Beyond the image: high-frequency FWI for 3D Ultra High-Resolution velocity models in offshore wind site characterisation

Luca Limonta[1]*, Allan McKay[1], Bent Erlend Kjølhamar[1] and Roberto Ruiz[1] present a depth-domain velocity-model-building workflow applied to a 92-km² UHR3D dataset from the East Irish Sea.

Abstract

Offshore wind developments need a reliable picture of the first hundred metres below the seabed, because foundation design and geotechnical risk depend on it. 3D Ultra-High-Resolution Seismic (UHR3D) surveys now provide the dense sampling and broad bandwidth required, but velocity analysis has often stayed in the time domain, where semblance picking gives only approximate velocities and no reliable interval P-wave velocity. We present a depth-domain velocity-model-building workflow applied to a 92 km² UHR3D dataset from the East Irish Sea. The workflow combines Kirchhoff Pre-Stack Depth Migration, 3D reflection tomography over the full survey, and acoustic Dynamic Matching Full Waveform Inversion (FWI) run to a maximum frequency of 600 Hz over two test areas. Because the streamers are short, the inversion relies on reflected rather than refracted energy. The resulting model resolves features narrower than 10 m and vertical structure better than 1 m, including iceberg scour infills, stiffened clay intervals and dewatered zones above bedrock. Inverted velocities track an independent seismic cone penetration test profile closely, while the time-domain velocity diverges, and a bedrock depth mistie of about 2 m is largely removed. High-frequency FWI turns UHR3D data into a quantitative input for foundation engineering.

Introduction

Offshore wind projects need a detailed and reliable description of the shallow subsurface. Foundation design, geotechnical risk management and installation planning all depend on how well we understand the first tens of metres below the seabed, and the growing scale of these projects has increased the demand for information at the spatial scales that matter to foundation design. 3D Ultra-High-Resolution Seismic (UHR3D) data have become a key dataset in this context, because the data combine dense spatial sampling with the broad bandwidth needed for near-surface imaging (Limonta *et al*. 2024; Caselitz *et al*. 2025). Modern surveys also acquire hydrographic and other geophysical sensors in the same pass, which shortens the route from acquisition to a ground model (McKay *et al*. 2025).

Acquisition technology has advanced quickly, but standard processing and interpretation workflows have often stayed rooted in the time domain. Velocity analysis is commonly performed by semblance-based picking, which produces root-mean-square velocities that flatten common-midpoint gathers and improve the stack. This is adequate to produce an interpretable seismic image, and it remains standard practice. It provides only approximate velocity information, however, and it does not yield reliable interval P-wave velocities (Vp). As a result, features that are subtle on the seismic image but significant for geotechnical work, such as localised sediment stiffening, partial cementation or dewatering, may not be resolved.

In this paper we argue that interval velocity is a valuable product, rather than a step towards a better seismic image. Interval velocity provides the link between seismic observations and geotechnical properties such as stiffness, shear strength and uniaxial compressive strength (UCS) (Lindh and Lemenkova 2022). Interval velocities that are well-estimated and conform with soil units also underpin accurate time-to-depth conversion, amplitude-versus-offset analysis and seismic inversion. Together these requirements motivate a move from time-domain velocity analysis to depth-domain velocity-model building, which is far better at handling near-surface complexity.

Full Waveform Inversion (FWI) has long been recognised in the oil and gas industry as a powerful way to recover high-resolution velocity models. Recent progress in acquisition, computing and inversion algorithms, in particular Dynamic Matching FWI (Huang et al. 2023), has made it possible to extend FWI into the ultra-high frequency range. This study applies FWI at frequencies up to 600 Hz to a 3D seismic dataset from the East Irish Sea and evaluates the result against independent geotechnical measurements.

The site and its geological setting

The dataset was acquired at the NISA site in the East Irish Sea during autumn 2024, covering 92 km² in about 50 m of water. The shallow section consists of soft, clay- and mud-dominated pre- and post-Quaternary sediments resting on a hard and irregular bedrock surface (Figure 1). Bedrock lies between 20 and 50 m below the seabed, and its relief varies sharply across the site.

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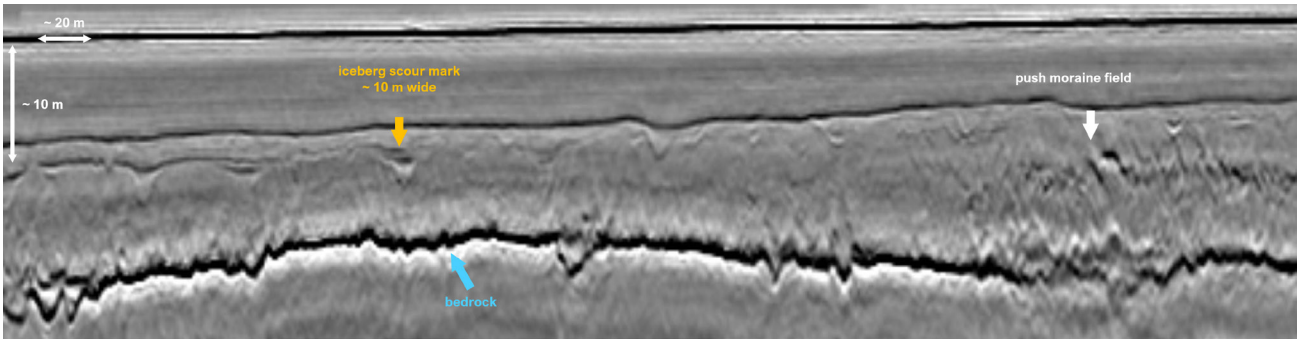


Figure 1 Inline through the UHR3D volume at the NISA site, showing the shallow succession above an irregular bedrock surface at approximately 20 m below the seabed. Annotations mark an iceberg scour mark about 10 m wide and a push moraine field.

