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R/V Helmer Hanssen

19-08-20 to 31-08-20

Tromsø – Tromsø

CAGE-20-5 Cruise Report

Tectonic stress studies and seismic surveys on the West-Svalbard margin

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With contributions by cruise participants

DOI:

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INTRODUCTION AND OBJECTIVES

Cruise CAGE20-5 with UiT's research vessel R/V Helmer Hanssen is carried out to collect cross-disciplinary data for addressing the objectives of the SEAMSTRESS project (*Tectonic stress effects on Arctic methane seepage*) and the Norwegian Centre of Excellence for Arctic Gas Hydrate, Environment and Climate, CAGE.

The primary goal of cruise CAGE20-5 is to continue the large-scale ocean-bottom seismic experiments on the eastern segment of the Vestnesa Ridge that commenced in 2019 during cruise CAGE19-1 (Figure 1). Furthermore, we will acquire important site survey seismic data for International Ocean Discovery Program (IODP), proposal 985 and additional regional seismic data on the western Svalbard Margin. Other data that will be acquired on this cruise are Chirp sub-bottom profiling, multibeam and water column hydro-acoustic data.

In 2019, seven ocean-bottom seismometers (OBS) were deployed along the crest of the eastern segment of Vestnesa Ridge in order to monitor microseismic activity aiming to detect regional and local earthquakes and potentially events related to active gas seepage from the pockmarks along this eastern segment (Figure 1). These seven OBS will be recovered during this cruise. Two of the seven OBS belong to UiT and will be reequipped for another year-long deployment together with 8 OBS from the Alfred-Wegener Institute (AWI). Together, these 10 OBS will be deployed in a larger array on the southern flank of Vestnesa Ridge, northward from the corner where the Molloy Transform Fault (MTF) encounters the termination of the Knipovich Ridge. The overall aim is to detect local and regional earthquakes that relate to and/or impact local faulting within Vestnesa Ridge and may control fluid flow.

IODP proposal 985 *Eastern Fram Strait Palaeo-archive* (FRAME) proposed to drill five sites on the western Svalbard margin in order to study amongst other chronostratigraphy, palaeoceanographic and palaeoclimatic evolution, forcing mechanisms responsible for main climatic transitions and the dynamics of the Svalbard Barents Sea Ice Sheet complex (SBSIS). This cruise will acquire additional site survey seismic data for proposed primary and alternate drill sites and for identifying additional alternate sites.

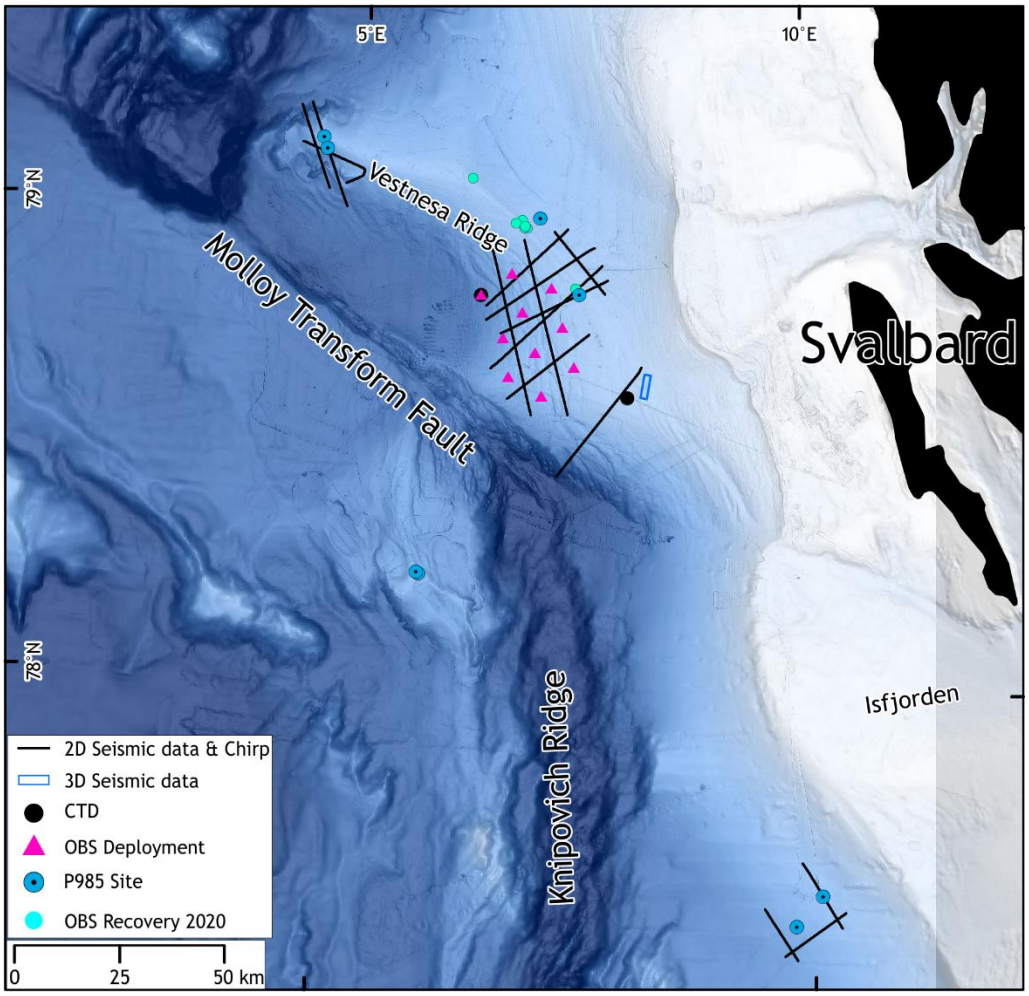


Figure 1: Overview of the working areas and surveys.

METHODS

Seismic methods

The high-resolution P-Cable 3D seismic system was used together with a Granzow high-pressure (210bar) compressor and mini-GI guns. Onboard seismic processing and QC of P-Cable seismic data provided preliminary 3D cubes and migrated 2D seismic sections for quality assessment and preliminary interpretations.

During this cruise we 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.

Other acquisition systems that were partly used include SIMRAD EK 60 38 and 18 kHz echosounder, the Edgetech Discover penetration sub-bottom profiler and a CTD to extract information about different (T, S) properties of water masses to calculate the speed of sound for calibrating the acoustic systems.

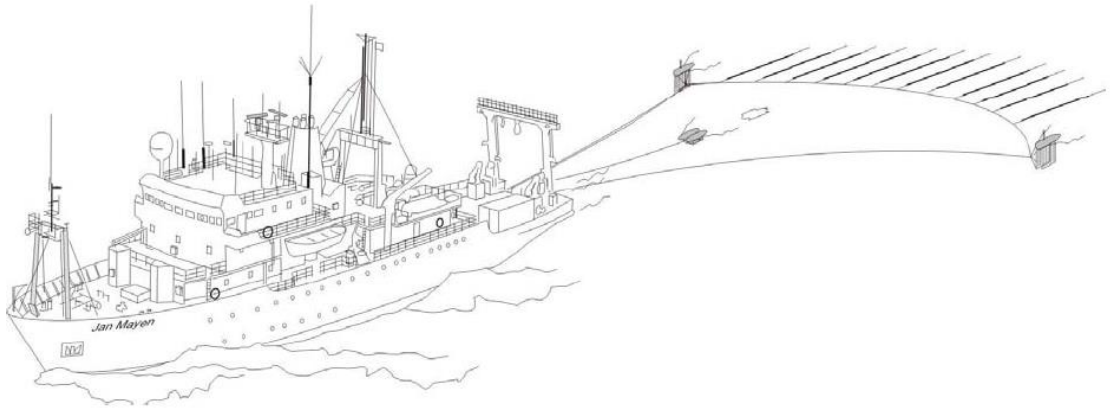
The P-Cable 3D (2D) seismic system

The P-Cable 3D high-resolution seismic system consists of a seismic cable towed perpendicular (cross cable) to the vessel's steaming direction (Figure 2). 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 2). 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 3.125 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 to 2.5 m, and to 3 m when weather conditions were worse and wave height above 2 m.

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.



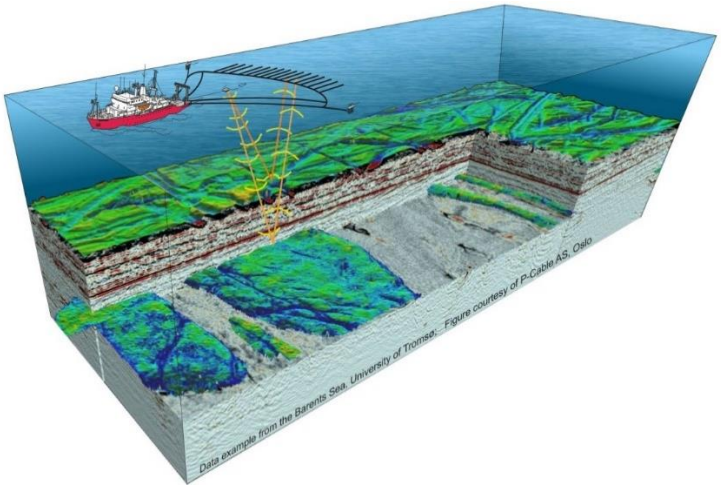


Figure 2: Schematic sketch an acquisition principle of the P-Cable high-resolution 3D seismic system.

