Recent experiences of using UHR3D for site characterisation in offshore wind farms

Bent Kjølhamar[1]*, Alexander Smith[1], Allan MacKay[1], Luca Limonta[1] and Roberto Ruiz[1] present new experiences using UHR3D data that enable geohazards and two dimensional features to be better understood and more accurately imaged.

Introduction

Geophysical technologies and workflows analysing multi-sensor data in the shallow subsurface for marine wind turbine installation are in rapid development. It is now possible to acquire all relevant sensor data simultaneously together with Ultra High-Resolution 3D data in a single pass integrated geophysical survey (Caselitz et al. 2025 & McKay et al. 2025). Seismic UHR3D data is a relatively new addition to the otherwise 2D dominated subsurface interpretation workflows utilised in offshore wind. This paper will present new experiences using UHR3D data over the classical UHR2D-based workflows. Especially geohazards like boulders, shallow gas, and sand channels are obvious, but also two-dimensional features like iceberg scour marks or faults are now better understood and structurally more accurately imaged.

The top 100 m below the seafloor, and typically at high latitudes with strong glacio-marine influence, is of super complex geology with short-lived structure and small-scale facies changes in sedimentology. As seen in recent UHR3D data, many important features and sedimentological facies changes are seen over just 100 m laterally. Therefore, the soil unitisation models defined in Integrated Ground Models (IGM) are evolving in both their detail and complexity. Often, we have a chaotic and non-reflective seismic facies where geo-technical (Geotech) measurements indicate distinct soil stiffness changes. Furthermore, the Geotech data and the seismic data, especially UHR2D, often have poor depth matching, requiring manual vertical shifts to one or the other. This makes the ground modelling work complex and time-consuming. UHR3D seismic data with highly resolved P-wave velocity volumes and depth imaging methods enable better depth correlation between the 3D seismic and geotechnical data. In addition, the 3D P-wave velocity volumes themselves offer new volume-based approaches discussed in this article.

Floating iceberg dropped boulders and iceberg scour marks are a topic that 3D seismic data has shed new light on. In both 3D time-slice and along 3D interpreted horizons, iceberg scour marks are easily seen and classified as such. Using Sub-Bottom Profiler (SBP) data, the two-dimensional image of scour marks has a close resemblance to a point diffractor or boulder and may be misinterpreted in the absence of 3D data (Limonta, et al., 2025). From UHR3D data, a diffraction imaging volume can be used to interpret migrated boulder diffractions and be used to distinguish robustly between point features such as boulders and other geological structures.

New volume-derived interpretation approaches

We have found that traditional interpretation workflows are not well-suited to using UHR3D seismic data. For example, carefully picking time equivalent base or top of ground units, using incremented inline and crossline guide picks together with current 3D auto-trackers often disappoint and fail. The use of geo bodies, where we have seismically well contrasting

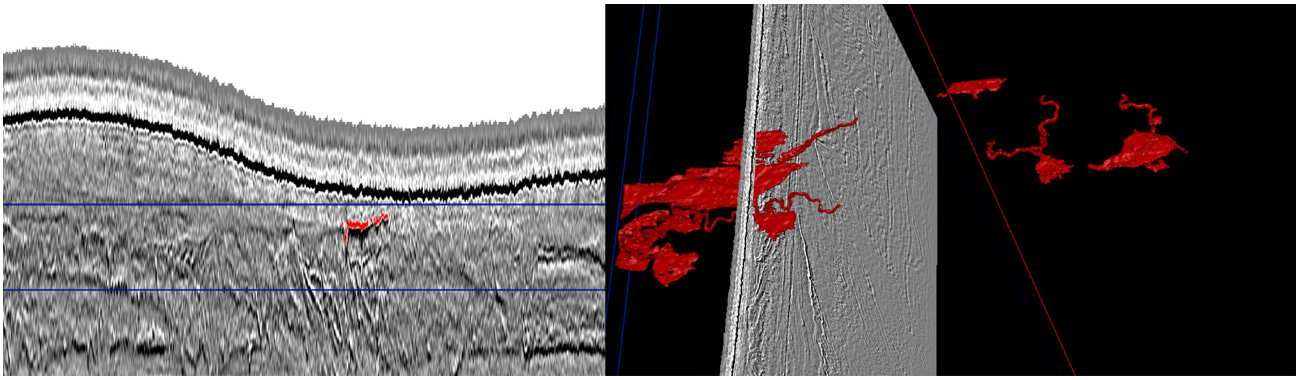

Figure 1 Geo bodies of presumed peat in red defined by high negative amplitude, soft anomaly (red), (Data: RVO_UUHR_3D_IJ56).

