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R/V Helmer Hanssen

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Tromsø – Tromsø

CAGE-22-5 Cruise Report

High-resolution 2D and 3D seismic investigations on the Vøring Margin

Chief scientist: Bünz, Stefan

Capt. R/V: Jon Almestad

Report prepared by: Bünz, Stefan

With contributions by cruise participants: S. Planke, S. Singhroha, N. Lebedeva-Ivanova, C. M. Binde, A. Akinselure, U. Nagpal, J. Wear, T. Holm, S. Jensen

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NO-9037 Tromsø • postmottak@uit.no • http://uit.no • Switchboard: (+47) 77 64 40 00 • Fax: (+47) 77 64 49 00

Department of Geoscience • Phone 77 64 44 09 • Fax 77 64 56 00

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PARTICIPANT LIST

Stefan Bünz (chief scientist)	UiT The Arctic University of Norway
Truls Holm	UiT The Arctic University of Norway
Stormer Jensen	UiT The Arctic University of Norway
Sunny Singhroha	UiT The Arctic University of Norway
Cornelia M. Binde	UiT The Arctic University of Norway
Abidemi Akinselure	UiT The Arctic University of Norway
Umang Nagpal	Indian Institute of Technology (ISM) Dhanbad
Sverre Planke	University of Oslo, Norway
Nina Lebedeva-Ivanova	Volcanic Basin Petroleum Research AS
Jonathan Wear	University of Nebraska, Lincoln

PREFACE and ACKNOWLEDGEMENT

This document reports on the acquisition and processing of the seismic, subbottom-profiling and multibeam data acquired during a cruise with the Arctic University of Norway's research vessel RV Helmer Hansen from 5-20th July 2022. This expedition targeted areas on the outer Vøring Margin and into the Lofoten Basin, with emphasis on IODP Expedition 396 drill sites (Planke et al., 2022). The seismic acquisition was conducted under the framework of cruise *CAGE22-5* of the *Centre of Excellence for Arctic Gas Hydrates, Environment and Climate (CAGE)* (Norwegian Research Council (NFR) project number 223259/F5 at the University of Tromsø in collaboration with the *Centre for Earth Evolution and Dynamics (CEED)* at the University of Oslo (NFR project number 223272).

We sincerely acknowledge financial support from Lundin Energy. We also thank the captain and his crew of R/V Helmer Hanssen of UiT the Arctic University of Norway for their excellent support during the scientific surveys.

Tromsø, 20.07.2022

INTRODUCTION AND OBJECTIVES

The overall goal of this expedition was the acquisition of geophysical data on the Vøring Plateau and the southernmost part of the Lofoten Basin to improve the understanding of the subsurface structures and geological processes at four sites (U1571-U1574) where scientific drilling was recently successfully completed as a part of the the International Ocean Discovery Program (IODP) Expedition 396 (Planke et al., 2022a). The primary cruise objectives were (1) to acquire regional 2D high-resolution seismic tie-lines between the four IODP sites and legacy ODP/DSDP sites on the margin (Figure 1), and (2) to acquire high-resolution P-Cable 3D seismic surveys across two or more of the IODP sites. This expedition is part of a collaboration between the Center for Arctic Gas Hydrate, Environment and Climate (CAGE) at UiT Norway's Arctic University, and the Center for Earth Evolution and Dynamics (CEED) at the University of Oslo and completes a two-leg seismic well-tie program initiated in 2020 (Bünz et al., 2020; Planke et al., 2022b).

The scientific objectives of the cruise are linked to the objectives of the drilling applied through IODP Proposal 944-Full (Huismans et al., 2019), which investigates the cause and climate consequences of voluminous magmatism during the Northeast Atlantic continental break-up (Berndt et al., 2019). The overarching Exp. 396 goals were 1) to test hypotheses related to the formation of voluminous continental breakup magmatism and other Large igneous provinces (LIPs) and (2) to test the hypothesis that the associated Paleocene/Eocene Thermal Maximum (PETM) was caused by hydrothermal release of carbon in response to magmatic intrusions.

The cruise address in particular two primary and one secondary Exp. 396 objectives as described by Planke et al. (2022a).

> ***Objective 3 (primary):*** *determine the depositional environment (subaerial vs. submarine) of Inner and Outer Lava Flows (e.g., SDRs) and implications for vertical motions during late synrift, breakup, and early postrift oceanic spreading.*
>
> ***Objective 4 (primary):*** *determine the timing of magmatic activity and potential relationship(s) through analysis of a large variety of paleoenvironmental proxies proximal to the NAIP.*
>
> ***Objective 6 (secondary):*** *study early Eocene hothouse and freshwater during initial opening of the Northeast Atlantic.*

The main target areas for this expedition were the four northern drill sites at Skoll High, Eldhø and Lofoten Basin (IODP Sites U1571, U1572, U1573 and U1574) (Figures 1 and 2). The acquisition did also tie IODP Expedition 396 boreholes to former ODP and DSDP boreholes in this area through carefully planned long 2D seismic high-resolution profile.

All main cruise objectives were successfully met, with the acquisition of one P-Cable high-resolution 3D cube across Sites U1571-72 and more than 1000 km of high-resolution 2D data tying eight scientific drill site and one commercial borehole. The collected data have been fast-track processed on-board and show great results. The data will be post-processed and quality controlled after the cruise in a collaboration between UiT / CAGE and UiO / CEED.

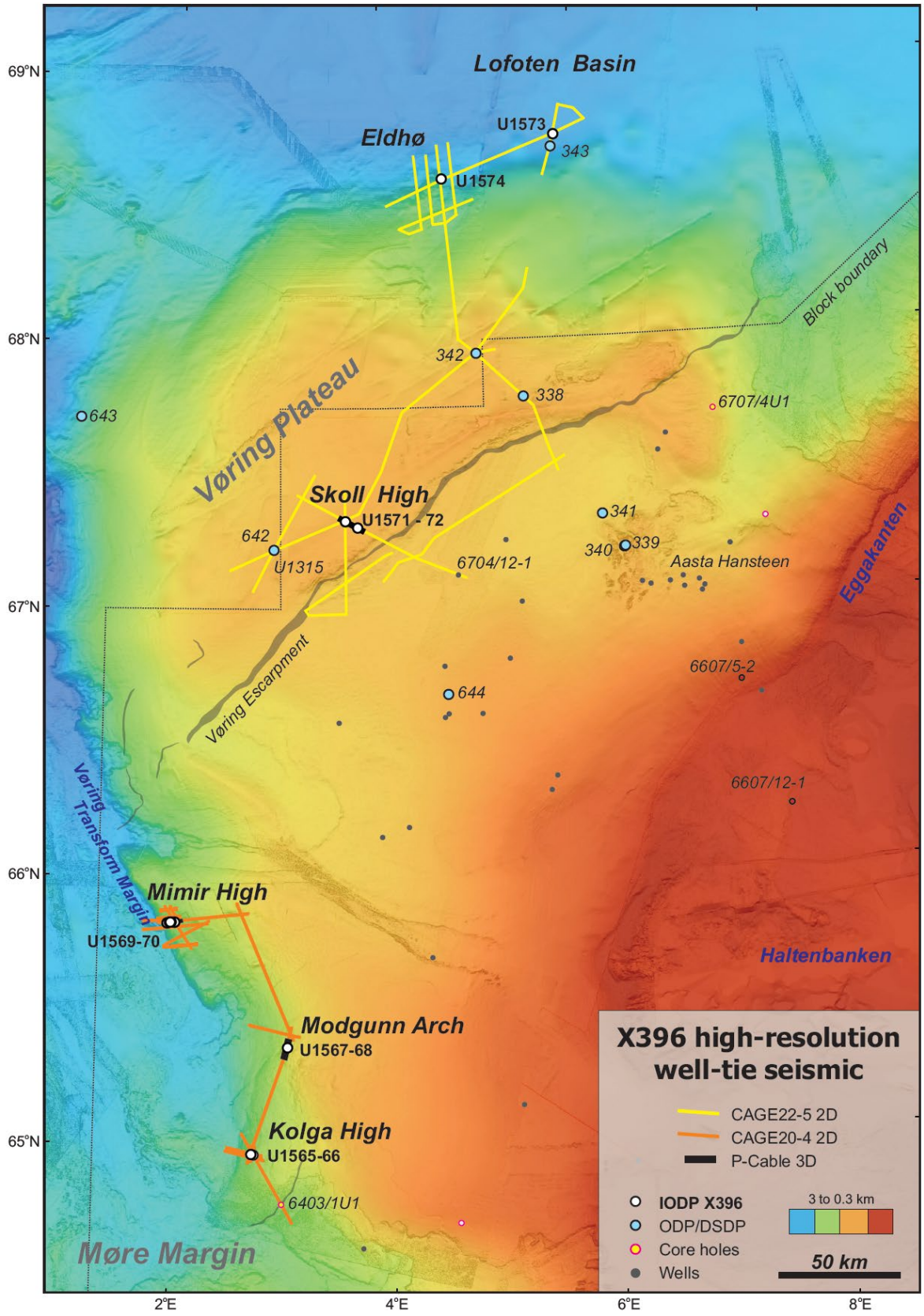

Figure 1: Location of the study areas on the outer margin of the Vøring Plateau and the southern Lofoten Basin. Cruise CAGE22-5 focused on the northern IODP Exp. 396 sites at Skoll High, Eldhø and the Lofoten Basin