Survey Area:	92 sq. Km
Number of Streamers:	10
Streamer length:	150 m
Cable separation:	12.5 m
Sailline spacing:	62.5 m
Acq/Proc Sampling rate:	0.125 ms / 0.25 ms
Sources:	4 x DuraSpark
Acq/Proc Bin size:	1.56 x 1.56 m

Integrated sensors acquired simultaneously with UHRS:
- **MBES**: Multi-Beam Echo Sounder
- **SBP**: Sub Bottom Profiles
- **MAG**: Magnetometer
- **SSS**: Side Scan Sonar

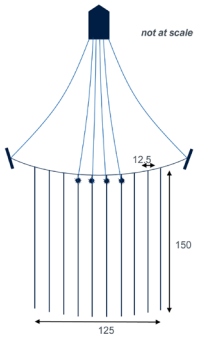


Figure 2 Survey and processing parameters for the NISA UHR3D dataset.

The sedimentary cover records strong and repeated glacial influence, with glaciomarine, glaciolacustrine and deltaic deposits interfingering over short distances. Quaternary glacial processes have reworked this succession further. Advancing ice sheets loaded and pushed the sediments, forming push-moraines, and the associated compaction and later dewatering left localised zones of increased stiffness embedded within otherwise soft clay. The result is a highly heterogeneous near-surface environment in which important facies changes occur over as little as 100 m laterally (Kjølhamar et al. 2026).

One of the original objectives of the survey was to map bedrock geometry accurately and to better understand bedrock quality, because geotechnical investigations had identified both fresh and weathered bedrock. The initial foundation concept targeted bedrock as the anchoring layer, using bedrock piling or, at greater cost, bedrock drilling and grouting. Early in the interpretation of the survey data, attention moved instead to the stiffer mud-dominated intervals above bedrock, described as ground units 2 and 3 (GU2 and GU3), as possible foundation units.

This shift created the central geophysical challenge of the project. The interval immediately above bedrock is chaotic and largely non-reflective (Figure 1). Cone Penetration Test (CPT) and Seismic CPT (SCPT) data acquired at selected locations show clear increases in corrected cone resistance (q_t), and therefore in stiffness, at levels where no laterally continuous reflector can be picked and interpreted reliably. The reverse also occurs, with strong reflections that carry no corresponding stiffness change. Conventional horizon picking therefore cannot map the units that matter most for foundation design.

Velocity behaves differently. Even at the time-domain processing stage, we observed a correlation between elevated seismic velocity and increased cone resistance, particularly in the interval just above bedrock. This is the key observation behind the present study. Where reflectivity fails, the velocity model still delineates the zones of higher V_p that correspond to higher stiffness, and it does so as a volume rather than as a set of picked surfaces. Kjølhamar *et al*. (2026) show that this relationship is robust enough to support iso-velocity horizons, with 1595 m/s tying to GU2 and 1820 m/s tying across twelve CPT locations at this site. Realising that potential, however, requires a velocity model whose resolution approaches the scale of the features themselves, which is what the workflow described below sets out to deliver.

Depth velocity model-building workflow

Acquisition and dataset

The survey used ten 150 m streamers separated by 12.5 m, with a sail-line spacing of 62.5 m; see Figure 2. Four sparker sources were deployed in a wide-tow configuration (Widmaier *et al*. 2019), which shortens the radial distance to the first offset class and improves near-offset sampling, an important consideration for very shallow targets. The sources emit useful energy from approximately 150 Hz upwards, and the shot interval was 250 ms. Data were acquired at 0.125 ms and processed at 0.25 ms, giving a Nyquist frequency of 2 kHz, and a processing bin size of 1.56 × 1.56 m.

The 150 m streamer length allows reflection angles up to approximately 35° angle of incidence (AOI) over most of the survey area. Maximum AOI decreases with depth, but it remains sufficient for moveout analysis and reflection-based velocity updates to roughly 40 to 50 m below the seabed. This range reaches down to and includes the bedrock surface shown in Figure 1, so it covers the whole interval of interest, but the limited offset is still central to the choices made later in the workflow.

Pre-processing

All data used for velocity analysis passed through an extensive pre-processing sequence, following the workflow described by Limonta *et al*. (2024). This included denoising, receiver-side and source-side deghosting, designature, sea-state statics correction with re-datuming to mean sea level (MSL), water-velocity correction and demultiple. Deghosting deserves particular mention, because the combination of very high frequencies, relatively deep tow depths (3 m) and a changing sea surface makes the receiver ghost period strongly non-stationary. Inversion-based and machine learning-based methods have been developed specifically for UHR3D data (Bekara *et al*. 2024; Farmani *et al*. 2024).