Multi-component ocean bottom seismometer (OBS)

10 multi-component OBS were deployed to record microseismic activity during a year-long deployment. The OBS systems are autonomous sea floor recording platforms, designed to record both, compressional and shear waves from regional seismicity or reflected and refracted through the sediments during active experiments (Figure 3). It consists of a titanium frame with buoyancy made of syntactic foam, a KUMQUAT acoustic release system, and a digital data recorder (6D6) in a separate titanium pressure cylinder. A hydrophone and a 3-component seismometer are used to record the seismic wavefield. The Tromsø OBS has a 4.5 Hz K/MT 210 seismometer (three-compnent geophone) attached whereas the 8 OBS from AWI have a Trillium broadband seismometer that is self-levelling and has a broader frequency range. While the hydrophone is fixed to the frame of the OBS, the geophone is detached from it for the UiT OBS. This design insures that the geophone is mechanically decoupled from the frame, to avoid noise generated by the frame being recorded by the geophone. On the AWI OBS the Trillium Seismometer is located between frame and anchor weight so coupling to the ground is via the anchor. The whole system is rated for a depth of up to 6000 m. The OBS is attached to a ground weight (anchor) via the acoustic release system in order to make it descend to the sea floor after deployment. When the seismic experiment is completed, the OBS is released from its ground weight by sending an acoustic code and it rises to the sea surface by its buoyancy.

Figure 3: Ocean-bottom seismometers of UiT (left) and AWI (right).

The OBS systems were prepared, programmed and the releasers tested at 2000 m water depth prior to deployment. The first channel records the hydrophone data, while channel two, three and four are connected to horizontal and vertical components of the geophone. The locations were selected based on seismic anomalies in the 3D seismic data and previously acquired OBS data. The station list is given in the appendix.

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 at Svalbard was …….

The cruise mobilized in Tromsø on the 18th August and departed on the 19th.

Wednesday, 19.08.2020

The scientific personnel arrived in the morning hours and started to prepare OBS instruments and lab areas. Most other seismic equipment was already prepared from the previous cruise. Departure from Tromsø at 14:00.

Thursday, 20.08.2020

On transit to the West-Svalbard Margin. At 20:30 we received a call from the Norwegian coast guard that a small passenger vessel lost its propulsion due to fishing gear in the propeller, and is now drifting 100 nm north of Bear Island. We agreed with the coast guard to tow the passenger vessel to the Isfjorden Fan where it would be overtaken by the coast guard vessel KV Harstad. It meant that we had to cancel our planned seismic survey at Bellsund Fan at the SW Svalbard Margin and have to come back to it at the end of the cruise.

Friday, 21.08.2020

We arrived at the Isfjorden Fan at 18:00 and left the passenger vessel with the coast guard. As weather forecasts show poor weather starting Sunday we also cancelled 3 seismic lines as part of the IODP site survey at Isfjorden Fan since it is considerably more important to recover the seven OBS in good weather.

Saturday, 22.08.2020

At 01:00 we conducted a releaser test in 2000 m water depth on our way to the study area. We arrived at the southernmost OBS30 deployment at 06:30 and released the OBS successfully from its anchor weight. It was on deck 45 min afterwards. At 08:45, the three OBS surrounding the Lunde pockmark were simultaneously released and all recovered 09:30. Slightly further north in this seepage area, two more OBS were recovered and on deck at 11:15. The last of the seven OBS is an hour sailing NW at the bend of Vestnesa Ridge and successfully recovered at 13:00. Meanwhile, several AWI OBS have been prepared for deployment. Another releaser test is required and conducted at OBS1 deployment site in 2000 m water depth. This test was followed by a CTD cast with one water sample for calibration, completed at 17:00. By this time 3 AWI OBS and 1 UiT OBS were ready prepared for deployment. These four OBS were deployed at OBS stations 1, 4 and 5 (AWI) and station 2 (UiT) between 18:30 and 10:30. Subsequently, we deployed the 2D seismic system in order to acquire 3 seismic lines as part of the site survey for the IODP proposal 985.

Sunday, 23.08.2020

2D seismic line 01 starts at 00:10 heading NE onto and across the Vestnesa Ridge crest. Line 3 finished at 09:30. We continued with deploying the long-term OBS. Two AWI OBS were deployed at stations 8 and 7. The second UiT OBS was deployed at station 10 at 14:20. The three remaining AWI OBS were deployed between 15:30 – 18:10 at stations 9, 6 and 3. A grid of 5 seismic lines was planned across the OBS array. Those lines provide seismic sources with exact positioning which are to be used to relocate the OBS position at the ocean floor. Seismic line 04 starts heading S at 20:00.

Monday, 24.08.2020

Unfortunately, weather conditions had deteriorated, winds were up to 15 m/s and wave heights were approaching 2 m. We had to suspend the seismic survey after line 04 at 00:30. Rough weather conditions persisted over most of the day. Winds and sea state slightly calmed down in the evening and forecasts showed even calmer conditions. At 09:45, we continued with the seismic survey on line 05.

Tuesday, 25.08.2020

Seismic line 05 was finished at 02:30. The next 3 lines crossed the OBS array in East-West direction and are completed between 05:00 and 17:00. We recovered the 2D seismic system and sailed west towards the end of Vestnesa Ridge. Here, additional 2D seismic data was needed as part of the IODP site survey. Seismic line 09 started at 19:45 heading NW there by crossing both the proposed primary and alternate IODP drill site. Seismic line 10 started in opposite direction, offset by 2.5 km to the SW.

Wednesday, 26.08.2020

Seismic line 11 started at 01:50 parallel to the Vestnesa Ridge end on its southern flank thereby crossing multiple existing seismic lines. Line 11 was completed at 04:15. We recovered the 2D seismic system and sailed east towards an elongated depression, a fluid flow anomaly in 900 m water depth on the Svalbard continental margin close to the northern termination of the Knipovich Ridge. The P-Cable 3D seismic system was prepared during the transit. We arrived at the depression at 09:45. At 10:15 we started to deploy the P-Cable 3D seismic system, and at 11:28 it was operating on our pre-survey setup routine. The 3D seismic survey started on acquisition line 01 at 12:26.

Thursday, 27.08.2020

Acquisition line 13 started exactly at midnight. During line 25, one of the streamer sections showed delayed responses or missing data. This would have been the second to last line of the 3D survey, however, given the trouble, we finished after this on and recovered the P-Cable system. The seismic was configured back to 2D mode and ready to deploy at 23:00. We acquired a CTD station and a Chirp line during reconfiguration and then deployed the 2D seismic.

Friday, 28.08.2020

2D seismic line 12 started shortly before 01:00 and finished at 04:30. We recovered the seismic system again and sailed to the Isfjorden Fan in order to acquire the seismic data for the IODP site survey that we missed in the beginning of the cruise. Three seismic lines (13, 14 and 15) were acquired between 11:15 and 16:00. This concludes all surveys during this CAGE20-5 cruise as bad weather is approaching from the north. We started our 2-day journey back to Tromsø.

Saturday, 29.08.2020

Transit to Tromsø in bad, stormy weather.

Sunday, 30.08.2020

Transit to Tromsø in bad weather. Arrival in Tromsø at 21:00

Monday, 31.08.2020

08:00 End of cruise. Demobilization.

OBS deployments at Vestnesa Ridge

The CAGE19-1 cruise deployed seven OBS long-term along the eastern segment of the Vestnesa Ridge in 2019 (Figure 4). All those OBS were successfully recovered during this cruise (Table 1). This cruise sub-sequentially deployed ten OBS for another long-term experiment (Figure 5). Eight of those ten OBS were provided in a collaboration with AWI. The ten OBS were deployed in a larger array on the southern flank of Vestnesa Ridge towards the Molloy Transform and Knipovich Ridge in order to detect local and regional earthquakes that relate to and/or impact local faulting within Vestnesa Ridge and may control fluid flow.

Details of the deployment position, configuration and auto-release are listed in Tables 2, 3 and 4. These OBS will be recovered during a cruise in 2021. Five 2D seismic lines that cross between the OBS locations were acquired in order to provide seismic sources with exact position for relocation of OBS systems.

