New Shallow Seismic Insights

We will continue to use high-resolution seismic to understand the subsurface risks and opportunities in marine areas as we transition to renewables and lower carbon energy sources as a complement to fossil fuels. CO2 storage in aquifers must be monitored for shallow seal integrity and offshore wind farms require geotechnical ground models and seismic characterization of the near surface. This article addresses the question of whether we will necessarily require entirely new seismic acquisition solutions, or whether existing methods can be adapted to provide new value and insights.

Towed-streamer seismic using tailored acquisition configurations provide an efficient method of accessing high-resolution datasets for several purposes, and some examples are given below. I also show how full wavefield imaging solutions can high-grade existing seismic data to significantly enhance the resolution and quality of shallow images.

New Energy Focus Upon Shallow Seismic Imaging

A clear acceleration of industry focus is underway towards ‘new energy’ alternatives to traditional hydrocarbons. An expected growth in carbon capture and storage / carbon capture utilization and storage (CCS/CCUS) and in large wind farms will both have requirements for optimal shallow seismic imaging in many shallow water offshore areas. In the case of CCS/CCUS, available aquifers in offshore settings adjacent to gas processing installations are an obvious candidate for long-term CO2 sequestration, and a long-term obligation will exist for 4D monitoring of the CO2 plume—including an ability to resolve the near-surface with high-resolution seismic images. In the case of offshore wind farms, a detailed ground model will be required prior to installation; typically down to a few hundred meters depth.

Whilst a market will presumably be created for bespoke shallow seismic acquisition solutions that use new engineering designs, a natural question is “What can be recovered using traditional 3D seismic solutions?” Many areas likely to see CCS/CCUS and/or offshore wind farm activity already have significant 3D seismic data coverage, or are likely to see future exploration 3D seismic activity in the same areas of interest. I briefly review the state-of-the-art in towed streamer acquisition and imaging that can translate to significant improvements in legacy shallow seismic image resolution.

Wide-Tow Multi-Source Towed-Streamer is Surging Ahead

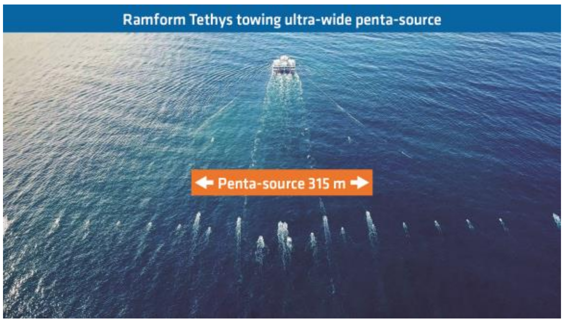
Wide-tow of multiple -sources has been successfully introduced to marine towed-streamer seismic acquisition, with several commercial projects conducted during the last two years. The transition from standard source configurations to wider separations has been enabled by modified towing solutions for seismic source arrays.

The benefits of wide-tow source configurations are two-fold: 1. Wide-tow sources enable higher streamer counts, and thus higher acquisition efficiency without compromising the near offset coverage, and 2. If the streamer spread is kept constant and the sources are spread out, the near offset coverage can be improved without sacrificing efficiency and increasing cost. Imaging workflows and products benefit from modern data with rich near offset coverage necessary to optimize shallow seismic image resolution and quality.

A recent PGS survey in the Barents Sea employed a dense multisensor GeoStreamer spread and five sources with a total separation of 315 m – a world first. Benefits included the following:

- High-resolution imaging of shallow targets and geohazards
- Uniform ultra-near-offset coverage (refer to Figure 1)
- Robust AVO for shallow targets
- Improved pre-processing, especially multiple removal (SRME)
- Dense spatial-sampling and high trace-density

Note that the vessel also towed three long streamer 'tails' to facilitate deep transmission FWI (full waveform inversion) velocity model updates; thereby providing a 'two for one' acquisition solution.