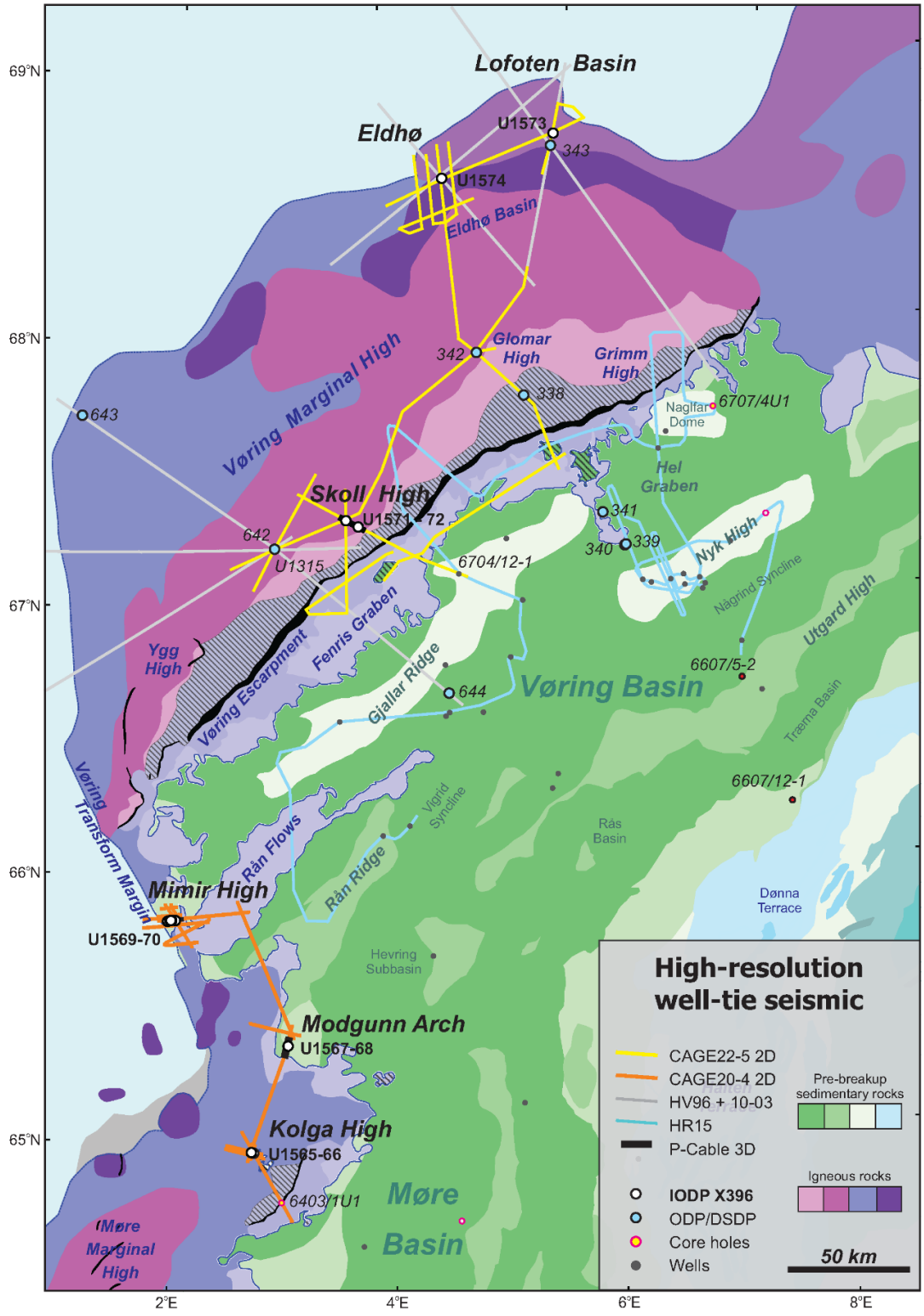

Figure 2: Geological map of the Møre and Vøring margins, with their marginal highs and sedimentary basins. Both the CAGE20-4 (orange) and this year's CAGE22-5 (yellow) seismic surveys are shown. Structures based on Gernigon et al. (2021).

METHODS

Seismic methods

The primary tool for the expedition was the UiT high-resolution P-Cable 3D seismic system used together with a Granzow high-pressure (210 bar) compressor and two mini-GI guns. Onboard seismic processing and QC of the P-Cable seismic data provided preliminary 3D cubes and migrated 2D seismic sections for quality assessment and preliminary interpretations using Radex and in-house software.

During this cruise we also used the Kongsberg EM302 high-resolution multibeam system. The EM302 provides excellent seabed resolution with a maximum of 864 beams. In addition, the system allows mapping the water column in order to detect gas flares. The new narrow beam parametric sub-bottom profiler SES-2000 from Innomar provided ultra high-resolution 2D seismic data of the upper 10s of meters below the seabed. CTD casts were conducted to extract information about different (T, S) properties of water masses to calculate the speed of sound for calibrating the acoustic systems.

The P-Cable 3D (2D) seismic system

The P-Cable 3D high-resolution seismic system consists of a seismic cable towed perpendicular (cross cable) to the vessel's steaming direction (Figure 3; Planke and Berndt, 2007; Lebedeva-Ivanova et al., 2018). An array of multi-channel streamers is used to acquire many seismic lines simultaneously, thus covering a large area with close in-line spacing in a cost efficient way. The cross cable consists of two 62,5-m long and one 87,5-m long section with a total of 14 streamers attached to it. Including lead-in cables, the cross cable has a total length of 233 m between paravanes (doors) (Figure 3). The cross-cable is spread by two paravanes that due to their deflectors attempt to move away from the ship. The paravanes itself are towed using R/V Helmer Hanssen's large trawl winches. The spacing between the streamers is 12.5 m but due to curvature of the cross-cable, the effective spacing between the streamers may be shortened in cross line direction to about 6-12 m. Each digital streamer is 25 meters long and consists of an A/D-module and 8 channels. Geometrics solid state streamers are used that are much less affected by sea swell and hence provide data with significantly less noise. The A/D-module converts the analogical signal from the channels to digital signals. The group spacing of channels along the streamer is 3.1 m.

A 300-m long signal cable is run off the P-Cable winch and connects to the starboard termination of the cross cable. It contains wiring for power and data transmission. The data is transferred via Ethernet protocol. Ethernet-to-Coax switches at the ends of the signal cable allow data transmission over long distances. The digital data is recorded using Geometrics GeoEel software.

The P-Cable system can be reconfigured to a multi-channel 2D seismic streamer. During this cruise we used 12 streamer sections for a 300 m long active hydrophone cable with 96 channels at a receiver spacing of 3.25 m. The lead-in cable to the active streamer had a length of 70 m behind the ship. The depth of the streamer cable was controlled by two ION Digicourse II birds and set mostly to 3 m as weather conditions were mostly quite rough with wave height above 2 m during acquisition.

Details on the acquisition parameters like recording length, sampling rates, etc. can be found in tables below and the seismic line log in the Appendix of this report.

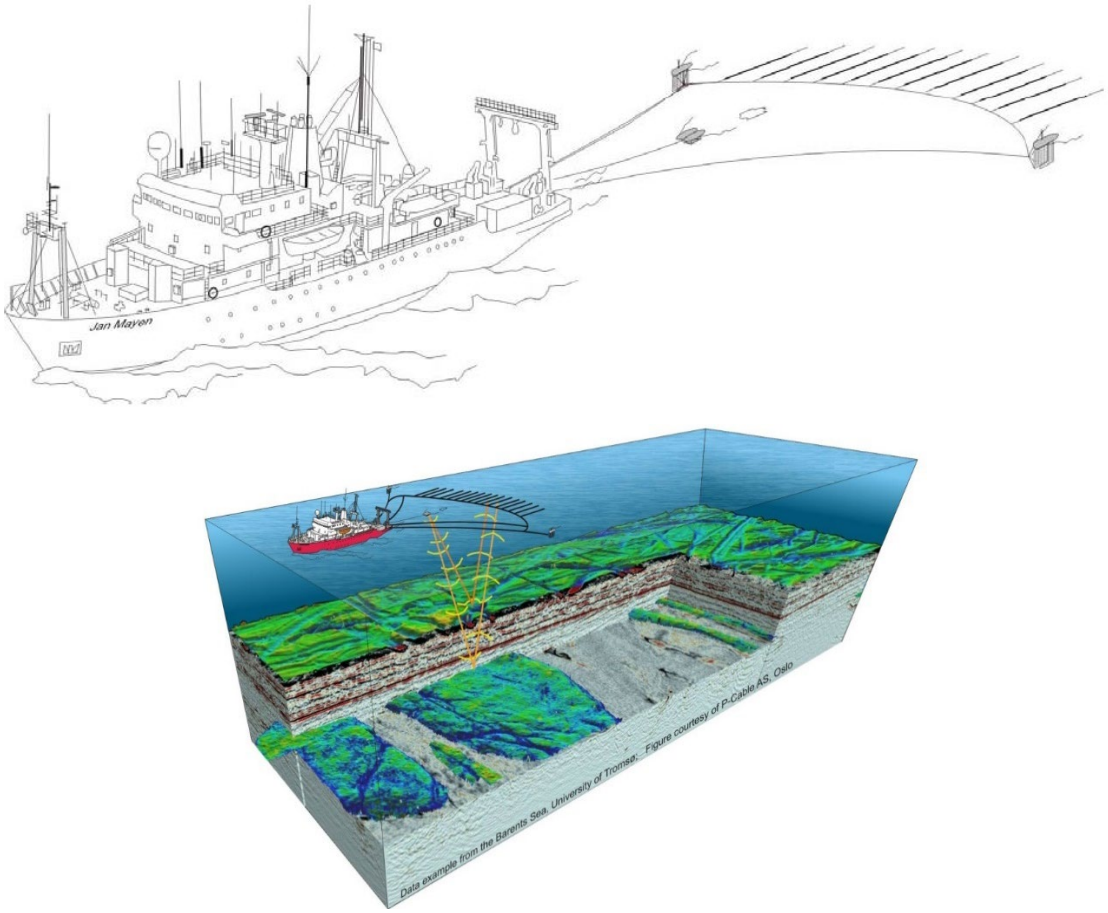

Figure 3: Schematic sketches of the P-Cable high-resolution 3D seismic system. A cross-cable is extended between two paravanes that are towed behind the vessel. Fourteen 25 m long active streamer sections were attached to the cross-cable during this cruise. The GPS locations of the paravanes, the source (air gun), and the vessel were determined using the Kongsberg Seatrack system.

NARRATIVE OF THE CRUISE

Times in this report are given in local time (local time -2 hrs = UTC), seismic data are logged in UTC time and ship logs are given in UTC time. Weather was mostly rough during this cruise with wave heights over 2 m. However, as this was mainly related to long waves travelling from distance, it still allowed 2D seismic acquisition with the exception of two days with gale force wind and 5 m waves.