Initial model and depth migration

Shallow borehole data and sonic logs above bedrock were limited, so the final Kirchhoff Pre-Stack Time Migration (KPSTM) velocity model was used as the starting point for depth-domain work. Below the bedrock interface, velocities were replaced using kriged sonic log values combined with a preliminary geological interpretation.

No check-shot data were available at the site, which makes anisotropy difficult to estimate reliably. We therefore adopted an isotropic assumption for both depth migration and velocity analysis. This is a pragmatic choice rather than a statement about the medium, and we return to it in the closing section. An initial Kirchhoff Pre-Stack Depth Migration (KPSDM) was then produced on a 3.125 × 3.125 m grid with 0.2 m vertical sampling, to a maximum imaging depth of 180 m.

3D reflection tomography

Velocity updates were obtained first by 3D reflection tomography applied across the full 92 km² survey. Residual moveout was picked on Common Reflection Point (CRP) gathers, with a mute applied above 36° AOI to reduce sensitivity to any anisotropy that the isotropic assumption does not account for. Two complete iterations of migration, picking and tomographic inversion were run over the whole area. The outcome is a smooth but geologically plausible model that already improves on the time-domain field, and, just as importantly, a stable starting point for FWI.

High-frequency Full Waveform Inversion (FWI)

Full Waveform Inversion is an imaging and velocity-model-building technique that compares recorded shot gathers with synthetic shot gathers produced by forward modelling. Because the forward modelling depends mainly on velocity, in this acoustic case the compressional velocity (Vp), the velocity model can be updated through an inversion scheme so that the mismatch between observed and synthetic data is reduced at each iteration. FWI is well established in the oil and gas industry at low frequencies, of the order of a few tens of hertz, and here we push it to much higher frequencies, which makes this a novel application.

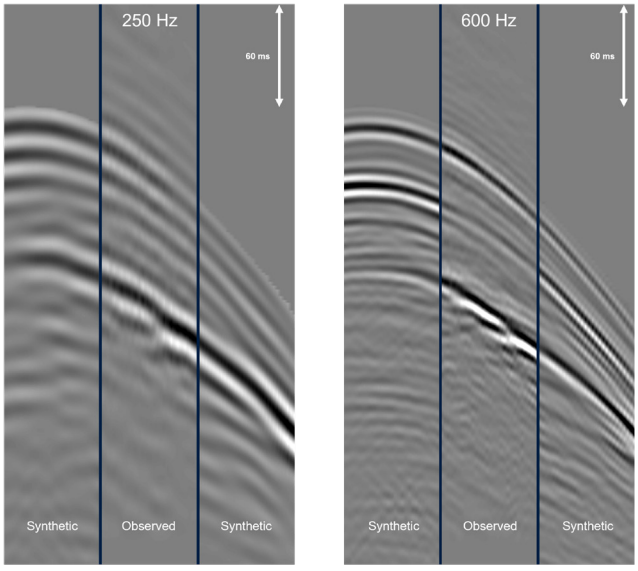


Figure 3 FWI quality control on the final model. The same shot gather is displayed with modelled and observed data interleaved, band-limited to a maximum frequency of 250 Hz (left) and 600 Hz (right).

We applied acoustic Dynamic Matching FWI (DMFWI) to two targeted test areas of approximately 3 km² each, to recover detail below the resolving power of reflection tomography. For this study we used the DMFWI objective function of Huang *et al*. (2023). Rather than minimising the sample-by-sample amplitude difference used in conventional FWI, this objective function maximises the local cross-correlation between the recorded and modelled data after they are dynamically matched. This de-emphasises amplitude differences and lets the inversion concentrate on kinematic mismatch, and the multichannel correlation makes the algorithm robust where the signal-to-noise ratio is poor. The implementation used here is acoustic and isotropic.

The input to FWI was the shot gathers after demultiple and re-datuming to MSL. Because the offsets are short and the water depth is only about 50 m, the dataset contains little clear critical refraction energy, so the updates were driven primarily by reflected energy.

We used a multi-scale strategy, raising the maximum inverted frequency progressively from approximately 200 Hz to 600 Hz so that the algorithm fitted the longer wavelengths before adding finer detail. The inversion starts at about 200 Hz rather than lower because the sparker sources emit little useful energy below approximately 150 Hz, so there is no reliable low-frequency signal to fit at the bottom of a conventional multi-scale ladder. Shots were sub-sampled at roughly 10 × 10 m for each stage, which balanced computational cost against consistent illumination of the test areas. No dedicated muting was applied to the input gathers for FWI. Instead, the inversion relied on the quality of the preconditioning steps and on the stability of the tomographic starting model.

Putting 600 Hz in perspective

A maximum inverted frequency of 600 Hz sounds extreme to readers used to oil and gas exploration, where FWI typically reaches a few tens of hertz. The comparison is misleading, because everything at this site is relative to scale. We image the first 100 m or so below the seabed using a trace length of about 200 ms, and the maximum offset is very small compared with an exploration survey. In both record length and offset there is roughly a factor of fifteen between the two settings. In addition, the starting model comes from tomography performed on very high-resolution data and is already detailed by the standards of an exploration tomography model. Seen this way, 600 Hz FWI on UHR3D data is not an aggressive extrapolation of the method but a proportionate application of it.