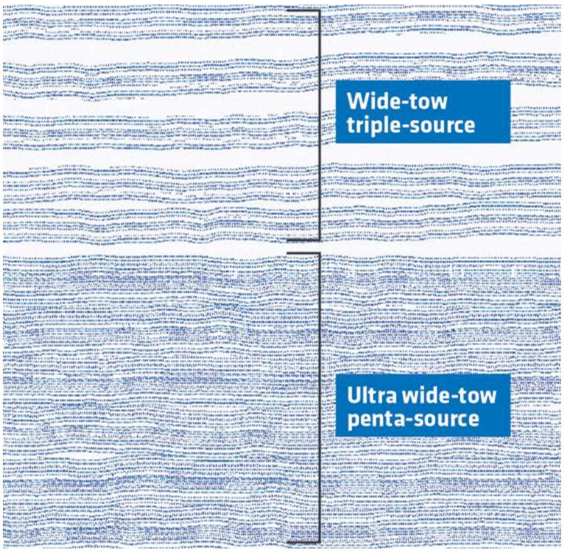


Figure 1. Overhead perspective of the penta-source configuration with 315 m outer source separation (above); and the ultra-near offset coverage over the 0-100 m offset class calculated from the navigation data belonging to two adjacent wide-tow source surveys in the Barents Sea in 2020 (right). The ultra-wide tow penta-source solution delivers almost gap-free live fold, while keeping the same efficiency. Refer also to the raw data comparison in Figure 2.

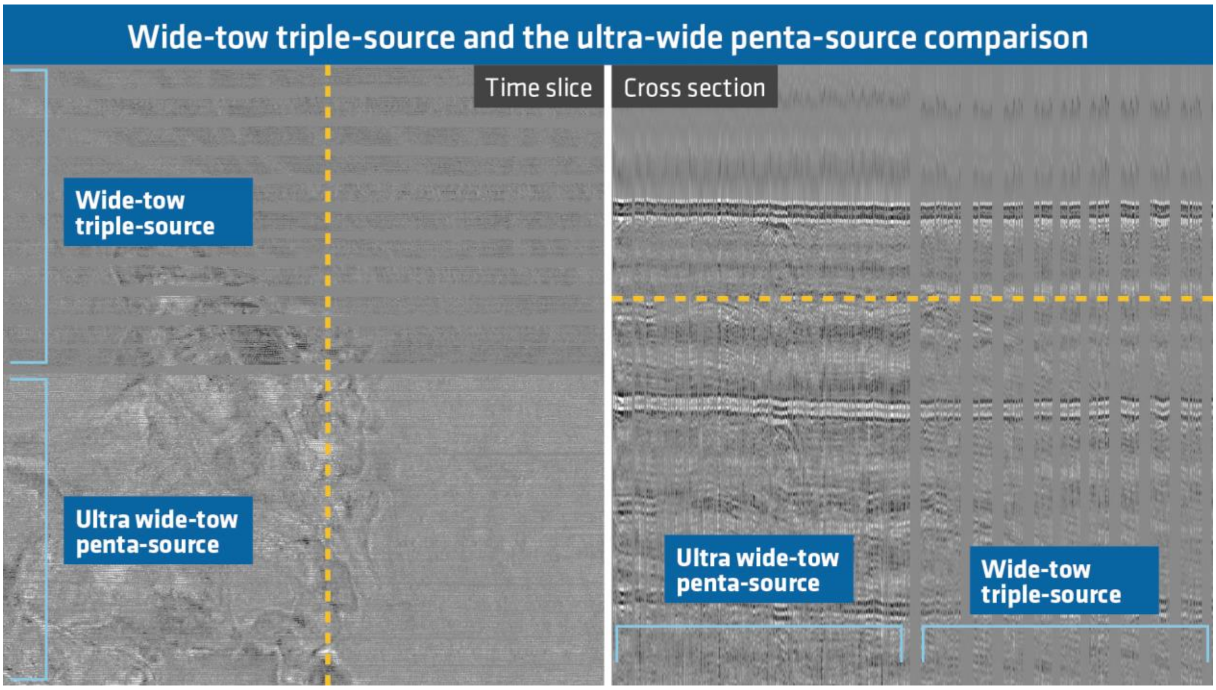


Figure 2. Time slice and cross section extracted from the ultra-near offsets acquired by wide-tow triple source and the ultra-wide penta-source as shown in Figure 1. The water depth is about 400 m and targets are expected as shallow as 600 m. The data in these examples are raw and still show multiples and source bubble energy. Sail line boundaries are no longer visible in the area acquired with the penta-source.

