Redefining marine towed-streamer acquisition

Martin Widmaier[1]*, David O'Dowd[1] and Carine Roalkvam[1] describe novel marine acquisition solutions addressing the need for accurate velocity models, high resolution imaging, and reliable AVO.

Introduction

The demand for better seismic data has increased in the search for new offshore energy resources. The launch of multisensor towed streamer technology in 2007 can be considered as a key milestone in marine seismic acquisition and imaging technology development (Widmaier et al., 2015) as high resolution imaging and quantitative interpretation has clearly benefited from the availability of true broadband data. Recent successful applications of full waveform inversion (Shen et al., 2017) are another breakthrough for seismic exploration technology.

Longer offsets, improved near-offset sampling, higher trace density, denser spatial sampling, and larger azimuthal coverage are often referred to as the desired ingredients of modern marine seismic data. Innovative and smart technical solutions are required to meet such demands in a cost-effective manner. We will discuss how streamer and source geometries can be modified to address modern exploration objectives and geophysical challenges. Will novel solutions become the new paradigm in towed streamer acquisition?

Multi-sources for efficiency and improved spatial sampling

For many years dual-source configurations combined with streamer separations of 50 m, 75 m, and 100 m were the preferred option for acquiring seismic data. The revival of triple-source shooting by Langhammer et al. (2015) extended the solution space for modern towed-streamer survey design. This is especially relevant for large-scale exploration surveys in deep-water areas, where 12 x 150 m streamer spreads have frequently replaced the standard 12 x 100 m configurations. The larger streamer spread width increased the footprint significantly, and thus reduced the corresponding acquisition cost. In this configuration example, triple-source shooting keeps the crossline bin size at 25 m despite the sparse 150 m streamer separation. As the step from dual-source to triple-source shooting with equal shot interval results in a reduction of CMP fold coupled with coarser spatial sampling in CMP gathers, triple-source surveys typically use shorter shot intervals to avoid these penalties. By necessity, blended (simultaneous) acquisition techniques are often used instead of sequential mode shooting. So processing often has several challenges. Shot deblending is necessary, and the sparser receiver sampling in the crossline direction may result in spatial aliasing complications for any shot domain processing solutions.

Nevertheless, high-density 3D surveys in regions with relatively shallow water depths and shallow geological targets such as in the Barents Sea have rapidly adopted triple-source shooting. While crossline bin sizes smaller than 18.75 m were difficult and costly to achieve in the past, the combination of high-density streamer spreads with multi-source configurations enable significantly improved spatial sampling without necessarily sacrificing acquisition efficiency. The move towards better spatial sampling can be regarded as the logical and necessary step following the success of multisensor broadband streamers: the recording of 3D broadband seismic data must be accompanied with appropriate spatial sampling in order to preserve the higher frequency content throughout the processing flow. While triple-source shooting has become common for high-density acquisition, novel surveys with quad-, penta-, and hexa-source configurations have also been reported by the industry (e.g., Hager and Fontana, 2017).

Operational risk mitigation has also been a driver for triple-source shooting. One example is conducting marine seismic in areas with strong rip currents. It is safer in such environments to deploy spreads with less streamers and larger separations in order to minimize the risk of tangling of in-sea equipment.

Wide-tow sources for accurate AVO analysis of shallow targets

The modern shift from single- and dual-source arrays to triple- and multi-source configurations has initiated new discussions about source separation and the position of the sources relative to the streamer spread. The standard location of marine source arrays is behind the streamer vessel, distributed between the two central streamers, and ahead of the two central streamers. The nominal source separation for streamer acquisition is given by the streamer separation divided by the number of source arrays. i.e., for a high-density streamer spread with 50 m separation, the corresponding source separation would be 25 m for dual-source and 16.66 m for triple-source. If multi-source arrays are built from several uniformly spaced gun strings, the lateral distance between adjacent outer strings belonging to different source arrays can easily fall below 10 m. With this short distance, the operational risk increases and physical interaction between the source arrays becomes possible. These limitations may

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DOI: 10.3997/1365-2397.2019035

