Multipurpose high-resolution seismic acquisition: the deep-sea mining case

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Summary

The oil and gas industry has developed highly sophisticated technology for offshore hydrocarbon exploration. The traditional focus has been on hydrocarbon exploration and production targets. These targets are commonly buried under a few kilometres of sedimentary layers and 3D seismic technology has been the main type of data acquired for characterizing these targets. A secondary focus has been on the shallow section, and it has mostly been driven by shallow hazard investigations to aid the drilling of those targets. This characterization is commonly done with 2D high-resolution seismic referred to as site surveys. In recent years, shallower targets have been sought for carbon capture and storage (CCS). It is best to store carbon dioxide in its critical state which is achieved at burial depths of about 800 m. Thus, the goal is to locate porous rocks with a natural seal at depths of 800 m-1500 m below the seabed. Deeper reservoirs can be used for CCS, but shallower ones are more economical. In addition, offshore mineral exploration is at the point of becoming a commercial activity. To characterize these mineral reservoirs or deposits, the selected type of data needs to resolve the very near surface (first few decameters) at a very high resolution in an efficient way that enables the location of targets with an area extension of 100 to 300m. Thus, in 2021 3D seismic is aimed at best resolving the very shallow and the very deep. These facts motivated the set of experiments acquired in the AM20-lab in the Norwegian Atlantic Margin in 2020.

In this paper, we focus on AM20-lab test 2. While the focus of test 2 is to achieve ultra-high resolution near surface 3D seismic for mineral exploration, the data provides multipurpose value for medium and deep targets as well. The survey was designed and acquired with a novel signal apparition decasource encoding and was benchmarked against pentasource data from a production multiclient survey which was designed for hydrocarbon exploration

Introduction and motivation

In late summer 2020, a set of test surveys were acquired as an extension of the TGS 3D multiclient streamer survey Atlantic Margins (AM20) in the Norwegian Sea. We refer to these tests as the AM20-Lab. They comprise:

1) Sparse OBN with free-fall nodes – Hybrid survey test, where the shot carpet comes from the simultaneously acquired AM20 pentasource streamer survey. The largest recorded offsets were ~60 km.
2) Ultra high-density simultaneous sourcing towed streamer – Near-surface studies and minerals test, using a decasource simultaneous sourcing scheduled with signal apparition encoding.
3) Ultra high-density simultaneous sourcing sparse OBN – 2D R&D test using the decasource shots from test 2.

In this paper, we concentrate on test 2, motivated by deep-sea mineral (DSM) exploration.

There has been an increasing need for precious metals worldwide and this need is expected to continue rising in the following decades. Besides the increase in population and prosperity, this need is driven by the fact that access to metals and rare earth minerals is an important prerequisite for producing batteries, wind turbines and solar panels, which in turn is important for reducing greenhouse gas emissions. It has been known for decades that within the deep ocean spreading ridges (such as the Norwegian Mohn's Ridge), there are sulphide deposits rich in copper, zinc, cobalt, and rare earth minerals. These deposits are located at deep water areas (average bathymetry of 2300 m), over a volcanic layer.

Offshore mineral deposits start their life as black smokers or white smokers (Figure 1). These smokers are hydrothermal vents similar to hot springs or geysers found onshore, but they exist on the ocean floor. They are fissures on the seafloor near spreading ridges that are volcanically active areas where tectonic plates are moving apart at spreading centres. The fissures allow magma to rise into the cold deep seawater and it is rapidly cooled to form new crust. As the process continues, seawater is filtered through these fissures. The filtered water increases the pressure in the rocks, and it is heated by the magma. Then the water and pressure set off a reaction that dissolves minerals. As the water is less dense than the rocks, it rises to the surface of the crust and exits, bringing these minerals out and forming chimneys. The minerals in the chimneys are cooled down by the deep seawater and get solidified into mineral deposits. For commercial DSM exploitation, the goal is not to find and produce active smokers but extinct ones. Where the cycle has stopped and there are no active chimneys.

Extinct deep sea mineral deposits consist of small structures (collection of metals and rare earth minerals) of a horizontal

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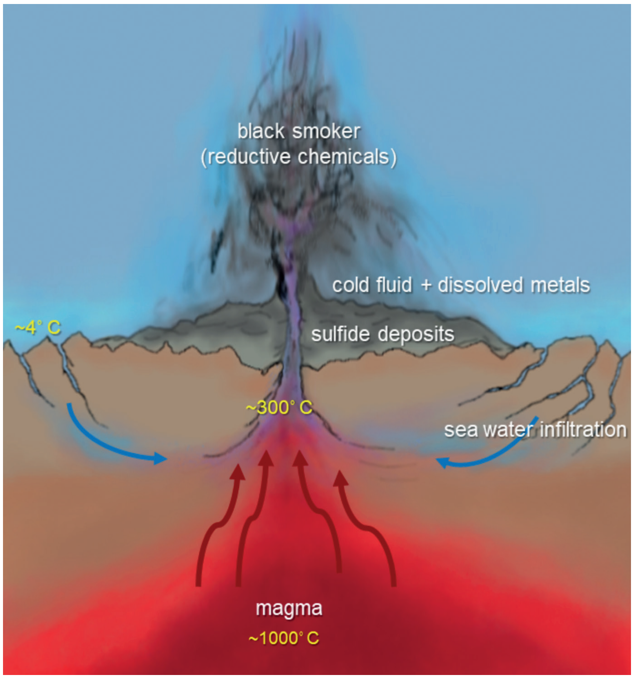

Figure 1 Illustration of a black smoker.

extent of about 100-300 m and a few decameters vertically, generally covered by a layer of pelagic mud that ranges in thickness from ten to a few hundred metres. These are very shallow, high contrast targets, with p-wave velocities in the range of 4000-6500 m/s and densities between 3000 and 4500 kg/m^3 (Ludwig et al., 1998).