The quality control in Figure 3 illustrates this comparison. We model a single shot gather with the final FWI model, band-limit it first to 250 Hz and then to 600 Hz, and display each version interleaved with the observed data. At both frequencies the modelled and observed events are kinematically well matched, and the match holds as the bandwidth increases. Equally telling is the appearance of the gathers. Once time, offset and wavelength are scaled to this setting, the 600 Hz gather looks as well proportioned as a conventional low-frequency FWI gather from oil and gas exploration. This is a direct visual sign that the inversion is working in a familiar regime rather

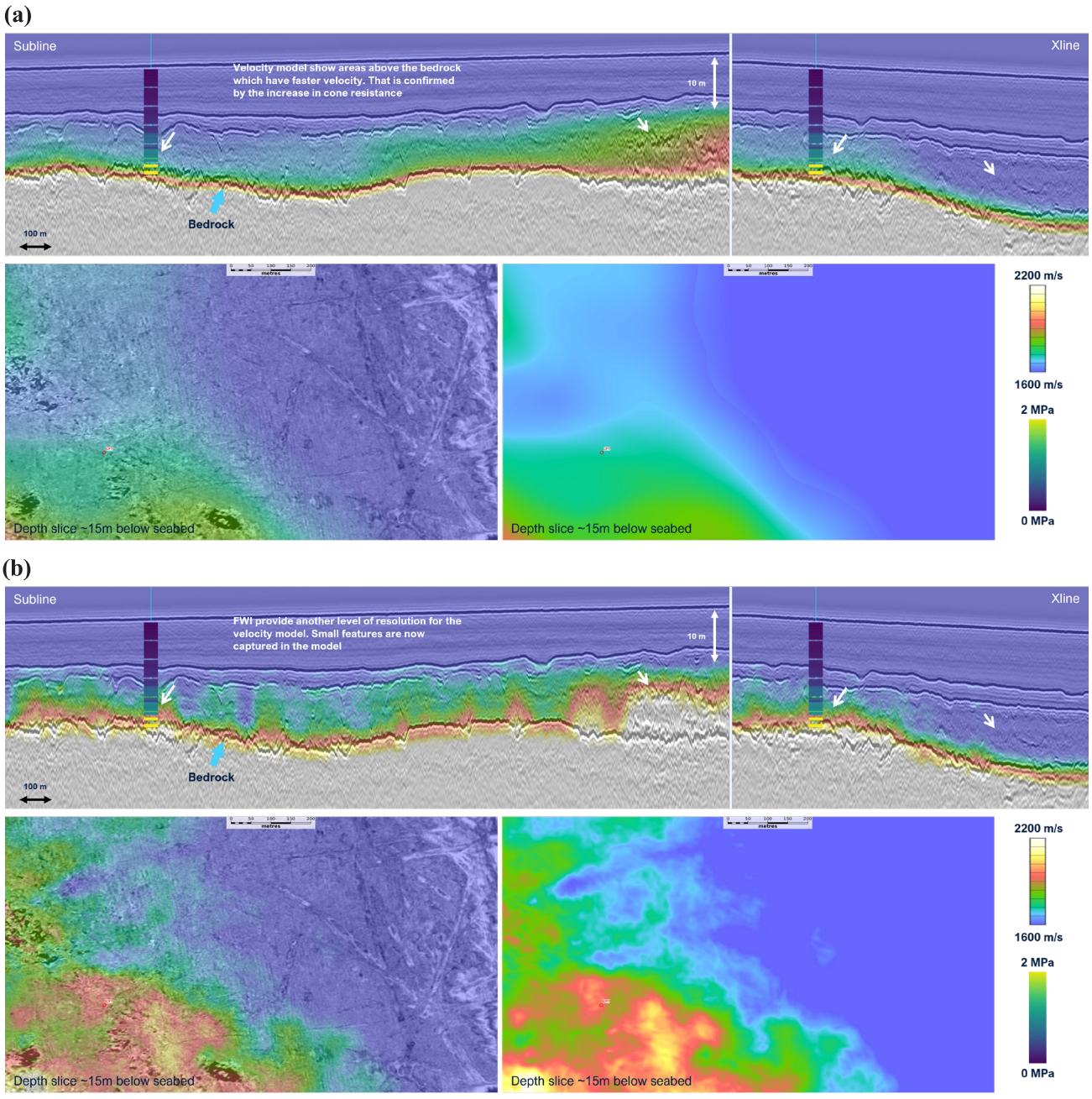


Figure 4 Velocity model comparison at a CPT location, shown as subline, crossline and a depth slice approximately 15 m below the seabed, with corrected cone resistance overlaid. (a) Time-domain velocity model from 1D tomography, used for KPSTM. (b) Model after Dynamic Matching FWI to a maximum frequency of 600 Hz. Velocity is displayed from 1600 to 2200 m/s and cone resistance from 0 to 2 MPa.

than an exotic one. In a setting where refraction constraints are largely absent, the check matters, because it shows that the final model reproduces reflection-dominated kinematics and wavelet behaviour at high frequency. That is the practical prerequisite for trusting the sub-metre velocity variations taken from the inversion.