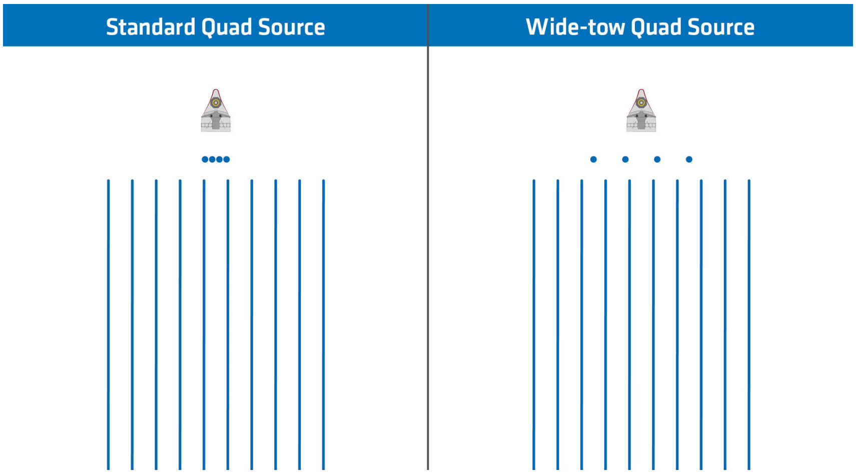

Figure 1 High-density streamer configurations of 10 streamers at 50 m separation combined with a standard quad-source set-up (left) and a wide-tow quad-source set-up (right). The wide-tow source separation is 62.5 m, resulting in a total source spread with of 187.5 m. The resulting improved near offset separation is shown in Figure 2.

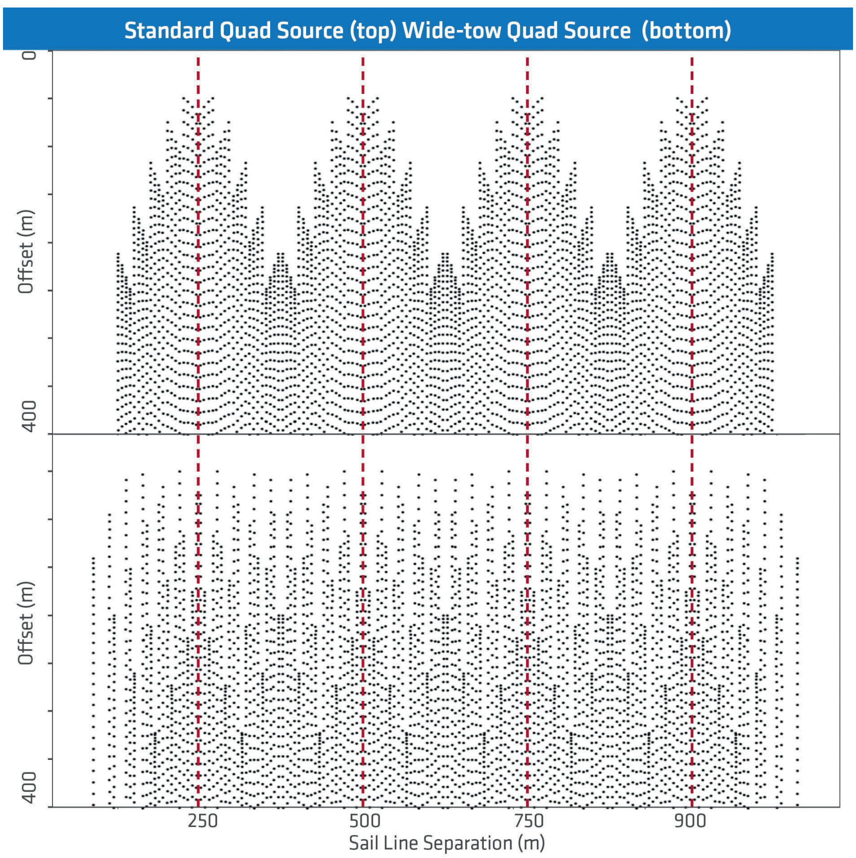

Figure 2 Near-offset distribution for a quad-source configuration with 12.5 m standard source separation (top) and 62.5 m wide source separation (bottom). The streamer separation is 50 m in both examples. The red dashed lines indicate the centre of each sail line. CMP-X positions are along the x-axis, and source-receiver offsets are along the y-axis. The wide source configuration provides an improved near offset coverage for shallow AVO analysis.

become even more critical for narrow streamer separations and a larger number of source arrays. Wider source tow is one obvious alternative to avoid this problem. The first nominal position to preserve crossline spatial sampling for a wide source separation is given by the sum of the standard source separation and the streamer separation (Long, 2017).

