CCS2022-2024 WP1: The Havnsø structure - Marine acquisition report

Offshore seismic acquisition Havnsø-Nekselø 2022, with seismic source from the onshore acquisition

Thomas Funck & Egon Nørmark

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2023/22**

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Thomas Funck[1] & Egon Nørmark[2]

[1] Geological Survey of Denmark and Greenland
[2] Department of Geoscience, Aarhus University

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1. Summary

A combined onshore-offshore seismic survey (GEUS2022–HAVNSOE) was conducted in 2022 to map the Havnsø structure in northwestern Zealand. The overall objective of the survey was to define if the structure is suitable for underground storage of CO_2. GEUS had the overall project management for the survey and contracted Uppsala University for carrying out the land component of the acquisition that is described in Malehmir & Papadopoulou (2023). The survey used two Vibroseis trucks as seismic source. One of the survey lines (line GEUS22–HVN–P1) had to cross a 2-km-wide waterway (Sejerø Bugt) between the port of Havnsø and the island of Nekselø. To bridge the water, marine receivers were used to record the onshore vibroseismic sources. Marine sources were not an option due to the shallow water and the protection status as Natura2000 area. With the additional marine data, it will be possible to connect the land data from Nekselø with those from Havnsø. In addition, existing offshore seismic lines can be tied to the new onshore data. This report describes the recording and initial processing of the marine data, including data examples. Ultimately, the data from the marine receivers have to be merged with those recorded on land, which is described in Malehmir & Papadopoulou (2023).

For the marine component of the acquisition, 18 ocean bottom seismometers from the national Danish seismometer pool DanSeis were deployed at the seafloor between Havnsø and Nekselø. These short-period instruments are equipped with three-component geophones and a hydrophone. The latter one has the best data quality. Some stations stopped recording before all Vibroseis sweeps on the two segments (Nekselø and road towards the beach in Havnsø) were completed. However, the data quality of the recorded signals is good. After corelation with the source sweep, reflections can be seen from depths below 2 s two-way travel time.

A second type of receivers was used close to Havnsø. Here a 600-m-long marine streamer with 96 channels was deployed from a winch located on the beach. After pulling out the streamer seaward, lead was added to it to lower it down to the seafloor. Data quality is good with exception of the channels close to shore and at the seaward end of the streamer. The poorer data channels are probably caused by increased noise levels due to the surge of waves at the beach and by motion that was transferred from the recovery buoy attached to the tail end of the streamer. Sweeps from the area close to Havnsø produce an almost complete record from the surface to depths greater than 2.5 s two-way travel time, while the larger shot-receiver offsets for the sweeps on Nekselø result in a lack of data in the upper 1.0 to 1.5 s of the record section.

2. Introduction

From August to October 2022, a seismic reflection acquisition was carried out across the Havnsø structure as part of the Carbon Capture and Storage (CCS) project for which GEUS is the project leader. The Havnsø structure in Northwest Zealand is one of several possible sites for CCS and an updated seismic database is required to assess its suitability for CCS. The structure extends from Zealand into the Sejerø Bugt, where some older marine seismic reflection lines exist (Figure 1). To tie the existing offshore lines with the new seismic data from 2022 on NW Zealand and on Nekselø, the onshore acquisition was accompanied by deploying seismic receivers offshore located in the area between Havnsø and Nekselø. These receivers consisted of 18 ocean bottom seismometers (OBS) provided by the national seismometer pool DanSeis and a 600-m-long streamer (Hydroseis) owned by the University of Aarhus and placed on the seafloor north of Havnsø (Figure 1). This report describes the marine seismic data acquisition with both types of receivers. The seismic sources (two Vibroseis trucks) are described in the acquisition and processing report for the land component of the survey (Malehmir & Papadopoulou 2023), which should be consulted for a full understanding of the combined onshore-offshore experiment. Malehmir & Papadopoulou (2023) also present the merging of the marine and land data to a joint record section.

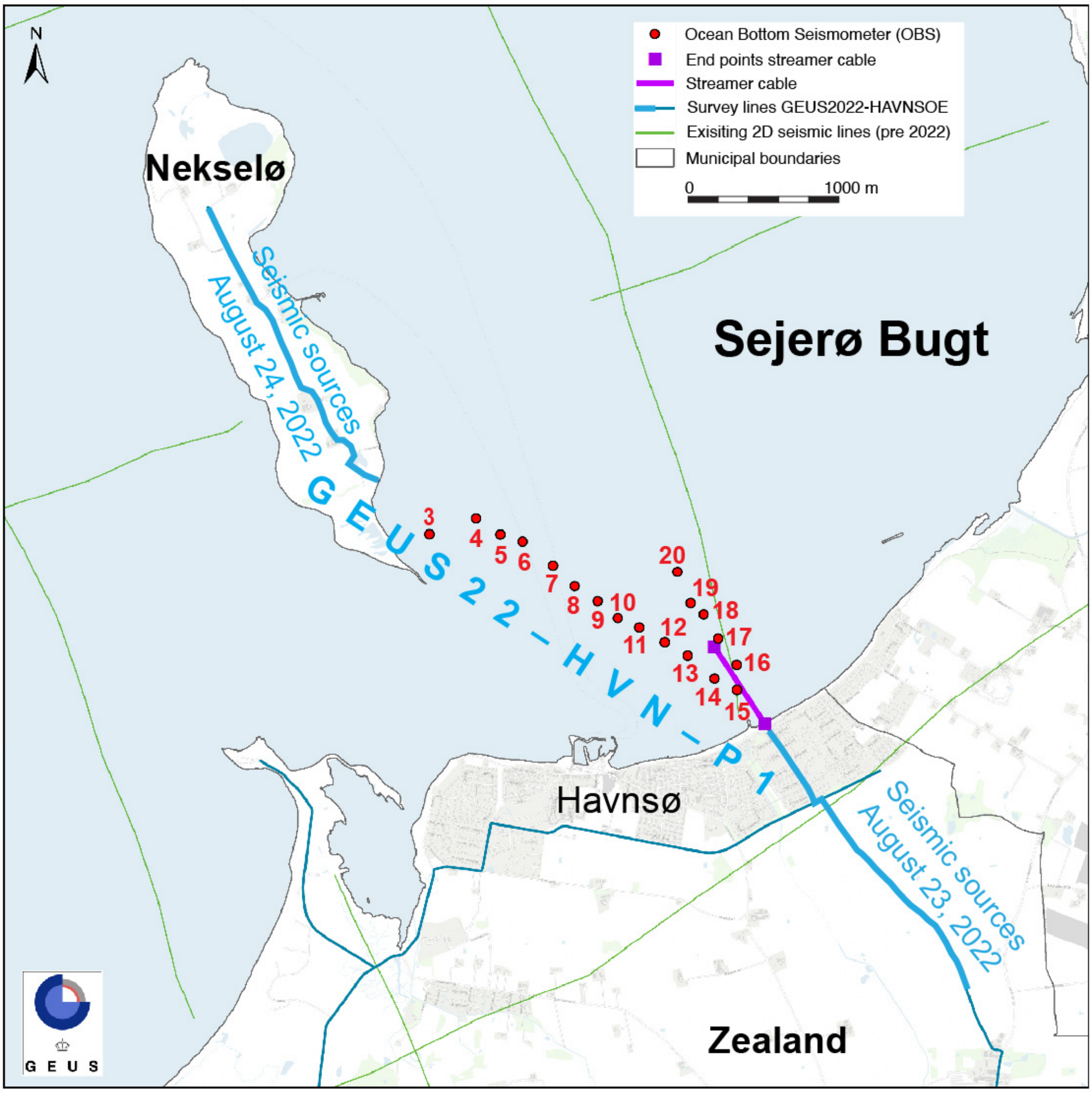

Figure 1. *Map showing the location of marine receivers (ocean bottom seismometers and marine streamer) and the seismic sources (Vibroseis sweeps) onshore. Red numbers indicate the station number. Line GEUS22–HVN–P1 continues further to the south but those sweeps were not recorded by the marine receivers.*

3. Data Acquisition with Ocean Bottom Seismometers

3.1 Instrumentation

3.1.1 Ocean Bottom Seismometers

A total of 18 OBS were made available from the national Danish seismometer pool DanSeis. The OBS were manufactured in 2016 and 2017 and are of the type Sercel MicrOBS_Plus. These instruments are an advancement of the previous model MicrOBS. The development of the MicrOBS is based on four conceptual ideas:

1. Integration of acquisition and instrument release: This integration is possible due to the use of a broadband hydrophone which allows recording of the low-frequency signal from air gun shots or earthquakes (from 0.1 Hz up to several 100 Hz) as well as the high-frequency release signal (about 10 kHz). This significantly reduces the weight of the instrument and therefore facilitates its handling.

2. Rechargeable batteries: To avoid the opening and resealing of the instrument, which remains a delicate operation at sea, a rechargeable battery pack is used in the MicroOBS.

3. Data download by USB cable: The data are downloaded from the instrument via a USB 1.1 cable connection, to avoid opening and closing the instrument between successive deployments at sea.

4. Size reduction: The substantial size reduction of the MicrOBS compared to older OBS was possible due to the three points mentioned above, the integration of the electronics with the release, the reduction of the battery weight and the download of the data. Thus, it was possible to fit the complete instrument into a 13-inch glass sphere. The complete mass of the instrument is only 20 kg plus 20 kg for the anchor.

In 2006, Sercel started producing a new generation of MicrOBS instruments with the objective to allow for longer deployments during wide-angle seismic surveys. To contain a larger number of batteries, the instrument named MicrOBS_Plus (Figure 2) is housed in a 17-inch glass sphere. The disk space was enlarged to 8 GB resulting in a deployment length of up to 31 days with 24 days of recording at a sampling rate of 4 ms (250 Hz). Acquisition electronics, geophone and hydrophone are identical with the original MicrOBS. The weight of the instruments is 36 kg and an anchor weight of 28 kg is used for the deployment. With the anchor attached, the OBS will sink to the seafloor.

For recovery of the instruments from the seafloor, a transducer is used, which sends an acoustic release signal to the OBS. This initiates a current in the burn wire that holds the OBS to the anchor. After a few minutes, the burn wire is corroded and the hook between the OBS and anchor snaps open upon which the OBS can ascent to the sea surface due to its buoyancy.

Figure 2. *Sercel MicrOBS_Plus at the seafloor. The OBS is attached to an anchor (two crossing steel bars at the bottom) to allow for a good coupling of the geophones to the seafloor. Once the OBS is released from the anchor, it has enough buoyancy to return to the sea surface.*

3.1.2 Seismic Sources

The seismic source signal was produced by two Vibroseis trucks that created 18-s-long sweeps (Figure 3) along public and private roads on Zealand and on Nekselø. Details on the source are described in the onshore acquisition report (Malehmir & Papadopoulou 2023). For the marine receivers, only the days August 23 and 24, 2022 are relevant. On August 23, the Vibroseis trucks moved northward towards Havnsø along a 2100-m-long section of line GEUS22–HVN–P1. On August 24, the trucks moved in northward direction on the island of Nekselø, covering a length of 1900 m along the same profile. There was a shooting break from 10:05 to 11:58 UTC that day related to a technical failure in one of the trucks.

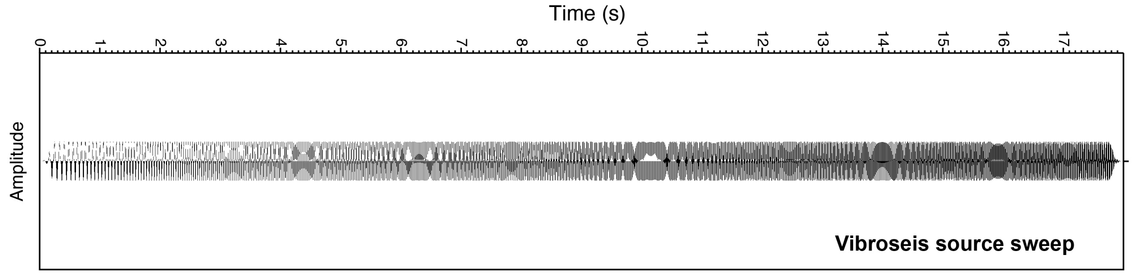

Figure 3. *Source sweep created by the Vibroseis trucks. Length of the sweep is 18 s and the frequencies range from 10 to 140 Hz (filename Sten_10-140_18s.sgy).*

3.2 Acquisition of OBS Data

In the original design of the experiment, OBS deployments were planned for 20 stations (1 through 20). However, DanSeis could only provide 18 instruments and the two stations closest to Nekselø were dropped (stations 1 and 2). Therefore, the map in Figure 1 only shows the location for stations 3 through 20. Another setback for the experiment came from the engine breakdown of the GEUS-owned boat *Maritina* on the way to Havnsø, which could not be repaired by the shipyard prior to the acquisition. *Maritina* is used for scientific experiments and is equipped with modern navigation systems as well as with multibeam echosounder. The only other available boat that could be found at short notice was the tugboat *Buller* based in Hundested on Zealand, which was then hired for the deployment of the OBS. The crew on the tugboat was unexperienced for that type of work and had problems with their GPS navigation system. This resulted in a misplacement of the OBS at station 3. There are also gaps in the recording of the water depth during deployment that were partially filled during the later recovery of the instruments.

All OBS with exception of the one at station 15 were deployed on August 20, 2022 (Table 1) on the day the boat *Buller* was available. The draught of Buller was too high to reach station 15. For this position, a small sailing boat was chartered in Havnsø and the OBS was deployed on August 22, 2022.

The data with the Vibroseis source were acquired on August 23 and 24, 2022. Both days with warm and mainly sunny weather, the sea was calm. Source sweeps were generated from 06:57 to 14:27 UTC and 06:14 to 17:37 UTC on August 23 and 24, respectively. For the recovery of the OBS, a local fishing boat was chartered in Havnsø and the operation was under great time pressure as the boat was only available for August 25 and also explains the gaps in the recording of recovery positions and times (Table 1). The recovery started off Nekselø progressing from station 3 to 14 without any problems. However, problems arose during the retrieval of OBS 16 through 20, as the instruments were deployed in reverse order due to a misunderstanding with the crew on *Buller*. Therefore, wrong release codes were sent to those OBS and they did not come to the sea surface. Eventually, the problem was realized, and recovery could continue with the boat being back in port at 20:00 UTC when it was already dark.

