Harnessing 3D ultra-high-resolution seismic technology for offshore wind farm development: Advancements, challenges, and future prospects

Bertrand Caselitz[1], Allan McKay[2], Martin Widmaier[2], Julien Oukili[2], Daniel Davies[3], and Noemie Pernin[1]

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Abstract

The global transition toward renewable energy has intensified the demand for more offshore wind power generation. Advanced geophysical techniques to enhance near-surface site characterization and ensure the rapid, safe, and efficient installation of wind turbines are of considerable value. Traditional 2D ultra-high-resolution seismic (UHRS) methods, while useful, generally lack the resolution and spatial coverage required for modern offshore projects. Depending on the requirements, 2D surveys are often acquired over multiple years. In contrast, 3D UHRS technology, acquired in a single campaign, provides detailed and comprehensive subsurface data, significantly improving the reliability of ground models. This article highlights the value of 3D UHRS technology in offshore wind farm development, demonstrating the importance of an integrated approach to survey design, acquisition, and data processing and how this enhances subsurface imaging, reduces uncertainties, and supports more informed decision making. The technology's ability to capture volumetric data across an entire survey area or along corridors allows for the accurate mapping of critical geological features, such as key soil units and hazardous objects (e.g., shallow gas and boulders). The expanded 3D UHRS volume offers flexible options for adjusting turbine locations if any anomalies are detected at the initial sites. Furthermore, 3D UHRS subsurface data provide the reliable framework required for quantitative interpretation, particularly in predicting soil properties, thereby optimizing foundation designs and reducing the need for extensive geotechnical investigations. Most importantly, an integrated 3D UHRS solution can reduce the time required for new wind farm developments to become fully operational and deliver clean energy to consumers.

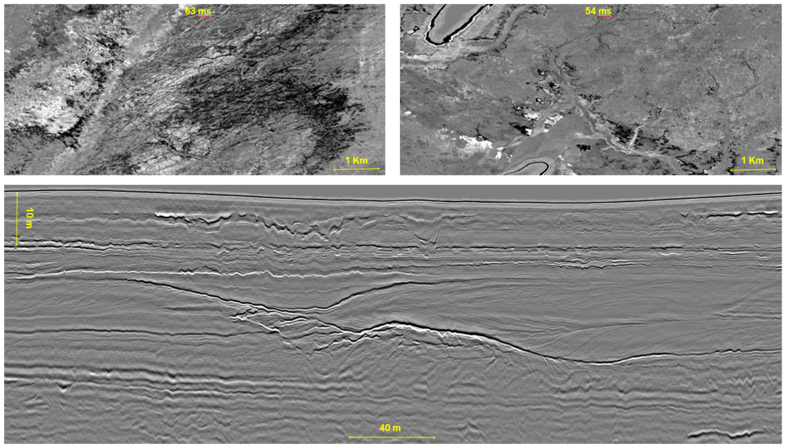

Figure 1. Three-dimensional migrated stack: two time slices on the top and a section at the bottom.

Introduction

The global push toward renewable energy sources, especially offshore wind, has necessitated the use of advanced geophysical techniques for site characterization. Not only are the number of offshore wind farm projects significantly increasing, but their areal extent is also increasing. Offshore wind developments require detailed knowledge of the subsurface, known as a ground model, to ensure the structural integrity and longevity of wind turbines and their foundations. The complexity of the near-surface environment, coupled with the need for rapid and accurate assessments, has driven the development and application of 3D ultra-high-resolution seismic (UHRS) technology.

Traditional 2D seismic methods, while useful, often lack the resolution and spatial coverage required for modern offshore projects. As wind developments grow in size and number, the limitations of 2D surveys, such as incomplete subsurface images and lower resolution, become increasingly apparent. In contrast, 3D UHRS surveys offer the ability to comprehensively characterize subsurface structures, properties, and potential hazards, enabling more reliable and robust site assessments (Figure 1). The continuous 3D data set offers more accurate interpretation of the soil units compared to a 2D data set. Additionally, it facilitates the detection of small-scale features like boulders or shallow gas pockets that could pose significant risks during turbine foundation work and any geotechnical sampling. A 3D UHRS volume is expected to deliver high-quality input data that enable more detailed quantitative interpretation (QI), aiding in the estimation of soil properties and the development of a comprehensive ground model (Figure 2). By providing the ability to assess soil properties and their variability across a site in 3D, this approach could potentially optimize geotechnical sampling and investigations and may even help reduce the scale and duration

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[1]TGS UK, Weybridge, UK. E-mail: bertrand.caselitz@tgs.com; noemie.pernin@tgs.com.
[2]TGS Norway, Oslo, Norway. E-mail: allan.mckay@tgs.com; martin.widmaier@tgs.com; julien.oukili@tgs.com.
[3]TGS USA, Houston, Texas, USA. E-mail: daniel.davies@tgs.com.