Wide-tow sources can also provide geophysical benefits. Distributing multi-sources across the front of a streamer spread can improve the near-offset sampling (Widmaier et al., 2017). This is especially relevant for shallow targets in shallow water, as towed streamer surveys with a standard source set-up in front of the central streamers may not provide the near-offset/near angle coverage required for AVO analysis. Acquisition footprints in shallow crossline seismic images are also a consequence of poor near-offset coverage. Until recently, the most common way to improve the near-offset coverage has been to reduce the total streamer spread width and the corresponding sail line separation. The latter results in increased survey turnaround and cost. The lack of near-offsets/near angles can also be overcome by utilizing separated wavefield imaging technology as demonstrated, e.g. in recent Barents Sea case studies (Rønholt et al., 2015). Several authors (e.g., Long, 2013; Vinje et al., 2017) have revived the idea of placing the seismic source array in the centre of a streamer spread. While such a solution provides close to zero offset for the receivers closest to the source, the crossline distance to the outermost streamers remains the same. This methodology is also associated with extra cost and risk as it requires an additional source vessel operating on top of a streamer spread. Another solution is to operate with many distributed smaller sources in a wide-tow source configuration. Such concepts have been discussed by Widmaier et al. (2017) and Long (2017) who focused on single vessel solutions in towed-streamer seismic acquisition.

Wider towing of source arrays in front of streamer spreads has recently become operationally feasible. During 2019, total source separations of up to 250 m have been successfully tested by PGS and will be deployed in upcoming programmes. Total separation of 400 m is in reach. Modified towing solutions now also enable wide-tow source arrays in close to zero distance from the streamer front ends.

Figure 1 illustrates the concept for a quad-source configuration in front of a streamer spread with 50-m streamer separation. The source separation for the standard narrow source tow is 12.5 m, and for the wide-tow it is increased to 62.5 m. Furthermore, if the sail line separation is made a function of the source geometry (4 x 62.5 m, i.e., 250 m), the lateral source line spacing (62.5 m) becomes regular for the entire survey area. The regular dense source line spacing in combination with the high-density streamer spread provides significantly improved near-offset coverage (Figure 2). In addition to the improved near-offset sampling, this configuration provides a symmetrical bin size of as little as 6.25 m x 6.25 m. This concept can be extended to higher source count configurations and even denser streamer spacing.

Wide-tow Sources to reduce turnaround

Wide-tow sources may also be utilized to increase operational efficiency without sacrificing quality. The streamer spread geometry usually determines the midpoint coverage and consequently the sail line separation. For example, the sail line separation for 12 streamers with 75 m separation is 450 m, and for 14 streamers is 525 m, i.e., an efficiency increase of more than 16%. The efficiency increase, however, will exaggerate the variation in near-offsets and near incidence angles. Therefore, very wide streamer spreads are generally used in areas with rather deep exploration targets. However, wide-tow sources may enable wider streamer spreads to become practical in areas with shallow targets as moving the sources towards the outer streamers reduces the near-offset gap (Figure 3).

Brice et al. (2015) pointed out that wide-tow sources can laterally extend the midpoint coverage, and Long (2017) developed geometric relationships for relevant survey planning. As the number of CMP lines per sail line (the product of the number of sources and number of streamers) is the same for standard source configurations and wide-tow source configurations, the extended coverage comes with a trade-off (Figure 4). While the CMP line spacing is normal in the centre, the outside coverage is sparser, and instead of using interpolation techniques, the gaps in the CMP lines can be mitigated by shooting with appropriate sail line separation. When the sail line separation is defined by the streamer spread width, the adjacent sail lines provide complementary CMP coverage and missing CMP lines are nominally filled in (Figure 5).