Stat-ion No.	OBS Serial No.	OBS Int. No.	Deployment Date and time (UTC) (YYYY-MM-DD HH:MM)	Deployment Latitude	Deployment Longitude	Deployment Easting (m) UTM Zone 32	Deployment Northing (m) UTM Zone 32	Depth (m)	Recovery/Release Date and time (UTC) (YYYY-MM-DD HH:MM)	Recovery Latitude	Recovery Longitude	Recovery Easting (m) UTM Zone 32	Recovery Northing (m) UTM Zone 32
3	200-124	S01	2022-08-20 11:57	55.767393°N	11.308182°E	644805.33	6182603.67	4.0	2022-08-25 11:33	55.767433°N	11.307596°E	644768.43	6182606.90
4	200-146	S02	2022-08-20 12:33	55.768236°N	11.313172°E	645115.19	6182707.90	6.8	2022-08-25 12:03	55.768072°N	11.312204°E	645055.08	6182687.63
5	200-144	S03	2022-08-20 12:36	55.767226°N	11.315661°E	645275.06	6182600.75	7.3	2022-08-25 12:44	55.767386°N	11.315462°E	645261.98	6182618.13
6	200-150	S04	2022-10-20 12:38	55.766776°N	11.318013°E	645424.26	6182555.62	–	2022-08-25 13:00				
7	200-129	S05	2022-08-20 12:43	55.765264°N	11.321128°E	645625.28	6182393.93	–	2022-08-25 13:19				
8	200-125	S06	2022-08-20 12:46	55.764031°N	11.323338°E	645768.51	6182261.40	7.4	2022-08-25 13:33				
9	200-148	S07	2022-08-20 12:52	55.763097°N	11.325713°E	645920.98	6182162.48	–	2022-08-25 13:48				
10	200-132	S08	2022-08-20 12:55	55.762023°N	11.327768°E	646053.90	6182047.32	8.4	2022-08-25 14:09				
11	200-149	S09	2022-08-20 12:57	55.761421°N	11.330019°E	646197.37	6181985.09	8.4	2022-08-25 14:25				
12	200-128	S10	2022-08-20 13:00	55.760504°N	11.332660°E	646366.48	6181888.64	7.4	2022-08-25 14:42				
13	200-131	S11	2022-08-20 13:03	55.759664°N	11.335019°E	646517.62	6181800.17	7.4	2022-08-25 16:25				
14	200-130	S12	2022-08-20 13:05	55.758245°N	11.337792°E	646696.91	6181648.16	7.3	2022-08-25 16:45				
15	200-126	S18	2022-08-22	55.757533°N	11.340100°E	646844.39	6181573.83	0.8	2022-08-25 19:16				
16	200-117	S17	2022-08-20 13:43	55.759004°N	11.340164°E	646842.87	6181737.63	7.3	2022-08-25	55.759108°N	11.339107°E	646776.17	6181746.96
17	200-143	S16	2022-08-20 13:38	55.760621°N	11.338293°E	646719.42	6181913.57	7.7	2022-08-25				
18	200-133	S15	2022-08-20 13:34	55.762070°N	11.336866°E	646624.46	6182071.77	7.9	2022-08-25				
19	200-147	S14	2022-08-20 13:29	55.762780°N	11.335520°E	646537.36	6182147.91	–	2022-08-25	55.762841°N	11.335231°E	646519.00	6182154.09
20	200-145	S13	2022-08-20 13:21	55.764664°N	11.334252°E	646450.75	6182354.84	7.8	2022-08-25 17:20				

Table 1. *Deployment and recovery information for the OBS.*

Table 1 shows the deployment and recovery positions of the OBS. Positions were marked as waypoints on a handheld GPS device that were downloaded after the experiment. All handwritten deployment sheets were scanned and are available with the digitial data. Water depths were taken from the navigation echosounder on *Buller* and the fishing boat and were corrected for the depth of the echosounder below sea level. The depth for the OBS at station 15 is estimated, it was reachable by foot from the beach.

As required by the permission for the survey, all OBS anchors had to be removed from the seafloor after the experiment. For this reason, the OBS was attached to the anchor by a 10-m-long rope, stored in a small container on the anchor. When the OBS was released from the anchor, it raised to the surface and thereby pulled the rope out of the container. After the OBS was lifted onto the fishing boat, the anchor was pulled up on the rope. All anchors were recovered from the seafloor.

3.3 Data Processing and Archiving

The four sensors of the OBS (hydrophone and three-component geophones) were recorded continuously on the flash card of the OBS. Once a raw data file reaches the size of 20 MB, the data are stored in a new file and the file number is increased by one. These raw data files in an internal format are downloaded from the OBS for further processing together with the XML file that contains some meta data for a particular instrument.

Before deployment and after recovery, the recorders are synchronized with the GPS time signal to determine the time drift (skew time) during the experiments that are also stored in the XML files (Table 2). The drift of the OBS clock is assumed to be linear and the skew time is then applied to correct the data for this drift. Then a resampling of the data is carried out. The drift correction is applied when the raw data are converted to pseudo-SEGY format using the *micrOBS* software by Sercel. In this conversion process, four continuous pseudo-SEGY files are created, one for each of the four channels of the OBS. These four channels are

- Channel 1: hydrophone
- Channel 2: vertical geophone component
- Channel 3: horizontal geophone component 1
- Channel 4: horizontal geophone component 2

The pseudo-SEGY files use the following nomenclature:

S[01-18]-[1-4].pseg

where the first parameter is the internal OBS number (01 through 18), and the last parameter is the channel number. The file names are listed in Table 2 that also links the station number with the internal OBS number.

Station	Internal OBS No.	Serial Number	Synchronization start (UTC)	Synchronization end (UTC)	Skew (ms)	Number of raw data files	Datafiles (SEGY)	Data files (Pseudo-SEGY)
3	S01	200-124	2022-08-17 17:14:00	2022-08-27 12:27:59	-101	287	stat03ch[1-4]-AUG[23/24]_2022.sgy	S01-[1-4].pseg
4	S02	200-146	2022-08-19 12:00:00	no end sync	–	1 (empty)	–	–
5	S03	200-144	2022-08-19 12:39:00	2022-08-27 12:33:00	41	287	stat05ch[1-4] - AUG[23/24]_2022.sgy	S03-[1-4].pseg
6	S04	200-150	not recorded	not recorded	–	–	–	–
7	S05	200-129	2022-08-19 14:49:00	2022-08-27 12:36:59	-42	287	stat07ch[1-4] - AUG[23/24]_2022.sgy	S05-[1-4].pseg
8	S06	200-125	2022-08-19 15:17:00	2022-08-27 12:39:59	-165	287	stat08ch[1-4] - AUG[23/24]_2022.sgy	S06-[1-4].pseg
9	S07	200-148	2022-08-19 15:39:00	2022-08-27 12:41:59	-1	287	stat09ch[1-4] - AUG[23/24]_2022.sgy	S07-[1-4].pseg
10	S08	200-132	2022-08-19 16:04:00	2022-08-27 13:43:59	-117	287	stat10ch[1-4] - AUG[23/24]_2022.sgy	S08-[1-4].pseg
11	S09	200-149	2022-08-19 16:43:00	2022-08-27 12:46:59	-85	287	stat11ch[1-4] - AUG[23/24]_2022.sgy	S09-[1-4].pseg
12	S10	200-128	2022-08-19 17:18:00	2022-08-27 12:48:59	-108	287	stat12ch[1-4] - AUG[23/24]_2022.sgy	S10-[1-4].pseg
13	S11	200-131	2022-08-19 18:52:00	2022-08-27 12:50:59	-105	287	stat13ch[1-4] - AUG[23/24]_2022.sgy	S11-[1-4].pseg
14	S12	200-130	2022-08-19 19:15:00	2022-08-27 12:48:51	-8238	15	stat14ch[1-4] - AUG[23/24]_2022.sgy	S12-[1-4].pseg
15	S13	200-145	2022-08-20 06:58:00	2022-08-27 12:55:59	-46	287	stat15ch[1-4] - AUG[23/24]_2022.sgy	S13-[1-4].pseg
16	S18	200-126	2022-08-22 16:02:00	2022-08-27 12:16:59	-51	242	stat16ch[1-4] - AUG[23/24]_2022.sgy	S18-[1-4].pseg
17	S17	200-117	2022-08-20 10:52:00	2022-08-27 12:12:59	-135	287	stat17ch[1-4] - AUG[23/24]_2022.sgy	S17-[1-4].pseg
18	S16	200-143	2022-08-20 09:16:00	2022-08-27 13:04:59	-60	287	stat18ch[1-4] - AUG[23/24]_2022.sgy	S16-[1-4].pseg
19	S15	200-133	2022-08-20 08:54:00	2022-08-27 12:59:59	-136	287	stat19ch[1-4] - AUG[23/24]_2022.sgy	S15-[1-4].pseg
20	S14	200-147	2022-08-20 08:20:00	2022-08-27 12:57:59	-66	287	stat20ch[1-4] - AUG[23/24]_2022.sgy	S14-[1-4].pseg

Table 2. *OBS clock synchronization before and after deployment.*

In the next processing step, receiver gathers are extracted from the pseudo-SEGY files using shot tables that contain the time and position of the Vibroseis sweeps. For this step, the contractor (Uppsala University) provided tables with the coordinates (*ShotCoordinates_Havnso_20220823.csv* and *ShotCoordinates_Havnso_20220824.csv* for August 23 and 24, respectively) and the start times of the sweeps (*gpstime_Havnso_line1_20220823.txt* and *gpstime_Havnso_line1_20220824.txt* for August 23 and 24, respectively).

The time files specify the time in μs in GPS time that is 18 s ahead of UTC, to which it was converted for the conversion from pseudo-SEGY to SEGY. Uppsala University stated that the provided times might be off by a full second without specifying if the second would need to be added or subtracted. From inspection of the records, it appears that the provided sweep times are one second too early. This must be verified by further processing of the data and a corresponding static correction would need to be applied if this is confirmed.

The shot coordinates were converted from UTM (Zone 32) to geographical coordinates to comply with the required format for the pseudo-SEGY to SEGY conversion in the *micrOBS* software by Sercel. The UTC times and geographical coordinates were then merged into one combined shot table (havnsoe2022.nav) for the actual conversion.

After creation of the SEGY files, the SEGY headers were edited to change the source and receiver coordinates to UTM coordinates (Zone 32), specified in cm. In addition, the offset between source and receiver, the source and receiver depths (in cm), the source number and the FFID were added to the headers. The editing was done in Seismic Unix version 44R18 using the headers shown in Table 3.

Bytes	**Parame-ter**	**Description**
9-12	fldr	FFID (taken from time table)
17-20	ep	Source station (taken from time table)
37-40	offset	Distance between Vibroseis sweep and OBS in m
41-44	gelev	Elevation of receiver (OBS) relative to sea level in cm (=negative water depth)
45-48	selev	Elevation at the source (sweep) in cm
65-68	gwdep	Water depth at receiver (OBS) in cm (positive numbers)
73-76	sx	Source coordinates/easting (Vibroseis sweeps) in cm in UTM Zone 32
77-80	sy	Source coordinates/northing (Vibroseis sweeps) in cm in UTM Zone 32
81-84	gx	Receiver coordinates/easting (OBS) in cm in UTM Zone 32
85-88	gy	Receiver coordinates/northing (OBS) in cm in UTM Zone 32

Table 3. *SEGY headers in the final SEGY files.*

The SEGY files are in little endian byte order with a record length of 25 s and a sampling rate of 1 ms. File names use the following naming conventions:

stat[03-20]ch[1-4]-AUG[23/24]_2022.sgy

where the first parameter is the station number (03 through 20) where the OBS was deployed, the second parameter is the channel number (1 through 4, see above), while the third number (23/24) provides the date on which the data were acquired (August 23 for the sweeps towards Havnsø, August 24 for the ones on Nekselø). The file names are listed in Table 2 and all SEGY files and shot tables are stored in the data archive.

3.4 Data Quality and Problems with the Data

The OBS deployed at stations 4, 6, and 14 had technical problems and did not return any data. OBS 4 had a power failure, OBS 6 did not record any files, while OBS 14 stopped recording after four hours well before the acquisition started. Another issue with the instruments was that they stopped recording prematurely. According to the technical specifications of the OBS, they are equipped with an 8 GB flash card for data recording, suitable for 24 days of survey at a sampling rate of 4 ms. During this survey, the sampling rate was set to 1 ms, which should have given six days of recording. However, the flash card was filled with data after four days and nine hours. The total size of all raw data files was 6 GB and thereby less than the 8 GB as specified by the manufacturer. This is why a number of OBS did not record the sweeps generated on August 24, 2022 or only a part of them. One OBS (at station 3) did not record any sweeps at all, which is the same station that was placed at a wrong location (see above). Table 4 lists the problems encountered at the various stations.

<table>
<tr><th>Station</th><th>Record section (ch1/hydrophone) for August 23, 2022 (Havnsø)</th><th>Record section (ch1/hydrophone) for August 24, 2022 (Nekselø)</th></tr>
<tr><td>1</td><td colspan="2">No OBS deployed due to shortage of instruments</td></tr>
<tr><td>2</td><td colspan="2">No OBS deployed due to shortage of instruments</td></tr>
<tr><td>3</td><td>Recording stopped before SOL</td><td>Recording stopped before SOL</td></tr>
<tr><td>4</td><td colspan="2">OBS had power failure, no data stored</td></tr>
<tr><td>5</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>6</td><td colspan="2">Failure of OBS, no data recorded</td></tr>
<tr><td>7</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>8</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>9</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>10</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>11</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>12</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>13</td><td>OK</td><td>Recording stopped before SOL</td></tr>
<tr><td>14</td><td colspan="2">Failure in OBS, recording stopped shortly after programming the instrument</td></tr>
<tr><td>15</td><td>OK (but low S/N ratio)</td><td>OK (but low S/N ratio)</td></tr>
<tr><td>16</td><td>OK</td><td>OK</td></tr>
<tr><td>17</td><td>OK</td><td>OK</td></tr>
<tr><td>18</td><td>OK</td><td>OK (but recording stopped before EOL)</td></tr>
<tr><td>19</td><td>OK</td><td>OK (but recording stopped before EOL)</td></tr>
<tr><td>20</td><td>OK</td><td>OK (but recording stopped before EOL)</td></tr>
</table>

Table 4. *Data quality of channel 1 (hydrophone) of the OBS records. Abbreviations are ch, channel; EOL, end of line; OBS, ocean bottom seismometer; OK, okay; S/N, signal-to-noise; SOL, start of line.*

Appendix A shows the record sections for the hydrophone component (channel 1) of the OBS that recorded data and they are all good quality. The vertical geophone (channel 2) is not as good as the hydrophone. In the Appendix, the final SEGY files were correlated with the source sweep (filename *Sten_10-140_18s.sgy*) and a bandpass filter from 8 to 70 Hz was applied.

4. Data Acquisition with Marine Streamer

4.1 Marine Streamer

To describe the geological structure at Havnsø for Carbon Capture and Storage (CCS), land seismic data were acquired by Uppsala University under contract to GEUS. The northern part of the Havnsø structure extends into the sea in Sejerø Bugt. Thus, marine seismic data are needed to describe this part of the structure. However, this region belongs to a Natura2000 zone with restricts many activities including seismic work. With the existing regulations for acquisition of seismic reflection data in Denmark, data acquisition with active sources was not an option inside or close to this Natura2000 zone. As an alternative, it was decided to lay out a marine streamer on the seafloor and record the reflections from the land-based survey that used a Vibroseis source (Malehmir & Papadopoulou 2023).

This setup was used on line GEUS22–HVN–P1 to bridge the gap between Havnsø in north-western Zealand and the island of Nekselø (Figure 1). The streamer was mobilized and laid out approximately perpendicular to the shoreline east of Havnsø. The direction of the line was defined by the same orientation as the onshore part of line P1 in Havnsø.

An oil-filled streamer with 96 channels and a group distance 6.25 m was used. Each group consists of seven hydrophones evenly distributed over the group. The length of each group is 3.125 m. The streamer is divided into four sections consisting of 24 channels each.

In preparation for the survey, the streamer was refilled with oil (kerosene) and at the same time an attempt was made to remove air from the streamer (Figure 4). This turned out to be a rather difficult process and was only partly successful. Thus, the streamer still contained some air over significant intervals. To do a better job in removing air from the streamer, it was considered to place the streamer on a slope at a suitable site onshore. Since air is only moving slowly in the streamer, some time would have been required to let the air move to the top of the streamer and to refill it with oil. However, with the remaining available time prior to acquisition and the need for a truck, this turned out not to be an option.

Figure 4. *Refilling the streamer with kerosene.*

The streamer (Figures 4 and 5) was unloaded from a truck at the beach in Havnsø from the road running parallel to the coast (Strandvej). To get the streamer out in the water, an attempt was made to unroll the streamer using the engine on the winch. This attempt failed and instead the streamer was dragged out in the water, first by a small boat, around 5 m long. This boat turned out to be too small. In the next attempt a small fishing boat was used. Due to the water currents, it was not possible to lay out the streamer perfectly straight.

Figure 5. *The streamer winch. The buoy attached to the near-shore OBS (station 15) is also seen.*

The positions at the beginning and at the end of the streamer are listed in Table 5. Positions for all channels are given in the file streamer_XY.txt. The water depth at channel 1 was approximately 1.5 m. The depth at channel 96 was unknown but estimated to be maybe 7.0 m. The correct bottom depth should be read from a bathymetry map.

Streamer channel	**Easting (m)**	**Northing (m)**
Channel 1 (near the shoreline)	646693.48	6181859.12
Channel 96	646995.20	6181371.50

Table 5. *UTM coordinates of the first and last channel of the marine streamer using UTM Zone 32 and datum EUREF89.*

The waypoints given in Table 5 are plotted in Figure 6. The blue line indicates the straight line between the first and last channel of the streamer. The red line is more in agreement with the actual position of the streamer and is confirmed by extra waypoints taken along the streamer.