To date, the mapping of these deposits has been mainly an academic endeavour with limited budgets, but this is about to change particularly in Norway for two reasons: i) the already stated global demand for batteries and ii) because Norway is the first country to pass a law that would allow production of these offshore resources (Kjølhamar et al., 2020). Several types of geophysical data had been measured and used, but only a handful of these deposits had been found. This is likely caused by the limitations in the type of surveys acquired (mainly UAV-based multi-beam echo sounder, a few CSEM, and 2D seismic profiles). The small size of these targets makes them easy to miss with the used technology. Based on this and the future commercial opportunities, modern 3D streamer seismic technology could become the data of choice. If designed properly, it can provide efficiency (large footprint, penetration, high resolution) and be cost-effective.

Modern 3D vessels combined with wider-towed source arrays can provide a footprint of about 1 km crossline with up to 6 source lines (if each string of airguns is used as an individual source array) with standard equipment. To increase source sampling density, it is now common to acquire overlapping source records and deblend them in processing. A constraint of the field test was to achieve higher sampling density and efficiency at the same cost per square kilometre as the multiclient AM20 programme that used a pentasource, staggered grid configuration with overlapping source records every three seconds on average. Thus, a signal-apparition source encoding design was chosen for test 2, to acquire a much denser shot carpet with truly simultaneous sources and a blending pattern that can be sufficiently decoded into individual source records.

The location of test 2 was selected to cover shallow anomalies (nearby the Egga Slide in the Norwegian Sea) that can be used as analogues to the DSM targets in the Mohn's Ridge, where the first DSM Norwegian licensing round is expected. The contrast and geological setting are not the same, but the size, complexity, bathymetry, and depth of these shallow anomalies are sufficiently similar. Furthermore, the decoded data isolated long shot records that can be used for imaging of deeper targets for, e.g., CO_2 sequestration or even hydrocarbon exploration.

On simultaneous sourcing

For over two decades, the industry has implemented different simultaneous sourced seismic data acquisition technologies [Beasley et al., 1998]. Most methods for simultaneous sourcing rely on random time delays for encoding, combined with coherency-based filtering techniques for decoding [Hampson et al., 2008]. These random time delays or dithers can either explicitly be introduced when selecting firing times or by shooting on position where a natural variation on the order of 100s of ms per sailline is caused by varying vessel speeds, which are influenced by the presence of waves and currents, among other operation variables. Random dither decoding techniques often exploit the fact that when aligning/time-shifting the simultaneous source data in the time-frame of a first source, energy from one or more of the other sources appear incoherent (e.g., Akerberg et al. [2008], Ji et al. [2012], Abma et al. [2015], Andersson et al. [2016]). Alternative deblending methods are based on, e.g., principal component analysis [Ikelle 2007], robust linear algebra [Moore et al. 2016], and inversion [Jiawen et al. 2020]. Whereas enhanced productivity was the original motivation for simultaneous source surveys, the surveys can be designed to also enable quality improvements (less noise per isolated shot record and increased sampling density). This improvement assumes that the contributions from the different sources can be sufficiently well separated in processing.

In most common designs, the sources are not shooting simultaneously or even close to simultaneously. Instead, the approach relies on selecting shot point intervals that are shorter than those used in conventional flip/flop survey designs. The SPI is selected to obtain a time interval in the data where no strong energy from the succeeding shot is present (often within the time interval associated with the conventional recording of the wavefield produced by an isolated source, propagating through the subsurface of the earth, reaching the main target and propagating back to be fully recorded at the receivers). The assumption is that within this time window, the energy associated with the preceding shot is also significantly weaker than that of the current shot, and that data in this region appear relatively clean even without any attempt of removing the residual shot noise caused by the preceding shot.

An alternative simultaneous source technique is to encode sources using signal apparition, as first presented by Robertsson et al. [2016]. Such an approach allows for all sources to fire essentially at the same time (within a few 10's of ms relative to each other). Due to the fact that seismic data is contained in a signal cone in the FK-domain, the problem of separating the contributions from the different sources following signal-apparition style encoding can be shown to be exact in FK subdomains [Andersson et al., 2017a]. Amundsen et al. [2018] derive explicit formulas for the separation of an arbitrary number of signal-apparition encoded sources. The region where such a direct approach is applicable to fully separate the individual source contributions is limited and additional structure needs to be imposed to fully separate the sources in practice. Andersson et al. [2017b] describe a methodology for this purpose that is based on quaternion representations.