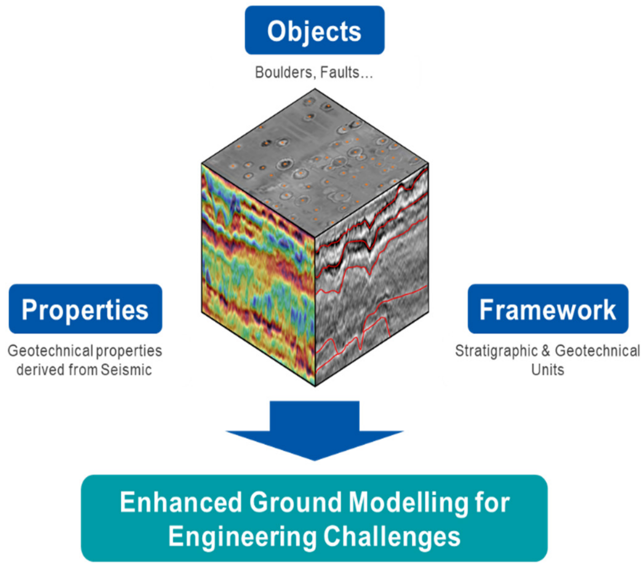

Figure 2. Three-dimensional UHRS applications: objects detection, geological interpretation, and soil properties estimation.

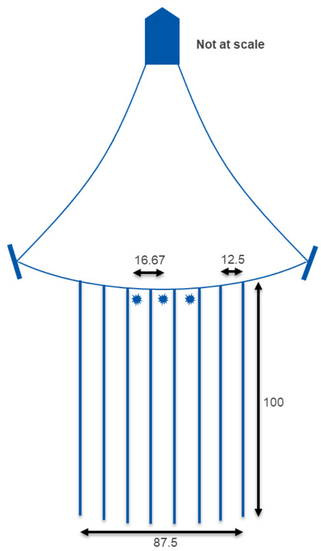

Figure 3. Acquisition layout (unit in meters).

of traditional geotechnical surveys, which are often extensive, time consuming, and costly.

While 3D UHRS surveys generally require a higher initial investment compared to 2D surveys, they can be more cost effective in the long run, particularly in complex areas. The comprehensive data provided by 3D UHRS technology reduce the need for additional surveys, potentially lowering overall project costs. Additionally, the ability to acquire complete coverage in a single survey reduces the time required for data acquisition and interpretation, helping to keep projects on schedule. In offshore wind farm development, where timelines are often tight and any delays can have significant financial implications, the time efficiency offered by 3D UHRS technology is a considerable advantage. By providing a more complete and accurate subsurface image, a 3D UHRS data set enables faster and more confident decision making, reducing the likelihood of delays during the construction phase.

This article focuses on 3D UHRS technology, from survey design to QI, including acquisition and imaging. We will discuss the achievements and challenges in setting up this solution and explore the opportunities that 3D UHRS technology presents for improving and accelerating offshore wind farm development projects.

Survey design and acquisition

The goal of survey design is to find the optimal acquisition parameters that meet the geophysical and geological objectives while reducing survey turnaround time. Site characterization of the near surface generally requires 3D UHRS data with a horizontal bin size of approximately 1–2 m and a vertical resolution less than 50 cm. Offshore wind surveys are mostly located in shallow water, making near-zero-offset data important to achieve the desired resolution. In the recent past, 3D UHRS survey designs did not allow for the acquisition of large 3D surveys in a time- or cost-efficient manner. Davies and Rietveld (2020) explained that it took six days to acquire 1 km^2 of UHRS data with an acquisition bin size of 0.5 × 2 m because 118 sail lines were needed to cover the area. It is clear that this kind of design is not viable for area sizes commonly used in offshore wind projects, where a typical 3 GW wind farm license may cover more than 500 km^2, as it would take a year to acquire 60 km^2.

Building on experiences gained in seismic survey design for oil and gas and carbon capture and storage, the use of wide-towed multisources, in combination with a large number of streamers (Widmaier et al., 2023), enables the acquisition of 3D UHRS data in a time-efficient manner. Increasing the number of sublines per sail line and speeding up the vessel should enable larger areas to be acquired in less time. Thus, the strategy should be to use the largest number of streamers and sources possible. Operational and geophysical limitations must be addressed to ensure that near-offset requirements, clean record, and desired spatial sampling are met. Figure 3 shows an acquisition layout with eight streamers separated by 12.5 m and three multilevel sparker sources, achieving a bin size of 1.56 × 2.08 m. This layout has been used to acquire approximately 600 km^2 in a a single campaign (Caselitz et al., 2024). The sources were fired sequentially at intervals of 250 ms. The nominal source and receiver depths were 30–60 cm and 3 m, respectively. It is the largest full 3D UHRS survey ever conducted, taking less than 130 production days to complete.

To acquire uniformly distributed near-offset data, the three sparkers were towed in a wide-tow source configuration above the front end of the streamer spread. Figure 4 highlights the sampling in offset coverage in the crossline direction. The figure shows that this acquisition setup is expected to provide sufficient input data sampling to allow for reconstruction using 4D regularization (inline × crossline × offset × time), even with small gaps in the near-offset sampling. Streamer lengths of 100–150 m are generally used in conjunction with fast-firing sources (typically 200–250 ms pop intervals) to build up fold coverage and improve the signal-to-noise ratio of the final processing products. Despite the relatively short streamers and therefore offset ranges, these acquisition configurations often provide sufficient incidence angles to support prestack QI work.

