# Advanced 3D seismic crossover technologies between hydrocarbon exploration, CCS development, and offshore wind

Martin Widmaier[1]*, Carine Roalkvam[1] and Okwudili Orji[1] revisit modern towed-streamer acquisition configurations and demonstrate how the same concepts have recently been used to design and acquire the first large CCS development surveys as well as ultra-high resolution 3D site surveys for offshore wind farms.

## Introduction

The need for high- and ultra-high-resolution 3D towed-streamer seismic data has grown quickly during recent years. The increased demand can be explained by the shift towards near-field hydrocarbon exploration and by an increasing need for 3D seismic data as part of the energy transition. Near-field exploration typically requires improved seismic data quality compared to legacy data. Better spatial sampling, higher trace density, improved near-offset coverage but also longer offsets for velocity model building are the typical geophysical survey design objectives. The emerging new energy market utilises 3D seismic data for carbon capture and storage (CCS) development projects and as a key part of site surveying for future offshore wind farms. In addition, high resolution marine seismic data is being used in the context of marine mineral exploration (Helland-Hansen et al., 2023) as well as nuclear waste management (Strand et al., 2023). These relatively new applications have in common that the subsurface targets tend to be shallow and high-quality imaging of the near surface or even the seabed is key. The shallower the targets the more important the near offset coverage and dense spatial sampling in 3D seismic acquisition becomes. Both factors are cost drivers and thus advanced technologies and solutions are needed to enable cost-effective 3D acquisition.

Innovative towing configurations which combine wide-tow multi sources with multisensor streamer spreads have become the new standard for hydrocarbon exploration in Northern Europe. These acquisition solutions enable accurate imaging from very shallow targets and geohazards to deep geological structures in a cost-effective manner. The improved near-offset coverage and the dense spatial sampling provided by the wide-tow multi-source configurations enable subsurface imaging with temporal and spatial resolution in the meter range. Equivalent survey design concepts have recently been utilised for high-resolution site characterisation for carbon storage or ultra high-resolution 3D site surveying for offshore wind farms.

## Revisiting wide-tow multi-source technology

New concepts for high-resolution streamer acquisition and imaging of shallow targets and the near surface were introduced by Widmaier et al. (2017 and 2020). A key step was the transition from narrow to wider source separations. Applying this technique to multiple sources (e.g., triple, quad, penta, etc.) leads to a distribution of sources along the front of a streamer spread. The wide-tow multi-source solution was launched as an alternative to the marine survey design method commonly used to improve

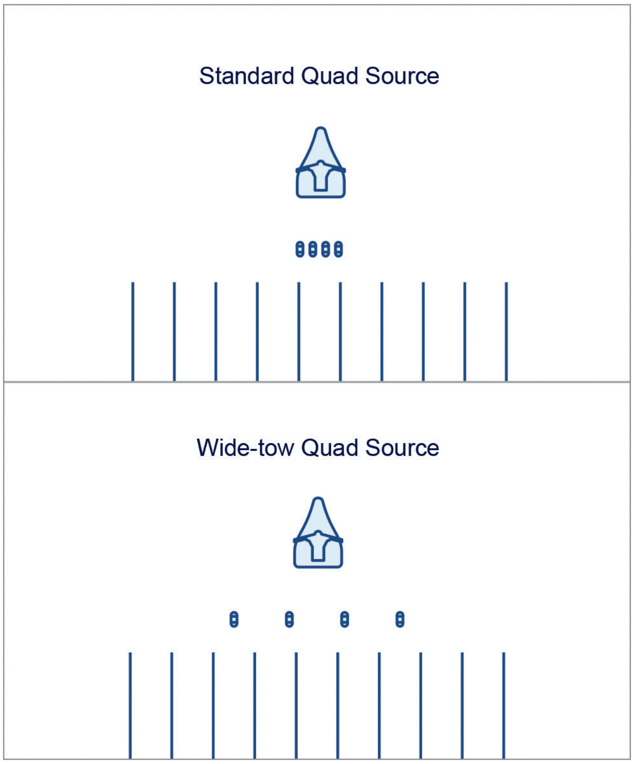


**Figure 1** High-density streamer configurations of 10 streamers combined with a standard quad-source set-up (top) and a wide-tow quad-source set-up (bottom). The wide-tow source separation is 62.5 m, resulting in a total source spread width of 187.5 m. The resulting improved near-offset separation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