AM20-Lab Test 2

The 3D AM20 multiclient programme was acquired with 12 streamers deployed at a 12.5 m crossline separation and 5 sources (1510 cu.in. and 2000 psi) at 50 m crossline separation, shot in a staggered grid with overlapping records. The inline separation between sequential shot points was 7.5 m, with a shot point interval (SPI) for a given source of 37.5 m. The sampling rate was 2 ms. This pentasource dataset, the benchmark, was deblended and resampled at 3 ms, following the processing sequence of the multiclient programme.

The same vessel and physical configuration were used to acquire test 2 with signal-apparition source encoding. Each of the five sources in the vessel consisted of a single airgun array string. For test 2, the latter was partitioned (by the gun controller) into a front and an aft sub-array and shot as independent sources (Wallace et al., 2020). Resulting in 10 sources, each corresponding to a sub-array of 900 cu.in. and 1800 psi. At each SPI, 10 sources were fired almost simultaneously, achieving a decasource configuration grouped in 5 source lines, resulting in a much denser regular source-carpet sampled at 8.33 m by 50 m. The sampling rate was 1ms. The signal-apparition decasource measurements were decoded at 1ms and compared against the benchmark.

A note on acquiring the first-ever decasource streamer seismic experiment

There have been several years of multi-source survey design development and field experiments to validate the evolving concepts. The start, for streamer seismic, can be tracked back to three key field tests comparing three to two sub-array sources in offshore Norway (Langhammer and Bennion, 2015), offshore Australia (Hager and Fontana, 2017) and offshore Brazil (Rocke et al., 2018). These tests provided valuable evidence supporting the concept of reducing source output by about a third while still producing sufficient signal, well above the noise floor. This concept combined with reduced shot point intervals and deblending processing steps allows acquisition geophysicists to optimize spatial sampling and reduce survey duration.

The concept evolved by using single sub-array sources as independent sources, allowing up to six sources with more flexibility in towing arrangements with existing hardware. Single sub-array sources further reduce the source output, typically 9 dB down from a three sub-array source and 6 dB down from a two sub-array source. This concept is now standard in the industry.

The need to design an ultra-high-resolution 3D seismic survey for DSM exploration enabled the testing of the next evolution of the concept to improve the shot density along individual

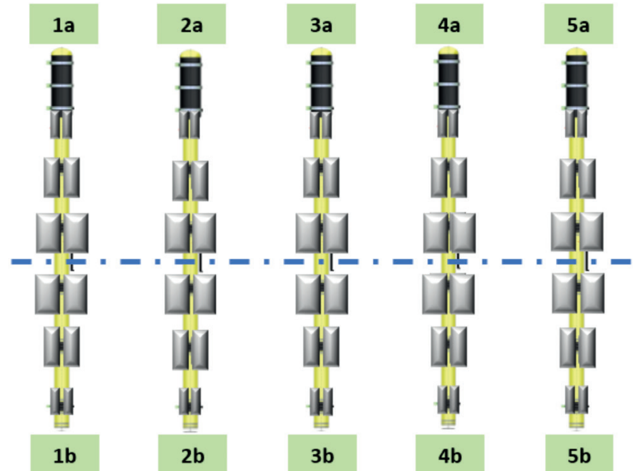

Figure 2 Source Configuration.

subsurface lines by firing all sources almost simultaneously. To overcome the inherent acquisition challenge of having sufficient time to recharge the guns with air, the inline geometry and symmetrical design of the arrays would be leveraged to create two sources per sub-array so that the centre of each source (front half and back half) would populate a shot grid of half of the required SPI (figure 2). Thus, the AM20-lab test 2 was designed to test this concept by repeating a sail line from the pentasource production survey, as mentioned above. The test required no physical reconfiguration of in-sea equipment, only adjustments to the onboard operating systems. The SPI used was 16.67 m, allowing the desired grid and sufficient time to recharge all sources before the next shotpoint.

The 40 km test line was successfully completed, overcoming two main challenges: The first was related to the gun controller: as this was a non-standard setup, the configuration files had to be adjusted to fire all ten sources almost simultaneously. The second was related to the gun firing pressures. The original idea was to maintain the same pressure as in the pentasource. However, this is not feasible when simultaneously firing sources at this short SPI. The constraint is mechanical; the size of the gun orifice and the rate at which pressurized air can be forced through being the limiting factor. Thus, to maintain vessel speed and this short SPI, it was decided to reduce the internal firing pressure by 200 psi less than nominal at 1800 psi. No negative geophysical impact was expected and non has been observed.

AM20-Lab Test 2

The goal of the test was to achieve higher frequencies and overall signal resolution than in the pentasource benchmark. Figure 3 shows common channel gathers for the central source line and central receiver line from (a) the decoded decasource data set and (b) the deblended pentasource data set for the first two seconds after the water bottom reflection. As can clearly be seen in the zoom-ins (Figure 3 (b, d) (1-2)) in the bottom row, the much denser source sampling (8.3 m inline interval) of the decasource dataset results in better-resolved diffractors. The decasource dataset has about 4.5 times more inline samples than the pentasource dataset, sampled at 37.5 m inline source interval.