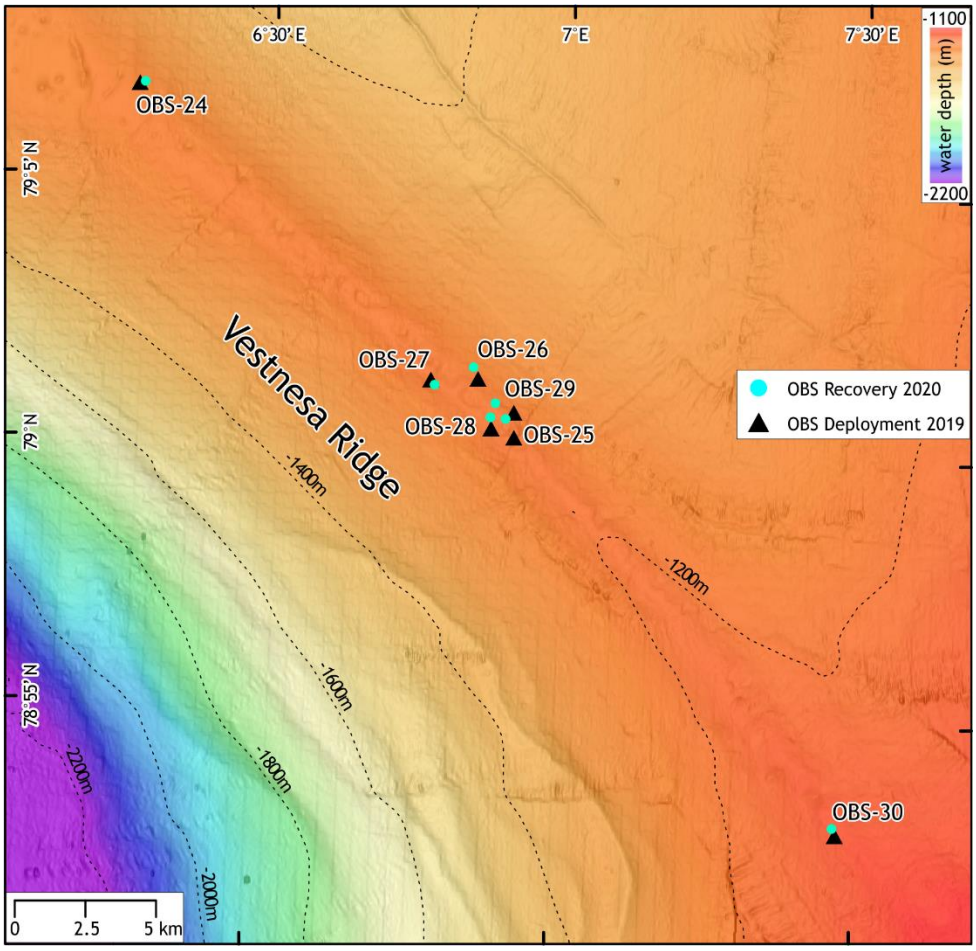


Figure 4: Positions of the OBS deployed during CAGE19-1 in 2019 and recovered during this expedition.

Station Name	Recovery Date	Recovery Time (UTC)	Recovery position	Recovery Depth (m)	Comment
OBS-24	22.08.2020	10:52	7906.794N 0616.863 E	1215	UiT
OBS-25	22.08.2020	07:11	7900.668N 0654.400 E	1200	UiT
OBS-26	22.08.2020	09:14	7901.621N 0651.022E	1200	Geomar
OBS-27	22.08.2020	08:26	7901.265N 0647.18E	1200	Geomar
OBS-28	22.08.2020	07:20	7900.689N 0652.910E	1200	Geomar
OBS-29	22.08.2020	07:29	7900.955N 0653.310E	1200	Geomar
OBS-30	22.08.2020	07:15	7853.067N 0728.073E	1133	Geomar

Table 1: Recovery positions of the 7 OBS deployed in 2019. Notice that no depth was recorded for the recovery position for OBS 25-29 as the echosounder was switched off due to interference with the acoustic releaser system.

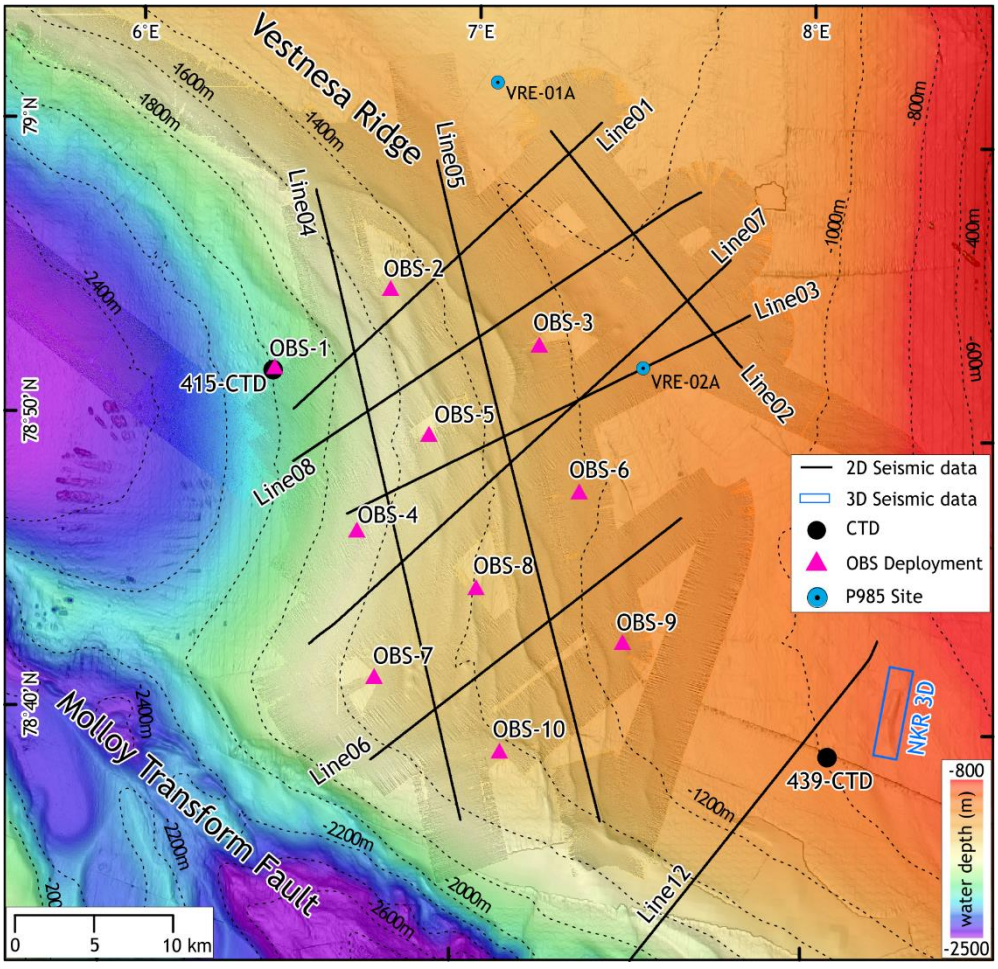


Figure 5: Overview figure showing OBS deployed and seismic data acquired during this expeditions.

	Deployment		Deployment Position		
Station	Date	Time UTC	Latitude	Longitude	Depth (m)
VSN01	22.08.2020	16:29	78° 51.983‘ N	06° 26.925‘ E	1960
VSN02	22.08.2020	19:23	78° 54.796‘ N	06° 45.797‘ E	1507
VSN03	23.08.2020	16:09	78° 53.056‘ N	07° 12.306‘ E	1237
VSN04	22.08.2020	20:22	78° 46.536‘ N	06° 41.439‘ E	1679
VSN05	22.08.2020	17:46	78° 49.899‘ N	06° 53.411‘ E	1539
VSN06	23.08.2020	15:08	78° 48.097‘ N	07° 20.095‘ E	1215
VSN07	23.08.2020	11:25	78° 41.601‘ N	06° 45.452‘ E	1526
VSN08	23.08.2020	10:40	78° 44.728‘ N	07° 02.603‘ E	1412
VSN09	23.08.2020	13:34	78° 43.017‘ N	07° 28.305‘ E	1162
VSN10	23.08.2020	12:20	78° 39.206‘ N	07° 07.615‘ E	1425

Table 2. OBS deployment positions

	Recording	Sample	Gain	Seismo-meter	Hydro phone	6d6	Comment
Station	Start time	Rate (Hz)	HXYZ	Type	Inverted (I)	SN	
VSN01	22.08.2020 15:38:43	100	2 1 1 1	Trillium	H	61607077	Black flagpole 140 cm
VSN02	22.08.2020 14:43:08	100	4 4 4 4			61607191	UiT
VSN03	23.08.2020 14:59:58	100	2 1 1 1	Trillium	H	61607084	Black flagpole 130 cm
VSN04	22.08.2020 18:34:43	100	2 1 1 1	Trillium	H	61607073	White flagpole 130 cm
VSN05	22.08.2020 17:02:02	100	2 1 1 1	Trillium	H	61607204	White flagpole 138 cm
VSN06	23.08.2020 14:19:38	100	2 1 1 1	Trillium	I	61607080	Black flagpole 140 cm
VSN07	23.08.2020 09:23:43	100	2 1 1 1	Trillium	H	61607201	White flagpole 139 cm
VSN08	23.08.2020 09:29:52	100	2 1 1 1	Trillium	I	61607102	White flagpole 137 cm
VSN09	23.08.2020 12:30:17	100	2 1 1 1	Trillium	H	61607069	White flagpole 98 cm
VSN10	22.08.2020 14:49:30	100	4 4 4 4			61607185	UiT

Table 3. Recording parameters of the OBSs

	Synchronisation		Auto release		
Station	Date	Time UTC	Date	Time UTC	Release Code
VSN01	22.08.2020	15:34:50	04.10.2021	08:00	443422
VSN02	22.08.2020	14:42:43	05.10.2021	10:00	225437
VSN03	23.08.2020	14:58:51	04.10.2021	15:00	432174
VSN04	22.08.2020	18:31:01	04.10.2021	10:00	230555
VSN05	22.08.2020	16:58:57	04.10.2021	09:00	423721