Figure 6. *Blue line: straight line between the two endpoints of the streamer. Red line: the actual position of the streamer. Waypoints at the beginning and at the end of the streamer are marked by a red circle.*

For the deployment, the streamer was pulled out with buoys attached to the streamer at several places. When the streamer was pulled out completely, the buoys were removed and the streamer was supposed to sink down to the seafloor. However, air in the streamer caused the streamer to float over significant intervals. To increase the weight, lead was mounted on the streamer at 20 positions. In between these lead mounts, the streamer was most likely floating in the water column, although it could not be seen from the surface. Thus, vertical, and most likely also horizontal bends occurred along the streamer. This is why the horizontal distance between the start and end point was less than the expected 593.75 m (6.25 m times 96-1). Based on the map (Figure 6), the horizontal distance along the curved streamer path was estimated to be 576 m. To obtain the interpolated hydrophones positions, the group distance was therefore adjusted to 6.06 m from which the positions for each channel were determined. The interpolated positions are displayed in Figures 7 and 8. Each of the four streamer sections had its own seismic acquisition module where the data were recorded. The name of the modules and sections are shown in Figure 9.

Figure 7. *Interpolated positions of hydrophones. Original channel numbers are annotated.*

Figure 8. *Interpolated positions of hydrophones. The renumbered channels are annotated.*

Figure 9. *The four streamer sections are indicated by colored lines with the numbers indicating the module names used during the acquisition.*

4.2 Verification of Timing

At the northernmost point of line GEUS22–HVN–P1 on Zealand, a short geophone cable was laid out to check the timing between the vibroseismic source and data acquired on the marine streamer. The lay-out of this short geophone cable is shown in Figure 10. The geophone cable consisted of 24 channels with single channel 14 Hz vertical geophones. The distance between geophones was 1.25 m. Positions of geophones are shown in Figure 11 with the coordinates of the first and last geophone listed in Table 6.

Geophone cable	Easting (m)	Northing (m)
Channel 1	647056.85	6181307.43
Channel 24	647041.72	6181331.87

Table 6. *UTM coordinates of channels 1 and 24 of the short geophone cable using UTM Zone 32 and datum EUREF89.*

Positions for all channels are given in the file *geophone_cable_XY.txt*. The acquisition module for the geophone lay-out is the same type that is used for the marine streamer. Therefore, no timing differences are expected between the geophone cable and the marine streamer. The acquisition units used in the main onshore vibroseismic experiment are equipped with GPS. However, the position from the unit located next to channel 24 of the geophone cable was not as accurate as the reading from the orthophoto. Therefore, the positions have been read from the orthophoto instead and the coordinates of the geophones have been extracted from there. The land seismic streamer used for the vibroseismic survey is shown in Figure 12. The seismic vibrators at the last vibration point are also shown.

Figure 10. *The short geophone cable with its geophones and the acquisition unit (orange box). The cable is coincident with some nodes (grey units) used in the main vibroseismic survey to verify the timing between the two independent acquisition systems.*

Figure 11. *Position of geophones (red circles) used for the verification of the timing of the data. The near-shore part of the marine seismic streamer is seen top left. Channel numbers are annotated.*

Figure 12. *Left: short geophone cable (red cable in the grass) used to verify the timing of the signals. The land seismic streamer and nodes (on the pavement) and one of the wireless geophones (white box in the grass) used for the vibroseismic survey are also seen. Right: vibrator trucks at the closest vibration point to the shore.*

4.3 Data Acquisition and Compilation

Data from both the marine streamer and the geophone cable were recorded on Geometrics Geodes. Each Geode records 24 channels (modules 101 through 104 on the marine streamer). One additional Geode was used for the short land seismic geophone cable with 24 channels (module 105). Records were acquired with a record length of 8 s and sampled at 1 ms intervals. Continuous recordings were made. By using a system developed at Geoscience Aarhus University, the PPS pulse from an external GPS device triggered the Geodes at 8 s intervals. The initiation of each record took place at a whole second. The precision of the PPS signal is estimated to be 30 μs. The raw data were acquired in SEGD format, where the GGA string from the GPS device was written to the extended header of the SEGD files in ASCII format.

From the provided start times of the vibration sweeps, given in the files *gpstime_Havnso_line1_20220823.txt* and *gpstime_Havnso_line1_20220824.txt*, for August 23 and 24, 2022, respectively, the time intervals of interest were calculated. A sweep length of 18 s was assumed, and the final correlated record length was set to 6 s. Thus, 24 s of data were compiled from the raw data, which was sufficient for this data set. The start times of the vibration sweeps appear as

```
GPS TIMESTAMP,SRC LINE,SRC STATION,FFID,SAMPLE PERIOD,RECORD LENGTH,TYPE OF DUMP,SOURCE TYPE
1345273090733221,1,13571,19007,2000,25000,0,0
1345273128262589,1,13571,19008,2000,25000,0,0
1345273158307038,1,13571,19009,2000,25000,0,0
1345273390433241,1,13571,19011,2000,25000,0,0
1345273421948800,1,13571,19012,2000,25000,0,0
1345273452307174,1,13571,19013,2000,25000,0,0
```

in this example of file *gpstime_Havnso_line1_20220823.txt* that shows the first sweeps created on August 23, 2022.

File numbers (starting with 19007) are moved to the SEGY output files. One output file was generated for each module. These files were entered into the processing software *Promax* and a joint record for all modules and for each sweep was compiled. During this process, channel numbers were renumbered from 1 to 96, with the near-shore hydrophone being channel 1. The positions of all channels are shown in Figure 8. Data from the land seismic module went through the same process. In *Promax*, the original files numbers were replacement with the vibration file numbers (FFID).

The output files containing the marine streamer data are named *havnsoe_mod101-104_raw_aug23.sgy* and *havnsoe_mod101-104_raw_aug24.sgy,* one for each of the two acquisition days. Data from the short geophone cable used for the time check are stored in the files *havnsoe_mod105_raw_aug23.sgy* and *havnsoe_mod105_raw_aug24.sgy*. The time check against the vibroseismic data has not been performed as part of this report.

4.4 Preliminary Processing

For correlation of the marine data, the source sweep provided in file *Sten_10-140_18s.sgy* (Figure 3) has been used. An example of correlated output data is shown in Figure 13. Both the near-shore data but also data from the outermost channels are rather poor in quality. On the near-shore part of the streamer, this is most likely due to noise from traffic along the beach and due to the surge of waves. At the outermost channels, the reason for the poor data quality is unknown. An explanation might be drag in the streamer from the buoy being attached to it. Data acquired in the central part of the streamer on channels 25 through 80 gave reasonably good signals, although some isolated channels had to be removed due to increased noise. This is probably related to air in some short sections of the streamer, which prevented the signals to be recorded by the hydrophones.

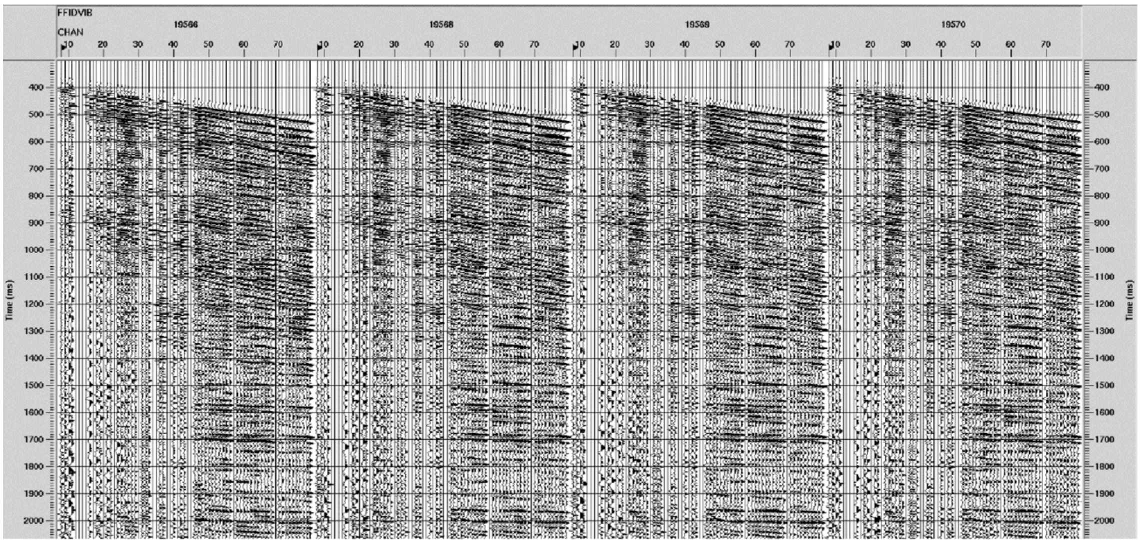

Figure 13. *Correlated raw data acquired on the marine streamer. Offset interval: 800–1200 m. Vibration file numbers are annotated above the data.*

Based on the positions provided in files *ShotCoordinates_Havnso_20220823.csv* (vibration coordinates near Havnsø) and *ShotCoordinates_Havnso_20220824.csv* (vibration coordinates on Nekselø) and on the position of the marine streamer, the geometry of a seismic line has been defined (Figures 14 and 15).

Figure 14. *Vibration points on line GEUS22–HVN–P1 near Havnsø are shown as orange circles (every 10th point is shown). Vibration file numbers are annotated. CDP (common depth points) points for data acquired on the marine streamer for vibrations on the Havnsø side are shown as green circles. CDP numbers are annotated.*

Figure 15. *Vibration points on line GEUS22–HVN–P1 on the southern part of Nekselø are shown as orange circles (every 10th point is shown). Vibration file numbers are annotated. CDP (common depth points) points for data acquired on the marine streamer from sweeps on Nekselø are indicated by green circles. CDP numbers are annotated.*

A preliminary processing of the vibroseismic data acquired on the marine seismic streamer was carried out. First, the geometry was set followed by trace editing, bandpass filtering, F-k filtering, AGC (automatic gain control), NMO (normal moveout) correction and stacking. No real velocity analysis has been made. Estimated velocities have been applied in the NMO correction. No trace muting has been performed either. Therefore, some data not representing *P*-waves are most likely present in the stack, although F-k filtering has suppressed some of those signals. Figures 16 and 17 show preliminary stacks of the vibroseismic data recorded on the marine seismic streamer for sweeps on the Havnsø side and Nekselø, respectively.

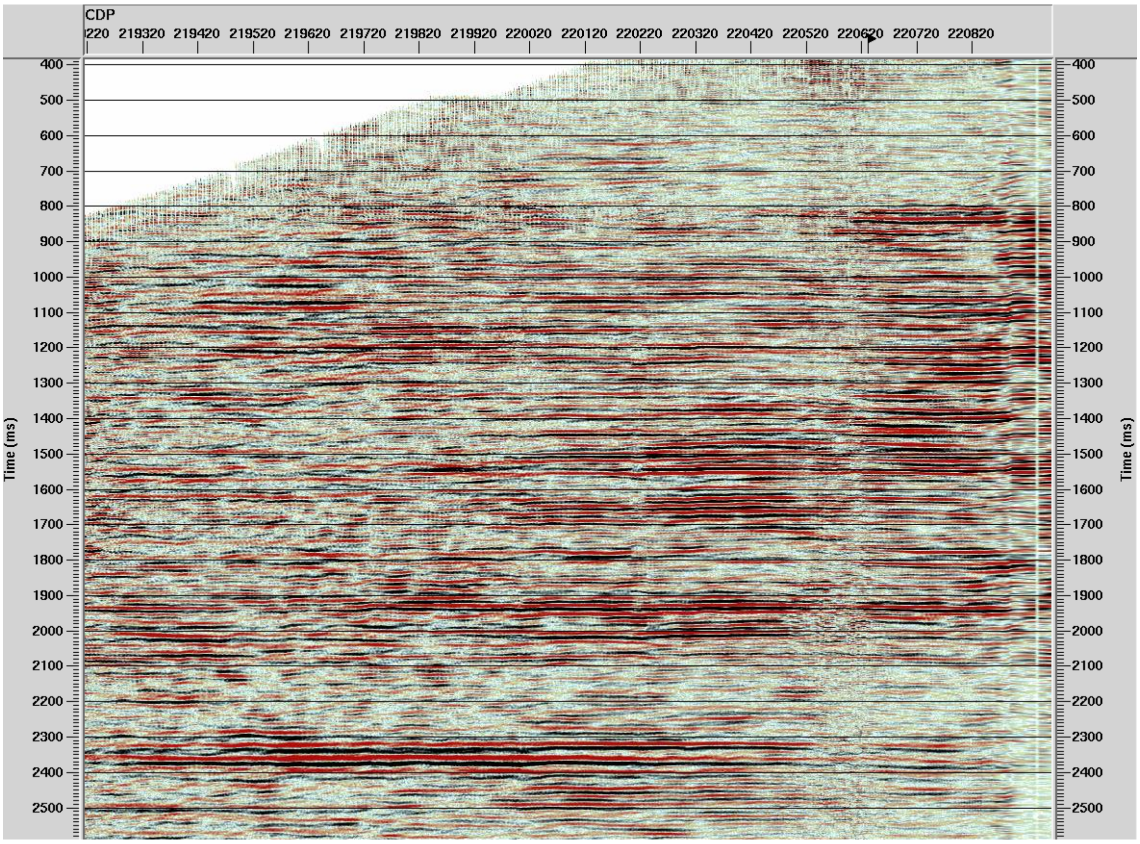

Figure 16. *Preliminary stack of vibroseismic data from line GEUS22–HVN–P1 acquired on the marine seismic streamer. CDP numbers are annotated. The stacked data are based on the sweeps near Havnsø.*

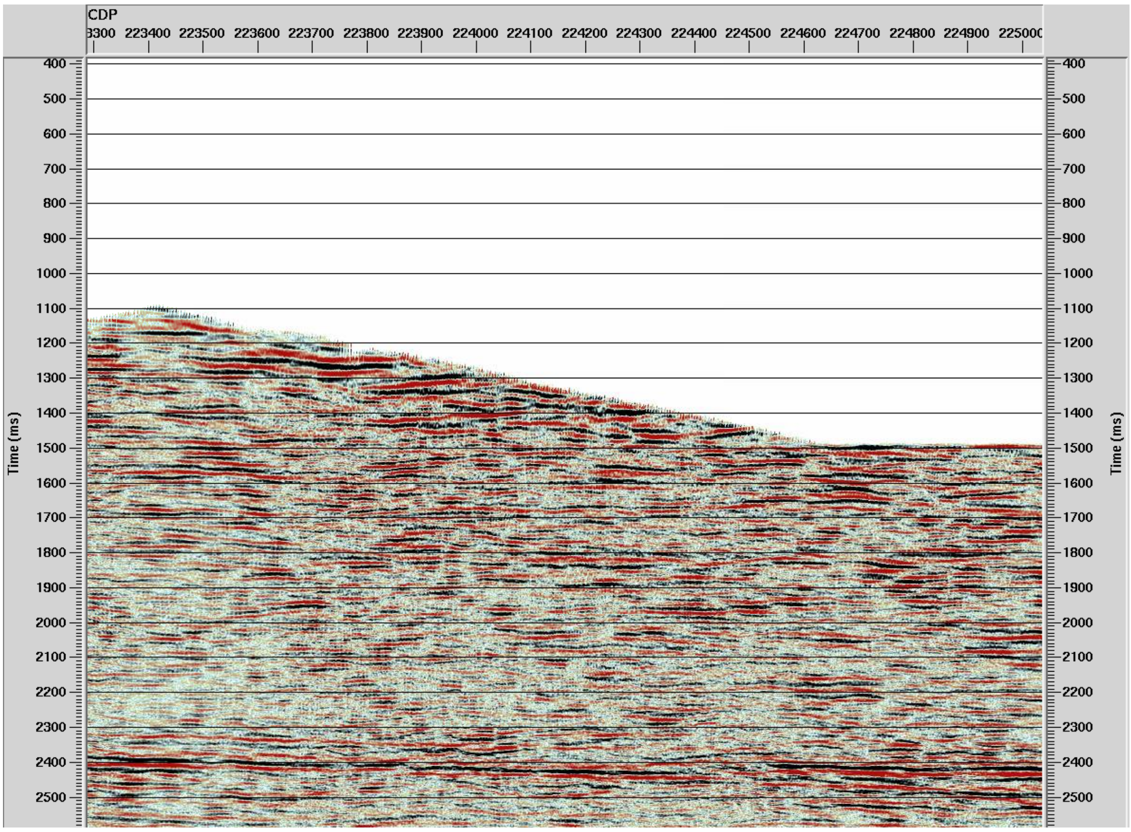

Figure 17. *Preliminary stack of vibroseismic data from line GEUS22–HVN–P1 acquired on the marine seismic streamer. CDP numbers are annotated. The stacked data are based on the sweeps on Nekselø.*

Stacked data originating from sweeps on Nekselø have been subject to significant larger offset (distance between source and receiver) of 2600 to 5000 m, compared to data from the Havnsø side. Here, the offsets are in the interval of 0 to 2500 m. This is the main reason for the different data quality of the two seismic profiles. On the stacked data with the vibrations near Havnsø (Figure 16), numerous reflections are observed in the time interval from 400 to 2600 ms. At greater depth (not shown in figure), reflections are present as well but at lower amplitude level. Even though the offsets were substantial for the stacked section resulting from the sweeps on Nekselø, reflections can still be observed (Figure 17). However, shallow reflections (<1200 ms) are problematic on those data due to the significant angle of incidence.