[1] TGS

* Corresponding author, E-mail: Bent.Kjolhamar@tgs.com

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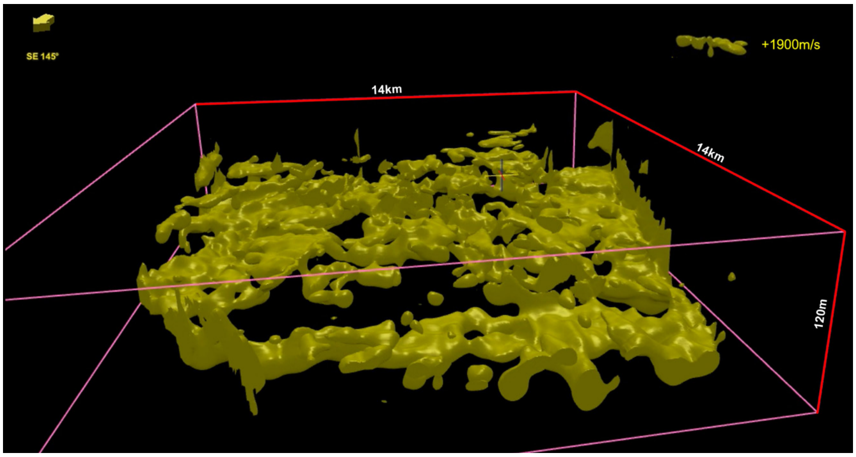

Figure 2 P-wave velocity from a UHR3D production processed PSTM velocity dataset, where high-passed 1900m/s interval velocity is seen as yellow geo bodies.

events like gas pockets, channel sands, peat, or bedrock, is recommended over traditional horizon picking (Figure 1). Utilising UHR3D pre-stack timemigrated (PSTM), or pre-stack depthmigrated (PSDM) interval velocity as a soil stiffness model can also make use of geo-body extractions (Figure 2). Here, a survey-wide extraction of higher P-wave velocity anomalies, likely caused by glacio-marine processes, can be displayed in a 3D view or overlaid on stacked 3D seismic data. Captured geo bodies of high or low amplitude events, like boulders, gas or soil stiffness models defined by UHR3D velocities, can then be exported as SEGY data, surface extents as shapefiles, or exported as a horizon snapped down from a seafloor horizon to the geo bodies below. The geo body extraction tools also need further development to be optimised for UHR3D data, and the need is seen for the shallow surface. Still, the geo body outputs are focused, precise, and time-efficient to produce in UHR3D data.

Recent studies show that Quantitative Interpretation (QI), based on inversion of geotechnical measurements and wireline well logs, offers an effective means of integrating geotechnical and seismic data. By using geotechnical information to constrain and calibrate the seismic inversion results, this approach enables optimised soil unitisation despite sparse geotechnical coverage (Polyaeva et al., 2024, and Ruiz et al., 2025). Another approach suggested here and indicated by Limonta et al., 2025 is to use high-resolution velocity models estimated using traditional tomography or more advanced Full Waveform Imaging (FWI) approaches on UHR3D datasets. Our recent experience is that a 3D seismic P-wave velocity volume is by itself a robust way of estimating sediment stiffness and strength variations in chaotic soft mud-dominated units affected by likely glacio-marine processes such as icesheet pushing the sediments (push-moraines), or ice sheet loading effects compressing and dewatering the muddy soils (Figure 3, 9, and 10). Figure 3 shows an example of where there is no distinct seismic reflection to define a slight soil stiffness increase indicated by the geotechnical data, but the soil stiffness change correlates well with a change in interval velocity. In addition, having high-quality and well-resolved