VSN06	23.08.2020	14:18:18	04.10.2021	13:00	446171
VSN07	23.08.2020	09:23:14	04.10.2021	11:00	445717
VSN08	23.08.2020	09:01:46	04.10.2021	12:00	431547
VSN09	23.08.2020	12:24:11	04.10.2021	14:00	427332
VSN10	22.08.2020	14:47:45	05.10.2021	11:00	135253

Table 4. Synchronization and auto-release parameters

2D and 3D seismic acquisition at Vestnesa Ridge

The main objectives of the 2D seismic survey on the western Svalbard margin were: 1- to acquire site survey data for IODP drilling proposal 985 (Lucchi et al., 2020). This proposal has identified 5 sites from the Bellsund Fan in the south to the Vestnesa and Svyatogor Ridges on the northern part of this margin to be drilled for paleoceanographic and paleoclimatic studies. Several of the proposed drill sites lack a crossing line that have highest priority to be acquired. Our seismic survey will try to identify additional alternate sites for the proposal. The locations of most of the 2D seismic lines were carefully planned prior to the cruise based on existing seismic data; 2- have shooting lines recorded by the deployed OBSs to ease their relocation after recovery (Figure 5)

A short P-Cable 3D seismic survey was acquired over a subtle elongated depression feature located on the West-Svalbard continental margin in 900 m water depth directly north of where the Knipovich Ridge is abutted by the Molloy Transform. Existing 2D seismic data showed a leakage structure and strong BSR reflection. In addition, a 50-cm long gas hydrate section was cored during CAGE17-5 cruise, and piezometer measurements during CAGE19-3 cruise showed indications of a leakage event (Sultan et al., 2020). The P-Cable surveyed contained 25 acquisition lines and the final cube has an extent of 5,8x1,6 km covering the whole depression feature.

Multibeam bathymetry and sub-bottom profiler data were acquired simultaneously with the seismic data. Parameters for the 2D seismic and 3D seismic acquisition are given in Tables 5 and 6, respectively. A principle sketch of the 2D seismic acquisition geometry is shown in Figure 6 and for the 3D seismic geometry in Figure 2.

Table 5: The detailed survey parameters for the 2D seismic survey.

Survey parameters	
Deployment / recovery	0,5 h
Survey speed	5 kt
Source	1 mini GI 30/30 in^3 & 1 mini GI 15/15 in^3
Shooting rate	5-6 s
Shooting pressure	170 bar
Source towing depth	2 m
Dominant frequency (bandwidth)	140-180 Hz (20-400 Hz)

Positioning	GPS transponder on gun raft
Streamer length	370 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	2.5 m, 3 m on some lines in bad weather (see line log in appendix)
Sampling rate / interval	4000 Hz / 0.25 ms or 2000 Hz / 0.5 ms
Recording length	4-5 s

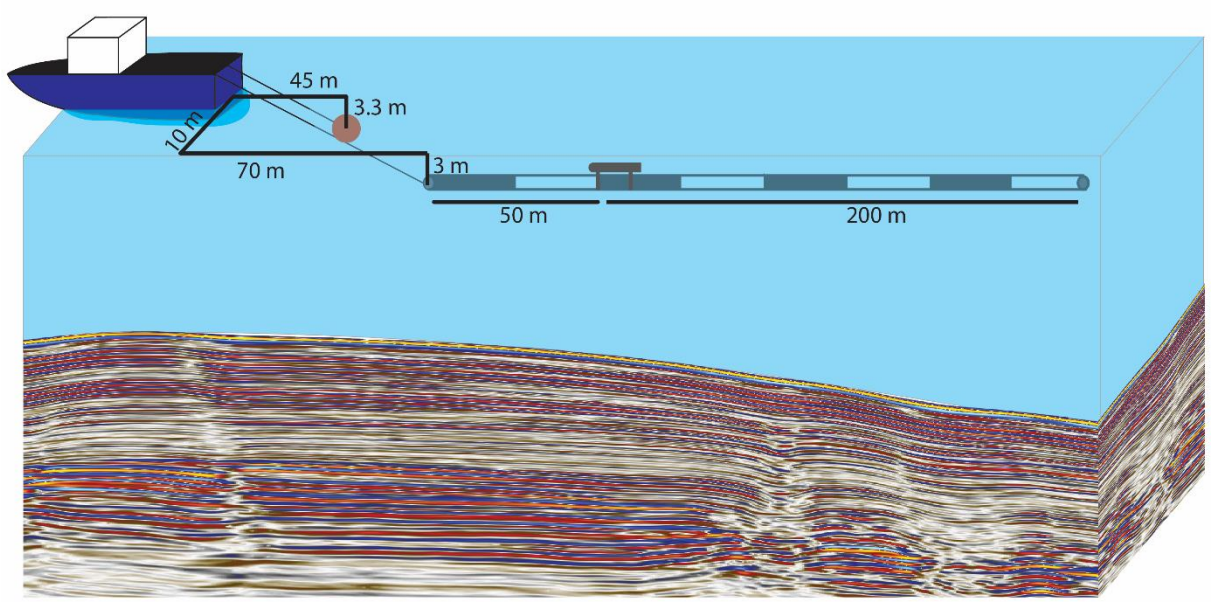


Figure 6: Acquisition geometry of the 2D multi-channel seismic streamer. Notice that in this cruise we used 12 streamer sections. Hence, the active section was 300 m instead of 250 m. The distance of the source behind the vessel varies but can be obtained from nav track records of the gun and aft Seatrack antennas.

Table 6: The detailed survey parameters for the 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	5 s
Shooting pressure	170 bar
Source towing depth	2 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 receiver group spacing
Streamer towing depth	1,5 m
Sampling rate / interval	4000 Hz / 0.25 ms
Recording length	4 sec

2D seismic processing

We processed 2D seismic data on board in RadExPro 2020.1 software, following a standard processing routine consisting of SEG-D import, geometry assignment, bad channels removal, burst noise removal, stacking, migration and post-migration amplitude equalization (Table 7).

The geometry parameters for this survey are outlined in Table 5 and Figure 6. Bad channels and removal, burst attenuation and a simple bandpass filter was applied to all lines. F-K filtering was applied to 2 of the lines (see table 7). Amplitude corrections (normalization, spherical divergence) were also applied.

In general the migration algorithm used was the Post Stack Kirchhoff Time migration with a constant velocity of 1500 m/s and a apertures ranging between 300 and 900 depending on the sources of the diffractions in specific lines. Without having velocity information, this was the most consistent migration across all lines. For complex geological settings, such as lines 9 and 10, a detailed velocity table is required as input to the Kirchhoff migration. In such cases, the Stolt F-K migration algorithm was used in addition, with a constant velocity of 1500 m/s. Processed data examples are shown in **Error! Reference source not found.**7 and **Error! Reference source not found.**8.

Table 7: Processing parameters for the 2D seismic survey.

Seismic processing flow	
SEG-D import and geometry assignment	Input of SEG-D files Geometry assignment and offset calculation
Filtering in the shot gathers	Removal of bad channels Bandpass filter 20-30-300-400 Hz Burst noise removal
F-K filtering in CDP gathers	Applied to lines 13-15 in the Isfjørden drift.
NMO and stacking	NMO (1480 m/s) Ensemble Stack
Migration	Pre/post-Stack Kirchhoff Time Migration ; constant Vp 1500 m/s; constant aperture 300-400 (most of the lines) 600-900 the steep lines (e.g., 12)
SEG-Y output	IBM floating point CDP_X,4R,IBM,181/ CDP_Y,4R,IBM, 185 Coordinate system: WGS-84-UTM32N