5. References

Malehmir, A. & Papadopoulou, M. 2023: GEUS2022-HAVNSOE seismic survey: Acquisition and processing report. Report Uppsala University, Uppsala, Sweden, 45 pp.

Appendix A

Record sections of ocean bottom seismometers (OBS) at stations 5, 7 to 13, and 15 to 20 recorded on the hydrophone component (channel 1) for sweeps near Havnsø (from August 23, 2022) and on Nekselø (from August 24, 2022) on line GEUS22–HVN–P1.

The data in the plots are resampled to 2 ms, debiased, correlated with the source sweep, band-pass filtered (corner frequencies: 6 Hz, 8 Hz, 70 Hz, 80 Hz), and scaled by dividing by rms value on each trace. The processing was done in the free software package *Seismic Unix*.

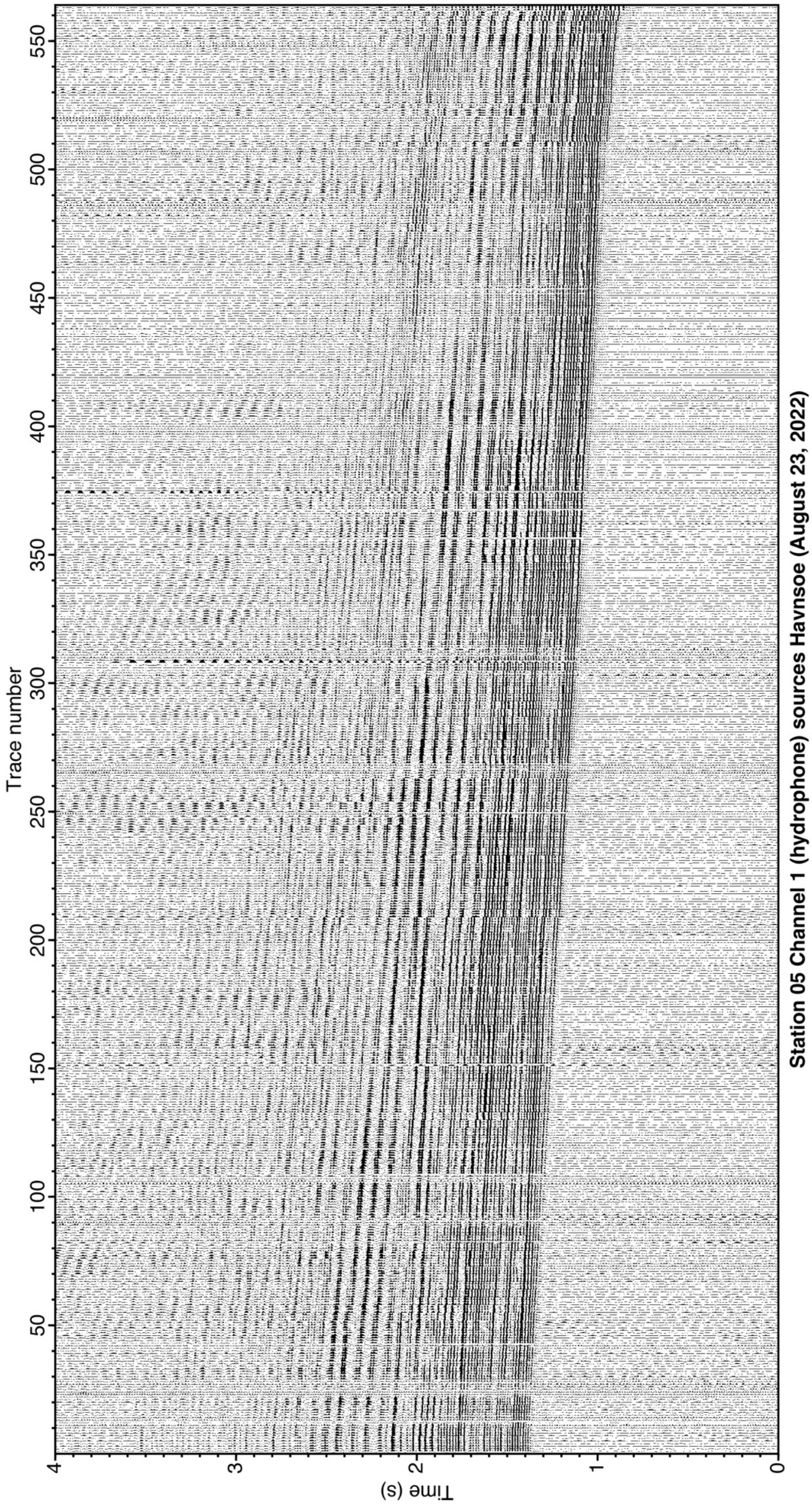

Figure A1. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 5 recording the sweeps from the Havnsø area.*

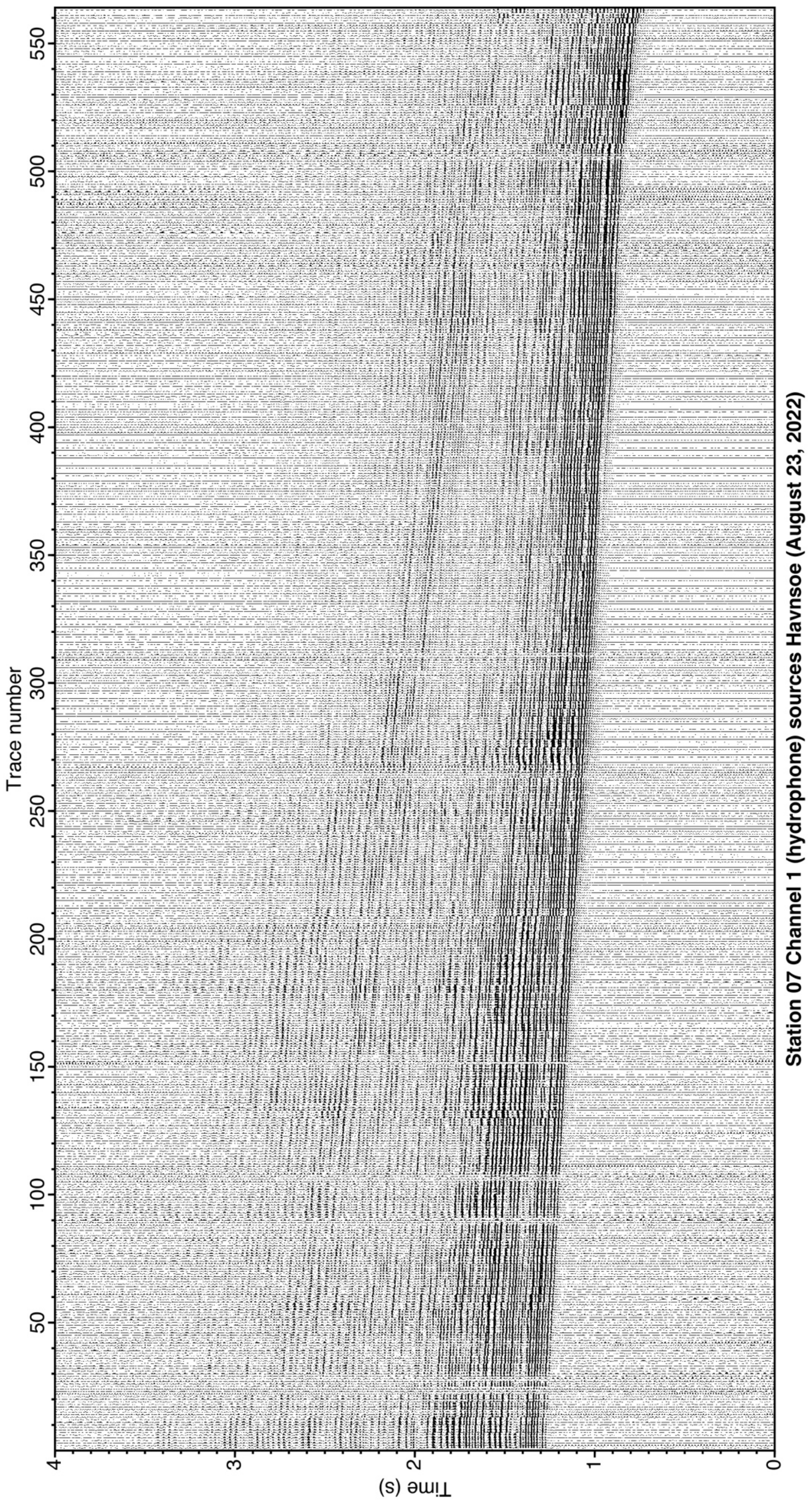

Figure A2. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 7 recording the sweeps from the Havnsø area.*

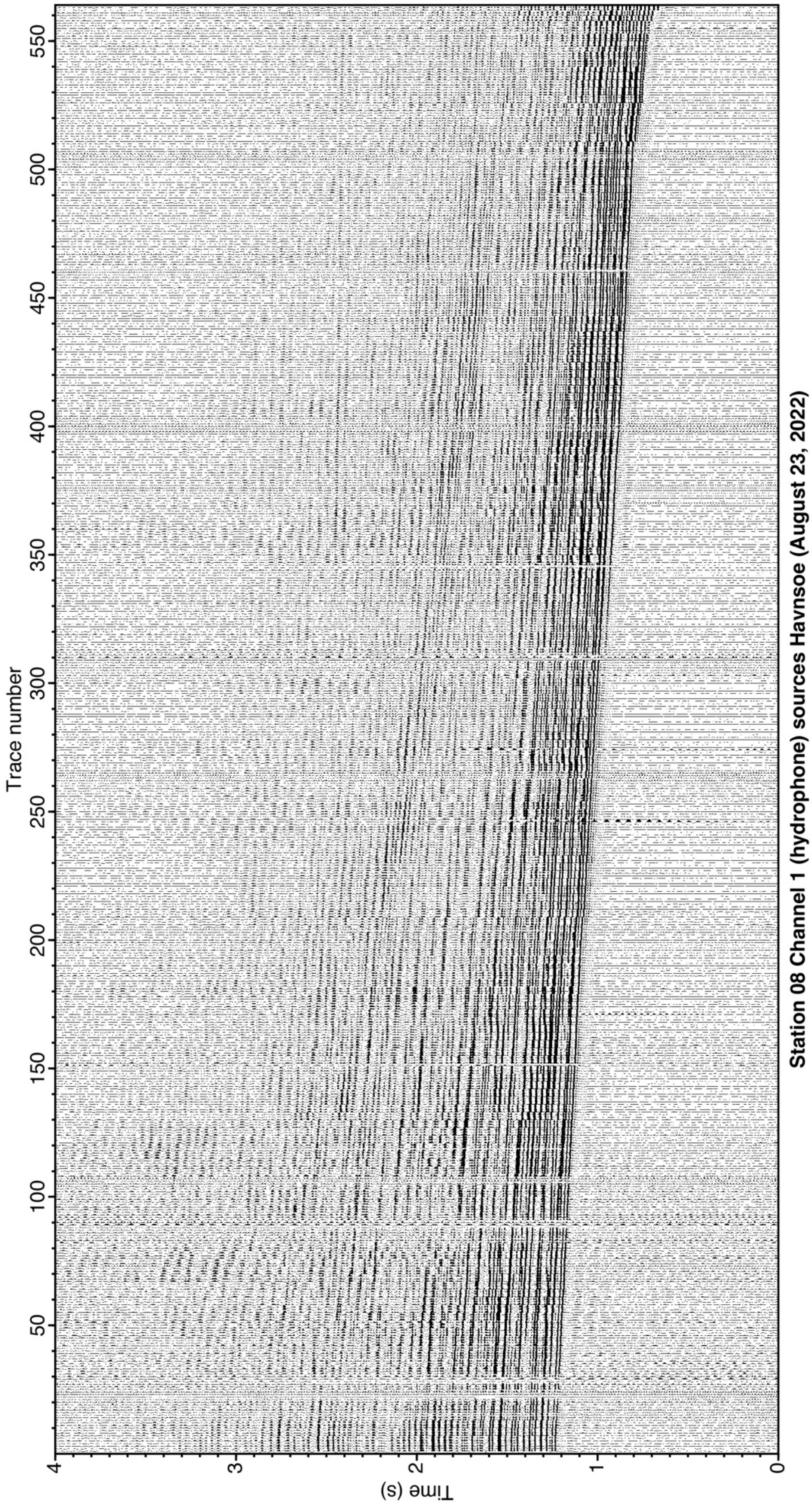

Figure A3. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 8 recording the sweeps from the Havnsø area.*

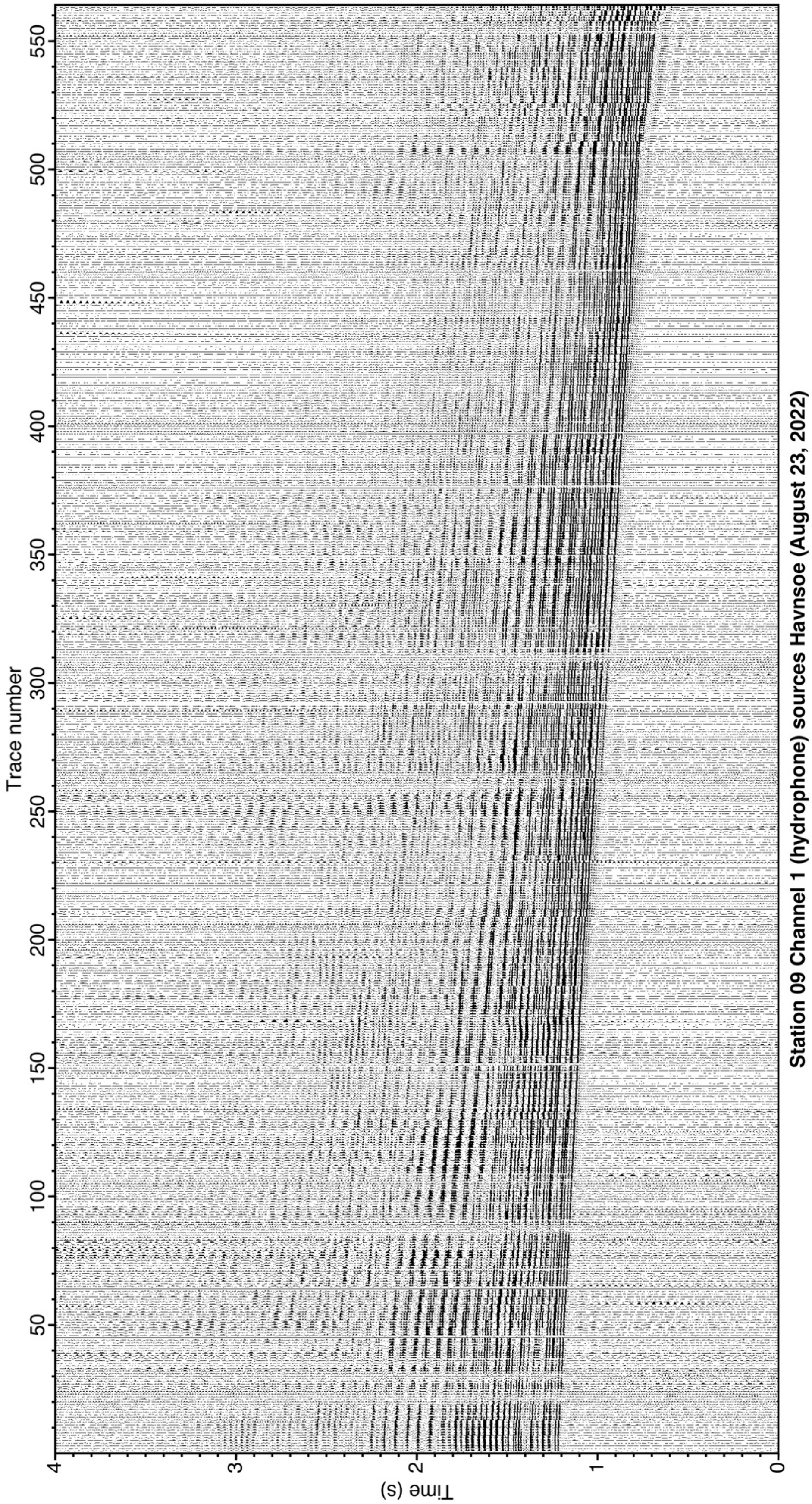

Figure A4. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 9 recording the sweeps from the Havnsø area.*