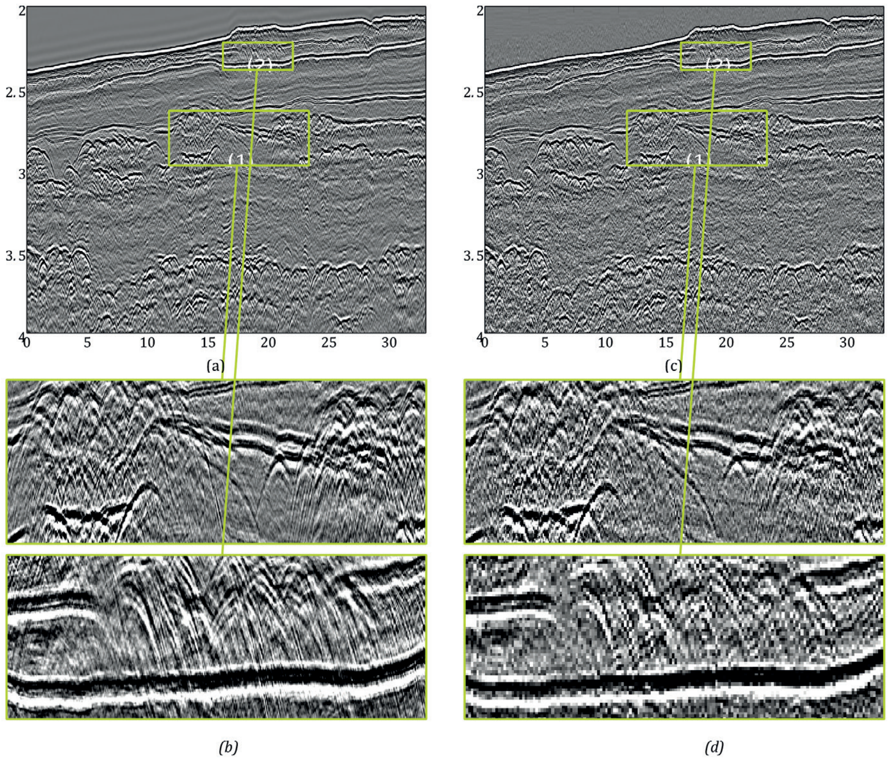

Figure 3 Comparison of channel gathers for the central source lines and receiver lines in a time window of 2-4 seconds (top row) and a zoom in (bottom row). The horizontal axis shows inline position along the sail line in km. Left column: Apparition decoded data. Right column: Decoded pentasource data.