Results

Figure 4 compares the same inline, crossline and depth slice through the time-domain and FWI velocity models, with cone resistance overlaid at a CPT location. The progression in resolution and conformance is clear. The time-domain model already indicates faster zones above bedrock, consistent with the increase in cone resistance, which is what encouraged the depth-domain work in the first place. After depth-domain velocity-model building, that is 3D tomography followed by FWI, the model reaches a far higher level of detail, resolving small features that the time-domain model simply could not represent.

It is worth noting that the post-tomography model was already valuable on its own. It revealed stiffer clay intervals that were not practically interpretable from the migrated stacks, and it improved our ability to separate soil units where reflectivity is weak or chaotic. FWI, however, delivered a step change rather than an incremental gain regarding resolution of velocity features.

For example, Figure 5 shows the FWI model on an inline and on a depth slice 10 m below the seabed. The inverted field resolves lateral features narrower than 10 m and vertical structure better than 1 m. Two examples illustrate the point. First, an iceberg scour mark about 10 m wide and less than 1 m thick appears as a localised velocity increase, consistent with an infill of harder sediment than the surrounding clay. Second, a chaotic push moraine field about 10 m wide also stands out, interpreted as having undergone dewatering with an associated increase in stiffness and *Vp*. The progression in the velocity model with each modelling step is shown clearly in Figure 6 with depth slices 20 m below the seabed through both the KPSDM stack and each velocity model in turn. Also shown in Figure 6 is the FWI velocity update alone, at ±100 m/s, which isolates the inversion added to the tomography model.

Taken together, these displays show that the FWI velocity model is more than an imaging aid. It is a high-resolution property volume that indicates stiffness heterogeneity which reflectivity alone expresses poorly, precisely in the chaotic intervals where the choice and viability of the offshore wind foundation concept is critical.

Validation against geotechnical data

Independent validation is essential before inverted velocity variations can be treated as real mechanical contrasts. At one location, SCPT data provided shear-wave velocity (*Vs*) measured at 1 m intervals. Figure 7 overlays the FWI velocity, the tomography velocity, the time-domain velocity and a calibrated *Vs* profile on the migrated stack. The Vp/Vs ratio is held constant for this display, so the comparison assesses trend rather than absolute values.

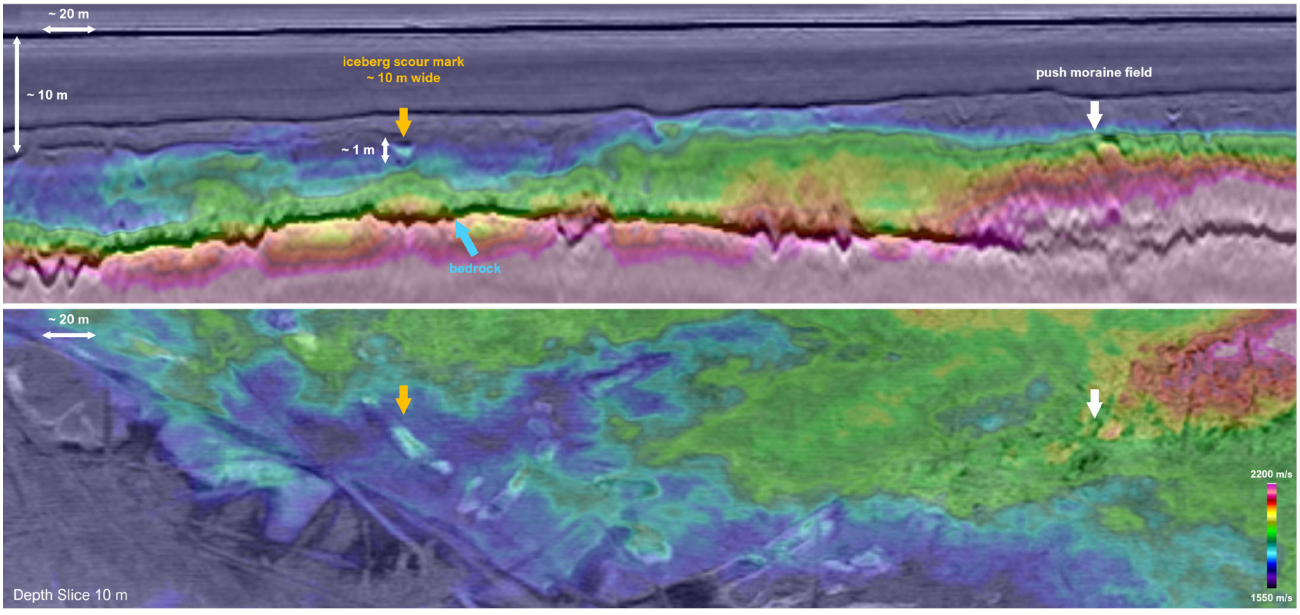


Figure 5 FWI velocity model at 600 Hz, displayed on an inline and on a depth slice 10 m below the seabed, with the migrated stack overlaid. The iceberg scour mark, about 10 m wide and less than 1 m thick, and the push moraine field are both resolved. Velocity is displayed from 1550 to 2200 m/s.