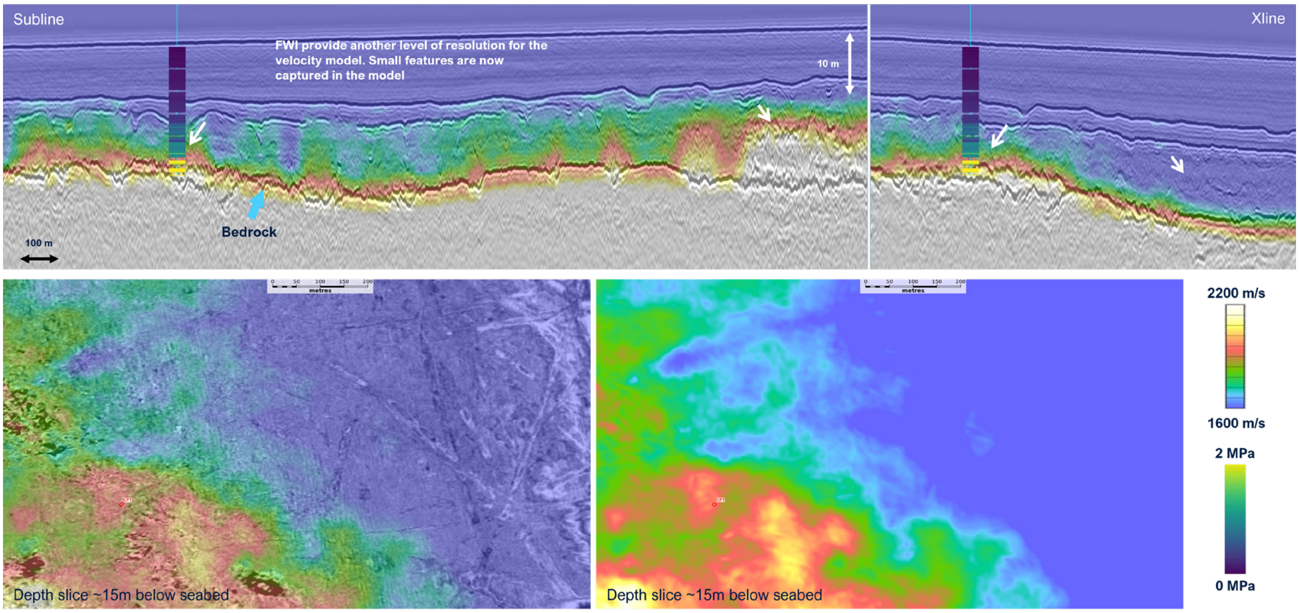

Figure 3 Enhanced-resolution PSDM interval velocity overlaid on UHR3D reflection data in inline, crossline and depth slice views (position of lines presented as dotted lines), centred around a cone penetration test (CPT) location. The corrected cone resistance (qt) log is displayed at the CPT position, where increased seismic velocity correlates with increased qt, while no laterally continuous reflector is observed.

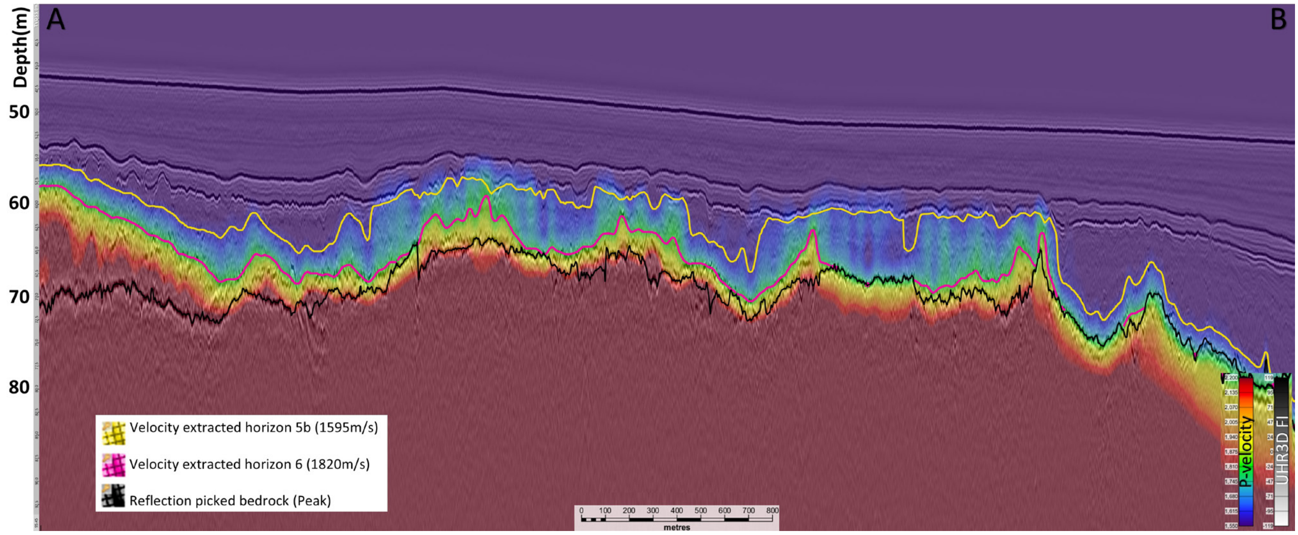

Figure 4 Two iso velocity horizons derived from a PSDM P-wave velocity volume (Nisa) that match well with two ground units (GU) defined by 12 CPT locations within the Nisa UHR3D area (CPT defined GU2=1595m/s, GU3=1820m/s).

pre-stack depth migration (PSDM) velocity volume will also further increase the quality of QI results by presenting a better, higher-resolved background start model, as shown by Ruiz and Limonta, 2025.