Air temperatures were between 8-12°C. The cruise was mobilized in Tromsø on the 4th and 5th July with assembly of the equipment. More details and notes on the seismic data acquisition can be found in the seismic line logs at the end of this document.

Tuesday, 05.07.2022

Mobilization of equipment. All participants onboard. Departure from Tromsø at 21:00.

Wednesday, 06.07.2022

Transit to the working area on the outer Vøring Margin is estimated to take 1.5 days.

Thursday, 07.07.2022

Arrival at Skoll High at 09:00. Winds are at 10 m/s and swell is around 2 m and slightly higher, some long high waves coming from afar. Conduct CTD station to obtain acoustic velocity for water in order to calibrate acoustic systems. Deployed seismic streamer and airguns at 10:15 and ran a pre-survey warm-up to test all systems and define acquisition parameters. Line 01 started shortly before 13:00 and crossed IODP holes U1571B and U1572B before finishing at 23:15. The seismic system was recovered for a short transit to start of line 02. Checkup of the equipment discovered that the steel frame of the airguns was broken twice. The engineer on board quickly repaired the damage.

Friday, 08.07.2022

Redeployed streamer and airguns for a southbound line at 01:00. The line quickly crossed line 01 and finished at 09:25. The seismic systems were picked up again for another short transit to line 03. Line 03 started at 11:12 also crossing U1572B and then followed a magnetic anomaly on a semi-circle heading NE and then E. Wind speeds decreased over the course of the day being as low as 2 m/s. However, the acquisition still suffers from a high swell of up to 2,5 m coming from the SW.

Saturday, 09.07.2022

Line 03 crossed DSDP Site 342 before finishing at 07:05. The seismic systems was picked up and checked. Again, a small break on the airgun frame had to be welded. A short transit south reached the start of line 04 heading N crossing line 03 and then connecting to U1574B. The line finished in the southern part of the Lofoten Basin at 22:18. After a check of the systems and a short transit, line 05 started at 23:07. A series of shorter lines were aimed at mapping a volcanic structure at Eldhø High. Weather had calmed to wave heights of 1-1,5 m towards the end of the day.

Sunday, 10.07.2022

Line 05 ended at 02:35 and line 06 started at 02:38. Line 06 finished at 03:47. Line 07 started at 04:00. Line 07 finished at 08:42. Line 08 started at 08:44 and finished at 13:19. Line 09 started at 13:21 and finished at 14:29. Line 10 started at 14:31 and finished at 18:13. The seismic systems were recovered and checked during a transit westward to the starts of line 11. Line 11 started at 21:16 and is a long line in ENE direction connecting to IODP Hole U1573A. The wind picked up again over the day and was at 8-9 m/s at the end of the day, the sea swell coming along at 1,5 m.

Monday, 11.07.2022

Line 11 ended in the Lofoten Basin at 09:59. The last part of the line is actually a transit west to the start of line 12, which started 10:01. Line 12 is a short line tying U1573A with DSDP 38-242. The line went in SSW direction towards the Vøring Plateau and ended at 13:49. The seismic systems were picked up and we transited 2 hours south onto the Vøring Plateau for the start of line 13 at 16:34. Line 13 runs in SW direction tying Site 342 and finished at 22:00. Winds had increased to about 12 m/s and the swell was around 2 m, conditions marginal for seismic acquisition. After a short transit to the west, we again crossed DSDP 342 now heading SE and connecting to DSDP 338 on line 14 starting at 22:20.

Tuesday, 12.07.2022

By early morning the swell had risen to 2,5 m with winds still around 12 m/s. With weather forecast predicting even worse conditions for the day, we suspended the survey at 08:41 after the end of line 14.

Wednesday, 13.07.2022

Deteriorated weather forced us to lay down. Wave heights of above 4 m.

Thursday, 14.07.2022

Weather has improved slightly. Waves were still above 2 m but wind was down to below 10 m/s and the surface of the sea looked less rough. At 09:30 we deploy the 2D seismic system to acquire line 15 heading SW. The line finished at 22:23.

Friday, 15.07.2022

After a short transit northward, we started 2D seismic line 16 at 00:36. Line 17 at 06:34 is a 2-hour transit westward. Line 18 started at 07:00 and finished at 15:40. As weather conditions finally were looking to improve and only few days left of the expedition, we recovered the 2D seismic system and changed configuration to P-Cable 3D seismic. Reconfiguration finished at 23:00 and we started to deploy the P-Cable.

Saturday, 16.07.2022

At 00:30 the P-Cable was in the water and our pre-survey tests and warm-up showed that all systems were working nominally. 3D seismic acquisition line 1 started at 02:58. We reordered the first 10 lines to allow more space for the turn on either side of the 3D area (order: 1, 10, 3, 8, 5, 6, 7, 4, 9, 2, 11, 12, ….). During the third acquisition line, the GPS on the port side paravane occasionally did not send position updates. We observed that the floatation unit of the paravane has rotated and the GPS pod is partly drowned or water is splashing over it. The problem aggravated on line 4 (actual acquisition line 8) with the GPS pod at one point sending no updates for 25 min. We finished the line at 13:12 and pulled in the port side paravane. Unfortunately, the floatation unit had not only rotated by almost 90 degrees, but also moved backward within its mount positions. We had no

other option than to recover the P-Cable system in order to fix the paravane. The paravane was lifted onto the helicopter deck and fixed. The floatation unit in the starboard paravane also was tightened up. In addition, we discovered another break on the gun frame, which was welded and repaired by the ship's technician. We started to redeploy the P-Cable system at 17:15 and 1.25 h later it was in the water. All tests were nominal and 3D acquisition line 5 started at 19:07. Line 6 was completed at 23:27. Waves were around 1-1,5 m over the course of the day and wind was calming towards midnight.

Sunday, 17.07.2022

By mid-day, acquisition line 12 was completed and all systems are working fine. Wind was calm over the night but picked up again in the morning with speeds up to 10 m/s. Waves are around 1 m. One of the airguns failed right after the start of Line 17 at about 21:30. The Line was aborted and the leaking airgun was replaced with a spare airgun. Just before midnight, we re-started Line 17.

Monday, 18.07.2022

10 more 3D seismic acquisition lines were completed by 20:00 in the evening when we had to terminate the survey and sail home to Tromsø.

Tuesday, 19.07.2022

On transit back to Tromsø.

Wednesday, 20.07.2022

Arrival in Tromsø at 07:00. Demobilization.

2D and 3D seismic acquisition

During this expedition on RV Helmer Hanssen, our primary target areas for high-resolution seismic acquisition are located on the Vøring Marginal High and southernmost Lofoten Basin and included the four northernmost IODP Expedition 396 drill sites at Skoll High, Eldhø and Lofoten Basin (Planke et al., 2022a). A total of 18 2D seismic lines and one 3D seismic cubes were acquired in these areas (Figure 4), tying in total 12 scientific boreholes at 8 sites and one commercial borehole. Multibeam bathymetry and sub-bottom profiler data were acquired simultaneously with the seismic data. The locations of most of the 2D seismic lines were carefully planned prior to the cruise based on existing scientific and industry seismic data. However, note that the seismic data base if very limited outside the defined exploration blocks, with almost no new data acquired during the past 25 years. Parameters for the 2D seismic and 3D seismic acquisition are given in Tables 1 and 2, respectively. A principal sketch of the 2D seismic acquisition geometry is shown in Figure 5 and for the 3D seismic geometry in Figure 3.

The seismic acquisition started with a line tying well 6704/12-1 with the Skoll High Sites U1571 and U1572 (Figure 4). Subsequently, two 2D seismic lines tied Sites 642 and U1315

before heading east towards U1572. The planned 3D seismic acquisition at Skoll High was postponed due to weather, and 2D acquisition was therefore continued towards DSDP Site 342 (line 03), followed by a grid of six lines acquired across Eldhø and Site U1574 (lines 04 to 11). Line 11 was extended to tie U1573, whereas the next regional profile, line 12, was acquired as a regional tie-line between U1573 and DSDP Site 343. Due to upcoming bad weather, the vessel was steaming to the start of line 13 along an existing HV96 profile. Line 14 started just northwest of Site 342 and tied both wells 342 and 338 before crossing the Vøring Escarpment. Due to bad weather, strong gale force wind and up to 5 m waves, acquisition was stopped for two days. It commenced with acquisition of lines 14 to 18 as weather gradually improved, being sufficiently calm to deploy the UiT 3D P-Cable system at the Skoll High drilling sites on Saturday 16th of July. Here, 26 3D acquisition lines of about 10 km each were acquired during the next three days, resulting in a 18 km^2 large high-resolution 3D seismic cube.