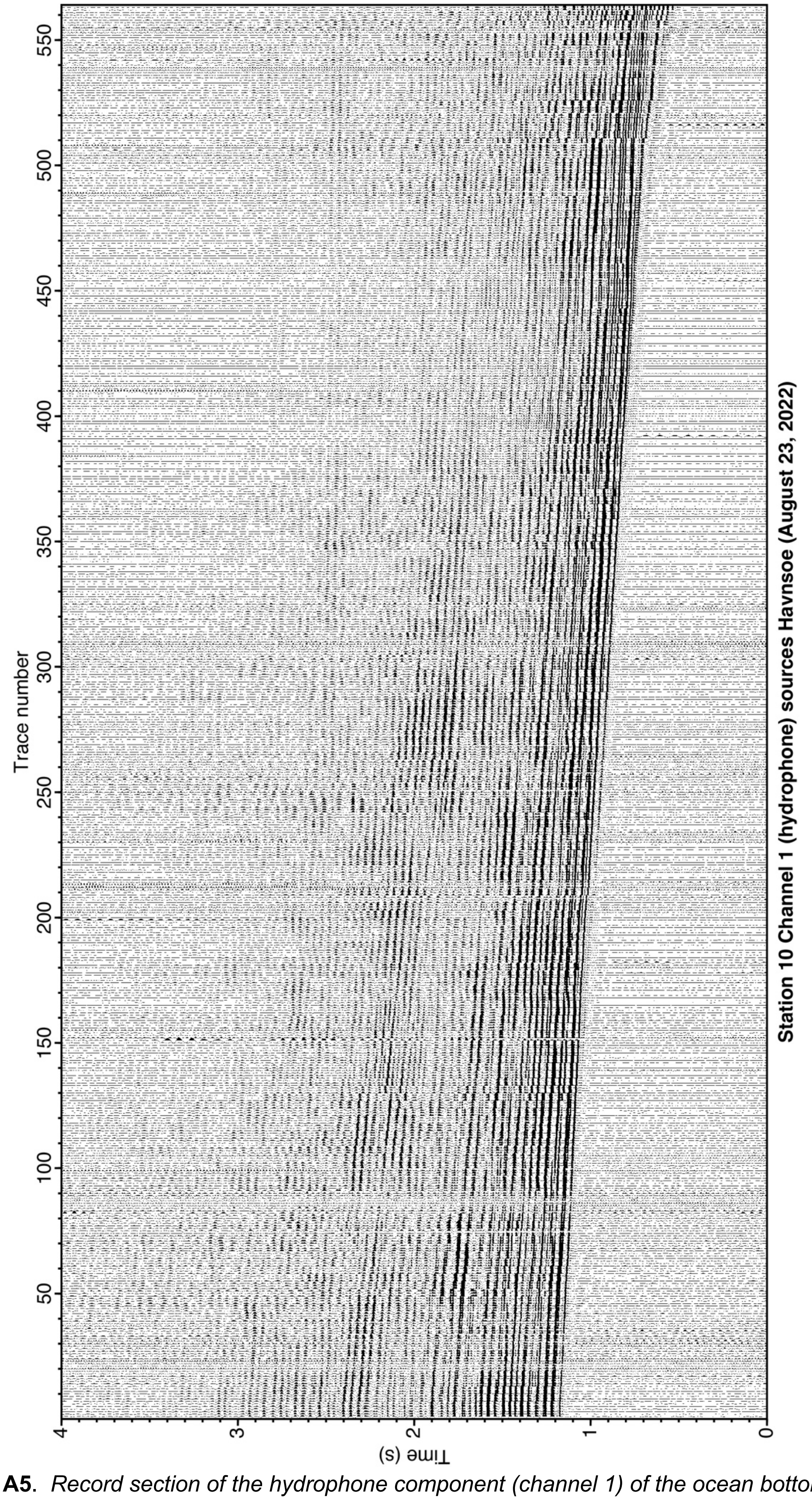

Figure A5. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 10 recording the sweeps from the Havnsø area.*

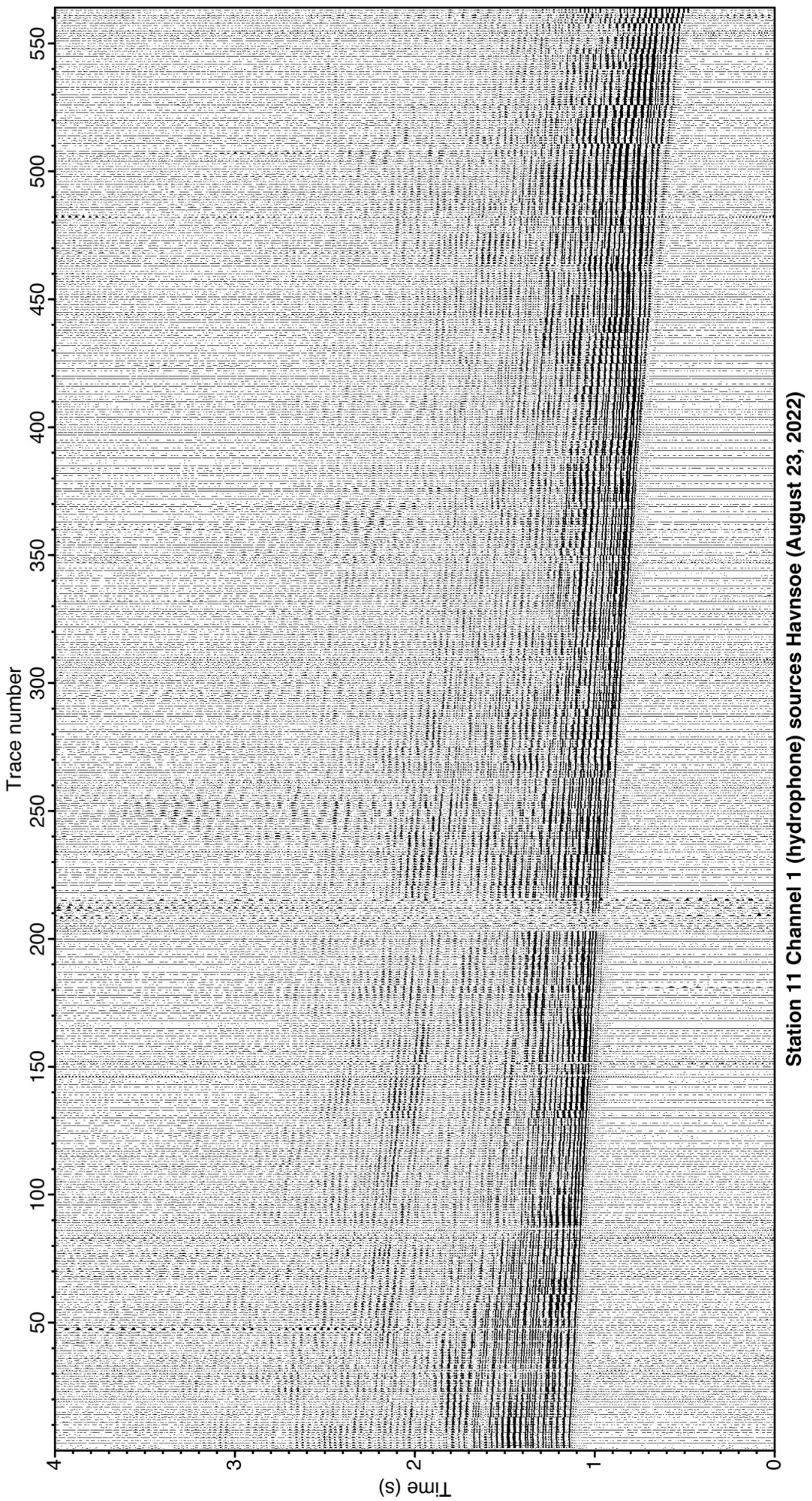

Figure A6. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 11 recording the sweeps from the Havnsø area.*

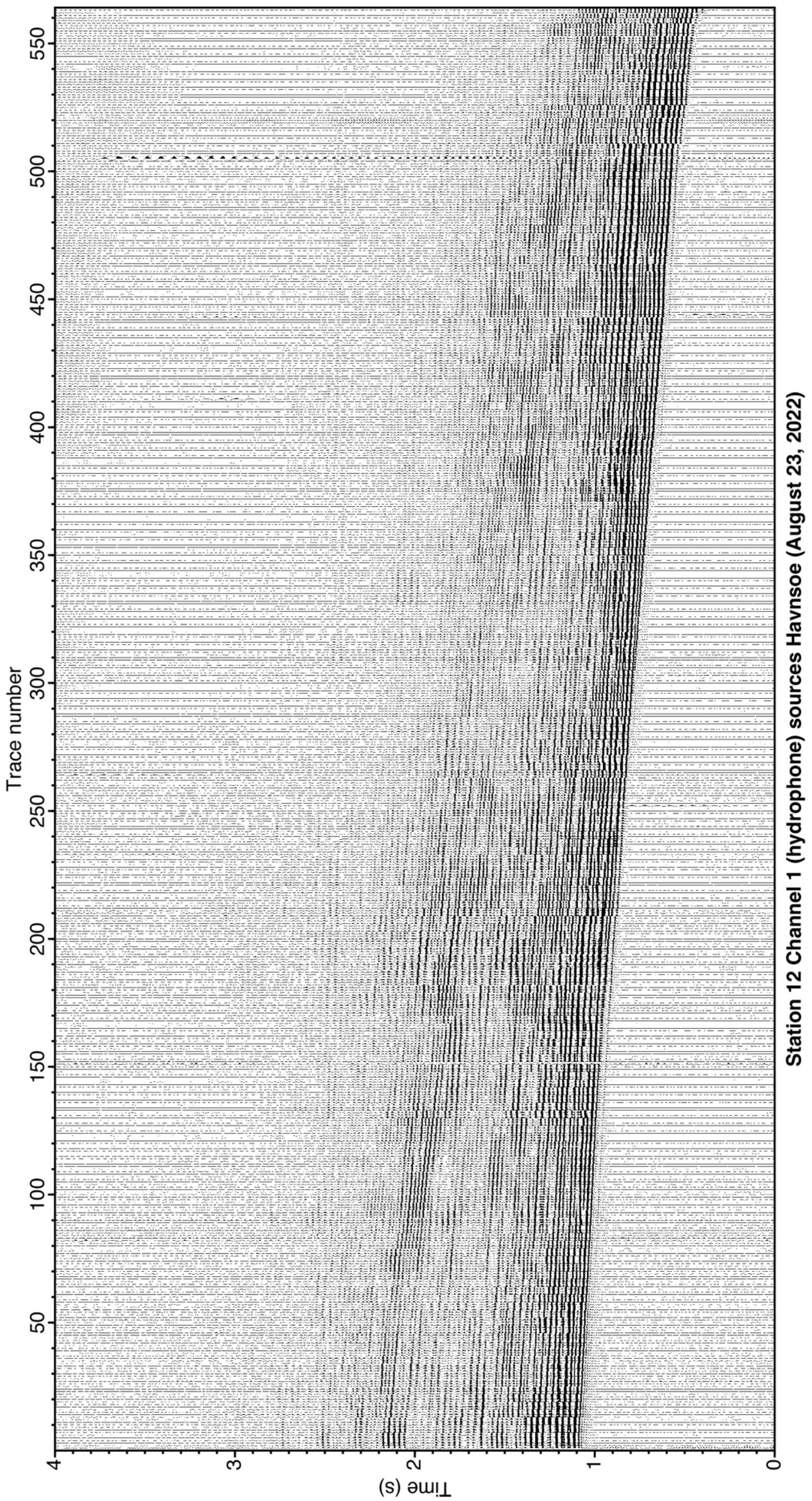

Figure A7. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 12 recording the sweeps from the Havnsø area.*

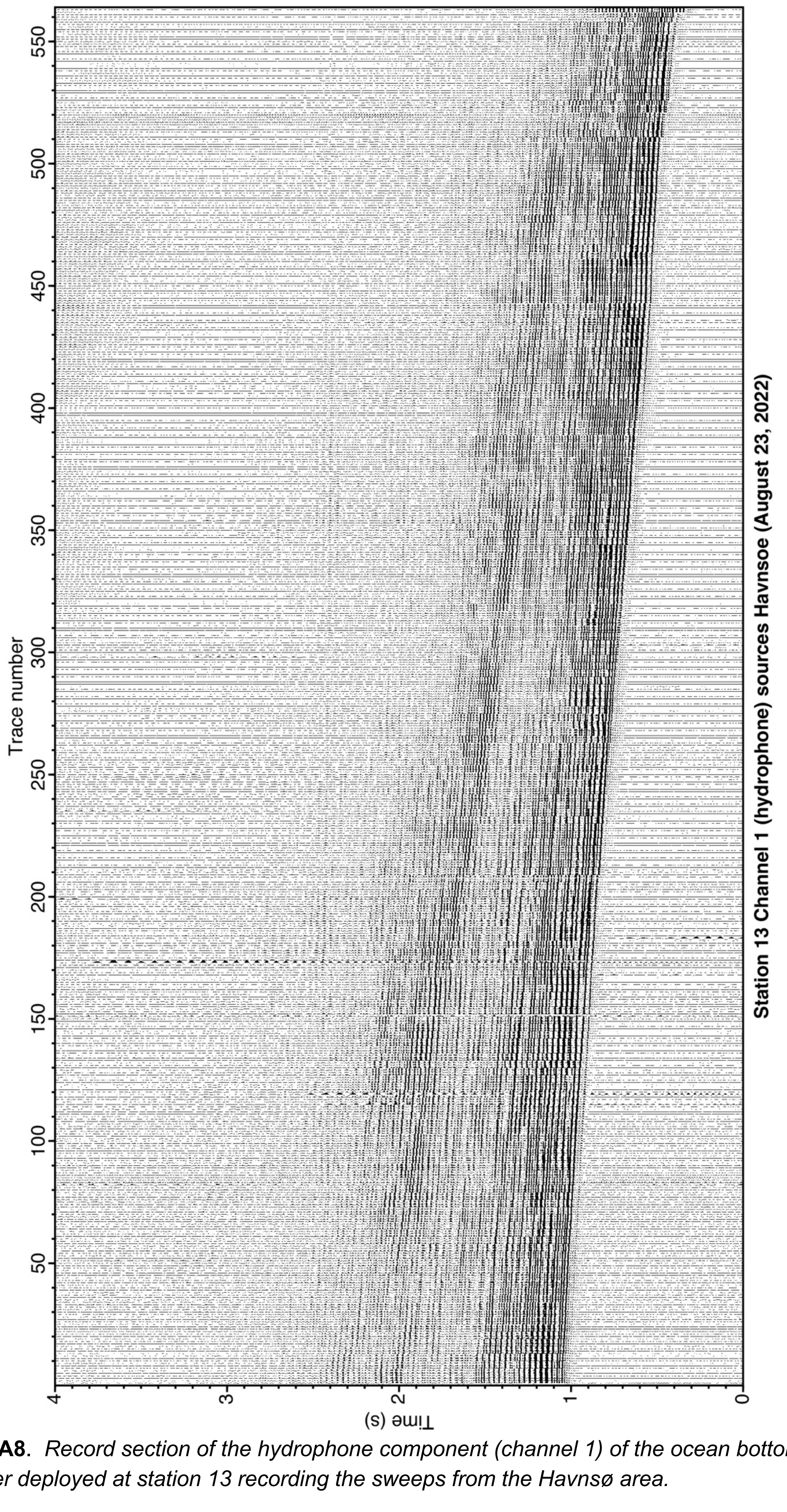

Figure A8. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 13 recording the sweeps from the Havnsø area.*