[1] PGS
* Corresponding author, E-mail: Martin.Widmaier@pgs.com
DOI: 10.3997/1365-2397.fb2023090

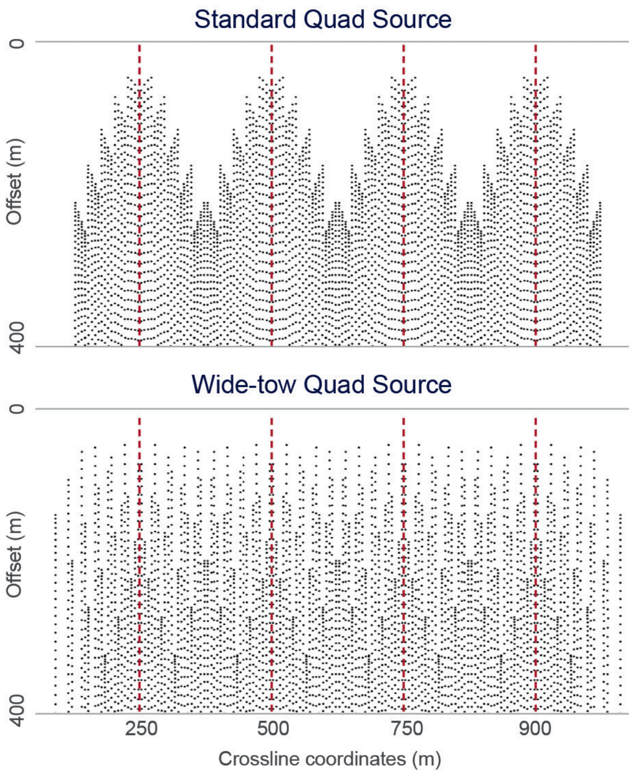


**Figure 2** Near-offset distribution for a quad-source configuration with 12.5 m standard source separation (top) and 62.5 m wide source separation (bottom). The streamer separation is 50 m in both examples. The red dashed lines indicate the centre of each sail line. Crossline coordinates are along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

near-offset coverage, i.e., the reduction of the streamer spread width to minimise the distance between the sources in the centre and the outermost streamers. The latter method implied higher acquisition cost as reducing the spread width results in a smaller 3D coverage per sail line.

Figure 1 was originally published by Widmaier et al. (2019) and 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 alternative it is increased to 62.5 m. 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 compared to the narrow source geometry (Figure 2). Instead of the typical near offset trace accumulations following the sail lines and the large near-offset gaps between the sail lines for the narrow quad-source scenario (Figure 2, top), the wide-tow quad-source configuration distributes the nearest offset traces more evenly in crossline direction and the width of the near-offset gaps is reduced to a few CMP lines only (Figure 2, bottom). The more evenly balanced sampling of the nearest offsets is a much better starting point for regularisation and interpolation techniques that can be applied in seismic processing. These regularisation and interpolation techniques enable an effective mitigation of the typical acquisition footprint observed historically in shallow depth slices of towed-streamer data (Widmaier et al., 2020). In addition to the improved near-offset sampling, the wide-tow quad-source 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 (e.g., penta or hexa source) and high-density streamer spreads with significantly more streamers.

## Proof of concept: High-resolution hydrocarbon exploration surveys

The concept for the wide-tow multi-source method was proven successfully in novel exploration surveys offshore Norway in 2019 and 2020. A wide-tow triple source with a source separation of 112.5 m was deployed with a 12 x 84 m streamer spread in the Viking Graben/North Sea in 2019 to enable both optimised near-offset coverage and improved acquisition turnaround (Widmaier et al., 2020). Figure 3 shows a shallow imaging comparison between legacy data acquired with a 10 x 75 m streamer spread and a standard dual source in 2011 and the result of the 2019 seismic survey with a wide-tow triple source. The latter enabled seamless shallow imaging despite the wider streamer spread and higher acquisition efficiency.