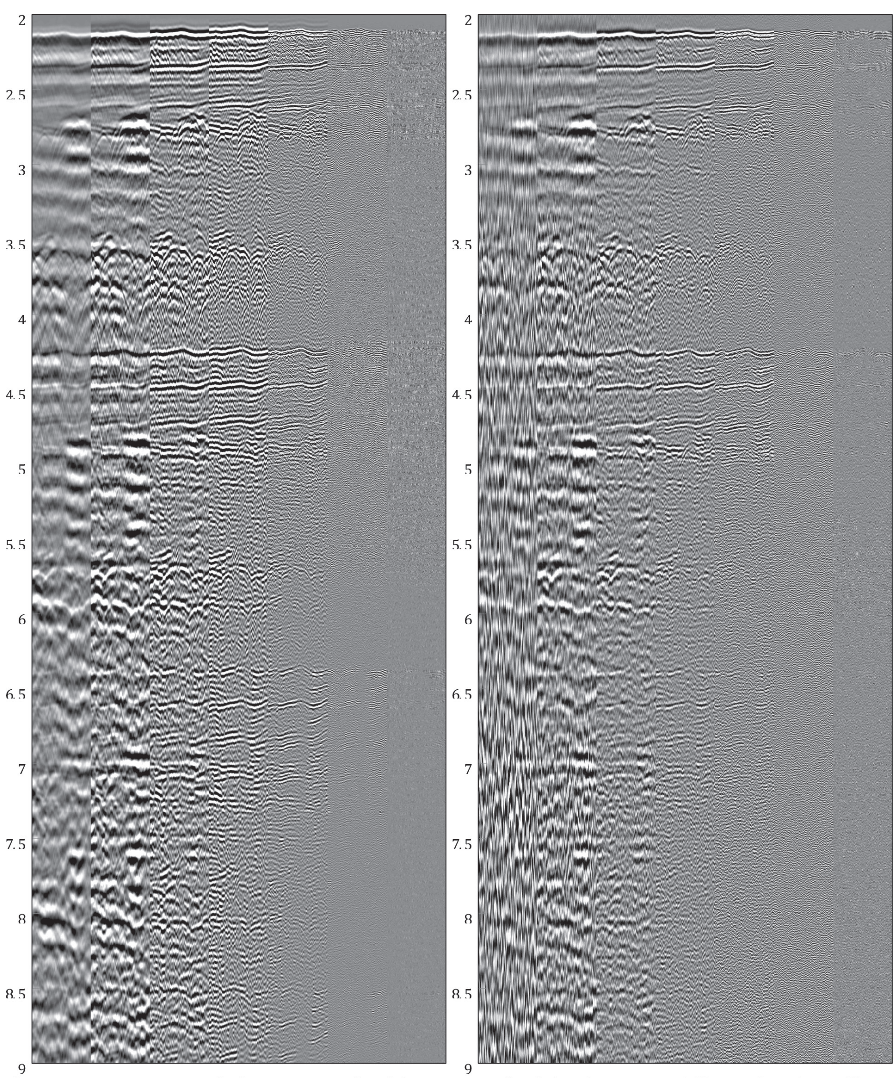

Figure 4 Frequency panels for 2-9 seconds of data. For each of the data sets 7 different bandpass filters have been applied. From left to right 2-4, 4-8, 8-16, 16-32, 32-64, 64-128, 128-256 and 256-512 Hz, respectively. Left: Apparition decasource; Right: Staggered pentasource.

In Figure 4 the same common channel gathers (19-23 km by 2-9 s) are shown in different frequency panels. For each of the frequency panels a combination of a Butterworth low-cut and a Butterworth high-pass filter was applied, each at 18 dB per octave. Even though the main objective of test 2 was high resolution for shallow targets, it is relevant to observe that the signal at longer times (deep targets) is also well recovered, and different orders of diffracted sea surface multiples are well sampled. Again, the data from test 2 has higher SNR at all travel-times than that of the benchmark, even though the source strength is 40% weaker.

Figure 5 displays a comparison of the common channel gathers in a time window from 2-10 s, after applying a 4 Hz low-pass filter (18 dB/octave Butterworth). The decoded decasource data has better SNR than the deblended pentasource data. Both the higher fold and the constructive interference of the apparition encoded sources at low frequencies are factors that contribute towards the enhanced signal. The quantification of the quality of this low frequency signal is the subject of future work.

For high-resolution shallow imaging, the effects of the ghost must be eliminated. The presence of the ghost creates a smearing effect in depth. If the primary and its ghosts are migrated as if they corresponded to a single event with a wavelet, then the vertical extent of this event is about 25 m. For 500 Hz maximum frequency at 1 ms sampling, several orders of ghost notches must be dealt with and the ghost events removed. The ghosts can simplistically be viewed as time shifted (along with sign change) replicas of the true data, where the time-shifts vary depending on the offsets or recorded angles. The time shifts are typically small, about 10-20 ms (depending on the source and receiver depths which in this case are 6 and 12 m). In this regard, the impact that they leave on the data will be similar to the time-shift caused by the signal-apparition encoding for the simultaneous sources. Thus, rather than first decoding the simultaneous data and then deghosting the result, the decasource was processed with a joint decoding, deghosting and designature algorithm. This is illustrated in Figure 6.

AM20-Lab Test 2 Geological setting

The survey area sits in the Norwegian Sea, the outer western part of the Møre Basin, and onto the Møre Marginal Plateau, a row of SSW-NNE trending basement highs covered by break-up volcanism (55 ma). These highs have evidence of block faulted sedimentary rocks covered by thick sections of basalts (Figure 7). Within the survey area these basalts are estimated to be a few hundred metres thick in the west and thinning within the inner flows,