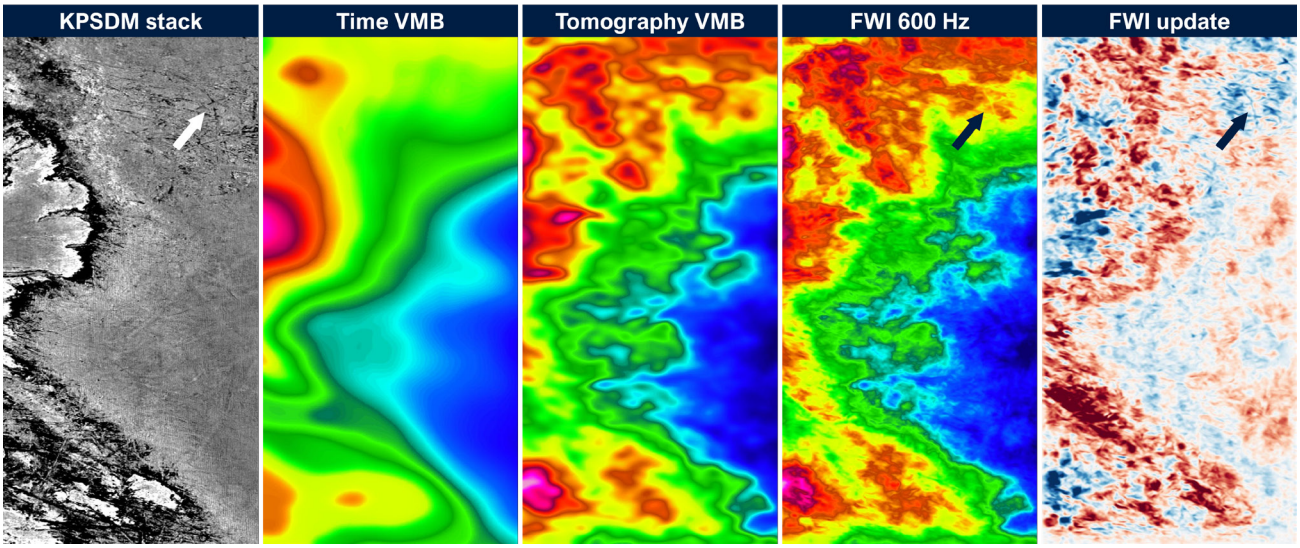


Figure 6 Depth slices approximately 20 m below the seabed through, from left to right, the KPSDM stack, the time-domain velocity model, the tomography velocity model, the 600 Hz FWI model, and the FWI velocity update. The arrows are pointing at small iceberg scour marks, visible only in the FWI velocity and seismic display.