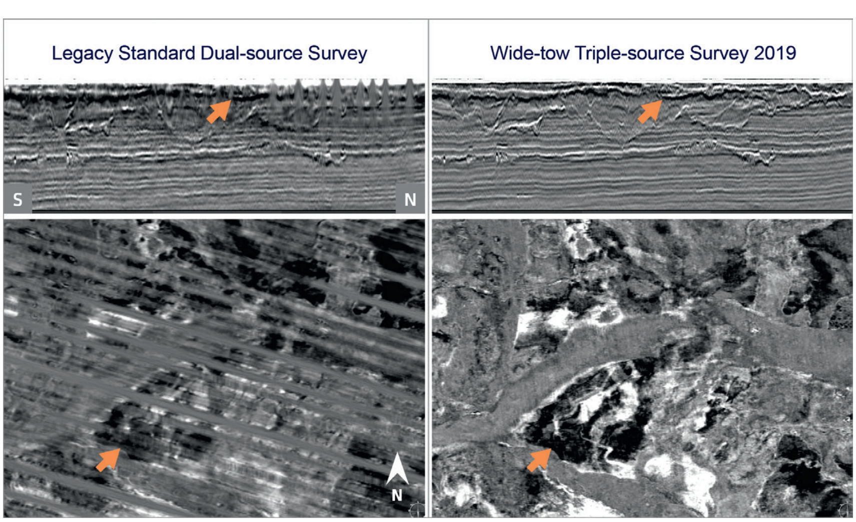


**Figure 3** Comparison of time slices at ca.200 ms two-way traveltime and (inset) shallow seismic cross sections. The example shows significant footprint and illumination gaps (left) when acquired with a standard dual source and a 10 x 75 m streamer spread in 2011. The wide-tow triple source configuration used in the same area in 2019 enabled seamless shallow imaging and higher efficiency. The orange arrows indicate the respective positions of the slices and the cross-sections.

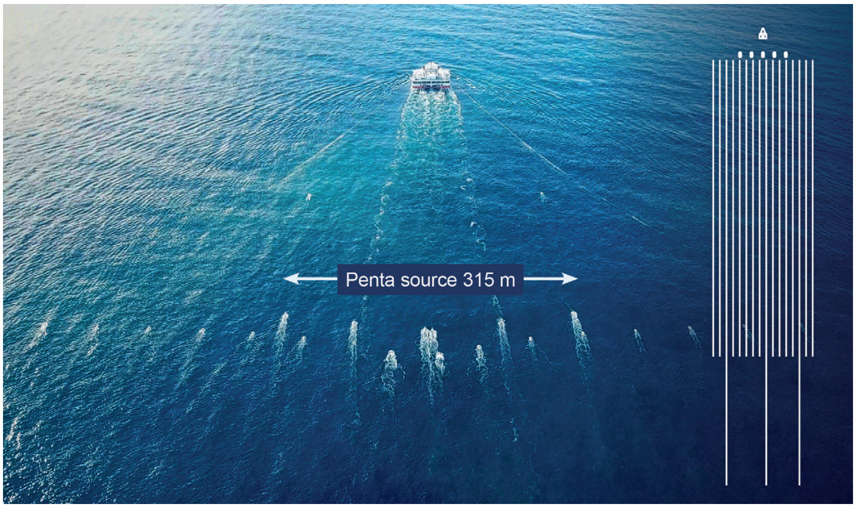


**Figure 4** Schematic illustration of the nominal vessel configuration and a drone photo showing Ramform Tethys during the seismic program in the Barents Sea in 2020. The vessel is towing a 16 x 56.25 m x 7000 m multisensor streamer spread comprising three long streamer tails (10 km length) for refraction FWI velocity model building. The source configuration consisted of an ultra-wide penta source with 78.75 m source separation and 315 m total source spread width. Note that the source separation is larger than the streamer separation (56.25 m).

In the following year, the number of distributed sources was increased from triple to penta in an exploration survey in the Hammerfest Basin/Barents Sea (Widmaier et al., 2021). A high-density multisensor 16-streamer spread was combined with a wide-tow penta source (Figure 4). The separation between adjacent source arrays was 78.75 m, resulting in a total source spread width of 315 m. The inline offset between the sources and the streamer front-end was as short as 65 m. The multisensor streamer spread consisted of 16 multisensor streamers of 7 km length towed with 56.25 m nominal separation and enabled in combination with the penta source a processing bin size of 6.25 m x 6.25 m. Again, the wide-tow multi-source solution led to literally footprint-free imaging of the shallow sub surface without compromising efficiency (Widmaier et al., 2021).