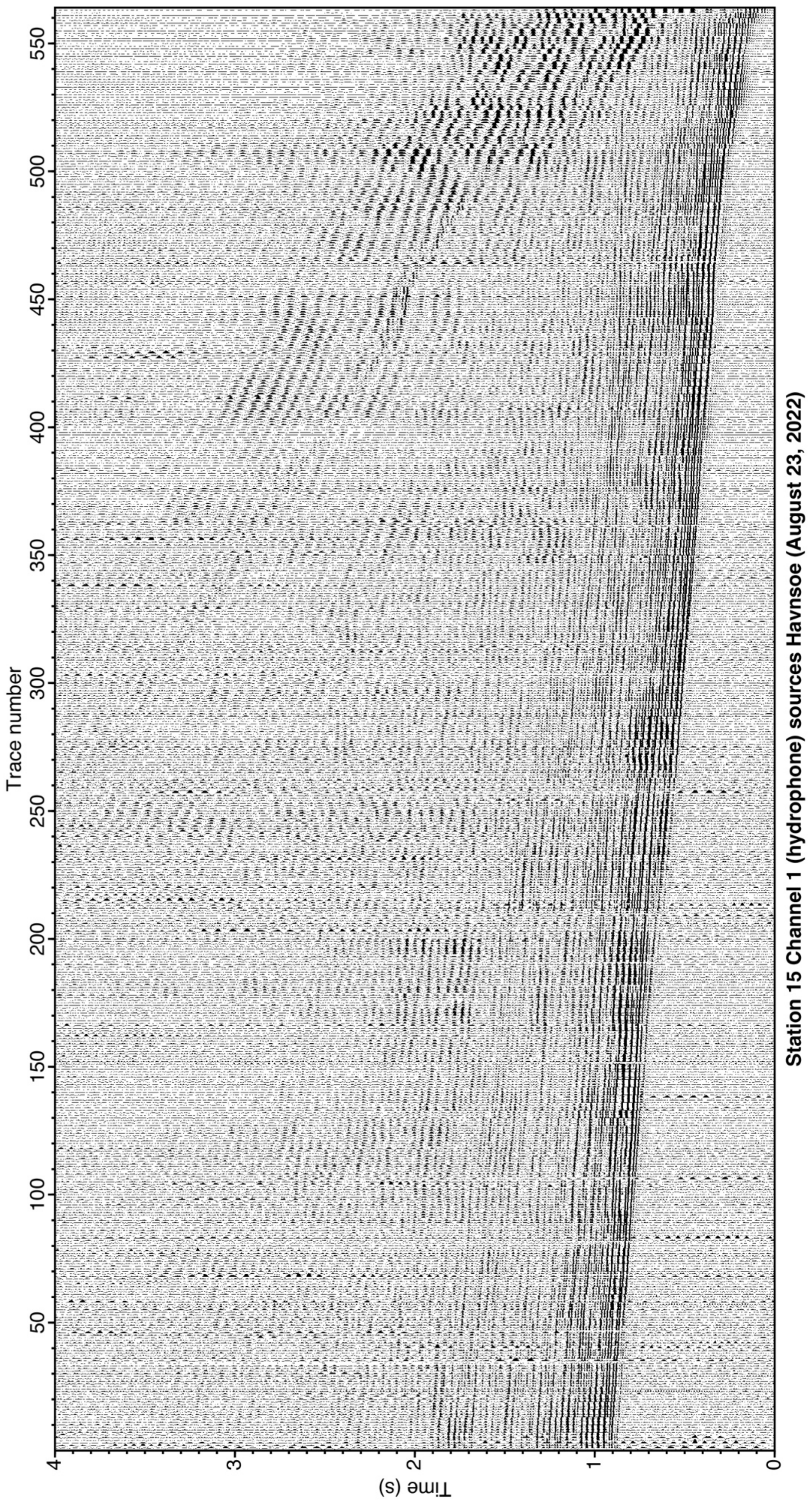

Figure A9. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 15 recording the sweeps from the Havnsø area.*

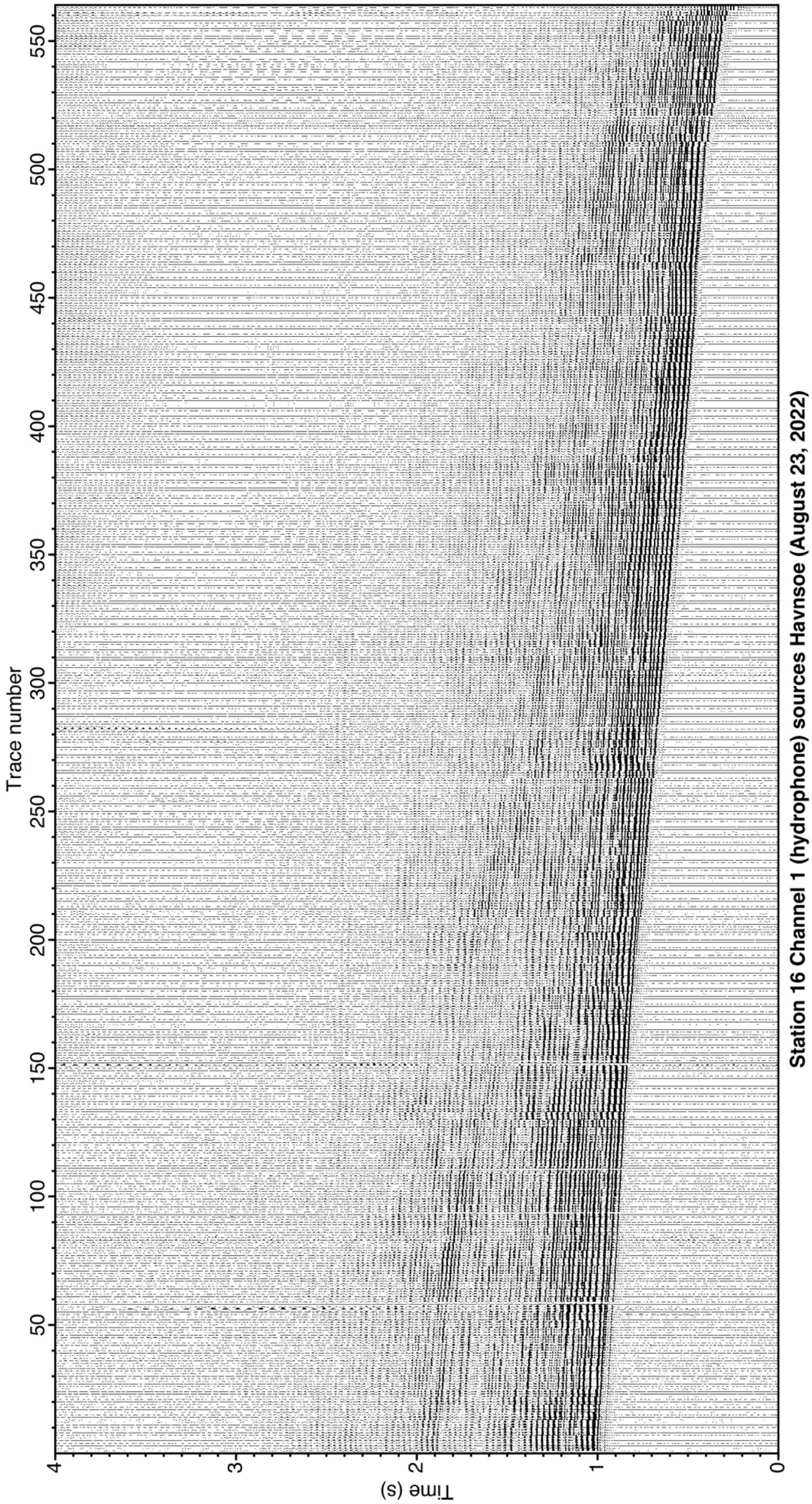

Figure A10. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 16 recording the sweeps from the Havnsø area.*

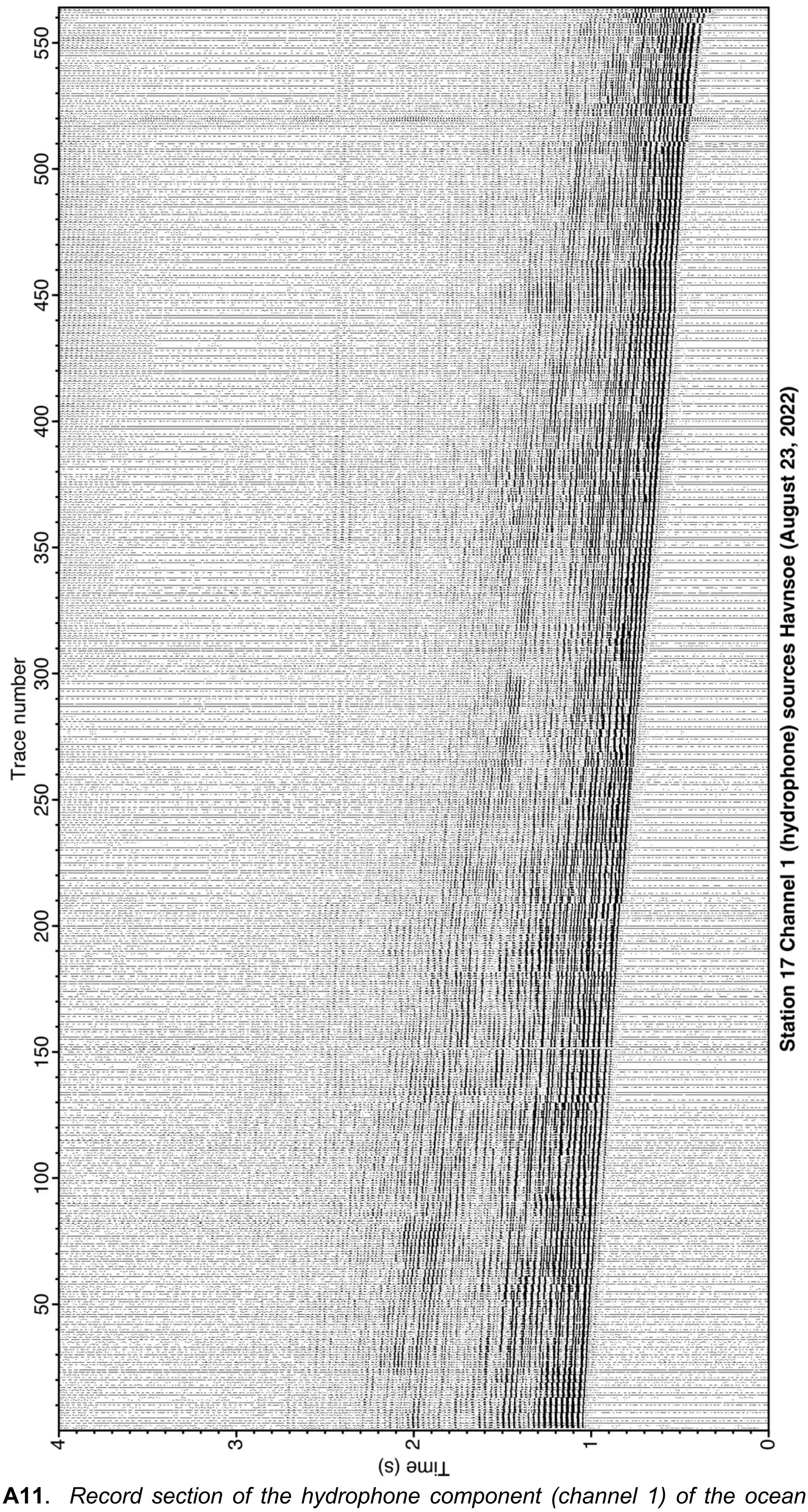

Figure A11. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 17 recording the sweeps from the Havnsø area.*

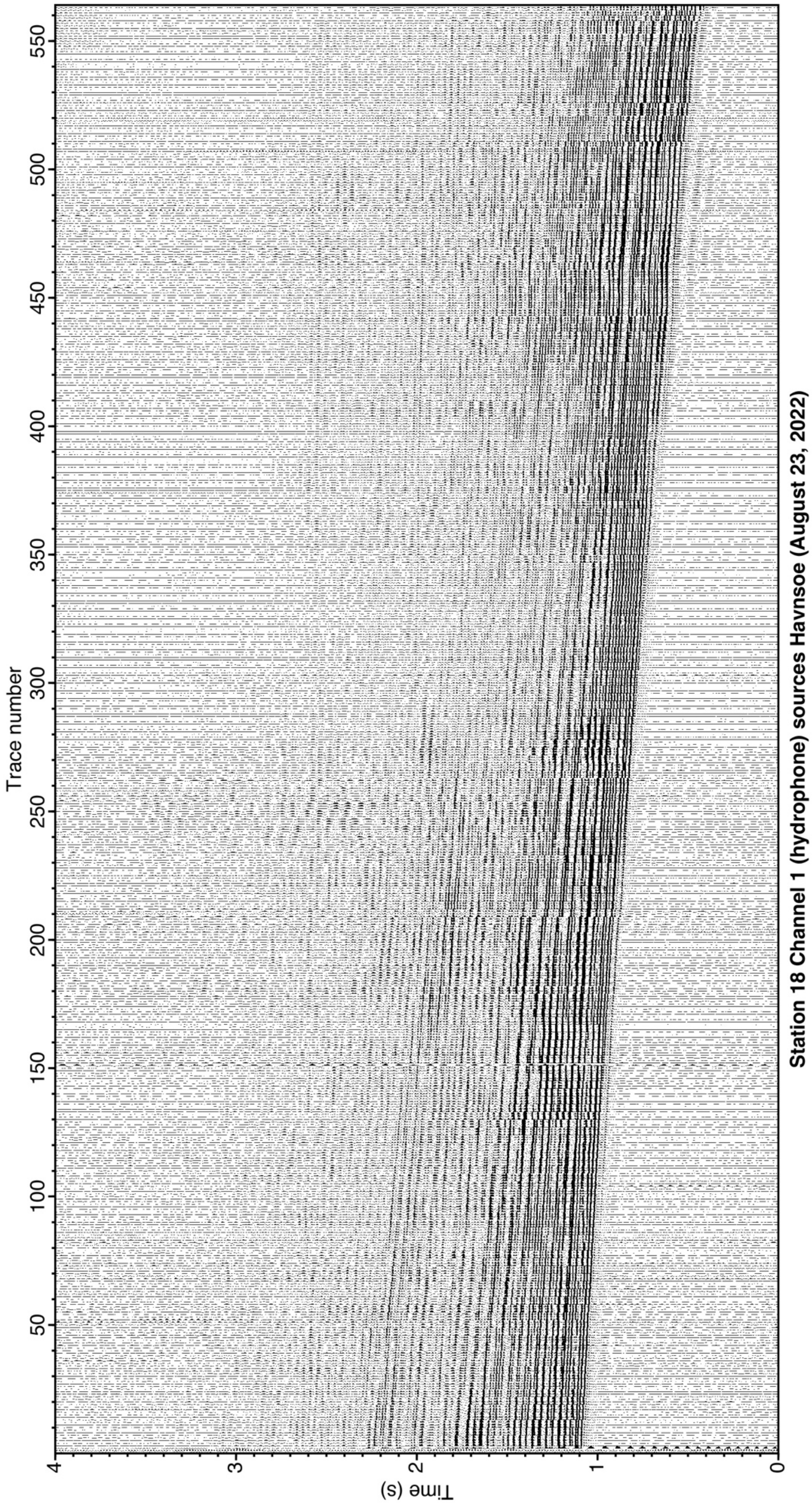

Figure A12. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 18 recording the sweeps from the Havnsø area.*