Longer offsets for reliable velocity model building

Successful applications of full waveform inversion (FWI) in velocity model building have increased the demand for long

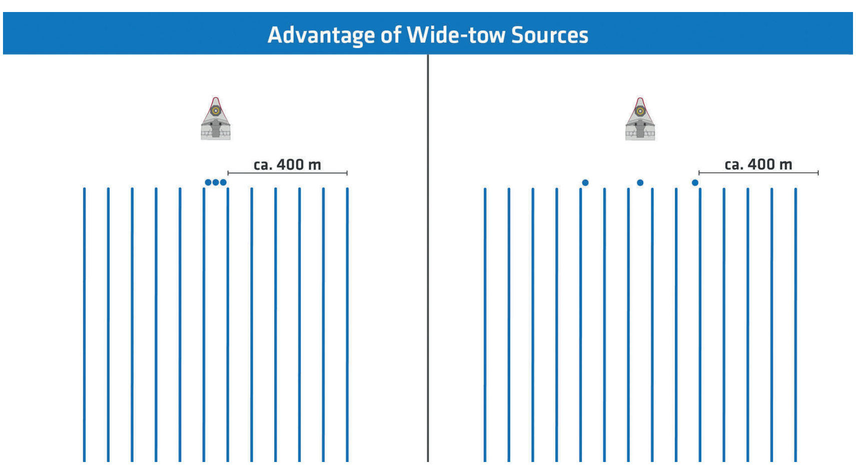

Figure 3 A 12 x 75 m streamer spread with a standard triple-source configuration (left) and a 14 x 75 m configuration with a wide-tow triple-source (right). The wide-tow configuration provides a smaller distance from source to outer streamer thus increasing efficiency without further compromising the near offsets.

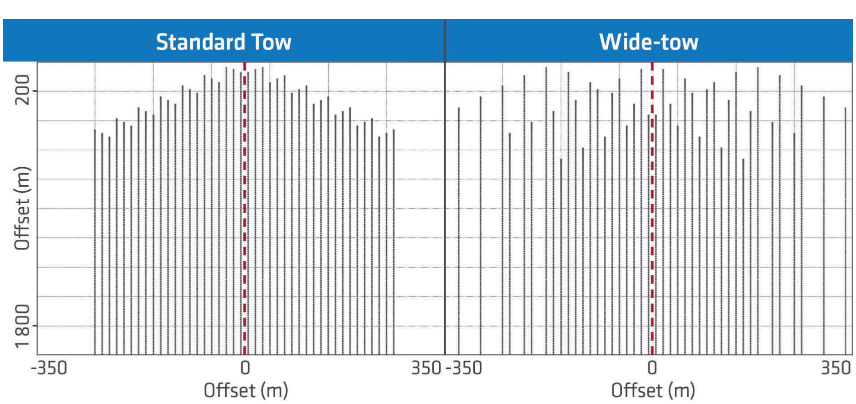

Figure 4 CMP line coverage for a 14 x 75 m streamer spread with standard triple-source (left) and a wide-tow triple-source (right). The total separation for the wide-tow triple-source is 2 x 175 m (i.e. 350 m). The CMP coverage is laterally extended but the outer coverage has gaps between adjacent CMPs. These gaps can be compensated for as demonstrated in Figure 5.

offset towed marine streamer acquisition. Refracted energy and diving waves are recorded at larger offsets than the corresponding reflections from the same geological structures. Recently, so-called velocity surveys have been introduced which are mainly designed to acquire sparse long offset data in order to improve velocity models in complex areas. Imaging can then be done with existing seismic data acquired for imaging purposes.

The capability of acquiring seismic data with long streamers is constrained by several factors. The longer the streamers, the higher the tension and forces acting on the front of the spread. Streamers are typically designed for maximum offsets in the 10,000 m to 12,000 m range.” The towing capacity of a seismic vessel is another factor, as the total drag is increased compared to a spread with the same number of shorter streamers. A limited streamer inventory may confine efficient long offset operations.