The high-density multisensor streamer spreads were in both surveys complemented by 10 km-long streamer tails. A streamer configuration with tails had already been successfully used in the Barents Sea in 2018. The innovative configuration with variable streamer lengths delivered optimal wavefield sampling both for high resolution imaging and for refraction full waveform inversion (FWI) velocity model-building (Naumann et al., 2019).

The tow depth of the multisensor streamers was 25 m for the high density spread and 28 m for the 10km-long streamers to minimise the tangling risk. Thanks to the deep tow, the surveys could be acquired with minimal exposure to weather-related downtime and without rough sea effects compromising data quality (e.g., signal-to-noise ratio). With multisensor streamers, the receiver ghost problem is solved at all frequencies by combining pressure and particle motion recordings and thus the deeper tow does not limit the spectral bandwidth.

Since 2019, the wide-tow multi-source method has been utilised in more than 20 commercial seismic programs. In some cases, source-over-the spread solutions (e.g., Dhelie et al., 2023) were used to achieve close-to-zero offset coverage for imaging of shallow targets. The method has also been extended to commercial applications with non-uniform towed-streamer geometries (Widmaier et al., 2022). More recently, CCS development surveys and site surveys for offshore wind farms have successfully adopted the same survey design concepts although at smaller scales.

## CCS high-resolution development survey with wide-tow quad source

The wide-tow quad source configuration shown in Figure 1 (bottom) was the starting point for a novel high-resolution survey over three CCS structures in the Southern North Sea, that was designed and acquired for the Northern Endurance Partnership (operated by bp) in 2022 (Cooper, 2023). Survey design criteria for CCS can be different from hydrocarbon exploration and reservoir monitoring and are mostly driven by the need to image shallower targets. The typical geophysical objectives are the quantification of the CO2 storage capacity, an assessment of the integrity of the seal, detection of shallow hazards but also injection well planning and establishing baseline datasets for future seismic monitoring.

One of the specific challenges for the Northern Endurance project was accurate imaging and characterisation of the geological formations above the CO2 storage reservoirs. Seismic modelling indicated that imaging of the near subsurface in the environment with water depths as shallow as 20 m required uniform coverage of near offsets at least in the 30-60 m offset range. More specifically, the operator's technical requirements determined that 25% of all CMP lines must have near offsets smaller than 30 m, and 50% of the CMP lines smaller than 60 m assuming a crossline bin size of 12.5 m. While the wider tow of the quad source enables an optimised near-offset coverage in the crossline direction (Figure 2, bottom), it was still a challenge to meet the nearest offset requirement given the typical towing solution with sources circa 65 m in front of the spread. The inline offset challenge was solved by moving the sources over the front ends of the streamers.

The final configuration comprised nine streamers separated by 50 m and a quad source with a source separation of 62.5 m. The source inset relative to the streamer front ends was circa 130 m. Figure 5 shows the *Ramform Hyperion* with the innovative and complex towing solution during a line turn on the Northern Endurance 3D high-resolution survey. Again, deeper tow of multisensor streamers was key for broadband acquisition and to ensure high efficiency also under rougher weather conditions. The shallow water restricted the tow depth, however, to 15 m and to 12 m in the most challenging part of the survey area.

The survey was acquired in an efficient manner and resulted in high data fidelity, enabling 3D imaging of the shallow overburden including the seabed (Cooper, 2023).

## Ultra-high-resolution 3D site surveys for offshore wind farms

The planning of future offshore wind farms requires ultra-high resolution seismic as part of site surveying to characterise the near surface around the potential locations for wind turbines. The shallowest part of the subsurface (e.g., upper 100 m) including the sea floor must be imaged in great detail. The identification of shallow geohazards and the detection of boulder accumulations are a key part of the risk assessment.

Until recently, ultra-high resolution seismic site surveys for offshore wind farms were mainly conducted as 2D acquisition. The site investigation effort involves a reconnaissance phase where development areas for offshore wind farms are typically covered by a grid of 2D seismic lines. A grid could consist of 2D lines with, e.g., 200 m line separation in one direction and 2D tie lines with larger spacing (e.g., 500 m) in the orthogonal direction. An initial assessment of the area is then followed by a refinement phase where additional 2D infill lines are acquired resulting in a denser grid of 2D lines. Ultra-high-resolution 3D seismic has the potential to shorten the overall cycle time from initial site evaluation to the installation of the turbines and to provide better 3D subsurface images and more accurate characterisation of the near surface.

