases, met twee verschillende survey schepen: MS Seazip Surveyor is gebruikt tijdens de multi-channel seismische survey. MS Breaker is gebuikt voor het multibeam echolood, side-scan sonar, magnetometer en hoge resolutie sub-bottom profiler surveys. Vergelijking van de seismische data van MS Seazip Surveyor en de sub-bottom data van MS Breaker toont dat de data van beide technieken goed overlapt.

De meetresultaten zijn gepresenteerd in een serie kaarten in A0 en A3 formaat. Ze zijn geleverd in CAD en ESRI ArcMap formaat. De A0 kaarten tonen de gevaren lijnen van MS Seazip Surveyor en MS Breaker. Daarnaast zijn de bathymetrische metingen en gevonden objecten in kaart gebracht. De A3 formaat kaarten tonen de geïnterpreteerde geologische isopachen en laagdiktes.

De bathymetrische data laat zien dat de waterdieptes in kavel II variëren van -14.0 en 38.5 meter LAT. De aanwezigheid van grote zandduinen en kleinere zandgolven laten een dynamische zeebodem zien.
De door de multibeam gegenereerde backscatter data is gebruikt voor de zeebodemclassificatie. De zeebodem is ingedeeld in zes mogelijke klassen, van klei tot grind. Binnen kavel II behoort bijna alle sediment in de naburige klassen 'zand' en 'siltig zand'. De beschutte gebieden tussen de zandgolven tonen fijnere sedimenten, terwijl grovere sedimenten zijn aangetroffen op de toppen van de zandbanken. De classificatie toont dat er op grotere schaal weinig verschil in sediment is tussen de toppen en dalen van de grote zandduinen. Gebieden met grover zand en grind zijn sporadisch aangetroffen.

De side-scan sonar survey heeft kavel II vlakdekkend in kaart gebracht. De magnetometermetingen zijn uitgevoerd langs lijnen met 100 meter onderlinge afstand. De magnetometer resultaten zijn niet geschikt voor de detectie van CE.
In kavel II is een totaal van 189 objecten aangetroffen die niet geassocieerd kunnen worden met kabels, pijpleidingen of wrakken. Hiervan zijn 89 objecten enkel met magnetometer aangetroffen, 97 objecten alleen met de side-scan sonar en 3 objecten met beide survey technieken.

Een aantal kabel en pijpleidingen doorkruisen kavel II. De volgende kabels en pijpleidingen zijn aangetroffen.

Naam	Type	Gezien in MAG	Gezien in SSS	Gezien in MBE
Concerto 1 Segment East	kabel buiten bedrijf	ja (op locatie)	nee	nee
Farland N	kabel in bedrijf	ja (offset 100m noord)	nee	nee
UK-NL 8	kabel buiten bedrijf	ja (op locatie)	ja	nee
UK-NL 11	kabel buiten bedrijf	ja (op locatie)	ja	nee
Zeepipe	pijpleiding in bedrijf	ja (op locatie)	ja	ja

In kavel II zijn tevens twee magnetische lineaties aangetroffen die mogelijk gerelateerd zijn aan onbekende of niet gekarteerde kabels. Beide hebben een oost-west oriëntatie.

Binnen kavel II liggen twee bekende wrakken. Eén is gedetecteerd, zie tabel hieronder. Er zijn geen voorheen onbekende wrakken aangetroffen in de side-scan beelden.

Locatie nummer	Gezien in MAG	Gezien in SSS	Gezien in MBE
3657	nee	nee	nee
3658	ja	ja	ja

Een hoog resolutie sub-bottom profiler survey is uitgevoerd met MS Breaker langs lijnen met 100 meter onderlinge afstand. De zo verkregen dataset is gebruikt om een isopach te creëren van de basis van de mobiele, onderzeese zandduinen. Deze laag is aangetroffen in de overgrote meerderheid van de sub-bottom profiler survey lijnen.

De multi-channel sparker metingen voor informatie over de diepere lagen is uitgevoerd met MS Seazip Surveyor. De resulterende dataset toont de aanwezigheid van twee hoofdunits tot 100 meter onder de zeebodem.

- Horizontaal gelaagde marine en kust gerelateerde Tertaire afzettingen;
- Ondiepe marine en fluviatiele Kwartaire afzettingen.

In de Tertaire afzettingen zijn vijf seismische units aangetroffen, gebaseerd op hun seismische karakteristieken en stratigrafische omlijsting. De grens tussen de Tertaire en Kwartaire afzettingen wordt gevormd door een erosievlak. De Kwartaire unit worden gevormd door rivier en ondiepe marine afzettingen. Ze bestaan voornamelijk uit zand, met verdeelde voorkomens van grind of klei.

De hoog resolutie sub-bottom profiler data en de seismische multi-channel sparker data is gebruikt om geologische risico's ('geo-hazards') in kavel II te identificeren. Mogelijke risico's omvatten paleokanalen, grindlagen, bodemvervloeiing structuren, voorkomens van ondiep gas en organische afzettingen en hexagonale breukwerking. Op basis van de beide sub-bottom profiling datasets is een voorstel voor grondboringen locaties voor kavel II uitgewerkt.

EXECUTIVE SUMMARY

RVO contracted Deep BV to conduct geophysical surveys in early 2015 in two areas of the Borssele Wind Farm Zone (BWFZ) in the southern part of the Dutch Exclusive Economic Zone (EEZ) of the North Sea. The BWFZ consists of four areas, each intended for a wind farm. Total expected energy capacity is expected to be 1400 MW. This report is concerned with the presentation of the survey results of WFS-2 (Wind Farm Site).

The objective of the geophysical survey is to establish the WFS area's current situation with respect to the hydrodynamic environment of the wind farm site, as well as providing information about hazards associated with debris, infrastructure and geological features. The results from these geophysical surveys will be used to update the geological and morphodynamic desk studies performed earlier so one information package can be supplied during the next tender phase. The results of these geophysical surveys, especially from sub-bottom profiling surveys, will also be used for the planning of the geotechnical investigations of the WFS-2 of the BWFZ and will ultimately be input for an updated geotechnical model to be created by the geotechnical contractor.

To meet all survey objectives, a full geophysical and bathymetric survey was conducted with the following activities:

- Bathymetric mapping with multibeam echosounder for full seafloor cover within the survey area;
- Side-scan sonar mapping with full seafloor cover within the survey area, to detect man-made objects on the seabed as well as for seabed feature classification;
- Magnetometer profiling to detect ferro-magnetic objects (≥ 5 nano Tesla (nT)). This survey was not intended for the detection of UneXploded Ordnance (UXO);
- Sub-bottom profiling with two systems: one high resolution parametric echosounder to image the part of the seabed and a multi-channel sparker seismic system to for deeper penetration into the seabed.

The survey was conducted in two operational phases, with two separate survey vessels: MV Seazip Surveyor was used to acquire the multi-channel sparker seismic data; MV Breaker was used to acquire the multibeam echosounder, side-scan sonar, magnetometer and high resolution sub-bottom profiler data. Comparison between the seismic data acquired by MV Seazip Surveyor and the sub-bottom data acquired by MV Breaker showed a correct overlap between the data from both systems.

The survey results have been presented as series charts of A0 format and A3 format. They are delivered in CAD and ESRI ArcMap products. In the A0 charts the track plots of the MV Seazip Surveyor and the track plots of the MV Breaker are shown. Additionally, the bathymetric model is charted, as well as man-made detected contacts are shown. The charts in A3 format show the interpreted geological isopachs and layer depths.

The bathymetric data shows water depths ranging between -14.0 and -38.5 meters LAT in the WFS-2 area. Large sand dunes are present throughout the area, as are smaller sand waves, creating a dynamic seabed.
The multibeam derived backscatter data was used for seabed classification purposes, classifying the soil within six possible soil classes, ranging from clays to gravel. In the WFS-2 area the found sediment classes nearly all fall within the two neighboring classes 'sands' and 'muddy sands'. The finer sediments were found sheltered from the currents between the sand waves. Coarser sediments were found on the exposed tops of the sandbank. The classification shows that there is little large scale sediment difference between the tops and bottoms of the large sand dunes. Patches of coarse sand or gravel are found sporadically.

The side-scan sonar survey resulted in full data coverage of the WFS-2 area. The magnetometer survey was executed along survey lines with 100 meter line spacing. The magnetometer results are not suitable for a UXO analysis. In the WFS-2 area a total number of 189 contacts not associated with pipelines, cables or wrecks have been detected. Of these contacts 89 were detected with MAG only, 97 contacts with SSS only and 3 with both survey systems.

A number of cables and pipelines cross the WFS-2 area. The following pipelines and cables were found.

Name	Type	Seen in MAG	Seen in SSS	Seen in MBE
Concerto 1 Segment East	out-of-service cable	yes (in place)	no	no
Farland N	active cable	yes (offset 100m north)	no	no
UK-NL 8	active pipeline	yes (in place)	yes	no
UK-NL 11	out-of-service cable	yes (in place)	yes	no
Zeepipe	active pipeline	yes (in place)	yes	yes

In WFS-2 two magnetic lineations have been found that might be related to unknown or uncharted cables. Both have an east-west orientation.

Two known wrecks are present in the WFS-2 area. One has been detected, see table below. No previously unknown wreck locations were identified from interpretation of the SSS data.

Location number	Seen in MAG	Seen in SSS	Seen in MBE
3657	no	no	no
3658	yes	yes	yes

A high resolution sub-bottom profiler survey was executed using MV Breaker with 100 meter line spacing. The resulting dataset was used to create an isopach of the base of the mobile, subaqueous dunes on the seabed. The base of this layer has been found in the large majority of the sub-bottom profiler survey lines.

The deep penetrating multi-channel sparker survey was performed using the vessel MV Seazip Surveyor. The resulting dataset shows the presence of two major units within 100 meters below seabed:

- Horizontally stratified marine and coastal Tertiary deposits;
- Shallow marine and fluvial Quaternary deposits.

Within the Tertiary deposits, five seismic units were identified based on their seismic facies and stratigraphical boundaries. The boundary between Tertiary and Quaternary deposits is of erosional behaviour. The Quaternary units are formed of river and shallow marine deposits. They consist of sand deposits, with patches of gravel or clay present.

The sub-bottom profiler data and the multi-channel sparker data was used to identify any geo-hazards present in the WFS area. Possible geo-hazards include paleo channels, gravel beds, liquefaction structures, shallow gas and organic deposits and hexagonal faulting. Based on the sub-bottom profiling datasets a proposed borehole location plan has been made for the WFS-2 area.

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ABBREVIATIONS

AC	Active Cable
AIS	Automatic Identification System
BV	Besloten Vennootschap (Dutch equivalent to Ltd.)
BWFZ	Borssele Wind Farm Zone
CD	Chart Datum
CDP	Common Depth Point
CE	Conventionele Exposieven (Dutch equivalent to UXO)
C-O	Computed-Observed
CoG	Centre of Gravity
dGPS	Differential Global Positioning System
DPR	Daily Progress Report
DTM	Digital Terrain Model
EEZ	Economic Exclusive Zone
ETRS	European Terrestrial Reference System
FMGT	Fledermaus Geocoder Toolbox
GLONASS	(Russian) Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRS	Geodetic Reference System
HSE	Health, Safety and Environment
HV	High Voltage
LAT	Lowest Astronomical Tide
LW	Light Weight
MAG	Magnetometer
MBE	Multibeam Echosounder
MCS	Multi-Channel Seismic
MRU	Motion Reference Unit
MS	Motorschip (Dutch equivalent to MV)
MV	Motor Vessel
MW	Mega Watt
NE	North-East
NW	North-West
nT	nanoTesla
OOS	Out Of Service Cable
PEP	Project Execution Plan
PPE	Personal Protective Equipment
PPS	Pulsed Power Supply
PQP	Project Quality Plan
PS	Portside
QC	Quality Check
QMS	Quality Management System

RMS	Root Mean Square
RTK	Real Time Kinematic
RVO	Netherlands Enterprise Agency (Rijksdienst Voor Ondernemend Nederland)
SB	Starboard Side
SBE	Single Beam Echosounder
SBP	Sub-bottom Profiler
SD	Standard Deviation
SE	South-East
SNR	Signal to Noise Ratio
SSS	Side-scan Sonar
SVP	Sound Velocity Probe
SW	South-West
TVU	Total Vertical Uncertainty
TWTT	Two-way Travel Time
USBL	Ultra-Short Baseline underwater positioning
UTM	Universal Transverse Mercator
UXO	UneXploded Ordnance
WFS	Wind Farm Site
WFZ	Wind Farm Zone
WoW	Waiting on Weather
WPR	Weekly Progress Report

1 INTRODUCTION

1.1 General

The Netherlands Enterprise Agency (Rijksdienst Voor Ondernemend Nederland –RVO-), awarded Deep BV the contract for the execution of a geophysical site investigation survey of the WFS-1 and WFS-2 areas in the Borssele Wind Farm Zone (BWFZ), which is located near the southern border of the Dutch Exclusive Economic Zone (EEZ), approximately 0.5 km from the Belgian EEZ. The total area is approximately 344 square kilometers in size and is expected to be divided into four wind farm sites, each to be used for the development of a wind farm. The expected total energy capacity will be 1400 MW.

The geophysical site investigation survey was conducted by Deep BV, using two vessels and covered the first two wind farm sites (future total capacity of approximately 700 MW).

This report starts with a description of the objectives and scope and then presents survey results and conclusions and recommendations of the geophysical site survey. Subsequently, the operational and processing methods are described, as well as listings of personnel and survey equipment involved in the project. The results of the calibrations executed on board of MV Seazip Surveyor and MV Breaker prior to the seismic multi-channel sparker survey are presented in a separate calibration report that has been made available to the client during the survey and are added as Appendix D.

All activities for the works were executed in compliance with Deep BV's Quality Management System (QMS) which is NEN-EN-ISO 9001:2008 and OHSAS 18001:2007 certified.
Supplementary to the QMS, project specific plans and regulations are applicable, which are summarized in the References chapter.

1.2 Project key plan

In Figure 1-1 an overview is provided of the location of the Borssele Wind Farm Zone (BWFZ), west of the Dutch province of Zeeland. The area is located near the southern border of the Dutch Exclusive Economic Zone (EEZ), indicated with the dashed pink line in Figure 1-1. At the south-east side of the wind farm zone a sand extraction area is located and at the east side of the BWFZ a piloting area is located. Anchoring areas and a shipping lane are located at the north side of the zone. At the south-east side of the wind farm zone the Belgian dedicated offshore wind zone is located.

WFS-2 is approximately 68 km^2 in size. Around the WFS-2 site a buffer zone between 500 and 750 m was defined that bounded the survey area, making the total area to be surveyed around WFS-2 approximately 81 km^2.

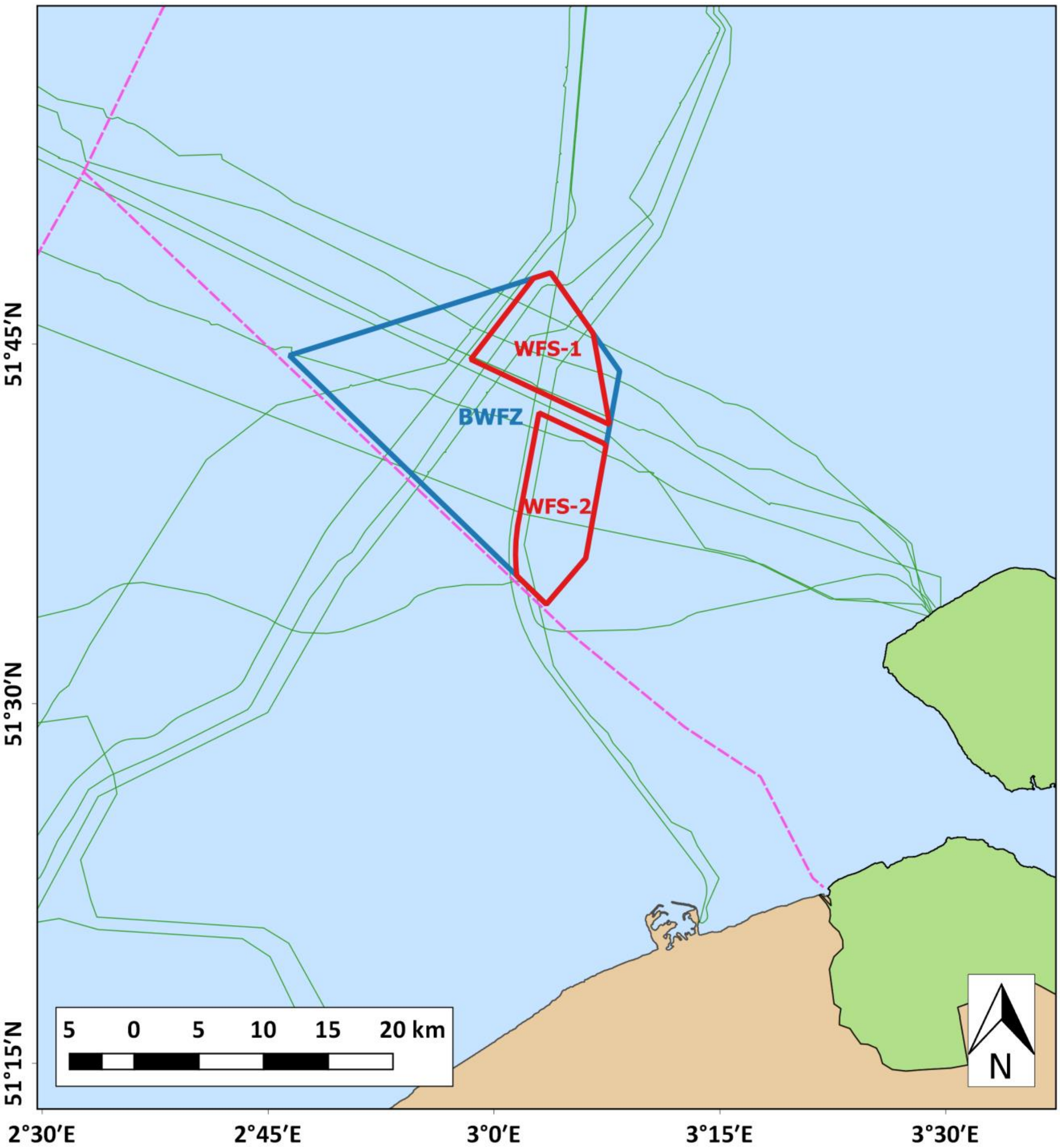


Figure 1-1: Overview map Borssele Wind Farm Zone location

2 OBJECTIVE AND SCOPE

The following chapter gives a summary of the objective and scope of work.

2.1 Objective of work

The objective of the geophysical soil investigation is to improve the geological and geotechnical understanding of the Borssele Wind Farm Zone (BWFZ) that is planned in the Dutch EEZ and to obtain geophysical information on these locations, which is suitable for the preparation of geotechnical investigations and suitable to progress the design and installation requirements for offshore wind farms, including, but not limited to foundations and cables.

The investigation for WFS-2 should provide:

- Accurate bathymetry of the site;
- Seabed morphology and sediment classification;
- The presence of seabed features including:
    - Any natural objects such as boulders;
    - Any large non-natural objects such as wrecks or debris.
- The exact position of existing cables and pipelines;
- Isopach charts to show the thickness of the main geological formations including any mobiles sediments and any other significant reflector levels which might impact on the engineering design;
- Locations of any structural complexities or geohazards within the shallow geological succession such as faulting, accumulations of shallow gas, buried channels etc;
- Input into the specification and scope for a geotechnical sampling and testing programme following the completion of the geophysical survey;
- A comprehensive interpretative report on the survey results obtained to assist design of the offshore foundations / structures and cable burial.

The outline of the area under investigation is defined as follows.

Table 2-1: Geographical boundaries of WFS-2

UTM (ETRS89, Zone 31)		
Point ID	**X**	**Y**
98	508800.53	5726317.36
38	507087.05	5716811.66
39	504039.56	5713246.09
86	501212.81	5715983.99
87	501191.85	5716293.61
88	501174.83	5716767.02
89	501165.14	5717508.21
90	501194.99	5718210.40
91	501324.49	5719365.41
93	503140.24	5729028.16

2.2 Scope of work

To meet the project objectives and standards, a full geophysical seabed survey was required including:

- Multibeam Echosounder (MBE) bathymetric mapping with full seafloor search (>100% coverage) within the survey area. Acquired data standard according to IHO S-44 Order 1a, which includes identification of all objects greater than 2.0mx2.0m dimensions. Acquired results should be able to produce a 1m resolution gridded DTM;
- Side-scan sonar (SSS) mapping (overlap >125% to cover nadir regions of adjacent survey lines). Acquired data should be logged with dual frequency where lowest frequency is at least 100 kHz. Acquired results should be able to produce a mosaic of 0.5m resolution and a target picking threshold of 0.3m resolution where data quality allows;
- Magnetometer (MAG) profiling along all survey lines. A 5 nT threshold will be used for detection purposes;
- Sub-bottom profiling with two systems:
    - High resolution sub-bottom profiler system (SBP). Acquired (high frequency) data should have overlap with MCS;
    - Deep penetration multi-channel sparker (MCS) system. Acquired (low frequency) data should be able to penetrate to at least 80m below seabed.

The results of the geophysical survey were expected to allow a detailed mapping of the seabed in order to:

- Provide an accurate bathymetry of the survey areas;
- Map natural seabed features, morphology and type (e.g. sandbanks, sand dunes, loose and mobile material, sandy surfaces);
- Highlight surfaces and objects of potential marine archaeological relevance (e.g. historical shipwrecks including anchors and related items, possible relics of ancient settlements);
- Identify large possible man-made obstructions, lost fishing gear, waste left on the sea bottom, exact routes of known and unknown cables and pipelines.

Furthermore, mapping of the upper portion of the subsurface was to be carried out to a sufficient level of detail to:

- Map geological layers and structures to well below the expected maximum foundation depths of wind turbines, which may extend down to approximately 100m below the seabed depending on the local geological setting and foundation type;
- Identify structural complexities or potential geo-hazards within the shallow geological succession such as faulting, accumulations of shallow gas, buried channels or soft sediments along the survey lines.

The activities needed to obtain the information detailed in section 2.1 are grouped into the following project phases:

- Preparation: preparation of the geophysical survey and plans needed before the works started;

- Mobilization and installation: mobilization of both survey vessels, as well as the installation of all survey equipment on board;
- Calibration: calibration of the survey equipment to assess accuracy of the survey systems;
- Execution of the survey: acquisition of the following data:
  - High-resolution multibeam bathymetry;
  - High-resolution side scan sonar data;
  - Magnetometer data;
  - High-resolution seismic profiler data.
- Data processing, reporting and charting: the acquired geophysical survey data is processed to specific standards and presented in clear reports and drawings.

2.3 Reporting deliverables

2.3.1 Reports

Both WFS sites were surveyed in one survey campaign, but for each WFS site an individual report was compiled, with exception of the Field Report, which was reported for both WFS-1 and WFS-2. The calibration reports were split for each survey, one with MV Seazip Surveyor, the other with MV Breaker.

Table 2-2: Report deliverables

Report	Deliverable ID
Calibration report MV Seazip Surveyor	20150227_SDB_DEEP_Calibration report Seazip Surveyor_V03_F
Calibration report MV Breaker	20150311_SDB_DEEP_Calibration report Breaker_V04_F
Field report WFS-1 & WFS-2	20150310_SDB_DEEP_Field report_V02_F
Draft final report WFS-1	20150303_SDB_DEEP_Draft final report WFS1_V01_D
Draft final report WFS-2	20150303_SDB_DEEP_Draft final report WFS2_V01_D
Final report WFS-1	20150403_SDB_DEEP_Final report WFS1_V02_F
Final report WFS-2	20150403_SDB_DEEP_Final report WFS2_V02_F

2.3.2 Charts and profiles

With the final reports the following accompanying charts in A0 size were delivered:

Table 2-3: A0 Chart deliverables WFS-2

Data type	Chart Content	Scale	Format	#	Deliverable ID
Tracks	Tracks Sub Bottom Profiler and Multibeam	1:20000	.PDF .DWG	1	20150327_SDB_DEEP_Tracks-SBP&MBE-WFS2-chart-1of1_V01_F
	Tracks Magnetometer and Side Scan Sonar	1:20000	.PDF .DWG	1	20150327_SDB_DEEP_Tracks-MAG&SSS-WFS2-chart-1of1_V01_F
	Tracks MC Sparker	1:20000	.PDF .DWG	1	20150327_SDB_DEEP_Tracks-MCS-WFS2-chart-1of1_V01_F

Bathymetry	Shaded relief bathymetry with contours	1:10000	.PDF .DWG	2	20150327_SDB_DEEP_Bathymetry-WFS2-chart-#of2_V01_F
Backscatter	Backscatter seabed classification	1:20000	.PDF .DWG	1	20150327_SDB_DEEP_Backscatter-WFS2-chart-1of1_V01_F
Contacts	Side Scan Sonar and Magnetometer contacts	1:10000	.PDF .DWG	2	20150327_SDB_DEEP_Contacts-WFS2-chart-#of2_V01_F
Geo-hazards	Geohazards form SBP and MCS interpretation	1:20000	.PDF .DWG	1	20150327_SDB_DEEP_Geohazards-WFS2-chart-1of1_V01_F

With the final reports the following accompanying charts in A3 size were delivered:

Table 2-4: A3 Chart deliverables WFS-2

Data type	Chart	Scale	Format	#	Deliverable ID
MCS	Isopach charts geological units	1:100000	.PDF	5	20150327_SDB_DEEP_Isopach-MCS-chart-#of05_V01_F
	Base chart geological units	1:100000	.PDF	6	20150327_SDB_DEEP_Base-MCS-chart-#of06_V01_F
SBP	Isopach charts geological units	1:100000	.PDF	1	20150327_SDB_DEEP_Isopach-SBP-chart-01of01_V01_F
	Base chart geological units	1:100000	.PDF	1	20150327_SDB_DEEP_Base-SBP-chart-01of01_V01_F

With the final reports the following accompanying geological profiles were delivered:

Table 2-5: Profile deliverables WFS-2

Data type	Profile	Scale	Format	#	Deliverable ID
MCS	MCS seismic data with geological interpretation	1:10000 (horizontal) 1:1000 (vertical)	.PDF .DXF	74	Line Name.pdf

2.3.3 Electronic deliverables

The following electronic deliverables are submitted with the report

Table 2-6: Electronic deliverables WFS-2

Data type	Deliverable	Format	Deliverable ID
MBE	Multibeam Raw data Full density, cleaned xyz per line	.XYZ	Prefix_Line Name_B_WFS1-2_P2849_ yyyymmdd_MSE - Sequence.xyz
	Backscatter Raw data	.GSF	Prefix_Line Name_B_WFS1-2_P2849_ yyyymmdd_MSE - Sequence.gsf

Data type	Deliverable	Format	Deliverable ID
	Bathymetry DTM 1m resolution	.XYZ	20150327_SDB_DEEP_WFS2_MBE-bathymetry-1x1_V01_F.xyz
	Bathymetry uncertainty grid (95% confidence) at 1m resolution	.XYZ	20150327_SDB_DEEP_WFS2_MBE-uncertainty_1x1_V01_F.xyz
	Backscatter intensity image at 1m resolution	.TFW .TIF	20150327_SDB_DEEP_WFS2_MBE-Backscatter Intensity-1x1m_V01_F.tif
	Backscatter seabed classification image at 25m resolution	.TFW .TIF	20150327_SDB_DEEP_WFS2_MBE-Backscatter Classification-25x25m_V01_F.tif
	Bedform zonation image at 10m resolution	.TFW .TIF	20150327_SDB_DEEP_WFS2_MBE-Bedform Zonation-10x10m_V01_F.tif
	Bedform zonation polygons	.DWG	20150327_SDB_DEEP_WFS2_MBE-Bedform Zonation Polygons_V01_F.dwg
SVP	Sound velocity profiles	.XLSX	yyyymmdd_SDB_DEEP_CAL_ SVP #_V01_F.xlsx
SSS	Side scan sonar RAW data after positioning QC	.XTF	Prefix_Line Name_B_WFS1-2_P2849_ yyyymmdd_GEO - Sequence.xtf
	Side scan sonar image per survey line	.TFW .TIF	Line Name.tif
	Side scan sonar mosaic grayscale Geotiff 0.5x0.5m resolution	.TFW .TIF	20150327_SDB_DEEP_SSS MOSAIC-WFS2-GRAY-50x50cm_V01_F.tif
	Side scan sonar mosaic colorscale Geotiff 0.5x0.5m resolution	.TFW .TIF	20150327_SDB_DEEP_SSS MOSAIC-WFS2-RGB-50x50cm_V01_F.tif
	Side scan sonar mosaic tiles grayscale Geotiff 0.5x0.5m resolution	.TIF	20150327_SDB_DEEP_SSS MOSAIC-WFS2-GRAY tile #-50x50cm_V01_F.tif
	Side scan sonar mosaic tiles colorscale Geotiff 0.5x0.5m resolution	.TIF	20150327_SDB_DEEP_SSS MOSAIC-WFS2-RGB tile #-50x50cm_V01_F.tif
	SSS target table, including cross-reference with MAG	.XLSX	20150327_SDB_DEEP_SSS Listings WSF-2_V01_F.xlsx
	SSS target details	.DOC	20150327_SDB_DEEP_SSS Target Details WFS-2_V01_F.doc
	SSS targets as points/lines/polygons	.DWG	20150327_SDB_DEEP_Contacts-WFS2-chart-#of2_V01_F.dwg
MAG	De-spiked Raw magnetometer data per survey line	.TXT	Line Name.txt
	De-trended magnetometer data per survey line	.TXT	Line Name_detrended.txt
	MAG targets as points/lines/polygons	.DWG	20150327_SDB_DEEP_Contacts-WFS2-chart-#of2_V01_F.pdf

Data type	Deliverable	Format	Deliverable ID
	MAG target table, linear contacts	.XLSX	20150327_SDB_DEEP_MAGGY Listings linear WFS-1_V01_F.xlsx
	MAG target table, including cross-reference with SSS	.XLSX	20150327_SDB_DEEP_MAGGY Listings WFS-2_V01_F.xlsx
SBP	SBP raw profiles	.SGY	P2849_B_WFS1-2_SBP_Line Name.segy _yyyymmdd_hhmmsslong_LF.sgy
	SBP processed profiles	.SGY	P2849_B_WFS1-2_SBP_Line Name _yyyymmdd_hhmmsslong_LFproc.sgy
MCS	MCS RAW seismic profiles	.SEGY	Line name_sequence.segy
	MCS RAW data with geometry loaded to the headers	.SGY	Line name_GEOM.sgy
	MCS Stack up to multiple attenuation	.SGY	Line name_MUL_tide.sgy
	MCS Migrated stack	.SGY	Line name_MIG_tide.sgy
	MCS Migrated stack Low Cut	.SGY	Line name_MIG_tide_LC.sgy
	MCS Depth converted stack	.SGY	Line name_DPT_tide.sgy
	MCS Depth converted stack Low Cut	.SGY	Line name_DPT_LC_tide.sgy
	Interactive Velocity Analysis: RMS velocity models	.DAT	Line name_IVA_RMS.dat
	Interactive Velocity Analysis: Interval velocity models	.DAT	Line name_IVA_INT.dat
	Seismic interpretation (pick) files	.DAT	Horizon/Geohazard.dat
	Seismic grids of horizon depths	.DAT	Horizondptgrd.dat
	Seismic grids of Unit thickness	.DAT	UnitThickgrd.dat
GEN	Tidal data	.TXT	Date_SDB_DEEP_Tidal data VESSEL_V01_F.txt
	GIS data	Various	Various

3 RESULTS

Results from the survey operations in WFS-2 are presented in this chapter. Reference is made to supporting information presented in drawings that accompany this report.

Full data coverage over WFS-2 was achieved for all survey systems and all recorded data was considered of good and excellent quality throughout the survey. If data was initially of lesser quality due to adverse weather conditions, the data was re-recorded in better weather conditions in a later stage of the survey campaign.

3.1 Disclaimer

In the processing and interpretation of the geophysical data, Deep BV employees have relied on experience and have exercised their best judgment. However, all interpretations are opinions based on interferences from acoustical and/or other measurements. Features that do not produce measurable geophysical anomalies or are hidden by other features may remain undetected. Geophysical surveys may compliment invasive/destructive methods and provide a tool for investigating the subsurface; they do not produce data that can be taken to represent all of the ground conditions found within the surveyed area. Areas that have not been surveyed due to obstructed access or any other reason are excluded from the interpretation. Therefore Deep BV cannot and does not guarantee the accuracy or the correctness of any interpretations. As such, Deep BV shall not be liable for any loss, damages or expenses resulting from reliance on such interpretation.

3.2 Bathymetry

This section describes the bathymetry within survey site WFS-2 as determined from the MBE survey. The results are presented as charts in Appendix J.

3.2.1 Geomorphological background

In Figure 3-1 the BWFZ and WFS-1 and WFS-2 are plotted on the nautical chart of the North Sea, compiled by the UK Hydrographic Office. As can be observed from this plot, four parallel sandbanks are crossing the survey area. From shore to sea these are the Rabsbank, Schaar, Buitenbank 3 and Buitenbank 2. A morphodynamic desk study was carried out by Deltares (Deltares 2014). From historical bathymetric surveys in the BWFZ area they have found that the water depth in the area ranges from 15 to 40 meters below Lowest Astronomical Tide (LAT). The seabed morphology in the area of the BWFZ is characterized by high sedimentary dynamics, with static shore-parallel sandbanks overlaid with dynamic shore-perpendicular sand waves. The sandbanks and sand waves observed in Belgian sector of the North Sea, directly adjacent to the BWFZ area are up to 30 meters high and can be several kilometers wide and several tens of kilometers long (Le Bot et al. 2005).
Statistical analysis of sand wave mobility (Deltares 2014) shows that there are two main directions of sand wave movement, one in NE-direction with an average speed of 1.7 m/yr and one in SW-direction with an average speed of 3.2 m/yr. According to Ashley (1990) seabed features (ripples, sand waves and dunes) can be classified in terms of dune height, spacing between features and dune shape (2D or 3D) as first order descriptors (*Table 3-1*). This classification is used to describe the morphological features in the BWFZ area.

Table 3-1: Classification scheme for subaqueous bedforms (after Ashley et al. 1990)

General class: Dune				
First Order Descriptors				
Size				
Spacing	0.6-5m	5-10m	10-100m	>100m
Height	0.075-0.4m	0.4-0.75m	0.75-5m	>5m
Term	***small***	***medium***	***large***	***very large***
Shape				
2D	Straight-crested, little or no scour in through			
3D	Sinuous, caternary or linguoid/lunate crested, deep scour in through			
Second Order Descriptors				
Superposition				
Simple	No bedforms superimposed			
Compound	Smaller bedforms superimposed			

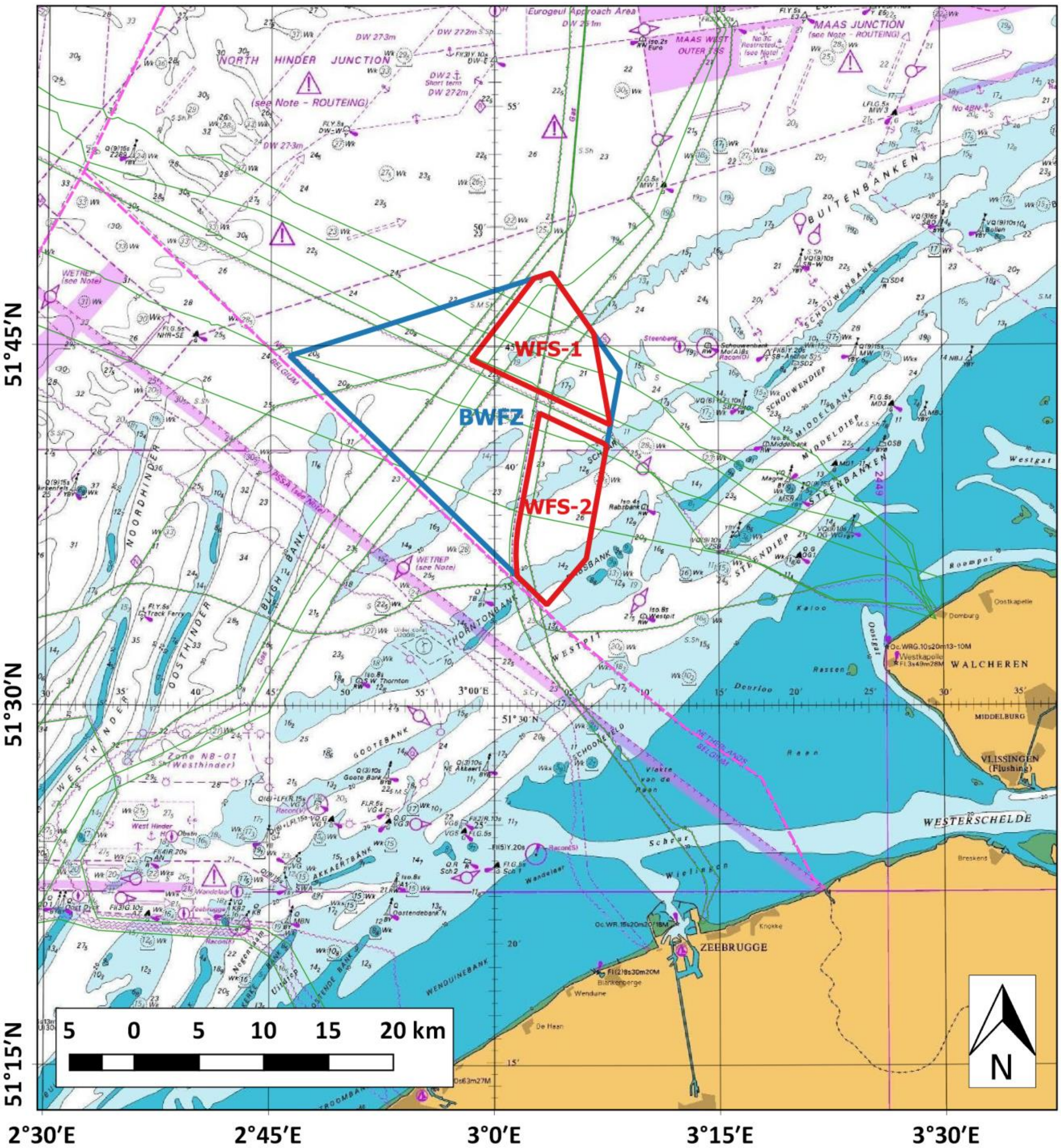


Figure 3-1: Location of the BWFZ, WFS-1 and WFS-2 on a nautical chart
blue: outline of BWFZ, red: WFS-1 (north) & WFS-2 (south), green: pipelines & cables, pink dashed: boundary of EEZ

3.2.2 Bathymetry results

Figure 3-2 shows an overview of the bathymetry in both WFS-1 and WFS-2. The bathymetry can be described as a complex pattern of parallel sandbanks with subaqueous dunes (sand waves) superimposed. The sandbanks stretch out in SW to NE direction, the subaqueous dunes have a general NW to SE or W to E direction. In WFS-2 the sandbanks present are the Schaar and Rabsbank, water depth ranges between -14.0 and -38.5m LAT.

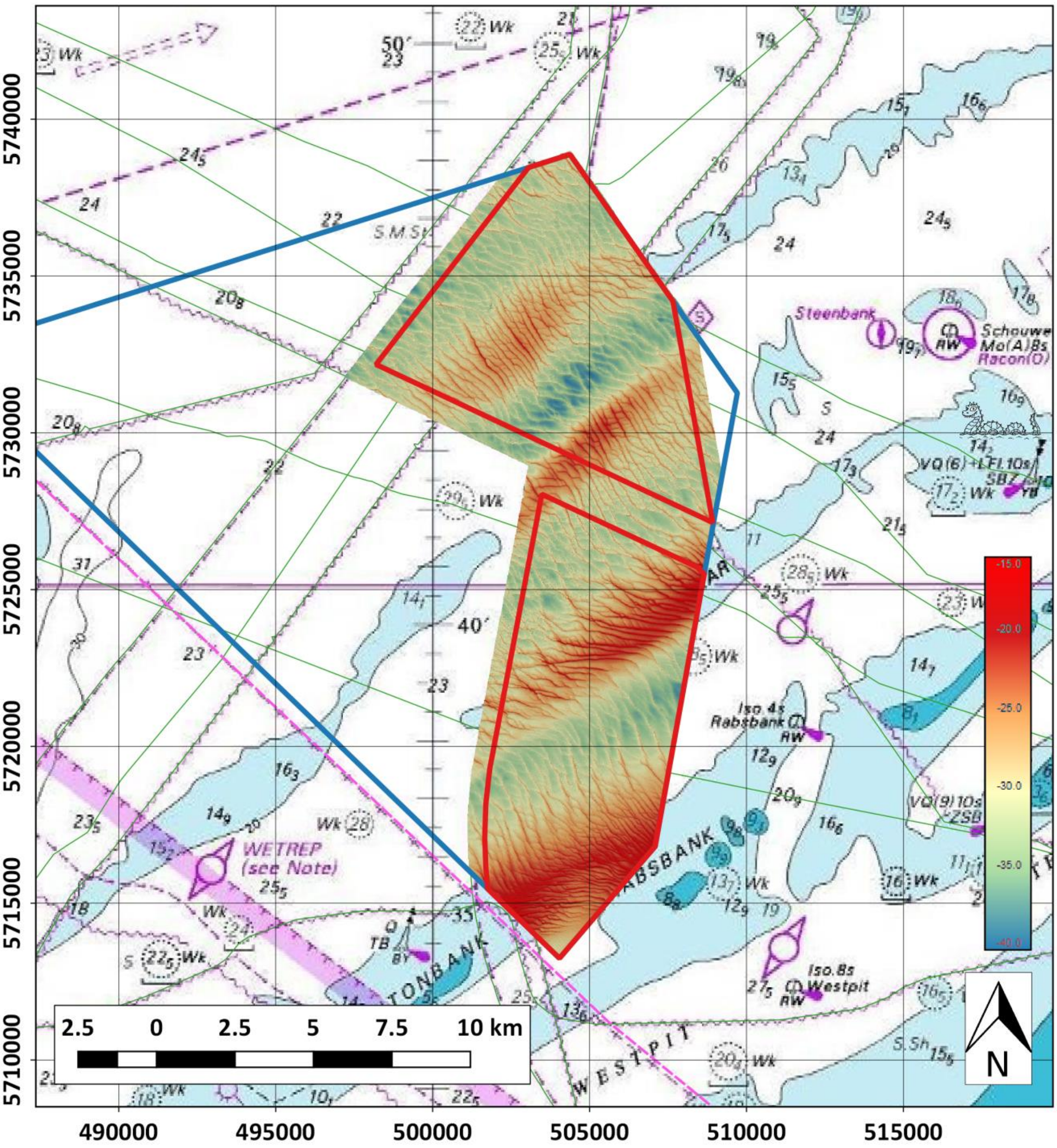


Figure 3-2: WFS-1 and WFS-2 MBE survey grid superimposed on the nautical chart
Elevation in m LAT

3.2.3 Observed bedforms

The MBE survey of the entire survey area results reveals the clear presence of the four sandbanks (Figure 3-2). The depth on the sandbanks is between -14 and -30m LAT, the surrounding seabed is -25 and -38 m LAT. In WFS-2 the Schaar and Rabsbank sandbanks are present (Figure 3-3). The general direction of both sandbanks is from SW to NE with an average distance between the two banks of 6000 meters.