NISA UHR3D: A testing ground for new interpretation workflows

Within the soft mud-dominated pre- and post-Quaternary soils at NISA in the East Irish Sea, the primary foundation solution for the wind developer was bedrock piling or, alternatively, bedrock drilling, which is more expensive. However, early in the 3D seismic interpretation workflow, it was apparent that there is most likely little deeply weathered bedrock, and a piling solution exploiting weathered bedrock therefore vanished. Stiffer mud-dominated units – poorly defined using seismic reflections alone but defined by geotechnical data – were raised as a possible soil unit for foundation placement. Mapping two slightly stiffer ground units (GU 2 & 3) was not an easy task, as no strong continuous reflector could be used in the middle of a chaotic facies. A glance at the PSTM production velocity against the Geotech ground units found the solution. Approximately 1600m/s gave a good tie with a narrow spread against GU2 in all twelve Cone Penetrometer Test (CPT) locations spread across the site area. With a thorough QC of the available CPT data, we found that 1595m/s had the best correlation to GU2 markers, whilst a velocity of 1820m/s correlates well with GU3.

With a new development plan, additional workflows incorporating a high-resolution P-wave velocity PSDM volume and test of 600Hz FWI velocity (Limonta *et al.*, 2025) were implemented. Furthermore, an AI-supported QI workflow was tested (Ruiz *et al.* 2025). Figure 3 shows highly resolved PSDM velocities overlaid on the UHR3D reflection stack with a Cone Penetrometer Test (CPT) soil stiffness curve scaled to match the seismic velocity. We observe no strong seismic reflection that is corresponding to the stiffness increase seen in the CPT data (blue to green/yellow). Opposite, above this level, we see two strong seismic reflections (black), but with no corresponding stiffness increase seen in the Geotech curve. However, the seismic PSDM P-wave velocity matches well with the stiffness trend from the CPT data.

UHR3D data and boulder hazard evaluation

At high latitudes in former glaciated margins, subsurface boulders are one of the most mentioned geo-hazards for wind farms. Up until recently, UHR2D data and Sub Bottom Profiler data

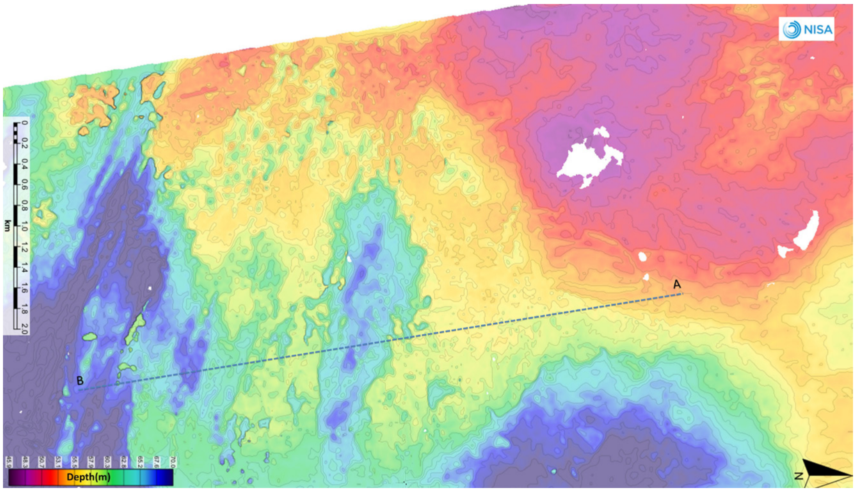

Figure 5 1820m/s iso velocity horizon derived automatically from higher resolved PSDM P-wave velocity volume. 'B-A' is the location of line in figure 4.