However, the seismic wavefield must be sampled at higher sampling rate temporally (kHz range) and much denser spatially (bin sizes in the one-metre range) for seismic site surveys compared to the hydrocarbon exploration and CCS development surveys discussed in the previous sections. The configurations must consequently be scaled down significantly, and at the same time a certain level of efficiency must be maintained to make ultra-high resolution 3D seismic a commercially viable alternative to the traditional 2D approach.

The P-cable system, originally developed by Planke and Berndt (2003), has recently been adopted for applications in the energy transition (MacGregor et al, 2022). In the P-cable system, short hydrophone-only streamers (typically 50-100 m long) are towed from a cross cable. For ultra-high-resolution applications, sparker or boomer sources are used, and temporal sampling rates are 0.125-0.25 ms. In contrast to multisensor streamers referred to in the previous sections, ultra-high resolution systems such as the P-cable are still towed at very shallow depths to emphasise the high-frequency content in the recorded data. Neither acquisition nor processing-based source and receiver deghosting methods are best practice yet. Consequently, the shallow tow depth increases the weather exposure of ultra-high-resolution seismic surveys.

**Figure 5** Schematic illustration of the nominal vessel configuration and a photo of Ramform Hyperion acquiring the high-resolution CCS development survey for the Northern Endurance Partnership offshore UK in 2022. The configuration consisted of nine multisensor streamers with 50 m separation and a wide-tow quad source that was towed over the front end of the streamer spread. The resulting nominal acquisition bin size was 6.25 m x 6.25 m.

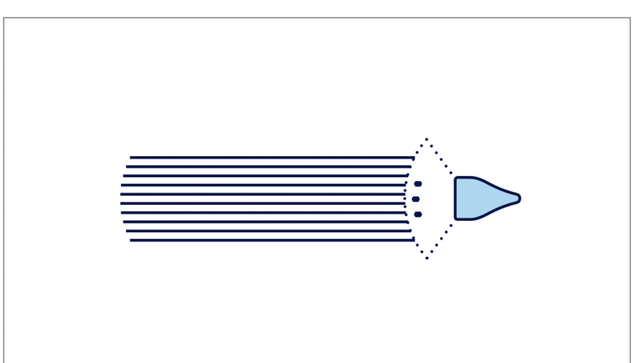

**Figure 6** High integrity ultra-high-resolution configuration with a 10 x 6.25 m x 100 m streamer spread and a wide-tow triple source.