The world-record 315 m outer source separation will soon be exceeded by a survey acquired for Lundin Energy, also in the Barents Sea. A two-vessel operation will acquire long offsets into an efficient multisensor GeoStreamer spread, whilst simultaneously being recorded over the entire survey duration by over one thousand sparse seafloor nodes designed to complement the towed streamer data with extremely long offsets and full-azimuth coverage. In probably the most sophisticated 3D seismic survey ever acquired, a hexa-source configuration with 437.5 m nominal outer source separation towed over the deep-tow streamer spread will yield optimized near-offset coverage for shallow seismic imaging, and a source tuned to improve the very-low frequency data available for FWI model building will also be towed in front of the streamer spread. All seven sources will be acquired in a blended manner with proprietary source-firing technology.

Note also that in terms of the *shorter offsets* relevant to high-resolution near-surface imaging, the offset sampling is more uniform, the source wavefield sampling is approaching uniformity in all directions, and both the source and receiver wavefield spatial sampling is denser than for typical OBC/OBN acquisition. These features would exist even without acquisition of sources placed over the streamers; a strategy specific to near-surface challenges in the survey location. Any such highly-sampled data can be augmented by the imaging platforms discussed below.

High-Grading Existing Seismic for Geohazards

The seismic appraisal component of geohazard analysis typically follows a two stage approach: a screening of the seismic data to detect outliers based on reflection strength, and an AVO analysis to predict the composite nature of those anomalies.

High resolution 'site' surveys are often acquired with very shallow source and streamer depths, highly compact source concepts, hydrophone-only streamers, short maximum offsets, and limited spatial area restricted to the immediate drilling area. Collectively, such data are band-limited in frequency content by surface ghost effects, biased towards high frequency content at the expense of low frequency content, and operational cost restrictions may result in poor crossline spatial sampling between sublines.

New wide-tow multi-source marine streamer solutions solve the challenge of efficiently acquiring dense near-offset coverage, but what about existing 3D seismic coverage that does not have optimal near-offset coverage? If the seismic data is multisensor, either towed streamer (i.e. GeoStreamer) or seafloor receivers (OBN/OBC), then high-end imaging options such as separated wavefield imaging (SWIM) and full wavefield migration (FWM) may provide significant shallow imaging improvements in the reprocessing of existing data, particularly if complemented by least-squares migration (LSM) frameworks. Figures 3 and 4 provide examples of high-resolution shallow imaging being augmented by SWIM.

In a short on-demand webinar titled 'Shallow Resolution, Achieved in Many Ways', I showed examples of SWIM run to 240 Hz in a comparison against a traditional high-resolution viscoacoustic imaging effort applied to multisensor GeoStreamer data (see Figure 3). Although the primaries-only seismic volume used a processing bin size of only 6.25x6.25 m, the shallowest geology has degraded image quality and resolution, but in contrast, the SWIM data reveals a remarkable near-surface image. A pragmatic approach was used to seamlessly merge the shallow SWIM volume with deeper conventional imaging. One benefit of such an approach is that vast GeoStreamer surveys, such as the 10 000 square kilometer volume in this Barents Sea example, could potentially be high-graded very efficiently.

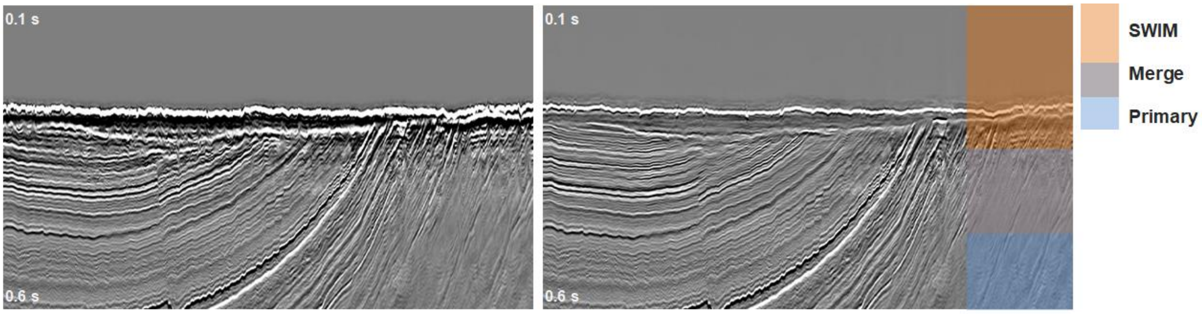


Figure 3. Traditional primaries-only high-resolution imaging result (left) vs. SWIM imaging of the shallow section blended with primaries-only imaging at larger depths (right).