High capacity streamer vessels are best suited to operate with long offset and streamer counts of 12 or higher to ensure production efficiency. In 2018, two Ramform T-Class vessels deployed 14 x 10 000 m configurations for exploration surveys, a first in 3D seismic history. Streamer sections of 140 km in total were towed behind each of the seismic vessels.

Offset ranges beyond 10,000 m can be provided by two vessel or multi-vessel operations. The continuous long offset (CLO) or simultaneous long offset (SLO) acquisition techniques utilize an extra source vessel that is typically positioned in front of the streamer vessel (Figure 6). The distance between the leading

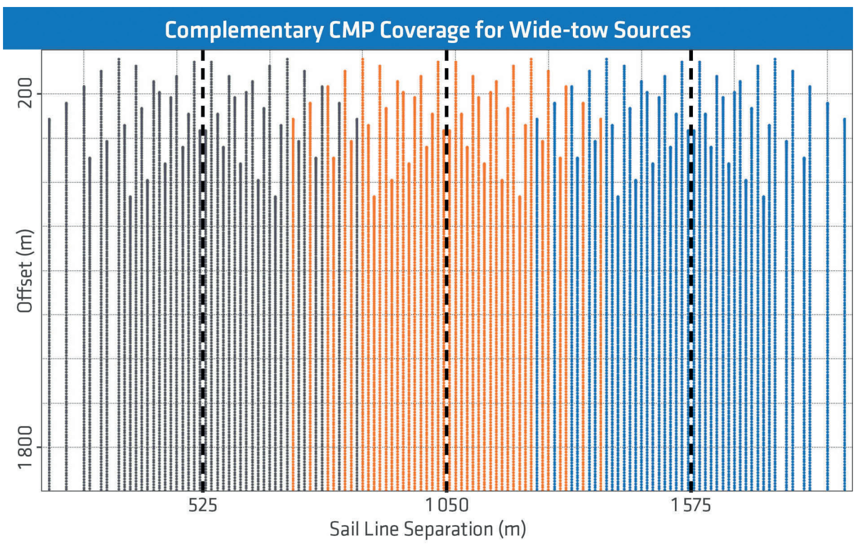

Figure 5 Complementary CMP line coverage for a wide-tow source acquisition. The black dashed lines indicate three adjacent sail lines. The colour-coding marks the CMP lines generated by the same sail line.

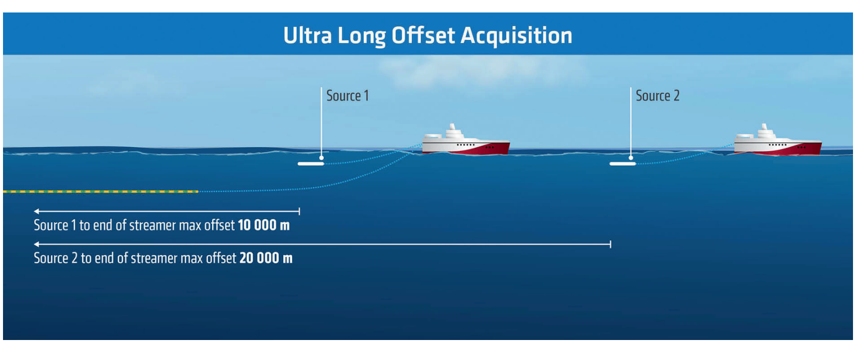

Figure 6 A two-vessel configuration that can deliver effective source-receiver offsets up to 20 km for FWI applications. The lead vessel only operates sources.