On the sandbanks and the interlaying troughs a complex pattern of sand waves is present, or large to very large subaqueous dunes according to the classification of Ashley (1990). A bedform zonation map was derived from the MBE data, demarcating more or less homogeneous areas in terms of sand dune shape and spacing and crest line orientation. The results for WFS-2 are depicted in Figure 3-4, with average figures per zone for sand dune spacing/height (where quantification was meaningful) and dominant aspect summarized in Table 3-2.

Table 3-2: Bedform zonation summary

Zone	Height	Spacing	Bedform	Dominant Aspect
II-C	Min. 3m to max. 8m Average 5.5m	Min. 200m to max. 350m	Large to very large compound 2D sand dunes. More or less straight crest lines with few bifurcations.	50/230
I-C	Variable from 3m to 10m	Variable from 200m to 500m	Large to very large compound 2D sand dunes with bifurcations Tend to 3D shapes at the south side of the area	30/210
II-D	Variable from 3m to 8m	Variable from 150m to 400m	Large to very large compound 2D sand dunes with bifurcations	30/210
III-C	Min. 2m to 6m Average 5.5m	Variable from 150m to 350m	Large to very large compound straight sand dunes	10/190
I-D	Variable from 3m to 7m	Variable from 200 to 500m	Large to very large compound 2D sand dunes with bifurcations	50/230
II-E	Variable from 2m to 5m	Variable from 100m to 300m	Large to very large compound 2D sand dunes with bifurcations	30/210
III-D	Min. 2m to max. 5m Average 4.5m	Min. 100m to max. 300m	Large compound sand dunes with bifurcations. Tend to 3D sand dunes at the south side of the area	10/190
IV-A	Average 0.5m	Average 12m	Medium straight sand dunes	40/2220

The spatial distribution in bedform morphology is strongly related to the sand banks present in the area. Except for area IV-A, the spacing between and height of the large and very large sand dunes on top of the tidal ridges generally shows less variability and is smaller than in the deeper areas of the troughs. Crestlines of the large-scale dunes show a strong NW-SE trend and mostly have a symmetrical stoss-lee relationship. In zones III-C and III-D contain sand dunes with a W-E orientation. Area IV-A is very different from the other zones as it only shows medium straight sand dunes with almost no branching between crests.

On the very large dunes another pattern of medium dunes is superimposed. On the sandbanks these dunes are medium-sized, with spacing between 5 and 8 meters, and height ranging from 0.3 to 0.5 meters. In the troughs these medium dunes have spacing between 7 and 10 meters, with height ranging from 0.2 to 0.4 meters.

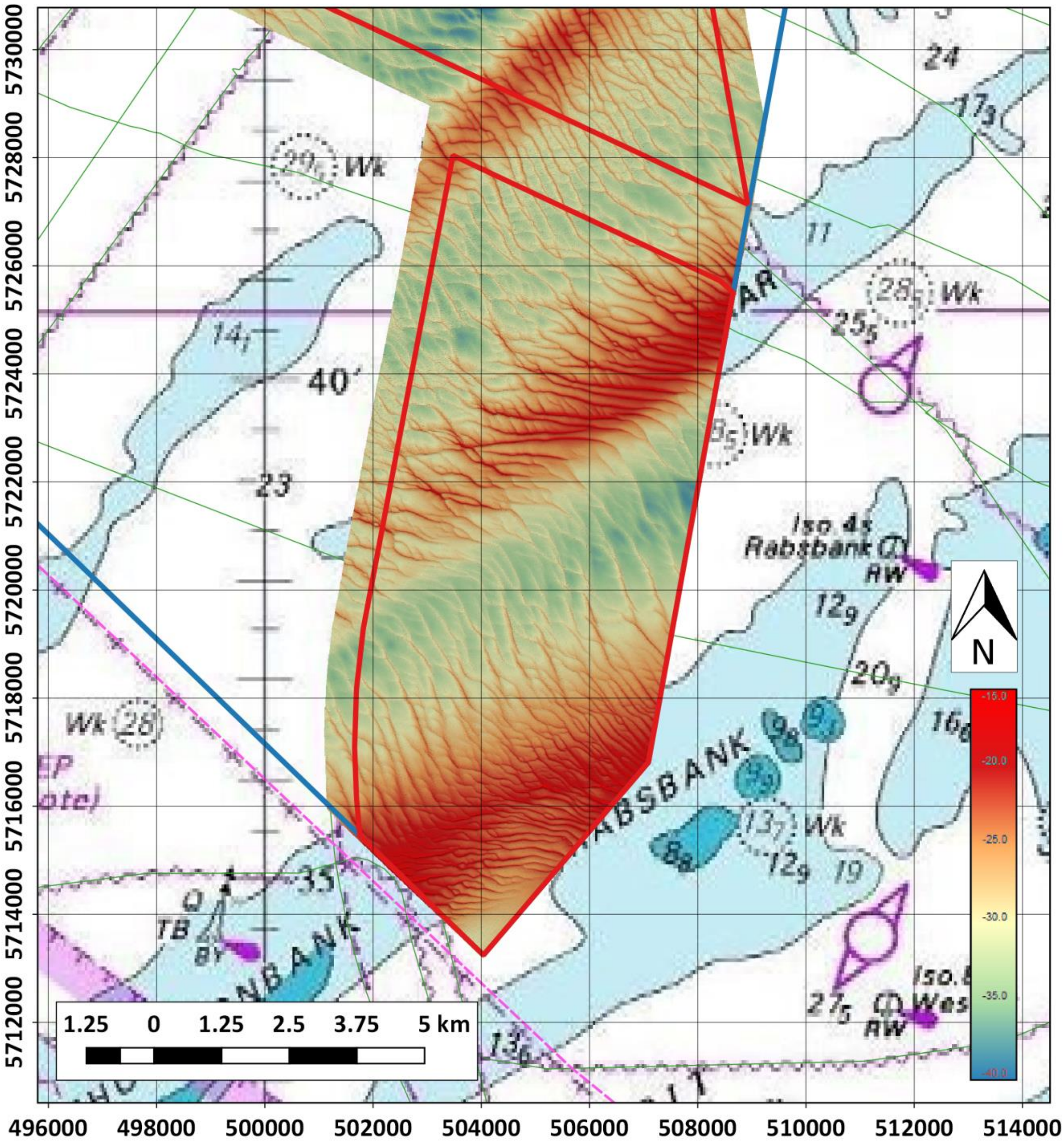


Figure 3-3: WFS-2 MBE survey grid superimposed on the nautical chart
Elevation in m LAT

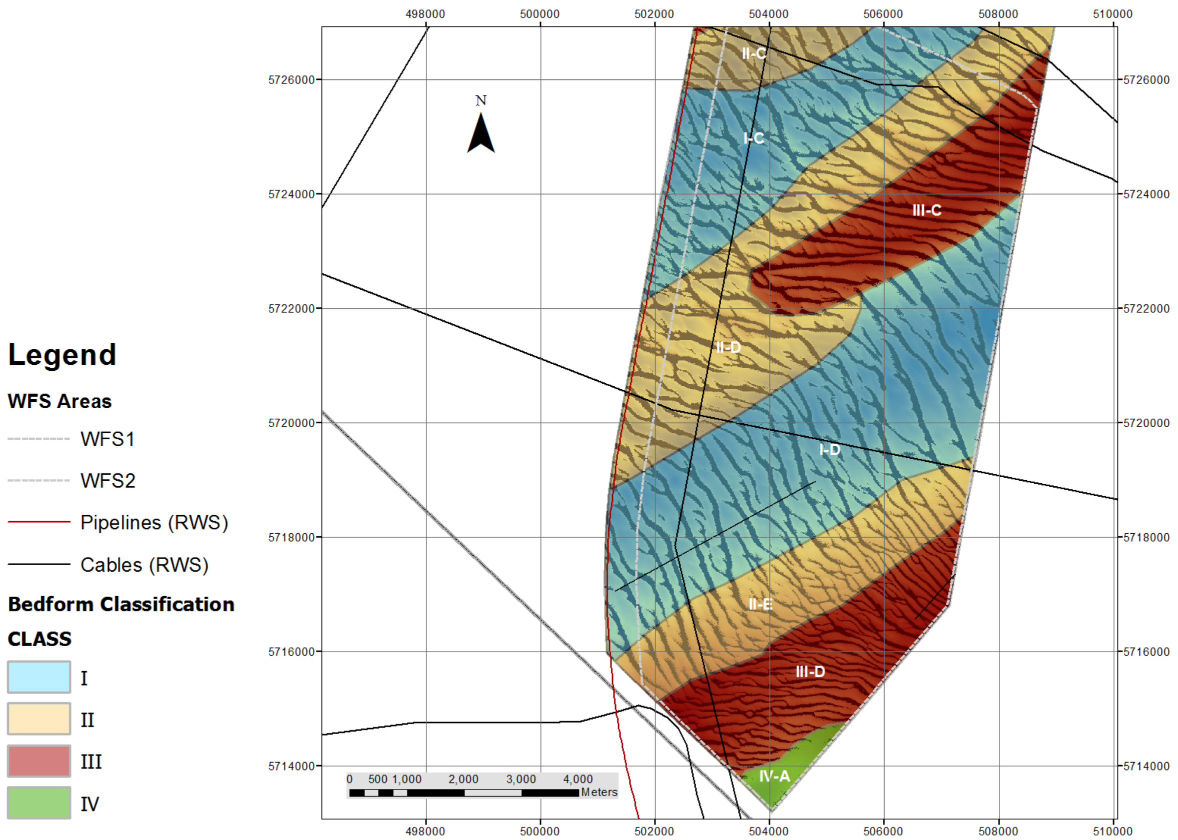


Figure 3-4: Overview map of seabed bedform zonation of WFS-2

3.2.4 Seabed sediment classification

A general classification of the seabed sediment is calculated from backscatter analysis of the MBE data. The general principles behind this analysis is explained by Beaudoin et al. (2014). The resulting seabed analysis is correlated with the SSS seabed mosaic to provide additional information for seabed sediment classification. The classification software used six main sediment classes, shown in Table 3-3. The sediments that can be found within the WFS-2 area consist mostly of sands and muddy sands. Occasional coarser material, coarse sands and gravel, can be seen in small quantities. The finer sediment classes, silts and clays, are essentially not found.

The backscatter analysis of the WFS-2 area shows a general trend of coarser material on the top of the sand waves, while finer material is found between the sand waves. This is most likely caused by the sand dunes providing shelter from the worst of the currents. Finer sediments are given the opportunity of settling in these calmer conditions. The stronger currents and more dynamic milieu outside of these sheltered areas keep the finer sediments in suspension. Only the coarser materials can settle here, on top of the sand waves.

While the big sand waves show a clear difference in sediment type between the tops and the valleys, such a difference is not noticeable for the small sand waves. As can be seen in Figure 3-5, most of WFS-2 is classified as either 'sands' or 'muddy sands'; two neighboring classes. At the southern end of the WFS area the coarser categories 'coarse sands' and 'gravel' appear in larger quantities, on the Rabsbank.

The sediment classification of the WFS-2 area shows the following distribution:

Table 3-3: Sediment classes overview WFS-2

Sediment class	Cover [%]
Gravel	0.95
Coarse sands	7.48
Sands	65.14
Muddy sands	26.27
Silts	0.16
Clays	0

Cross-correlation between the bedform classification of the previous section and the backscatter seabed sediment classification shows that in general, coarser sediment is found on the small scale and tidal ridge crests on slopes and tops of the sand banks. The finer sediment is generally associated with depressions between the sandbanks.

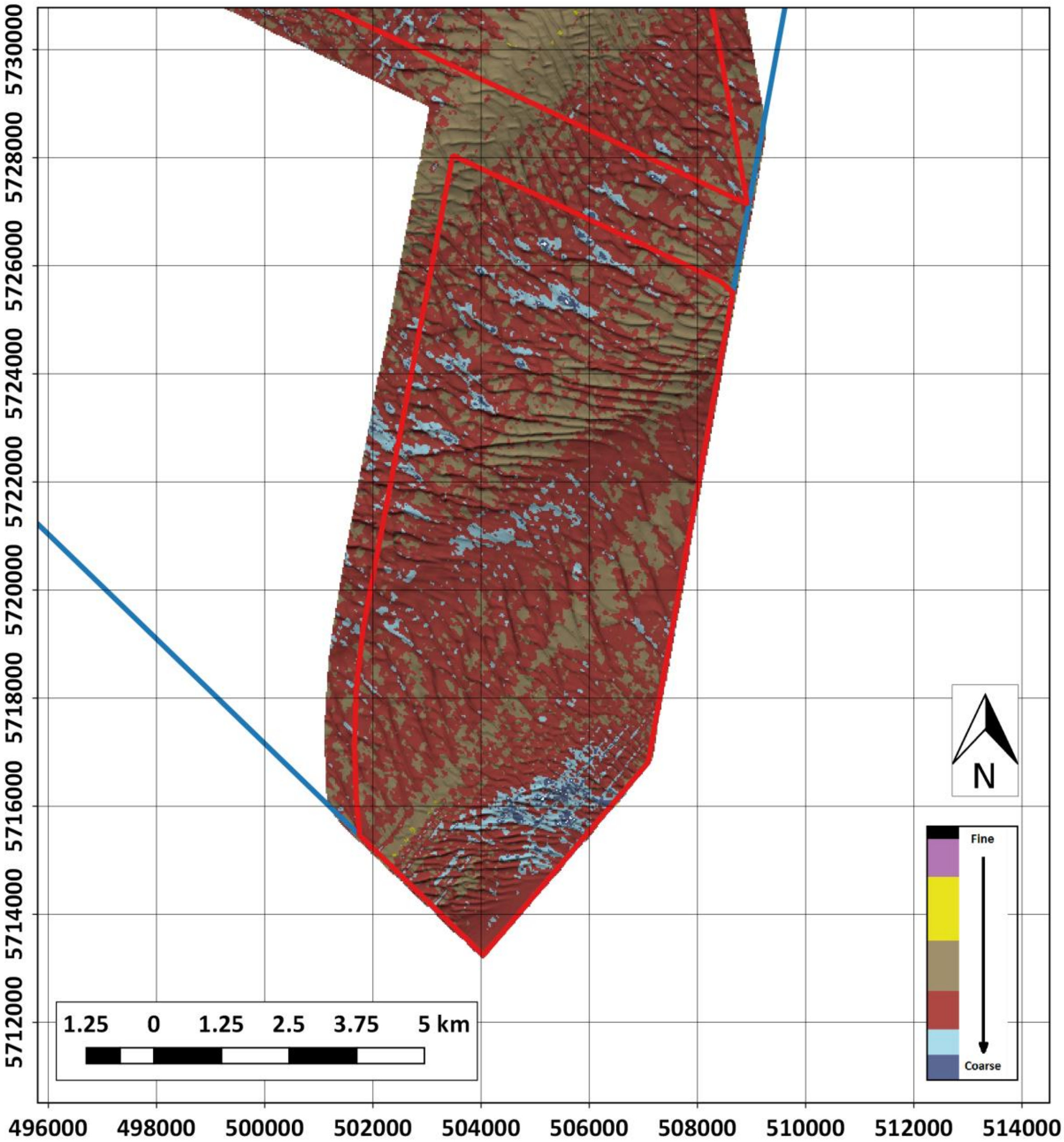


Figure 3-5: Overview map of MBE backscatter sediment classification for WFS-2

3.3 Seabed contacts

This section describes the results from the SSS and MAG survey, with regard to the detection of contacts on the seabed. The resulting contact lists from both surveys have been cross-validated to ensure no contact locations are reported twice. The results are discussed below and are presented in charts in Appendix L.

3.3.1 Archeological background

An archaeological desk study prepared by Vestigia (Vestigia 2014) focusses on two types of archaeological remains. Of both types the archaeological sensitivity is expressed (i.e. how likely it is in a given area to encounter archaeological remains).

The first relates to early prehistoric sites and finds, either directly on the seabed, or covered by later sediments, buried under the seabed. Presently early prehistoric sites have not been identified within the wind farm zone itself. Overall, the chance to encounter prehistoric archaeology within the wind farm zone is small (=low sensitivity).

The second relates to historic wrecks and other objects, such as lost equipment or cargo and crashed airplanes. Thus far, three objects have been identified as a shipwreck within the boundaries of the whole wind farm zone. Only one has been further identified and is considered to be of no archaeological value. There are a number of obstructions reported within the wind farm zone, at the time of writing of the desk study, these were unidentified and could be wrecks, part of wrecks, but also lost objects, e.g. anchors, chains, cargo, garbage, etc. They may also be the remains of aircrafts, lost in the World War II. For the entire wind farm zone the chance to encounter historic archaeology (shipwrecks, airplanes, etc.) is average (=medium sensitivity).

The results for this survey might include potential archaeological features although none of the contacts encountered could be positively identified as such. Therefore, all contacts labelled as ‘unknown’ could potentially be archaeological features.

3.3.2 Wrecks

The known wreck locations that Vestigia identified in the area of the BWFZ from the Wrakkenregister (Hydrografische Dienst Nederland 2011) are displayed in Figure 3-6.

Table 3-4 shows the coordinates of the known wreck locations within the WFS-2 survey area.

Vestigia’s desk study also mentions the possible presence of wrecks 43 and 44. However, as only approximate coordinates were known, it was not feasible to sail extra survey lines over these approximate wreck locations. Furthermore, the remains of these wrecks were not detected in the results of any technique.

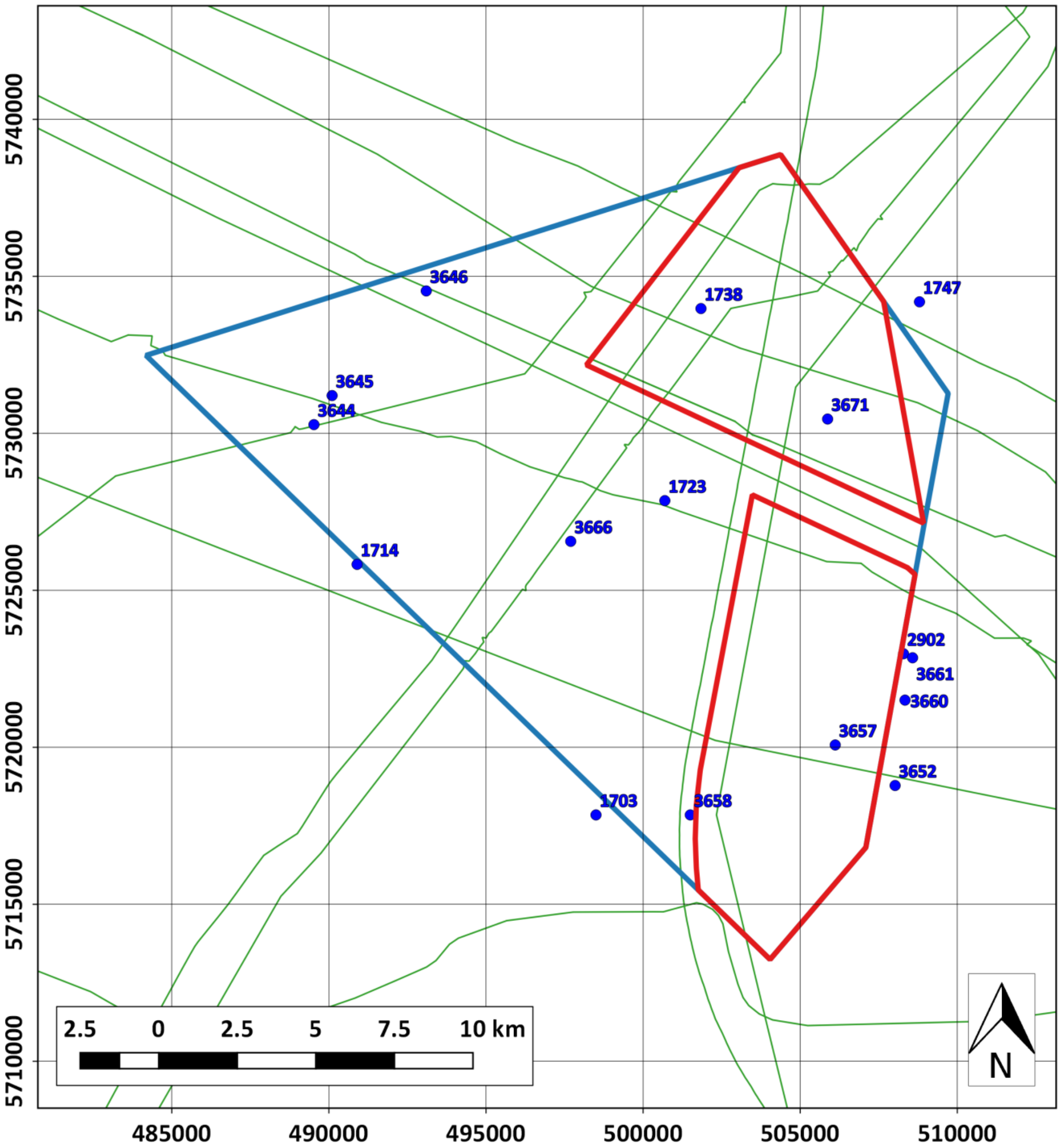


Figure 3-6: Known wrecks locations in the area of the BWFZ.

Table 3-4: Known wreck location in WFS-2

Location number	Easting (UTM31)	Northing (UTM31)
3657	506113.77	5720076.12
3658	501500.26	5717848.33

In the WFS-2 area wreck location 3658 was confirmed with MBE, SSS and MAG. Wreck location 3657 was not detected with any of the survey techniques. No previously unknown wreck locations were identified from interpretation of the SSS data.

3.3.3 Pipelines and cables

The BWFZ area is crossed by a number of pipelines and cables. The routes of these pipelines and cables have been identified with MBE, MAG and SSS and, where needed, adjusted.

In WFS-2 the Zeepipe pipeline was detected to be often exposed on the seabed. These exposures have been cross-referenced between the two survey techniques and mapped (Figure 3-7). The pipeline was found to be located in the same location as the location delivered by the client.

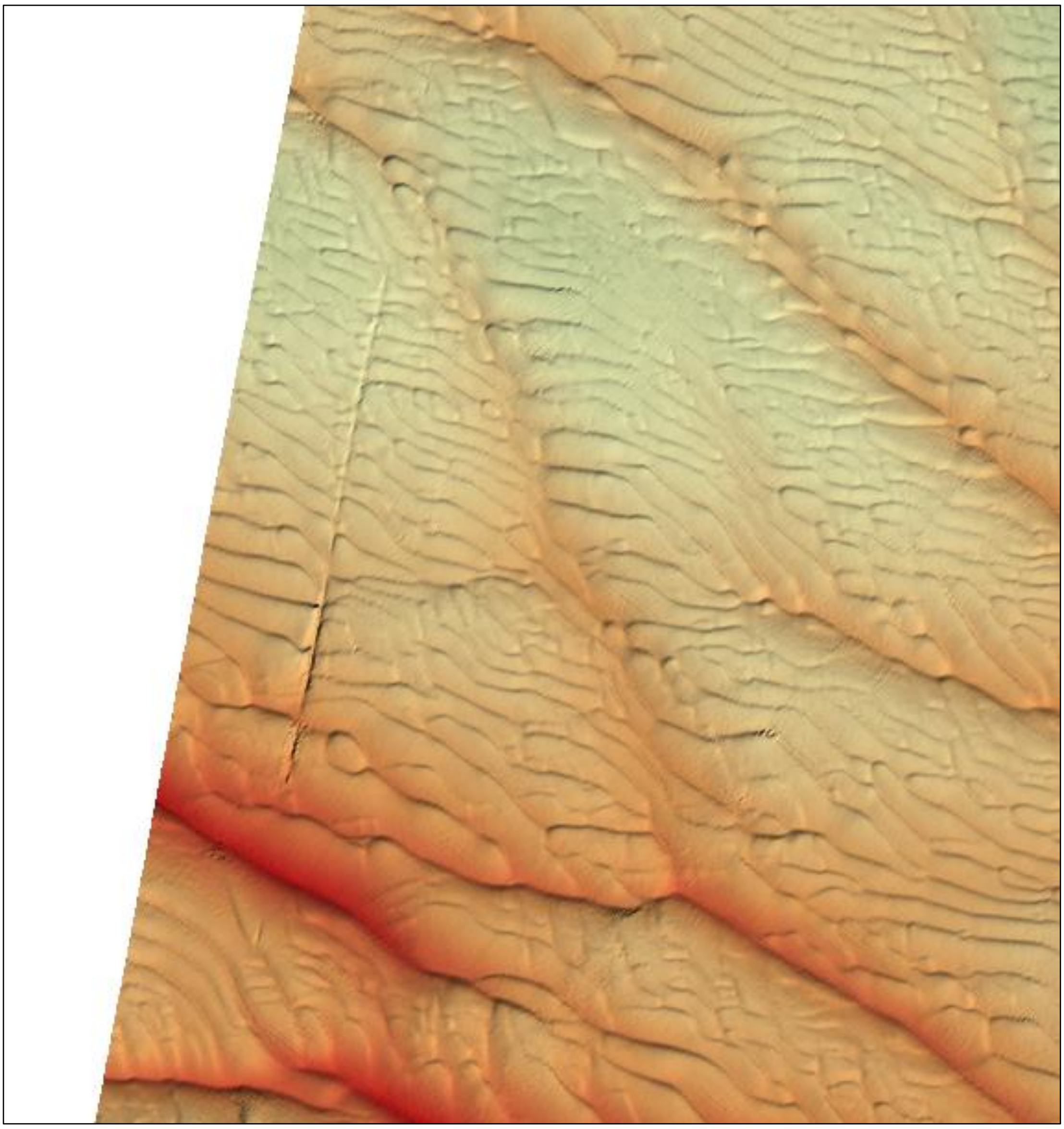


Figure 3-7: MBE data example of Zeepipe exposure pipeline in WFS-2.

In WFS-2 the cables and pipelines were found to be in the approximate locations as provided by the client. Additionally, two linear anomalies were detected with the magnetometer, both crossing the area in W-E direction. These contacts have a route more or less parallel to the known UK-NL 11 cable (Figure 3-8).

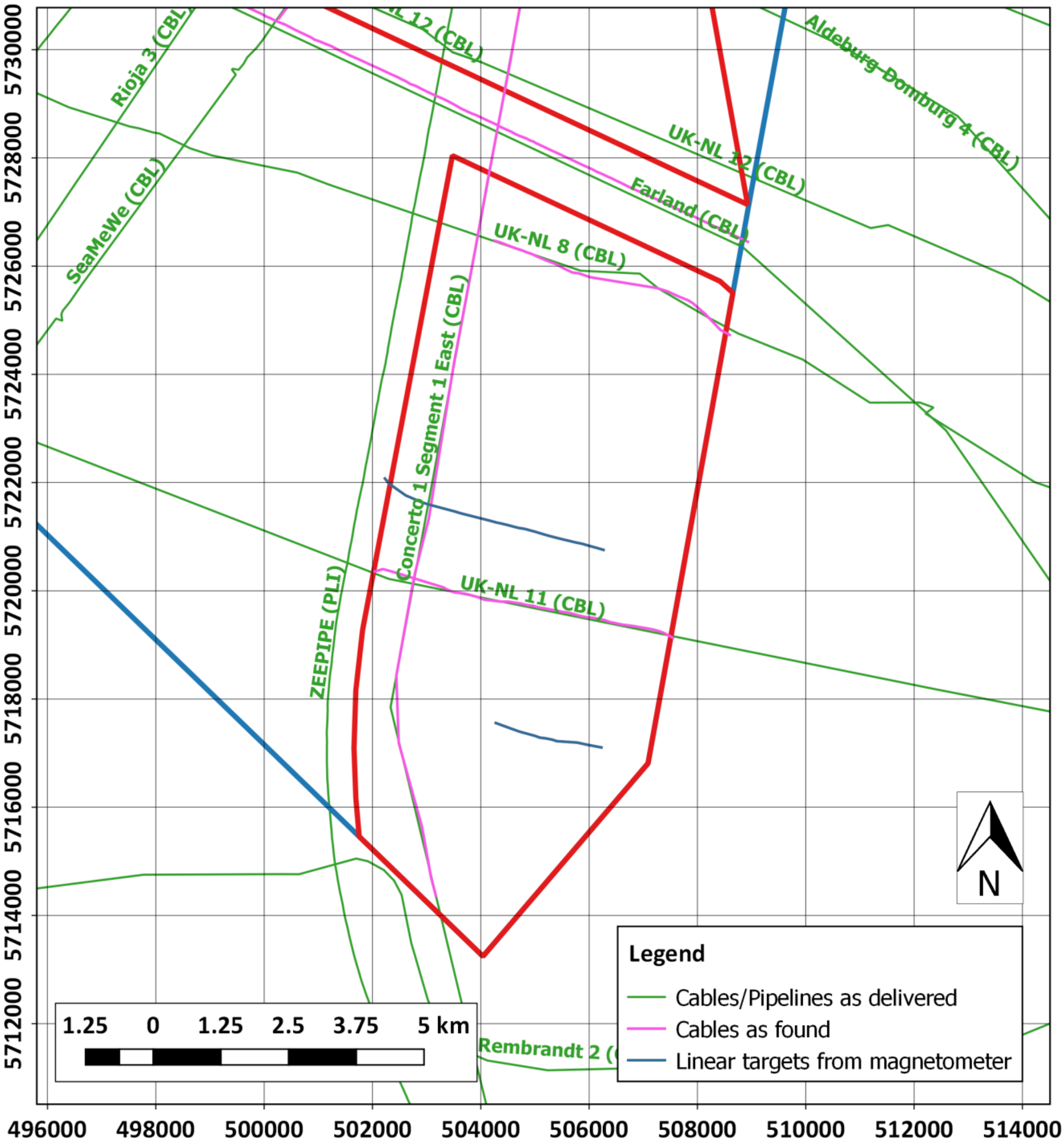


Figure 3-8: Overview map of cables and pipelines in WFS-2, as found and as provided by the client

3.3.4 Other contacts

A UXO desk study was prepared by REASeuro (REASeuro 2014). It comprised a historical inventory, a risk assessment and recommendations. The historical research indicated that the entire survey area is to be considered as an UXO risk area due to World War I and II related activities. Based on the report from the following hazards are likely to be encountered:

- Naval mines
- Bombs

- Depth charges
- Naval mine destruction charges
- Torpedoes
- Grenades

Due to seabed dynamics and intensive post war seabed disturbance (i.e fishing/trawling activities) UXO might have moved. It is however stated that:

> "*Until 2005 most of the UXO that were encountered in fishing nets were simply put overboard, often in the direct vicinity of known shipwrecks. These locations were normally avoided because of the risk of damaging the fishing nets, thus offering a gathering place of remnants of war*".

During the surveys in the BWFZ no UXO detection survey was carried out. The 100 meter line spacing between the magnetometer survey lines was not suitable to perform an UXO survey. The acquisition of high resolution magnetometer data does facilitate identification or confirmation of positions of known wrecks (potential gathering places) and other possible unknown ferruginous debris. The high resolution MBE and SSS survey allow better understanding of the morphology and movement of the sand dunes and forms a base that can be used to identify objects, debris fields and wrecks.
As is stated in the desk study it is recommended to reassess the UXO related risks based on the first draft of the design for the wind farm.

The side-scan sonar records show a limited number of trawl marks on the seabed. Due to the dynamic nature of the seabed it is well possible that trawl marks remain only visible for a short space of time. During the fieldwork phase of the survey fishing activities in or near the WFS area were noted.

In the WFS-2 area a total number of 189 contacts not associated with pipelines, cables or wrecks have been detected. Of these contacts 89 were detected with MAG only, 97 contacts with SSS only and 3 with both survey systems (Table 3-5).

Table 3-5: Overview detected contacts not associated with pipelines or cables in WFS-2

SSS	MAG	SSS/MAG	SSS/MAG/MBE	Total
97	89	2	1	189

In Figure 3-9 an overview plot is provided of the seabed contacts identified with SSS and MAG. A more detailed chart with point labelling can be found in Appendix L.

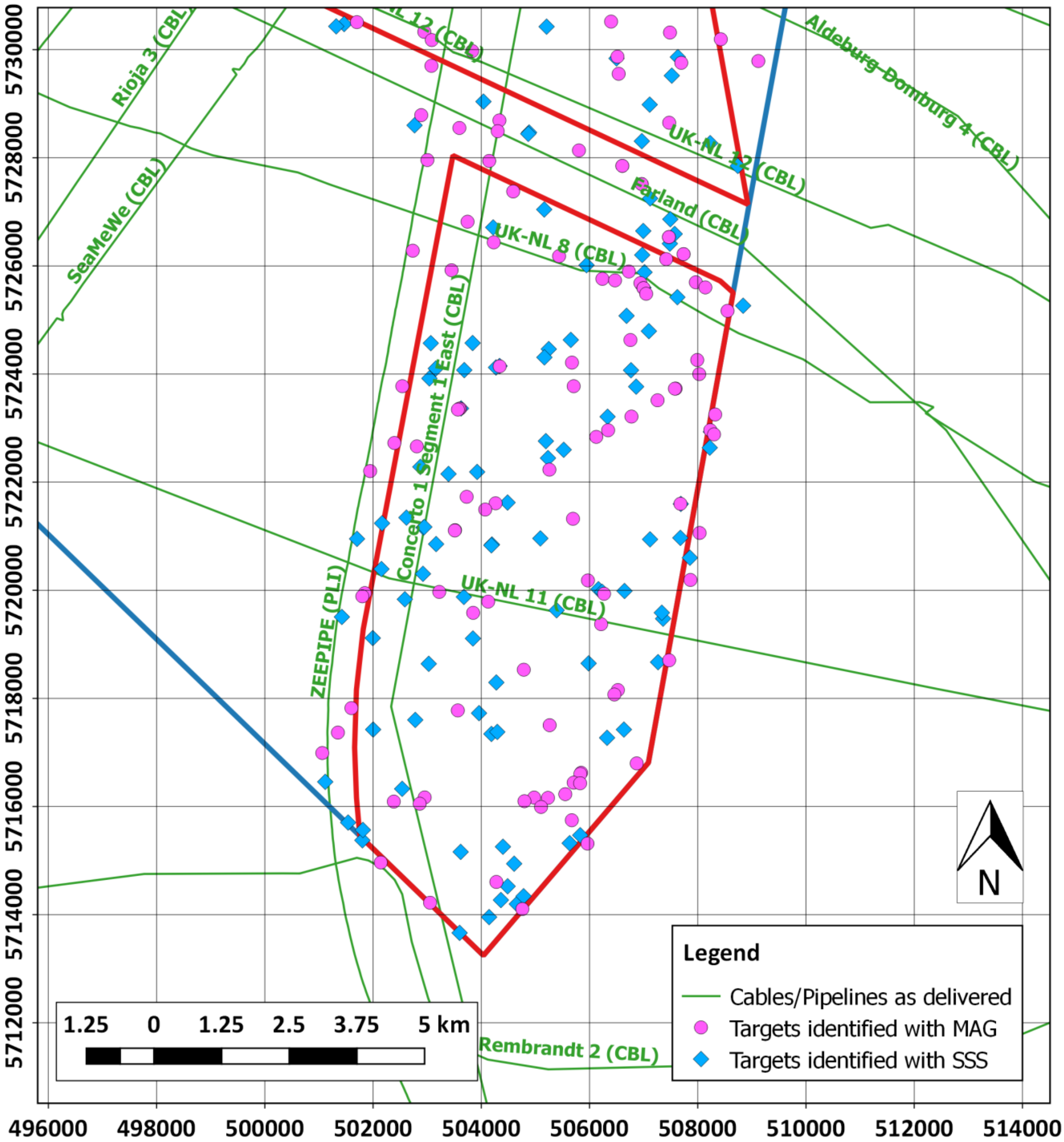


Figure 3-9: Overview map of contacts in WFS-2, detected with SSS and MAG

3.4 Geology

In this section the results from the geophysical SBP and MCS surveys are presented. A brief introduction into the geological framework of the BWFZ is presented, followed by a description of the interpretation of the seismic data sets. The seismic interpretation is correlated with the geological literature to give information about expected lithologies and potential geo-hazards.

3.4.1 Geological background

A geological desk study has been carried out by CRUX Engineering BV (2014). Most information in this report was derived from the geological maps compiled by British Geological Survey et al. (1991). More recent lithological descriptions are suggested by Rijsdijk et al. (2005). In this report, however, the terms used in the geological maps (British Geological Survey et al. 1991) will be maintained.

The survey area is located in the southern North Sea, offshore Netherlands, near the border with Belgium. The southern North Sea resulted from the tectonic spreading that started in the Triassic and is still active in recent times, although with reduced activity. To the south-west of the area, a major feature is present: the London-Brabant High, having constituted a major structural high since Paleozoic times (see Figure 3-10). Between this high and the spreading center of the North Sea Rift system to the north-east, the geological units thicken and define a broad monocline structure dipping towards the north-east (see Figure 3-11).

In Cretaceous times, the area of the southern North Sea was a set in a shallow water environment and sediments from this period consist mainly of evaporites and limestones. In the Late Cretaceous the Alpine orogeny started in Central Europe, which led to large volumes of erosional material rocks being exposed to sub-areal erosion and contributed to the deposition of sediments in the North Sea throughout the **Tertiary** period. During this period the area experienced different rates of subsidence and the sediment accumulation related to variable water depths. During the **Pleistocene**, the North Sea basin has been subject to numerous sea level changes related to glacial and inter-glacial periods. This has resulted in shallow marine deposits in inter-glacial periods, alternated with erosional processes during low-stands in the glacial periods (Figure 3-12). During the **Holocene**, a rapid sea level rise was experienced due to melting of glacial ice caps. The North Sea basin was drowned and therefore deposits from this period, which in the area are found on and directly under the seabed, are related to a shallow marine environment and to the subaqueous mobile sands (sand dunes) that make up the more recent geological formations.

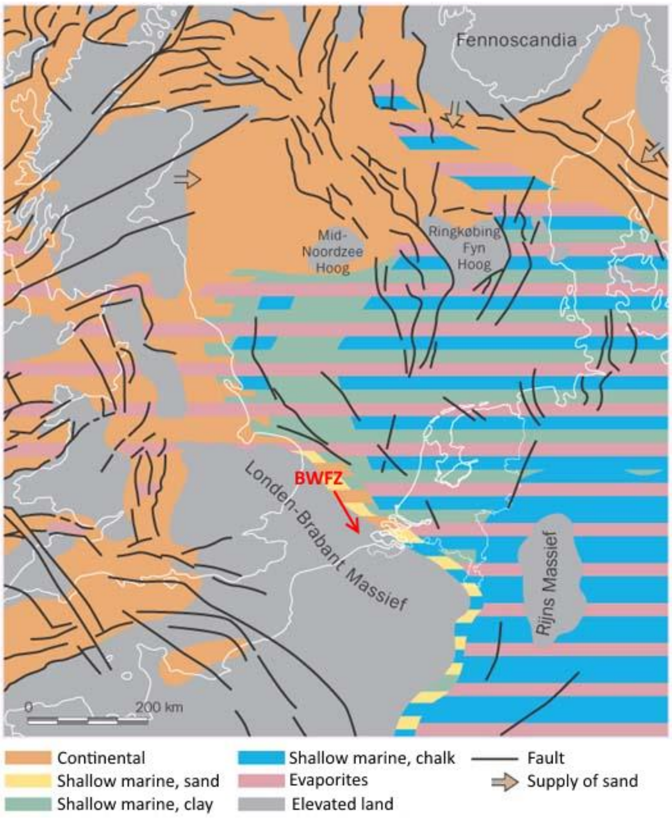


Figure 3-10: Paleo-geographic map of Northwestern Europe in the Triassic period. The location of the BWFZ is indicated. Modified from TNO-NITG (2015).

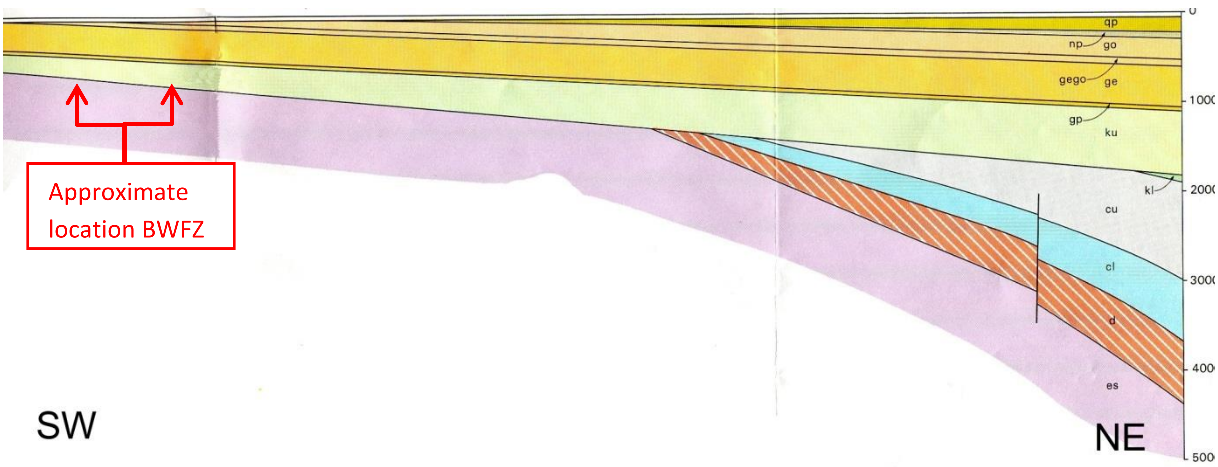


Figure 3-11: Schematic cross-section showing the Southern North Sea monocline. Approximate location of BWFZ is indicated. Vertical exaggeration of 5x. Units age range from Cambrian to Tertiary, colors and nomenclature according to British Geological Survey et al. (1991)

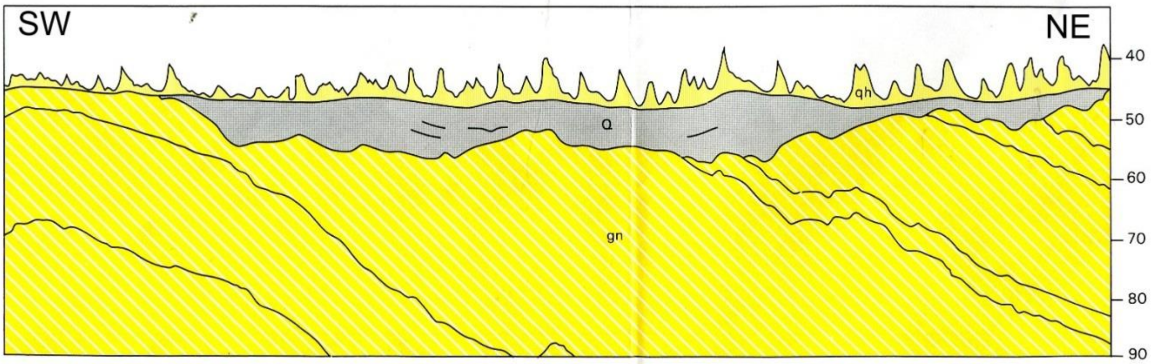


Figure 3-12: Schematic cross-section showing the relation between Quaternary and Tertiary deposits. Quaternary deposits depicted in gray, Tertiary deposits are the tilted yellow layers underneath. Vertical exaggeration 50x. Colors and nomenclature in accordance with British Geological Survey et al. (1991).