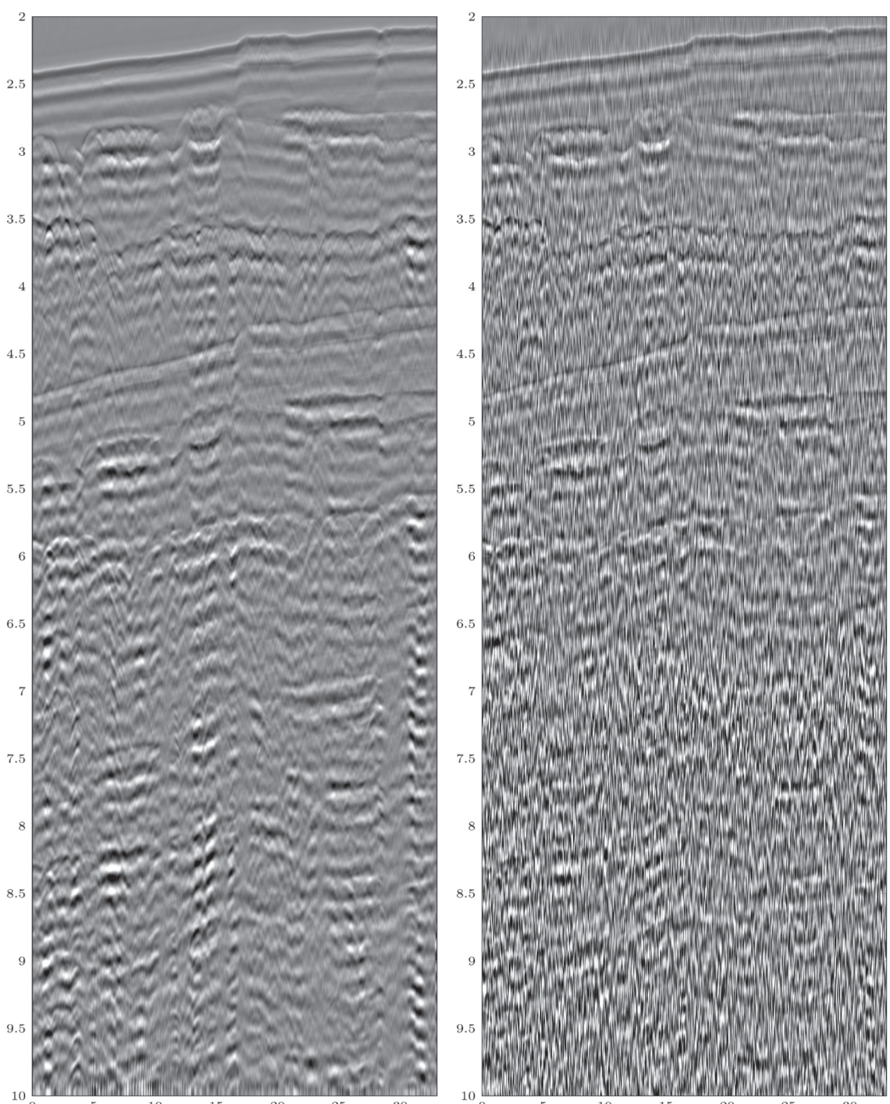

Figure 5 Low frequency results at 4 Hz. Comparison of channel gathers for the central source lines and receiver lines in a time window of 2-10 seconds. The horizontal axis shows inline position along the sail line in km. Left: Decoded decasource data. Right: Decoded pentasource data.

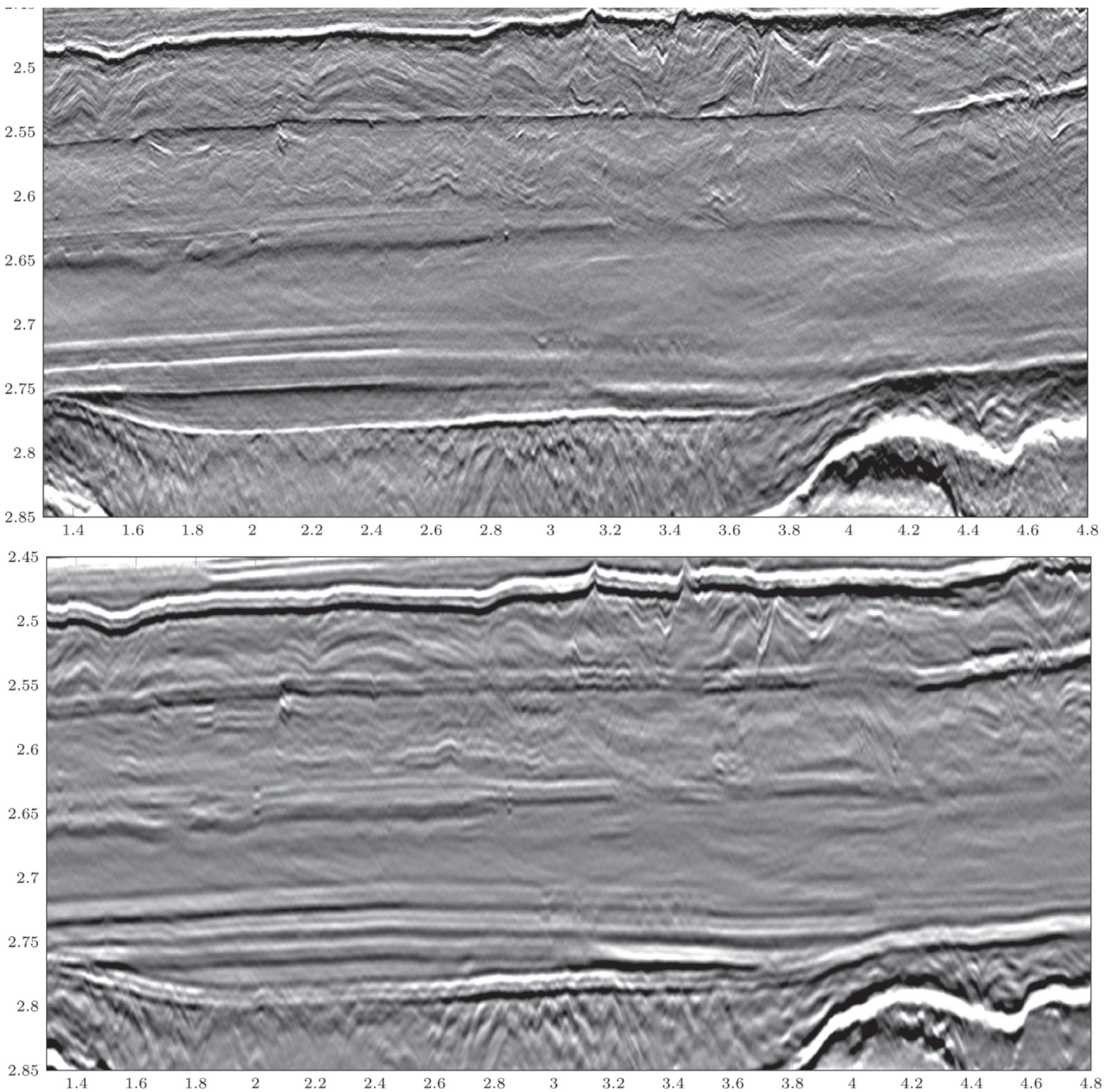

Figure 6 Zoomed in section of migrated results. Top: Decasource joint decoded/deghosted/designature; Bottom: Pentasource deblended (post-migration deghosted).