Acquiring 3D UHRS data presents several challenges, particularly in terms of maintaining data quality in variable sea conditions. During UHRS surveys, streamers are towed close to the sea surface, usually at a depth of 1 m or less. By towing the streamers deeper, down to 3 m, we were able to collect data even in relatively rough sea conditions, significantly reducing weather-related downtime. Another challenge associated with 3D UHRS acquisition is the need for accurately positioning data, both spatially and vertically. Given the fine spatial resolution of the seismic data, even small positioning errors can lead to significant misalignments in the final seismic images. To address this, the survey is equipped with advanced GPS systems, and streamer positions are continuously monitored using acoustic positioning devices.

To achieve an extremely high vertical resolution, electric sources such as sparkers and boomers are used. These sources emit signals at very high frequencies but lack low frequencies below 100–150 Hz, which limits signal penetration. This is not generally a concern as the zone of interest for offshore wind farm development lies within the first 50–100 m below the seabed.

Depending on the wind farm development stage and/or budget constraints, a 3D UHRS survey may cover the entire area or focus on narrow 3D corridors that are aligned with the preliminary turbine locations. Given the importance of time-efficient solutions in accelerating offshore wind farm development, recent surveys have incorporated additional geophysical measurements such as multibeam echosounders, subbottom profilers, magnetometers, and side-scan sonar. These supplementary data can be collected simultaneously with the seismic campaign.

To enable the processing team to begin work immediately after acquiring the first sail line, raw seismic shot gathers are continuously streamed to the cloud via low-earth-orbit satellites. It is important to note that the 3D UHRS data volume is substantial due to the small spatial and temporal sampling intervals, necessitating the use of high-performance computing (HPC) for processing. For a given area size, 3D UHRS surveys are typically 5 to 10 times larger than standard oil and gas exploration surveys.

Data processing

The typical processing workflow for 3D UHRS data closely resembles the one used for oil and gas seismic data, incorporating steps like denoise, signal processing, demultiple, regularization, and migration. This enables the processing flow to take advantage of the technological advancements made in recent years including broadband processing. However, due to the fine sampling interval (e.g., 0.125 ms), variations in sea height are captured in the data with high precision, presenting challenges during processing. Wave heights as little as a few decimeters, significantly affect key steps such as deghosting, sea surface statics, and demultiple. One advantage of sparker and boomer sources is that they do not emit frequencies below approximately 100 Hz. This means that swell noise attenuation is not a concern, as this type of noise does not interfere with the signal. Access to HPC resources is essential for processing high-density and small sampling rate 3D UHRS data in a timely manner.

Deghosting. Receiver-side deghosting is particularly challenging due to the high-frequency content of 3D UHRS data and variations in receiver depth caused by sea state variations. The deghosting process involves estimating the receiver depths in local time-slowness windows using an inversion-based methodology. This approach accounts for the variations in receiver depth and optimizes the deghosting process in the frequency domain, resulting in a clearer and sharper seismic signal (Bekara et al., 2024).

Source-side deghosting, while less challenging, also requires careful attention. The sparker or boomer units are suspended from floating devices, which naturally follow the sea surface, maintaining a consistent depth. This setup ensures that the source ghost notch frequencies remained stable across the survey, allowing for a deterministic approach to be used effectively. It is important to note that for multilevel sources, deghosting is addressed simultaneously with the designature, as the effects of source ghosts are minimized during the shot firing.

Given the computational intensity of inversion-based deghosting, a machine learning (ML) alternative has recently been introduced that delivers comparable quality results much more quickly. This solution employs a convolutional neural network akin to the one developed by Farmani et al. (2023) to denoise raw shot gathers. Figure 5 shows a common-midpoint (CMP) stack comparison between input, inversion-based receiver deghosting, and ML receiver deghosting. In this example, the nominal source depth is 0.3/0.6 m and the receiver depth is 3 m. This deghosting

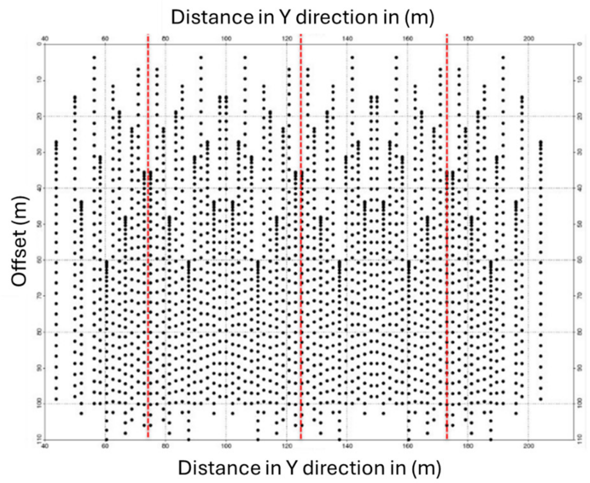

Figure 4. Offset coverage for three sail lines. The center of the sail lines corresponds to the red dashed lines.