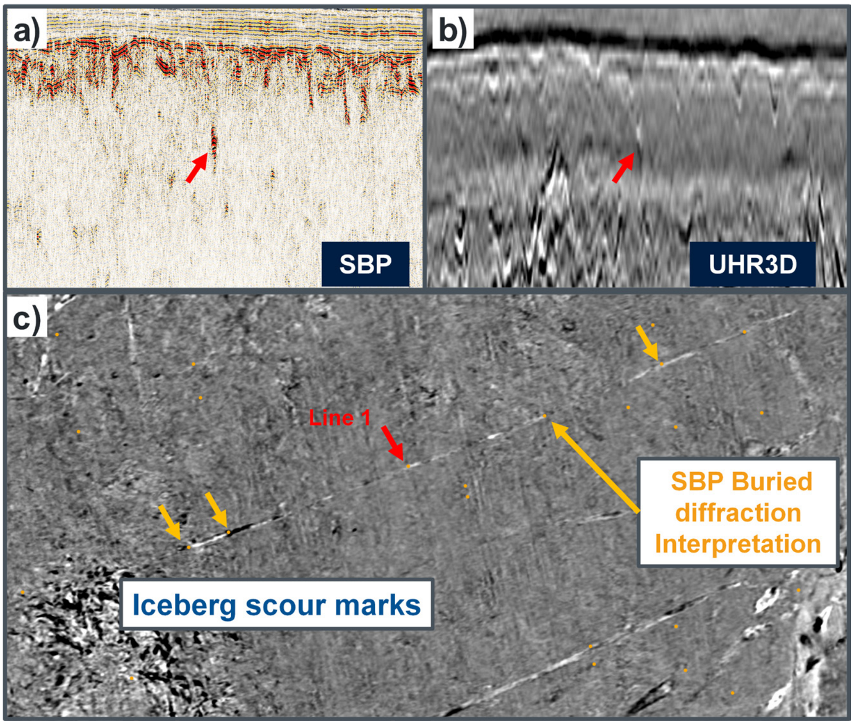

Figure 6 (a) Potential boulder interpreted on SBP 2D data (red arrow), where the event polarity is consistent with a hard point diffractor. (b) Corresponding UHR3D section showing opposite polarity, indicating a different physical origin. (c) Overlay of SBP-derived boulder leads (orange points) on a UHR3D depth slice, demonstrating that many SBP picks align with iceberg scour marks rather than isolated boulders.

(SBP) were the data used in site characterisation for offshore wind farms. In these 2D datasets, a boulder creates a distinct diffraction event (Figures 6 and 7). Iceberg scour marks are often sharp, V-shaped and sometimes broader U-shaped structures 1-3m deep. As determined via interpretation of 3D seismic data, they are often filled with slightly softer mud, and they are easily recognised as a soft then hard narrow three-dimensional structure. In SBP 2D data, the same scour marks are seen as two-dimensional diffractions, and due to amplitude-phase fidelity in SBP data, they also look like hard events. In projects where we have access to both 3D seismic data and 2D SBP – such as the NISA project – we discovered that most of the SBP boulder picks picked by an experienced interpreter were, in fact, iceberg scour marks, when 2D boulder picks were overlaid on 3D time-slices.

Diffraction imaging of the 3D seismic data can show boulders hidden inside strong reflectors; see, for example, Limonta et al. 2025. Although a 3D migrated seismic diffraction volume is an optimised boulder detection dataset, in interpretation workflows, other volumes like full-stack UHR3D or occasionally unmigrated full-stack volumes may be consulted after a boulder lead initially has been spotted in the diffraction imaging volume. Our recent experience is that the unmigrated UHR3D data is less practical to use for small boulders < 3m in diameter. The diffraction rings seen in time slices of a boulder within complex Quaternary units are hard to see, bordering on impossible, in our experience. This approach may, though, be used for bigger boulders >3m in an unstructured and weak reflective ground unit.

As mentioned above, at NISA one of our recent integrated sensors UHR3D projects, boulders picked on 2D SBP counted >6000 boulder leads versus 771 in UHR3D diffraction imaging (Kjølhamar *et al.*, 2025). The soil unit with the most boulders also had an abundance of iceberg scour marks or plough tracks. Most of the SBP boulder picks were present on these scour marks, an overall two-dimensional structure seen in time slices.

The SBP 2D lines were separated by ~62 m, whereas the 3D in-line separation was 1.56 m. This means that the 2D boulder picks are then over-represented 40 times by line density alone and then 7.8 times the actual number picked, indicating a total of 312 times more boulders in this terrain than the interpretation of the 3D data alone. If we calculate the area-wise fraction of boulders, the boulder geo-hazard for the NISA area should be low. The UHR3D specifications allow boulders down to about 2 m in diameter geometrically to be sampled and imaged in the diffraction imaging volume. 771 boulders were found, and if the average areal size is 4 m^2, then the boulders cover 0.003% of the area (boulders 3,084 m^2 within 92 million m^2 of the survey area).

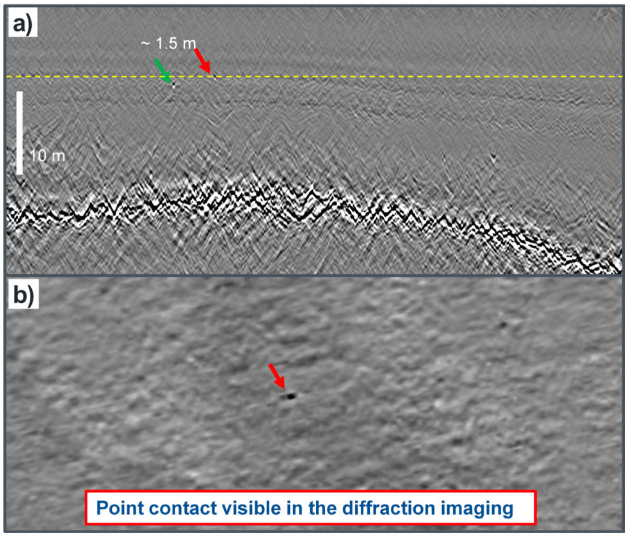

Figure 7 (a) Section from a UHR3D diffraction-only volume, with arrows highlighting collapsed diffraction responses interpreted as boulder candidates. (b) Depth slice from the diffraction-only volume at the position of the dashed yellow line. Integration of UHR3 imaging reduces uncertainty in boulder identification and decreases the number of boulder leads from >6000 (SBP 2D) to 771.