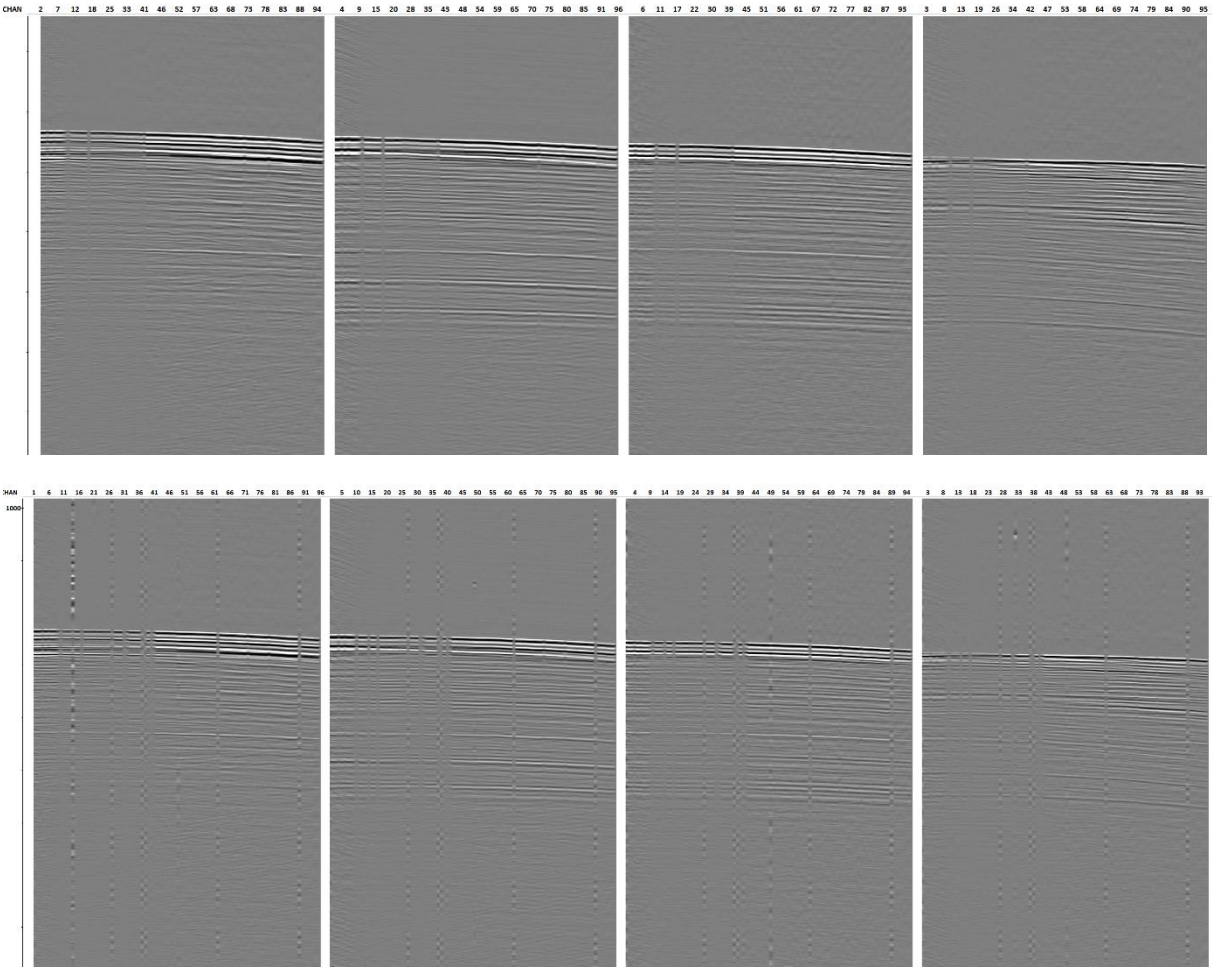


Figure 7: Shot gathers after (above) and before (below) burst noise removal for line 12.

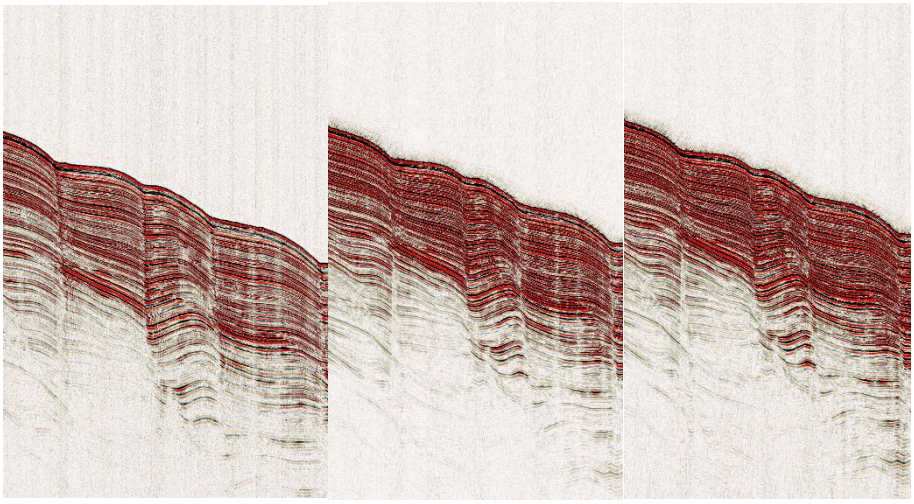


Figure 8: From left to right: example of stack, Kirchhoff migrated, and amplitude equalization results for line 3.

3D seismic processing

We processed 3D seismic data on board in RadExPro 2020.1 software, following a standard processing routine consisting of SEG-D import, geometry assignment and refining, burst noise removal, merging sailing lines, CDP binning, NMO and stacking, interpolation and finally migration (Table 8).

After importing SEG-D shot files into RadExPro, geometry is first assigned and then refined. Assigning receiver positions within RadExPro is based upon the GPS positions of the paravanes, the gun and the aft of the ship, assuming the streamer approximates a catenary curve.

Noise in the data was reduced by using a simple bandpass filter and burst noise removal.

The 3C CDP binning was done using 6.25 x 6.25 m grid size, NMO correction and Stack, interpolation followed by migration. CDP binning to 6.25 x 6.25 m results in an average trace fold of 4-5 traces per CDP bin (Figure 9). NMO correction and stacking assumes a constant velocity of 1500 m/s. Here, we used a simple Stolt 3D Post Stack migration with a constant velocity of 1500 m/s with the intention of improving the migration after the expedition. A data example of the 3D seismic data from NKR3D is shown in Figure 10.

Table 8: Processing parameters for the 3D seismic survey.

Seismic processing flow	
SEG-D import and geometry assignment	Input of SEG-D files Geometry assignment and offset calculation
Filtering in the shot gathers	Removal of bad channels Bandpass filter of 20-40-350-500 Hz Amplitude correction / Trace equalization Burst noise removal
NMO and stacking	NMO (constant velocity, 1480 m/s) Ensemble Stack using mean stack mode
Interpolation	Empty bins filled in by interpolation
Migration	Migration using a stolt migration (constant velocity 1500 m/s)
SEG-Y output	IBM floating point, big-endian ILINE_NO,4I,,189/XLINE_NO,4I,,193/CDP_X,4R,IBM,181/CDP_Y,4R,IBM,185 Coordinate system: WGS84-UTM32 N