3.4.2 Geology of the survey area

Limited geophysical and geotechnical research has been carried out in the BWFZ so far. From the DINOloket repository, managed by the Dutch Geological Survey (TNO 2015) only a limited number of borehole locations are found in the survey area, none of them reaching deeper than 6 meters. Therefore, lithological and thickness information presented in this report refer to values found in available publications and onshore geological information.

In this section the lithological formations are described that are expected to be present in the research area less than 150 meters under the seabed. The geology of the survey area can be separated in two main divisions:

- Horizontally stratified marine and coastal **Tertiary** deposits;
- Shallow marine and fluvial **Quaternary** deposits.

Between these two main geological units, a main erosional surface can be seen throughout the area. In the study area, the Tertiary deposits form a monocline dipping towards the NE, these are truncated in the top and the Quaternary deposits rest on top of that erosional unconformity (see Figure 3-12). The Tertiary units become older to the south-west and therefore the depositional hiatus between these units and the upper Quaternary deposits increases towards the south-west. The Tertiary deposits are mainly sand and clay in different proportions with local variable amounts of gravel and calcareous contents. The Quaternary deposits are mainly made up of sand with local occurrences of gravel and clay.

3.4.2.1 Seismic interpretation

A proposed geological or stratigraphic correspondence with these horizons was attempted, based on published geological information about the survey area. The seismic units are described according to their seismic facies; emphasizing that seismo-stratigraphical boundaries have a chronostratigraphic meaning and cannot be interpreted in lithostratigraphical terms. A synthetic table is shown at the end of the chapter displaying all horizons, seismic units and their

correspondence with the geological formations (see Table 3-6). Appendix M contains all the geological interpretation grids displayed throughout this chapter in a higher resolution format.
The seismic interpretation of the seismic profiles is based on 6 reflectors that were chosen because of their geological significance and spatial continuity. These reflectors are the base of the defined seismic units U2, U3, U4, U5, U6 and U7 and are B2, B3, B4, B5, B6 and B7, respectively (see Figure 3-13).
Picking was carried out on the seismic profiles on top of clear identifiable reflectors with good spatial continuity. Although automatic picking (2D hunt) mode yielded nice results for some horizons, other horizons and some profiles (more noisy) did not gave out same good results (very wiggly interpretation). Therefore, in an attempt to have a uniform and similar picking mode, manual mode was chosen as the picking mode.

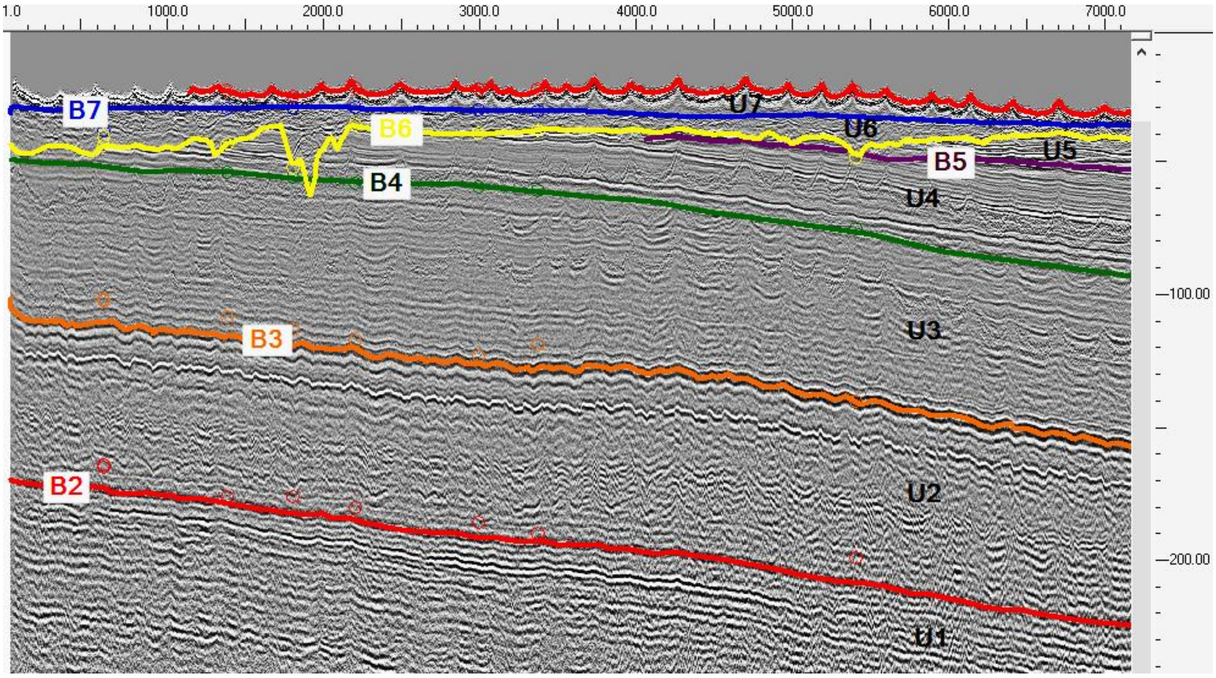


Figure 3-13: Example of mapped seismic units (U1 to U7) and horizons (B2 to B7) on profile 72. Numbers on top are CDP (approx. every meter), on the side of profile are meters.

The **Tertiary** deposits in the North Sea basin form a monocline dipping towards the NE. In the area of the North Sea graben they reach a maximum thickness of about 2500 meters, although in the area of the BWFZ they are only about 800 meters thick (see Figure 3-11).

Seismic units **U1** and **U2** are interpreted as the oldest Tertiary formation in the BWFZ survey area, the **Dongen Formation**, formed in the **Eocene** period (55.8 – 40.4 Ma BP). This formation was deposited in a shallow marine environment and has a maximum thickness of up to 510 meters. This formation is characterized by slightly calcareous clays with intercalated sand sequences, and tend to be more sandy towards the base (Nederlandse Aardolie Maatschappij et al. 1980). They are present in most of the Dutch North Sea sector (Weerts et al. 2000). This formation is unconformably overlain by younger formations.

Seismic units **U3** and **U4** are interpreted as the **Tongeren Formation.** This formation was deposited in the **Upper Eocene** to **Lower Oligocene** period (37.0 – 30.0 Ma BP), which was characterized by a rapid regression, and most of the BWFZ research area was set in a shallow marine or coastal environment (Figure 3-14). The formation has a maximum thickness of up to 125 meters onshore, it is however likely it is thicker offshore (Ebbing et al. 2003). This formation is dominantly fine to very fine sand at the base. The upper part is characterized by a very changeable lithology, with alternating clay and sand layers, deposited in lagoonal to terrestrial environments (Wouters et al. 1994). Layers of lignite have been found in the upper part of the formation. The boundary with the overlaying formation can be sharp, but is also continuous in places.

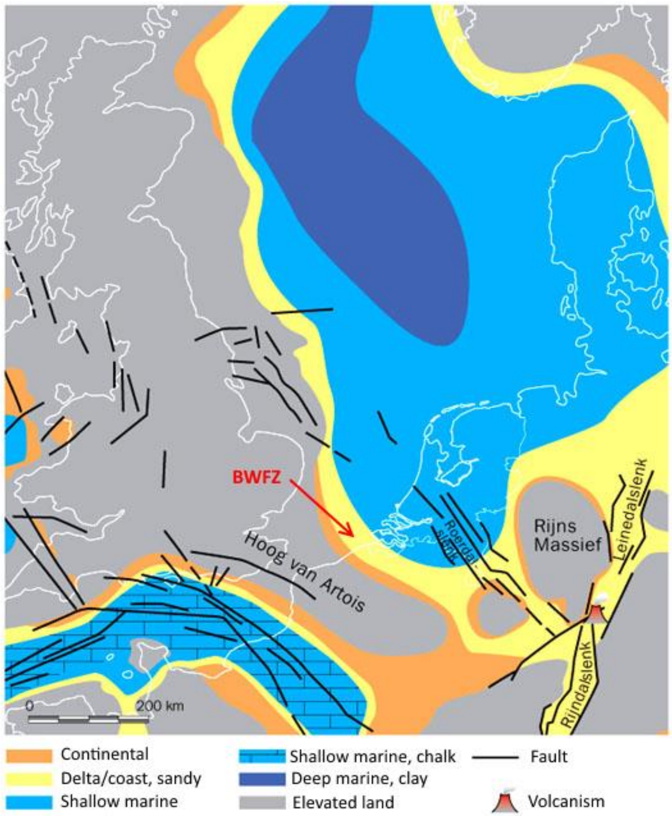


Figure 3-14: Paleo-geographic map of Northwestern Europe in the Oligocene period
The location of the BWFZ is indicated. Modified from TNO-NITG (2015).

Seismic unit **U5** is interpreted as the **Rupel Formation**, formed in the **Mid-Oligocene** period (33.9 – 28.4 Ma BP). This formation is made up of a variation of marine clays and sand beds and has an overall maximum thickness of 200 meters beds (Adrichem Boogaert et al. 1993; Lang et al. 2003). The base of the unit is onlapping towards the south-west and there is a truncature (boundary B5) that forms an unconformity with the older deposits of the Tongeren Formation (U4).

The **Pleistocene** period is characterized by repeating fluctuations of the sea level, associated with glacial and interglacial periods. The deposits from this period are a combined effect of complete exposure of the BWFZ area during glacial lowstands, associated with fluvial erosion and scour hollow formation (Liu et al. 1993) and infill deposits during interglacial periods. A scan of the geological map of the Pleistocene deposits (British Geological Survey et al. 1991) is provided in Figure 3-15. From interpretation of this map the presence of the following Pleistocene formations is expected:

- **Eem Formation**, deposited in the **Eemian** period. This is a shallow marine formation with a maximum thickness of approximately 10 meters in the survey area (Bosch et al. 2003). It consists of medium fine to very coarse grained sand with clay laminae. The formation is deposited in a transgressive and regressive cycle, shown by a transition from a shallow freshwater via a brackish to a fully marine environment in the lower part of the formation. In the upper part a regressional sequence is observed, with some peat deposits.
- **Brown Bank Formation**, formed during **late Eemian to Early Holocene**, consisting of laminated clay and some fine gravel, associated with the regression at the onset of the Weichselian ice age. The thickness of the formation is between <1 and 2.3 meters.
- **Kreftenheye Formation**, formed during the **Late Weichselian to Early Holocene**, the last glacial period before present day. The sea level was considerably lower than present day and the southern North Sea basin was dry. The thickness of this formation is highly variable between 1 and 100 meters (Busschers et al. 2003) and consists mainly of medium to very coarse grained sand and medium to very coarse gravel. They are mostly fluvial deposits from the Rhine and Meuse rivers, which, due to the low sea level, had their courses extended through the North Sea into the English Channel (Figure 3-16). Thin layers of volcanic tuff can occur, which are deposits of late-Weichselian volcanic activity in the Eifel area.

As is stated by Le Bot et al. (2005), the Pleistocene deposits in the Belgian sector of the North Sea, adjacent to the BWFZ, are characterized by localized deposits, displaying a laterally and vertically complex and heterogeneous facies assemblage. Due to this, lateral correlation of the different isolated Pleistocene deposits is difficult to accomplish. Due to this lack of lateral continuation of seismic reflectors of these formations, a consistent subdivision of these formations could not be made from the seismic data alone. Therefore the Pleistocene formations are grouped in seismic unit **U6**.

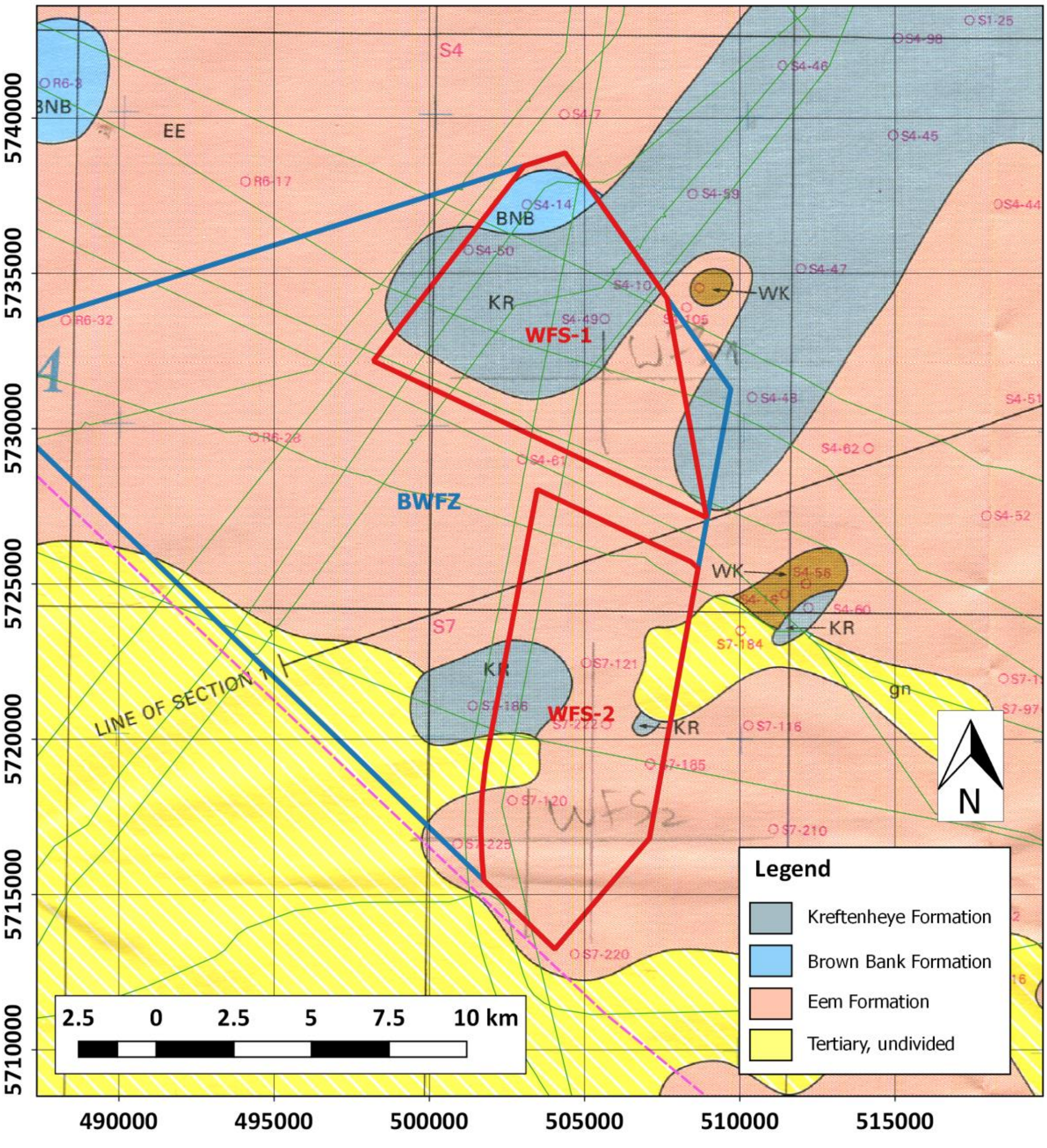


Figure 3-15: Geological map of Pleistocene deposits in the survey areas, from British Geological Survey et al. (1991)

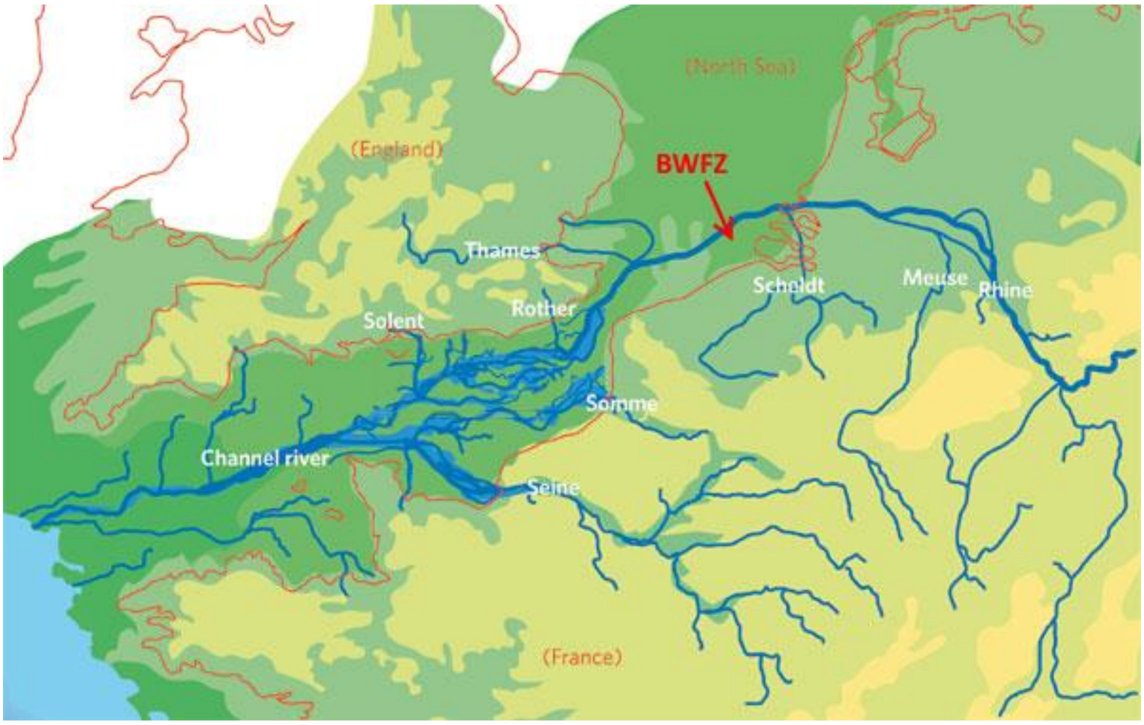


Figure 3-16: Paleo-Geographic map of Northwestern Europe during the Weichselian Ice Age. The survey area is indicated. Modified from Gibbard (2007)

The uppermost unit **U7** is associated with the **Bligh Bank Formation** and **Buitenbanken Formation**, deposited in the **Holocene** and both characterized by fine to medium sand. The main distinction between the Buitenbanken and Bligh Bank Formations is the greater gravel content in the Buitenbanken Formation. Separate identification of the two formations has not been achieved due to the lack of borehole information. The thickness of U7 is very variable and it is expressed on the seabed in sand waves and linear sandbanks, which can be up to 16 meters high. Inshore of the banks the formation can be thin or not present.

3.4.3 Description of seismic units

3.4.3.1 Tertiary deposits U1 and U2

In the BWFZ, five seismic units (U1, U2, U3, U4 and U5) were identified as Tertiary deposits. The boundary horizons as well as inner reflectors of these units are subparallel and dip to the nort-east, with exceptions of the truncature plane (B5) that forms the base of seismic unit U5 and the upper horizon (B6) of the Tertiary deposits which is an erosional surface.

The deepest units U1 and U2 are interpreted as the Dongen Formation and are seen throughout the entire BWFZ. Boundary B3 is the top boundary for this geological formation, B2 is interpreted as an inner reflection. The base of this formation was not observed in the seismic data, as it is deeper than the depth penetration of the MCS data. Therefore, the deepest reflectors identified on the seismic profiles (below B2) still belong to this formation. The top of the Dongen Formation lies at depths approximately 190 meters below LAT in the north-east sector of the BWFZ area and about 40 meters below LAT in the south-west sector (Figure 3-17), the maximum thickness observed in the MCS profiles was around 210 meters (Figure 3-18). The maximum thickness in observed in the offshore part of the North Sea is up to 510 meters (British Geological Survey et al. 1991). The unit is made of a succession of parallel, very shallow north-east dipping reflectors (<0.4 degrees), fairly straight with some degree of undulations. The reflectors display medium amplitude contrasts with some high amplitudes reflectors near the formation top and close to B2. Throughout the formation there are some sequences of low contrasts or transparent facies that correspond to a lithological homogenous sequence probably corresponding to a thick (up to 20m) sandstone package.

The formation is overlain by the Tongeren Formation with boundary B3. This reflector is well identifiable throughout the area as a strong, high amplitude reflector with good spatial continuity. At small scale, little undulations of the reflector are detected that might indicate some degree of disturbance, possibly due to tectonic deformation. This is also observed in internal reflector B2.

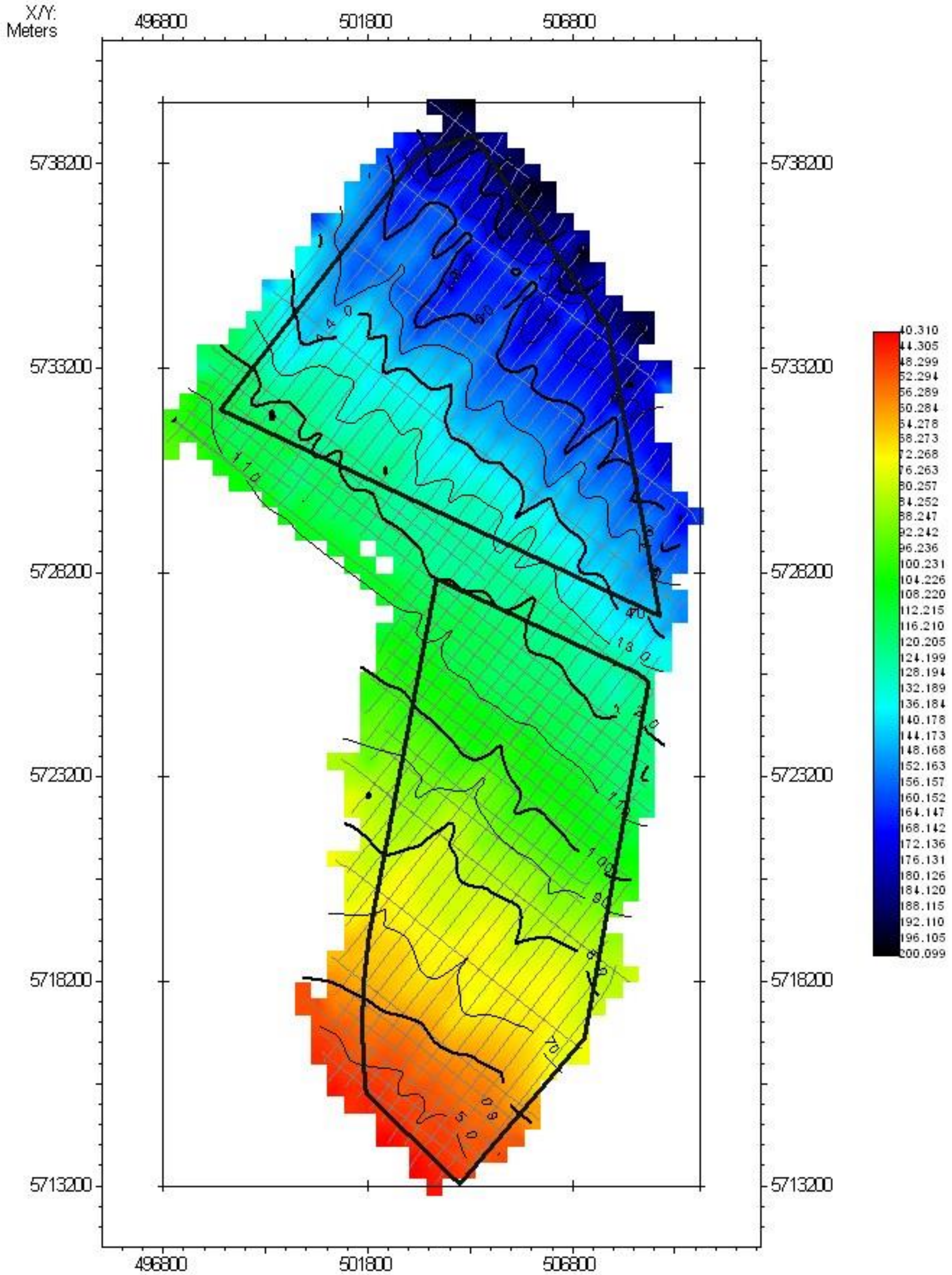


Figure 3-17: Elevation map of the top of the Dongen Formation (B3). Elevation in meters below LAT. Contour interval 10m.

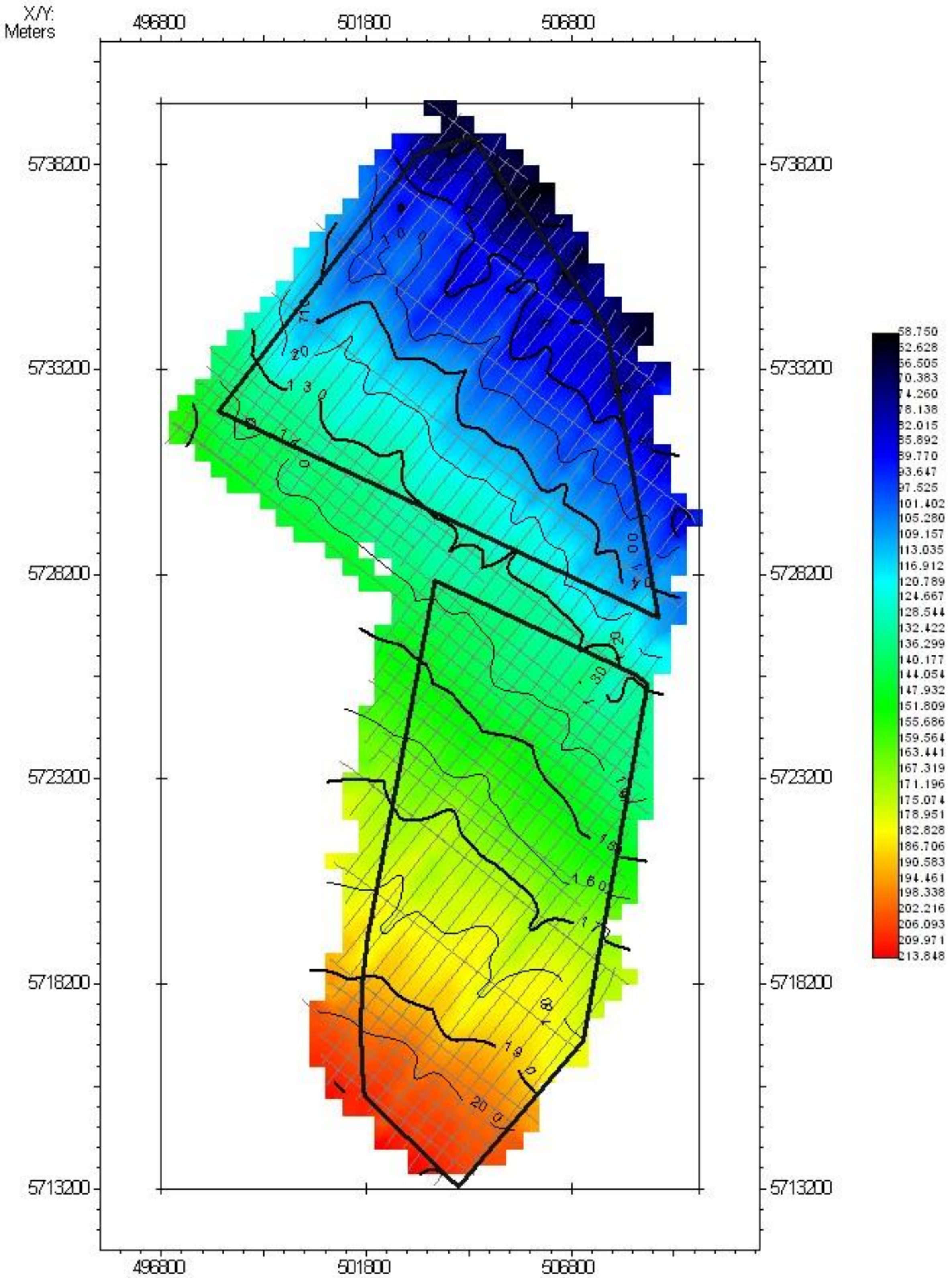


Figure 3-18: Isopach map of maximum observed thickness of Dongen formation (U1, U2). Thickness values in meters. Contour interval 10m.

3.4.3.2 Tertiary deposits U3 and U4

Seismic units U3 and U4 correspond to the Tongeren formation. Its basal horizon is B3, described in the previous paragraph as the top of Dongen Formation (see Figure 3-17).
The upper boundary of the U3 and U4 units are either the B5, B6 or B7 horizons depending on location. The character of the upper limit of U4 with overlaying deposits is either:

- Chrono-stratigraphic nut truncated boundary (B5) with U5
- Strongly erosional channel in-fill boundary (B6) with U6
- Erosional boundary (B7) with U7

The depth of the upper boundary of U4 with any of the overlaying deposits is displayed in Figure 3-19.

Seismic boundary B4 might correspond to the transition between the lower part of the formation (made up mainly of sands) and the upper part (consisting mainly of clays with thin intercalations of sands and lignites). The formation is tilted towards the north-east, its base (horizon B3) ranges from depths of 190m below LAT in the north-eastern sector of the area to about 40m below LAT in the south-west (see Figure 3-17).
The top of the formation ranges from depths of 60m below LAT in the north to 30m below LAT in the south, reaching the maximum depth of 90m below LAT in the central area (Figure 3-19).
The geological formation made up of these two units is mapped throughout the area although its thickness is not constant, mainly because its upper boundary is always of erosive nature. The greatest thickness values for these units are present where fewer deposits were eroded. The thickness of the Tongeren Formation ranges between approximately 10 meters in the southern part of the survey area to approximately 130 meters in the northern part of the survey area (see Figure 3-20). In the central part of the area, the B4 boundary subcrops below the younger formations, here the thickness of the formation is around 45 meters. The southern sector of the area is where this formation is thinner, at around 10 meters. The Tongeren formation is unconformably overlain by the Rupel Formation (U5).
The U3 and U4 units gently dip towards the north-east (<0.4 degrees) and conformably overlay the Dongen Formation as the inner unit reflectors are subparallel among them and to the basal horizon (B3). The lower deposits of this unit (mostly sand) are characterized by fewer reflectors of low amplitude contrasts. The upper part of the unit is made up of a succession of high amplitude reflectors which is in accordance with it being made up of clay with intercalations of sands and lignites. The transition between these two seismic units (B4, see Figure 3-21) also dips to the north-east, where it lies deeper (around 130m below LAT). The upper unit (seismic unit U4) is dominated by clay deposits and is present and thicker in the north-east sector, yet towards the south-west it gets thinner until it is completely obliterated by the overlying truncature (B5). In that case, the younger deposits (U5, U6 or U7) overlay directly and unconformably the older parts of this formation (U3).

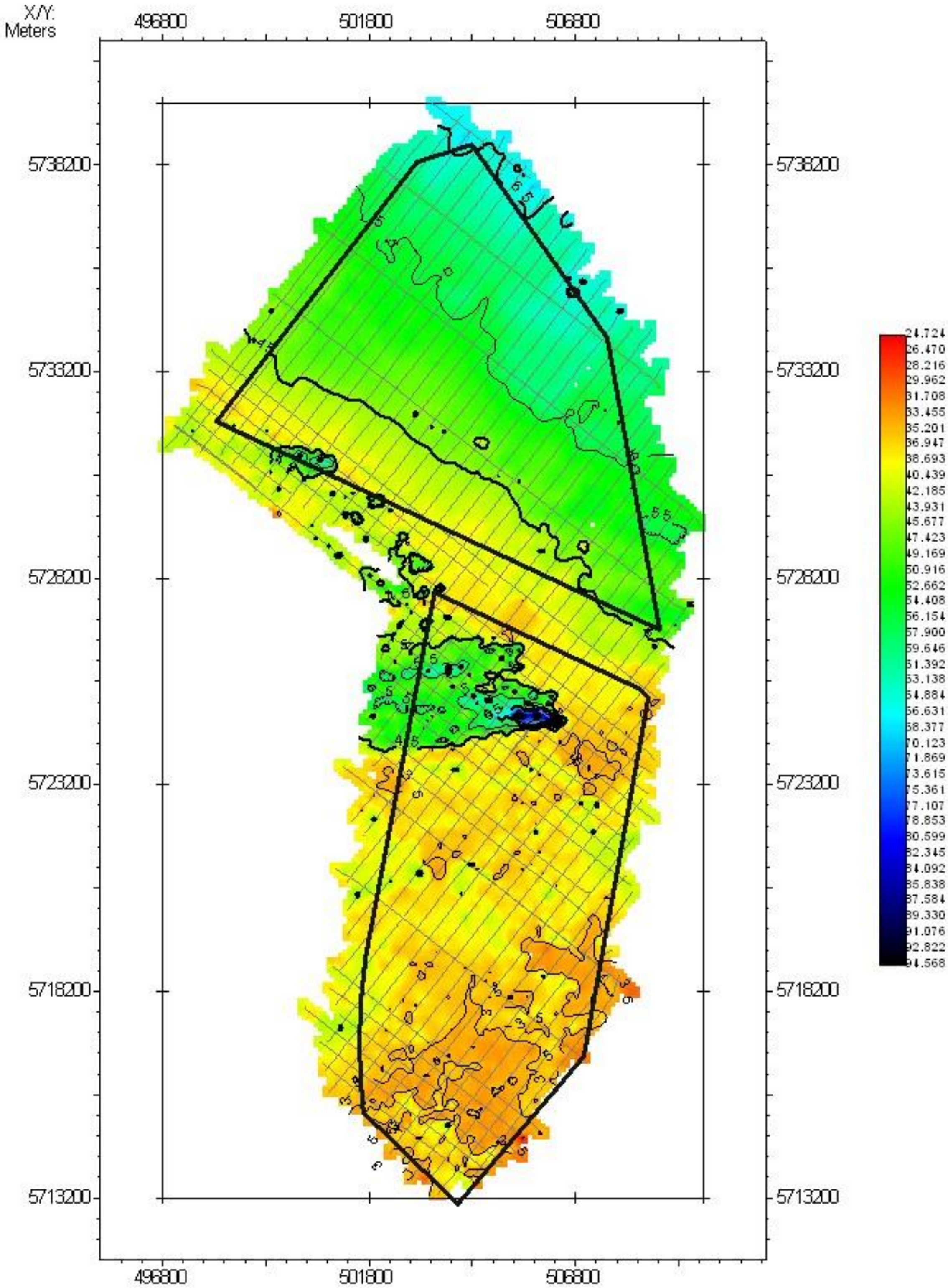


Figure 3-19: Elevation map of the top of Tongeren Formation (U3 and U4).
Boundary corresponding to either the B5, B6 or B7 boundaries, depending on location.
Elevation in meters below LAT. Contour interval 10m.

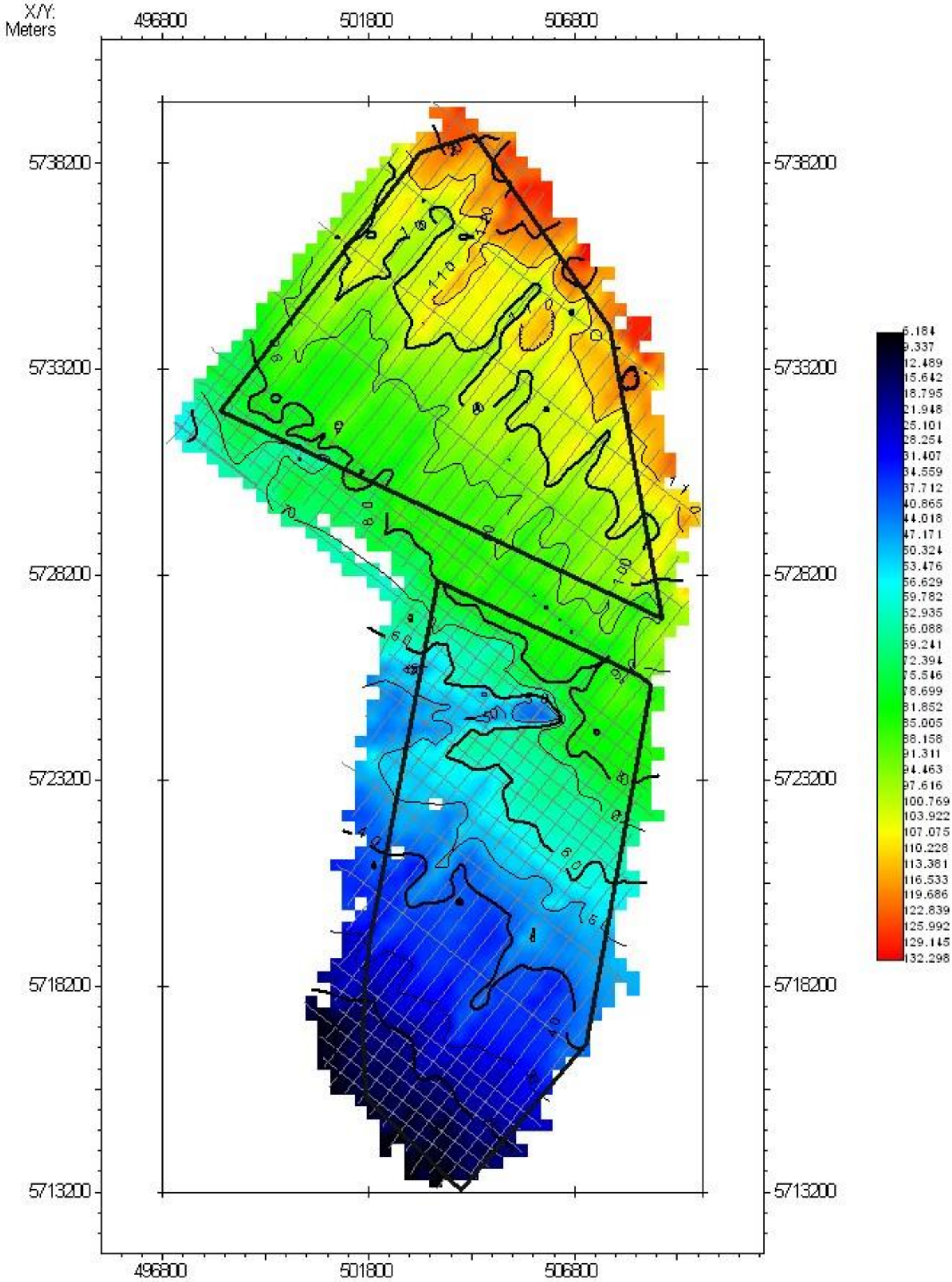


Figure 3-20: Isopach map of the Tongeren Formation (U3 and U4).
Thickness values in meters. Contour interval 10m.

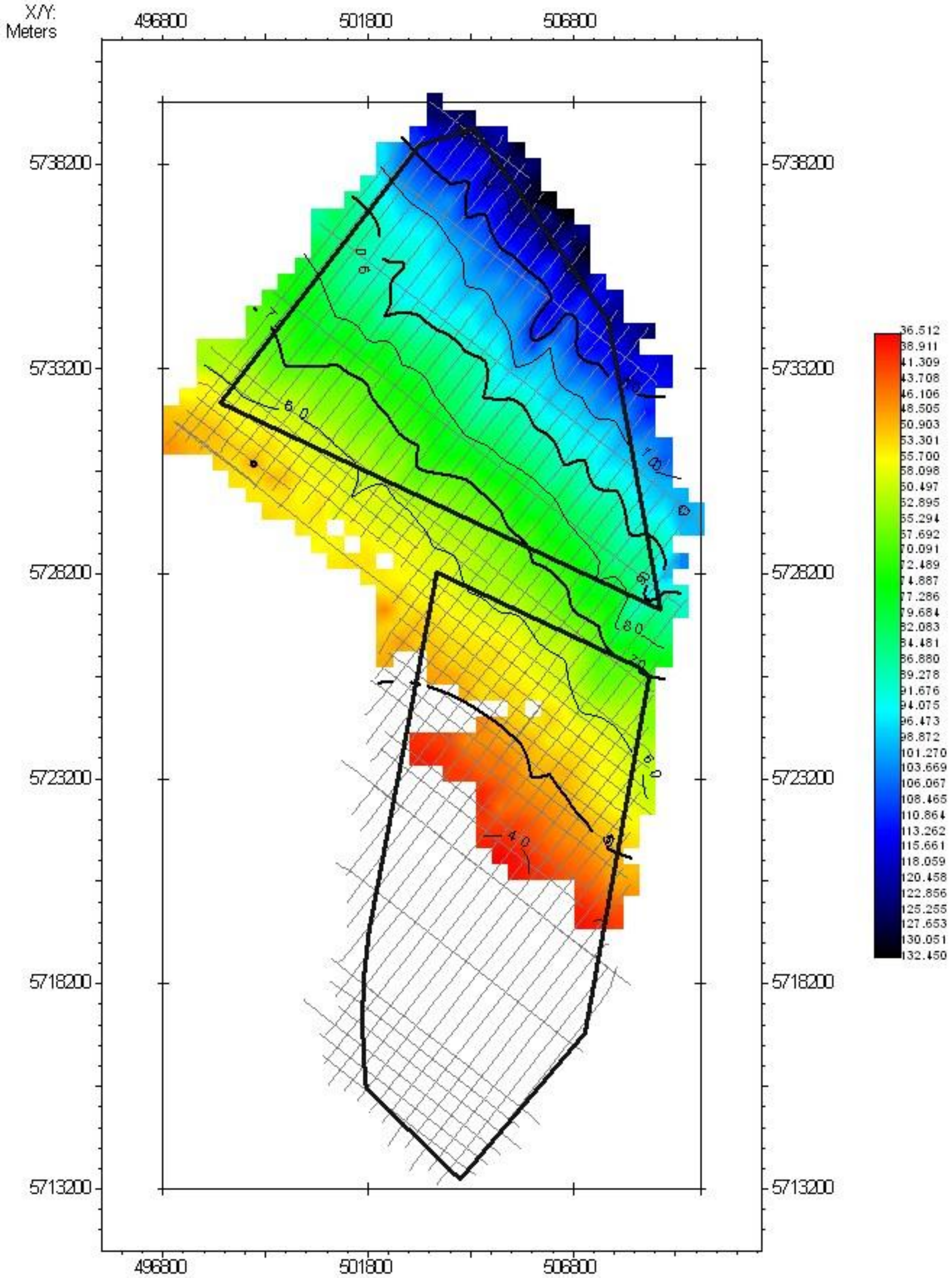


Figure 3-21: Elevation map of B4 horizon, internal reflector in the Tongeren Formation, separating U3 and U4. Elevation in meters below LAT. Contour interval 10m.