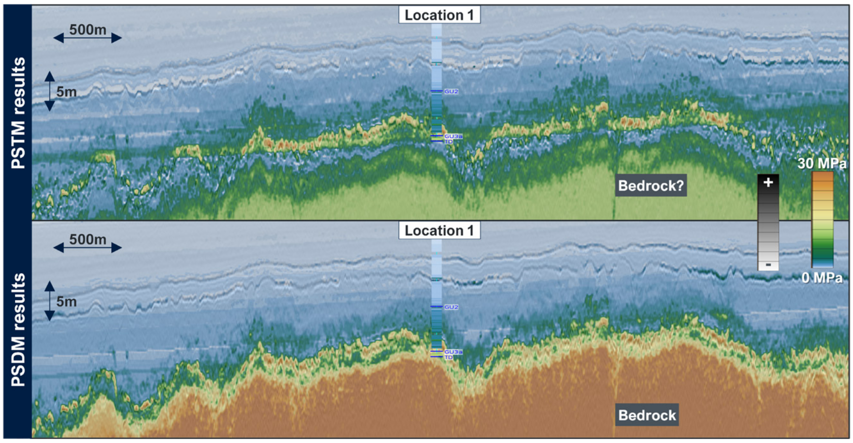

Figure 8 Machine learning prediction of q_t using instantaneous envelope and absolute acoustic impedance from PSTM attributes (top) and PSDM attributes (bottom).

Our conclusion is that the boulder hazard at the site is minimal. We have seen similar levels of boulder density in two other North Sea wind farm site characterisation projects, 3-7:100,000 by area.

Advancing quantitative ground modelling through depth-domain velocity models

Following the reduction of geohazard uncertainty through UHR3D diffraction imaging, the focus naturally shifts toward a more quantitative assessment of ground properties. In this context, the seismic velocity model plays a central role. Improved velocity models not only enable more reliable time-to-depth conversion but also provide a geologically consistent background against which seismic attributes measured in the time domain can be reconciled with geotechnical properties measured in depth.

Quantitative interpretation (QI) of near-surface sediments increasingly depends on robust integration between seismic attributes and geotechnical measurements. In shallow offshore environments, CPT data provide direct estimates of soil stiffness through corrected cone resistance (q_t). The predictive value of seismic-derived attributes, however, is critically dependent on the velocity model used both for depth conversion and as a low-frequency background trend. The NISA study allows for a direct comparison between QI workflows based on PSTM velocities and those using PSDM velocities.

When PSTM velocities are used as a baseline, machine-learning models trained on poststack seismic attributes exhibit clear limitations (Figure 8). Although attributes such as acoustic impedance and instantaneous amplitude show local correlation with q_t, these relationships are typically inconsistent and spatially unstable. On depth-converted volumes, this manifests as pronounced striping artefacts parallel to the seabed and a reduced sensitivity to subtle stiffness increases, particularly close to the top of bedrock and within stiffer glacially affected units. This behaviour increases the uncertainty when attempting to identify zones of partial bedrock weathering or remobilised bedrock material.

In contrast, PSDM velocity models significantly improve cone resistance prediction by providing more accurate depth positioning of seismic attributes and a geologically consistent low-frequency background model. When seismic inversions and attributes are converted to depth using PSDM velocities, correlations with q_t become stronger and collapse into a single, physically meaningful trend. Machine-learning models based on PSDM-derived attributes consistently show improved matching at CPT locations and enhanced spatial continuity away from control points. Importantly, PSDM-derived predictions are better able to resolve stiffness increases within higher-strength soil units that are poorly imaged when relying on PSTM velocities alone.

The uplift provided by PSDM velocities highlights the importance of depth-domain velocity model building for near-surface QI applications. By improving time-to-depth conversion while preserving genuine lateral velocity variations, PSDM velocities enable more reliable soil property prediction, reduce uncertainty in geotechnical interpretation, and provide a more robust foundation for data-driven approaches such as machine learning. These results demonstrate that advanced velocity models should be considered not merely as an imaging enhancement, but as a critical enabler of quantitative, geotechnically relevant seismic interpretation for offshore wind site characterisation.