the eastern part of the system. The inner flows represented in this survey consist of hyaloclastites, volcanoclastic debris flows, and invasive flows [Millett, J., et. Al., 2019]. The inner flows and the Cretaceous basin below have been intruded by volcanic sills creating a very challenging seismic terrain. The younger succession consists of clay-rich, unconsolidated sediments where the amorph silica to Opal-CT and the Opal-CT to Quartz seismic reflectors are predominant and typical for muddy rocks. Several weak layers have slumping features, are partly mobilized and several siliceous ooze diapirs are seen in intermediate levels between the seafloor and the basalts below (Box 1 in figure 3).

AM20-Lab Test 2 Geological observations

The test's target were analogues of DSM sulphide complexes (figure 8). The bathymetry in this area is between 2000-2300 m, analogous to the bathymetry at the Mohn's ridge in the Northern Atlantic. At the seafloor and in the upper hundreds of metres there are small faults and compressional features within the Neogene sediments. The survey line sits just west of the big sub aquatic Egga slide (~6000 bp) and this slide seems to have affected the near seafloor events on our survey line (Box 2 in figure 3). We interpret small scale reverse faults and shortening in the uppermost tens of metres probably as an effect from the Egga slide nearby. These features serve well as analogues to sulfide complexes with regard to size and their shallow position. In the preliminary time migrations of the decasource line, we can observe defined features down to 20 m horizontally and 1-2 m vertically (at water speed). Compared to the reported sizes of sulphide complexes [Murton et. al. 2019], typically 100-300 m in diameter and up to 60 m thick, a 20 m resolution should as

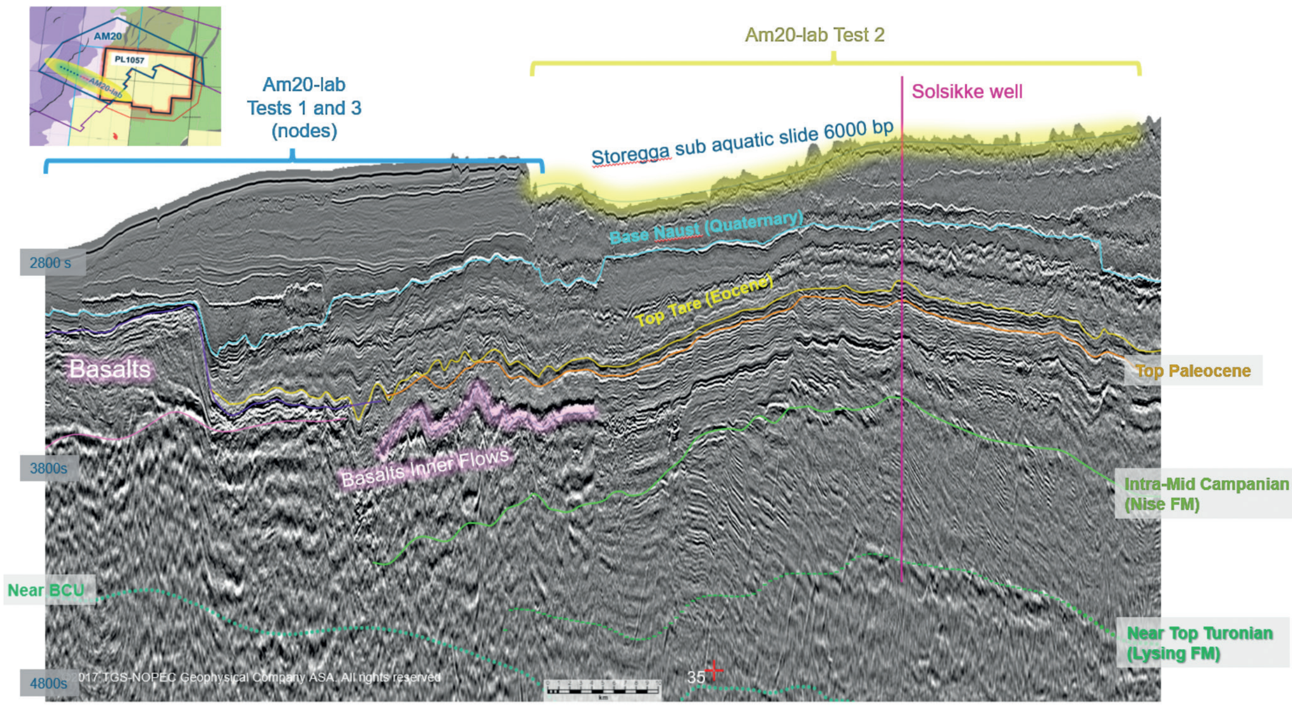

Figure 7 Legacy 2D data showing the geological setting of the AM20-lab.