In another example from the Norwegian Sea, I overlaid a small high-resolution site survey volume acquired with very shallow source and streamer depths, on regional GeoStreamer data (see Figure 4). The peak frequencies of the hydrophone-only site survey data are biased to high frequencies, and the site survey data is severely deficient in low frequencies. Reprocessing of the GeoStreamer data through a 'Shallow hazard' or 'SHAZ' flow has yielded a result with shallow resolution that is remarkably close to that of the site survey data. Furthermore, the SHAZ images are rich in low frequency signal, and again, the entire 30 000 square kilometer GeoStreamer dataset can be potentially high-graded anywhere using this type of flow.

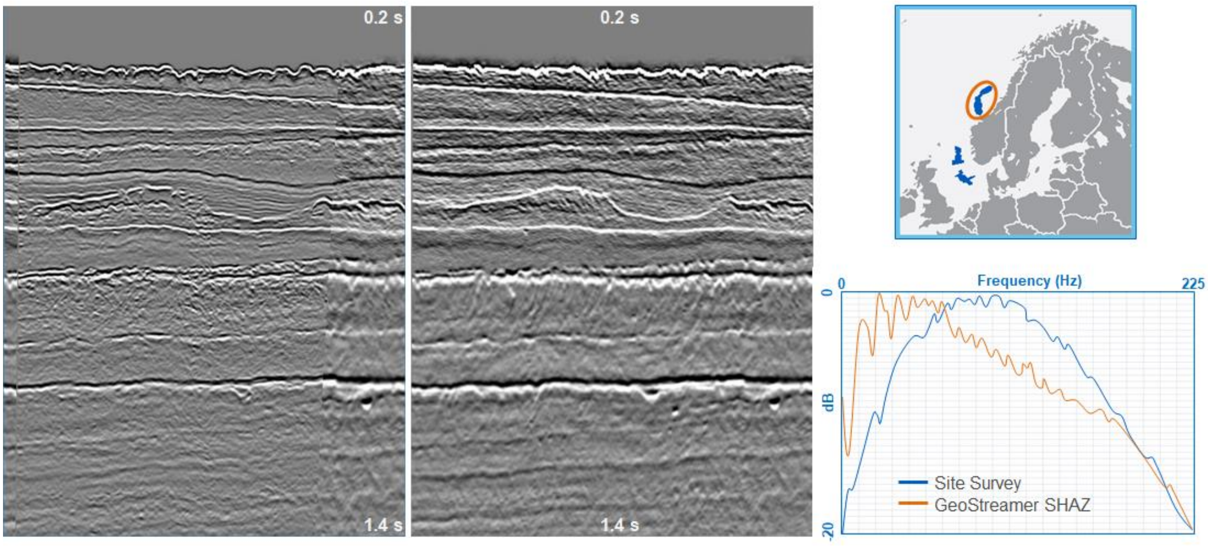


Figure 4. Traditional site survey data overlain on the GeoStreamer SHAZ volume (left); the comparative broadband SHAZ image (centre); and comparative amplitude spectra (right).

What about OBC/OBN data? A published application of SWIM for geohazard assessment, located in approximately 120 m of water, compared a high-resolution 2D site survey with a SWIM application to a multicomponent OBC survey. The interplay between water depth and OBC acquisition geometry makes interrogation of the near-surface reflectivity very challenging for conventional imaging. To mitigate overburden geohazards, a site survey was acquired with an inline spacing of 50 m and a 6.25 m shot interval, and yielded resolution fit for geohazard assessment. In contrast, the OBC data, acquired with 350 m line separation and 25m receiver separation, is completely uninterpretable in the first 500 m below the seafloor for geohazard analysis when conventional imaging is applied (see Figure 3 in the publication referenced above). However, the application of SWIM to the OBC data yielded an image with similar clarity and resolution as the site survey; but with the additional benefit of the much larger survey-wide areal extent of the OBC survey.

The pursuit of semi-permanent seafloor acquisition systems will expectably increase in shallow water areas where some form of near-surface monitoring is required; such as the applications discussed in the introduction. The capability of SWIM for high-resolution near-surface imaging, even when the receiver deployment is sparse or irregular, has obvious merits.