Discussion

Seismic interpretation workstations, software, and workflows are optimised for oil and gas deep exploration 3D data that is around 1000 times lower overall resolution than UHR3D seismic data. For complex horizons like push moraines or a weathered bedrock, the solution used in recent projects is time-consuming, where densely spaced manual picking and a combination of snapping and interpolation are needed. UHR3D data (1,56 x 1,56 m spatially and 1/8ms vertically) is simply another world than what the 3D auto trackers of today are trained for (12.5 x 12.5 m horizontally and 2ms vertically). To enable UHR3D seismic interpretation leading to the IGM to be time and cost-efficient, we recommend moving towards the volume-based and three-dimensional interpretation approaches outlined in this paper.

To date, we have interpreted the shallow UHR3D velocity volumes in multiple wind farms from New York Bight on the East Coast of the US, the Irish Sea, Dogger Bank, and Sørlige Nordsjø II, all at latitudes exposed to glacio-marine processes. Figure 9 shows a sketch of postulated P-wave velocity changes in shallow soils due to glacio-marine processes and dewatering effects due to loading effects and push-effects of the fluctuating ice sheets during the Quaternary period. The typical range of these effects seen in the P-wave velocity volumes ranges from 1600 to 2000m/s. We see many of the same situations across the four sites we have

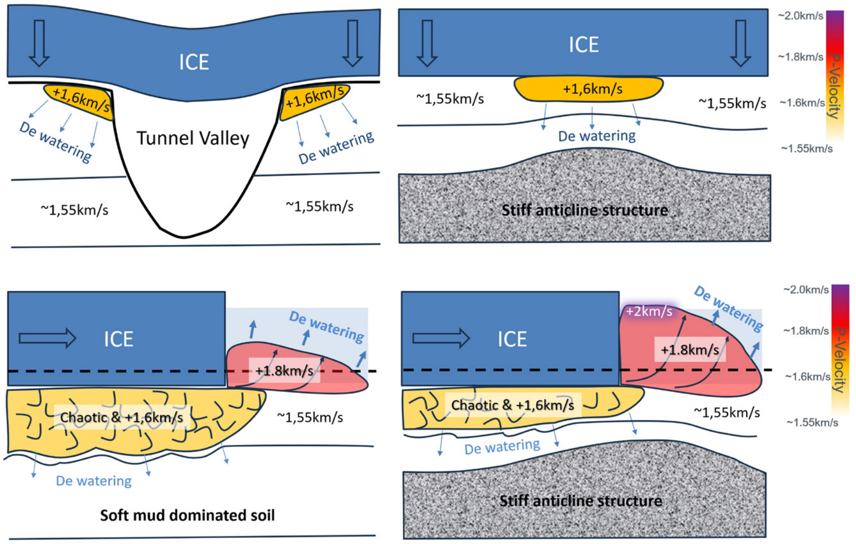

Figure 9 Sketch of glacio-marine processes, and the expected velocity increase due to dewatering of marine mud dominated units.

now interpreted: patchy P-wave velocity increases at the flanks of wide tunnel valleys, over stiff underlying anticlines, and in chaotic facies postulated, caused by combined push and loading effects of a progressing front of a thick ice sheet.

These effects are evident in Figure 10, where a late tunnel valley, maybe from the latest Weichselian glaciation, with lower P-wave velocity < 1750m/s, shows a strong P-wave contrast to the flanks showing > 1900m/s. These P-wave velocity changes are expected to be sub-linearly connected to soil stiffness, as seen from Figure 3. Therefore, we see a reason to investigate further and see if there are any global trends we can find between P-wave velocity and soil stiffness or strengths if you have a similar soil type. Similarly to seismic inversion using reflection strengths, we may encounter a strong correlation with soil stiffness and strength from optimised P-wave velocity volumes.

Looking at the examples shown by Limonta, L., et. al., 2025 and Figure 6 here, where SBP 2D picked boulders overrepresented the boulder hazards present at NISA by a factor of 312, we ask ourselves if the focus on boulders in North Sea wind farms is driven by the historic use of UHR2D data, crossing multiple layers with iceberg scour marks?

Summary

The end goal we see by optimising volume-based interpretation approaches is to save workstation time, produce higher quality estimates of soil stiffness and realistic identification of geohazards, and quantification of the risk of encountering during geotechnical testing, or during wind farm construction. Using the production 3D P-wave velocity, or preferably a higher resolved PSDM velocity volume directly as a soil stiffness model, is both cost-effective and yields precise, unbiased outputs. In well-processed 3D seismic data, extracting geo bodies of the highest negative amplitude features (potential gas geohazards), producing SEGY, GIS and horizon outputs from the geo bodies is very efficient.