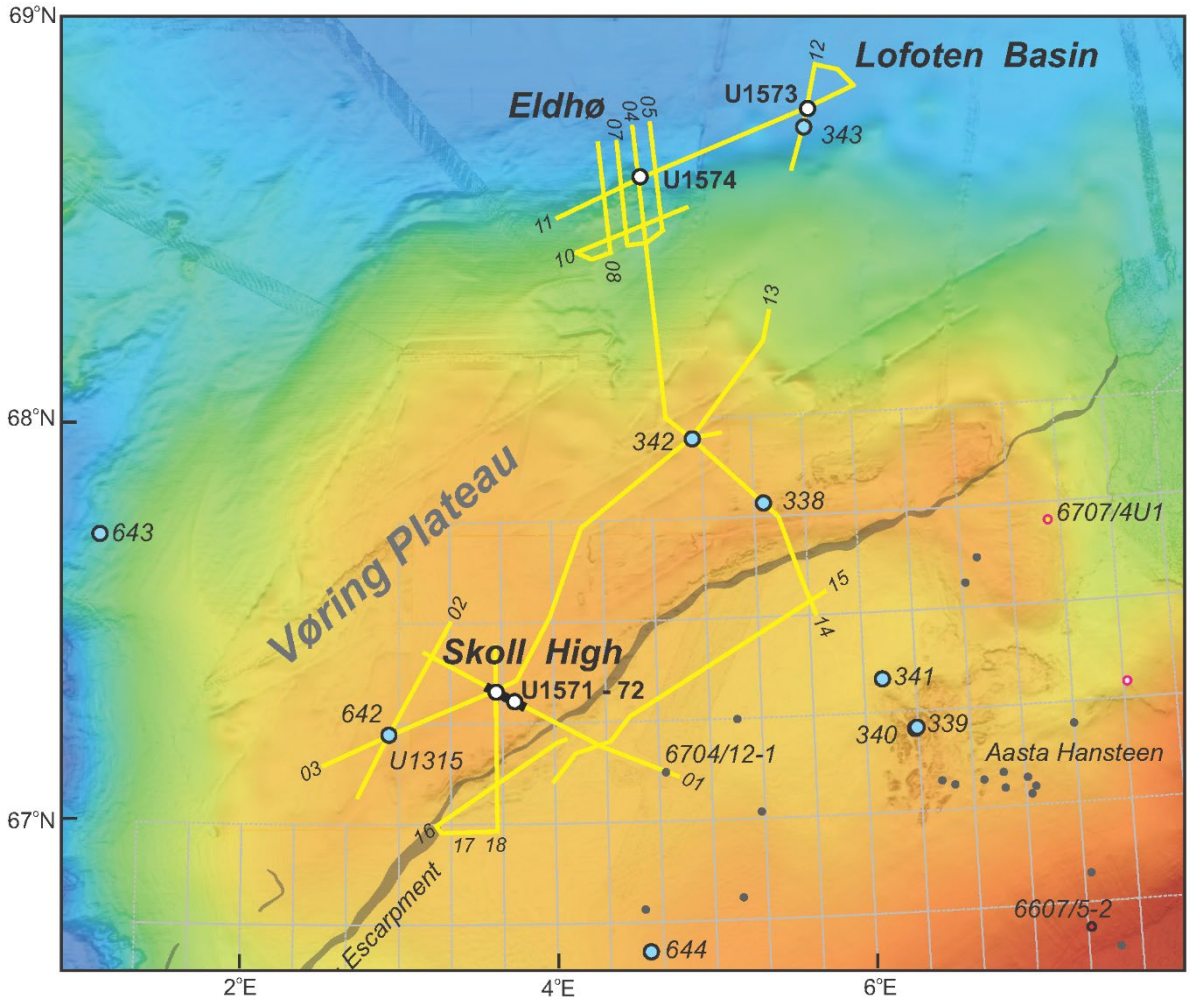

Figure 4: Overview of 2D (yellow lines) and 3D (black rectangle) seismic data acquired during this expedition with RV Helmer Hanssen at the three northern IODP drill sites at Skoll High, Eldhø, and Lofoten Basin. More than 1000 km of 2D and 18 km^2 of 3D data were collected in water depths of 1200 m (Vøring Plateau) to 3000 m (Lofoten Basin).

Table 1: The detailed survey parameters for the 2D seismic survey.

Survey parameters	
Deployment / recovery	0,5 h
Survey speed	4-5 kt
Source	1 mini GI 30/30 in^3 & 1 mini GI 15/15 in^3
Shooting rate	4-6 s
Shooting pressure	170 bar
Source towing depth	1.5-2.0 m
Dominant frequency (bandwidth)	140-180 Hz (20-400 Hz)
Positioning	GPS transponder on gun raft
Streamer length	320 m
Active section	300 m
Across track position relative to gun	11 m to port
Number of channels	96
Receiver group spacing	3.125 m
Streamer towing depth, 2 ION DigiCourse II Depth birds	3.0 m
Sampling rate / interval	0.25 – 0.5 ms
Recording length	3-4 s, delay of 1-2 s in deep water

Table 2: The survey parameters for the UiT P-Cable 3D seismic survey.

Survey parameters	
Deployment / recovery	1 h
Survey speed	4 kt
Turn time	~0.5-0.7 h
Source	1 mini GI 30/30 in^3 & 1 mini GI 15/15 in^3
Shooting rate	6 s
Shooting pressure	170 bar
Source towing depth	1.5 m
Dominant frequency (bandwidth)	140-180 Hz (20-400 Hz)
Positioning	GPS transponder on gun raft and the two paravans
Seismic streamer	14 25-m-long active sections towed parallel with streamer spacing of 12.5 m

Active section	8 channels per streamer section with 3.125 m receiver group spacing
Streamer towing depth	2.0 m
Sampling rate / interval	4000 Hz / 0.25 ms
Recording length	3.5 s

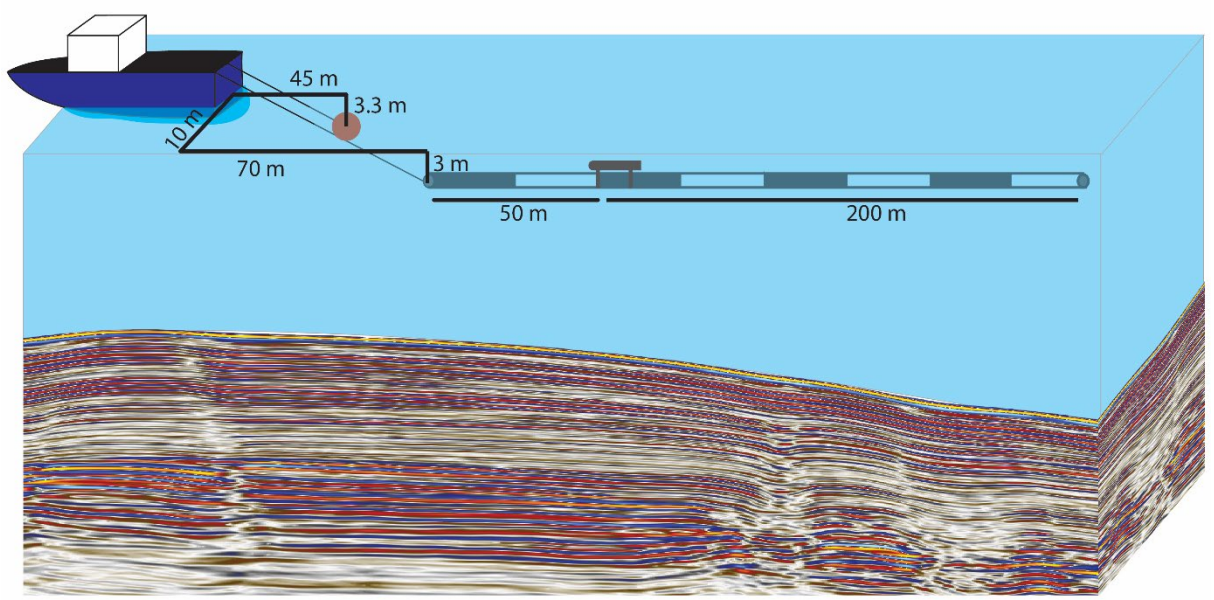

Figure 5: Acquisition geometry of the 2D multi-channel seismic streamer. Notice that in this cruise we used 12 streamer sections with an active section of 300 m (not 200 m as in the figure).

2D seismic fast-track processing

We processed 2D seismic data on board using the RadExPro 2020.1 software, following a standard processing routine consisting of SEG-D import, geometry assignment and 2D CDP binning, denoising, stacking, deghosting, migration and post-migration conditioning (Table 3).

The geometry parameters for this survey are outlined in Table 2 and Figure 5. Denoising of the 2D lines was largely dependent on the source of the noise. Bad/dead channels were treated separately from the good channels, and a split denoising flow with adjusted parameters was applied to the lines to preserve as much of the signal as possible. Simple bandpass filters parameterized to 20-30-800-1000 Hz and 62-78-800-1000 Hz, as well as burst noise removal algorithms were applied to the lines. Amplitude corrections and various additional noise filters were applied, including F-K filtering to remove coherent and low frequency electrical noise. The first stages of denoising were applied on source (shot) gathers, and later stages on channel gathers.

Static corrections for adjusting recording lengths and delays were applied prior to NMO correction and stacking. In order to account for the destructive interference of the short time lag multiple, or ghost, we applied a deghosting routine to the lines. Due to time limitations, the source ghost was targeted and suppressed using a predictive deconvolution algorithm. The

migration algorithm used was the Stolt F-K migration, with a constant velocity of 1500 m/s. Post-migration conditioning consisted in simple filtering and amplitude corrections. Two seismic examples are shown in Figures 6 and 7.

The data will be post-processed and quality-controlled at UiT, including testing alternative deghosting and migration algorithms (e.g. SharpSeis deghosting and Kirchhoff migration).

Table 3: Processing parameters for the 2D seismic survey.

Seismic processing flow	
SEG-D import and geometry assignment	SEG-D input Geometry assignment and offset calculation
Filtering in the shot gathers	Removal/filtering of bad/dead channels Bandpass filters of 20-30-800-1000 Hz or 52-78-800-1000 Hz Burst noise removal Amplitude corrections F-K filtering
Filtering in channel gather	F-K filter Butterworth filtering (zero-phase, 68-250 Hz)
NMO and stacking	Static corrections (delay) NMO (1500 m/s) Ensemble Stack
Migration	Top Mute (above seafloor) Stolt F-K (1500 m/s, maximum frequency 500 Hz, slope 50 Hz assuming maximum dip of 45)
Post-migration deghosting	Top Mute (above seafloor) Predictive deconvolution (deghosting) Butterworth filtering (zero-phase, 35-500 Hz) Amplitude correction Top Mute (above seafloor)
Post-migration conditioning	2D spatial filtering Butterworth filtering (zero-phase, 60-500 Hz) Amplitude corrections
SEG-Y output	Info in SEG-Y header IBM floating point Coordinate system: WGS84 UTM31N

