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A customised FWI workflow to solve the challenges of a highly irregular 3D Land acquisition dataset

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Summary

We investigate the application of Full Waveform Inversion (FWI) in challenging onshore environments characterised by sparse and noisy data acquisition, with a highly irregular geometry. The critical role of low frequency stabilisation is discussed, to maintain the stability of shallow velocity updates and to prevent the introduction of errors that could propagate into deeper structural interpretations. Through a carefully structured velocity model building workflow—integrating detailed diving wave tomography and a well constrained reflection tomography starting model—we demonstrate that robust FWI updates are attainable even when conventional low frequency refraction energy is lacking. Synthetic first breaks are shown to be useful for mitigating cycle skipping and supporting reliable long wavelength updates, thereby enhancing the inversion's consistency with well velocity profiles. The resultant FWI model exhibits superior vertical and lateral resolution, providing a more accurate subsurface image that underpins both seismic imaging and CO_2 storage evaluations. We demonstrate that innovative approaches can overcome traditional limitations in challenging, obstructed onshore seismic data environments.

A customised FWI workflow to solve the challenges of a highly irregular 3D Land acquisition dataset.

Introduction

Full Waveform Inversion (FWI) has become a standard tool for offshore imaging, and recent advances in acquisition and elastic inversion have expanded its use onshore. However, in regions with dense infrastructure and restricted access, such as Western Europe, acquisition designs often lack the low frequencies, dense sampling, and offsets needed for stable FWI. These limitations increase the risk of cycle skipping and reduce the reliability of near surface velocity updates.
This case study focuses on a sparse acquisition survey in Denmark acquired for CO_2 storage evaluation. The objective was to improve the accuracy and resolution of the velocity model, with particular emphasis on resolving shallow near surface velocities around key well locations.

Survey Description and Challenges

The 2025 survey used a Vibroseis 5–100 Hz sweep and Stryde nodes, but access restrictions around towns, industry, and farmland resulted in sparse, irregular shot geometry and uneven receiver coverage (see Fig. 1). While the seismic response shows strong reflectivity, the raw shot gathers are heavily contaminated by low-frequency noise, leaving refraction energy below 12 Hz largely unusable for FWI (see Fig. 2). Despite these limitations, PSTM and PSDM imaging performed well thanks to 5D interpolation and a robust reflection-tomography workflow, though the lack of reliable low-frequency refractions posed a significant risk of cycle skipping in subsequent FWI updates.