If sparse geotechnical data already exist, we can make good-quality QI models that can save on the amount of final geotechnical sampling required. Furthermore, a goal is to shorten the overall time used until the turbine foundation design and turbine layout in a wind farm can be decided. There are potentially big cost savings if we optimise the geophysical interpretation products for wind farms. In all windfarms covered by UHR3D so far, as well as the ones planned for 2026, all have a sparse geotechnical database available, and all can use the

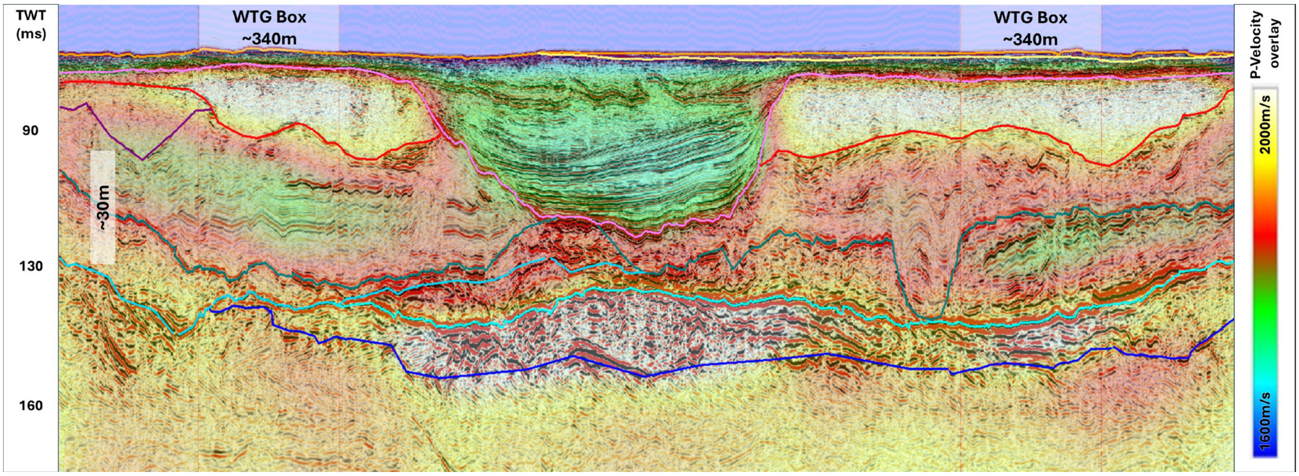

Figure 10 UHR3D inline overlaid by low resolution PSTM production p-velocities. Glacio-marine processes resulting in chaotic, high velocity patches are seen in yellow-white velocity overlay (>1900m/s) under two Wind Turbine Generator boxes seen in the top. We expect strong soil strength under the boxes and lower soil strength in the tunnel valley (green 1650-1750m/s) centrally.

geophysical-based modelling to optimise further geotechnical programs, save pre-income expenses, and shorten time to power production.

As shown by the pitfalls of picking boulders in 2D (examples from SBP shown here), where two-dimensional structures like scour marks exist, boulder geohazards have historically most likely been overestimated in general. Having 3D diffraction volumes will provide better hazard estimates, but this takes much workstation time today.

Picking boulders manually in any ultra-high-resolution data is tedious and time-consuming. The workstations presently need modified tools to isolate point contacts automatically by constraining a small geo body volume only. The geo body tools should, with new options like maximum volume constraints set to ~10m^3, isolate point reflectors in a UHR3D diffraction imaging volume and yield boulder lead picks automatically. This must still be followed by a human quality check, but overall, much time will be saved. The development of AI tools to automatically interpret high-amplitude, hard point reflectors in diffraction imaging volumes is being worked on in several companies, including at TGS.

Conclusions

Using UHR3D seismic velocity volumes to define subtle soil stiffness increases in chaotic Quaternary mud units has proved to be a valuable approach in recent studies. Automatically extracted iso-velocity horizons that correlate to CPT stiffness changes of pre-defined ground units are time-effective and more relevant for soil unitisation purposes.

Utilising geo body tools to extract extreme negative amplitude events is a time-effective way to isolate geo hazards, or in P-wave velocity volumes, or isolate high-velocity ground units with likely higher soil strength.

At high latitudes affected by glacio-marine processes, looking at the patchiness of the P-wave velocity field along a time equivalent horizon, and cases that lack CPT-measured soil stiffness variation across strong seismic reflectors, the traditional formation named horizon picking makes this approach less valuable for site characterisation within offshore wind farms.

Beyond qualitative interpretation, high-resolution UHR3D velocity models, such as PSDM-derived P-wave velocities, will become a foundation for Quantitative Ground Modelling (QGM). By improving time-to-depth conversion and alignment with geotechnical data, they enable more coherent CPT-based stiffness predictions and a more reliable delineation of higher-strength soil units than PSTM-based approaches.

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