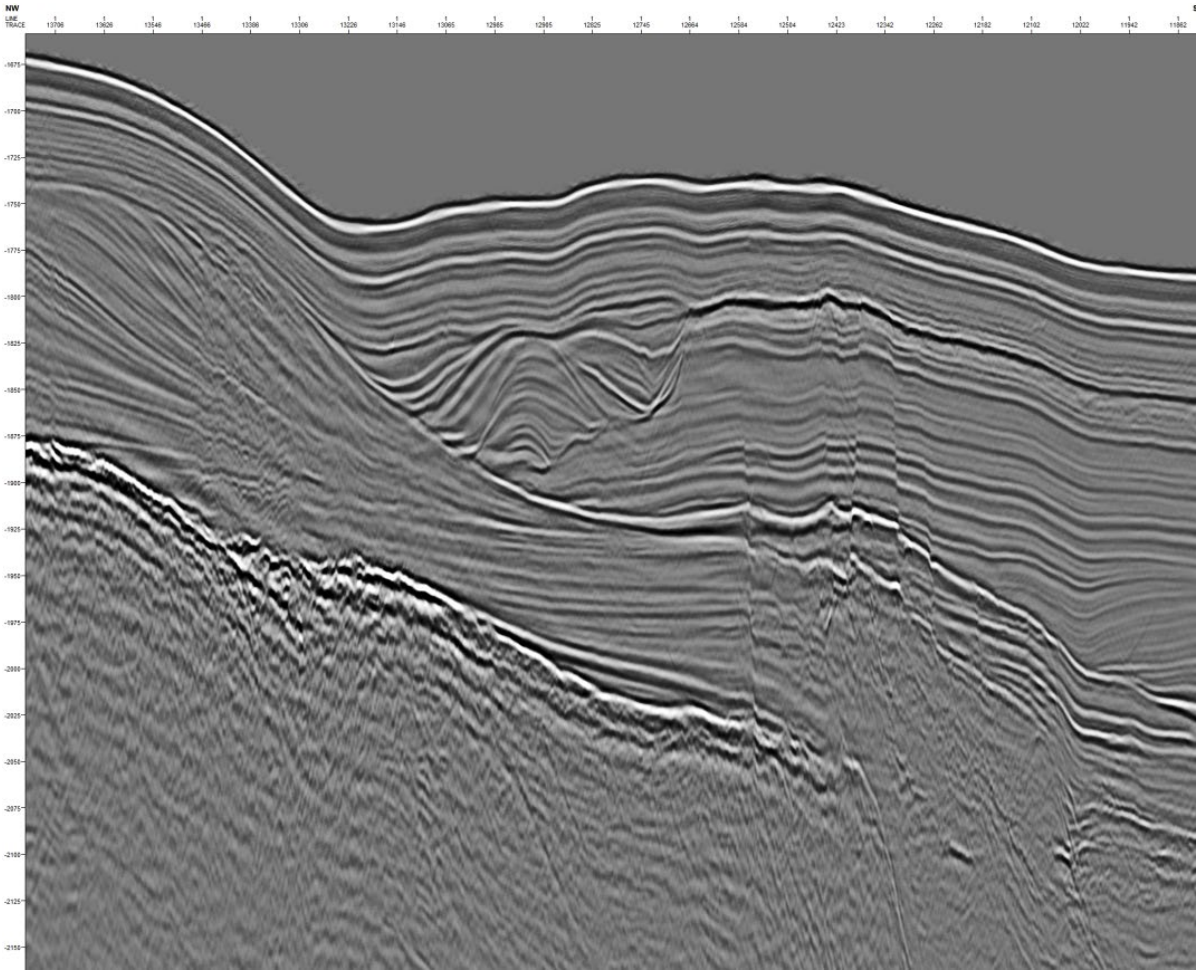

Figure 6: Example of fast-tracked processed 2D profile across the Vøring Escarpment (line 01).

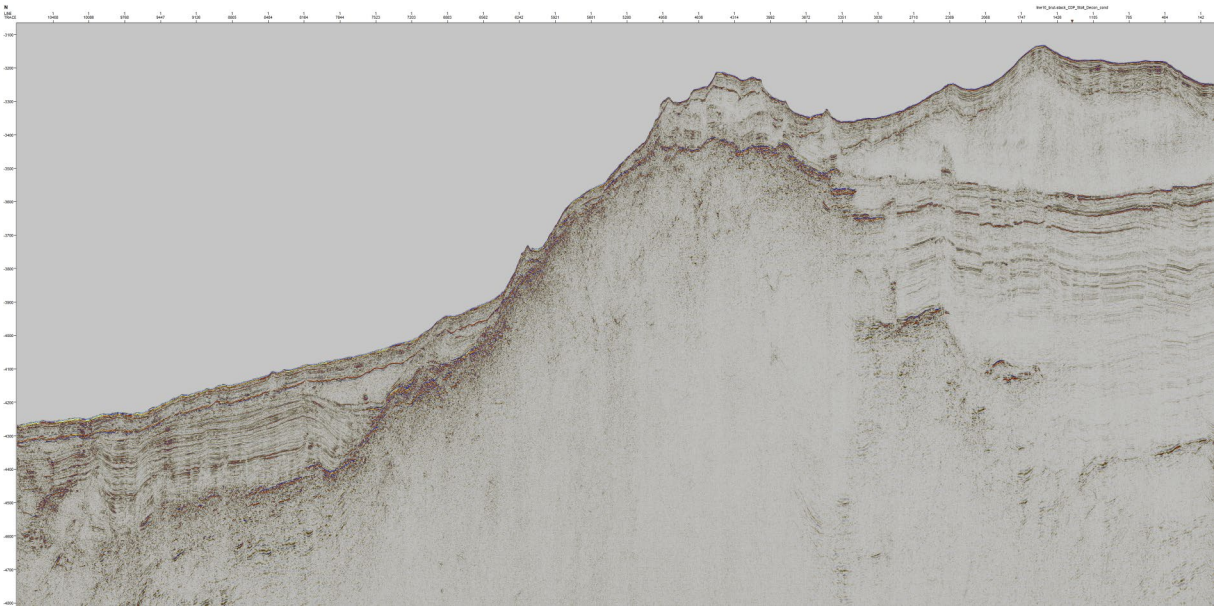

Figure 7: Example of fast-track processed 2D profile from the Lofoten Basin, across Eldhø, and into the Eldhø Basin.

3D seismic pre-processing

We processed 3D seismic data on board using the RadExPro 2020.1 software, following a standard processing routine consisting of SEG-D import, geometry assignment and refining, denoising, merging sail lines and 3D CDP binning. Due to time limitations, we were not able to continue with further processing (i.e. NMO and stacking, interpolation and migration).

After SEG-D input in RadExPro, geometry is first assigned and then refined. Assigning receiver position within RadExPro is based on the GPS positions of the paravanes, the gun and AFT of the ship, assuming the streamer approximates a catenary curve. Points along the catenary should thus be the position of the T-junctions, and then receivers are positioned an appropriate distance back. However, this presumes that the streamer is catenary, i.e. symmetrical in particular – weather and water current activity often preclude such symmetry, and therefore we refine the geometry by using least-squares approximation of the cross-cable curve, constrained by the length of the cross-cable, GPS coordinates of paravanes and known distances of receivers along the streamers. Noisy and weaker channels were treated separately from the good channels, with adjusted parameters according to the recorded signal. These channels were filtered with a wider averaging window. Misfit before refining geometry was on average 600-800 ms. The main portion of the lines have been included in the planned cube, with an average overall misfit (ms per shot) of 200 ms after refining receiver location. Outliers in QC plots after refining geometry are mostly related to turns during acquisition, and they have been excluded from cube during 3D CDP binning. Note: original geometry assigned in RadEx has been preserved for the raw lines, whereas the new and refined geometry was assigned to denoised lines.

Denoising was carried out on individual sail lines, applying first a simple bandpass filter parameterized to 20-30-1000-1500 Hz, burst noise removal, amplitude corrections and F-X predictive filtering for increasing coherency between channels. F-X predictive filtering gives best results when applied to shot gathers and improves results of later processing flows significantly. Denoised lines were subsequently merged and binned to 6.25 x 6.25 m. Median fold is 8.

Missing processing routines include deghosting, NMO corrections, stacking, interpolation and migration. The data will be further processed and quality-controlled at UiT.

Table 4: Processing parameters for the 3D seismic survey conducted during the survey. Processing will be completed at UiT.

Seismic processing flow	
SEG-D import and geometry assignment	SEG-D input Geometry assignment and offset calculation Geometry refined and offset calculation
Filtering in shot gathers	Removal of bad/dead channels Bandpass filter of 20-30-1000-1500 Hz Burst noise removal Amplitude correction F-X predictive filtering
Binning	3D CDP binning to 6.25 x 6.25

Sub-bottom profiling data

Sub-bottom profiling data were acquired along all 2D seismic lines and the 3D acquisition lines. Data were converted from RAW into SEG-Y format using SESConvert software. Data will be post-processed at UiT. An example of an SBP profile is shown in Figure 8.

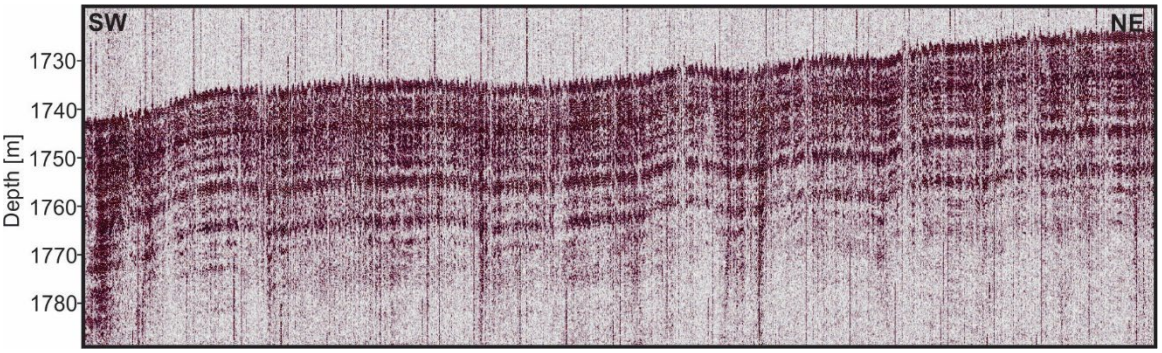

Figure 8: Data example of the sub-bottom profiler acquired during line 03.

Multi-beam data

Multibeam data were acquired continuously during all lines and transits. The data were processed and cleaned using QPS Qimera software. A number of different grid surfaces were generated depending on water depth. In water depths of 1200 – 1500 m on the Vøring Plateau, grid resolution was 20 - 30 m, in water depths in the Lofoten Basin down to depths of 3500 m, grid resolution was between 40 – 75 m. The total multibeam coverage is shown in Figure 9.