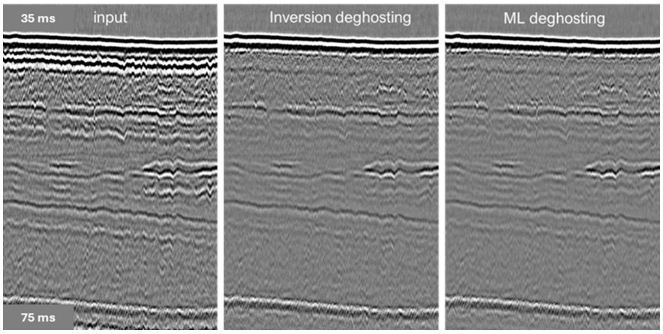

Figure 5. Premigration stack comparison: deghosting.

result shows that streamers can be towed at greater depths than previously expected, leading to reduced weather downtime and improved signal-to-noise ratio data.

Designature. Designature involves shaping each source signature to a common broadband zero-phase wavelet to eliminate variations between shots and sail lines. This step is essential for enhancing the resolution and consistency of the seismic data, providing a robust platform for future interpretation work. Source signatures are estimated from the seismic data on a shot-by-shot basis using high-order statistics, as described by Bekara (2021). This method offers the advantage of not requiring alignment with the water-bottom reflection, which is particularly challenging in the presence of sea surface statics. Additionally, source directivity compensation is applied using modeled notional signatures, resulting in enhanced resolution by harmonizing the wavelet across emission angles and azimuths. Figure 6 shows on CMP stack the successive changes associated with applying receiver deghosting, source deghosting, and designature, with a clear enhancement of the data in the shallow section.

Sea surface statics. Statics arise from sea state variations. In 3D UHRS surveys, statics correction is essential, as even minor changes in source and receiver elevation relative to the seabed can cause major time misalignments. The source tends to follow the sea surface, while the receiver, usually towed at greater depth, is affected by a combination of sea heights, currents, and vessel speed. Statics correction, derived from water-bottom reflections compared with simultaneous multibeam echosounder data (MBES; bathymetry data from the same seismic vessel) and receiver depths estimated during the deghosting step, compensate for sea surface variations. After applying statics correction, the data are redatumed and aligned with the bathymetric reference datum, taking tidal time variations into account. This ensures that the final 3D volume aligns with the measured bathymetry and delivers continuous seismic events throughout the data set. Figure 7 illustrates on CMP stack how the water bottom appears more continuous and flat following the application of sea surface statics.

Demultiple. Demultiple processing removes unwanted reflections that can mask primary seismic events. The workflow combines 3D surface-related multiple elimination and 3D wave-equation multiple modeling (Barnes et al., 2015) to create accurate multiple models. These models are then subtracted from the data, enhancing clarity.

Challenges arise during subtraction due to sea surface statics. Wave height variations affect multiples nonlinearly compared to primary events. To address this, the adaptation process allows for larger time-shift corrections in longer (time) and narrower (space) windows. This premigration demultiple step effectively eliminates water-bottom reverberations and peg-leg multiples, even in noisy areas with weak primary signals, as illustrated in Figure 8.

Imaging. Following the demultiple process, the data undergo 4D regularization, which involves reconstructing well-populated offset classes from the acquired data. This step is particularly important in 3D UHRS surveys, where

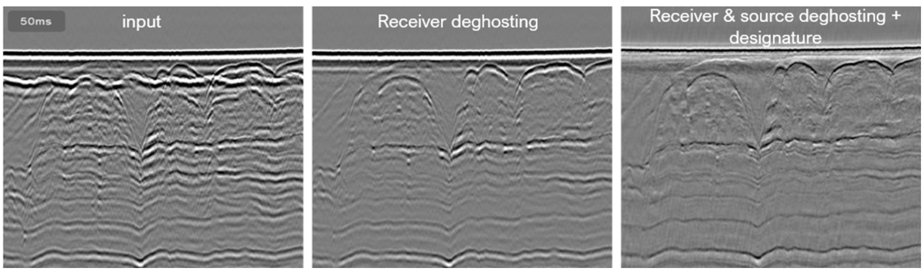

Figure 6. Premigration stack comparison: deghosting and designature.

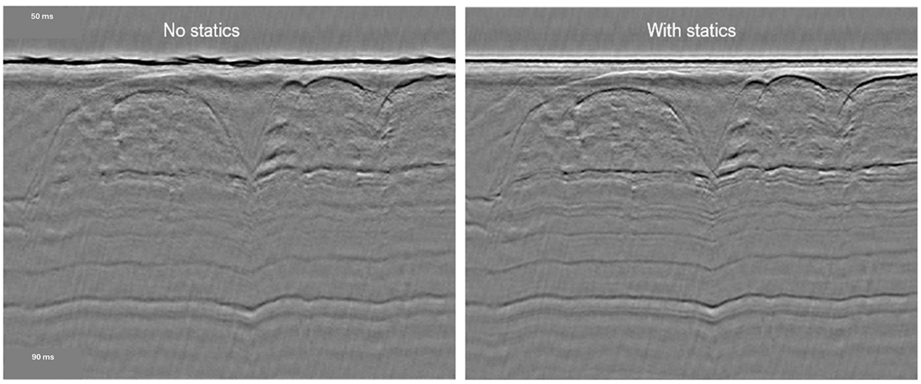

Figure 7. Premigration stack comparison: statics.