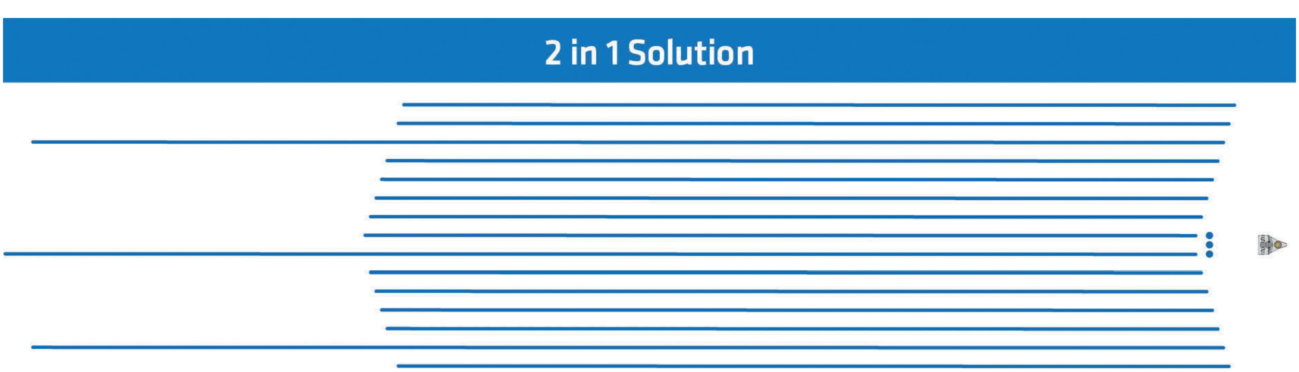

Figure 7 This ‘2 in 1 solution’ delivers ultra-high density data for imaging and is at the same time a velocity survey: It comprises a high-density 16 x 56.25 m streamer spread with a triple-source set-up. Three out of the 16 streamers were deployed with 10-km long streamer ‘tails’ providing long offsets for FWI.

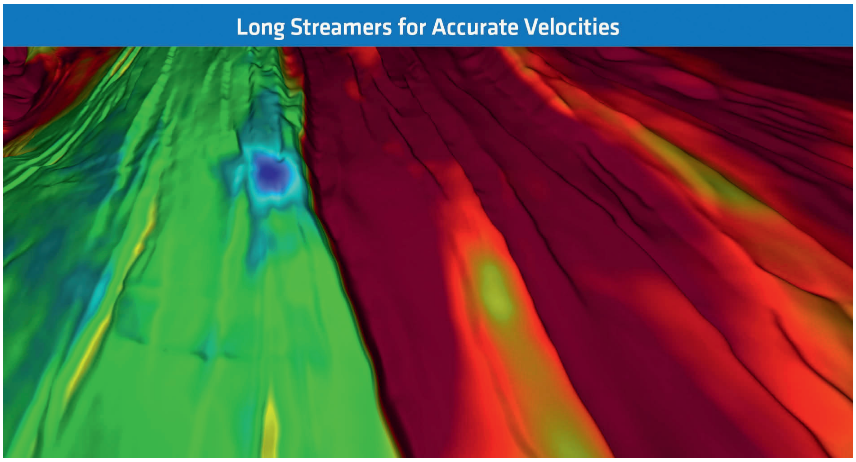

Figure 8 Velocity attribute map extracted for a high-density survey with long streamer tails in the Barents Sea. The low velocity anomaly (blue) correlates well with a potential structural closure. These velocity attributes can help in identifying new hydrocarbon plays.

source vessel and the front end of the streamers towed by the streamer vessel is roughly the same as the physical length of the streamers. The resulting effective offset range is then almost doubled, i.e., 20,000 m inline offsets can be rather easily achieved. In the past, staggered multi-vessel configurations have also been used to extend the seismic offset range (Mandroux et al., 2013).

On the source side, several techniques are available in order to optimize shot point sampling. Seismic data from the sources of the lead vessel and the sources of the streamer vessel are typically recorded continuously in overlapping (blended) records, and various processing solutions can deblend shots with dense spatial intervals. It is noted that FWI workflows have been developed that can model and invert energy from several blended sources in a record without the need for a prior deblending step (Chemingui and Valenciano, 2019). As the spectral bandwidth of the long offset diving and refracted waves is limited to the lower frequencies, the spatial sampling requirements for the ultra-long offsets can be relaxed. This means that the leading source vessel may operate with lower number of source arrays compared to the streamer vessel. A single source with an increased shot interval can fully satisfy geophysical sampling requirements.