3.4.3.3 Tertiary deposits U5

Seismic unit U5 corresponds to the Rupel Formation and gently dips towards the north-east. Its lower boundary (B5) is an erosive surface that truncates the underlying Tertiary deposits of the Tongeren Formation. The base can be found at depths around 70m below LAT in the north-east and around 37m below LAT in the central part of the area (see Figure 3-22). Its upper limit is the erosive base (B6) of the overlying Quaternary deposits (U6) or the base of seismic unit U7 (B7).

The lower boundary of this unit (B5) is generally planar, gently dipping to the north-east and is of erosive nature, hereby truncating the steeper underlying deposits from seismic units U3 and U4. Consequently, there is an angular unconformity between the two seismic units. Above the basal unconformity, the seismic reflectors within the U5 unit show sedimentary onlap on the underlaying formation towards the south-west. Therefore, the basal sediments belonging to this seismic unit U5 are older towards the north-east.

This unit thickness decreases from the north-eastern sector of the area with an average thickness of 30 meters to the central sector and is absent from the southwestern sector of the area where it is completely obliterated by the upper erosive surface (see Figure 3-23).

Seismic unit U5 is made up of high amplitude reflectors with good spatial continuity. In some areas these reflectors define small packages with several reflectors of high amplitude contrasts, with great lateral continuity, except when truncated by the upper boundary (see Figure 3-24). In other areas they appear in a relatively transparent sequence. This matches with the lithological content of this unit, made up of a succession of beds of sand and clay.

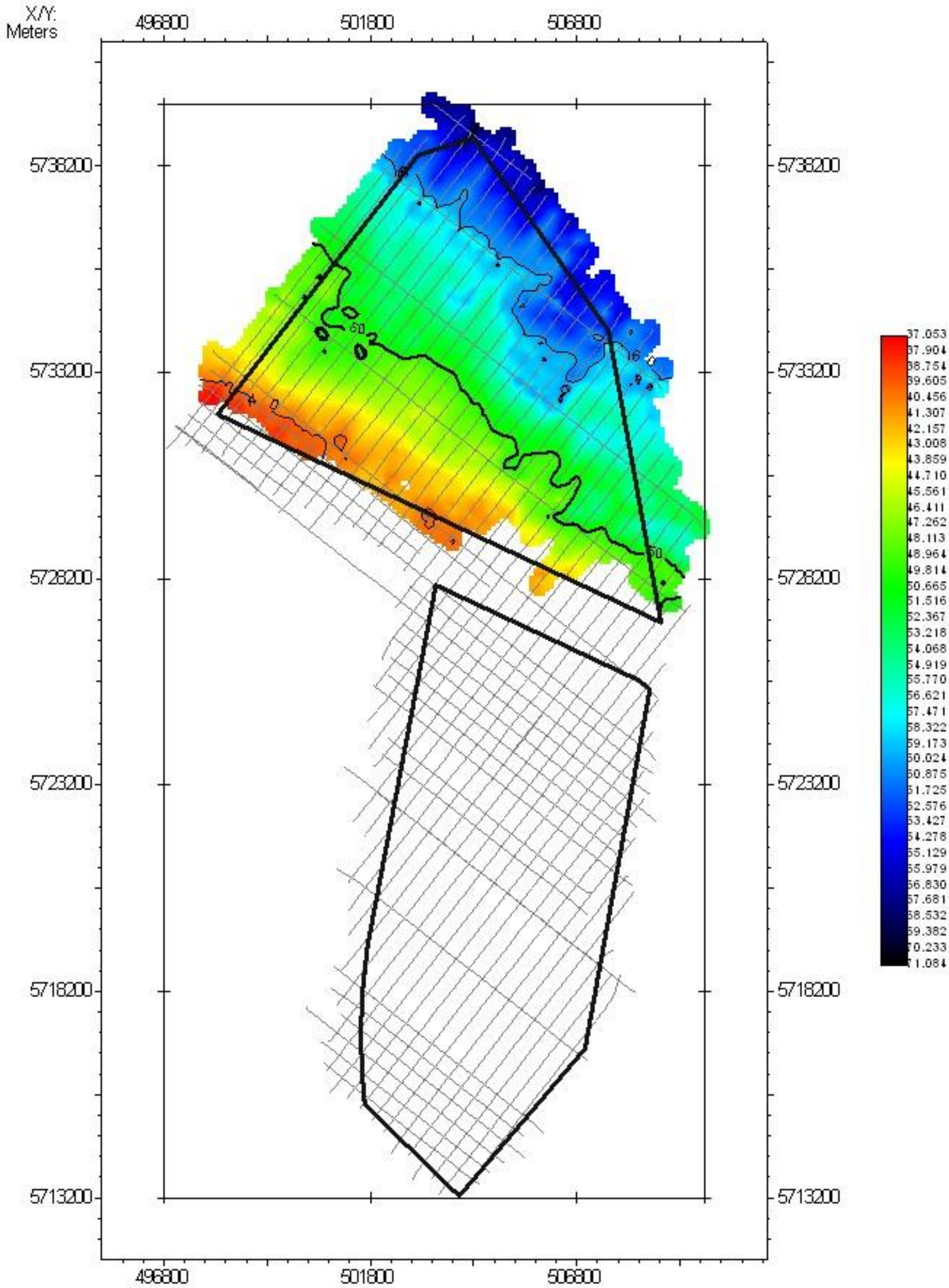


Figure 3-22: Elevation map of B5 horizon, corresponding to the base of the Rupel Formation (U5). Elevation in meters below LAT. Contour interval 10m.

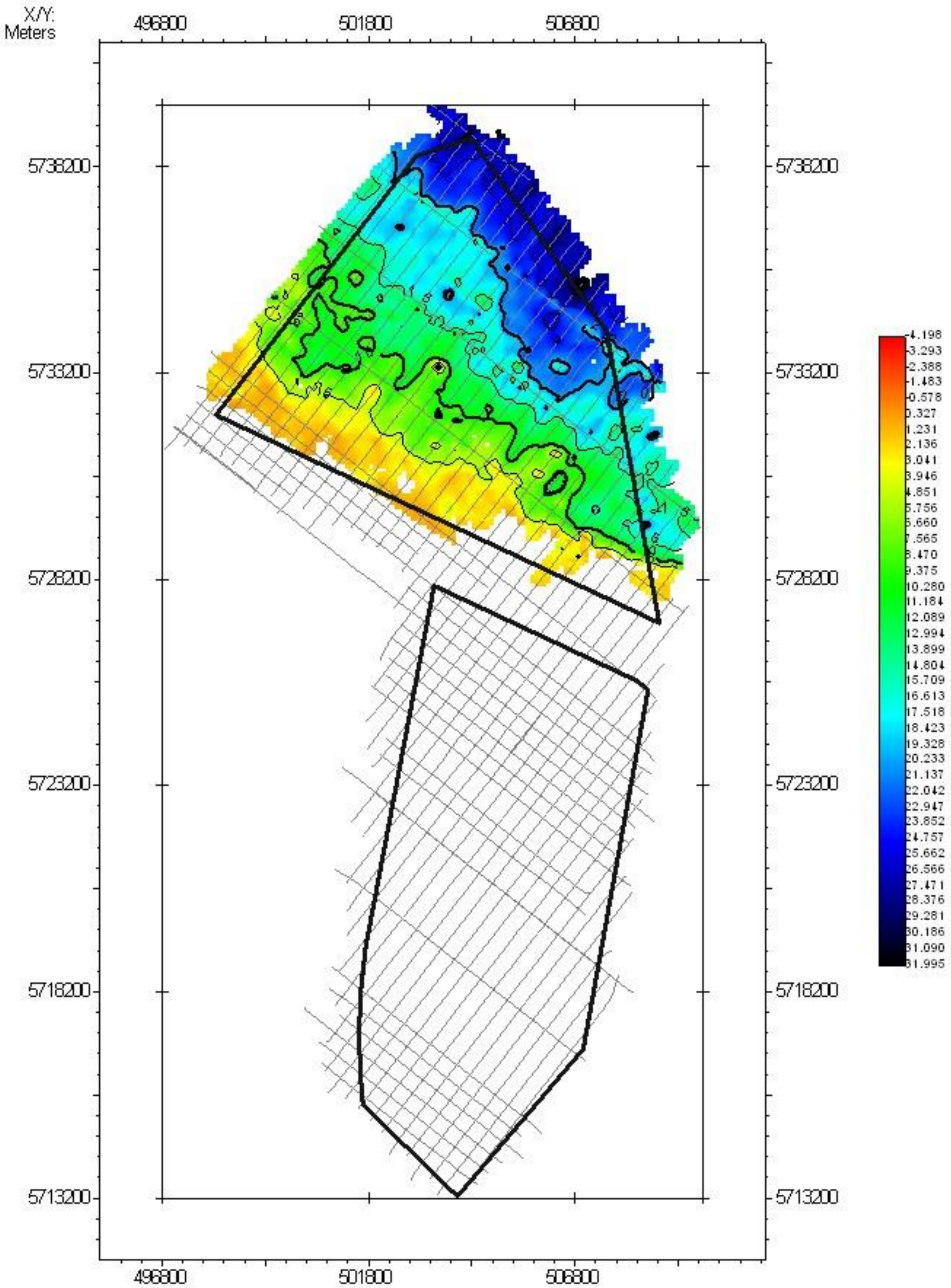


Figure 3-23: Isopach map of the Rupel Formation (U5).
Thickness values in meters. Contour interval 10m.

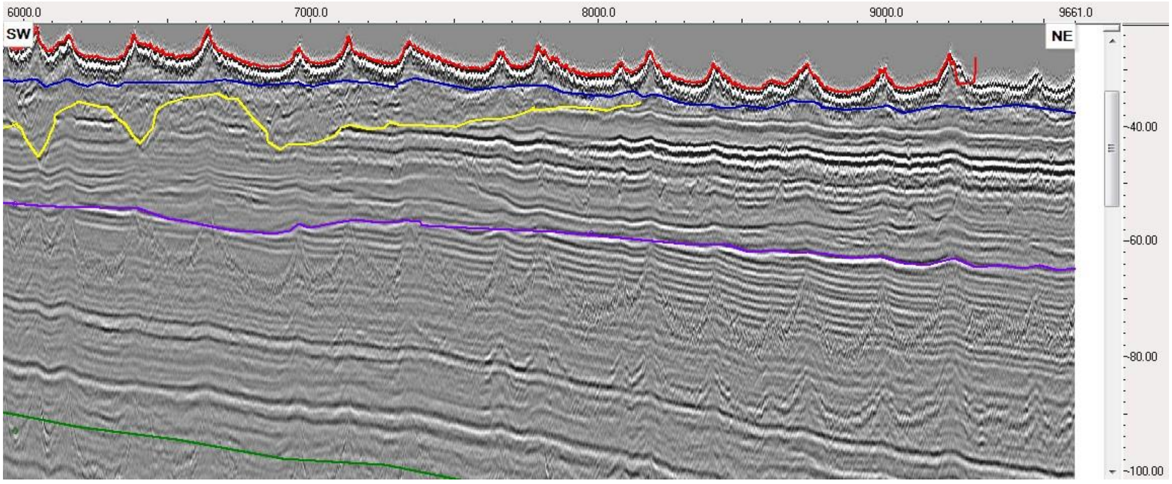


Figure 3-24: The Rupel Formation (U5) displaying reflectors with high amplitude contrasts. A clear truncature is visible at the base of U5 (B5 in purple) of the underlaying deposits of the Tongeren Formation. Image from MCS Line 40, marks on the right are every 2 meters (LAT), numbers on top are CDPs.

3.4.3.4 Pleistocene deposits U6

The Quaternary deposits in the survey area have been divided into two seismic: Unit 6 and Unit 7. They lie unconformably on top of Tertiary deposits (see Figure 3-11 and Figure 3-12).

From the analysis of the literature and general geologic maps published in the area an attempt was made to match the geological information with the seismic stratigraphy mapped. This matching produced good results, however, the unavailability of wells in the area did not allow for a full calibration of the seismic model. Nevertheless, by examining the maps and the schematic cross-section therein, the seismic model matches nicely with the published data. All the Pleistocene formations present in the area are to be included in seismic unit U6. Their low spatial continuity makes them hard to map, especially in the absence of wells. If formations other than Eem and Kreftenheye Formation are present, they are to be included in U6 and will not affect the seismic model.
Seismic unit U6 is the first post-Tertiary unit present in the BWFZ. It can be seen throughout the area, although it is discontinuous and has an irregular and patch-like map pattern. It possibly encompasses three different Pleistocene formations (base to top): the Eem Formation, the Brown Bank Formation and the Kreftenheye Formation.

B6 is the base of seismic unit U6. Its geometry will not be affected by the formations that will be proven to be there included. Its morphology is very irregular and cuts (sometimes very deep) into Tertiary deposits. Its mapping was carried out due to its spatial continuity and strong geological importance. The task of defining which geological formations make up seismic unit U6 has no implications in the mapping of B6. Its upper boundary is also an erosive surface, probably a paleo-topography (B7).

This unit is made up of sand with patches of gravel and clay and these materials are found above the erosive surface that truncates the Tertiary deposits, in some areas they make up the infill of the carved channels (see Figure 3-25). Therefore, this unit's thickness is highly variable. The maximum observed thickness for this unit is in the center of the area, where a deep channel is carved and reaches about 60m (see Figure 3-26). Outside the area with carved channels, the thickness of U6 is less than 15 meters or non-existing, here the Tertiary units underlay Holocene deposits (U7).
The unit's irregular base (B6) lies at depths of around 95m below LAT below a paleo-channel in the central area and at around 30m below LAT in the south sector of the area (see Figure 3-27). In this figure the gridding is tight. Where no surface/thickness is mapped it is because no deposits are present or were not recognized for the scope of this work.

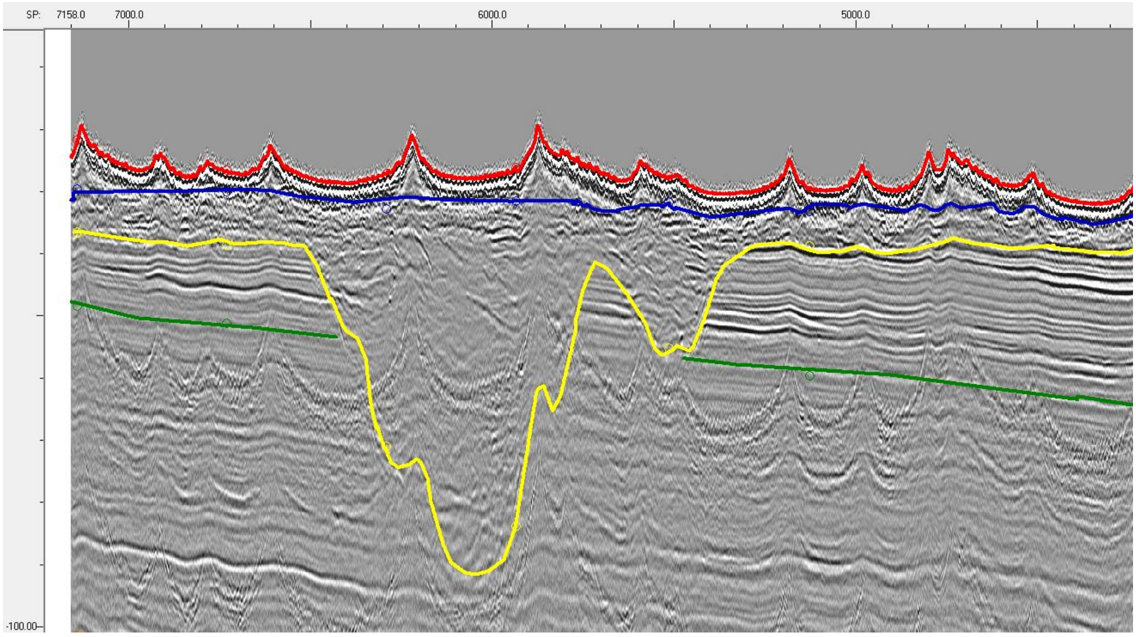


Figure 3-25: Seismic profile of seismic unit, visible as sometime as paleo-channels infill.
U6 indicated in yellow, from seismic Line 112, marks on the left are every 10 meters, numbers on top are CDPs.

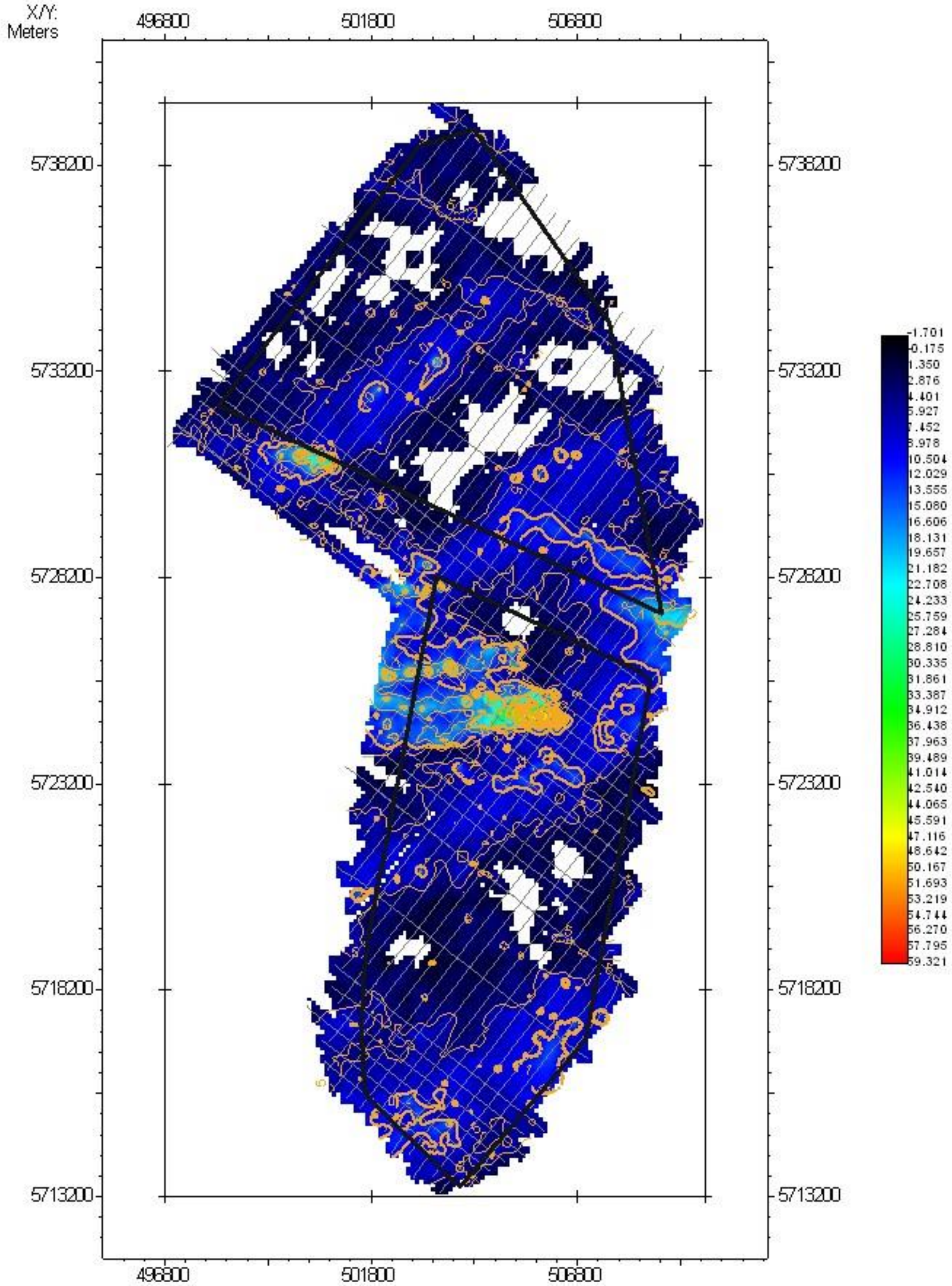


Figure 3-26: Isopach map of the Pleistocene formations (U6)
Thickness values in meters. Contour interval 5m.

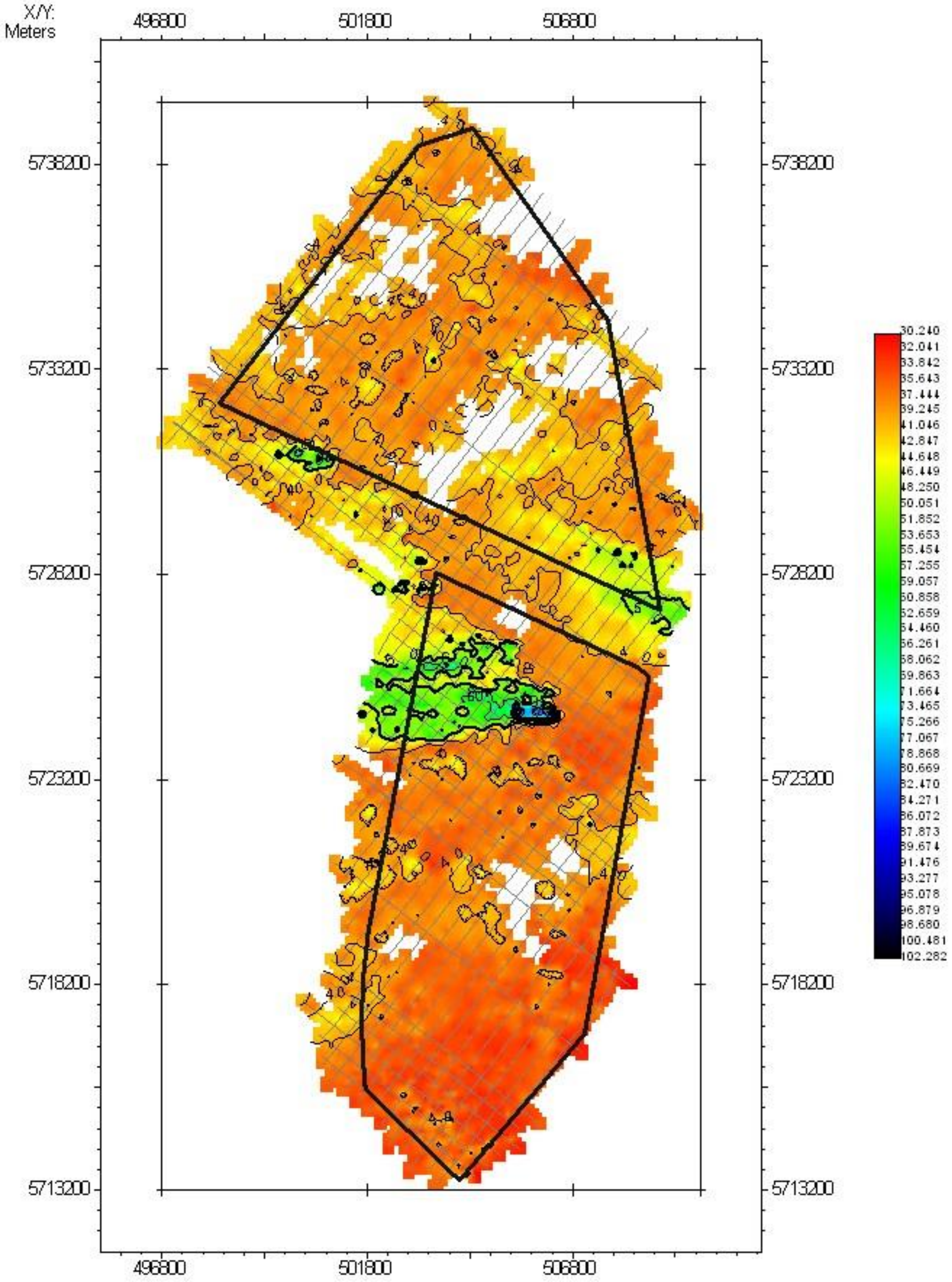


Figure 3-27: Elevation map of the Pleistocene deposits base (U6).
Elevation in meters below LAT. Contour interval 10m.

Seismic unit U6 displays a mostly chaotic (see Figure 3-28) or transparent (see Figure 3-29) facies, although sometimes a more continuous reflector can be identified. These internal reflectors generally have reduced spatial continuity and probably correspond to a local transition between clay and sand or gravel. In few areas, they can define thin sequences of a succession of subparallel reflectors of high amplitude contrasts.

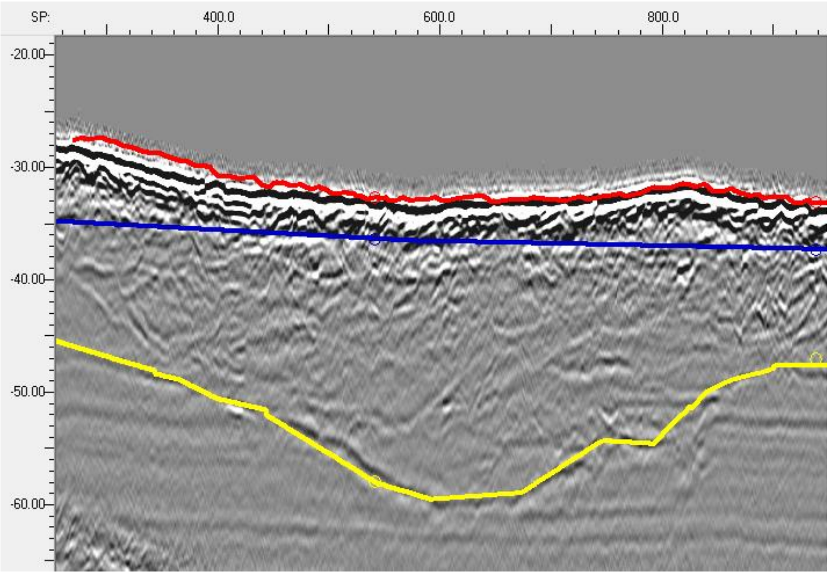


Figure 3-28: Seismic profile of U6 as a paleo-channel infill with seismic chaotic facies.
Profile is MCS x-inline1200_2, B6 indicated in yellow numbers on the left are meters, numbers on top are CDPs.

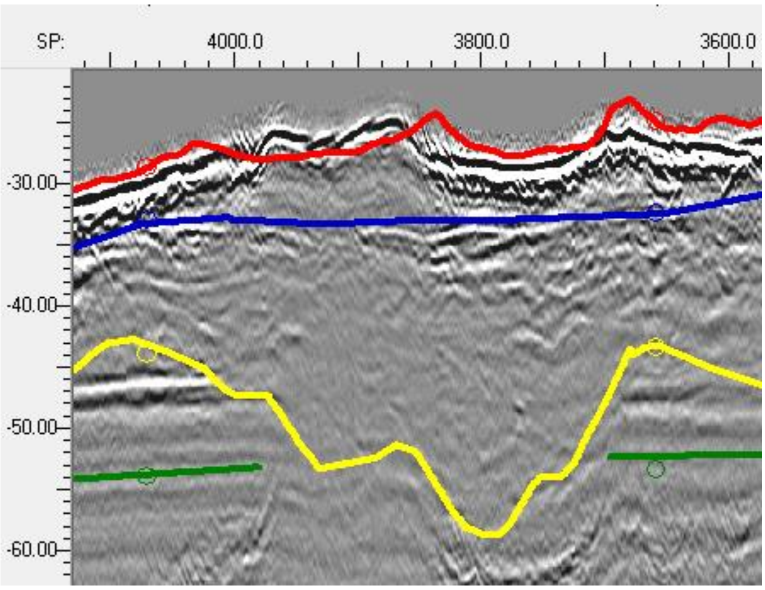


Figure 3-29: Seismic profile of U6 as paleo-channel infill with seismic transparent facies
Profile is MCS 178-x-10000, B6 indicated in yellow, numbers on the left are meters, numbers on top are CDPs. Note: red seabed reflector is from MB data (mistie tables are included in deliverables)

In places where the unit is less disturbed, near the top, more spatially continuous reflectors can be seen. In these cases they might correspond to the base of the Buitenbanken Formation that is possibly present in the area below the seismic unit U7 (see Figure 3-30). In some areas inner reflectors truncate older ones which would confirm the general high-energy environment present at the time this unit was formed.

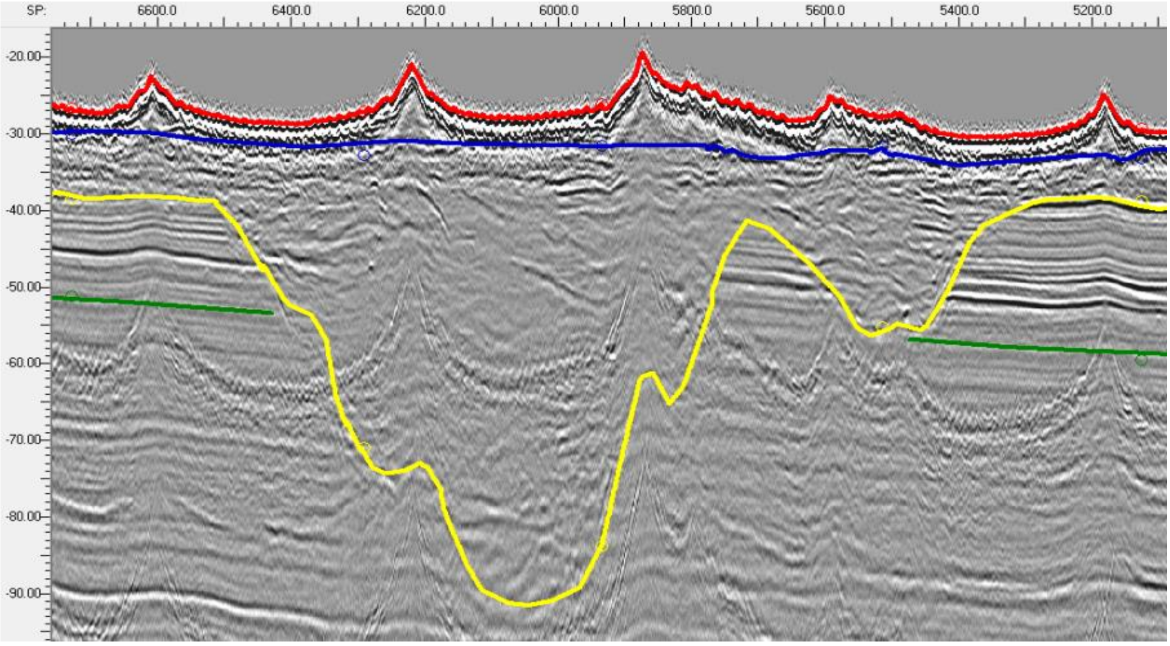


Figure 3-30: Seismic profile of U6 as paleo-channel infill with horizontal reflectors visible. Profile is MCS Line 112-11200c, B6 indicated in yellow, numbers on the left are meters, numbers on top are CDPs

3.4.3.5 Holocene deposits U7

Seismic unit U7 is identified throughout the entire area with both SBP and MCS surveys and corresponds to the Holocene Buitenbanken and Bligh Bank Formations. These are made up of sands that make up the complex geomorphology observed at the sea bed. The lower boundary of U7 is a fairly planar surface and it lies on top of seismic unit Pleistocene deposits (U6), or Tertiary units on U4 or U5 when the Pleistocene cover is not present. The basal unit is of an erosive nature, in some areas possibly corresponding to a paleo-topography. The upper limit for this unit is the seafloor itself since it is the youngest unit in the BWFZ.

The base (see Figure 3-31) sits between depths of around 20 to 40m below LAT. The thickness of this unit (see Figure 3-32) varies between less than a meter to about 17 meters. Since the base is relatively planar, the highest thickness values are found where the seafloor rises, on top of the sandbanks.

When this unit overlies the Tertiary deposits (U4 or U5) a clear unconformity is identified (see Figure 3-34). Where it overlies the Pleistocene unit (U6) usually a clear horizon is identifiable. However, because the underlying deposits rarely have an internal structure, the unconformity associated with the erosive nature of the base is not clear.

The seismic facies of this unit is transparent throughout the whole area. However, in a few areas some low lateral continuity reflectors of low amplitude contrasts can be found (Figure 3-35). These reflectors may correspond to small beds of coarser grain sands/gravel.

Interpretation of the SBP survey data has revealed the base of seismic unit U7 very consistently throughout the survey area. Nonetheless, underneath the sandbanks the penetration of the SBP seismic signal was not sufficient to identify the base of U7. The isopach map of U7 interpreted from SBP in WFS-1 is provided in Figure 3-33. In Figure 3-36 a data example of SBP interpretation is provided, showing the interpreted B7 horizon in green.

From cross-correlation between the MCS and SBP interpretation results it was shown that there was good overlap between the data sets. The isopach maps of U7 from both surveys showed that the modelled thicknesses correlated very well.

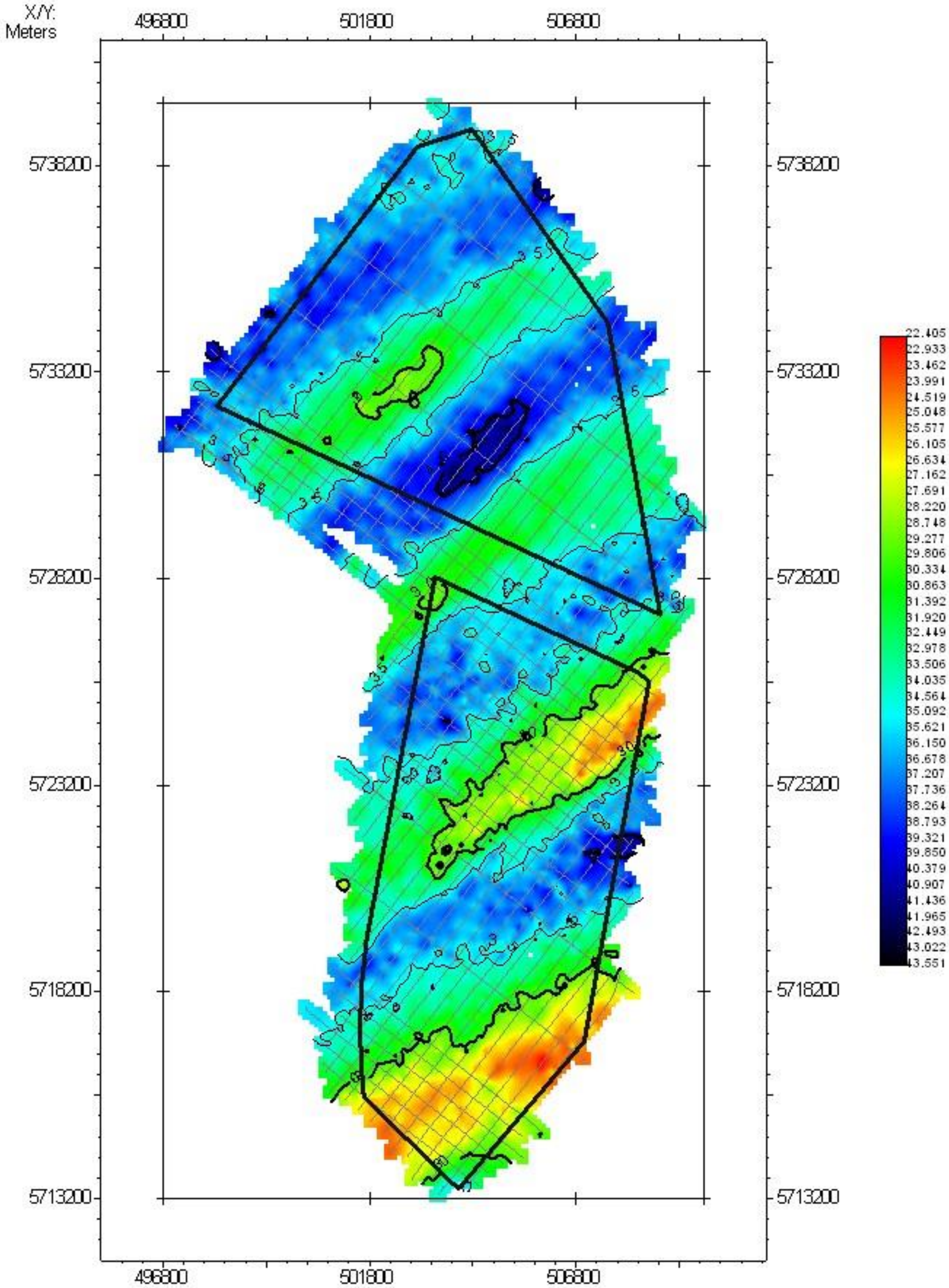


Figure 3-31: Elevation map of the Holocene formations base (U7).
Elevation in meters below LAT. Contour interval 5m.

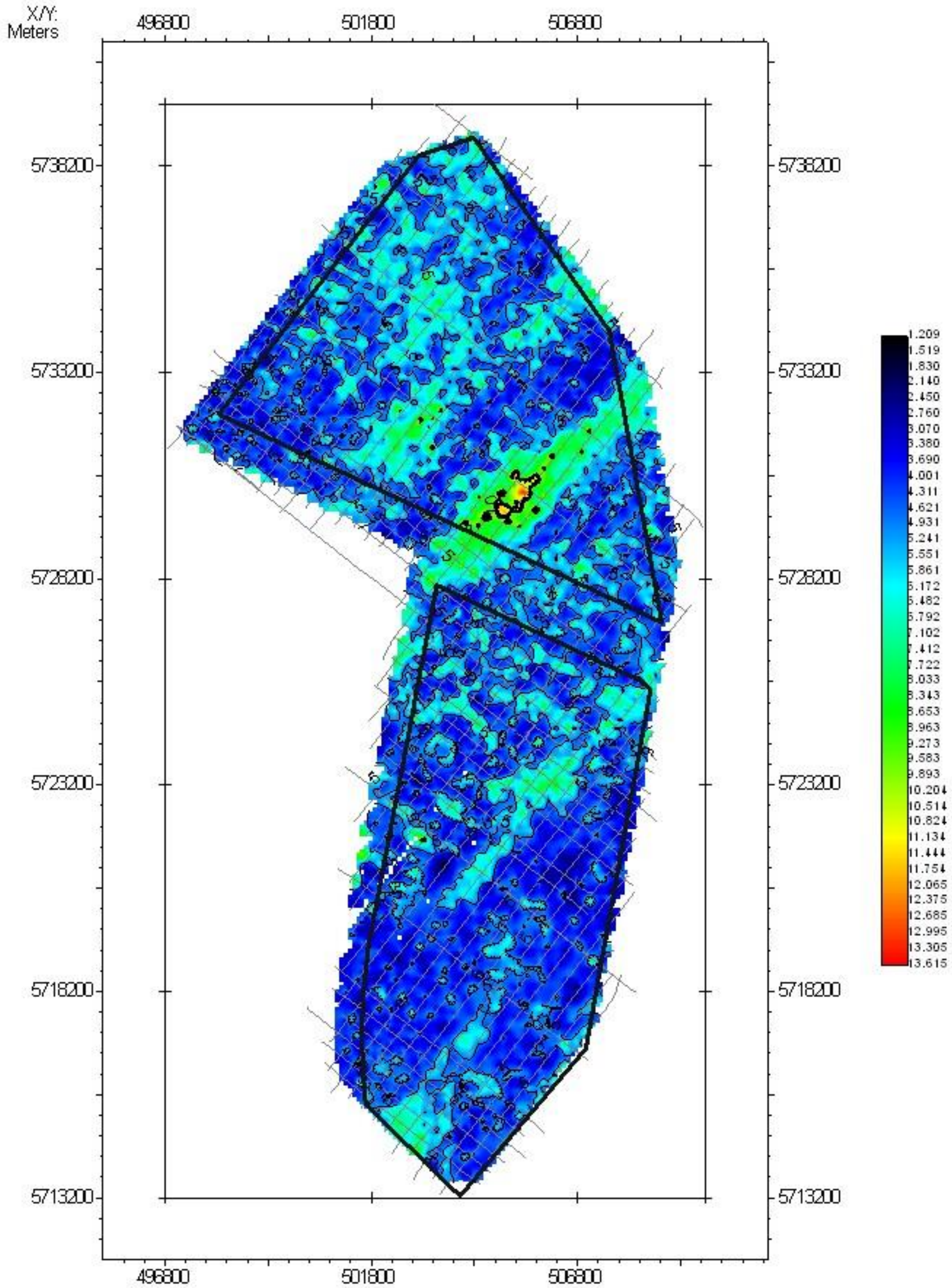


Figure 3-32: Isopach map of the Holocene formations (U7).
Thickness values in meters. Contour interval 5m.