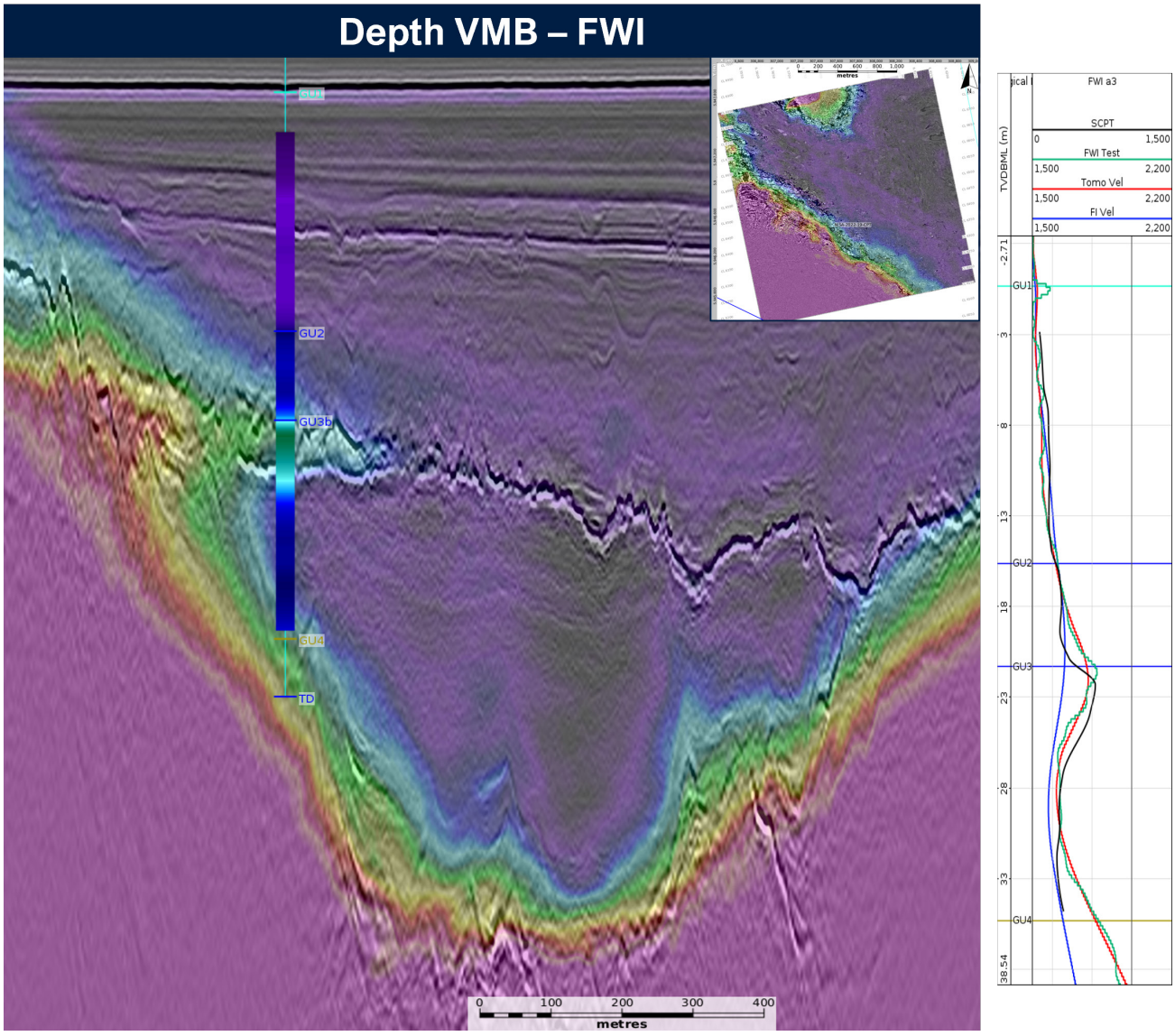


Figure 7 Final depth-migrated stack overlaid by the FWI velocity model (Vp), with velocity profiles (Vs) at an SCPT location. The Vp/Vs ratio is held constant for this comparison. Log curves are displaying SCPT Vs (black), Initial model Vp (blue), tomography update (red) and FWI results (green).

Both depth-domain models track the SCPT profile closely, while the time-domain velocity diverges significantly. This is the clearest single demonstration of what depth-domain velocity-model building delivers in a shallow, laterally heterogeneous setting. The FWI curve also shows vertical detail finer than the 1 m SCPT sampling interval, which indicates genuine sensitivity to sub-metre velocity variation. Displayed against the migrated stack, the FWI velocity contrasts conform well to the stratigraphic changes visible in the seismic image, supporting the view that the inverted field is geologically meaningful. The SCPT shear-wave data served only as a blind validation of the model. It did not constrain or drive the FWI update, so this agreement is an independent result.

Time-to-depth conversion

Improved velocities also improve depth positioning, which has direct practical consequences. This is particularly important because KPSDM delivers the seismic data directly in depth, the native domain of geotechnical investigation and foundation design, rather than requiring a separate conversion from time. With the initial velocity model, geotechnical units and seismic reflectors misfit by about 2 m at bedrock depth (Figure 8 a). A 2 m discrepancy is substantial when bedrock is only 20 to 50 m below the seabed and when it is being considered as a foundation horizon. With the final model, the misfit reduces clearly for all units (Figure 8 b). This removes a persistent source of manual vertical shifting between geotechnical and seismic data, makes ground modelling faster and less subjective, and eases the integration of geophysical and geotechnical data.

Value for qualitative and quantitative interpretation

Because the velocity field responds to stiffness where reflectivity does not, it supports interpretation approaches based on the volume itself. Iso-velocity horizons extracted from the depth-domain model tie to ground units defined by CPT, as demonstrated at this site by Kjølhamar *et al*. (2026), and geo-body extraction can isolate higher-velocity zones likely to carry higher soil strength. These outputs are quicker to produce

than densely spaced manual picks and less dependent on the interpreter.

The benefit extends to quantitative work. Kjølhamar et al. (2026) compared machine-learning prediction of corrected cone resistance at this site using attributes derived with time-domain velocities against the same prediction using depth-domain velocities. Predictions based on the depth-migrated volumes matched the CPT measurements more consistently, showed better spatial continuity away from control points, and reduced the striping artefacts parallel to the seabed that appear on depth-converted time-domain products. The overall error fell by about 30%. The improvement comes from two effects that a better velocity model provides at once, more accurate depth positioning of the seismic attributes, and a geologically consistent low-frequency background trend for inversion. A high-resolution FWI velocity model strengthens both, which is why the availability of reliable velocities matters for pre-stack inversion workflows as much as for imaging (Ruiz and Limonta 2025).

Conclusions and way forward

This study shows that Full Waveform Inversion can be applied successfully at frequencies up to 600 Hz to 3D seismic data acquired for offshore wind site characterisation. By combining KPSDM, 3D reflection tomography across the full survey and Dynamic Matching FWI over selected areas, the workflow produces a velocity model that is both detailed and geologically consistent, and that clearly outperforms the conventional time-domain approach.