A novel configuration with variable streamer lengths has recently been introduced for high resolution exploration surveys in the Barents Sea (Naumann et al., 2019). The first seismic 3D survey of its type was acquired in 2018. Sixteen multisensor streamers were towed with a dense separation of 56.25 m and a triple-source set-up to provide CMP bin dimensions of 6.25 m x 9.375 m (Figure 7), which is unusually small for a large-scale exploration survey. The dense spatial sampling improved seismic image resolution, and frequencies up to 210 Hz were imaged in the shallow overburden. Pre-survey modelling studies showed that imaging of reflections in the area would not require offsets longer than 7000 m. However, modelling also showed that 10,000-m offsets would allow refraction-based FWI model updates down to circa 5 km depth. As dense streamer spacing is not required to obtain stable FWI updates, only three out of the 16 streamers were 10-km long, while the majority of the streamers were 7000-m long. In other words, the variable streamer length set-up is a '2 in 1 solution': An ultra-high density survey for imaging, and at the same time a velocity survey. Figure 8 shows a velocity extraction example for this survey. This velocity attribute map highlights the spatial velocity distribution. A clear anomalous low velocity zone can be identified which correlates well with potential structural closures. Such details in FWI velocity models can be used to identify new hydrocarbon plays (Naumann et al., 2019).

Spreads with variable streamer length are a smart towing solution both with respect to using the streamer inventory with minimum drag while also optimizing the relevant sampling requirements both for imaging and FWI applications. However, such configurations may increase operational complexity. For example, line turns result in different radii for the longer streamers relative to the shorter streamers in the spread, and streamer crossovers may be the consequence. In the Barents Sea project, the nominal streamer depth was 25 m (in order to provide broadband data with a high signal-to-noise ratio of the low frequencies for FWI and quantitative interpretation). During the line turns, the long streamers were moved to 30 m depth in order to mitigate the tangling risk. Furthermore, strong currents may result in different feather angles for the streamers, and thus increase the tangling risk. This can be avoided by towing the streamers at a different towing depth during production. Multisensor streamers have the advantage that wavefield separation processing is insensitive to local variations in receiver depth.

Cost-effective multi-azimuth acquisition

Multi-azimuth, wide-azimuth, and full-azimuth seismic are well-known technologies with applications to areas with increasingly complex geological targets. High fold data with rich azimuth diversity can improve both illumination, multiple attenuation, and improve the signal-to-noise ratio as numerous case histories have demonstrated (e.g., Keggin et al., 2007). Multi-azimuth is in many cases the most flexible and scalable approach in marine seismic as the acquisition template is usually based on a single vessel while most other techniques (including OBN) require more complex multi-vessel operations.

Combining the latest acquisition solutions (wide-tow sources, multi-sources, and longer offsets) with the multi-azimuth concept offers a range of cost-effective solutions that can be tailored for any imaging challenge. This is especially relevant for regions where legacy 3D seismic data already exists.

Reprocessing of legacy data frequently suffers from short-comings such as poor signal-to-noise, limited spectral bandwidth, sparse sampling, relatively short offsets, or insufficient target illumination. In many cases, acquisition of more modern seismic data is needed that then may be combined with the existing seismic data in a complementary manner. A new survey can be acquired in a different direction for better azimuthal illumination. Multisensor streamer seismic provides the full bandwidth, and multi-sources together with high density streamer spreads deliver the optimal spatial sampling for the exploration objectives. High-density configurations can be upgraded with extra-long streamers or simultaneous long offset methods to support FWI-driven velocity model building. Wide-tow sources can deliver missing near-incidence angle coverage that is a requirement for accurate AVO analysis —in particular for shallow targets.

3D illumination or velocity building benefits from the acquisition of several survey directions. The acquisition of additional azimuths will not necessarily increase the cost in a linear manner. Additional directions can be designed with a larger sail line separation enabled by wide-tow source solutions and lead to better productivity and turnaround.

Conclusions

High-capacity streamer vessels combined with multisensor streamers, wide-tow multi-source geometries, and variable long-offset strategies can be utilized to solve imaging challenges for almost any geological regime. The survey designs recently made possible and described here are flexible and can be tailored for specific sampling requirements, and address modern demands for longer offsets and greater azimuth diversity. When acquired over legacy surveys, these strategies can significantly upgrade the quality of existing exploration data at moderate cost.

Acknowledgements

The authors would like to thank PGS for permission to publish this article.

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