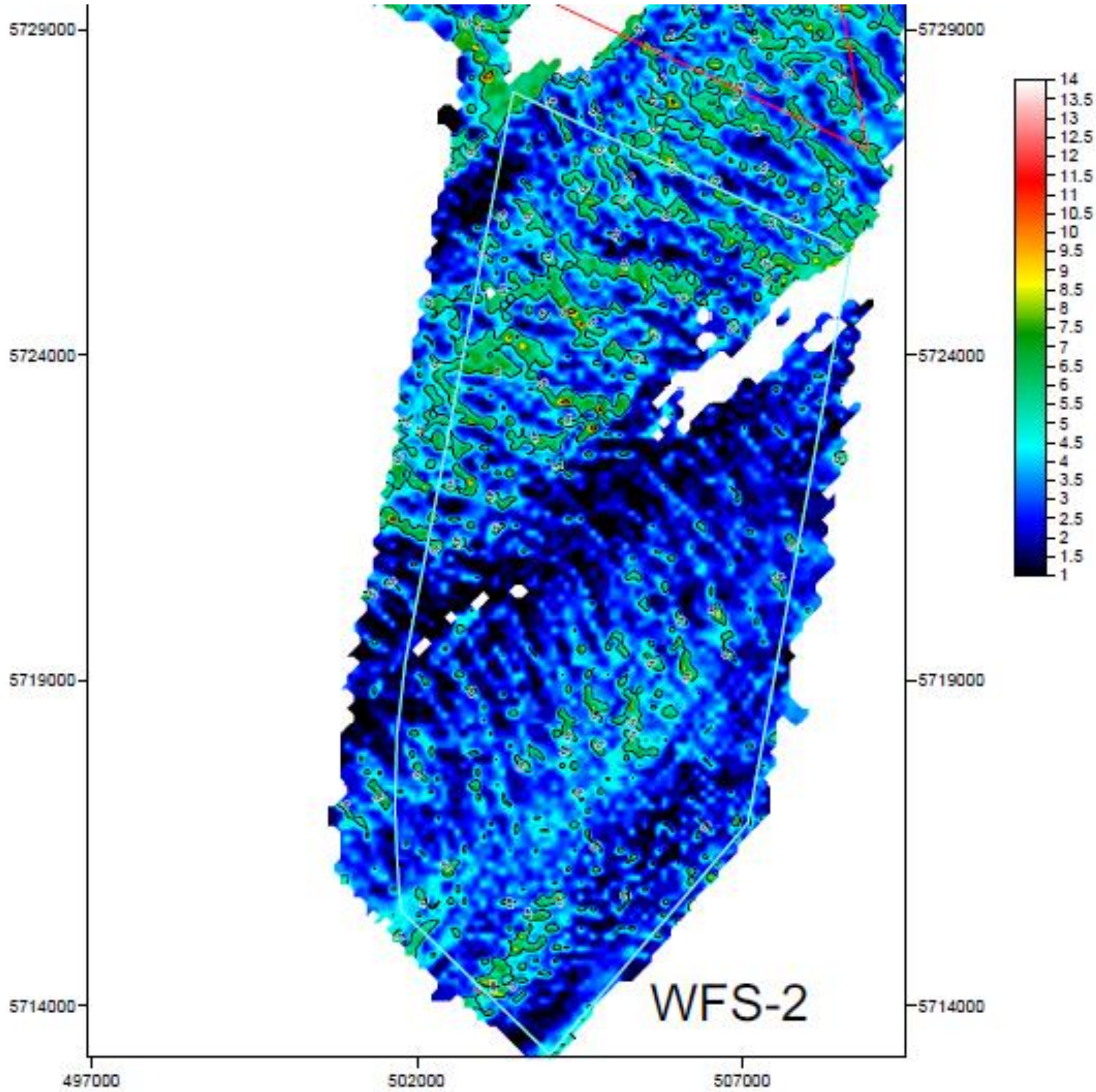


Figure 3-33: Isopach map of the Holocene formations (U7) in WFS-2, based on SBP interpretation Thickness values in meters, contour interval 5m.

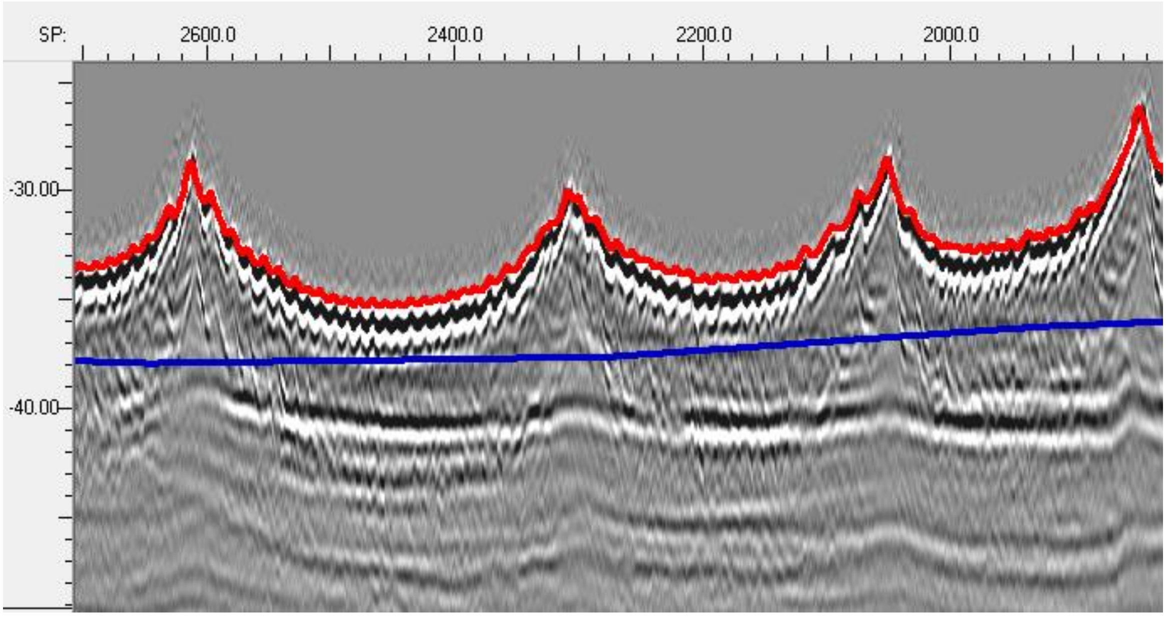


Figure 3-34: Seismic profiles of Bligh Bank formation (U7) resting unconformably on Tertiary deposits (U5). Profile is MCS Line 60-6000b, B7 indicated in blue, numbers on the left are meters, numbers on top are CDPs

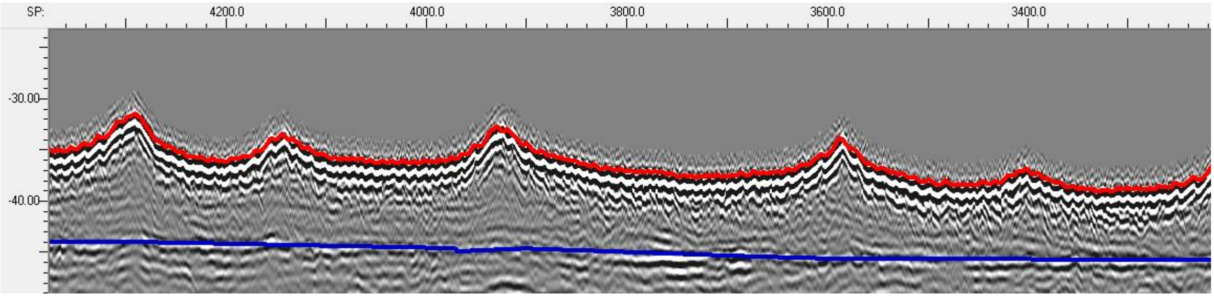


Figure 3-35: Seismic profiles of the Bligh Bank formation (U7), showing internal reflectors Profile is MCS Line 76-7600, B7 indicated in blue, numbers on the left are meters, numbers on top are CDPs

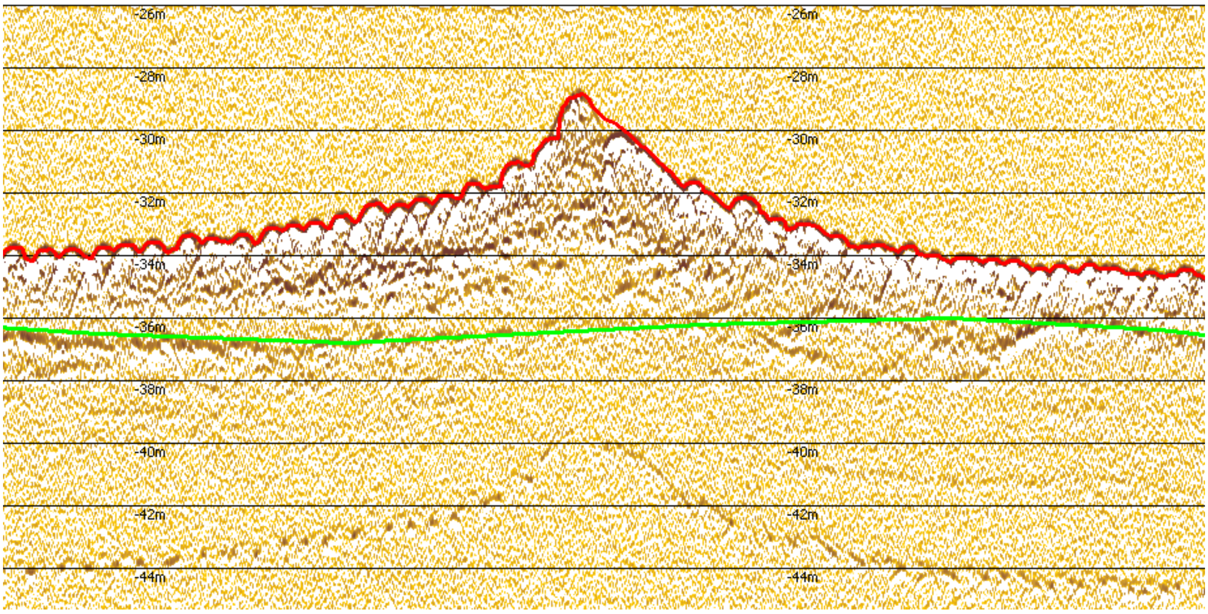


Figure 3-36: Seismic profiles of the Bligh Bank formation (U7), from SBP data.

3.4.4 Overview seismic units

Table 3-6 provides a quick overview summary of the various stratigraphic units interpreted from the seismic data.

Table 3-6:Overview of interpreted seismic units in the BWFZ

<table>
<tr><th rowspan="2">Seismic Units</th><th colspan="2">Boundaries</th><th colspan="2">Basal Surface</th><th rowspan="2">Acoustic facies and internal configuration</th><th rowspan="2">Lithological composition</th><th rowspan="2">Depositional Environment</th><th rowspan="2">Geology Nomenclature</th><th rowspan="2">Age</th><th rowspan="2">Observed Thickness (m)</th></tr>
<tr><th>Lower</th><th>Upper</th><th>Morphology</th><th>Nature</th></tr>
<tr><td>U7</td><td>B7</td><td>Seafloor</td><td>Overall relatively flat</td><td>Hard ground, paleo-seafloor, erosional</td><td>Almost no internal reflectors</td><td>Sand</td><td>Marine</td><td>Bligh Bank Formation Buitenbanken Formation</td><td>Holocene</td><td>1-13</td></tr>
<tr><td>U6</td><td>B6</td><td>B7</td><td>Irregular</td><td>Erosional</td><td>Chaotic facies with some reflectors with limited spatial continuity</td><td>Sand with patches of clay or gravel</td><td>Shallow marine & Fluvial</td><td>Eem Formation, Kreftenheye Formation</td><td>Upper Pleistocene</td><td>0-60</td></tr>
<tr><td>U5</td><td>B5</td><td>B6, B7</td><td>Planar truncature</td><td>Erosional</td><td>First sediments onlap near B5</td><td>Clay and sand beds</td><td>Marine</td><td>Rupel formation</td><td>Upper Oligocene</td><td>0-32</td></tr>
<tr><td>U4</td><td>B4</td><td>B5, B6, B7</td><td>Planar concordant</td><td>Sedimentary</td><td>Parallel reflectors, upper reflectors truncated by B5</td><td rowspan="2">Fine-grained sands overlain by lagoonal to terrestrial clay deposits</td><td rowspan="2">Shallow marine</td><td rowspan="2">Tongeren Formation</td><td rowspan="2">Lower Oligocene</td><td rowspan="2">10-130</td></tr>
<tr><td>U3</td><td>B3</td><td>B4, B6</td><td>Planar concordant</td><td>Sedimentary</td><td>Parallel reflectors</td></tr>
<tr><td>U2</td><td>B2</td><td>B3</td><td>Planar concordant</td><td>Sedimentary</td><td>Parallel reflectors</td><td rowspan="2">Calcareous clays with intercalated sandstones</td><td rowspan="2">Marine</td><td rowspan="2">Dongen Formation</td><td rowspan="2">Eocene</td><td rowspan="2">60-220</td></tr>
<tr><td>U1</td><td></td><td>B2</td><td></td><td></td><td>Parallel reflectors</td></tr>
</table>

3.5 Geo-hazards

In this chapter the potential geo-hazards in WFS-2 are described. Shallow potential geo-hazards identified with SBP are presented first, followed by deeper geo-hazards identified from the MCS survey. All geo-hazards are presented in A0 charts in Appendix O.

3.5.1 SBP interpretation

From the SBP data the presence of two types of geo-hazard in WFS-2 are interpreted:

- **Denser material** between transition of lithological units **U6** and **U7**.
- Shallow **paleo-channel infill** and local variations underneath **U7**.

A data example showing denser material is shown in Figure 3-37 below.

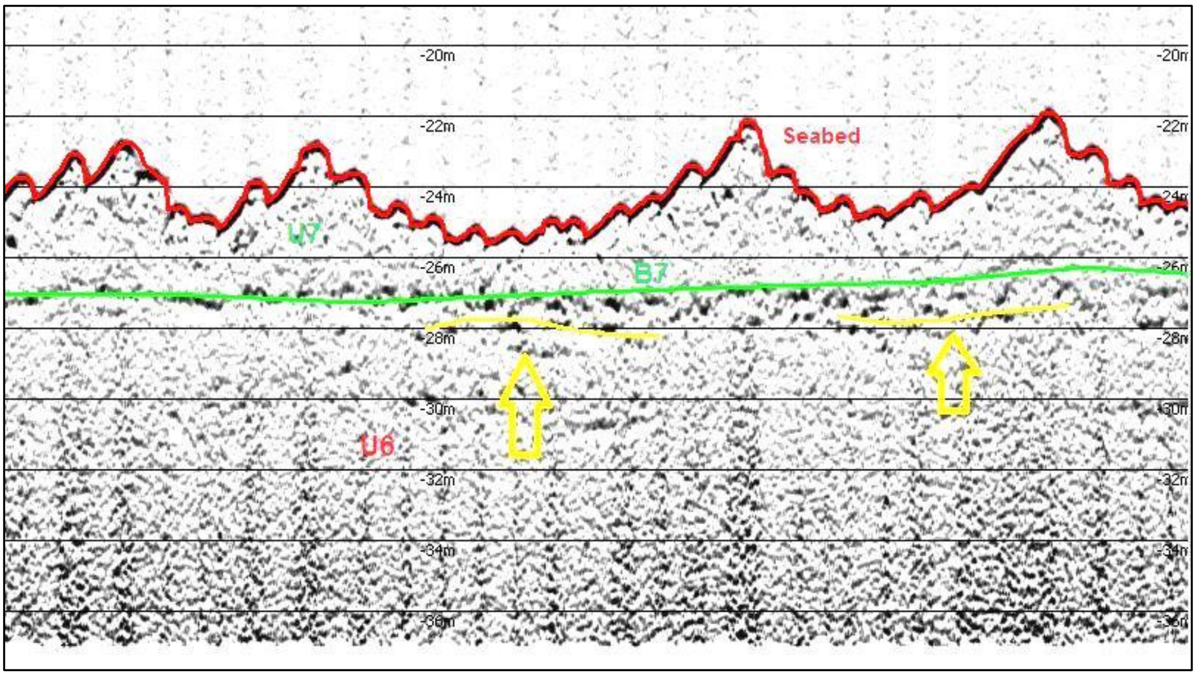


Figure 3-37: SBP data example showing denser material
Yellow arrows indicate reflectors just below B7

The occurrence of shallow infilled channels is limited to the southeastern end of WFS-2 (see Figure 3-38). The occurrence of denser material between transitions can be found clustered in the southwestern end of WFS-2, which could be related to fluvial channel infill. A few isolated occurrences appear near the eastern border of WFS-2.

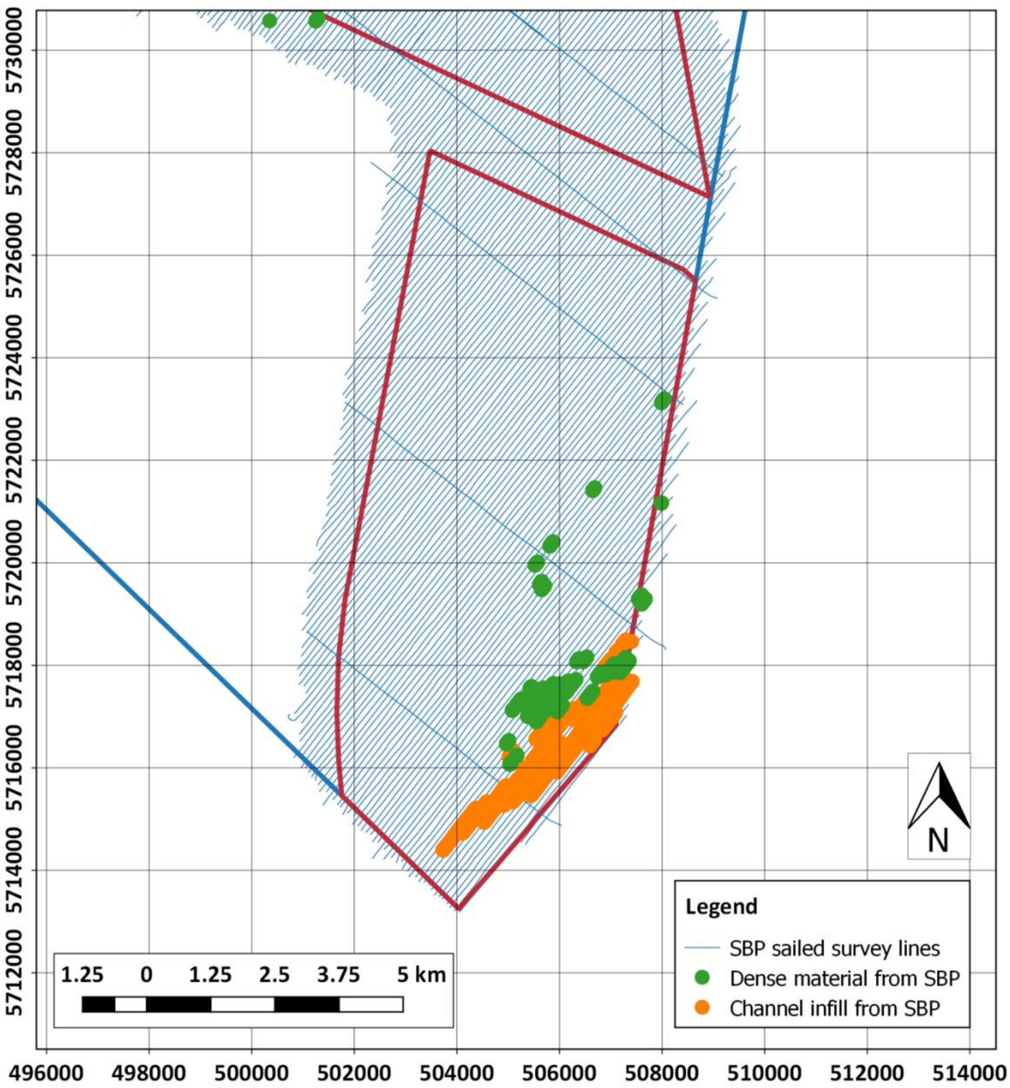


Figure 3-38: Overview map of WFS-2 with locations of dense material and channel infill from SBP survey

3.5.2 MCS interpretation

From the MCS data analysis the following seismic evidence of potential hazards to engineering works in the sub-surface has been found:

- **Paleo-valley infill** sediments, associated with **U6**.
- Point diffractors as evidence of **gravel and boulder deposits**, associated with **U4**, **U5** and **U6**.
- Seismic horizon deformation features suggestive of **sediment liquefaction** due to sediment overpressure and or fluid migration, associated with **U4.**
- Strong amplitude reverse polarity reflections indicating a strong decrease in acoustic impedance, possibly caused by **peat layers and/or shallow gas accumulations**, associated with **U3.**

- Kinked and irregular seismic reflections within an overall cake-layered seismic stratigraphy as evidence of **hexagonal faulting** due to desiccation or fluid loss of clay rich sediments, associated with **U2**.

Following is a detailed description of the geological hazards found. In Appendix P, a plan for boreholes to further investigate these hazards is proposed together with an overview table with all the general information. In total 15 locations for drilling are proposed for each of the WFS areas. From these 15 locations, six priority locations are suggested per area. It also presents all the relevant information available for each site and a reason to investigate that precise location.

3.5.2.1 Channel infills (U6)

Paleo-valley infill sediments frequently materialize sharp lateral changes in mechanic resistance to burden and represent a punch-through risk for jack up rigs. Interpretation of the MCS data has shown there are a series of paleo-valleys of probably Quaternary age associated with seismic unit U6 that, in places, can be over 60m thick. The sudden interruption of the drainage is suggestive of high energy tidal inlets in some locations. Examples of paleo-channel infill in WFS-2 are shown in Figure 3-39, a map plot of the layer thickness of the paleo-channel infill is provided in Figure 3-40.

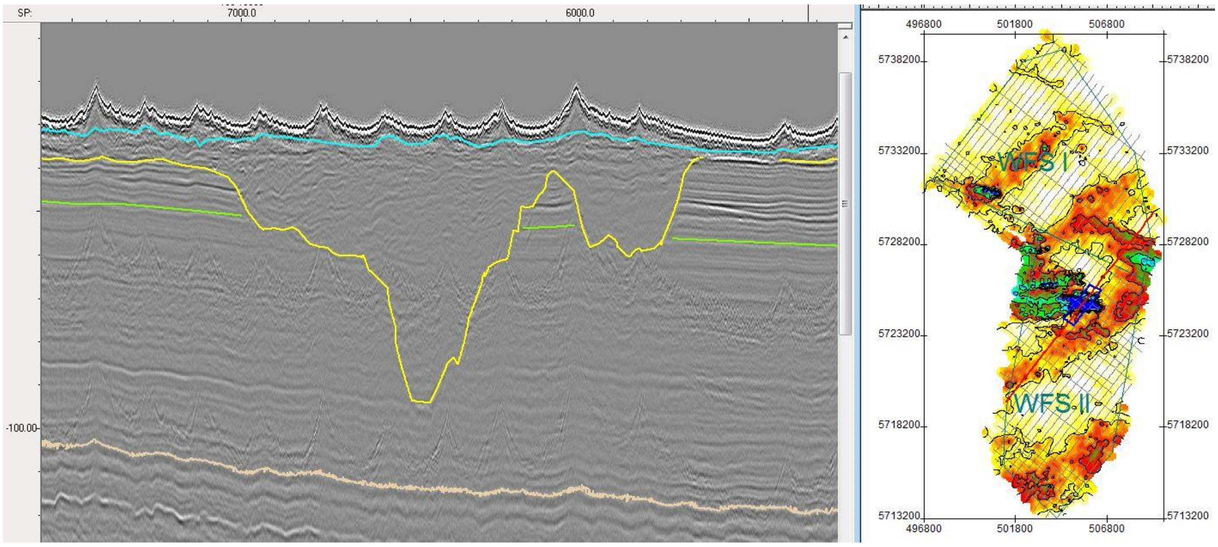


Figure 3-39: Evidence of paleo-channel infill in U6 in WFS-2 on MCS profile line 108-10800.

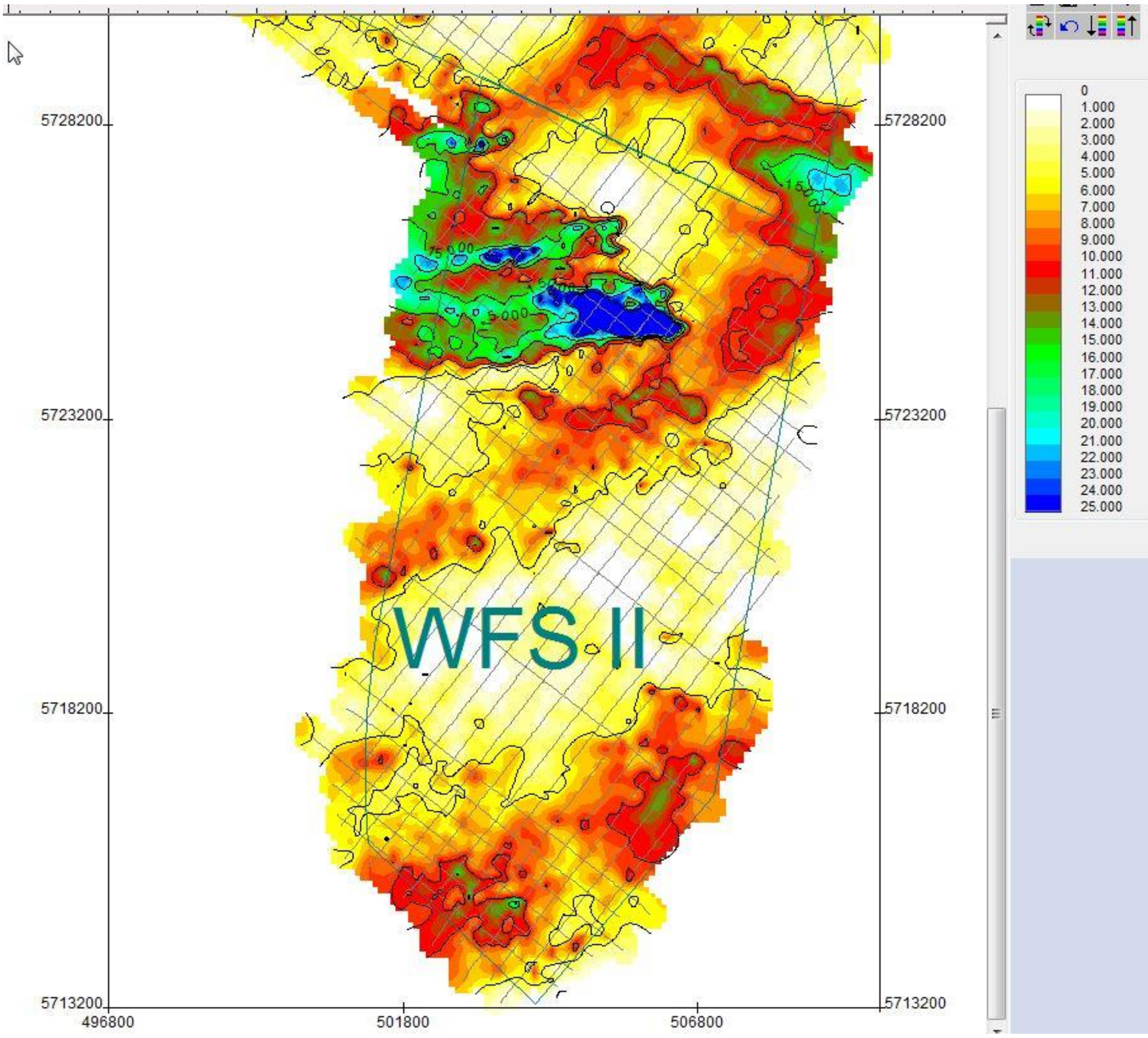


Figure 3-40: Thickness map of the paleo-channel infill unit (U6) in WFS-2.
Colour scale capped at 25m thickness for better visualization of the drainage pattern

3.5.2.2 Gravel beds (U4, U6)

Gravel and boulder accumulations present strong rheological contrasts in relation to the surrounding sediments, and can potentially hamper drilling operations (deviation or damage to drill bits) and to the installation of foundations. The evidence for gravel and boulder deposits is widespread in U6 and occurs in patches along specific horizons within U4.

Point diffractors are widespread in U6, particularly along the erosive boundary (B6) with the lower units (see Figure 3-41). Note that the horizon line was intentionally left out of the figure as the evidence at the base of unit U6 would not be visible otherwise.

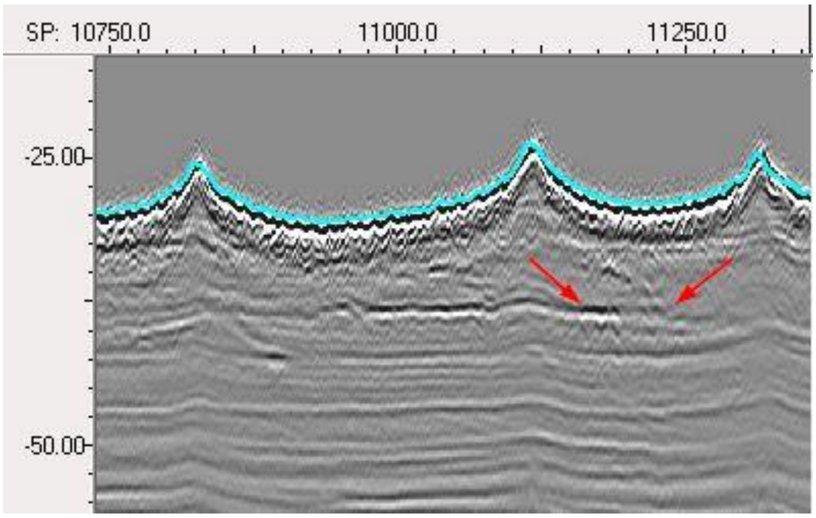


Figure 3-41: Evidence of gravel and boulders in U6.
Indicated with red arrows.

The evidence for gravel and boulders in U4 is observed in the central part of the survey area, crosses the two concession sites and shows relatively large accumulations along a main horizon. The accumulations range from -40 to -76m LAT and are relatively continuous (see Figure 3-42 and Figure 3-43). Due to some feathering the point diffractor interpretation was carried out more conservative on the cross lines.

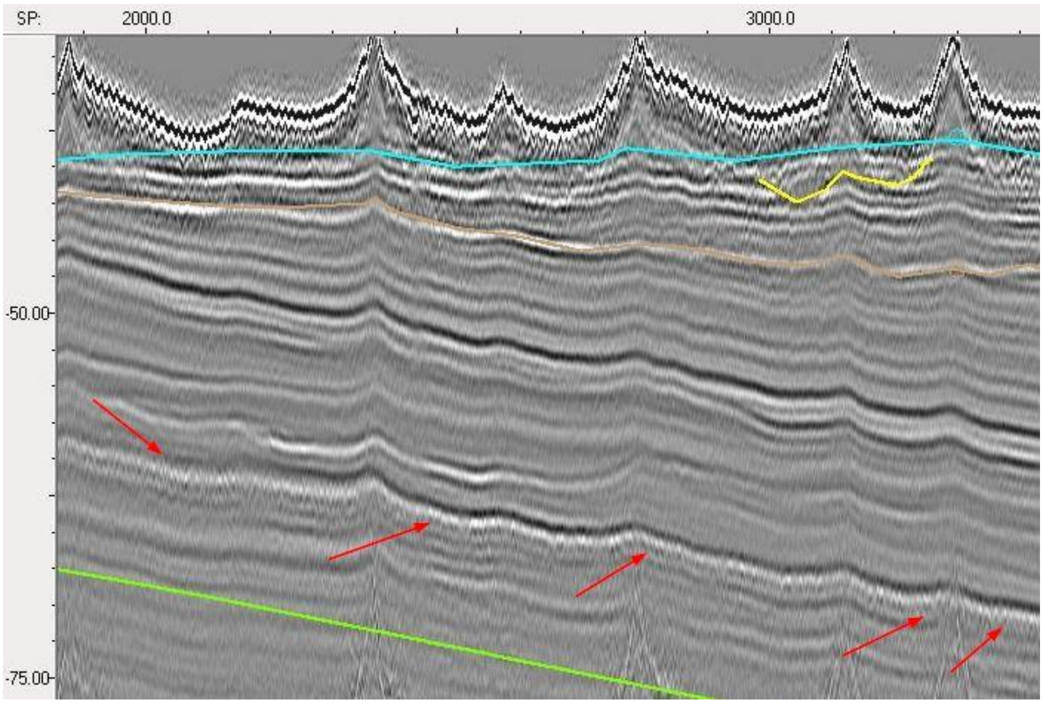


Figure 3-42: Evidence of gravel and boulders in U4.
Indicated with red arrows.

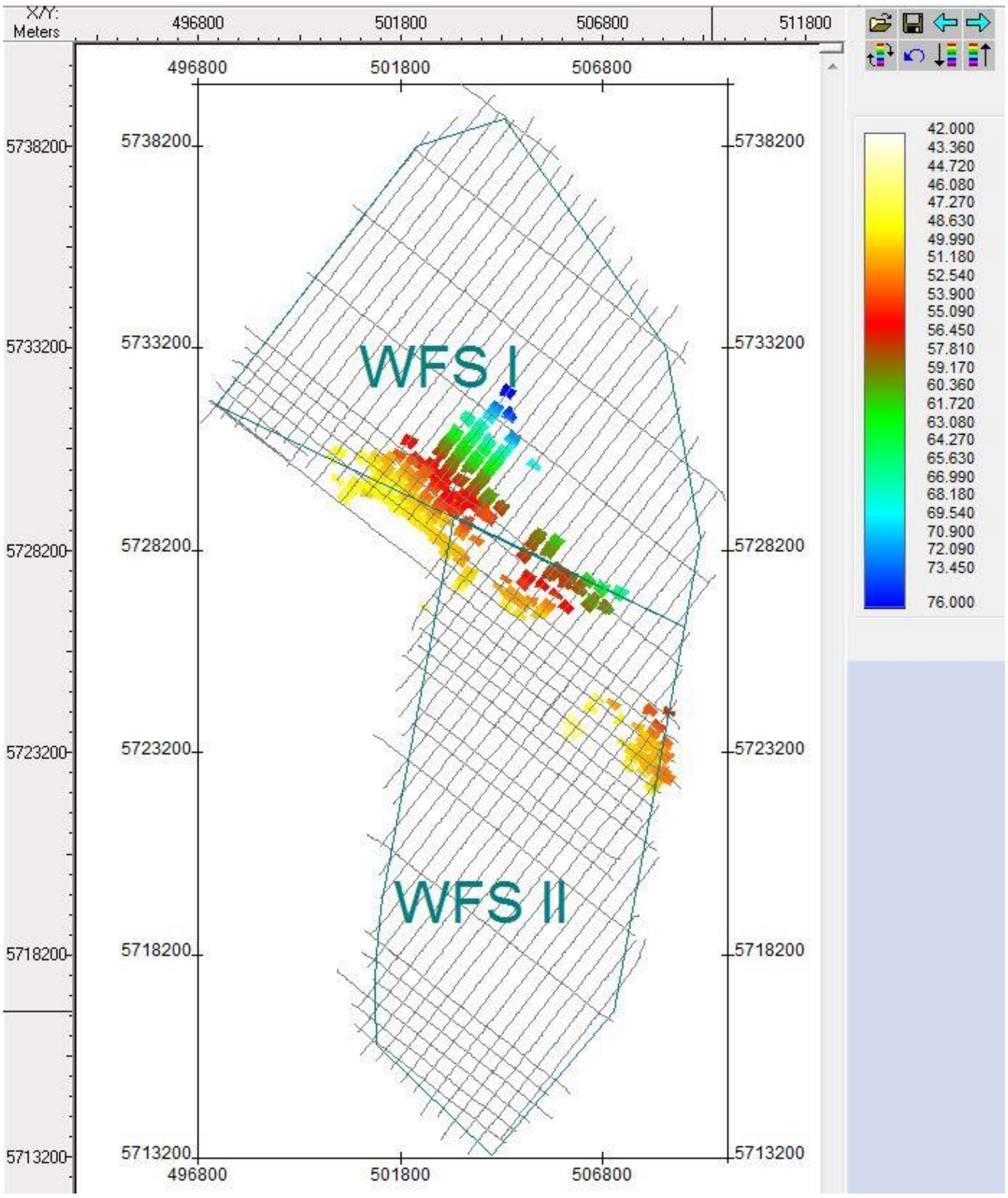


Figure 3-43: Overview map of patches of gravel and boulders in U4

3.5.2.3 Shallow gas and organic deposits (U3)

In WFS-2 reflectors with strong amplitude have been detected, with discontinuous nature and reverse polarity. These reflectors are indicative of a decrease in acoustic impedance that may be related to either shallow gas or peat accumulations in the seismic unit U3. These reflectors are found at depths from -35 to -70m LAT (see Figure 3-44 and Figure 3-45). There is no clear evidence for a shallow gas fluid flow system, gas source, fluid pathways or seepage features. Nevertheless, pending ground-truthing, the evidence is compatible with the hypothesis of shallow gas accumulations and should be taken into account.

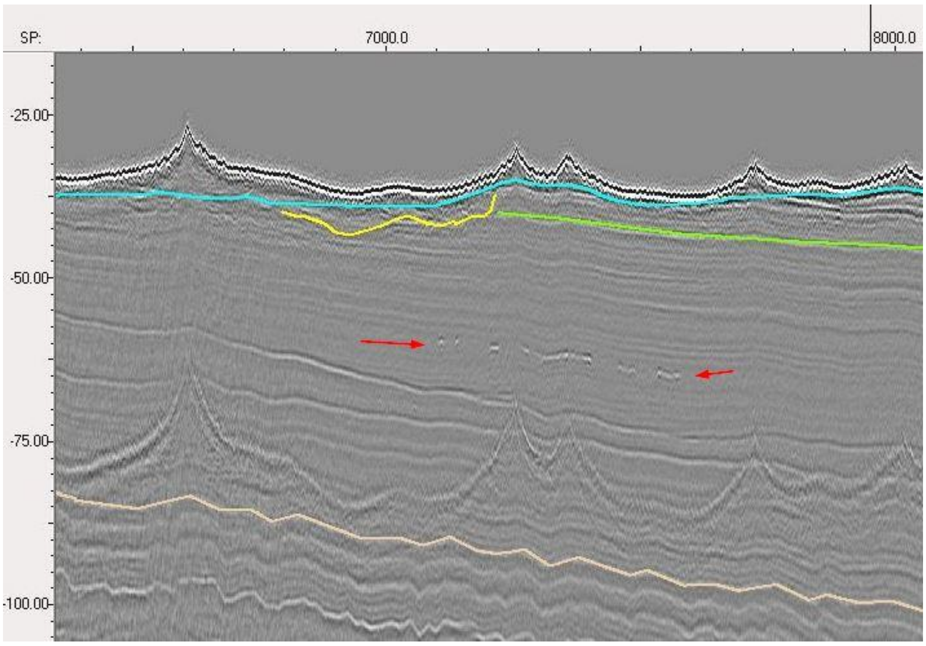


Figure 3-44: Evidence of peat accumulations in U3
Indicated with red arrows.

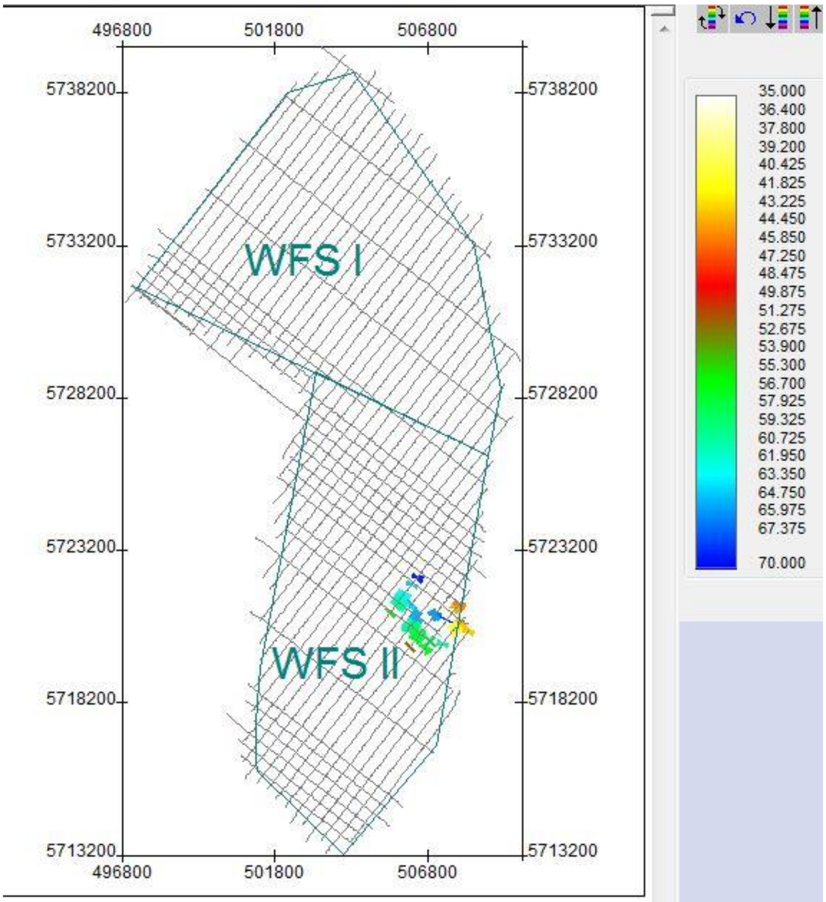


Figure 3-45: Overview map of peat accumulations in U3

3.5.2.4 Hexagonal faulting (U2)

Seismic unit U2 is affected by widespread deformation, partioned in a more ductile pattern in the upper sediments and a more brittle clearly fractured pattern at depth (see Figure 3-46). This deformation does not affect the lower and upper sediments, presenting a very probable example of hexagonal faulting due to dessication, i.e. loss of fluids in clay rich sediments (case study by Imbert et al. (2012), see Figure 3-47). A regional similar case was studied by Henriet et al. (1988), explaining the features as a result in changes in the mechanical and rheological properties of the sediment during compaction (see Figure 3-48).

The deformation pattern may pose engineering challenges due to the presence of a dense network for mechanic failures in the sediments. For an assessment of the depths and area of relevance for this hazard please refer to the depth and isopach maps of seismic unit U2 (see Figure 3-17 and Figure 3-18).