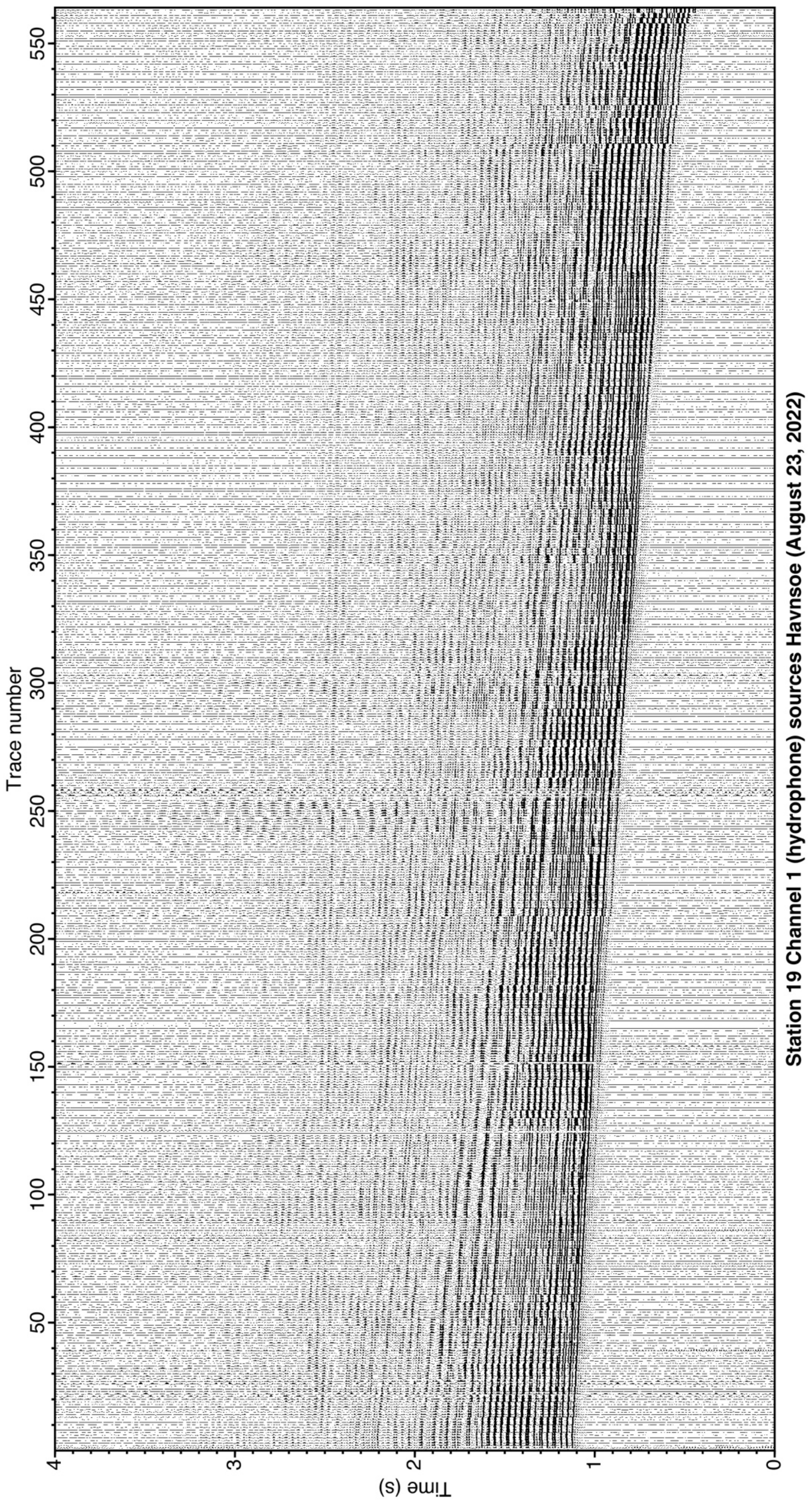

Figure A13. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 19 recording the sweeps from the Havnsø area.*

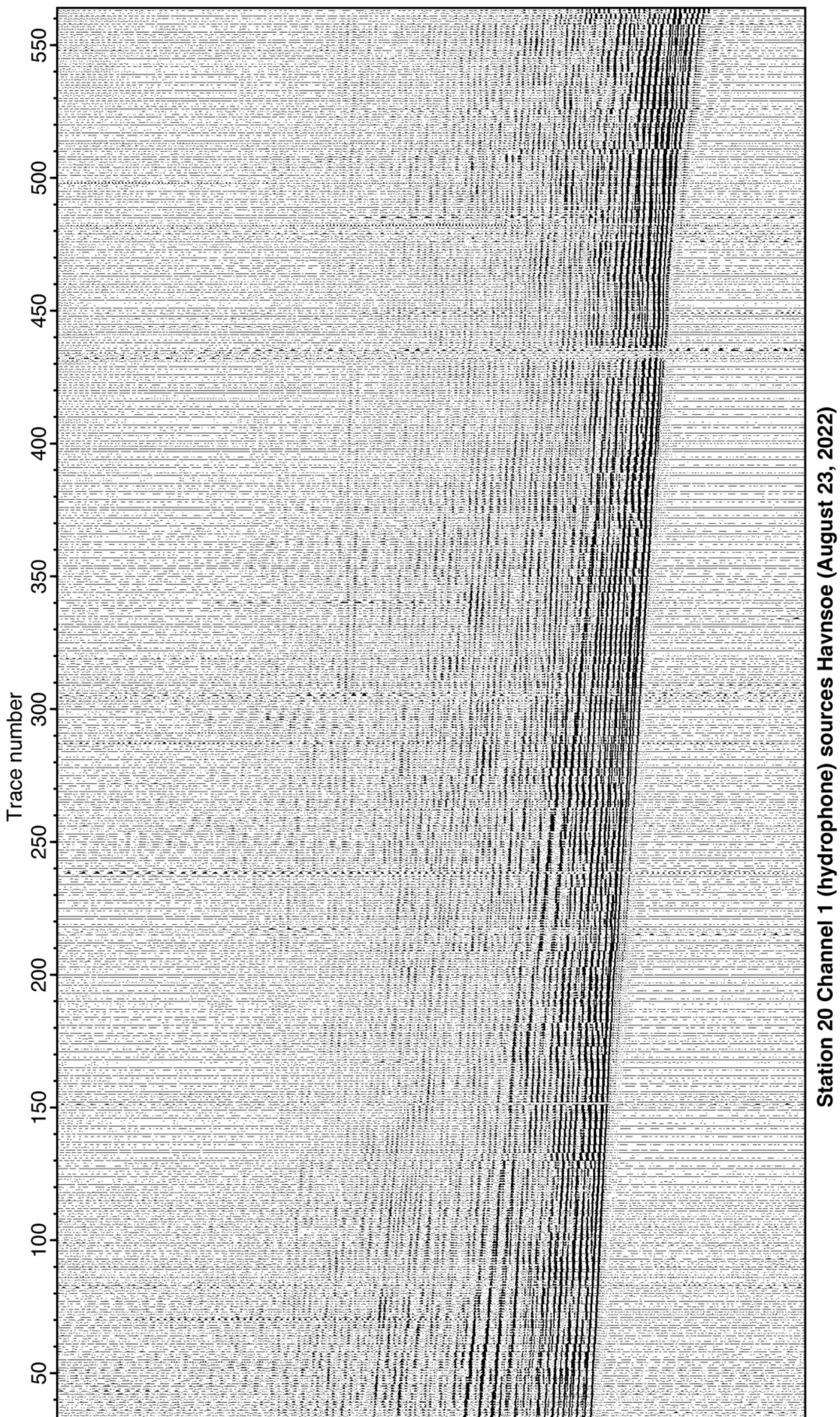

Figure A14. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 20 recording the sweeps from the Havnsø area.*

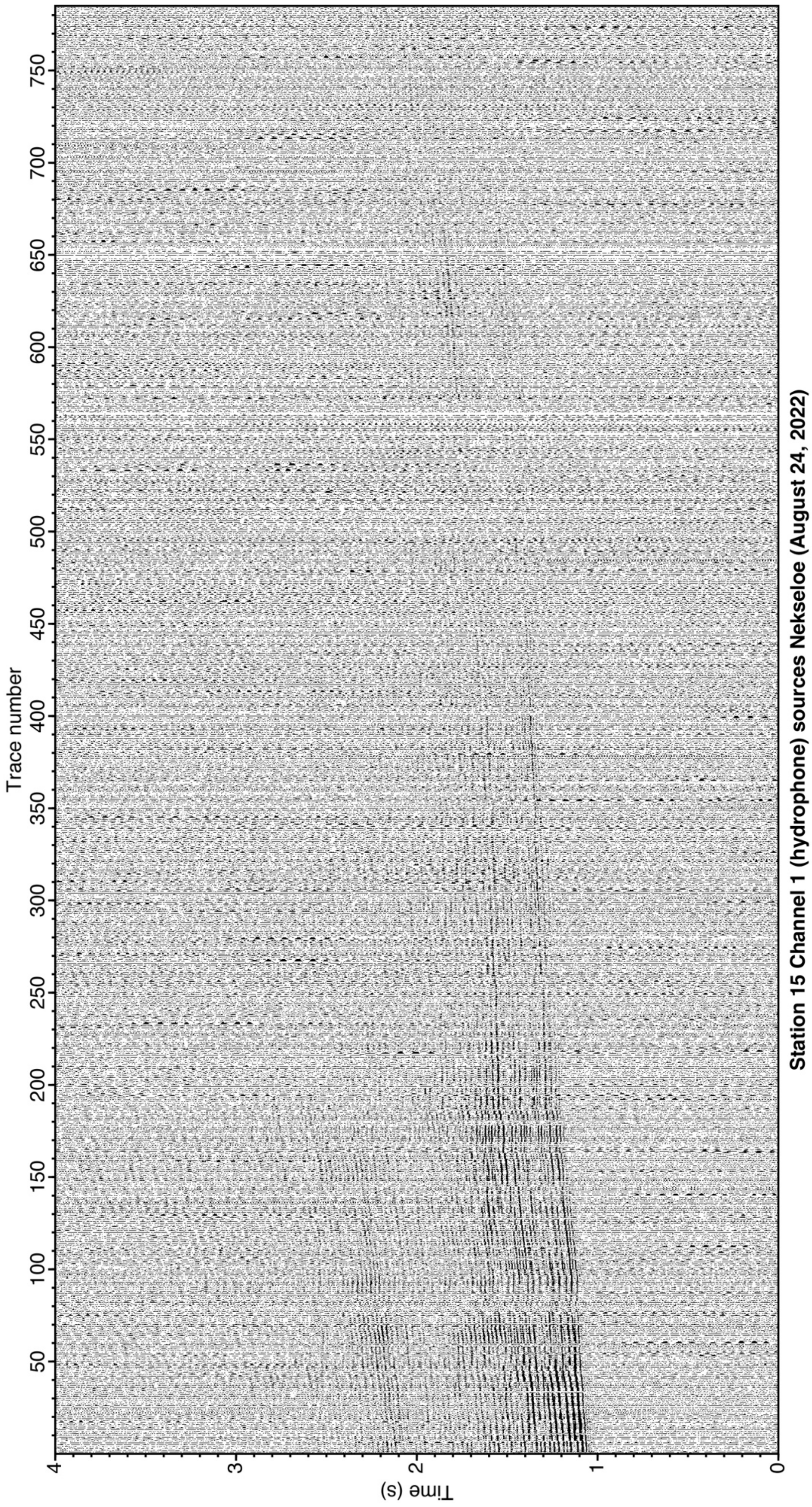

Figure A15. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 15 recording the sweeps on Nekselø.*

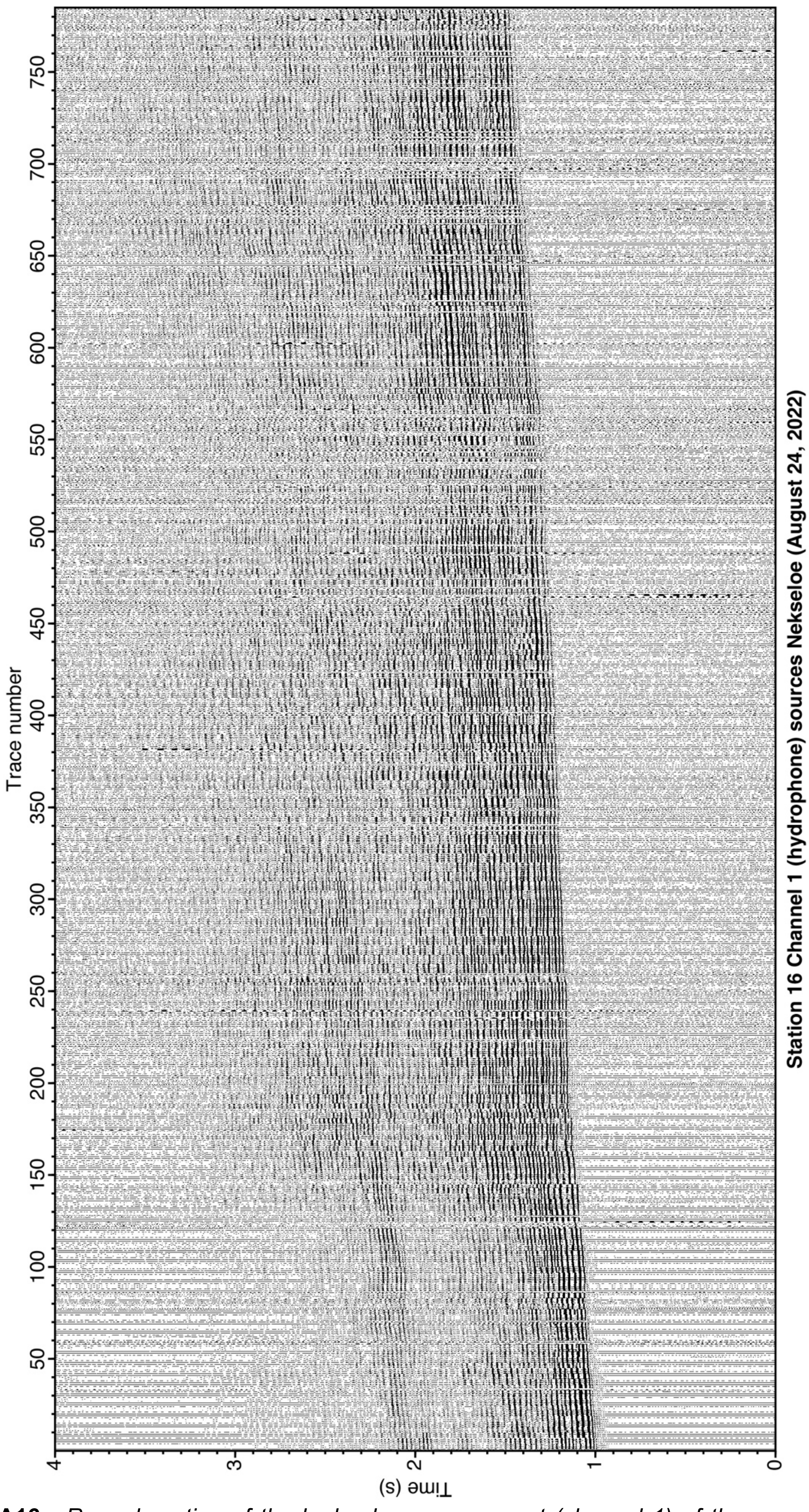

Figure A16. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 16 recording the sweeps on Nekselø.*