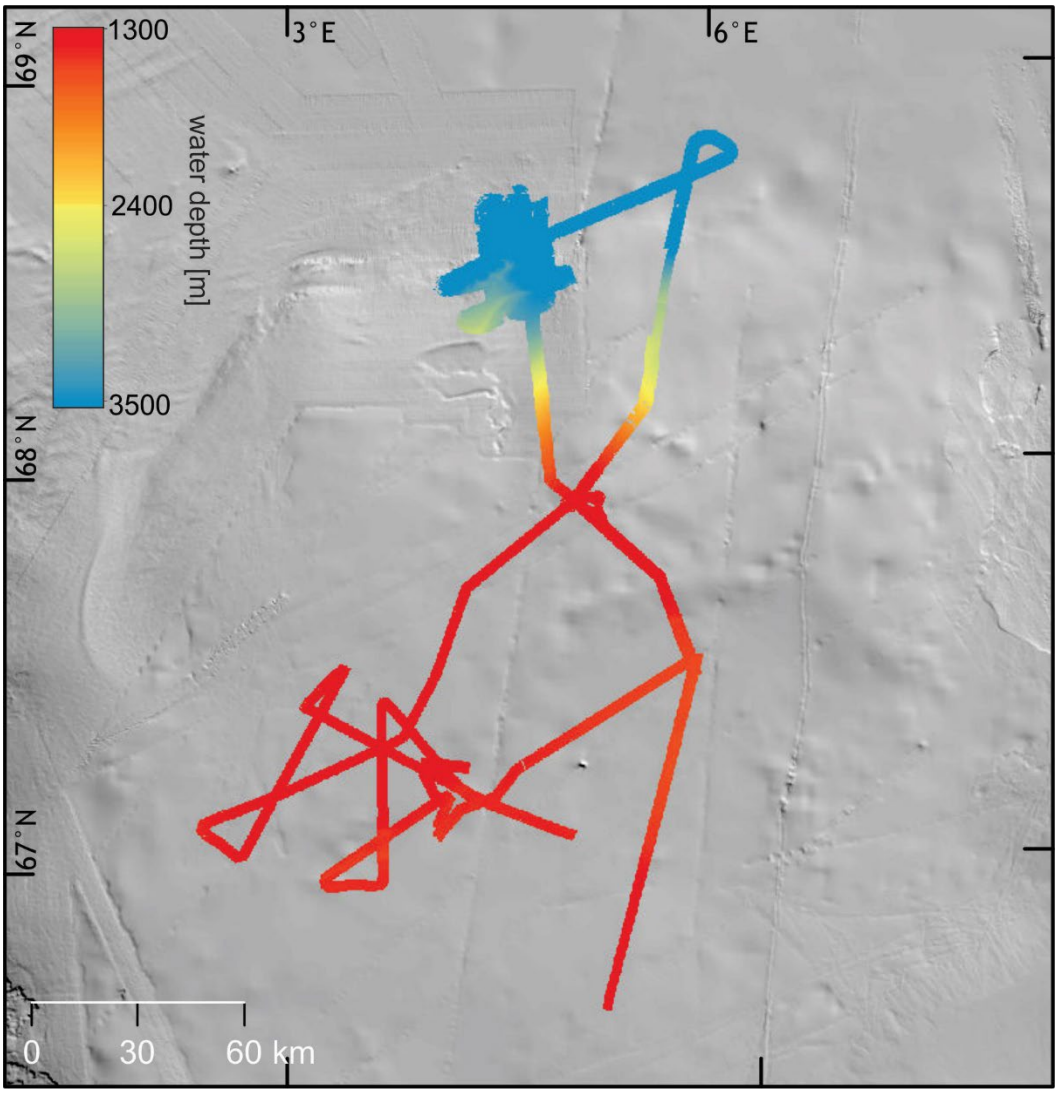

Figure 9: Map showing multibeam seafloor bathymetry acquired during CAGE22-5.

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APPENDIX

Shortened tables of station and line logs are included in this report. More extensive information in spreadsheets is available on request.

Station log CAGE20-4

Location	Station Id	Date	Time (UTC)	Lat. [N] Long. [E]	Bottles fired [#]	Water Depth [m]	Notes
Vøring Basin	CAGE22-5-HH-1126-CTD	07.07	09:28	67°05.014' 4°56.624'	0	1366	no water samples
Lofoten Basin	CAGE22-5-HH-1131-CTD	09.07	20:44	68°43.759' 4°36.659'	0	3132	no water samples

Line log CAGE20-4

Survey parameters, e.g. shooting rate, ship's speed etc are listed in Table 1.

Location	Line ID	Date	Time (UTC) START	Lat. [N] Long. [E] START	Time (UTC) STOP	Lat. [N] Long. [E] STOP	Comments
Skoll High	CAGE22-5-HH-001-CHIRP	07.07	10:15	67°06.080' 04°51.520'	21:15	67°25.830' 03°08.200'	Test line at the beginning with speed c.2.5 knots position and time are not exact, 10 ping settings. Later record is together with 2D seismic at speed of 4-5 knots. !! Lat/long in position F1 and F2 x100 of Inomar format .ses3 (SIS-ID) are correct, but X and Y in F7 and F8 are wrong!!
Skoll High	CAGE22-5-HH-001-2D	07.07	10:56	67°06.900' 04°46.000'	21:15	67°25.700' 03°08.750'	96 chan., streamer depth c. 3 m, guns are at 1.7-1.8 m depth. Dead channels: 18(?), 19(?) 24, 25, 95. Bed chan.: 14, 33, 46, 47, 54, 78, 96 Noisy chan.: 16, 74. Gun

							location missing from 14:19. Shot interval increased from 4 s to 5 s at c. 17:25
Skoll High	CAGE22-5-HH-Transit001-002-CHIRP	07.07	21:46	67°25.830' 03°08.200'			Lat/long in position F1 and F2 x100 in format DD MM.mmm of Inomar format .ses3 (SIS-ID) are correct. X and Y in F7 and F8 are set in WGS84 UTM31N
Skoll High	CAGE22-5-HH-002-2D	07.07	23:11	67°31.250' 03°21.700'	07:25 +1 day	67°03.980' 02°43.240'	changed rec length to 3.5 sec at shot 9355; 7 m/s wind from S, high swell 2m from S. Dead channels: 18(?), 19(?) 24, 25, 95. Bed chan.: 14, 33, 46, 47, 54, 78, 96 Noisy chan.: 16, 74
Skoll High	CAGE22-5-HH-002-CHIRP	07.07	23:13	67°31.200' 03°21.600'	07:26 +1 day	67°03.980' 02°43.240'	
Skoll High	CAGE22-5-HH-003-2D	08.07	09:12	67°08.720' 02°29.680'	05:04	67°57.426' 05°02.927'	8 m/s wind from SW. Swell 2 to 2.5 m from SSW. Small gap between 15838 and 15839 due to reconfig of serial input. Windspeed came down to 1-3 m/s towards the end of the line. Dead channels: 18, 19 24, 25, 95. Bed chan.: 14, 33, 46, 47, 54, 78, 96 Noisy chan.: 16, 74. This 2D line has 3 bends.
Skoll High	CAGE22-5-HH-003-CHIRP	08.07	09:12	67°08.720' 02°29.680'	05:12	67°57.503' 05°04.330'	
Eldhø	CAGE22-5-HH-004-2D	09.07	07:36	67°53.970' 05°05.680'	20:18	68°42.798' 04°36.892'	recording length adjusted to 4 sec from shot 33148. water depth now at 1770m. Winds 7 m/s from N, waves calmed down to 1,5m. Shooting interval 6 sec from shot 34298. rec delay 1s, rec window 4 sec and sampling rate 0.5 ms from shot 34319.
Eldhø	CAGE22-5-HH-004-CHIRP	09.07	07:34	67°53.970' 05°05.680'	20:22	68°42.798' 04°36.892'	17.30 UTC: Tests of 2-10kHz at depth 2.6 km for 5 min. Settings returned to 3kHz. Acquisition briefly interrupted to change recording length.
Eldhø	CAGE22-5-HH-005-CHIRP	09.07	22:55	68°42.924' 04°44.380'	02:33 +1 day	68°28.245' 04°47.252'	
Eldhø	CAGE22-5-HH-005-2D	09.07	23:07	68°42.170' 04°44.669'	02:35 +1 day	68°28.052' 04°47.142'	Problem with compressor. Initial shots (37895-38023) in the line without any energy. Acquisition resumed 23:22:50 from 38024 shot number. 5 m/s windspeed 8 degree wind

							direction. 1.5m swells . Record delay 1s , record window 4 sec. Sampling interval 0.5 ms. 4.5 kn
Eldhø	CAGE22-5-HH-006-CHIRP	10.07	02:33	68°28.120' 04°47.192'	03:54	68°25.971' 04°35.142'	transit line
Eldhø	CAGE22-5-HH-006-2D	10.07	02:38	68°27.811' 04°46.915'	03:47	68°25.891' 04°36.281'	transit line
Eldhø	CAGE22-5-HH-007-CHIRP	10.07	03:55	68°26.000' 04°34.833'	08:42	68°42.602' 04°25.219'	
Eldhø	CAGE22-5-HH-007-2D	10.07	04:00	68°26.075' 04°34.116'	08:42	68°42.602' 04°25.219'	4.7 m/s windspeed from 330 degrees direction. Waves around 1.5m. Record delay 1s , record window 4 sec. Sampling interval 0.5 ms. 4.5 kn speed. Crossed planned initial point of line around 4:16:00. Ended line on a long turn to line 008
Eldhø	CAGE22-5-HH-008-CHIRP	10.07	08:42	68°42.584' 04°24.797'	08:42	68°42.602' 04°25.219'	Changed Area on SPB to Line008 (has been recording lines 5,6,7 as Line005) updated sound speed on SPB to ctd 1131
Eldhø	CAGE22-5-HH-008-2D	10.07	08:44	68°42.584' 04°24.797'	13:19	68°25.139' 04°25.704'	2 m/s wind from NNW, swell 1-1.5 m, line started on a turn from line 007. Record delay 1s , record window 4 sec. Sampling interval 0.5 ms. Recording delay 2 s from SP 44480, recording 3 sec
Eldhø	CAGE22-5-HH-009-CHIRP	10.07	13:20	68°25.051' 04°25.497'	14:27	68°24.928' 04°13.071'	Transit line westward about 5 nm. Recording parameters unchanged.
Eldhø	CAGE22-5-HH-009-2D	10.07	13:21	68°25.051' 04°25.497'	14:29	68°25.089' 04°13.149'	Transit line westward about 5 nm. Recording parameters unchanged. Changed streamer towing depth to 2.5 m for transit to check whether birds keep stable at shallower tow.
Eldhø	CAGE22-5-HH-010-CHIRP	10.07	14:27	68°24.928' 04°13.071'	18:17	68°31.132' 04°55.585'	Part of line 10 recorded as line 09 untill 18:10 UTC
Eldhø	CAGE22-5-HH-010-2D	10.07	14:31	68°25.183' 04°13.556'	18:13	68°31.026' 04°54.836'	Sailing towards NE. Windspeed 5.9 m/s. Wind direction 132 degrees. Waves around 1 m. Recording parameters unchanged.