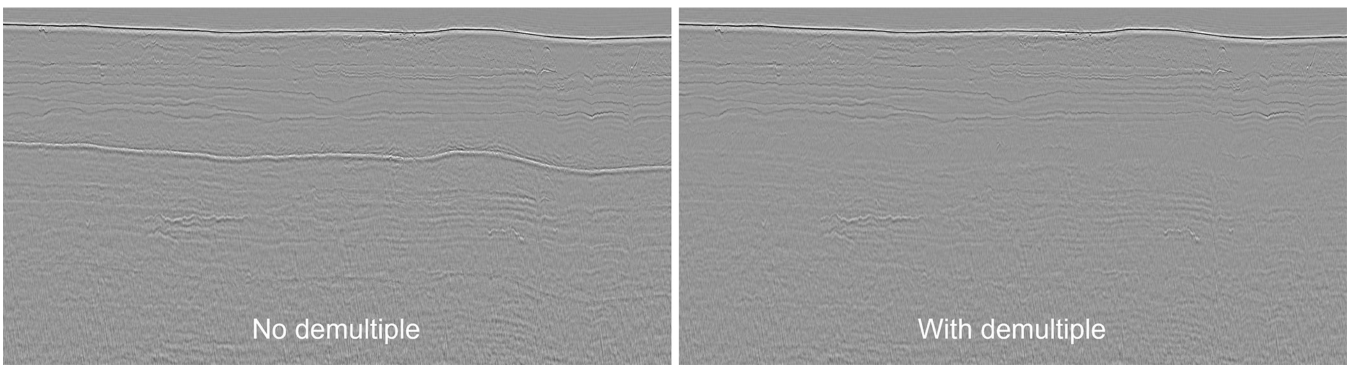

Figure 8. Migration stack comparison: demultiple.

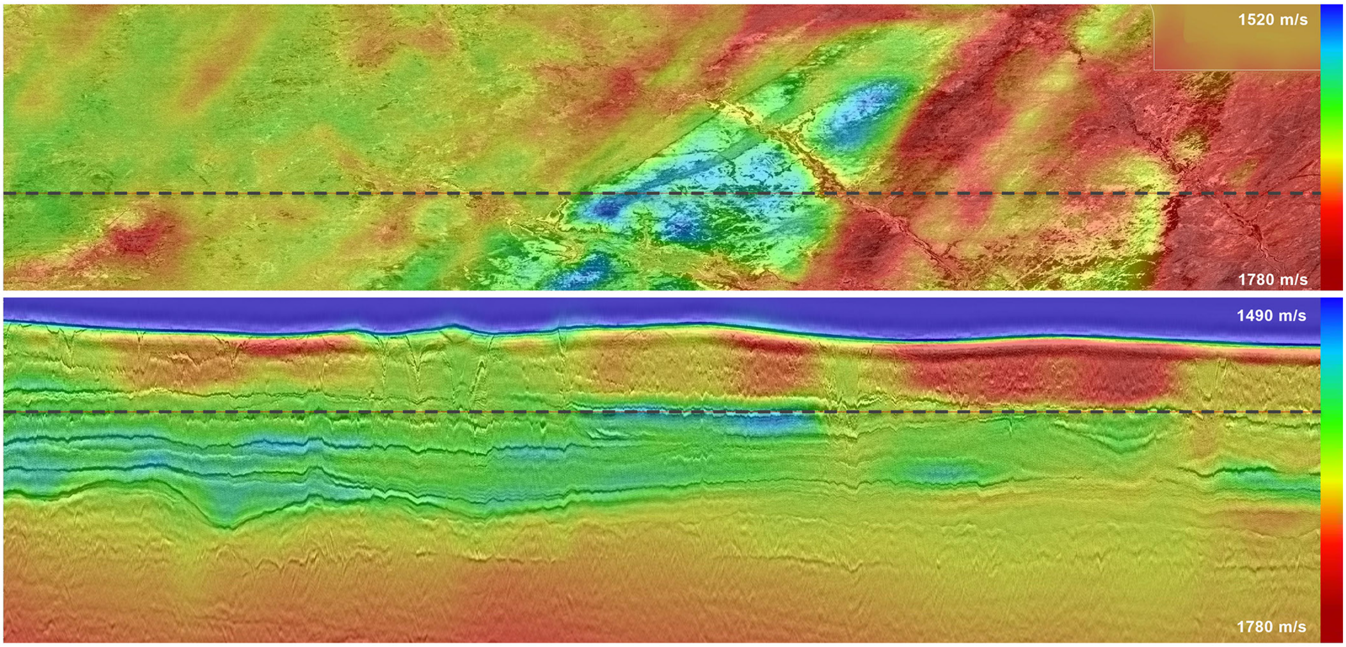

Figure 9. Migration velocity model rendered on migrated stack. The dashed line shows the location of the depth by time slice and the section.

dense spatial sampling can lead to data gaps if not properly regularized. The regularization process utilizes an antialias antileakage Fourier transform (Schonewille et al., 2009) to ensure high-fidelity reconstruction of the seismic signal.