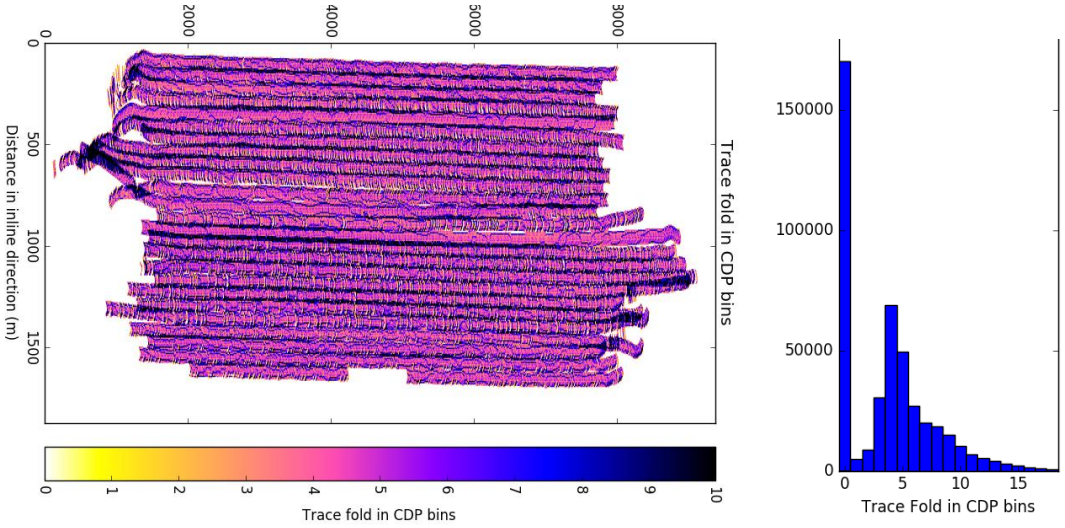


Figure 9: Fold map showing a dominantly fold of 4-5 traces in CDP bins

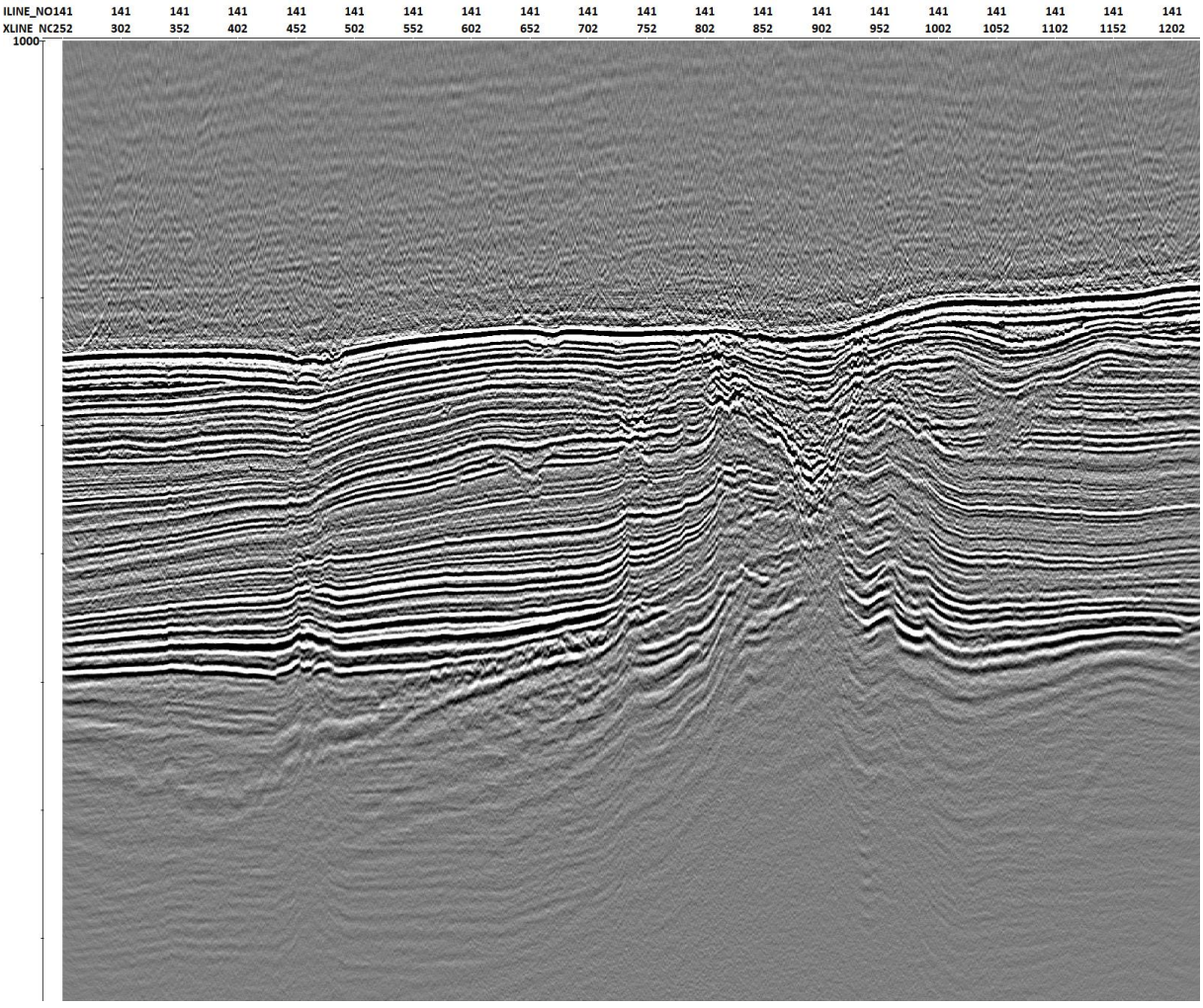


Figure 10: Inline example after 3D Stolt migration

ACKNOWLEDGEMENT

We 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. This cruise was conducted under the framework of the Centre of Excellence on Gas Hydrates, Environment and Climate (CAGE) (Norwegian Research Council (NFR) project number 223259/F5 at the University of Tromsø and the SEAMSTRESS project (Tectonic stress effects on Arctic methane seepage) supported by the Tromsø Research Foundation (TFS) and the Research Council of Norway (RCN-Frinatek) through two starting grants awarded to Andreia Plaza-Faverola.

APPENDIX

- CAGE20-5 Station log
- CAGE20-5 line log
- 3D seismic log NKR3D

CAGE20-5 Station log

Location	Station Id	Date	Time (UTC)	Lat. [N] Long. [E]	Bottles fired [#]	Water Depth [m]	Notes
Vestnesa Ridge	CAGE20-5-HH-415-CTD	22.08	14:58	78°51.841' 06°25.644'	1	1987	
Vestnesa Ridge	CAGE20-5-HH-416-OBS1-Dep	22.08	16:29	78°51.983' 06°25.925'		1960	
Vestnesa Ridge	CAGE20-5-HH-417-OBS5-Dep	22.08	17:46	78°49.899' 06°53.411'		1539	
Vestnesa Ridge	CAGE20-5-HH-418-OBS2-Dep	22.08	19:23	78°54.796' 06°45.797'		1507	
Vestnesa Ridge	CAGE20-5-HH-419-OBS4-Dep	22.08	20:22	78°46.536' 06°41.439'		1679	
Vestnesa Ridge	CAGE20-5-HH-423-OBS8-Dep	23.08	10:40	78°44.728' 07°02.603'		1412	
Vestnesa Ridge	CAGE20-5-HH-424-OBS7-Dep	23.08	11:25	78°41.601' 06°45.452'		1526	
Vestnesa Ridge	CAGE20-5-HH-425-OBS10-Dep	23.08	12:20	78°39.206' 07°07.615'		1425	
Vestnesa Ridge	CAGE20-5-HH-426-OBS9-Dep	23.08	13:34	78°43.017' 07°28.305'		1162	
Vestnesa Ridge	CAGE20-5-HH-427-OBS6-Dep	23.08	15:08	78°48.097' 07°20.095'		1215	
Vestnesa Ridge	CAGE20-5-HH-428-OBS3-Dep	23.08	16:09	78°53.056' 07°12.306'		1237	
North Knipovich Ridge	CAGE20-5-HH-439-CTD-Dep	27.08	18:25	78°39.229' 08°03.914'		1088	

CAGE20-5 line log

Location	Line ID	Date	Time (UTC) START	Lat. [N] Long. [E] START	Time (UTC) STOP	Lat. [N] Long. [E] STOP	Pulse mode	Shot Rate (HZ)	Ship Speed (kn)	Comments
INBIS	CAGE20-5-HH-01-CHIRP	20.08	13:58	73°50.881' 16°06.167'	17:42	74°31.100' 16°16.623'				
Vestnesa Ridge	CAGE20-5-HH-01-2D	22.08	22:10	78°50.597' 06°29.725'	01:01	79°00.681'	2 mini GI (30/30 & 15/15)	6	5	Wind 7.4 m/s, bird depth 2.5 m, briefly changed to 3 m in the beginning of line.
Vestnesa Ridge	CAGE20-5-HH-02-CHIRP	22.08	21:56	78°49.901' 06°26.687'	01:01	79°00.681' 07°22.381'			5	
Vestnesa Ridge	CAGE20-5-HH-02-2D	23.08	01:41	79°00.216' 07°13.695'	03:46	78°52.433' 07°48.180'	2 mini GI (30/30 & 15/15)	6	5	wind 9.5 m/s
Vestnesa Ridge	CAGE20-5-HH-03-CHIRP	23.08	01:40	79°00.334' 07°13.132'	03:46	78°52.426' 07°48.298'			5	
Vestnesa Ridge	CAGE20-5-HH-03-2D	23.08	04:18	78°54.167' 07°48.878'	07:24	78°47.059' 06°39.767'	2 mini GI (30/30 & 15/15)	6	5	Line across proposed IODP site VRE-02A P985. wind 10.5 m/s increasing to 12.3 at 6:34 UTC. Wind direction pushing the guns close to streamer often
Vestnesa Ridge	CAGE20-5-HH-04-CHIRP	23.08	04:14	78°54.288' 07°50.426'	07:23	78°47.088' 06°39.767'			5	
Vestnesa Ridge	CAGE20-5-HH-04-2D	23.08	18:00	78°57.916' 06°32.051'	22:23	78°36.740' 07°01.362'	2 mini GI (30/30 & 15/15)	6	5	Wind 12.0 m/s random noise on channel 41.
Vestnesa Ridge	CAGE20-5-HH-05-CHIRP	23.08	17:59	78°57.969' 06°31.934'	22:22	78°36.748' 07°01.352'			5	
Vestnesa Ridge	CAGE20-5-HH-05-2D	24.08	19:47	78°59.066' 06°53.273'	00:31	78°36.833' 07°25.311'	2 mini GI	6	5	Wind 10.7 m/s random noise on channel 41. Echo sounder and

							(30/30 & 15/15)			multibeam has been stuck for a significant time. Restarting accoustic instruments at 0:05 (UTC). Missing triggers during the 1st hour of acquisition.
Vestnesa Ridge	CAGE20-5-HH-06-CHIRP	24.08	19:51	78°58.871' 06°53.828'	00::31:23	78°36.833' 07°25.311'			5	
Vestnesa Ridge	CAGE20-5-HH-06-2D	25.08	02:56	78°47.189' 07°37.419'	05:36	78°38.704' 06°45.062'	2 mini GI (30/30 & 15/15)	6	5	Wind 10.9 at start. Slowed to 9 at the end.
Vestnesa Ridge	CAGE20-5-HH-07-CHIRP	25.08	02:55	78°47.229' 07°37.707'	05:37	78°38.704' 06°45.062'				
Vestnesa Ridge	CAGE20-5-HH-07-2D	25.08	06:54	78°42.692' 06°34.484'	10:48	78°56.121' 07°45.974'	2 mini GI (30/30 & 15/15)	6	5	Wind at start 7.5. Last two streamers show very weak reflections. Tail bird at 3 m depth from shot 13000. 13825 and 13846 have missing triggers.
Vestnesa Ridge	CAGE20-5-HH-08-CHIRP	25.08	06:39	78°41.937' 06°30.643'	10:48	78°56.121' 07°45.974'			5	
Vestnesa Ridge	CAGE20-5-HH-08-2D	25.08	11:29	78°58.321' 07°39.643'	14:49	78°48.748' 06°29.597'	2 mini GI (30/30 & 15/15)	6	5	Wind speed = 6.5 m/s at start.
Vestnesa Ridge	CAGE20-5-HH-09-CHIRP	25.08	11:28	78°58.350' 07°39.921'	14:45	78°48.908' 06°30.721'			5	
Vestnesa Ridge	CAGE20-5-HH-09-2D	25.08	17:43	00°00.738' 79°02.432'	20:32	79°15.324' 04°24.542'	2 mini GI (30/30 & 15/15)	6	5	
Vestnesa Ridge	CAGE20-5-HH-10-CHIRP	25.08	17:44	79°02.490' 04°52.742'	20:32	79°15.324' 04°24.542'			5	
Vestnesa Ridge	CAGE20-5-HH-10-2D	25.08	21:08	79°14.734' 04°18.104'	23:21	79°04.366' 04°18.104'	2 mini GI			