Eldhø	CAGE22-5-HH-Transit 010_011-CHIRP	10.07	18:23	68°31.216' 04°56.296'	20:43	68°30.152' 04°06.022'	Transit line.Line 11 in data now. Need to be changed to transit 10-11.
Eldhø	CAGE22-5-HH-011-CHIRP	10.07	20:45	68°30.144' 04°05.131'	09:59 +1 day	68°50.320' 05°50.951'	apply clicked on 21:18:00 (UTC). This is Line 12 which need to be changed to line 11.
Eldhø	CAGE22-5-HH-011-2D	10.07	21:16	68°30.822' 04°08.311'	09:59 +1 day	68°50.320' 05°50.951'	Seimsic line 11 and Chirp line 12 are same track. 10.5 m/s (increased to 13.5 m/s by 01:20 UTC) windspeed 168 degrees wind direction. 4.5 kn speed. Around 21:45:00 survey/GEOEEL closed and started again (shot number:49394) to avoid time issues in GPS string. 49393 only shot with wrong time in header. Bird target changed to 3m 06:45. at 08:00 the line started on a long turn to the nxt line, consider processing the turn separately. changed record length to 3.5 sec from shot 55824.
Lofoten Basin	CAGE22-5-HH-012-CHIRP	11.07	10:01	68°50.137' 05°50.782'	13:49	68°35.435' 05°40.223'	
Lofoten Basin	CAGE22-5-HH-012-2D	11.07	10:02	68°50.137' 05°50.782'	13:49	68°35.435' 05°40.223'	Line SSW into the wind of 12m/s, increasing sea state up to 2 m swell. Rec delay 2s, Rec window 3.5s, sampl.rate 0.5ms.
Lofoten Basin	CAGE22-5-HH-transit12-13-CHIRP	11.07	14:17	68°34.000' 05°38.690'	16:19	68°15.558' 05°28.815'	
Glomar High	CAGE22-5-HH-013-2D	11.07	16:34	68°15.065' 05°28.495'	21:59	67°56.315' 04°54.628'	Initial few shots with previous rec parameters. At 59027 shot number, recording delay changed to 1s and record length to 4s. At 59155 shot number rec length changed to 3 sec and sampling interval to 0.25 ms. Sailing towards S-SW with 4.5Kn speed , 11.8 m/s windspped 183 degree direction. Around 1.8-2.2 m high waves.
Glomar High	CAGE22-5-HH-013-CHIRP	11.07	16:20	68°15.508' 05°28.785'	21:50	67°56.879' 04°55.735'	
Glomar high	CAGE22-5-HH-014-CHIRP	11.07	22:18	67°57.025' 04°54.598'	06:41 +1 day	67°31.699' 05°40.915'	

Glomar High	CAGE22-5-HH-014-2D	11.07	22:20	67°57.023' 04°55.019'	06:41 +1 day	67°31.699' 05°40.915'	10.4 C seawater temperature, 10 m/s windspeed from 189 deg direction. Around 2m waves. Recording parameters same as previous line
Vøring Basin	CAGE22-5-HH-015-CHIRP	14.07	07:41	67°32.467' 05°42.364'	20:26	67°07.123' 04°00.218'	
Vøring Basin	CAGE22-5-HH-015-2D	14.07	07:41	67°32.467' 05°42.364'	20:23	67°07.268' 04°00.561'	Restarting survey. Rec.delay 1 sec, rec.window 3 sec, sample.rate 0.25ms. Wind 8m/s from W. Still high swell 2,5 m but relatively calm long waves. Sailing 4.1kn towards SW into waves and wind.
Vøring Basin	CAGE22-5-HH-016-CHIRP	14.07	22:30	67°12.193' 04°01.234'	04:22 +1 day	67°00.110' 03°14.974'	
Vøring Basin	CAGE22-5-HH-016-2D	14.07	22:36	67°12.060' 04°00.362'	04:22 +1 day	67°00.072' 03°14.917'	Recording parameters same as previous one. 9.7 m/s windspeed from 262 degrees. Around 2.2 m high waves. Sailing southwest.
Vøring Basin	CAGE22-5-HH-017-CHIRP	15.07	04 22:41	67°00.090' 03°14.945'	07:00	67°00.313' 03°37.297'	
Vøring Basin	CAGE22-5-HH-017-2D	15.07	04:34	66°59.283' 03°14.802'			7 m/s windspeed from 260 degrees direction. Waves around 2 m. sailing towards East. Recording parameters same as previous.
Vøring Basin	CAGE22-5-HH-018-2D	15.07	07:00	67°00.313' 03°37.297'	13:40	67°25.908' 03°37.161'	Data of line 018 is in line 017 as new line was not started at the end of the transit line 17. start of time is approximate 7:00:00 UTC
Vøring Basin	CAGE22-5-HH-018-CHIRP	15.07	07:00	67°00.313' 03°37.297'	13:39	67°25.838' 03°37.151'	

3D seismic line log

Expedition: Helmer Hanssen CAGE22-5 Survey: Skoll High 3D 15.07.2022 – 18.07.2022 Sheet #: 1 - 8

3D seismic over Skoll high, Vøring Margin

Survey configuration: see end of document Times are UTC

3D line number:	Date: Start - end	Time (UTC): Start - end	Shot point number First - last	Shot point number when crossing planned start and end of line	Comments (sailing direction, ship speed, depth sensor, wind speed, air temperature downtime, etc.)
00	15.07-16.07	23:07-00:56	1- 1256	N/A	Pre-survey warm-up and test. Test line at the beginning with speed c.2.5-4.0 knots. Initial records with manual trigger then with gun as source. 9 m/s windspeed from 274 degrees. Waves around 1.6 m. Water velocity of EM302 show 1490-1491 m/s in surface water
01	16.07-16.07	00:58-02:33	1257-2395	1330-2342	10.3 C sea temperature, 8.4 C air temperature 9.4 m/s wind speed (from 288 direction). Bad channels: 5,8,10,11,13,30,49,57,59,71,75,95,105
10	16.07-16.07	03:46-06:41	2396-4492	3270-4313	10.07 C sea temperature, 7.4 C air temperature 7.9 m/s wind speed (from 258 direction). GPS on port door missing occasionally
03	16.07-16.07	06:56-08:54	4493-5905	4635-5679	10.3 C sea temperature, 8.4 C air temperature 8 m/s wind speed (from 277 direction). Waves around 1 to 1.5m GPS on port door missing occasionally, likely due to floatation element having rotated thereby drowning the GPS

08	16.07-16.07	09:25-11:12	5906-7189	6164-7175	10.3 C sea temperature, 8.4 C air temperature 8 m/s wind speed (from 280 direction). Waves around 1 to 1.5m. GPS on port door missing almost all the time. Occasional values coming in. Based on Seatrack telemetry, these values seem 'jumpy' and unstable and a bit off. CHECK positions carefully. Floatation unit on paravane has rotated and GPS antenna is now partly drowned. After end of line, pick up port paravane to fix. Discovered also break on gun frame.
05	16.07-16.07	17:07-19:27	7191-8867	7574-8575	Paravane fixed and back in water. 10.3 C sea temperature, 8.0 C air temperature 10 m/s wind speed (from 270 direction). Waves around 1 to 1.5m. Dead channels: 5,8,10,11,13,30 (not dead but bad),49 (not dead but bad),57,59,71,75,78 (not dead but bad), 95,105 (not dead but bad),112. AFT missing in between
06	16.07-16.07	19:32-21:27	8868-10249	9100-10061	Sailing southeast with 10.28 C water, 8.4 C air temperature, 7.8 m/s win from 267 degrees. Waves around 1.0-1.3 m. Starboard GPS missing occasionally.
07	16.07-16.07	21:42-23:34	10250-11591	10363-11334	Sailing NW with 10.4 C water, 8.8 C air temperature, 7 m/s win from 267 degrees. Waves around 1.0-1.5 m.
04	16.07-17.07	23:38-01:37	11592-13021	11870-12813	Sailing southeast with 10.2 C water, 8.8 C air temperature, 3.6 m/s wind from 250 degrees. Waves around 1.0 m.

09	17.07-17.07	01:41-03:52	13022-14591	13245-14310	Sailing Northwest with 10.17 C water, 9.4 C air temperature, 4.9 m/s wind from 210 degrees. Waves around 1.0 m.
02	17.07-17.07	03:55-06:06	14592-16150	14944-15955	Sailing southeast with 10.2 C water, 9.8 C air temperature, 6.6 m/s wind from 170 degrees. Waves around 1.0 m.
11	17.07-17.07	06:09-08:06	16151-17552	16399-17335	Sailing Northwest with 10.17 C water, 9.9 C air temperature, 7.7 m/s wind from 140 degrees. Waves around 1.0 m.
12	17.07-17.07	08:10-10:12	17553-19016	17877-18855	Sailing southeast with 10.76 C water, 10.3 C air temperature, 9.6 m/s wind from 170 degrees. Waves around 1.0 m.
13	17.07-17.07	10:23-12:05	19017-20240	19162-20118	Sailing Northwest with 10.2 C water, 9.9 C air temperature, 9.4 m/s wind from 127 degrees. Waves around 1.0 m. Ship apparently has more problems tracking the designed acquisition line, deviations of up to 10 m.
14	17.07-17.07	12:30-14:27	20241-21644	20459-21487	Sailing southeast with 10.8 C water, 10.1 C air temperature, 10.5 m/s wind from 113 degrees. Waves around 1.0 m. 15 m off track to star board at the beginning of the line.
15	17.07-17.07	14:30-16:43	21645-23244	21958-22995	Sailing Northwest with 10.8 C water, 9.9 C air temperature, 9.9 m/s wind from 237 degrees. Waves around 1.0 m.
16	17.07-17.07	16:46-18:53	23245-24755	23601-24585	Sailing southeast with 10.85 C water, 10.1 C air temperature, 7.5 m/s wind from 230 degrees. Waves around 1.0 m.
17	17.07-17.07	18:55-	24756-25148	Line aborted	Sailing Northwest with 10.7 C water, 10.4 C air temperature, 7.9 m/s wind from 217 degrees. Waves around 1.0 m.