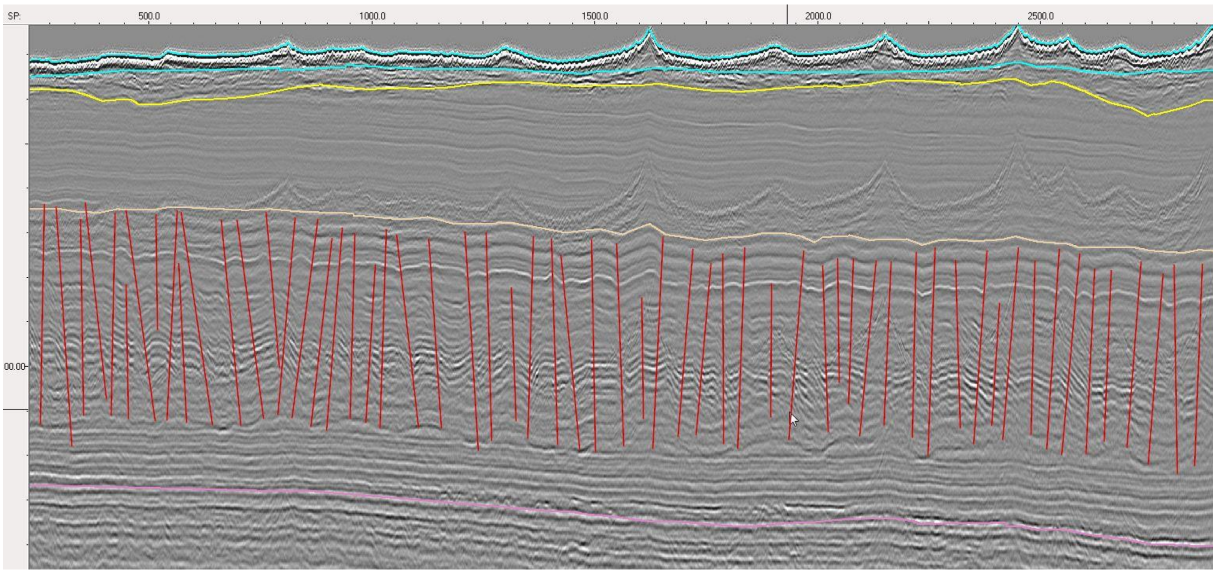


Figure 3-46: Evidence of hexagonal faulting in seismic unit U2

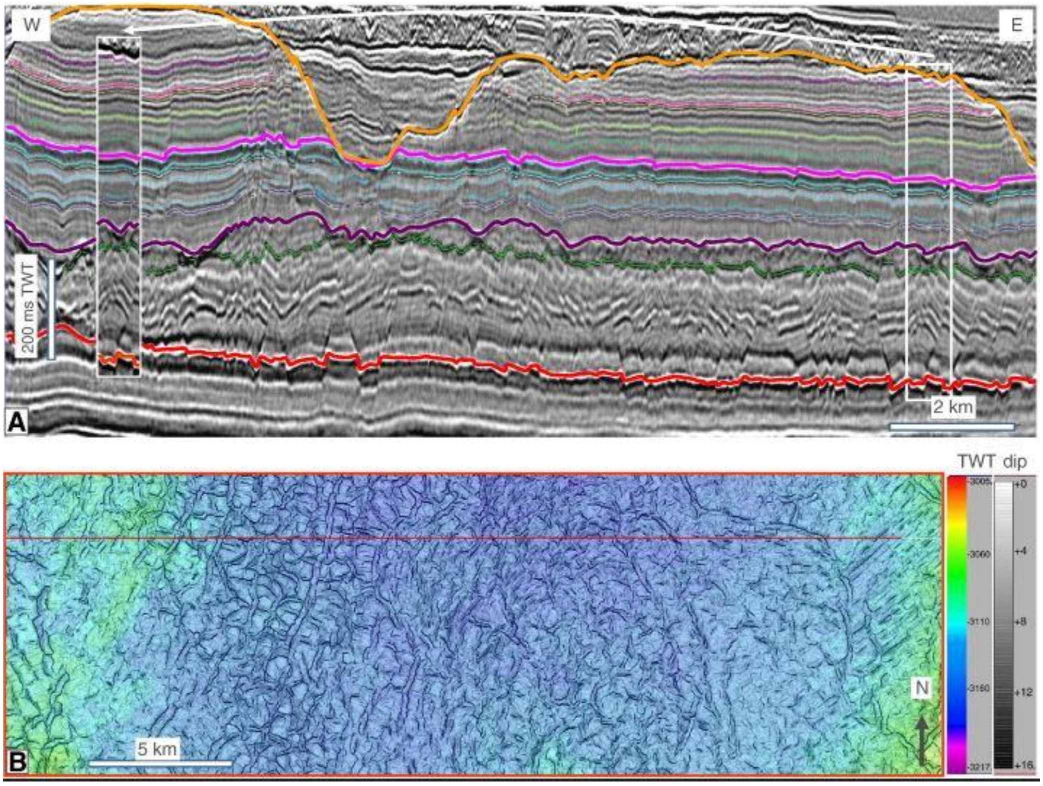


Figure 3-47: Example images of hexagonal faulting from Imbert et al. (2012)

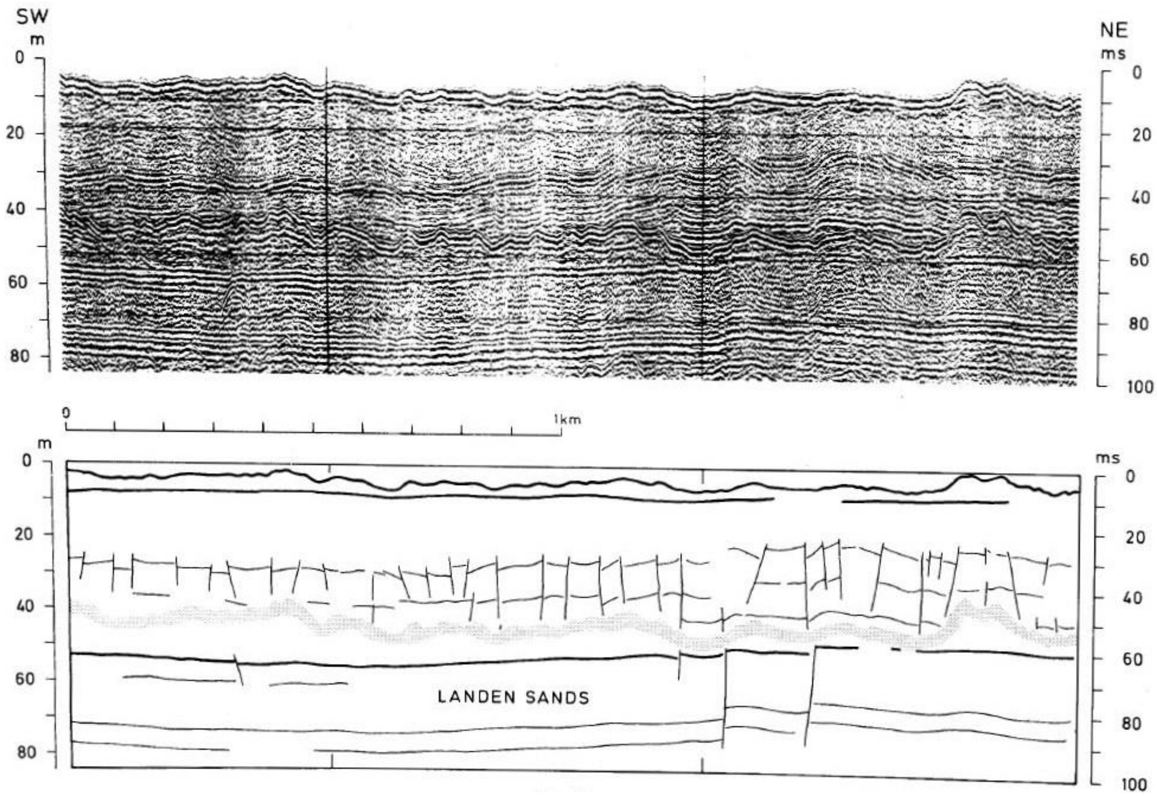


Figure 3-48: Sparker profile displaying intraformational faulting From Henriet et al. (1988)

3.5.3 Recommendations for borehole locations

Based on the interpretation of the MCS survey fifteen borehole locations have been proposed for each WFS area. The choice for these locations is based upon the interpretation of the MCS data in Chapter 3.5.

A priority ranking has been made for the top six borehole locations. These locations are expected to provide the interesting ground-truth information about geology, geotechnical implications and geo-hazards. The table with the proposed borehole locations can be found in Appendix P.

The recommended borehole plan is meant to serve as verification of the geophysical survey and as a starting point for the final borehole plan, which will be drafted by the team concerned with the geotechnical campaign.

4 CONCLUSIONS AND RECOMMENDATIONS

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland –RVO-) awarded Deep BV the contract for the execution of a geophysical site investigation survey of two of the four areas within the Borssele Wind Farm Zone.
The two areas were surveyed in one survey campaign in January and February 2015 using two offshore survey vessels. MV Seazip Surveyor was used for the multi-channel sparker seismic survey and MV Breaker for the simultaneous execution of the bathymetric, side-scan sonar, magnetometer and sub-bottom profiler surveys. The decision to split the operational survey into two operations allowed for a more flexible operation when the weather was favourable. Furthermore, by separating the multi-channel sparker survey from the other surveys, the expected interference from the sparker system on other survey techniques was avoided.

In total. 560 survey kilometers were sailed with MV Seazip Surveyor in WFS-1 and WFS-2, in the period of the 16th to the 28th of January 2015. In total 1640 survey kilometers were sailed with MV Breaker in WFS-1 and WFS-2 in the period between the 26th of January and the 15th of February 2015. Despite the risk of prolonged periods of weather delay by performing the survey in winter the weather proved to be above average for the time of year, allowing the surveys to be executed with a minimum of weather delay. In total, 13.3 days were lost by waiting on weather for both survey vessels.

The MBE data was recorded by using two R2Sonic multibeam heads to cover a large area fast and with high accuracy. The multibeam derived bathymetry proved to be of very good quality. The WFS area shows the presence of large sand dunes and sand waves. The water depths in the WFS-2 area range between -14.0 and -38.5m LAT.
The multibeam derived backscatter data was used for seabed classification purposes, classifying the soil within six possible soil classes. In the WFS-2 area nearly all sediments fall within the ‘sands’ and ‘muddy sands’ categories. Occasional small quantities of coarser material can be found. Material in the ‘silts’ and ‘clays’ classes are hardly found at all.

The side-scan sonar survey was executed with 100 meter survey line spacing. Total data coverage of 125% was achieved. The sidescan sonar data was used for the detection of objects on the seabed.
The magnetometer data was recorded using 100 meter survey line spacing. The data proved to be of very good quality, making for reliable contact picking. A 5 nT cut-off value was used for the contact picking.

In the WFS-2 area a total number of 189 contacts not associated with pipelines, cables or wrecks have been detected. Of these contacts 89 were detected with MAG only, 97 contacts with SSS only and 3 with both survey systems.

A number of pipelines, active cables and out-of-service cables cross the WFS-2 survey area. All pipelines and active cables have been found. In the WFS-2 area one active cable has been located with an offset with regard to its theoretical position. In WFS-2 two magnetic lineations have been found that might be related to unknown or uncharted cables. Both have an east-west orientation. There are two known wrecks are present in the WFS-2 are, of which one has been detected. No previously unknown wreck locations were identified from interpretation of the SSS data.

A high resolution sub-bottom profiler survey with 100 meter line spacing was executed using MV Breaker. The sub-bottom profiler data was of good quality and achieved the expected penetration. The resulting dataset was used to create an isopach layer of the base of the mobile, subaqueous dunes on the seabed. The base of this layer has been found in the large majority of the sub-bottom profiler survey lines.

The deep penetrating multi-channel sparker survey was performed using MV Seazip Surveyor. An initial line spacing of 400 meters was used. Based on the online data results areas with complex geology were surveyed with intensified line spacing for increased resolution. The geological units within 100 meters depth in the sub-surface are subdivided in two major units, divided by an erosional boundary:

- Horizontally stratified marine and coastal Tertiary deposits, subdivided into five seismic units;
- Shallow marine and fluvial Quaternary deposits, subdivided into two seismic units.

Both the high resolution SBP and the MCS data were used to identify potential geo-hazards along the survey lines. The following shallow geo-hazards were identified with SBP:

- Denser material between transition of lithological units;
- Shallow paleo-channel infill.

The following deeper geo-hazards were identified with MCS:

- Deeper paleo-channel infill;
- Localized gravel or boulder deposits;
- Features to suggest sediment liquefaction;
- Possible peat layers and/or shallow gas accumulations;
- Hexagonal faulting.

5 OPERATIONAL METHODOLOGY

This chapter describes the methodology used during the survey. The technical procedures followed to ensure data quality and integrity are explained. For more in-depth information about the equipment calibrations on both survey vessels the submitted calibration reports are available (see Table 5-1 and Appendix D).

Table 5-1: Calibration reports for MV Seazip Surveyor and MV Breaker

Report	Deliverable ID
Calibration report MV Seazip Surveyor	20150227_SDB_DEEP_Calibration report Seazip Surveyor_V03_F
Calibration report MV Breaker	20150311_SDB_DEEP_Calibration report Breaker_V04_F

Further information about the specifications of the survey vessels and the equipment used can be found in Appendices E and G, respectively.

5.1 Preparation

Prior to the geophysical survey Deep BV has obtained all necessary permissions to execute the survey.

5.2 Health safety and environment

The Party Chief had an overall responsibility for the survey activities, procedures and contacts with the Client. All undertaken activities during the survey operations were described in daily reports which were signed by the Party Chief and sent to the Client.

All personnel from Deep were committed to the HSE policy of the company. Additionally the role of the Party Chief was to inform the Client’s Representative in case of any health, safety or environmental hazards as well as any near-miss. Special attention was given to the proper use of PPE; including the use of survival suits should the water temperature fall below 12 degrees Celsius.

No project related health, safety, environmental hazards or near-miss occurred.

5.3 Survey control

5.3.1 Geodetic parameters

All geographical co-ordinates in this report are based on UTM 31N using the following parameters:

Table 5-2: Geodetic parameters used during the BWFZ survey

Parameter	Value
Horizontal datum	ETRS89 (EUREF89)
Spheroid	GRS 1980
Semi-major axis (a)	6378137.00m

Semi-minor axis (b)	6356752.314m
Inverse flattening (1/f)	298.257222101000
Flattening (f)	0.003352810681182
First eccentricity	0.081819191042816
First eccentricity squared (e2)	0.006694380022901
Second eccentricity (e')	0.082094438151917
Second eccentricity squared (e'2)	0.006739496775479
Projection	UTM zone 31 North
Latitude of grid origin	0;00;00.000
Longitude of grid origin	3;00;00.000
Grid Easting at grid origin	500000
Grid Northing at grid origin	0.00
Scale factor at longitude of origin	0.9996
Vertical datum	LAT GEONZ97 (Noordzee)

5.3.2 Equipment accuracy

The performance and accuracies of the used equipment, as stated by the manufacturers are given in Table 5-3.

Table 5-3: Accuracy of survey equipment

Equipment	Accuracy and performance
Trimble SP855 RTK GNSS, with 06-GPS correction signal	Horizontal position error: <0.10 m Vertical position error: <0.10 m
Trimble Marine-star dGPS	Horizontal position error: <0.10 m Vertical position error: <0.15 m
IXBlue Octans III gyrocompass and motion sensor	Heading accuracy: 0.1 deg. secant latitude. Roll / Pitch accuracy: 0.01 deg. Resolution: 0.001 deg Heave accuracy = 0.05m or 5% (whichever is highest)
Kongsberg 350P USBL	Position accuracy: 0.5% of slant range
Navitronic SVP 14 sound velocity probe	Sound velocity resolution: 0.1 m/s. Sound velocity accuracy: ± 0.25 m/s. Depth accuracy: 0.10m ± 0.2% of measured depth.
R2Sonic 2024 broadband multibeam echosounder	Maximum opening angle: 140° Across track beamwidth: 0.5° Range resolution: 0.125 m
Geometrics G882 Magnetometer	Absolute accuracy: 0.1 nT throughout range Depth sensor accuracy: 0.25m
Edgetech 4200 side-scan sonar	Operational range: 150m @ 400 kHz, 75m @ 900 kHz Resolution across track: 300 kHz: 3.6 cm, 600 kHz: 1.8 cm Horizontal beam width: 0.46° @ 300 kHz, 0.28° @ 600 kHz
Innomar SES-2000	Range resolution: up to 0.05 m Beam width: @ 3 dB: ± 2° / footprint < 7 % of water depth for all frequencies

Equipment	Accuracy and performance
Geo-Source 200 LW Sparker	Vertical resolution: up to 0.2-0.3 m Depth penetration: up to 200-300 ms

5.4 Mobilisation

5.4.1 Warehouse test

Prior to the mobilization of the survey equipment, all equipment was tested in the Deep workshop to ensure that equipment and all cables were in working condition.

5.4.2 MV Seazip Surveyor

The multi-channel seismic equipment was installed and calibrated onboard the MV Seazip Surveyor from the 12th to the 14th of January 2015 in the port of IJmuiden.

5.4.2.1 Installation of equipment

The following procedures were performed during equipment installation.

- The available deck space was confirmed to be sufficient to accommodate the multi-channel seismic system;
- The equipment was loaded onto the vessel and secured sea tight;
- The Pulsed Power Supply (PPS) was installed in the dry space of the workshop;
- The acquisition laptops and Mini-trace recorder unit were installed in the survey room, and the coax and network cables were connected;
- The PPS and Mini-trace recorder unit were grounded electrically to the ship;
- The HV deck lead cable was connected between the PPS and the sparker unit;
- The multi-channel streamer was balanced with lead weights.

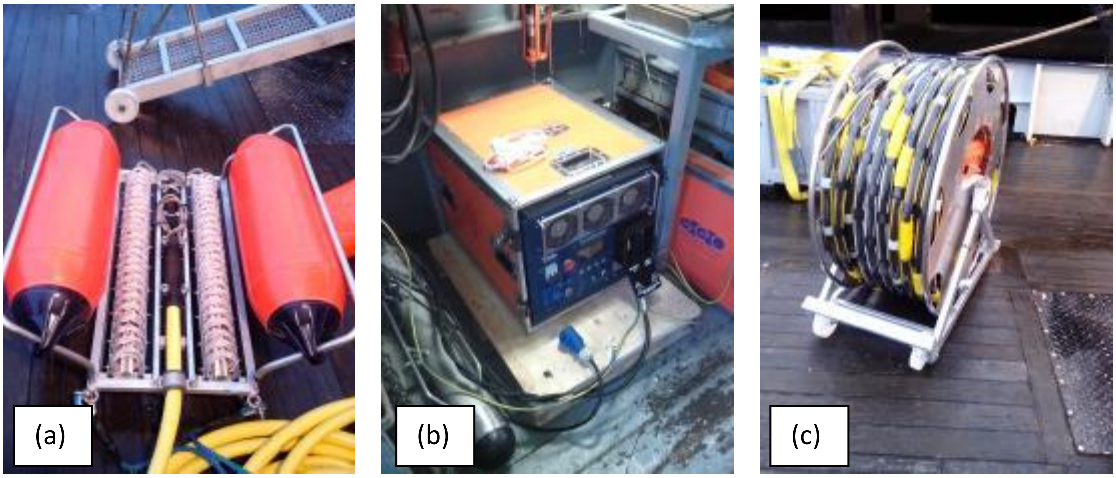


Figure 5-1: Installed multi-channel seismic survey equipment.
(a): the sparker unit installed on the deck,(b): the PPS installed in the workshop,(c): the multi-channel streamer with the lead weights attached on the winch on deck.

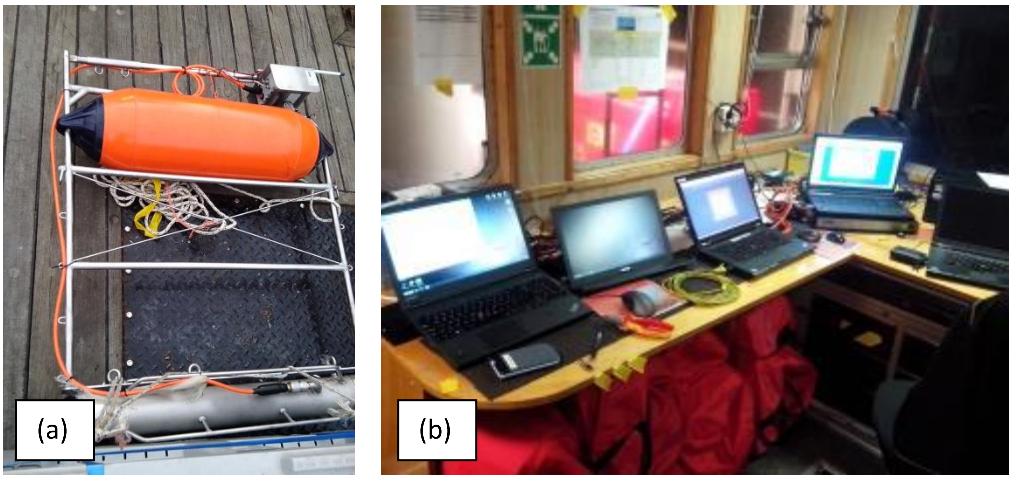


Figure 5-2: Installed multi-channel seismic survey equipment.
(a): the tail buoy of the streamer with AIS transponder, (b) the survey room with Minitrace recording unit and acquisition laptops.

5.4.2.2 Sensor offsets

The vessel geometry of MV Seazip Surveyor was measured using a measuring tape during mobilisation from the 12th to the 14th of January 2015. These measurements were made while the vessel was moored along the quay wall. The correctness of the measurements was confirmed by independently measuring each node twice and comparing the values for discrepancies. In Table 5-4 and Figure 5-3 the node offsets and the sign conventions are described.

Table 5-4: MV Seazip Surveyor vessel geometry offsets

Node	X[m] (+fwd)	Y[m] (+stbd)	Z[m] (+up)
CoG	0.000	0.000	0.000
RTK-GPS-antenna	-0.310	-3.590	3.647
Octans MRU	-1.760	-0.500	0.815
Quadrans MRU	-1.525	-0.570	0.800
Tow point sparker	2.450	-16.450	-1.000
Tow point streamer	6.310	-7.500	-1.800
Waterline SB	3.560	-3.590	-3.485

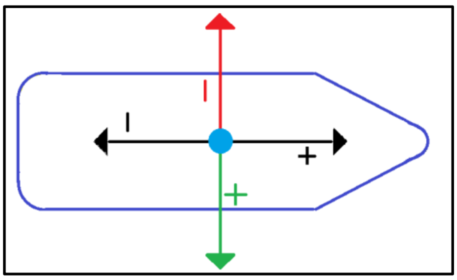


Figure 5-3: Node direction/sign convention

All multi-channel seismic equipment was deployed from the starboard side of the MV Seazip Surveyor vessel on a swinging boom (Figure 5-4).

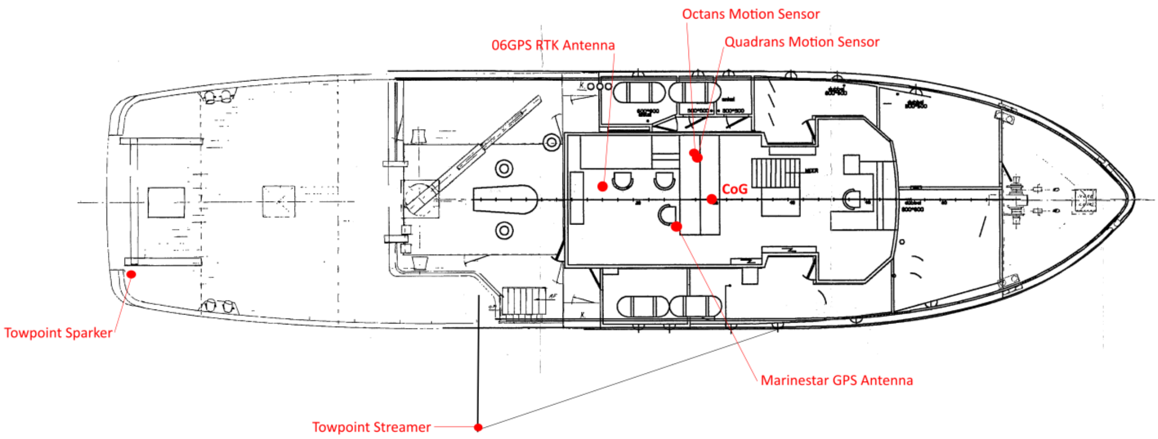


Figure 5-4: MV Seazip Surveyor vessel offset diagram

5.4.2.3 System configuration

The different survey systems were interfaced after installation. Figure 5-5 is a diagram of the interfacing of all the seismic survey equipment. The power supply for the Geo-Spark was separated from the power supply of the remaining survey equipment to avoid electrical interference. The raw data from the streamer was input into the Minitrace unit and consequently logged on both the GeoRecorder laptop and Processing Workstation.

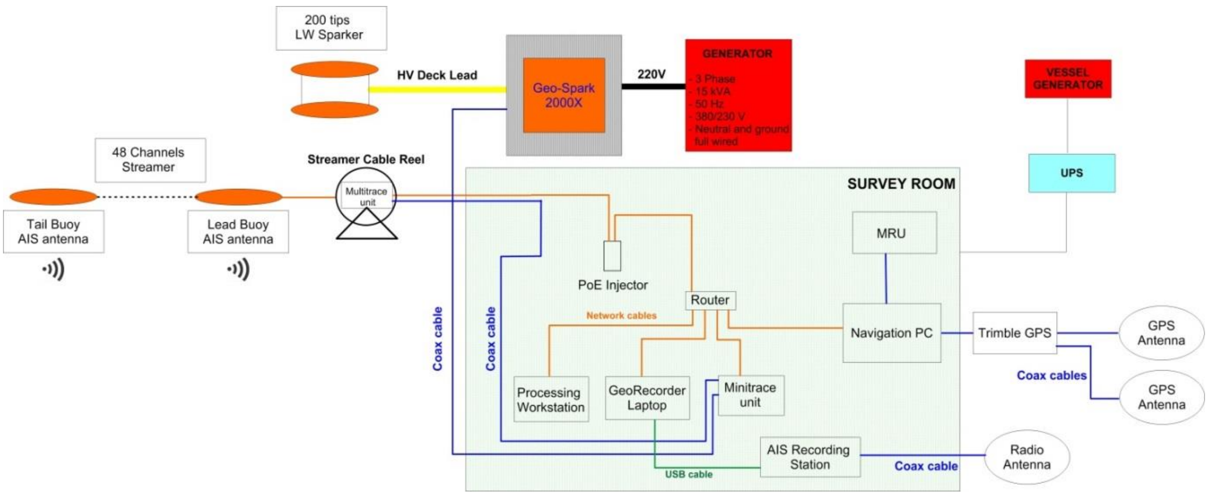


Figure 5-5: MCS survey system connection diagram

5.4.2.4 Equipment calibrations

The calibrations of the survey equipment on board MV Seazip Surveyor were carried out in the port of IJmuiden on the 14th of January 2015. The calibration report has been compiled and sent to the client during the geophysical survey (see Appendix D).

5.4.3 MV Breaker

Survey vessel MV Breaker was just commissioned by Deep BV before the start of this survey. The survey equipment needed for this survey was installed during the commissioning phase, after which calibration was carried out.

5.4.3.1 Installation of equipment

In

Table 5-5 the installation locations of the survey sensors are tabulated, with reference to Figure 5-6 and Figure 5-7.

Table 5-5: Overview locations survey equipment

Equipment	Position	Figure
Multibeam (2)	Portside moon pool	Figure 5-6 (a)
Motion sensor	Portside moon pool	Figure 5-6 (a)
Sound velocity sensor	Portside moonpool	Figure 5-6 (a)
USBL	Starboard moon pool	Figure 5-6 (b)
Innomar	Starboard moon pool	Figure 5-6 (b)
Top-units / computers	Survey room	Figure 5-7 (a)
Winch	Aft deck	Figure 5-6 (c)
Motion sensor	Deck (CoG)	Figure 5-6 (a)
GPS antennas	Mast	Figure 5-7 (b)

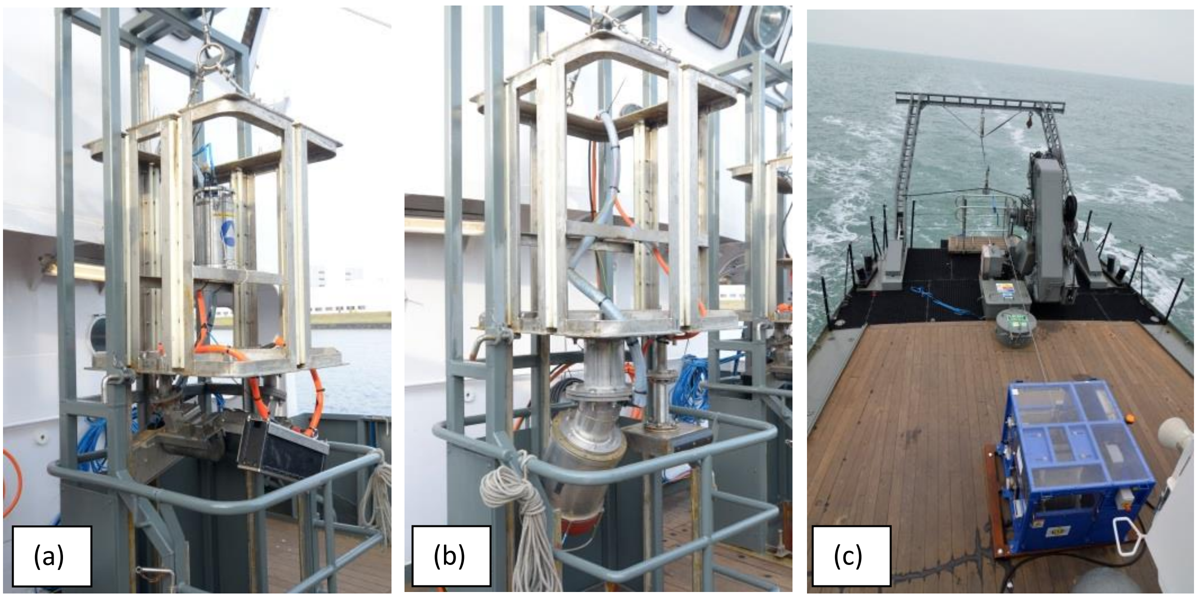
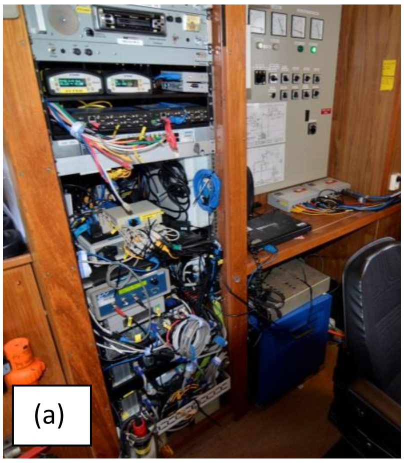


Figure 5-6: Pictures of installed survey equipment
(a): Moonpool portside, (b): Moonpool starboard side, (c): Aft deck



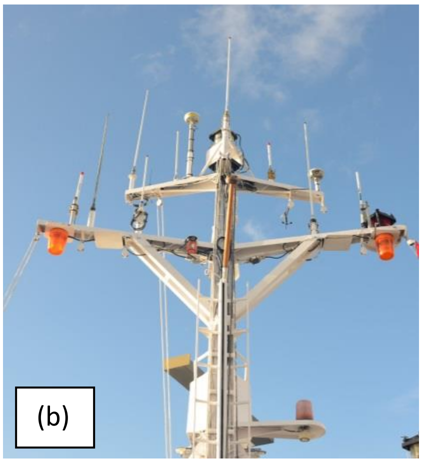


Figure 5-7: Pictures of installed survey equipment
(a): Survey room, (b): Mast

5.4.3.2 Sensor offsets

In Table 5-6 the offsets of the survey equipment are tabulated. The vessel geometry of MV Breaker was measured using land survey techniques while the vessel was moored motionless alongside the quay wall. A schematic overview of the locations of the survey equipment onboard the MV Breaker is provided in Figure 5-8.

Table 5-6: MV Breaker vessel geometry offsets

Node	X[m] (+fwd)	Y[m] (+stbd)	Z[m] (+up)
CoG	0.000	0.000	0.000
RTK-GPS-antenna	-0.271	3.135	12.217
Marinestar GPS Antenna	0.962	3.315	12.790
Octans MRU (Deck)	-0.595	6.584	-0.903
USBL Transducer	1.051	7.221	-2.830
Innomar SBP Transducer	0.742	7.503	-2.569
Moonpool CoG	-0.917	7.349	-1.684
Nodes relative to Node Moonpool CoG			
R2 Sonic Transducer PS	-0.027	0.083	-0.869
R2 Sonic Transducer SB	0.058	-0.072	-0.875
Octans MRU (Moonpool)	0.003	0.003	0.076

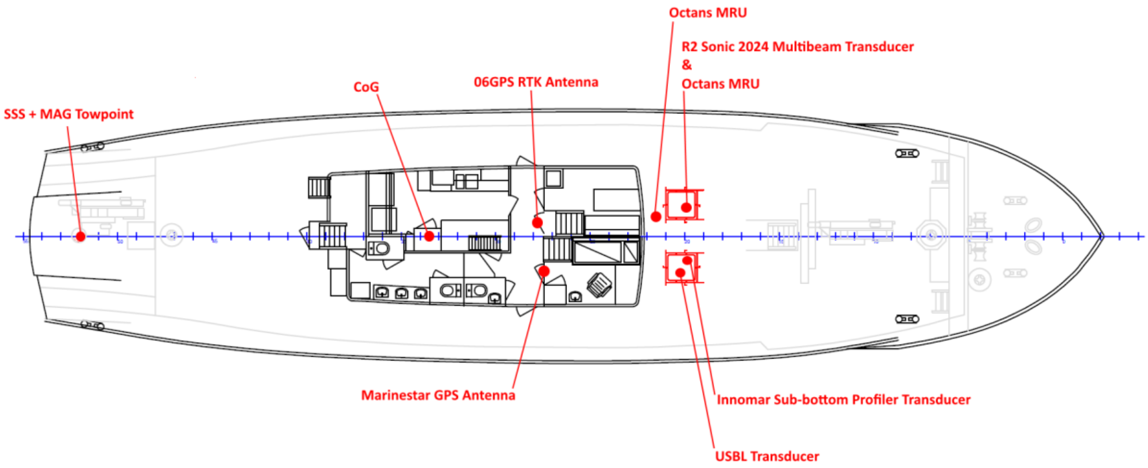


Figure 5-8: MV Breaker vessel offset diagram

5.4.3.3 Equipment calibrations

The calibrations of the survey equipment onboard MV Breaker were carried out between the 22nd and 25th of January 2015 in the Texelstroom near Den Helder and the port of IJmuiden. The calibration report has been compiled and sent to the client during the geophysical survey. It is added as Appendix D.

5.5 Execution of survey

This chapter describes the performance of the survey equipment during the execution of the surveys on board MV Seazip Surveyor and MV Breaker. Survey operations took place in a 24 hour regime for the offshore part of the project. Survey works started on 16th of January and ended on 15th of February.

5.5.1 Survey limitations

Survey limitations depended largely, but not exclusively, on wind, current, wave action, orientation of the survey lines and the amount of cable-out of the towed sensor. The limitation for the MV Seazip Surveyor seismic survey was a significant wave height of 1.25 meters. The limitation for MV Breaker surveys was a significant wave height of approximately 1.50 meters.

5.5.2 Daily Progress Reports

During the offshore execution of the survey Daily Progress Reports (DPR) were submitted daily, before 08:00 hrs the next day. They have been included in Appendix B. The DPR's included:

- Activities executed in the past 24 hours and cumulative to date described in all phases;
- Activities planned for the upcoming 24 hours;
- Any occurrence causing delay to the project, including but not limited to:
  - equipment downtime;
  - scheduled maintenance;
  - waiting on weather;

   - other standby.
- Daily observation and registration of weather and sea state;
- HSE occurrences such as incidents, accidents, near misses, safety meetings, safety stand downs, number of HSE observations, together with measures taken and status;
- Non-conformance reporting.

5.5.3 Weekly Progress Reports

The weekly progress reports provided progress data on the progress achieved during the reporting period based on a week cut-off date being each Sunday at 24:00 hrs. The reports were issued every Monday before close of business following the cut-off date. They have been included in Appendix C. The weekly progress report included the following subjects:

- Work in progress;
- Health Safety & Environment;
- Safety Statistics;
- Status summary work schedule, including weekly planning update;
- Forward looking information for the next two reporting periods;
- In case of deviations from the program: proposals for remedial action together with any revised plans and projections needed to substantiate or explain proposals;
- Status of queries / concession requests;
- Risk Log including areas of concern and actions taken to address them;
- Change control, including list of issued and Potential Variation Orders;
- Updated document register;
- Photographs of relevant achievements;
- Areas of concern.

5.5.4 Weather delay

The total weather delay (Waiting on Weather; WoW) for the survey of both survey areas for both vessels was 320 hours, or 13.3 days.

5.5.5 MCS survey (MV Seazip Surveyor)

The multi-channel seismic survey was carried out between the 18th of January 2015 and the 28th of January 2015. The survey lines were sailed with a line spacing of 400 meters in the alongside SW-NE direction and cross-lines every 2000 meters in the NW-SE direction. In some areas where interesting geological features were observed during the survey the cross-line pattern was intensified to survey lines every 200 meter. See Figure 5-9 for a graphic overview of sailed survey lines for the MCS survey with the MV Seazip Surveyor. Table 5-7 shows an overview of all sailed lines for both vessels.