The final model resolves sub-metre vertical variation and fine-scale lateral heterogeneity. For the study area it allowed stiffened clay intervals, iceberg scours and dewatered zones above bedrock to be identified where the seismic image is chaotic or non-reflective. Agreement with independent SCPT measurements validates the inverted velocities, and the reduction of the bedrock depth mistie from about 2 m to a few tens of centimetres demonstrates a direct engineering benefit. Reliable high-resolution velocities also improve the stability and geological consistency of low-frequency models used in pre-stack inversion. This information is not a refinement but highly valuable data to guide engineering and project development decisions.

Several directions would strengthen the approach further. The most useful change would be at the acquisition stage. Recording longer offsets and adding a low-frequency source such as a small airgun alongside the sparkers, would capture a more complete wavefield and make refracted arrivals usable. FWI would then be constrained by refractions as well as reflections, which should make the inverted model more robust, particularly at the deeper end of the interval of interest.

The isotropic assumption adopted here reflects the absence of check-shot data rather than a physical conclusion. Additional borehole information and check-shots would allow a proper anisotropy study and remove the need to mute the wider angles during tomographic picking. Therefore, to ensure the full value of geophysical data can be realised for shallow site characterisation then project developers may need to rethink geotechnical sampling and testing survey scopes to include suitable calibration data.

Elastic effects are the third area to pursue. Shear-wave energy and mode conversion are not represented in an acoustic inversion, yet the geotechnical measurements that we validate against are themselves shear-wave measurements. Studying these effects, and testing

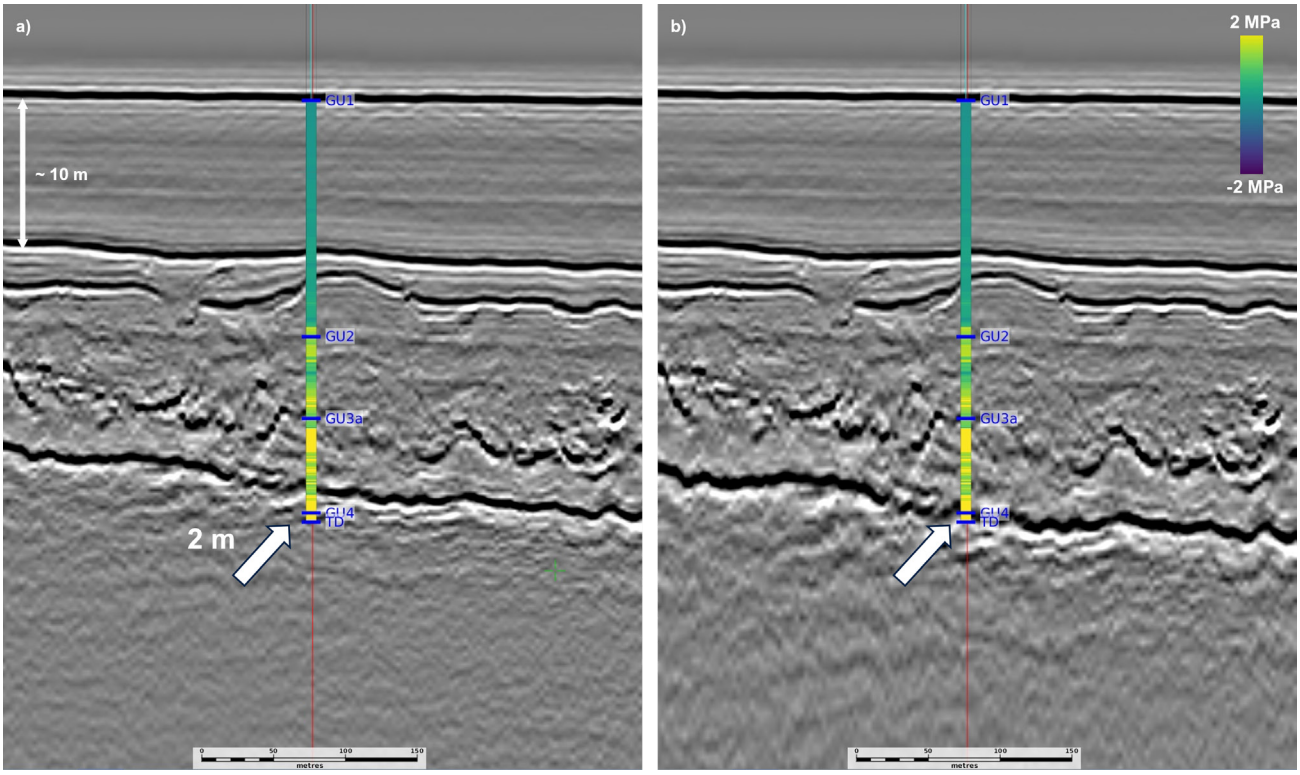


Figure 8 Time-to-depth conversion at a CPT location, shown as subline with corrected cone resistance displayed from -2 to 2 MPa. (a) Using the initial velocity model, geotechnical units and seismic reflectors misfit by approximately 2 m at bedrock depth. (b) Using the final velocity model, the misfit is clearly reduced for all units.

elastic FWI on UHR data, would close that gap and could give direct access to Vs rather than requiring an assumed Vp/Vs ratio.

Finally, the same workflow applies beyond offshore wind. Site characterisation for oil and gas well development and for carbon capture and storage projects raises very similar shallow-hazard and foundation questions.

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