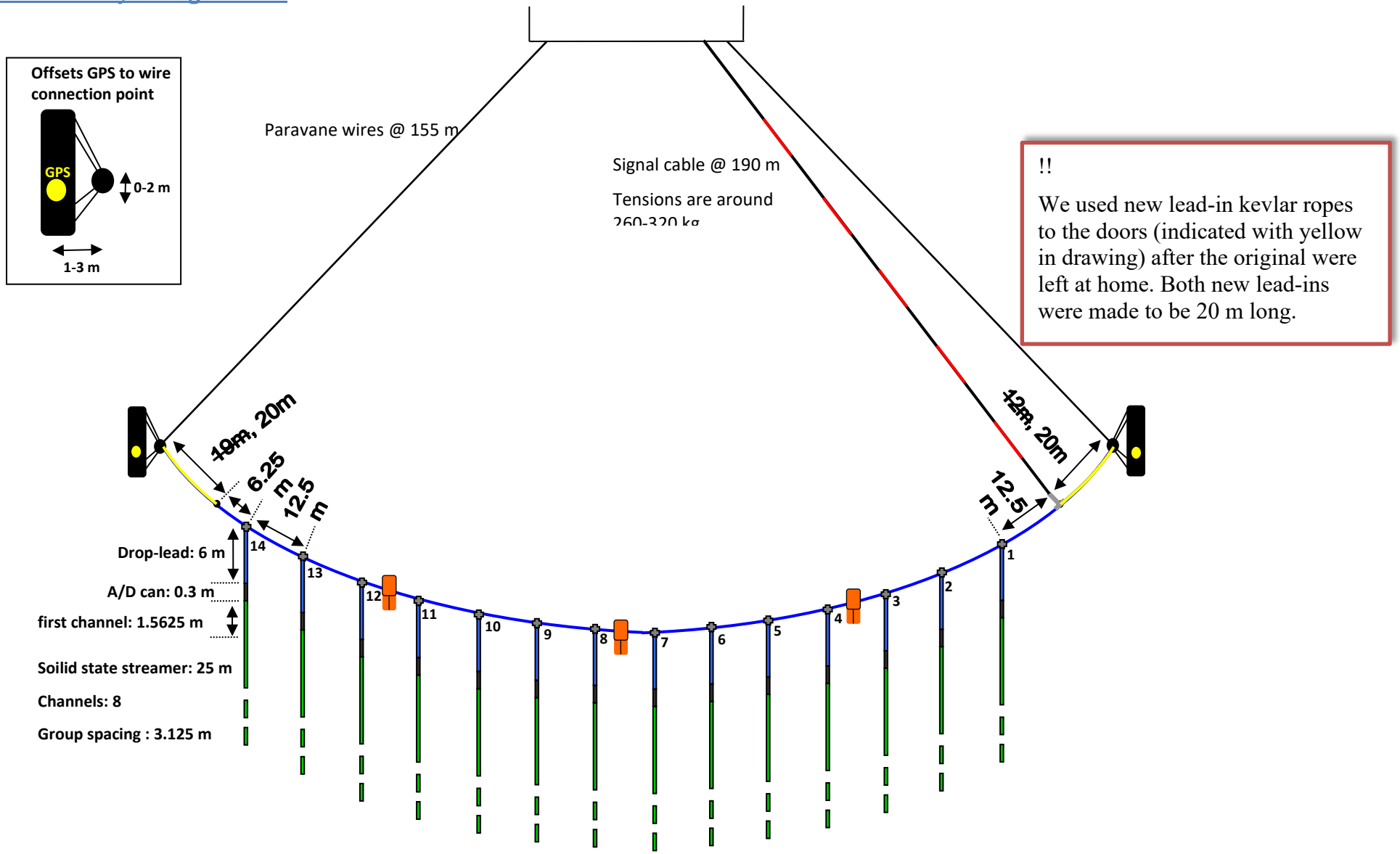
					Problems with one of the guns (15/15) at the start of the line: seismic data show significantly reduced energy. Line aborted to pick up guns.
17	17.07-17.07	21:55-23:57	25149-26611	25459-26434	The aft mini-GI gun was leaking air. Gun replaced with spare. Restarting line 17 1.5 nm off start of line. Sailing Northwest with 10.6 C water, 9.9 C air temperature, 8.8 m/s wind from 205 degrees.
18	18.07-18.07	00:01-02:02	26612-28069	26897-27910	Sailing southeast with 10.9 C water, 10.1 C air temperature, 7.5 m/s wind from 210 degrees. Waves around 1.5 m. STB GPS missing intermittently.
19	18.07-18.07	02:05-04:10	28070-29578	28280- 29350	Sailing Northwest with 10.72 C water, 10.4 C air temperature, 8.4 m/s wind from 195 degrees.
20	18.07-18.07	04:13-06:21	29579-31125	29879-30972	Sailing southeast with 10.7 C water, 10.1 C air temperature, 8.2 m/s wind from 230 degrees. Waves around 1 m.
21	18.07-18.07	06:24-08:25	31126-32578	31397-32375	Sailing Northwest with 10.62 C water, 10.1 C air temperature, 6.7 m/s wind from 220 degrees. Waves around 1.6 m.
22	18.07-18.07	08:27-10:20	32579-33937	32855-33807	
23	18.07-18.07	10:31-12:19	33938-35238	34125-35042	Sailing Northwest with 10.6 C water, 10.2 C air temperature, 5 m/s wind from 186 degrees. Waves around 1.6 m
24	18.07-18.07	12:21-14:23	35239-36701	35508-36600	
25	18.07-18.07	14:41-16:36	36702-38077	36792-37856	Sailing Northwest with 10.7 C water, 9.8 C air temperature, 2 m/s wind from several different angles (we are in the centre of a cyclone).

					Waves around 2 m but with long wavelength coming from SW.
26	18.07-18.07	16:45-18:19	38078-39212	38209-39190	Sailing southeast with 10.9 C water, 10.7 C air temperature, 4.2 m/s wind from 330 degrees. Waves (mostly long period/wavelength) around 1.6 m.

Planned acquisition lines:

Line number	Start coordinate	End coordinates	Crossline coverage (m)
01	67 17.7611 3 47.3257	67 20.3746 3 34.8874	65.00
02	67 20.4054 3 34.9306	67 17.7918 3 47.3692	130.00
03	67 17.7304 3 47.2823	67 20.3439 3 34.8441	195.00
04	67 20.4361 3 34.9738	67 17.8225 3 47.4126	260.00
05	67 17.6997 3 47.2389	67 20.3131 3 34.8009	325.00
06	67 20.4669 3 35.0171	67 17.8532 3 47.4560	390.00
07	67 17.6690 3 47.1955	67 20.2824 3 34.7577	455.00
08	67 20.4976 3 35.0603	67 17.8839 3 47.4994	520.00
09	67 17.6383 3 47.1521	67 20.2516 3 34.7144	585.00
10	67 20.5284 3 35.1036	67 17.9146 3 47.5429	650.00
11	67 17.6076 3 47.1087	67 20.2209 3 34.6712	715.00
12	67 20.5591 3 35.1468	67 17.9453 3 47.5863	780.00
13	67 17.5769 3 47.0652	67 20.1901 3 34.6280	845.00
14	67 20.5899 3 35.1901	67 17.9760 3 47.6297	910.00
15	67 17.5462 3 47.0218	67 20.1593 3 34.5848	975.00
16	67 20.6206 3 35.2333	67 18.0067 3 47.6732	1040.00
17	67 17.5155 3 46.9784	67 20.1286 3 34.5415	1105.00
18	67 20.6514 3 35.2766	67 18.0374 3 47.7166	1170.00
19	67 17.4848 3 46.9350	67 20.0978 3 34.4983	1235.00
20	67 20.6821 3 35.3198	67 18.0681 3 47.7601	1300.00
21	67 17.4541 3 46.8916	67 20.0671 3 34.4551	1365.00
22	67 20.7129 3 35.3631	67 18.0988 3 47.8035	1430.00
23	67 17.4234 3 46.8482	67 20.0363 3 34.4119	1495.00
24	67 20.7437 3 35.4063	67 18.1294 3 47.8469	1560.00
25	67 17.3927 3 46.8048	67 20.0056 3 34.3687	1625.00
26	67 20.7744 3 35.4496	67 18.1601 3 47.8904	1690.00

P-Cable survey configuration:



Observed spread of paravanes: 178-183 m
Observed distance between gun and paravanes: STB: 109 – 113 m, PRT: 112-122 m, deviations between distances to both paravanes up to 10 m, particularly large difference between lines in NW or SE direction. Distance more equal on SE lines both distances at 110-115 m, port paravane almost always 2-3 m further away.

Ship's speed: 4 kn ± 0,3 kn
Gun system: Two mini-GI (30/30 in^3 and 15/15 in^3)
Gun towing depth: 2 m
Shooting pressure: ~170 bar
Shooting interval: 5 sec
Recording window: 3.5 sec
Recording delay: 0 sec
Sampling interval: 0.25ms
Streamer depth: 2 m

Switches used:

Switch no	6013	6196	6031	6012	6017	6028	6011	6030	6183	6034	6175	6187	6022	6019
Depth reading on deck after survey (m)														

Yellow: kind of okay
Red: Wrong. Recalibration required