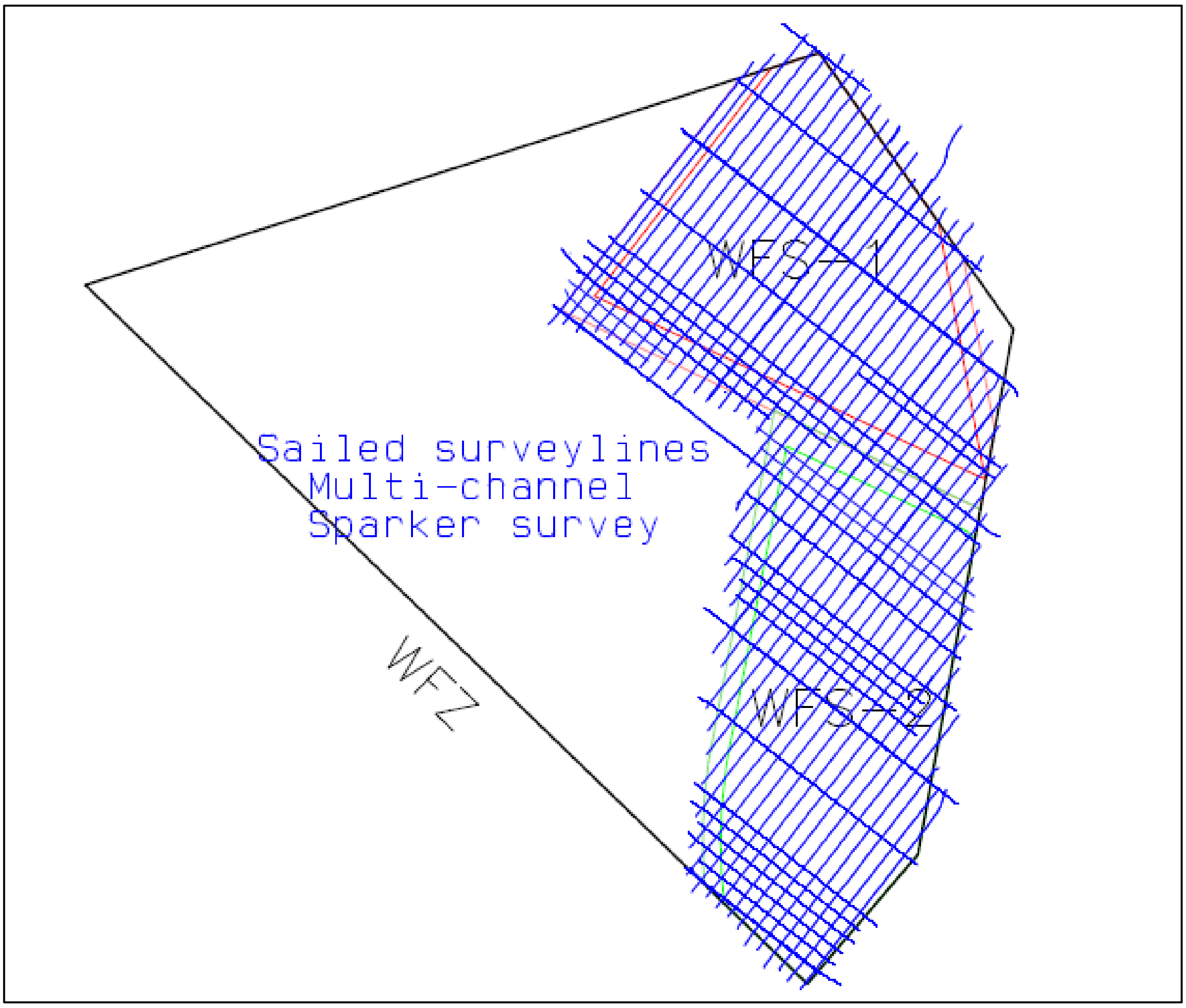


Figure 5-9: Graphic overview of sailed lines MCS

Table 5-7: Sailed survey lines overview

No.	Line Name	Survey vessel		No.	Line Name	Survey vessel	
		MV Breaker	MV Seazip Surveyor			MV Breaker	MV Seazip Surveyor
1	1-100	x	x	100	100-10000	x	x
2	2-200	x		101	101-10100	x	
3	3-300	x		102	102-10200	x	
4	4-400	x	x	103	103-10300	x	
5	5-500	x		104	104-10400	x	x
6	6-600	x		105	105-10500	x	
7	7-700	x		106	106-10600	x	
8	8-800	x	x	107	107-10700	x	
9	9-900	x		108	108-10800	x	x
10	10-1000	x		109	109-10900	x	
11	11-1100	x		110	110-11000	x	
12	12-1200	x	x	111	111-11100	x	
13	13-1300	x		112	112-11200	x	x
14	14-1400	x		113	113-11300	x	
15	15-1500	x		114	114-11400	x	
16	16-1600	x	x	115	115-11500	x	

No.	Line Name	Survey vessel		No.	Line Name	Survey vessel	
		MV Breaker	MV Seazip Surveyor			MV Breaker	MV Seazip Surveyor
17	17-1700	x		116	116-11600	x	x
18	18-1800	x		117	117-11700	x	
19	19-1900	x		118	118-11800	x	
20	20-2000	x	x	119	119-11900	x	
21	21-2100	x		120	120-12000	x	x
22	22-2200	x		121	121-12100	x	
23	23-2300	x		122	122-12200	x	
24	24-2400	x	x	123	123-12300	x	
25	25-2500	x		124	124-12400	x	x
26	26-2600	x		125	125-12500	x	
27	27-2700	x		126	126-12600	x	
28	28-2800	x	x	127	127-12700	x	
29	29-2900	x		128	128-12800	x	x
30	30-3000	x		129	129-12900	x	
31	31-3100	x		130	130-13000	x	
32	32-3200	x	x	131	131-13100	x	
33	33-3300	x		132	132-13200	x	x
34	34-3400	x		133	133-13300	x	
35	35-3500	x		134	134-13400	x	
36	36-3600	x	x	135	135-13500	x	
37	37-3700	x		136	136-13600	x	x
38	38-3800	x		137	137-13700	x	
39	39-3900	x		138	138-13800	x	
40	40-4000	x	x	139	139-13900	x	
25	25-2500	x		124	124-12400	x	x
26	26-2600	x		125	125-12500	x	
27	27-2700	x		126	126-12600	x	
28	28-2800	x	x	127	127-12700	x	
29	29-2900	x		128	128-12800	x	x
30	30-3000	x		129	129-12900	x	
31	31-3100	x		130	130-13000	x	
32	32-3200	x	x	131	131-13100	x	
33	33-3300	x		132	132-13200	x	x
34	34-3400	x		133	133-13300	x	
35	35-3500	x		134	134-13400	x	
36	36-3600	x	x	135	135-13500	x	
37	37-3700	x		136	136-13600	x	x
38	38-3800	x		137	137-13700	x	
39	39-3900	x		138	138-13800	x	
40	40-4000	x	x	139	139-13900	x	
41	41-4100	x		140	140-14000	x	x
42	42-4200	x		141	141-14100	x	
43	43-4300	x		142	142-14200	x	
44	44-4400	x	x	143	143-14300	x	
45	45-4500	x		144	144-14400	x	x
46	46-4600	x		145	145-14500	x	
47	47-4700	x		146	146-14600	x	
48	48-4800	x	x	147	147-14700	x	
49	49-4900	x		148	148-14800	x	x
50	50-5000	x		149	149-14900	x	
51	51-5100	x		150	150-15000	x	
52	52-5200	x	x	151	151-15100	x	

No.	Line Name	Survey vessel		No.	Line Name	Survey vessel	
		MV Breaker	MV Seazip Surveyor			MV Breaker	MV Seazip Surveyor
53	53-5300	x		152	152-15200	x	x
54	54-5400	x		153	153-15300	x	
55	55-5500	x		154	154-15400	x	
56	56-5600	x	x	155	155-15500	x	
57	57-5700	x		156	156-15600	x	x
58	58-5800	x		157	157-15700	x	
59	59-5900	x		158	158-15800	x	
60	60-6000	x	x	159	159-15900	x	
61	61-6100	x		160	160-16000	x	x
62	62-6200	x		161	161-16100	x	
63	63-6300	x		162	162-16200	x	
64	64-6400	x	x	163	163-16300	x	
65	65-6500	x		164	164-16400	x	x
66	66-6600	x		165	165-16500	x	
67	67-6700	x		166	166-16600	x	
68	68-6800	x	x	167	167-16700	x	
69	69-6900	x		168	168-16800	x	x
70	70-7000	x		169	169-16900	x	
48	48-4800	x	x	147	147-14700	x	
49	49-4900	x		148	148-14800	x	x
50	50-5000	x		149	149-14900	x	
51	51-5100	x		150	150-15000	x	
52	52-5200	x	x	151	151-15100	x	
53	53-5300	x		152	152-15200	x	x
54	54-5400	x		153	153-15300	x	
55	55-5500	x		154	154-15400	x	
56	56-5600	x	x	155	155-15500	x	
57	57-5700	x		156	156-15600	x	x
58	58-5800	x		157	157-15700	x	
59	59-5900	x		158	158-15800	x	
60	60-6000	x	x	159	159-15900	x	
61	61-6100	x		160	160-16000	x	x
62	62-6200	x		161	161-16100	x	
63	63-6300	x		162	162-16200	x	
64	64-6400	x	x	163	163-16300	x	
65	65-6500	x		164	164-16400	x	x
66	66-6600	x		165	165-16500	x	
67	67-6700	x		166	166-16600	x	
68	68-6800	x	x	167	167-16700	x	
69	69-6900	x		168	168-16800	x	x
70	70-7000	x		169	169-16900	x	
71	71-7100	x		170	170-17000	x	
72	72-7200	x	x	171	171-17100	x	
73	73-7300	x		172	172-x-0		x
74	74-7400	x		173	173-x-2000	x	x
75	75-7500	x		174	174-x-4000		x
76	76-7600	x	x	175	175-x-6000	x	x
77	77-7700	x		176	175-x-6000_2		x
78	78-7800	x		177	176-x-8000		x
79	79-7900	x		178	178-x-10000	x	x
80	80-8000	x	x	179	179-x-12000	x	x
81	81-8100	x		180	180-x-14000	x	x

No.	Line Name	Survey vessel		No.	Line Name	Survey vessel	
		MV Breaker	MV Seazip Surveyor			MV Breaker	MV Seazip Surveyor
82	82-8200	x		181	181-x-16000_3		x
83	83-8300	x		182	182-x-18000	x	x
84	84-8400	x	x	183	183-x-20000	x	x
85	85-8500	x		184	x-in1000_2_a2		x
67	67-6700	x		166	166-16600	x	
68	68-6800	x	x	167	167-16700	x	
69	69-6900	x		168	168-16800	x	x
70	70-7000	x		169	169-16900	x	
71	71-7100	x		170	170-17000	x	
72	72-7200	x	x	171	171-17100	x	
73	73-7300	x		172	172-x-0		x
74	74-7400	x		173	173-x-2000	x	x
75	75-7500	x		174	174-x-4000		x
76	76-7600	x	x	175	175-x-6000	x	x
77	77-7700	x		176	175-x-6000_2		x
78	78-7800	x		177	176-x-8000		x
79	79-7900	x		178	178-x-10000	x	x
80	80-8000	x	x	179	179-x-12000	x	x
81	81-8100	x		180	180-x-14000	x	x
82	82-8200	x		181	181-x-16000_3		x
83	83-8300	x		182	182-x-18000	x	x
84	84-8400	x	x	183	183-x-20000	x	x
85	85-8500	x		184	x-in1000_2_a2		x
86	86-8600	x		185	x-in1200_2_a2		x
87	87-8700	x		186	x-in1600_a2		x
88	88-8800	x	x	187	x-in400-a2		x
89	89-8900	x		188	x-in800_2		x
90	90-9000	x		189	x-in800_a2		x
91	91-9100	x		190	x-inline1200		x
92	92-9200	x	x	191	x-inline1600b		x
93	93-9300	x		192	x-inline2800		x
94	94-9400	x		193	x-inline3200		x
95	95-9500	x		194	x-inline8400		x
96	96-9600	x	x	195	x-inline8800_2		x
97	97-9700	x		196	x-inline9200_2		x
98	98-9800	x		197	x-inline9600_2		x
99	99-9900	x					

5.5.5.1 Acquisition geometry

During the survey the Geo-Sense multi-channel streamer was deployed from a boom on the starboard side of the MV Seazip Surveyor. The Geo Spark source unit was deployed from the starboard aft corner of the ship. The source unit was towed 33 meters behind the stern; the first element of the streamer unit was deployed next to it, with the other elements further behind, with a total length of the active part of the streamer of 75 meters. In Figure 5-10 a schematic overview of the acquisition geometry is provided.

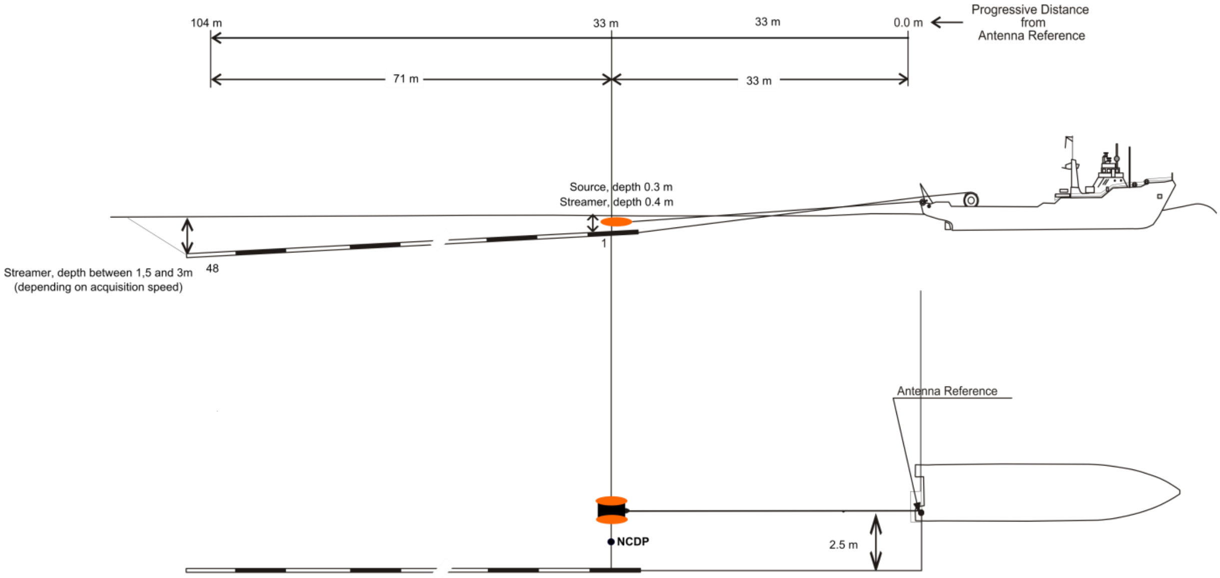


Figure 5-10: The geometry of the multi-channel seismic system during survey

5.5.5.2 Acquisition parameters

During data acquisition the source fired a seismic pulse every one meter, based on the displacement observed by the vessels GPS and recorded within the QINSy survey software. The further acquisition parameters are shown in Table 5-8.

Table 5-8: Multi-channel seismic acquisition parameters

Parameter	Value
Source Towing Depth	0.3 m
Source Deck Lead	33 m
Spark Interval	1 m
Operating Power	400 J
Sample Rate	0.1 msec
Record Length	300 msec

5.5.5.3 Feathering

The deviation of the towed receiver cables from a straight line-astern a survey vessel is known as feathering. Feathering is generally caused by currents, and impacts the homogeneous fold coverage of the recorded seismic data, particularly at far offsets. Ideally, the distance between the source and streamer is constant, but in practice this is difficult to achieve and disturbance can occur (Figure 5-11).

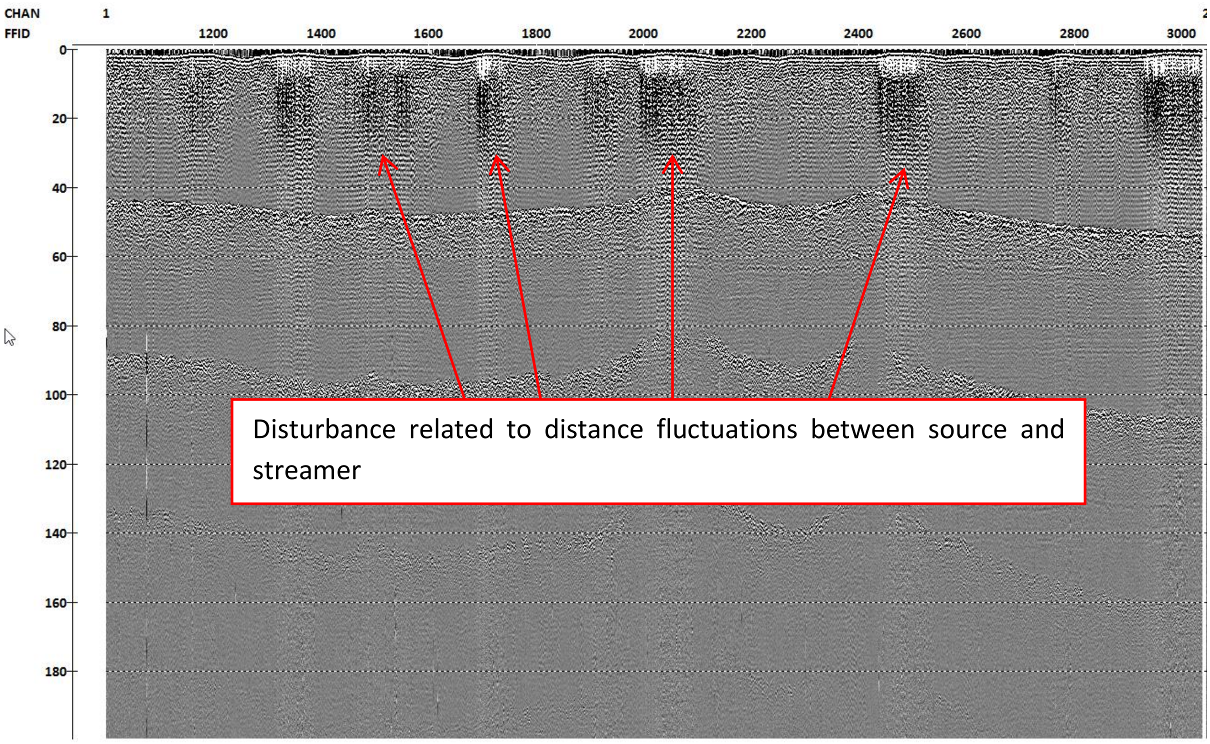


Figure 5-11: Data example of seismic data with feathering disturbance

During the survey the feathering variations were computed from the positions of the two AIS transponders from the respective lead and tail buoy attached to the streamer. The recorded feathering distance is used during processing. Figure 5-12 is a screen-dump plot of the feathering distance recorded during the multi-channel seismic survey. During processing, the feathering distance information is used for data improvement.

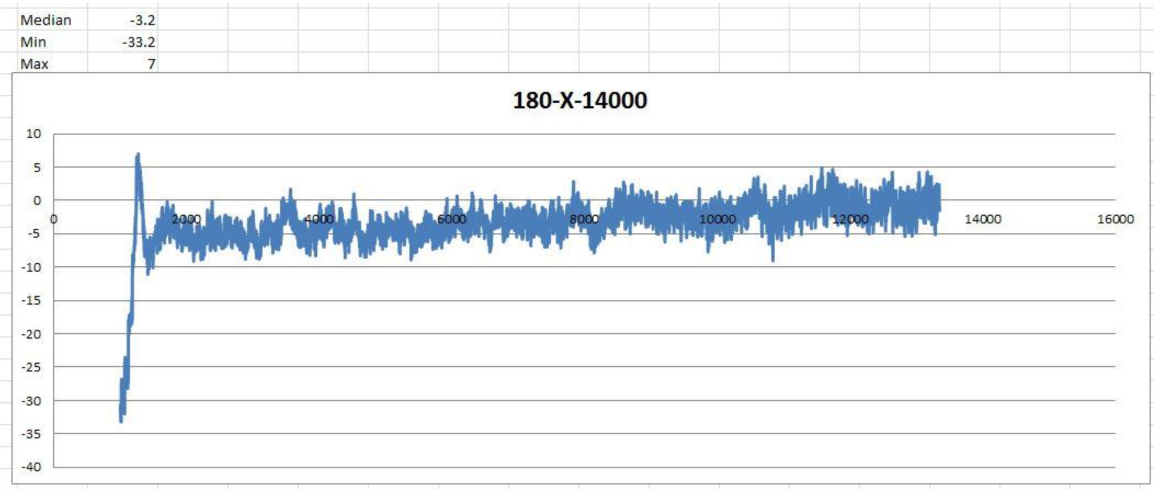


Figure 5-12: Plot of feathering distance recorded during the multi-channel survey

5.5.5.4 Online QC

All the acquired lines have been gone through a QC validation, which consisted of validation of correct navigation input, streamer feathering analysis along the line and assurance that all acquisition parameters were correct (trigger, record length, sampling interval, etc.). A regular assessment was made of the trigger regularity, missed shots, noisy channels and any other anomalies. All irregularities were logged in the operator log.

5.5.5.5 Offline QC

The seismic survey data was quality checked directly after recording to determine the common-depth-point fold statistics. These statistics were used to calculate near real-time brute stacks. Figure 5-13 is a screen-dump of a brute stack line with CDP fold information displayed.

Additionally, the coverage of the seismic profile lines was checked in QINSy to ensure that it complied with the original survey plan. The brute stack profiles were imported in Kingdom Suite software to assess whether the penetration depth and resolution was meeting the requirements. This was found to be in order.

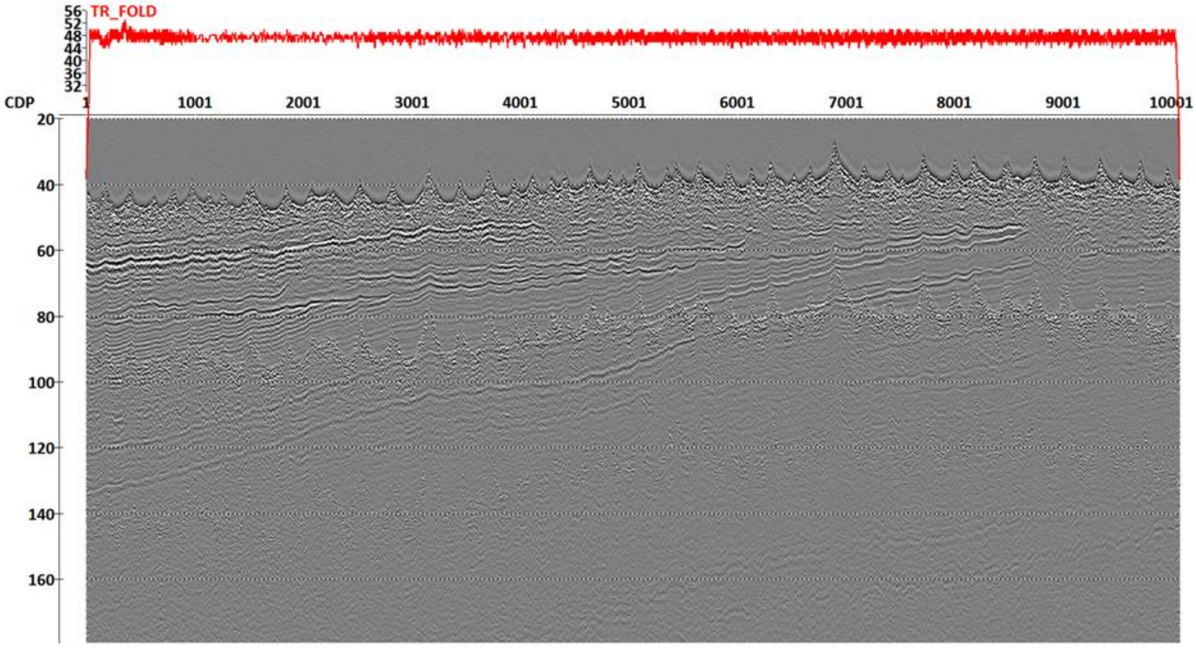


Figure 5-13: Brute stack line with CDP fold information displayed on top

5.5.5.6 Demobilisation MV Seazip Surveyor

On the 28th of January 2015, when the seismic survey was finished and approved by the Party Chief and client representative, the MV Seazip Surveyor was demobilised in the port of Vlissingen.

5.5.6 MBE, MAG, SSS and SBP survey (MV Breaker)

The survey with MV Breaker was carried out between the 26th of January 2015 and the 15th of February 2015. The survey lines were sailed at 100 meters interval. Additionally, three cross lines were sailed in WFS-2 with a spacing of 4000 meters. Around the known wrecks and detected large magnetic anomalies additional lines were recorded. See also Table 5-7 for an overview of sailed lines.

5.5.6.1 MBE survey

The acquisition of high resolution bathymetric data was carried out using two R2sonic 2024 multibeam echosounders, mounted in the portside moonpool. A sound velocity profile was taken with a Valeport MiniSVP sound velocity probe at the beginning and end of each survey period and if a considerable distance was travelled between different survey areas. A sound velocity profile was recorded at half meter intervals. The water column was sampled to the maximum practically possible depth. The SVP profiles were entered in the survey software.

5.5.6.2 SSS survey

The acquisition of high resolution side-scan data was carried out using an Edgetech 4200 side scan sonar system, deployed from the A-frame on the aft of MV Breaker. The Edgetech 4200 operated at 300 kHz and 600 kHz simultaneously. It was made sure that at least 100% data coverage was achieved, as well as double coverage of the data gap at nadir by adjacent lines by using a 125m range in combination with 100m survey line spacing. The system was towed between 10-19 m above the seabed during the entire survey. Data was acquired to IHO S-44 Order 1 standard, which includes the identification of all objects greater than 2.0m x 2.0m dimensions.

5.5.6.3 MAG survey

Acquisition of high resolution magnetometer data was carried out using a Geometrics G882 magnetometer system. The magnetometer towfish was towed at a distance of approximately 20 meters behind the Edgetech side-scan sonar towfish at 7-13 m above the seabed. The magnetometer was presented online in a graph that shows the ambient magnetic field in nT.
It has to be noted that due to the 100 meter line spacing the MAG survey is not suitable for UXO detection.

5.5.6.4 SBP survey

Acquisition of high resolution sub-bottom profiler data was carried out using an Innomar SES 2000 standard, mounted in the starboard moonpool. The system was operated at 6kHz, with dual pulse. The system was triggered alternating with the R2Sonic MBE system, to avoid interference between both systems.

5.5.6.5 Online QC

During the survey operations, continuous QC was taking place (Figure 5-14). This included monitoring status and/or quality indicators of the individual systems. Automated alerts were used when a status- or quality indicator of one of the sensors was out of the specified range. The specific alerts for all survey systems were as follows:

- Multibeam echosounder:
    - Monitoring of data coverage;
    - Monitoring of 95% confidence level;
    - Monitoring of overlapping data between adjacent survey lines;

- Continuous monitoring of sound velocity near the MBE transducer head with mini SVP profiler.
- Side-scan sonar:
    - Monitoring of data coverage;
    - Monitoring of overlapping data between adjacent survey lines.
- Magnetometer:
    - The magnetometer was presented online in a graph that shows the ambient magnetic field in nanotesla (nT). From the online graph, the following online QC was performed:
    - Visual inspection of the presence of noise;
    - Monitoring of the standard deviation (SD) of the recorded magnetic field.
- Sub-bottom profiler:
    - Online QC of the parametric echosounder survey was achieved by continuously monitoring the online data. The Signal to Noise ratio (SNR) is of importance here, as this is directly related to the quality of the recorded data. The SNR was monitored online in two ways:
    - Monitoring of the amount of noise present in the water column;
    - Monitoring of the wiggle window, which shows the intensity of the returned signal. An increase of noise in the data will show itself by the wiggle having a more irregular shape and more erratic movements, as opposed to a smooth shape and movement when the SNR is good.

Figure 5-14: Online QC in action on board MV Breaker

5.5.6.6 Offline QC

During the survey operations, offline QC was carried out to check the recorded data for inconsistencies that might have been missed during online acquisition. This included checking if the data quality and results were according to project specifications. When data quality or results were not meeting project specifications, additional survey lines were sailed. Preliminary data interpretation was done to confirm cable and wreck positions.

5.5.6.7 Contact positioning accuracy

In this section the achieved contact detection position accuracy of the SSS, MAG and SBP survey systems is summarised. In order to achieve this position errors are calculated by defining potential maximum position error in X, Y and Z directions and calculating the 1 sigma value. The position accuracies for the SSS, MAG and SBP surveys are tabulated in Table 5-9, Table 5-10 and Table 5-11, respectively.

Table 5-9: Potential maximum positioning contact detection error SSS survey

SSS survey		**Accuracy sigma 1 [m]**
Item	*Remarks*	*X, Y*
GPS Positioning system		0.05
Vessel geometry		0.01
USBL position (maximum sound velocity error between 1450 and 1500 m/s)	Average distance vessel-towfish 90 meters	3.10
SSS range position error (maximum sound velocity error between 1450 and 1500 m/s)	At 100 m range	3.30
Towfish heading (assumed error 0.1°)	Course over ground filtered	0.17
Click accuracy contacts in processing software		0.10
	Total static performance (m) *	4.53

** Position error only valid in direction along survey line*

Table 5-10: Potential maximum positioning contact detection error MAG survey

MAG survey		**Accuracy sigma 1 [m]**
Item	*Remarks*	*X, Y*
GPS Positioning system		0.05
Vessel geometry		0.01
USBL position (maximum sound velocity error between 1450 and 1500 m/s)	Average distance vessel-towfish 110 meters	3.70
Click accuracy contacts in processing software		0.10
	Total static performance (m)	3.70

Table 5-11: Potential maximum positioning contact detection error SBPE survey

SBP survey		**Accuracy sigma 1 [m]**	
Item	*Remarks*	*X, Y*	*Z*
Seabed depth accuracy (from MBE)	Total accuracy only	0.05	0.10
Positioning system		0.05	0.05
Vessel geometry		0.01	0.01
Resolution low frequency signal (5kHz)		N/A	0.16
Propagation velocity in sediments variance between 1620 - 1720 m/s*	Target at 5m depth	N/A	0.29
Click accuracy hyperbolas in processing software**		0.10	0.05
Click accuracy seabed in processing software		N/A	0.00
	Total static performance (m)	0.12	0.35

** DOB determined relative to seabed i.e. sound velocity in water only used in seabed accuracy*

*** The errors introduced by the fact how well the hyperbolas are visible in the surrounding seabed cannot be measured and are not part of this calculation.*

5.5.6.8 Demobilisation MV Breaker

After approval of the Party Chief and client representative, the survey operations with MV Breaker were finished on the 15th of February 2015, after which the vessel returned to the port of Vlissingen and the data was transferred to the office of Deep BV for processing and validation. Demobilisation took place in Ijmuiden on the 17th of February 2015.

6 PROCESSING METHOD

In this chapter the processing of the recorded survey data is described. The procedures carried out to check the quality of the acquired data, as well as the steps to derive to a final product are summarized for each survey system.

6.1 MBE processing

An overview of the MBE processing flow is provided in Figure 6-1. The processing flow is divided in two processing lines, one for bathymetry processing and one for the backscatter processing.

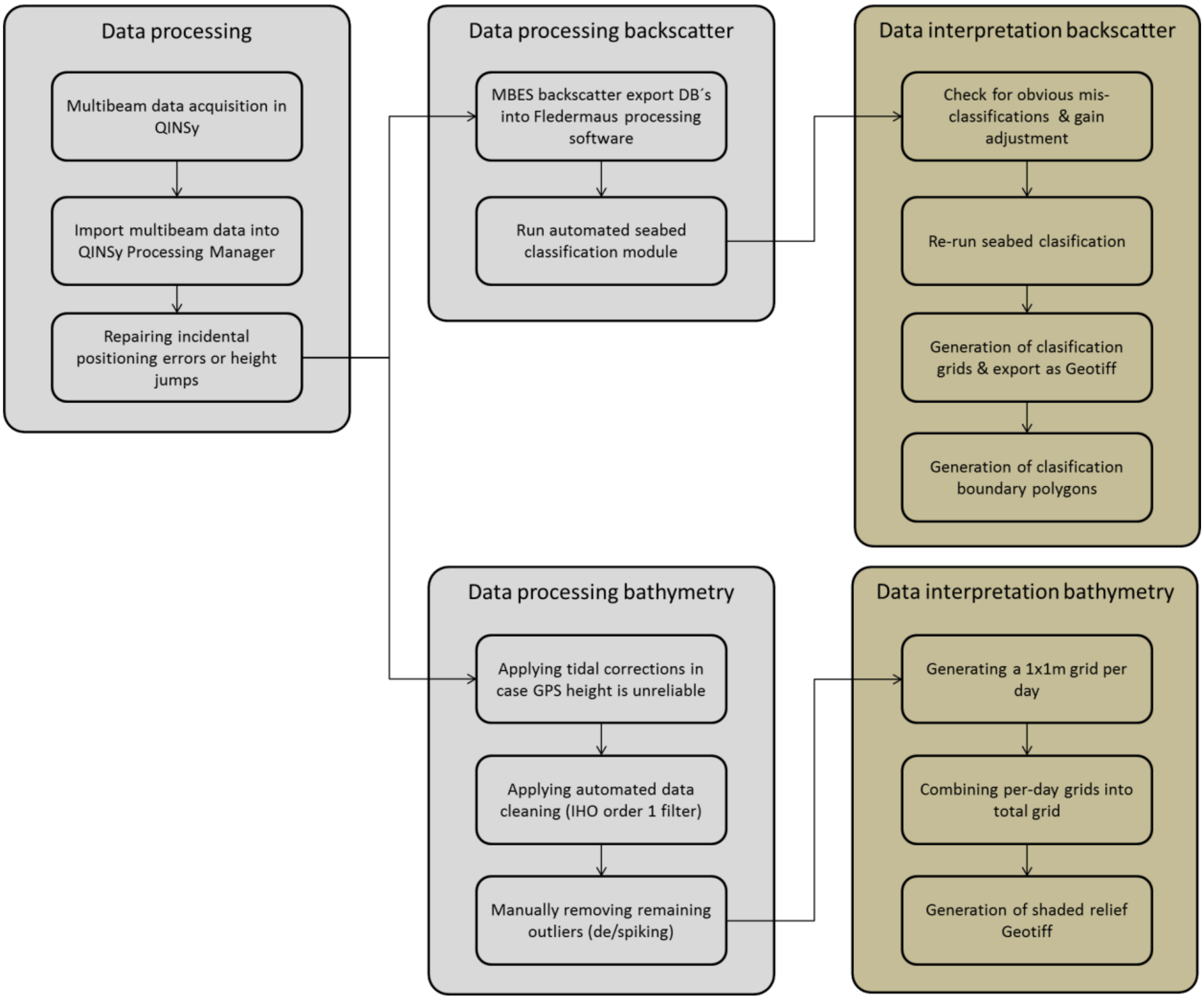


Figure 6-1: MBE processing flowchart

6.1.1 Data processing

The MBE data from the R2Sonic 2024 was recorded in QINSy 8.10 as DB and QPD files. Errors related to tidal level or sound velocity were checked during and straight after acquisition on board to be able to re-run a survey line, if needed. Back in the office the MBE data was checked for positioning errors and beam spikes using QPS Qloud editing software. Subsequently, the data was filtered according to the order 1a set by IHO (International Hydrographic Organization 2008).

The overall bathymetric data quality and consistency was excellent which is shown by the results of the various performed tests and regular checks. The overlapping survey lines were checked for relative height differences. No significant errors were found.

Compliance with the IHO S-44 order 1a was achieved. The uncertainties belonging to this quality standard are depth dependent. If an average water depth of 25m is chosen, the calculated THU (Total Horizontal Uncertainty) at 95% confidence level is 6.25m. The TVU (Total Vertical Uncertainty) at 95% confidence level is 0.59m. S-44 order 1a compliance at 25m depth for the dual head MBE setup on the MV Breaker was calculated and checked using the AMUST tool by Rijkswaterstaat.

In Figure 6-2, the calculated THU in a dual head setup as on the MV Breaker shows that the THU values fall well within the maximum allowable THU for order 1a. The figure shows the cumulative THU effect taking into account all relevant sensors and their respective accuracies. The Y-axis shows the horizontal uncertainty in meters. The X-axis shows both the scan sector (Theta) in degrees and the corresponding cross track distance in meters. During the survey, the maximum combined sector used was 140 degrees (70 degrees per head).

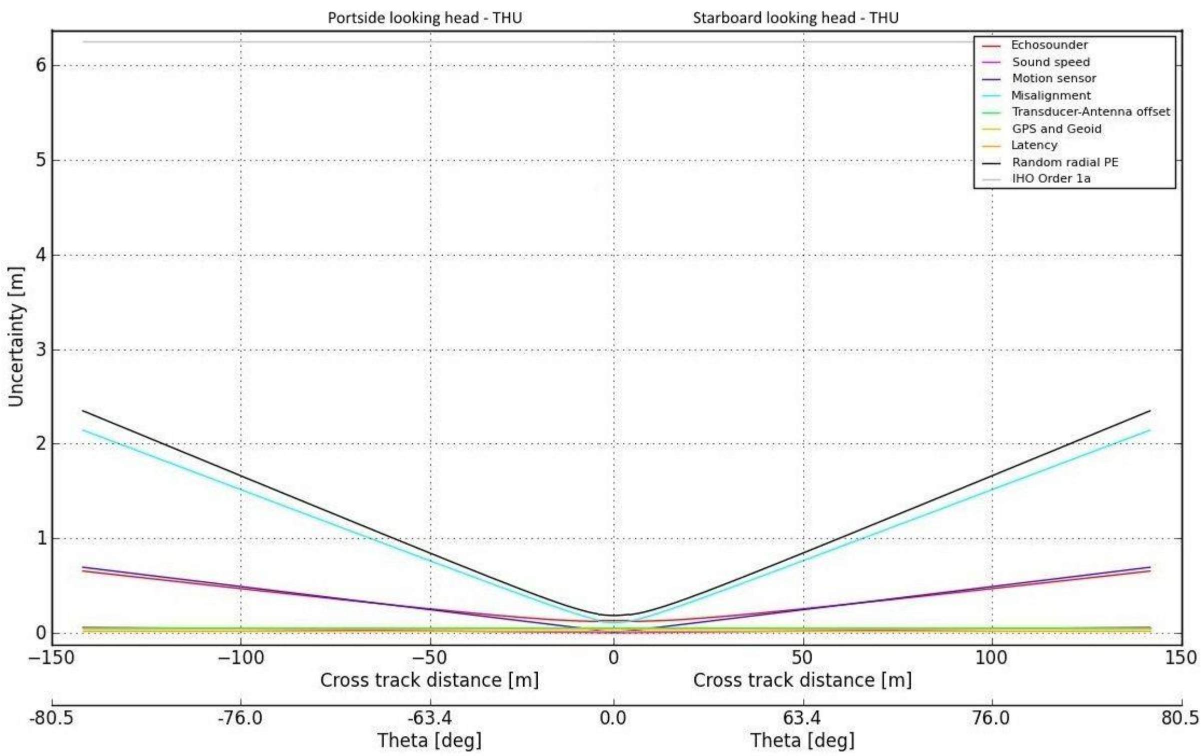


Figure 6-2: Dual head MBE THU

In Figure 6-3, the calculated TVU in a dual head setup as on the MV Breaker shows that the TVU values fall well within the maximum allowable TVU for order 1a. The figure shows the cumulative TVU effect taking into account all relevant sensors and their respective accuracies. The Y-axis shows the vertical uncertainty in meters. The X-axis shows both the scan sector (Theta) in degrees and the corresponding cross track distance in meters. Again, the maximum combined sector used was 140 degrees (70 degrees per head).

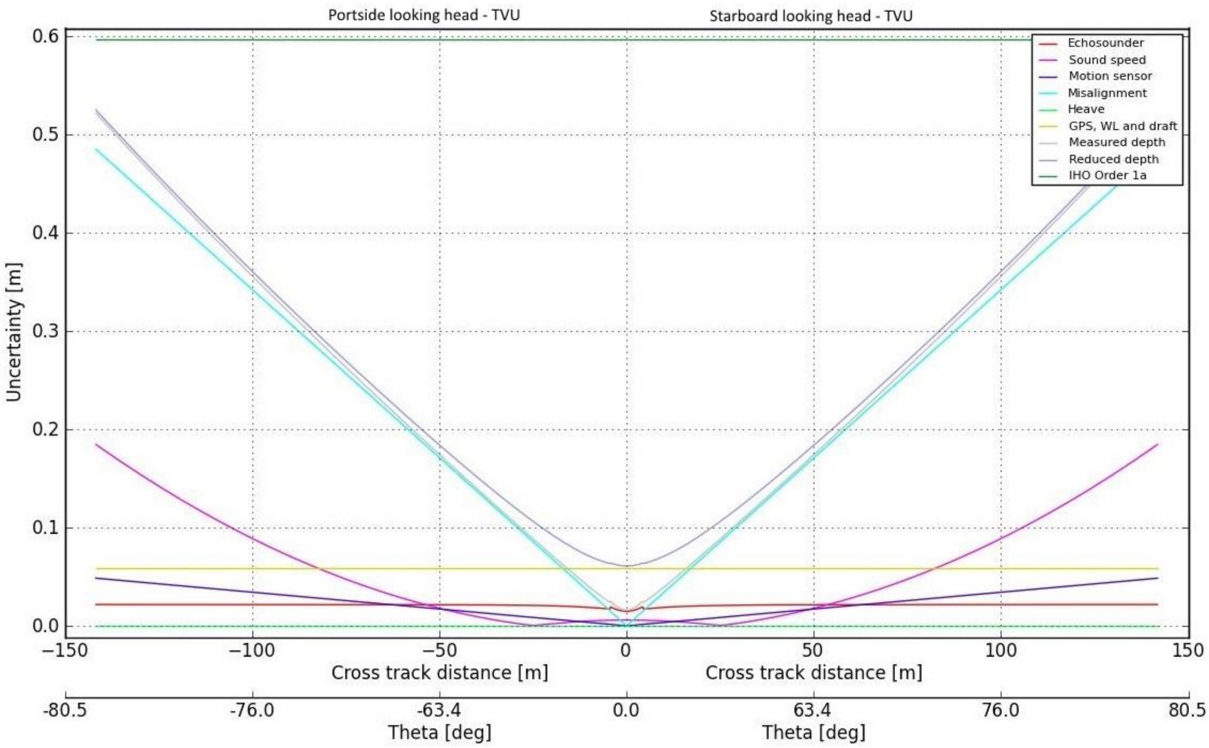


Figure 6-3: Dual head MBE TVU

Outliers in the data, often referred to as ‘spikes’, could be adequately removed using the filtering techniques available in this software module. See Figure 6-4 below: the red dots represent spikes that have been removed from the original dataset after filtering.

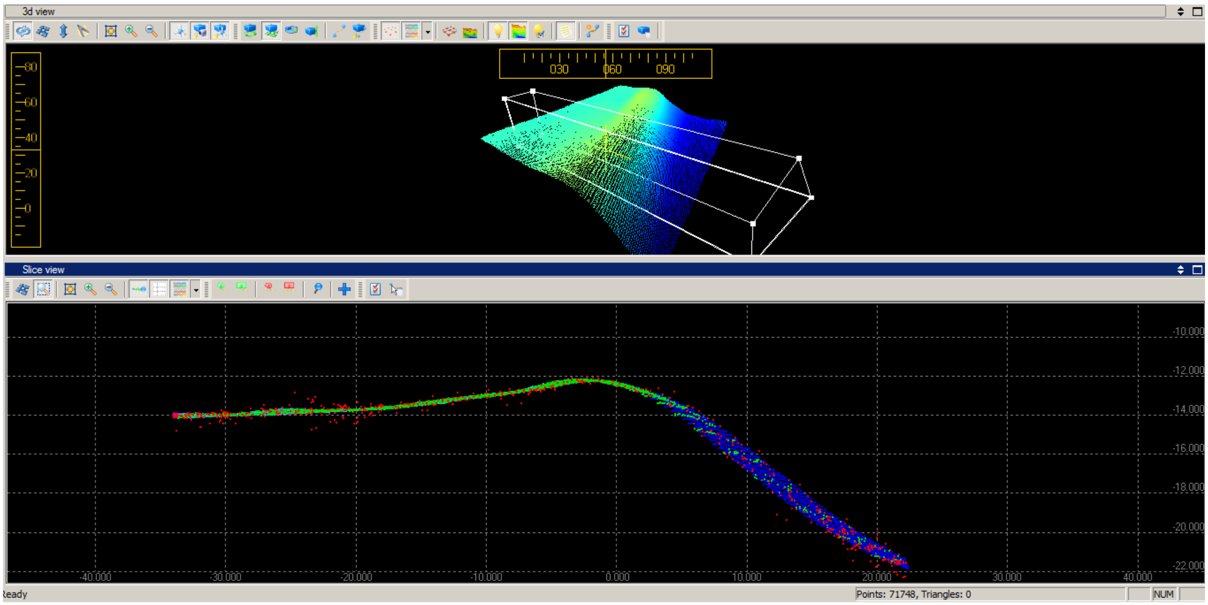


Figure 6-4: Processing of MBE data in Qloud software

The checked and despiked DB's were imported into Fledermaus Geocoder Toolbox (FMGT) processing software for automated soil classification using the backscatter data. The R2Sonic multibeam data has embedded backscatter data for these applications.

6.1.2 Bathymetry data interpretation

When all checks were completed, a gridded Digital Terrain Model (DTM) was created with a 1x1 meter grid cell size. These ASCII formatted XYZ files for each survey area were used as a basis for further analysis. Additionally, a 1x1m grid resolution Geotiff with shaded relief was created for charting and visualization purposes.
Bedform zonation for this study was performed in ArcGis software and based on a manual interpretation of the bathymetric grid (spacing 2m) and various derivatives (see **Error! Reference source not found.**). A Standardized Bathymetric Position Index (SBPI) (Wright et al. 2012) grid with a scale factor of 200m was calculated and reclassified to emphasize large scale sand dune crests and support manual demarcation of homogeneous areas in terms of dune spacing and crest line orientation. For each zone and only if statistical quantification was meaningful, the average dune spacing and height was sampled at representative locations. In addition, the dominant aspect for each area was determined using a zonal histogram GIS analysis.

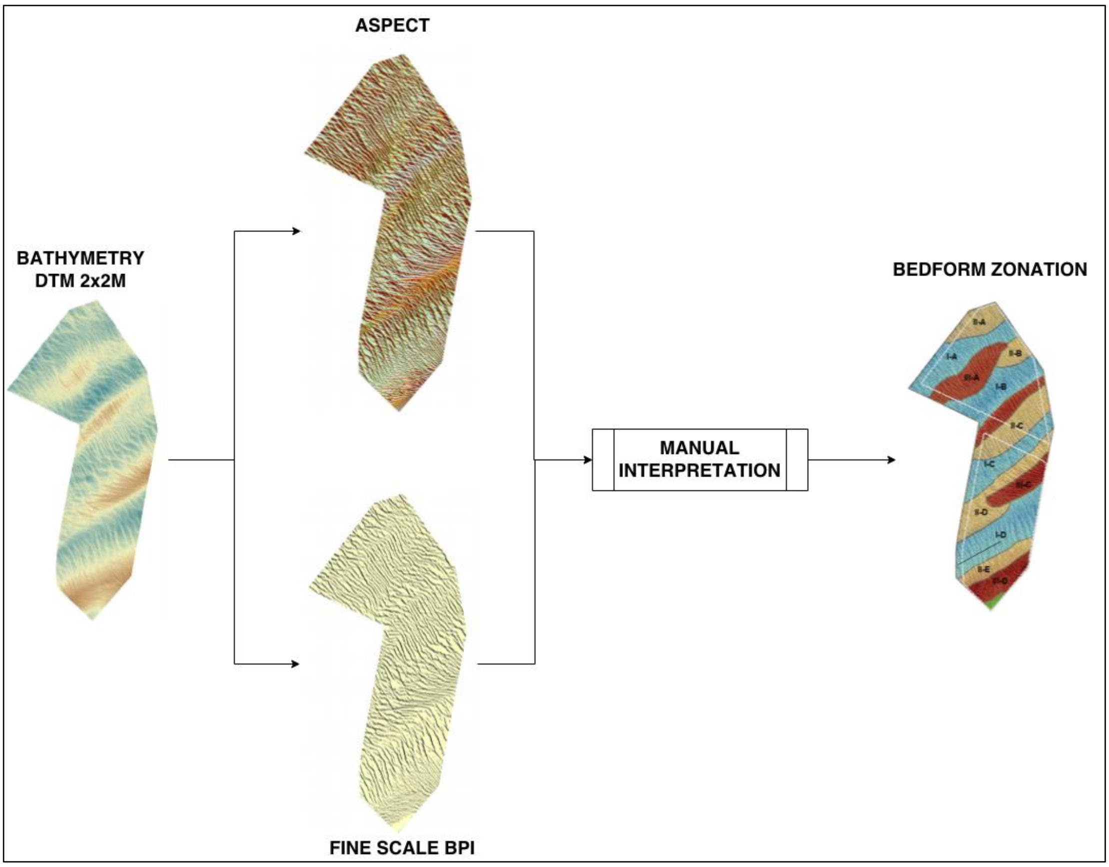


Figure 6-5: Processing flowchart of the Benthic Terrain Modeler

6.1.3 Backscatter data interpretation

The backscatter analysis was performed using Fledermaus processing software. This software runs an automated soil classification module based on MBE backscatter intensity. The classified data was checked for obvious mis-classifications. When these were noted the soil classification was re-run with adjusted settings. The following six main sediment classes can be identified:

Table 6-1: Sediment type classification scheme

Sediment type class	Sub-class
1) Gravel	Gravel
	Gravelly coarse sand
2) Coarse sand	Coarse sand – sandy gravel
	Coarse sand – gravelly sand
3) Sand	Medium sand – gravelly muddy sand
	Medium sand
	Fine sand
4) Muddy sand	Silty sand
	Muddy sand
	Very fine sand
	Clayey sand
5) Silt	Coarse silt
	Sandy silt
	Medium silt
	Sandy mud
	Fine silt
6) Clay	Sandy clay
	Very fine silt
	Silty clay

The relatively narrow window within which the sediments can be classified means there is little difference between the classes, leading to more difficulty in interpreting the backscatter data correctly. If an area displays a large variation of sediment types, from fine clays to coarse gravel, the seabed sediment classification becomes easier, as the extremes are so much further apart.