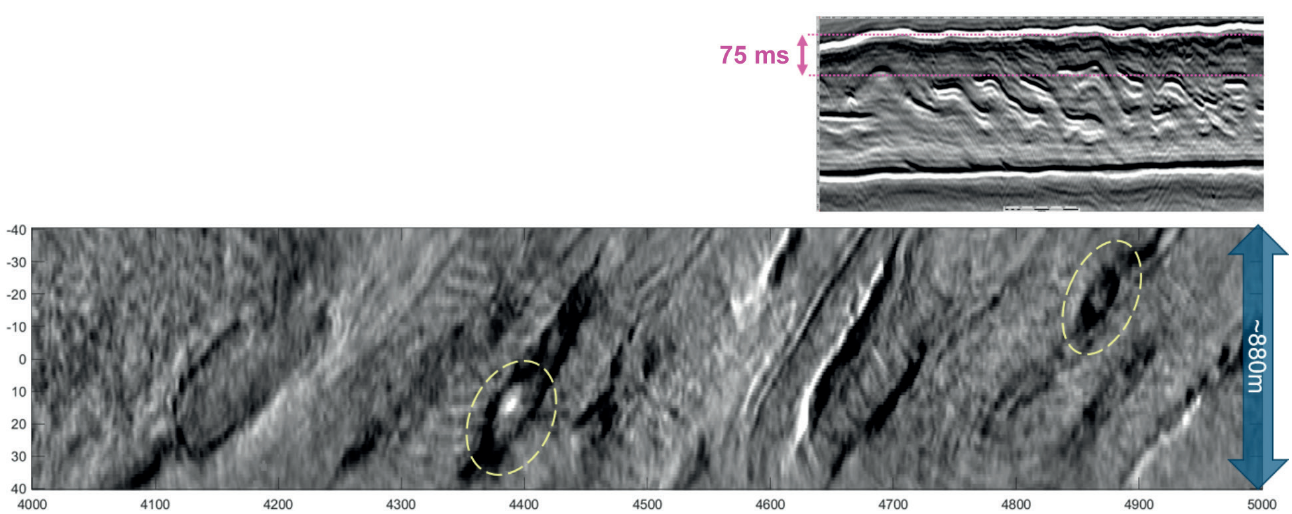

Figure 8 A time slice of the time migrated decasource at 75ms below the seabed with two structures highlighted that are analogs of sulphite deposits (the areas extend between 100-200m). As a reference, a vertical slice is also displayed.

such be sufficient to identify and find the extents of real sulphide complexes.

Murton, et. Al. [2019] reports that the sulphides' properties are within the ranges of $4000 < v_p < 6000$ m/s and $3000 < \rho < 4500$ kg/m^3, while the altered basalts have an estimated v_p =4100 m/s and $2600 < \rho <300$kg/m^3. There is a small range of sulphides that might be almost invisible in terms of p-impedance contrast with the altered basalts underneath them, but in general, the p-impedance contrast expected in the Mohn's Ridge is in the range of 25-35%. Our geological estimates for the first ~50m-80m of sediments in the area probed by the decasource test, indicate that the properties vary in the ranges of $1600 < v_p < 1900$ m/s and $1500 < \rho < 1800$ km/m^3 (density estimate is more uncertain), giving a p-impedance contrast of 16-17%. So, the contrast is lower than that expected in the sulphide deposits, but not too dissimilar. This fact combined with the analog structures give us a good indication that the results of this feasibility test are enough to qualify this technology for offshore mineral exploration.

Conclusions

Processing and imaging of towed marine seismic data benefit from the acquisition of multiple source lines along single sail lines. Typically, such data are acquired by trading inline sampling and length of non-interfering time windows against the number of cross line sources. Instead, by encoding sources by means of a signal apparition, it is possible to acquire a data set that is well sampled on the source-side both crossline and in-line.

When using seismic for the exploration of deep sea minerals it is crucial to achieve high resolution imaging. It is well known that there are sulphide deposits rich in precious metals as well as rare earth minerals within the deep ocean spreading ridges. The seismic structure that needs to be understood is in a rather shallow and small region underneath the seabed.

A field test has been conducted to assess the possibility to image these structures using a decasource signal apparition configuration with a 3D streamer spread. Results show that this is a feasible and cost-effective option for ultra-high resolution seismic and enhances shallow target characterization. In particular, the geophysical and geological objectives were met with more than sufficient resolution to identify analogues of sulphide complexes in slightly less seismic contrast than expected on real sulphides in the Mid Atlantic Mohn's Ridge. To get the final proof that 3D seismic is indeed an effective exploration tool for sulphides, we suggest repeating this test on the real targets. Thus, we are planning a scientific expedition to the Arctic in late summer 2021. Finally, the data also seem suitable for deeper target characterization in, e.g., oil and gas exploration due to its broadband features and improved deep data quality and SNR. This will be the subject of future publications.

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The AM20 multiclient dataset belongs to a TGS multi-year 3D programme in the Atlantic Margin. It was processed by TGS and migrated by Apparition Geoservices.

The AM20-lab test 2 dataset belongs to a TGS feasibility study for offshore mineral exploration. The test was acquired by Polarcus, the processing was done by Apparition Geoservices.

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