High-Resolution Velocity Models and Least-Squares Imaging

FWI using refractions and reflections has rapidly matured into an efficient component of modern processing workflows. Assuming that the reflectivity of the recorded data can be modeled accurately, depth domain velocity models can be derived with much higher resolution than is possible using ray-based tomographic solutions. For shallow depths, the resolution of FWI velocity models may be interpretable in a geological context. When combined with appropriate rock physics analysis, such models can enable a variety of high-resolution seismic data interpretation and QI workflows. One new and notable application of FWI to QI involves the application of calibrated rock physics workflows to use FWI models for low-frequency model building in pre-stack elastic seismic inversion. This has relevance for efforts to characterize the near-surface geology—particularly in areas with limited well control.

LSM (least-squares migration) has two notable benefits for near-surface high-resolution imaging and characterization: 1. Improved spatial resolution of small-scale geohazard features, and 2. optimizes amplitude-versus-angle (AVA) content of the data, particularly in areas affected by variable subsurface illumination associated with complex overburden. Such considerations are relevant for scenarios where the subsurface must be characterized continuously between the seafloor and the reservoir, such as CCS/CCUS. In another short on-demand webinar titled 'Illumination versus AVO, The Value of Least-Squares Migration', I briefly discuss the relevance of LSM for AVA analysis and quantitative interpretation (QI).

Other LSM benefits for near-surface imaging include mitigation of the sail-line acquisition footprint, and for shot-based LSM solutions, the ability to apply the algorithms in an efficient frequency-dependent manner to optimize cost vs. required resolution (refer also to the short on-demand webinar titled 'Illumination versus AVO, The Value of Least-Squares Migration'). In other words, the maximum frequency imaged, and therefore the computational cost, can be tuned to the local near-surface geology characteristics in a flexible manner.

Summary

Advances have recently occurred in both towed streamer acquisition survey designs and in full wavefield seismic imaging solutions that help to create significantly enhanced near-surface resolution and image quality, even when traditional imaging criteria suggest that the spatial sampling and near-offset sampling is inappropriate. Highly efficient vessel configurations can therefore be contemplated for regional survey ambitions, whilst simultaneously providing some benefits to near-surface appraisal and geohazard assessment. These benefits may also translate to emerging pursuits of lower carbon energy solutions in some marine areas.

It is likely that new exploration seismic data will be acquired in the same areas of interest for CCS/CCUS or offshore wind farms. Advances in wide-tow multi-source multisensor streamer acquisition mean such data can be of value in several ways. In particular, uniform near-offset coverage and dense spatial sampling are critical for shallow high-resolution imaging of primary reflections.

For existing multisensor seismic coverage, comprising both towed streamer and seafloor data, reprocessing using tailored full wavefield imaging workflows such as SWIM will lead to higher resolution near-surface images. SHAZ (shallow hazard) products can be cost-effectively merged in a seamless manner with conventionally-imaged data volumes; thereby providing opportunities to re-use exploration data for shallow imaging ambitions. Recent advances in LSM technology also enable pre-stack QI analysis as a complement to high-resolution reflectivity interpretation.

Acknowledgments

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Suggested Reading Material

- Norway | A First Look at Final Results from GeoStreamer X Viking Graben 2019 (Webinar): https://www.pgs.com/media-and-events/webinar-library/europe-africa--middle-east/europe/norway--geostreamer-x---a-first-look-at-final-results-from-viking-graben-2019/
- Recent Advances With Wide-Tow Multi-Sources in Marine Seismic Streamer Acquisition and Imaging (First Break 2020): https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_widmaier_et_al_dec2020_wide-tow-sources.pdf
- Shallow Hazard Imaging: https://www.pgs.com/imaging/services/shallow-hazard-imaging/
- Shallow Resolution | Achieved in Many Ways (TechByte Webinar): https://www.pgs.com/media-and-events/webinar-library/technology-webinars/webinars/shallow-resolution-achieved-in-many-ways/
- Illumination vs AVO | The Value of Least-Squares Migration (TechByte Webinar): https://www.pgs.com/media-and-events/webinar-library/technology-webinars/webinars/illumination-vs-avo-the-value-of-least-squares-migration/
- Separated Wavefield Imaging for Shallow Geohazard Analysis - An Ocean Bottom Study on a North Sea Dataset (EAGE 2018): https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/eage2018_pgs-maersk_martin_etal_june2018_obs-swim-geohazards.pdf