							(30/30 & 15/15)			
Vestnesa Ridge	CAGE20-5-HH-11-CHIRP	25.08	21:07	79°14.792' 04°17.994'	23:21	79°04.366' 04°18.104'				
Vestnesa Ridge	CAGE20-5-HH-11-2D	26.08	23.51.44	79°05.310' 04°52.126'	02:15	79°10.228' 04°20.124'	2 mini GI (30/30 & 15/15)	6	5	started line early during transit NE from line 10, crooked line for turn onto line 11!! True Line 11: shot 20300
Vestnesa Ridge	CAGE20-5-HH-12-CHIRP	26.08	00:00	79°05.615' 04°55.361'	02:16	79°10.261' 04°19.628'				
North Knipovich Ridge	CAGE20-5-HH-13-CHIRP	26.08	10:19	78°43.112' 08°17.215'	11:19	78°39.075' 08°14.000'				
North Knipovich Ridge	CAGE20-5-HH-14-CHIRP	26.08	11:38	78°38.928' 08°13.572'	12:33	78°42.536' 08°16.868'			5	
North Knipovich Ridge	CAGE20-5-HH-15-CHIRP	26.08	13:00	78°42.980' 08°17.547'	14:02	78°38.947' 08°14.037'			5	
North Knipovich Ridge	CAGE20-5-HH-16-CHIRP	26.08	14:21	78°38.621' 08°12.766'	15:23	78°42.631' 08°16.707'			5	
North Knipovich Ridge	CAGE20-5-HH-17-CHIRP	26.08	15:42	78°42.890' 08°17.686'	16:43	78°38.971' 08°14.205'			5	
North Knipovich Ridge	CAGE20-5-HH-18-CHIRP	26.08	17:03	78°38.486' 08°12.898'	18:05	78°42.582' 08°16.569'			5	
North Knipovich Ridge	CAGE20-5-HH-19-CHIRP	26.08	18:25	78°43.021' 08°17.951'	19:29	78°38.963' 08°14.396'			5	

North Knipovich Ridge	CAGE20-5-HH-20-CHIRP	26.08	19:44	78°38.697' 08°12.881'	20:45	78°42.641' 08°16.435'			5	
North Knipovich Ridge	CAGE20-5-HH-21-CHIRP	26.08	21:02	78°43.069' 08°18.175'	22:08	78°38.937' 08°14.729'			5	
North Knipovich Ridge	CAGE20-5-HH-22-CHIRP	26.08	22:21	78°38.765' 08°12.802'	23:21	78°42.591' 08°16.269'			5	
North Knipovich Ridge	CAGE20-5-HH-23-CHIRP	26.08	23:38	78°43.011' 08°18.204'	00:38	78°39.026' 08°14.851'			5	
North Knipovich Ridge	CAGE20-5-HH-24-CHIRP	27.08	00:53	78°39.162' 08°13.030'	01:46	78°42.566' 08°16.012'			5	
North Knipovich Ridge	CAGE20-5-HH-25-CHIRP	27.08	01:58	78°42.658' 08°18.043'	02:57	78°38.800' 08°14.717'			5	
North Knipovich Ridge	CAGE20-5-HH-26-CHIRP	27.08	03:06	78°38.984' 8127476°3 3.000'	04:05	78°42.783' 08°16.157'			5	
North Knipovich Ridge	CAGE20-5-HH-27-CHIRP	27.08	04:15	78°42.609' 08°18.316'	05:13	78°38.860' 08°14.967'			5	
North Knipovich Ridge	CAGE20-5-HH-28-CHIRP	27.08	05:22	78°39.012' 08°12.590'	06:19	78°42.727' 08°15.818'			5	
North Knipovich Ridge	CAGE20-5-HH-29-CHIRP	27.08	06:32	78°42.647' 08°18.413'	07:32	78°38.630' 08°14.779'			5	
North Knipovich Ridge	CAGE20-5-HH-30-CHIRP	27.08	07:44	78°39.044' 08°12.366'	08:39	78°42.799' 08°16.039'			5	

North Knipovich Ridge	CAGE20-5-HH-31-CHIRP	27.08	08:52	78°42.597' 08°18.760'	09:49	78°38.758' 08°15.097'			5	
North Knipovich Ridge	CAGE20-5-HH-32-CHIRP	27.08	10:00	78°39.068' 08°12.167'	10:51	78°42.569' 08°15.348'			5	
North Knipovich Ridge	CAGE20-5-HH-33-CHIRP	27.08	11:10	78°42.443' 08°18.592'	12:04	78°38.953' 08°15.627'			5	
North Knipovich Ridge	CAGE20-5-HH-34-CHIRP	27.08	12:17	78°39.021' 08°12.137'	13:12	78°42.622' 08°15.246'			5	
North Knipovich Ridge	CAGE20-5-HH-35-CHIRP	27.08	13:30	78°42.429' 08°18.836'	14:25	78°38.820' 08°15.550'			5	
North Knipovich Ridge	CAGE20-5-HH-36-CHIRP	27.08	14:39	78°39.162' 08°11.988'	15:34	78°42.755' 08°15.235'			5	
North Knipovich Ridge	CAGE20-5-HH-37-CHIRP	27.08	15:52	78°42.418' 08°19.021'	16:43	78°39.075' 08°16.107'			5	
North Knipovich Ridge	CAGE20-5-HH-38-CHIRP	27.08	19:31	78°42.206' 08°00.820'	21.55.35	78°44.839' 08°16.158'			8	Crooked line, passing through gas chimneys and potential flare location
North Knipovich Ridge	CAGE20-5-HH-12-2D	27.08	22.58.46	78°43.078' 08°12.339'	02:31	78°28.960' 07°18.760'	2 mini GI (30/30 & 15/15)	6	5	0.5 ms sampling interval, 5 sec record length. Shot interval 6 sec. 23113 missed shot.232248 missed shot.
North Knipovich Ridge	CAGE20-5-HH-39-CHIRP	27.08	23:01	78°42.940' 08°12.034'	02:32	78°28.920' 07°18.595'			5	3 seconds shooting interval for CHIRP.
Isfjorden Drift	CAGE20-5-HH-13-2D	28.08	09:26	77°39.547' 09°53.724'	11:19	77°31.212' 10°16.470'	2 mini GI	5	5	0.25 ms sampling interval, 4 sec record length. Shot interval 5 sec. 09:30 started missing shots. 3 shots

							(30/30 & 15/15)			missed starting 23620. 23641 missed as well.23714 shot missed. 23726,23761,23763, 23845,23860, two more in between (don't have the shot number, maybe 24001 and 24047??) 24121.24122,24124,24145,24180,24230,
Isfjorden Drift	CAGE20-5-HH-40-CHIRP	28.08	09:03	77°40.346' 09°51.337'	11:19	77°31.208' 10°16.481'			5	
Isfjorden Drift	CAGE20-5-HH-14-2D	28.08	11:57	77°33.133' 10°17.992'	13:53	77°27.720' 09°41.946'	2 mini GI (30/30 & 15/15)	5	5	
Isfjorden Drift	CAGE20-5-HH-41-CHIRP	28.08	11:55	77°33.227' 10°18.624'	13:54	77°27.710' 09°41.879'			5	
Isfjorden Drift	CAGE20-5-HH-15-2D	28.08	14:26	77°27.353' 09°49.378'	16:00	77°33.947' 09°30.243'	2 mini GI (30/30 & 15/15)	5	5	
Isfjorden Drift	CAGE20-5-HH-42-CHIRP	28.08	14:25	77°27.265' 09°49.634'	16:01	77°34.050' 09°29.980'			5	26448,26488,26499,26511,26624,26647,26878,26902,26903,26935,26944, 26945, missed

3D seismic line log

Expedition: Helmer Hanssen CAGE20-5 August 2020 Survey: NKR3D 26.08 – 27.08 Sheet #: 1 - 5

3D seismic over North Knipovich Ridge (NKR) Depression east of Molloy Transform

3D 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	26.08-26.08	09:28-10:25	1- 656	N/A	Pre-survey warm-up and test. Recording length 2.5 sec, sample interval 0.25 ms, shooting interval 5 sec. Lot of shots before start of line. Can be used as a 2D corridor. Navigation in Line01 log
01	26.08-26.08	10:26-11:20	657-1296	730-1270	6.36 C sea temperature, 4 C air temperature m/s wind speed 7 m/s (from 114 direction).
02	26.08-26.08	11:39-12:34	1297-1956	1354-1922	6.71 C sea temperature, 4.7 C air temperature m/s wind speed 5.9 m/s (from 128 direction).
03	26.08-26.08	13:00-14:01	1957-2692	2078-2647	6.70 C sea temperature, 4.4 C air temperature m/s wind speed 8.9 m/s (from 115 direction).