The final stage of the processing workflow involves 3D Kirchhoff prestack time migration, which is critical for accurately positioning and focusing the seismic wavefield. The migration process helps correct for the effects of dipping reflectors and other geological features, leading to improved interpretability of the seismic data. Velocity model building is an integral part of the imaging process. The initial velocity model is generally derived from geotechnical P-wave velocity logs, when available, and refined through iterative residual moveout (RMO) picking. The automated RMO picking is performed on a dense grid, ensuring that the velocity model accurately represents the geological structure of the survey area. The final velocity model is then used to guide the migration process, resulting in a high-resolution 3D seismic volume. Figure 9 shows a migrated stack (time section and time slice) with the velocity field overlaid. The velocity field correlates well with the geological structures.

Limonta et al. (2024) demonstrate that a 3D broadband processing workflow significantly improves vertical and spatial resolution over a vintage 2D UHRS processing data set, where reflections are frequently mislocated and diffractions remain visible.

Although the current migrated product is of high quality, future imaging enhancements could be made by migrating the data in the depth domain with a UHRS velocity model. This would provide a more reliable product for direct interpretation in the depth domain. The velocity model could potentially be developed using techniques like full-waveform inversion (FWI) (Ryan et al., 2024). When available, legacy conventional oil and gas seismic data can be utilized to build the background velocity model. Additionally, other imaging methods, such as imaging with multiples (Lu et al., 2014) and least-squares migration, could further enhance spatial and temporal resolution.

Geological interpretation

Geological interpretation is essential for constructing a ground model. Access to continuous 3D UHRS volumes offers a significant advantage over a grid of 2D UHRS data when it comes to interpretation. The primary goals of interpretation are to identify key soil units, map structural features, and detect potential geohazards such as gas pockets, subsurface voids, or unstable layers. In cases of shallow gas, this information is often required at the start of a geotechnical campaign. Therefore, beginning interpretation as soon as UHRS acquisition starts is crucial. An ultra-fast-track migrated 3D UHRS volume can be progressively built while data are still being acquired.

With 2D UHRS data, interpretation is a labor-intensive manual process. Applying this same approach to 3D UHRS data would be inefficient and could take months to complete. To ensure timely interpretation, semiautomated and fully automated methods should be employed. Pauget et al. (2009) describe a technology that enables global geological modeling while offering users a degree of control. While ML techniques are expected to facilitate this process on 3D UHRS data, we are still in the initial stages of their development.

Quantitative interpretation

One of the most promising applications of 3D UHRS data is in the field of QI, particularly for predicting soil properties. Accurate soil property prediction is crucial for the design and installation of wind turbine foundations, as it directly impacts the stability and longevity of the structures. Traditional methods of soil property estimation often rely on extensive borehole data and cone penetration tests (CPTs), which can be time consuming

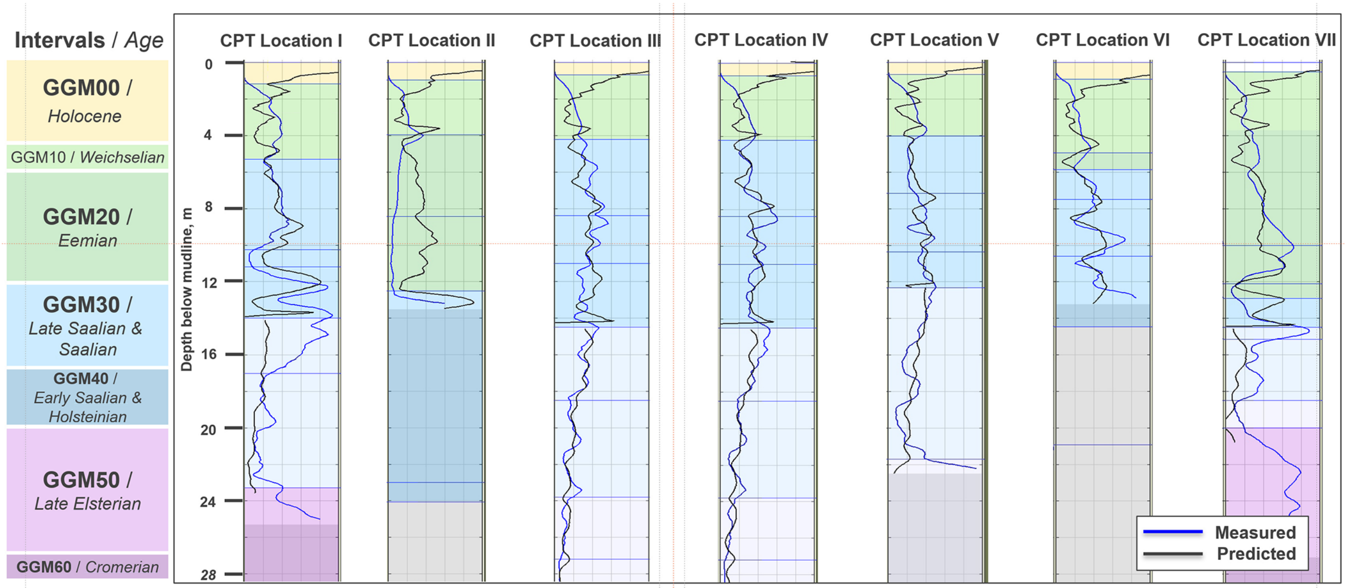

Figure 10. Measured and predicted cone resistance profiles at seven CPT locations from the Ten Noorden van de Waddeneilanden Wind Farm Zone.