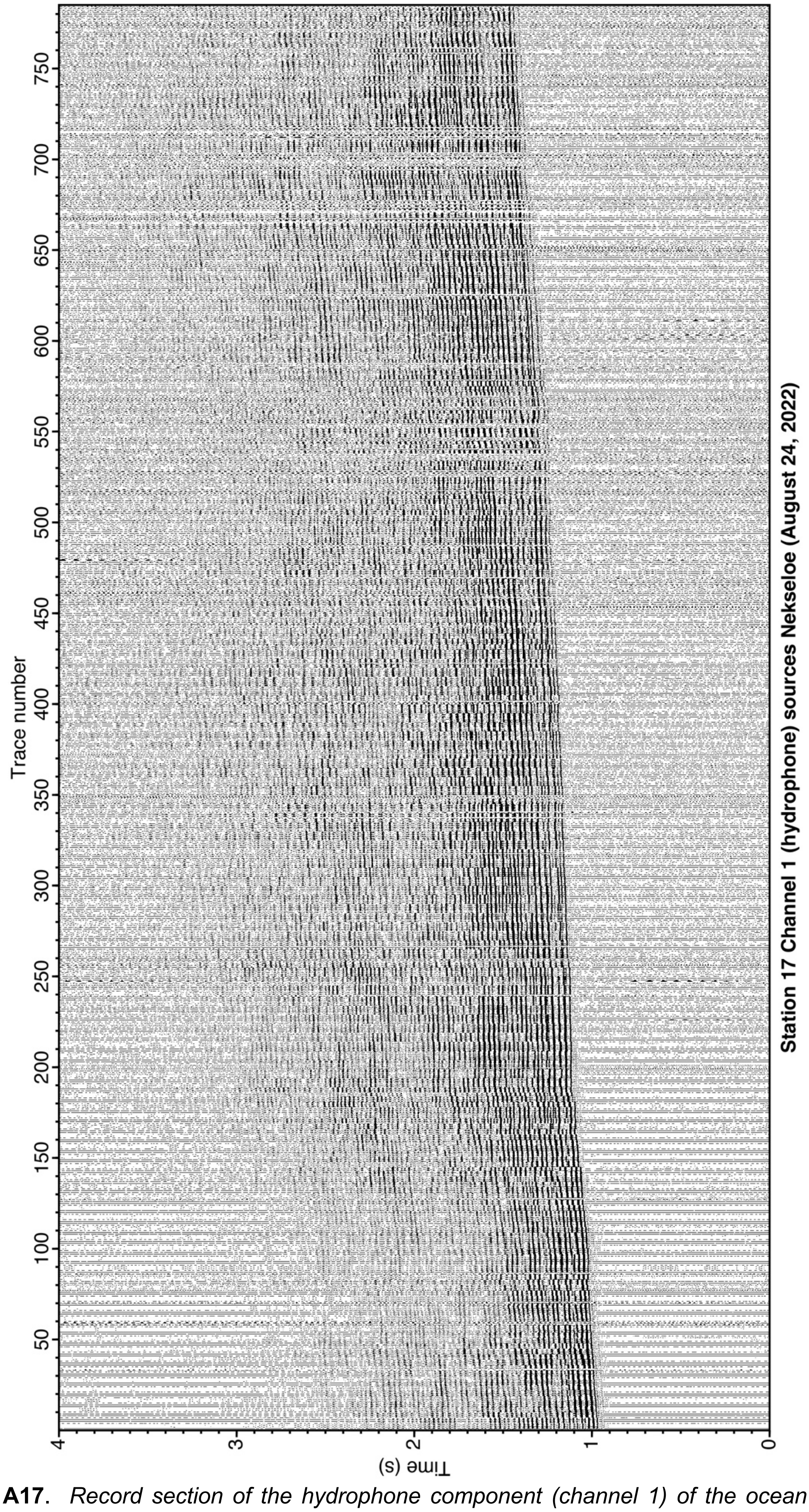

Figure A17. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 17 recording the sweeps on Nekselø.*

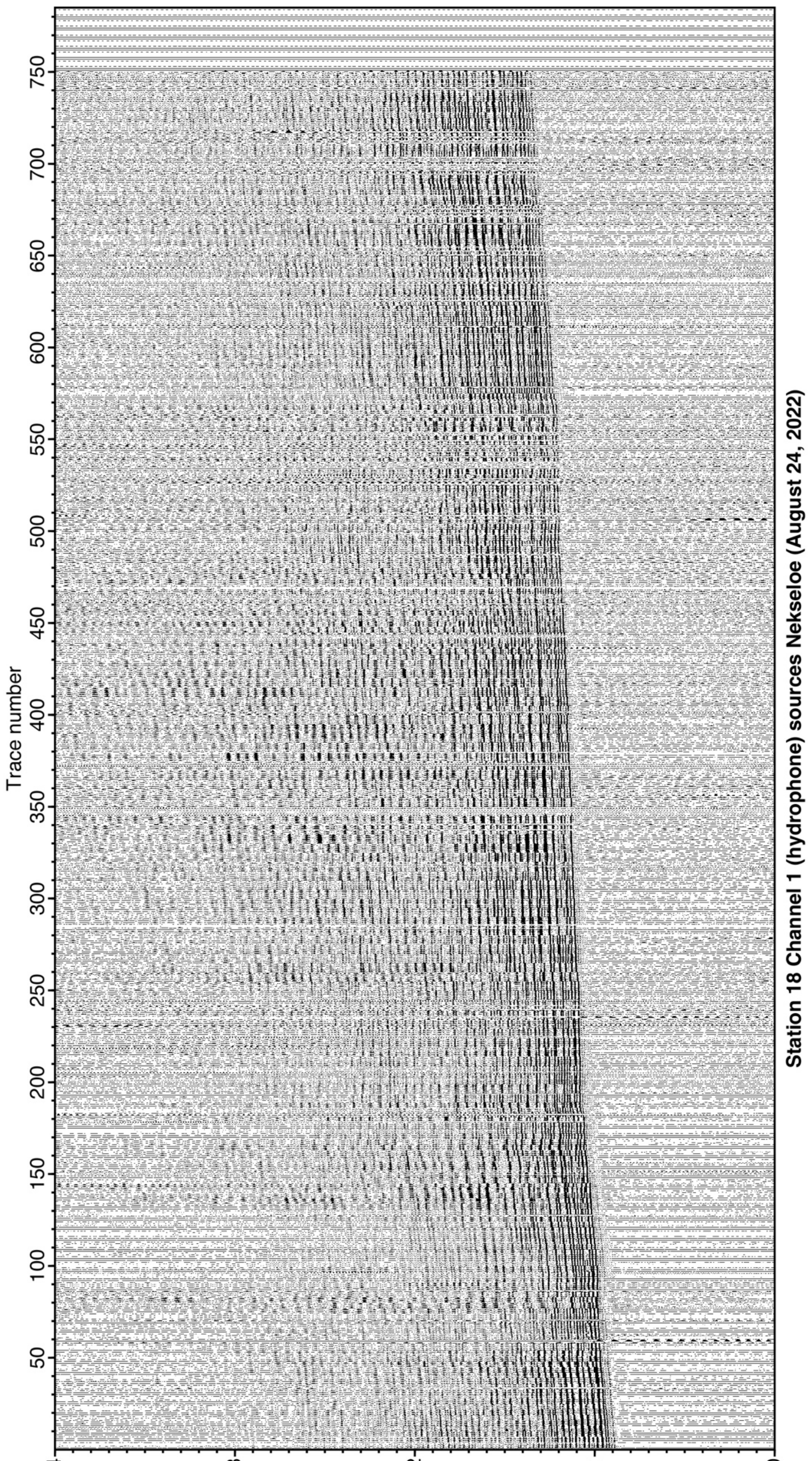

Figure A18. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 18 recording the sweeps on Nekselø.*

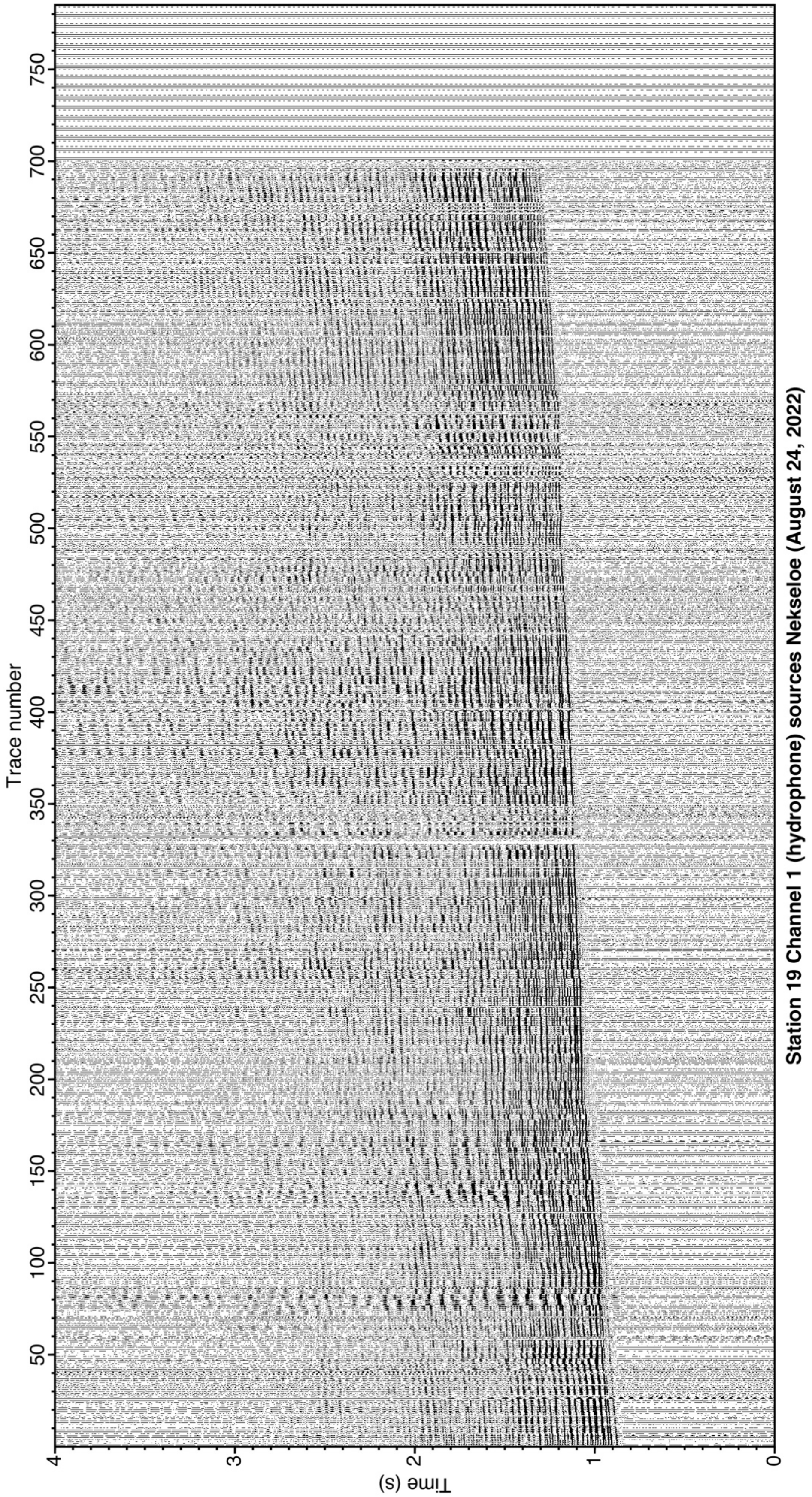

Figure A19. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 19 recording the sweeps on Nekselø.*

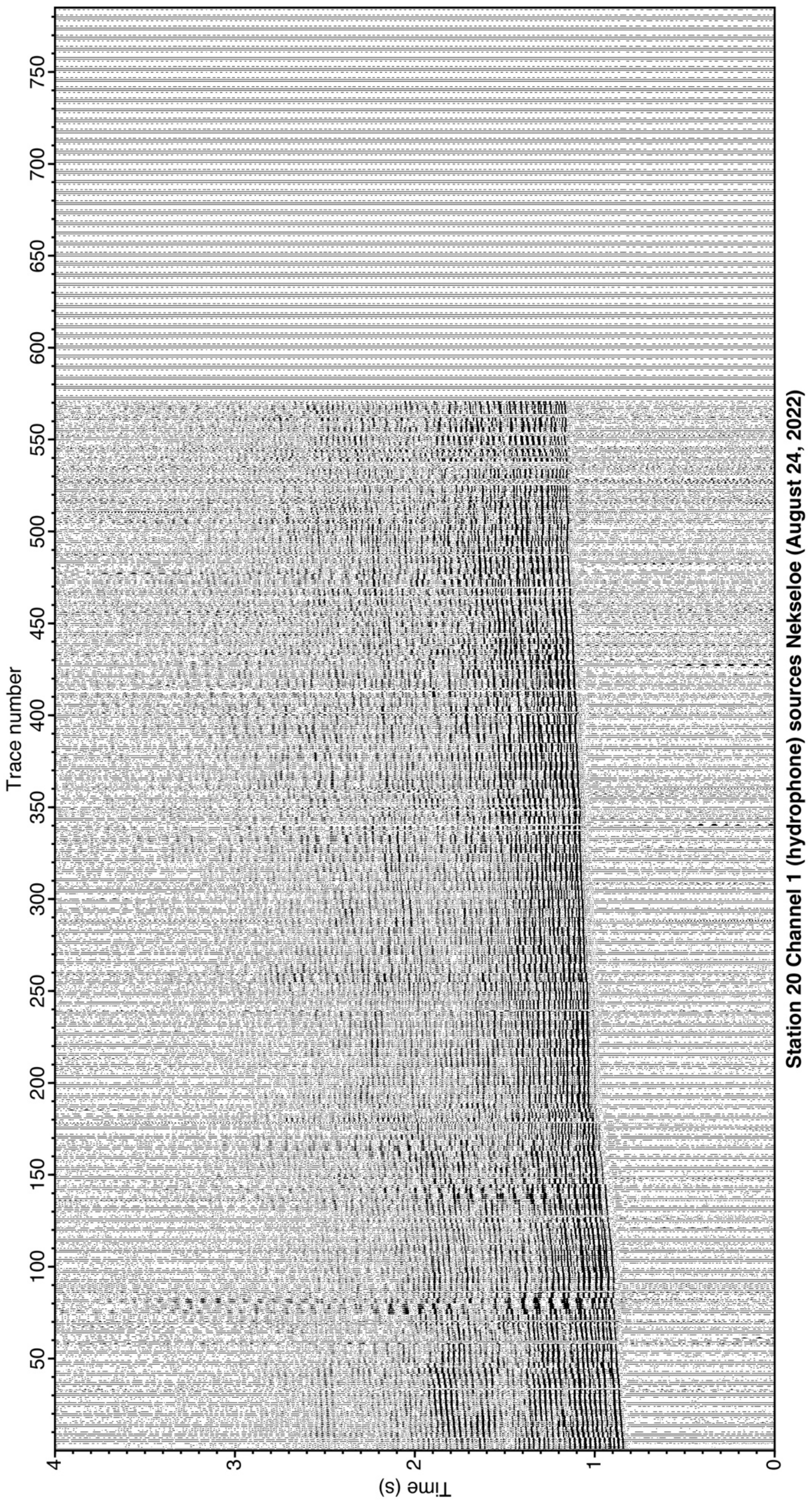

Figure A20. *Record section of the hydrophone component (channel 1) of the ocean bottom seismometer deployed at station 20 recording the sweeps on Nekselø.*