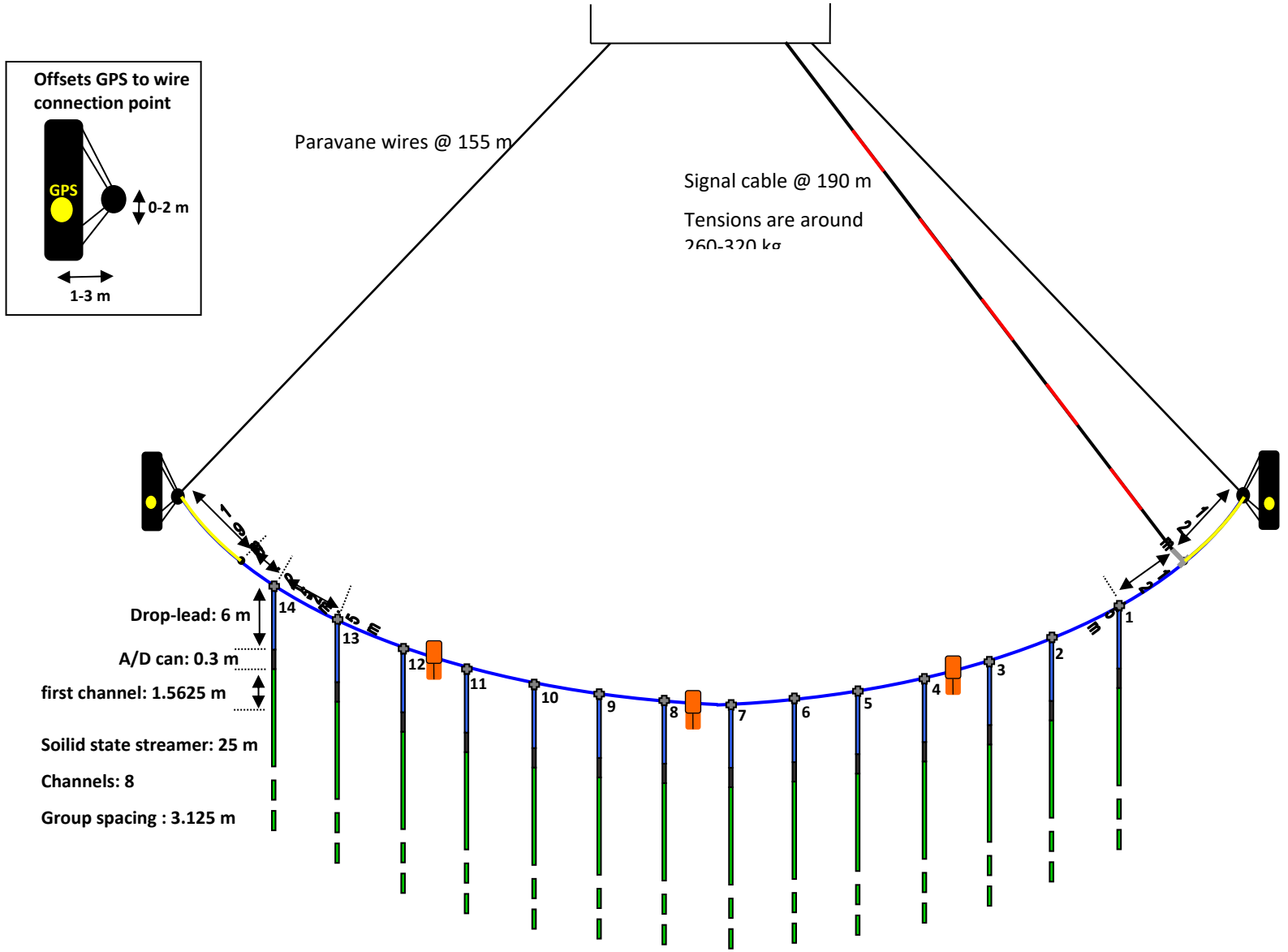
04	26.08-26.08	14:22-15:23	2693-3417	2779-3371	6.74 C sea temperature, 4.7 C air temperature m/s wind speed 9.1 m/s (from 123 direction).
05	26.08-26.08	15:42-16:42	3418-4139	3531-4103	6.65 C sea temperature, 4.3 C air temperature m/s wind speed 8.0 m/s (from 111 direction).
06	26.08-26.08	17:04-18:05	4140-4880	4268-4835	6.74 C sea temperature, 4.0 C air temperature m/s wind speed 10.2 m/s (from 104 direction).
07	26.08-26.08	18:26-19:29	4881-5637	5003-5590	6.70 C sea temperature, 4.2 C air temperature m/s wind speed 6.6 m/s (from 77 direction).
08	26.08-26.08	19:45-20:45	5638-6359	5737-6308	Started line a bit too early. Direction not very aligned with line 08 for the first 3min (shot 5676). 6.6 C sea temperature, 4.2 C air temperature m/s wind speed 9.4 m/s (from 104 direction).
09	26.08-26.08	21:03-22:08	6360-7137	6498-7084	6.65 C sea temperature, 4.2 C air temperature m/s wind speed 6.7 m/s (from 93 direction).
10	26.08-26.08	22:22-23:21	7138-7844	7229-7799	6.51 C sea temperature, 4.7 C air temperature m/s wind speed 8.7 m/s (from 112 direction).
11	26.08-27.08	23:39-00:39	7845-8569	7975-8542	6.52 C sea temperature, 4.1 C air temperature m/s wind speed 6.4 m/s (from 79 direction).
12	27.08	00:54-01:46	8570-9197	8585-9161	6.53 C sea temperature, 4.2 C air temperature m/s wind speed 6.7 m/s (from 75 direction).
13	27.08	01:59-02:57	9198-9885	9254-9814	6.47 C sea temperature, 4.1 C air temperature m/s wind speed 6.0 m/s (from 74 direction).
14	27.08	03:05-04:04	9886-10593	9949-10511	6.52 C sea temperature, 3.8 C air temperature m/s wind speed 7.2 m/s (from 81 direction).

15	27.08	04:14-05:13	10594-11286	10663-11225	6.48 C sea temperature, 3.6 C air temperature m/s wind speed 6.6 m/s (from 62 direction).
16	27.08	05:21-06:19	11287-11972	11347-11903	6.49 C sea temperature, 3.8 C air temperature m/s wind speed 6.1 m/s (from 51 direction).
17	27.08	06:31-07:32	11973-12696	12055-12595	6.47 C sea temperature, 3.8 C air temperature m/s wind speed 5.7 m/s (from 47 direction).
18	27.08	07:43-08:38	12596-13347	12753-13275	6.51 C sea temperature, 3.2 C air temperature m/s wind speed 8.5 m/s (from 40 direction).
19	27.08	08:52-9:47	13348-14012	13419-13944	6.37 C sea temperature, 4.2 C air temperature m/s wind speed 6.0 m/s (from 42 direction).
20	27.08	10:00-10:51	14013-14627	14054-14597	6.49 C sea temperature, 3.3 C air temperature m/s wind speed 6.3 m/s (from 50 direction).
21	27.08	11:10-12:04	14628-15268	14661-15235	6.36 C sea temperature, 3.2 C air temperature m/s wind speed 6.6 m/s (from 31 direction).
22	27.08	12:17-13:12	15269-15928	15298-15889	6.49 C sea temperature, 3.2 C air temperature m/s wind speed 4.2 m/s (from 62 direction).
23	27.08	13:30-14:24	15929-16573	15958-16515	6.41 C sea temperature, 3.4 C air temperature m/s wind speed 2.7 m/s (from 32 direction).
24	27.08	14:38-15:33	16573-17243	16622-17171	6.60 C sea temperature, 3.4 C air temperature m/s wind speed 4.5 m/s (from 43 direction). Two times warning about delay in data from channels(one at 17061 shot), logs need to be checked later,. Again 15:24 UTC.
25	27.08	15:51-16:42	17244-17819	17288-17793	6.43 C sea temperature, 3.4 C air temperature m/s wind speed 3.4 m/s (from 180 direction). Missed shot 17251. Delayed eels warning at 16:18 UTC. 17537-17547 incomplete data files. Until

					17558.Geoeel closed on 16:20 UTC. Restarted SPSU. 17561 next correct shot.17701 start missing data, missing section 12.Some data comes back from channel 12 only as separate files.

Comment:

3D Survey configuration:



Observed spread of paravanes: 170-175 m
Observed distance between gun and paravanes: 100 – 117 m, deviations between distances to both paravanes up to 10 m, particularly large difference between northward or southward acquisition lines

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: 4 sec
Recording delay: 0 sec
Sampling interval: 0.25ms
Streamer depth: 1.5m