and expensive. However, integrating 3D UHRS data and geotechnical data into QI workflows offers a more efficient and potentially more accurate alternative. This could also lead to a reduced and more focused geotechnical campaign. The use of certain attributes, such as RGB decomposition and coherency volumes, is generally valuable to QC the interpretation work.

Data-driven soil property prediction. Our data-driven workflow for predicting soil properties using 3D UHRS data involves several key steps. First, the seismic reflectivity and velocity data obtained from the 3D UHRS survey are used to derive acoustic impedance, which is then correlated with CPT measurements for key soil units. This approach allows for the prediction of soil properties, such as cone resistance, across the entire survey area, even in locations where CPT data are sparse or unavailable.

The value of this approach lies in its ability to provide detailed variations in soil properties at the resolution of the 3D UHRS data volume. By leveraging the dense and high-quality data provided by 3D UHRS technology, geophysicists can create more quantitative and reliable ground models, reducing the need for extensive CPT campaigns and potentially lowering project costs. Furthermore, the ability to predict soil properties across a large area allows for better planning and optimization of turbine foundation designs, ensuring that they are tailored to the specific conditions at each site.

The 3D UHRS poststack data from the Ten Noorden van de Waddeneilanden Wind Farm Zone has effectively demonstrated the method's capabilities (Polyaeva et al., 2024). The predicted cone resistance was validated against measured CPT data, and, as shown in Figure 10, the two profiles align well, even in geologically complex areas. Figure 11 illustrates the cone resistance attributes rendered onto the seismic section, interleaved with the CPT profile, further confirming the strong correlation between predicted and measured values. Additionally, the predicted cone resistance provided a continuous 3D UHRS volume, enabling the development of a more quantitative ground model. Compared to traditional 2D UHRS predictions, the 3D UHRS approach delivers more detailed and accurate results, particularly in capturing small-scale variations in soil properties.

Opportunities with QI. To derive soil properties such a *Gmax* (small strain modulus), it is essential to move from acoustic to elastic inversion and estimate shear velocity and density. This requires a sufficient range of incidence angles in the prestack domain and consistent high quality across near-, mid-, and far-angle stacks. Hence, having "long offset" is important. This approach is currently in the proof-of-concept stage, and if successful, it could significantly impact how geotechnical surveys are executed during offshore wind development projects.

Future directions and technological advancements

The application of 3D UHRS technology in offshore wind development is still evolving. As demand for renewable energy grows, further advancements in seismic acquisition, processing, and interpretation techniques will be crucial to meeting the industry's needs. Several key areas of development are likely to enhance the 3D UHRS capabilities in the future.

Enhanced acquisition technologies. Advances in seismic source and receiver technology will continue to drive improvements in data quality and resolution. Having an acquisition geometry where sources are located at the front end of each streamer would provide regular near-zero-offset data. However, this would imply the use of deblending techniques that are able to clean overlapping shot records.

Acquisition setup incorporating an air gun, could supply the lower frequencies that are lacking in the UHRS data. Furthermore, achieving longer offsets is possible by deploying ocean-bottom nodes on the seabed and/or using longer streamers. This combination should provide suitable data quality to derive a reliable velocity model.

Specialized acquisition methods can be employed to record shear waves or to focus on boulder detection. However, it is essential to consider that these techniques may increase both the cost and duration of development projects.