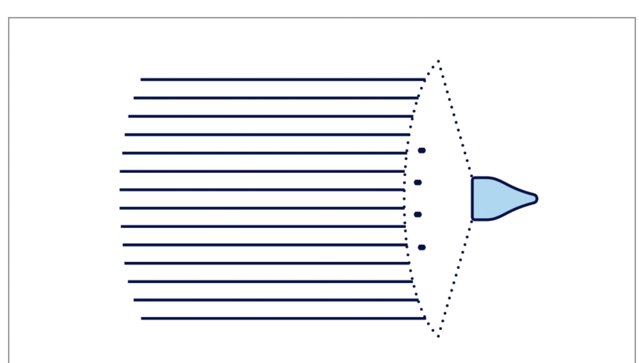

**Figure 7** Ultra-high-resolution configuration with a 14 x 12.5 m x 100 m streamer spread and a wide-tow quad source.

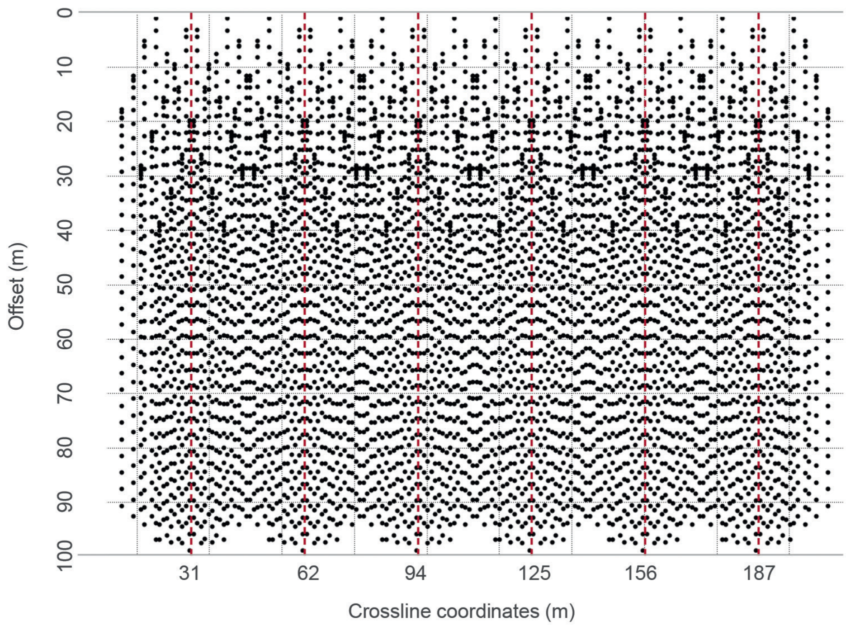


**Figure 8** Offset distribution resulting from six adjacent sail lines with the ultra-high-resolution 3D configuration comprising a wide-tow triple source shown in Figure 6. The six dashed lines indicate the centre of each sail line. The configuration delivers a good and uniform coverage of the nearest offset in the 0 m to 30 m offset range and fully populated offset classes for the larger offsets.

Lebedeva-Ivanova et al. (2018) discussed the path towards one-metre resolution in 3D seismic based on P-cable single- and dual-source acquisition. In this article, we propose to combine P-cable or equivalent ultra-high resolution streamer technology with the proven wide-tow multi-source approach. Two initial examples are shown in Figure 6 and Figure 7. In the first example (Figure 6), 10 short streamers with a separation of 6.25 m are combined with a wide-tow triple source with circa 10 m source separation. The resulting nominal acquisition bin size is circa 1 m and the sail line separation is 31.25 m. The second example (Figure 7) is a more efficient configuration. The number of streamers is increased to 14 and the streamer separation to 12.5 m. The source solution comprises a wide-tow quad source with approximately 22 m source separation. The configuration has a nominal sail line separation of 87.5 m, and an (effective) crossline bin size in the range of 1.5 m to 3 m, depending on near-offset sampling requirements, i.e., acquisition efficiency has been gained while the spatial sampling has been relaxed.

Although the source separations of 10 m and 22 m in the two examples appear to be rather small, the source separations are larger than the respective streamer separations and thus follow the same design principles as illustrated in Figure 1 and Figure 2. The 3D offset distribution resulting from acquiring six adjacent sail lines with the 10 x 6.25 m streamer configuration with the wide-tow triple source (Figure 6) is shown in Figure 8. The analysis demonstrates that the configuration delivers a good and uniform coverage of the nearest offset in the 0 m to 30 m offset range and fully populated offset classes for the larger offsets.

The two configurations are meant for illustration purposes only. Final solutions must be tailored depending on survey objectives such as spatial resolution and the sampling requirements of the nearest offsets which is determined by the water depth. First 3D site surveys based on this method have been acquired already and others are in planning. These case studies will be subject of future publications.

## Conclusions

The energy transition has increased the demand for high- or ultra-high resolution 3D seismic solutions to image shallow targets. Combining the wide-tow multi-sources method with high-density streamer spreads enables cost-effective acquisition of 3D seismic data with good coverage of the nearest offsets and dense spatial sampling. The concept was successfully proven in marine seismic exploration surveys acquired in the Viking Graben and the Hammerfest Basin. These novel surveys delivered high-quality images of the near surface just below the seabed without the acquisition footprint typically caused by the lack of near offsets.

The same survey design method can be utilised for high-resolution 3D studies for CCS site characterisation, or offshore wind farm site surveying. As near-surface seismic or seabed mapping in shallow water requires recording of seismic data with close-to-zero offset, the inline distance between sources and streamers can be minimised by moving the sources over the front end of the streamer spread as demonstrated in a novel quad-source acquisition over the Northern Endurance CCS structures. We have also illustrated how a down-scaled configuration (P-cable in the combination with the wide-tow multi-source method) can deliver ultra-high resolution seismic with spatial sampling in the one-metre range and thus become a commercially viable 3D solution for offshore windfarm site investigations.

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