For an area of this size, a grid cell size of 25mx25m was chosen to facilitate a smoother generalization of the sediment types and smoother polygon boundaries. In some areas, the weather has been of influence on the backscatter data. This has caused a striping effect in the sediment classes' Geotiff (and polygons).

After completion of the seabed classification map the grid was exported as a Geotiff. Boundary polygons were drawn around the different classification areas.

6.2 SSS processing

An overview of the side-scan sonar processing flow is provided in Figure 6-8.

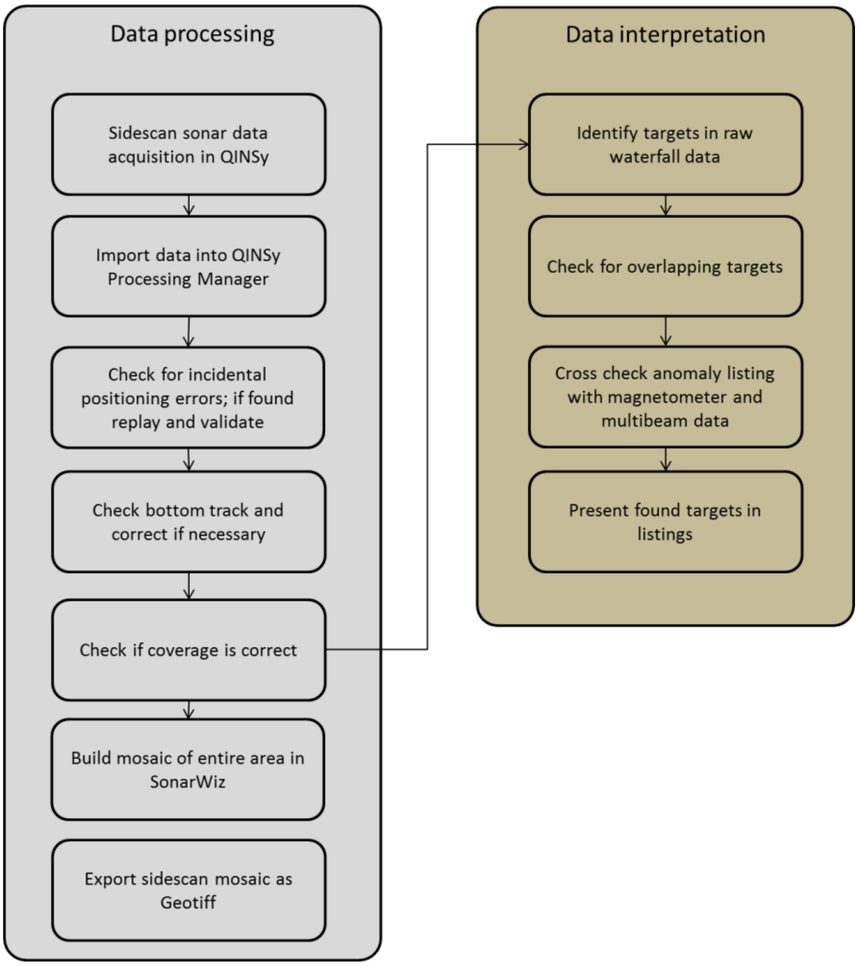


Figure 6-6: SSS processing flowchart

6.2.1 Data processing

The side-scan sonar data was digitally recorded on board. The 300 and 600 kHz channels were recorded simultaneously. On board QC was performed to check for positioning errors and overall data quality. Positioning errors can be caused by occasional false USBL readings. In these cases the data was corrected and replayed. The side-scan bottom track was checked and adjusted if necessary. Attention was also given to the data coverage to ensure all of the area was covered.

Further data preparation and processing was performed at the Deep office. Side-scan .xtf files were exported from the QINSy software and loaded into SonarWiz processing software. A side-scan mosaic using all side-scan data files was made using SonarWiz. Object detection was done in the QINSy Processing Manager waterfall display. The data required hardly any processing before contact picking commenced. Only a normalisation gain was applied to the data to make it more presentable (see Figure 6-7).

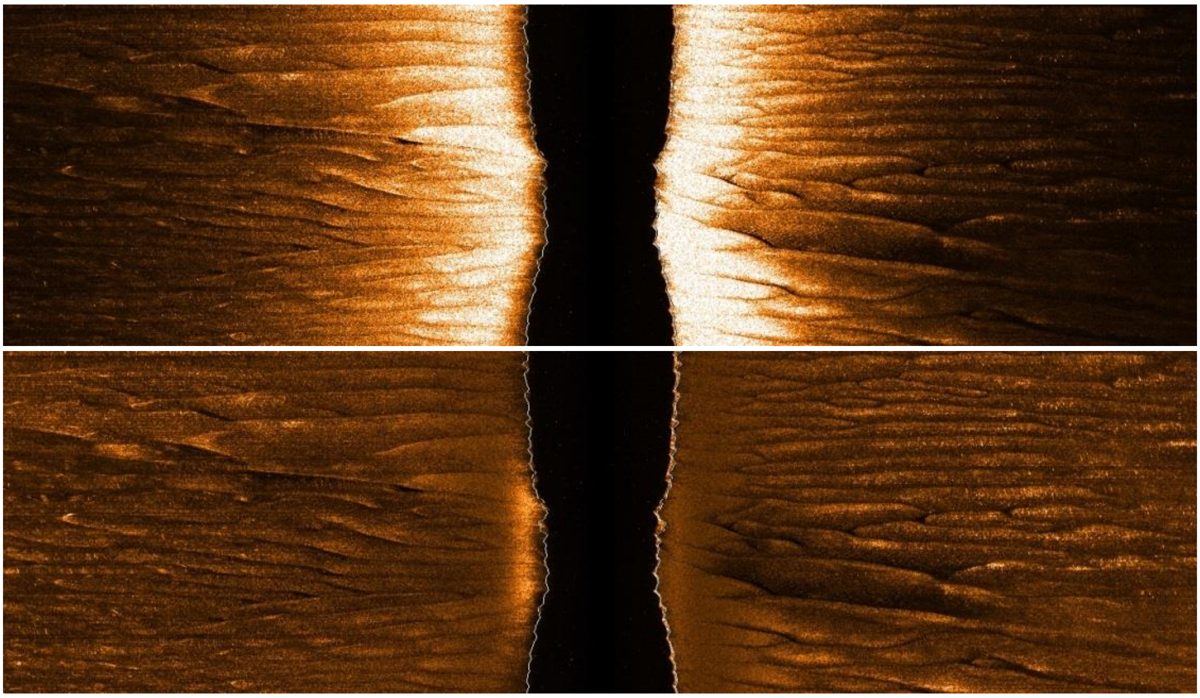


Figure 6-7: Side-scan sonar data before (top) and after (bottom) normalisation

6.2.2 Data interpretation

The object detection on the side-scan data files was done using the QINSy Processing Manager with the raw SSS waterfall data for optimal resolution. An object on the seabed shows up with different reflective properties than the surrounding sediments. This is visible in the side-scan data as an area of higher reflection. Often a man-made object shows sharper edges when compared to sediment structures. If the object protrudes from the seabed it will form a shadow behind it. The length of the shadow, combined with the distance from the side-scan fish and the fish's distance above the bottom will give an indication of the object height. A minimum object size of 2.0 meters was required, but were data quality allowed object detection of up to 0.3m resolution was realised.

Where objects were detected their geographic location was logged, as well as their length, width and, if possible, height and an identification. As the side-scan survey was carried out with 125% overlap between tracks, objects were often detected in multiple side-scan records. After contact picking it was necessary to check double entries. The final contacts are presented in listings including the position, length, width, height and identification (Appendix H). The SSS data was plotted in a mosaic with spatial resolution of 0.5 meters.

6.3 MAG processing

An overview of the magnetometer processing workflow is presented in Figure 6-10.

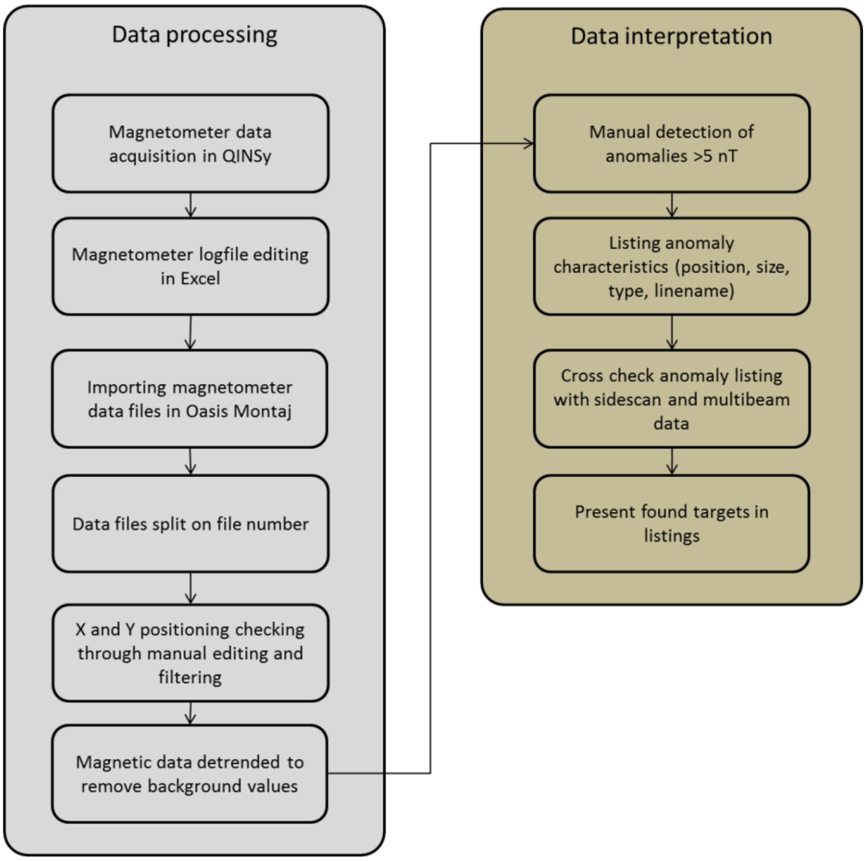


Figure 6-8: MAG processing flowchart

6.3.1 Data processing and validation

The magnetometer data was recorded digitally in QINSy survey software. During online survey the magnetometer data was written to dedicated .txt logfiles. These .txt files contained all the relevant data necessary for the magnetometer processing:

- Date
- Time
- Magnetometer easting
- Magnetometer northing
- Magnetic signal (peak-trough for dipole anomalies)
- Magnetic data quality
- Magnetometer depth
- Magnetometer altitude

The .txt files were imported into Excel for converting into an appropriate input format for Oasis Montaj processing software. The files were subsequently imported into Oasis Montaj. Here the files were split on line number and displayed in a plan view. Where necessary, a slight position filtering was applied to smooth the magnetometer track. Large position jumps were corrected manually. Obvious magnetometer measurement errors (data spikes and other obviously erroneous data) were removed. The magnetic signal was detrended using a non-linear filter. This removes the temporal variations of the earth magnetic field, leaving only true anomalies.

6.3.2 Data interpretation

The contacts were picked manually using a cut-off value of 5 nT. The exact location of the object was determined by choosing the high or low point of a monopole, or the middle between the high and low point in case of dipole anomalies. In Figure 6-9 an example of a magnetic dipole is shown, observed when the Zeepipe was crossed.

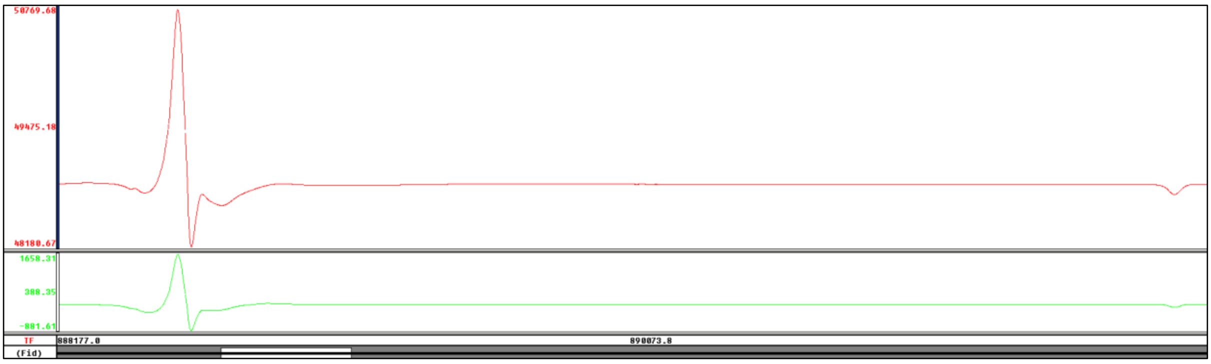


Figure 6-9: MAG data example.

Besides the position of the anomaly, its amplitude (peak-trough for dipole anomalies) in nT, its width and anomaly type were recorded. This provided a complete overview of the anomaly's characteristics.
Besides the single magnetic objects most cables and pipelines present in the survey area were identified in the magnetometer data. These are reported by lines rather than point contacts to improve data presentation. All found magnetic anomalies were cross-referenced with the SSS and MBE data. The magnetic contacts are presented in listings showing their characteristics.

6.4 SBP processing

An overview of the Innomar SBP data processing flow is provided in Figure 6-10.

6.4.1 Data processing

The SBP survey data files were recorded in the Innomar SESWIN software. Two types of data file are recorded; .ses files and .raw files. In most cases the .ses files will give a better quality image and are therefore the files used during processing. The .ses files are imported individually into the ISE processing software. Heave corrections from the ship's Octans MRU are applied to the data to counter the effect of waves on the sub-bottom profiles. The principle of any sub-bottom profiler is based on the two way travel time of a returned acoustic pulse. To convert this to a depth in meters a sound velocity must be chosen. Based on previous experiences an assumed velocity through the sediments of 1550 m/s was entered into the acquisition software. QC consists of checking the data

for positioning errors, though none were found in the data files. The sub-bottom profiles can be presented in several colour scales. The chosen colour scale has an influence on the visibility of certain features, so several colour settings are tested.
If possible, Innomar (company) recommends not to use the lowest (4kHz) or highest frequencies in the selectable range due to a decrease in SNR. However, the 4kHz frequency was used during test lines but gave no noticeable higher penetration and more noise. Since MCS data (in brute stack format) was already available during the start of the SBP survey it was evident that enough overlap existed between the 2 datasets, therefore the survey was executed using the 6kHz frequency.

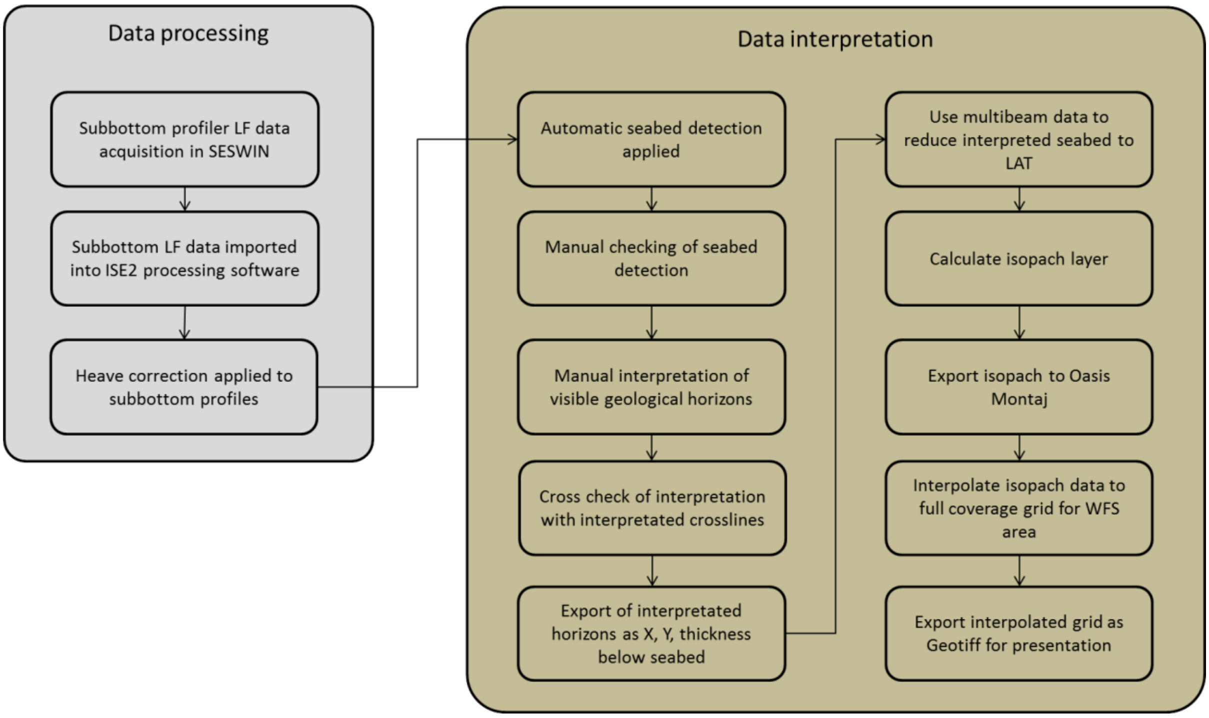


Figure 6-10: SBP processing flowchart

6.4.2 Data interpretation

The seabed can be traced automatically in the ISE software. This is done by searching the profile for the first strong reflector. After the automatic detection the profiles are checked manually for any mis-interpretation. Figure 6-11 shows an example of a SBP profile before and after manual seabed correction. Geological horizons can be detected by their reflective properties. All geological horizons visible in the SBP data were manually indicated. Three cross lines were sailed in each WFS area. At the crossings with the regular survey lines the interpreted horizons are checked against the cross lines to search for any mis-interpretations.

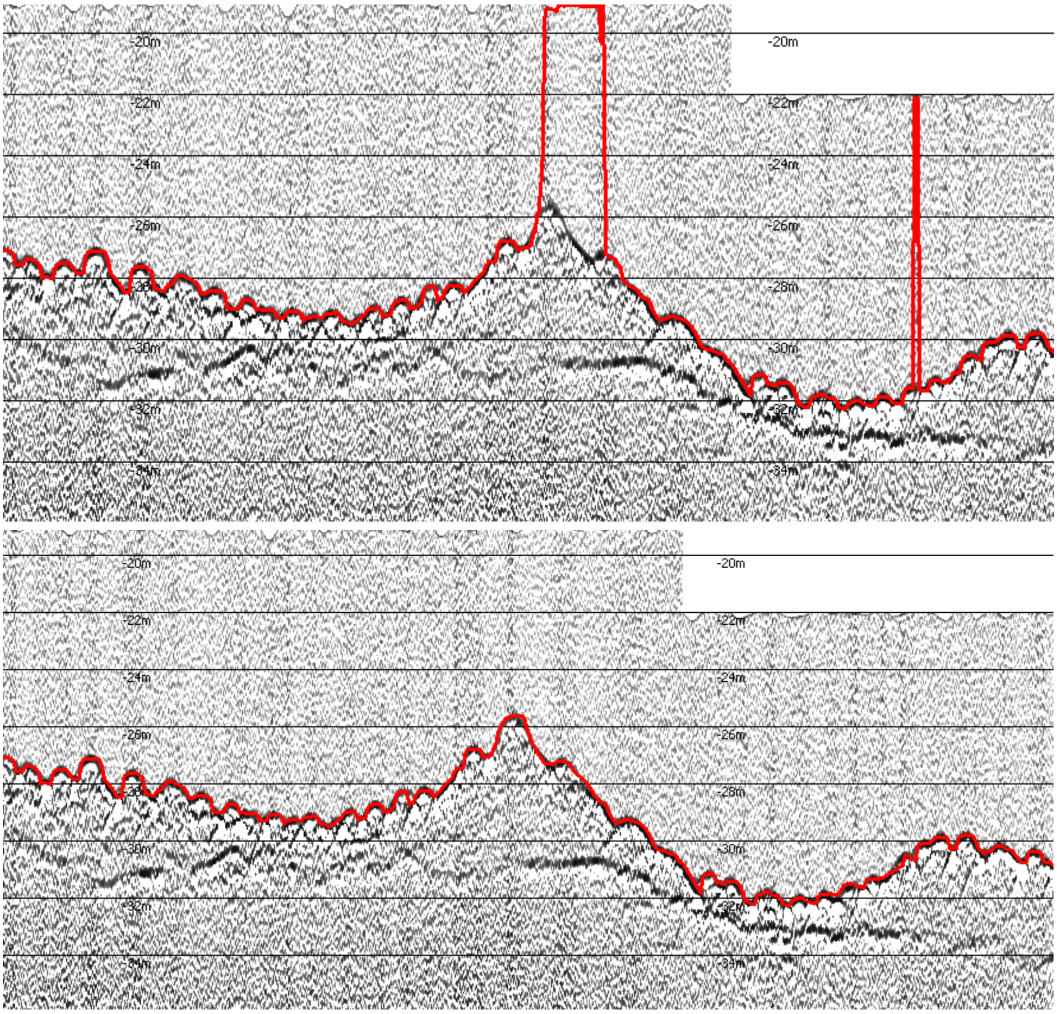


Figure 6-11: Example SBP data before (top) and after (bottom) manual seabed correction

The indicated horizons are exported as .txt files with position in easting and northing and their thickness below seabed. This allows the files to be placed below the multibeam derived bathymetry, thereby reducing the data to LAT. The base of the mobile seabed is used to produce an isopach map. This is the layer that forms the base of the large sand dunes found throughout the area. The isopach layers were exported to Oasis Montaj software to interpolate the data to achieve a full coverage isopach map of the WFS area. The isopach map shows some areas with no data. Here the base of the mobile seabed was too deep to be identifiable on the SBP records. The isopach map was exported as a Geotiff for reporting purposes.

6.5 MCS processing

The MCS data was acquired to model shallow geology in the survey area. In order to achieve this, the seismic profiles were interpreted to identify significant seismic reflectors (i.e. marking a geological boundary or change in sedimentary regime), up to a depth of 80 meters below seabed. Additionally identification of possible geological hazards was done.

The data processing was carried out in two phases; on board (related to the QC-ing) and in the office. The QC and processing work flow on during the survey was tailored to ensure processed data meet the necessary requirements to allow for:

- Production of processed seismic sections with a vertical resolution of 0.5m or better;
- Signal penetration of 80m or better;
- Adequately image any relevant geological features to the assessment of geological hazards for windfarm construction.

6.5.1 Onboard processing

For QC purposes on board, brute stacks were produced using the following processing procedure:

- Applying a geometry setup;
- Correct for spherical divergence;
- Simple interactive velocity analysis carried out (minimum one analysis every 500m);
- Normal move out correction applied;
- Stacking of Normal Moveout (NMO);
- Applying band pass filters.

The speed of sound in the water column that was used for depth migration was the average value recorded with an SVP during the survey works on MV Seazip Surveyor. Below the seabed the speed of sound used for data interpretation is based on an analysis of stacked velocity with 500m interval.

6.5.2 Office processing

This paragraph is a brief summary of the MCS data processing prior to interpretation of the seismic profiles. The full data processing report is prepared by GeoSurveys from Portugal and can be found in Appendix E.

The processing after the survey was carried out following a workflow using RadexPro and ProMAX software (Figure 6-12).

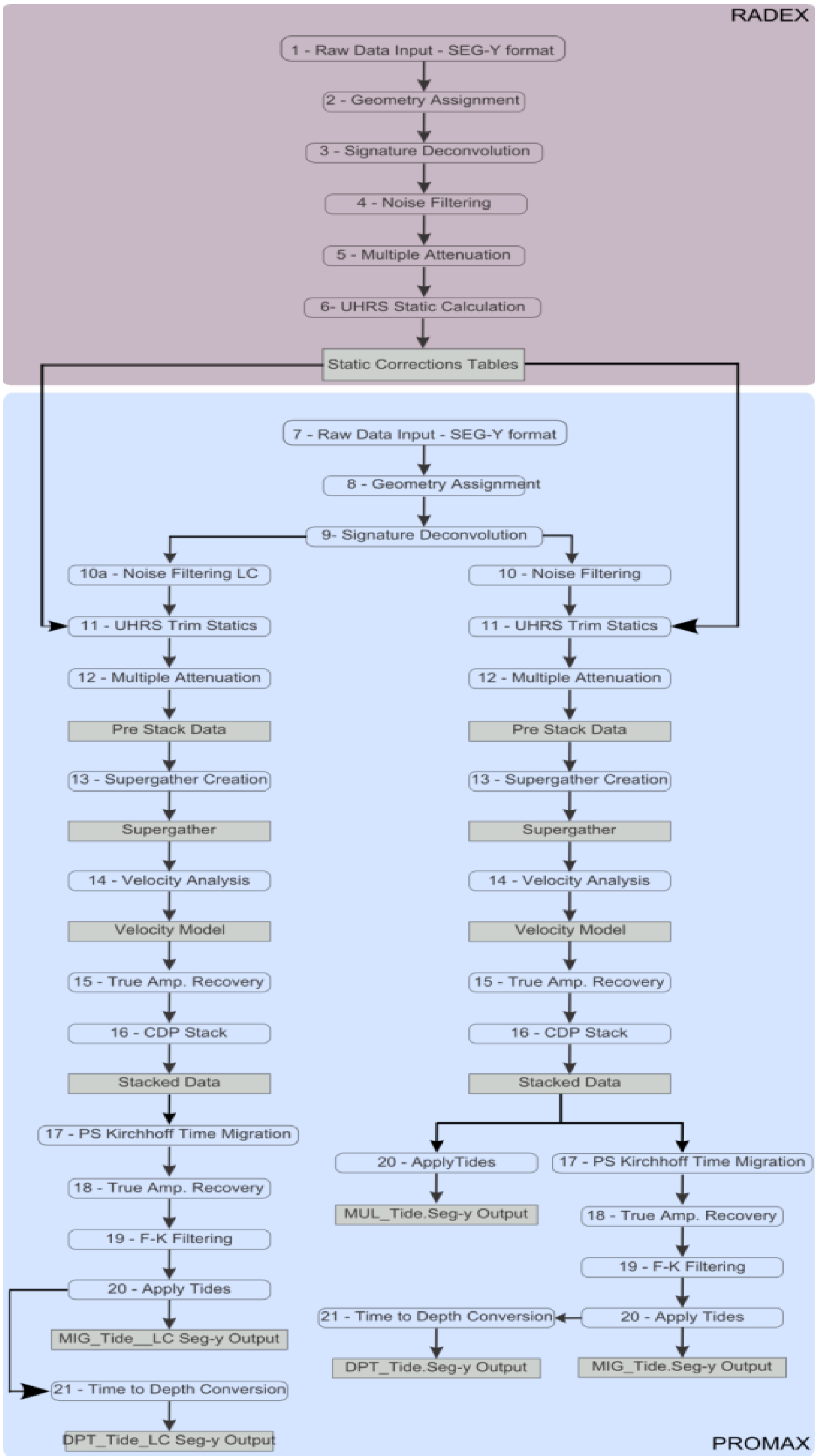


Figure 6-12: MCS data processing workflow

Table 6-2 depicts the settings used during the onshore processing steps. The step numbers coincide with the steps in Figure 6-12.

Table 6-2: MCS processing settings

RadexPro PROCESSING		
1	SEG-Y Data Input	
2	Geometry	
	CDP Bin size:	1
	Nominal CDP fold:	48
3	Pre-stack deghosting deconvolution	
	Filter option:	Inverse
	Percent additive noise factor:	3%
	Type of operator:	Time domain
	Filter length:	2.4-12 ms
4	Ormsby Bandpass Frequency Filter	
	lc – lp – hp – hc:	60 – 120 – 4000 – 5000
5	Butterworth Bandpass Frequency Filter	
	lc – dB – hc – dB:	600 – 12 – 1000 – 32
6	UHR Statics Calculations	
	Receiver Statics	Output of REC_STAT.dat file for ProMAX
	Source Statics:	Output of SOU_STAT.dat file for ProMAX
	Receiver Statics_2:	Output of .REC_STAT2 file for ProMAX
ProMAX PROCESSING		
7	SEG-Y Raw Data Input	
8	Geometry	
	CDP Bin size:	1
	Nominal CDP fold:	48
9	Pre-stack deghosting deconvolution	
	Filter option:	Inverse
	Percent additive noise factor:	3%
	Type of operator:	Time domain
	Filter length:	50 ms
10/10a	Butterworth Bandpass Frequency Filter	
	lc – dB – hc – dB:	190 – 16 – 1000 – 24
	lc – dB – hc – dB:	600 – 12 – 1000 – 24 *LC
11	UHRS trim statics	
	Receiver Statics:	Input of REC_STAT.dat file from RadEx Pro
	Source Statics:	Input of SOU.STAT.dat file from RadEx Pro
	Receiver Statics (only applied in data acquired in bad weather conditions):	Input of REC_STAT2.dat file from RadEx Pro
12	Wave Equation Multiple Rejection	
13/14	Interactive Velocity Analysis	
	Supergather size:	1 CDP for semblance, 31 for dynamic stack

	Interval of Analysis:	500 CDPs (500 m)
	Output Model:	IVA RMS 1st pass
15	Normal Moveout Correction	
	RMS velocities:	IVA RMS 1st pass
	Mute Stretch threshold:	35%
15	dB/sec corrections	
	Start time:	Water bottom
	Constant:	35
16	CDP ensemble stack	MUL.Seg-y Output
	Alpha-trimmed Mean:	35%
17	Post Stack Kirchhoff Time Migration	
	Maximum migrated frequency:	3000 Hz
	Migration velocity:	1:0-1486,70-1486,300-1700
18	Spherical Divergence correction	
	Basis for sherical spreading:	1/(time*vel^2)
	Velocity parameter:	IVA RMS 1st pass
18	dB/sec corrections	
	Start time:	Water bottom
	Constant	65
19	F-K Filter	MIG or MIG_LC Seg-y Output (depending on initial Filter)
20	Apply Tides	To all MUL and MIG Seg-y files
21	Convert time to depth	DPT Seg-y Output
	Maximum frequency of interest:	2000 Hz
	Velocity parameter:	IVA RMS 1st pass smoothed (triangular 1500 CDPs)

6.5.3 Data interpretation

Following the processing phase the MCS data was interpreted. The interpretation of the processed seismic data was performed using Kingdom Suite. The interpretation of the seismic data is based on recognition of the sedimentary facies, layer continuity and seismic texture of layers identified in the seismic profiles (see also paragraph 3.4.2). A number of seismic units were identified that were used to develop a geological model of the survey area. Subsequently, these units were fitted into the geological framework derived from desk studies and publications focusing on the geology of the area. The final geological model of the area is carried out with the depth migrated stacked profile to facilitate the creation of a geological model in depth rather than time (two-way travel time (TWTT)).

The following features were mapped:

- Isopach charts to show the thickness of the main geological formations including any mobile sediments and any other significant reflector levels which might impact on the engineering design;

- Locations of any structural complexities or geo-hazards within the shallow geological succession such as faulting, accumulations of shallow gas or buried channels;
- Detailed geological interpretation to show sedimentary facies variations and structural feature changes via appropriate maps and sections;
- Input into the specification and scope for a geotechnical sampling and testing program following the completion of the geophysical survey.

Gridding was done in Kingdom Suite. The cell size was chosen taking in account the seismic profiles' resolution and spacing and the geological surfaces' spatial variability. Gridding algorithm used was Flex Gridding and parameters are presented in Table 6-3.
The grids for B2, B3 and B4 depths and isopach maps for U1 and U2 (Dongen Formation) and U3 and U4 (Tongeren Formation) have a 400 meters cell size, a search radius of 200m. For these grids, interpolation was done with a minimum curvature value of 0.1 (from 1 – minimum tension, to 0 – minimum curvature) to fit to data and a value of 10 (out of 11) for smoothing.
The grids for B5, B6 and B7 elevation and isopach maps for U5 (Rupel Formation), U6 (Eem Formation, Kreftenheye Formation) and U7 (Buitenbanken Formation, Bligh Bank Formation) have a 100 meters cell size, a search radius of 150m, a medium curvature (value of 0.3 from 0 to 1) to fit to data and a value of 9 (out of 11) for smoothing.

Table 6-3: Gridding parameters

Grids	Cellsize (m)	Search radius from data (m)	Fit to data (1 to 0)	Smoothing (0 to 11)
B2, B3, B4, U1+U2, U3+U4	400	200	0.1	10
B5, B6, B7, U5, U6, U7	100	150	0.3	9

Mistie table is added in Geosurveys' report (Appendix E). Table contains offsets between profiles and multibeam data and between profiles and crosslines. The horizontal misties are mostly a result of uncertainty in the CDP estimate due to feathering:

- Feathering affects the quality of the layback computation.
- The CDP binning was done with crooked line geometry and the CDP bin centers are computed at the 'center of gravity' of the source-receiver midpoints. This minimizes the positioning error for the full trace, improves the overall image quality, but degrades the positioning of the shallowest part of the profile.

The vertical misties are mostly a result of the depth conversion method used; it is without calibration of the seismic model nor well data. All profiles were tide corrected so this is not an issue.

The interpretation will result in the following deliverables:

- Geological cross-sections identifying all significant features and horizons;
- Contour maps showing thickness of upper sediments;
- Contour maps (isolines) for each significant geological formation showing depth to top of formation below datum (LAT).

7 PERSONNEL AND EQUIPMENT

The following chapter gives a summary of the personnel involved and equipment used.

7.1 List of personnel

The following personnel were involved in the project:

Table 7-1: Personnel involved in the BWFZ project

Name	Role
Project management	
Gert-Jan Siepel	Operations manager
Erik Fijlstra	Project manager
Fieldwork MV Seazip Surveyor	
Wouter Wester	Party chief
Henrique Duarte	Senior data analyst
Nélia Alves	Online surveyor
Jhonny Miranda	Online surveyor
Miguel Oliveira	Online surveyor
Fieldwork MV Breaker	
Koen van het Hekke	Party Chief
Daniëlle Brandwijk	Senior data analyst
Sietse Bruinsma	Hydrographic surveyor
Bernd Monsma	Hydrographic surveyor
Willem Visser	Hydrographic surveyor
Jan Graven	Geophysicist
Martin Koelman	Geophysicist
Data processing and reporting	
Andries de Lange	Processing coordinator
Daniëlle Brandwijk	Senior data processor
Steven Pitka	Senior data processor
Tom Vanzieleghem	Senior data processor
Sybrand van Beijma	Data processor/ Reporting coordinator
Koen van het Hekke	Hydrographic surveyor
Willem Visser	Hydrographic surveyor
Henrique Duarte	Senior geophysicist
Daniela Gonçalves	Geophysicist
Jan Graven	Geophysicist
Emad Kader	Geophysicist
Vicky Kaland	Geophysicist
Martin Koelman	Geophysicist
Michiel Künzel	Geophysicist
Jhonny Miranda	Geophysicist
Vasco Valadares	Geophysicist
Wouter Wester	Geophysicist

Nélia Alves	Junior geophysicist
Bruno Duarte	Junior geophysicist
Miguel Oliveira	Junior geophysicist
Joana Santos	Junior geophysicist

7.2 List of equipment

The following chapter gives a summary of the equipment and software used during this project.

7.2.1 Survey vessel MV Seazip Surveyor

The MCS survey in the BWFZ area was done with MV Seazip Surveyor (Figure 7-1). This is a 27 meter long offshore survey vessel that was chartered for this survey. The vessel has ample rear deck space to store all equipment associated with a multi-channel sparker survey. The ship has been adapted to reduce acoustic noise to minimise disturbance in MCS data. Further information can be found in AppendixF.

Figure 7-1: Offshore survey vessel MV Seazip Surveyor

7.2.1.1 Equipment

Table 7-2 is an overview of the seismic acquisition equipment used during the multi-channel sparker survey:

Table 7-2: Summary of seismic acquisition equipment used for the MCS survey

Category	Specification
Power Supply	Geo Marine Survey Systems Geo-Spark 2000X
Seismic source	Geo Marine Survey Systems Geo-Source 200 LW
Receivers	Geo Marine Survey Systems Geo-Sense Multi-channel Streamer 48 Channel single element light weight streamer (between channel 1 and channel 24 group interval of 1m, between channel 24 to channel 48 group interval of 2m)

Category	Specification
Acquisition recorders	Geo Marine Survey Systems Multi-trace 48
Positioning	dGPS/RTK system and AIS

Table 7-3 is an overview of the navigation and positioning equipment used during the multi-channel sparker survey:

Table 7-3: Summary of positioning equipment used during the MCS survey

Category	Specification
Primary positioning	Trimble SP855 GNSS receiver using 06-GPS
Secondary (back-up) positioning	Fugro Marinestar
Primary motion sensor unit	IXblue Octans III motion and heading sensor
Secondary (back-up) motion sensor unit	IXblue Quadrans motion and heading sensor
Seismic sparker and streamer positioning	AIS transponders

Full equipment specifications are provided in Appendix G.

7.2.2 Survey vessel MV Breaker

The MBE, SSS, MAG and SBP surveys were performed with MV Breaker (Figure 7-2). This is a 31 meter long, dedicated offshore survey vessel operated by Deep BV. The vessel is a Swedish ex-navy ice-breaker and mine sweeper converted to perform 24hr offshore surveys. The vessel has two large moonpools in front of the wheelhouse and a large A-frame on the aft deck for safe and easy deployment of towed equipment. MV Breaker was commissioned just before the start of the survey. Further information can be found in Appendix F.

Figure 7-2: Offshore survey vessel MV Breaker

7.2.2.1 Equipment

Table 7-4 provides an overview of the survey equipment used for the survey on board MV Breaker.

Table 7-4: Summary of survey equipment used for the MBE, SSS, MAG and SBP surveys

Category	Specification
Primary positioning	Trimble SP855 GNSS receiver using 06-GPS
Secondary (back-up) positioning	Fugro Marinestar
Primary motion sensor unit	IXblue Octans G4 motion and heading sensor
Secondary (back-up) motion sensor unit	IXblue Octans 3000 (G4) motion and heading sensor
Subsurface positioning system	HIPAP 350P USBL
Sub-bottom profiler	Innomar SES 2000 standard pinger
Multibeam echosounder	R2Sonic 2024 multibeam, two transducer heads
Sound velocity profiler	Valeport MiniSVP & Reson SVP15
Side-scan Sonar	Edgetech 4200, dual frequent @ 300 and 600 kHz
Magnetometer	Geometrics G882 magnetometer

7.2.3 Software

Table 7-5 is provides an overview of software used during the surveys and data processing.

Table 7-5: Summary of software used for the MCS, MBE, SSS, MAG and SBP surveys

Category	Specification
Survey software	
Survey acquisition software (MBE, SSS, MAG)	QPS QINSy v8.1
Survey acquisition software (SBP)	Innomar SESWIN
Survey acquisition software (MCS)	Geo Marine Geo Recorder
Processing software	
MBE, SSS processing	QPS QINSy v8.1
MAG processing	Oasis Montaj 8.1
SSS processing	Cheaspeake SonarWiz 5.08
SBP processing	Innomar ISE2
MCS processing	Landmark Graphics Corporation ProMAX
	Deco Geophysical Radex Pro
Geophysical processing and modelling	Kingdom Suite
Charting software	Trimble Terramodel 10.3
	BricsCAD V11
	ESRI ArcGIS 10.1
	QGIS 2.6.1

8 REFERENCES

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2	QMS v_11 20140101	Quality Management System, Deep BV
3	P2008-HSE-01-R03	HSE Manual, Deep BV
4	Q4109_PEP_R03_150115	Project Execution Plan, Deep BV
5	Q4109_PQP_R03_v150115	Project Quality Plan, Deep BV
6	20150227_SDB_DEEP_Calibration report Seazip Surveyor_V03_F	Calibration report MV Seazip Surveyor
7	20150311_SDB_DEEP_Calibration report Breaker_V04_F	Calibration report MV Breaker
8	20150310_SDB_DEEP_Field report_V02_F	Survey field report
9	REP53101-RVO-OW_ProcRep_Final_02	MCS survey acquisition and processing report, prepared by GeoSurveys

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APPENDICES

A. ELECTRONIC DELIVERABLES

B. DAILY PROGRESS REPORTS

C. WEEKLY PROGRESS REPORTS

D. CALIBRATION REPORTS

E. MCS PROCESSING REPORT GEOSURVEYS

F. VESSEL SPECIFICATIONS

G. EQUIPMENT SPECIFICATIONS

H. TABULATED SURVEY RESULTS

I. TRACK CHARTS

J. BATHYMETRY CHARTS

K. BACKSCATTER SEDIMENT CLASSIFICATION CHARTS

L. CONTACT CHARTS

M. GEOLOGICAL CHARTS

N. GEOLOGICAL PROFILES

O. GEO-HAZARD CHARTS

P. PROPOSED BOREHOLE LOCATIONS

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