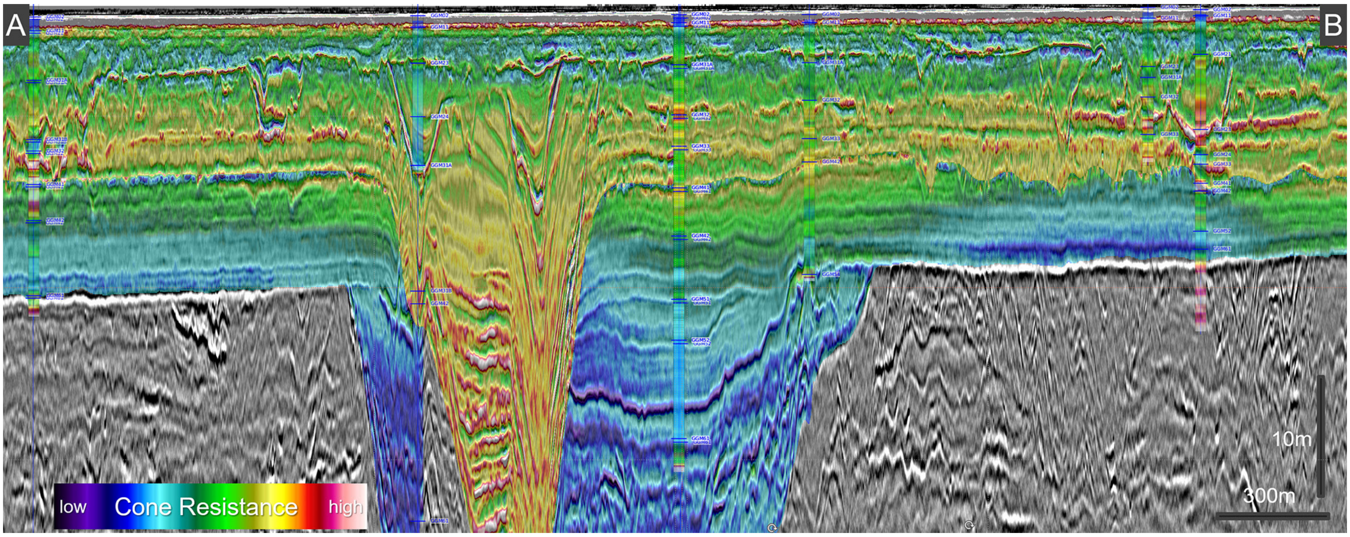

Figure 11. Cone resistance property derived from 3D UHRS migrated stack rendered on the seismic cube interleaved with the measured cone resistance from six CPTs from the Ten Noorden van de Waddeneilanden Wind Farm Zone.

The development of autonomous vessels equipped with seismic sensors presents opportunities for improving the efficiency and coverage of 3D UHRS surveys, especially in areas where traditional survey vessels are limited by obstacles and/or environmental constraints.

ML and AI in processing. The use of ML and artificial intelligence (AI) techniques in UHRS data processing is rapidly gaining traction. These methods have the potential to significantly accelerate the processing project turnaround time. By training ML algorithms on a wide selection of 3D UHRS data sets, it is possible to automate the key steps of the entire seismic processing sequence.

AI-based tools can also be used for feature recognition in seismic data, such as detecting boulders, gas pockets, or faults, which can be time consuming when performed manually. These automated methods not only speed up the interpretation process but also reduce human bias and increase the consistency of results. Finally, ML technology could play a significant role in generating reliable transfer functions between geophysical and geotechnical attributes.

Advanced inversion techniques. The prestack inversion techniques will focus on delivering even more reliable and accurate models of subsurface geotechnical properties. Advances in elastic inversion algorithms will enable more accurate predictions of parameters such as porosity, shear velocity, and density, which are essential for assessing soil stability and foundation integrity. These high-resolution models will provide developers with greater confidence in their site assessments and reduce the need for extensive ground truthing through boreholes or CPTs.

Moreover, improvements in FWI techniques, which utilize the entire seismic wavefield, will allow for the extraction of finer details from 3D UHRS data sets. FWI has already shown significant quality uplift in oil and gas exploration, and its application in offshore wind farm development could lead to a step change in the accuracy of subsurface imaging.

Integration with other geophysical methods. Integrating 3D UHRS surveys with other geophysical methods will become increasingly important for comprehensive site characterization. Techniques such as controlled-source electromagnetics (CSEM), marine magnetics, and high-resolution bathymetry can complement 3D UHRS data, providing additional information on subsurface properties that are not easily detected by seismic methods alone.

For example, integrating CSEM data with 3D UHRS data can help identify variations in sediment conductivity, which is useful for detecting gas hydrates, shallow gas, or fluid migration pathways. Similarly, combining seismic data with high-resolution bathymetric and multibeam echosounder data can provide a more complete picture of the seafloor's morphology, which is critical for assessing potential seabed hazards and optimizing turbine foundation designs.

Conclusion: The future of offshore wind farm development with 3D UHRS technology

As the offshore wind industry continues to grow, the role of 3D UHRS technology in supporting sustainable and efficient wind farm development will become even more significant. The ability to provide detailed high-resolution 3D images of the shallow subsurface will remain critical for optimizing turbine placement, minimizing environmental impacts, and reducing geotechnical risks.

Looking forward, advancements in acquisition technology, data processing, and QI will enhance the 3D UHRS capabilities and ensure that it remains a key tool in the development of offshore wind farms. The integration of AI, ML, and other geophysical methods will allow for more efficient workflows and deeper insights into subsurface conditions, while ongoing efforts to reduce the environmental footprint of seismic surveys will contribute to the industry's sustainability goals.

By continuing to innovate and refine 3D UHRS technology, the offshore wind sector can accelerate the global transition to renewable energy, driving down costs, improving project safety, and supporting the delivery of clean energy to millions of homes and businesses worldwide. With the combination of high-quality data and innovative technology, 3D UHRS technology is poised to play an essential role in the future of renewable energy development. TLE

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Data and materials availability

Data associated with this research are confidential and cannot be released.

Corresponding author: bertrand.caselitz@tgs.com

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