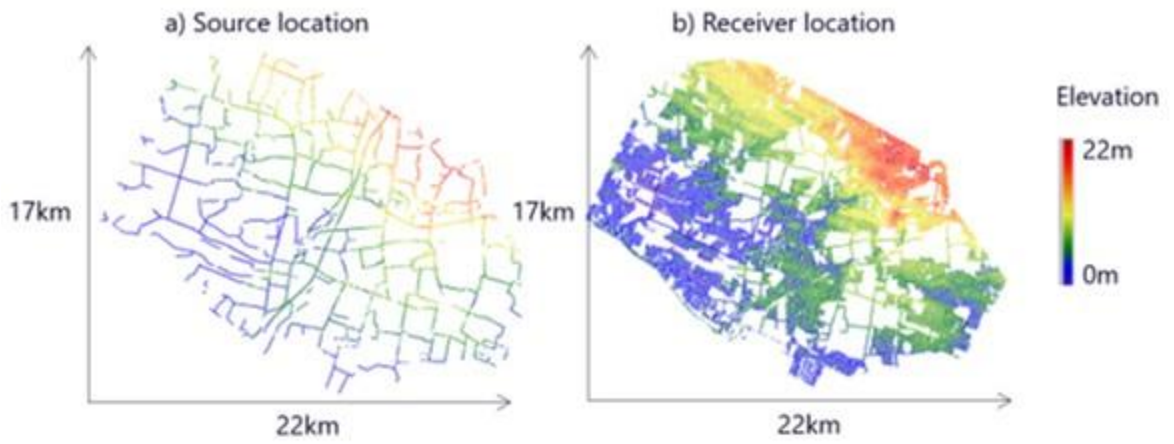

Figure 1 *Source and receiver location with elevation as colour attribute*

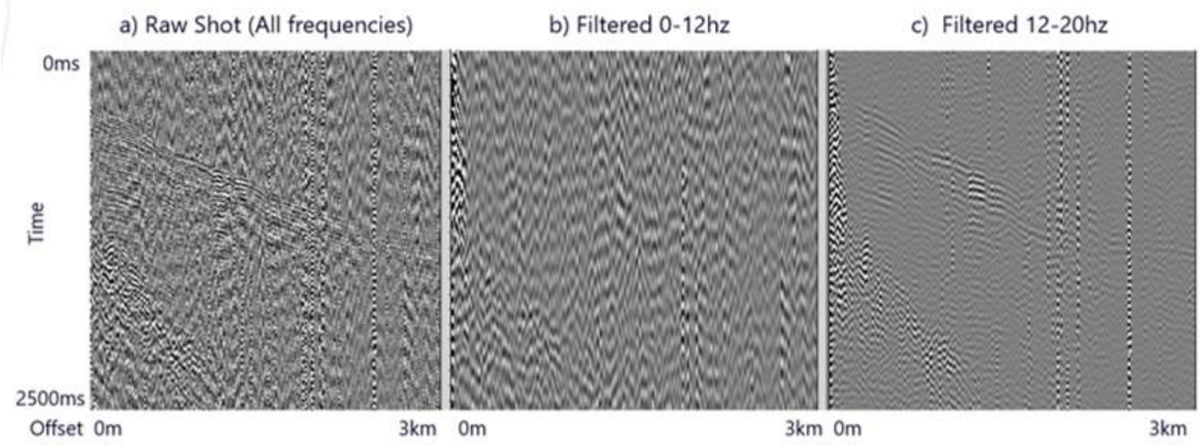

Figure 2 *Single raw shot a) unfiltered, b) filtered 0-12hz, c) filtered 12-20hz*

Methodology

The workflow (Fig. 3) leverages established land-processing technologies to support and stabilise the FWI process. Its success relies heavily on delivering the best possible starting velocity model, especially in the near surface, to minimise reliance on low frequencies and reduce the risk of cycle skipping.
The sequence begins with enhanced first-break picking, involving several rounds of manual and automatic picking until errors are reduced to a negligible level. These picks are then used in a non-linear diving-wave tomography to generate a very detailed near-surface velocity model (Fig. 4a) and a refraction-statics solution for the subsequent time-domain processing.
A crucial pre-processing step is 5D interpolation, which fills acquisition gaps and produces a more regular and consistent dataset for PSTM and PSDM. This improves the quality of the velocity-model-building stages and helps eliminate picking artefacts introduced by irregular acquisition geometry.
A full reflection-tomography workflow, including TTI anisotropy, is then applied to obtain the most accurate starting model possible. This incorporates the near-surface velocity model from diving-wave tomography into the shallow portion of the initial PSDM model, and uses available well data to constrain anisotropy parameters.
With the optimal PSDM velocity model established through this conventional sequence, the dataset is finally ready for FWI.

Because the first-break picking is highly reliable, synthetic first breaks can be generated from these picks and substituted for real refraction data at very low frequencies (Fig 4b & 4c). This approach stabilises the long-wavelength component of the FWI inversion, while real data are gradually reintroduced at higher frequencies (from 12 Hz up to 20 Hz), where the refraction energy becomes more trustworthy. When transitioning back to real data, careful muting of the observed input becomes essential. Allowing some reflection energy to remain, often stronger than the refractions, adds further stability to the inversion. Once the depth limit of refraction-based FWI is reached, the workflow switches entirely to Reflection FWI for continued velocity updating.

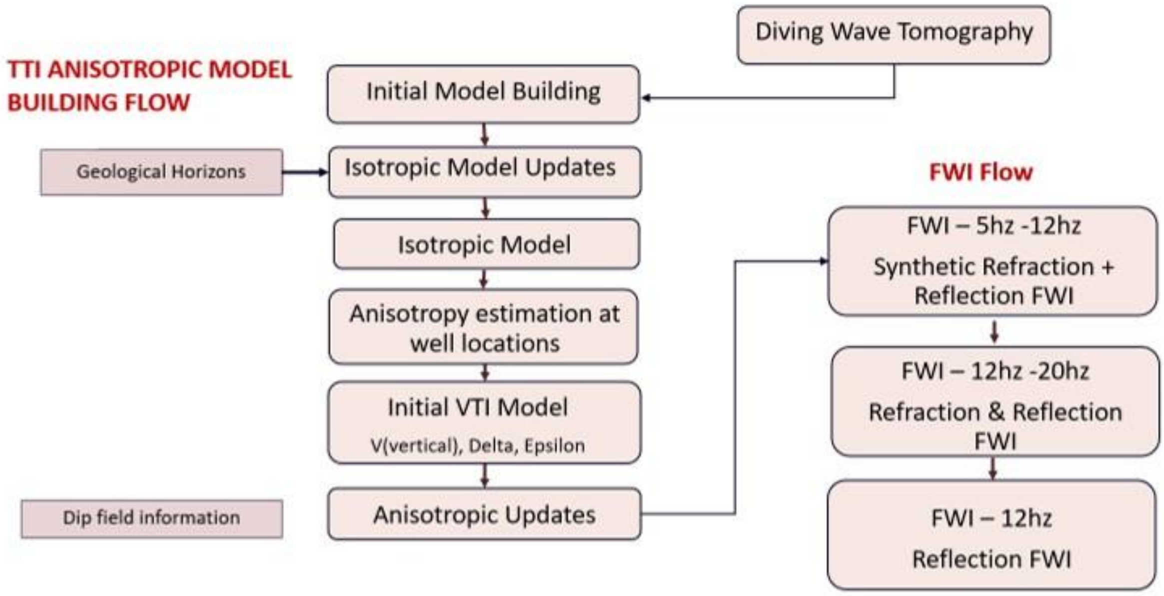

Figure 3 *Velocity Model Building Flow incorporating FWI*

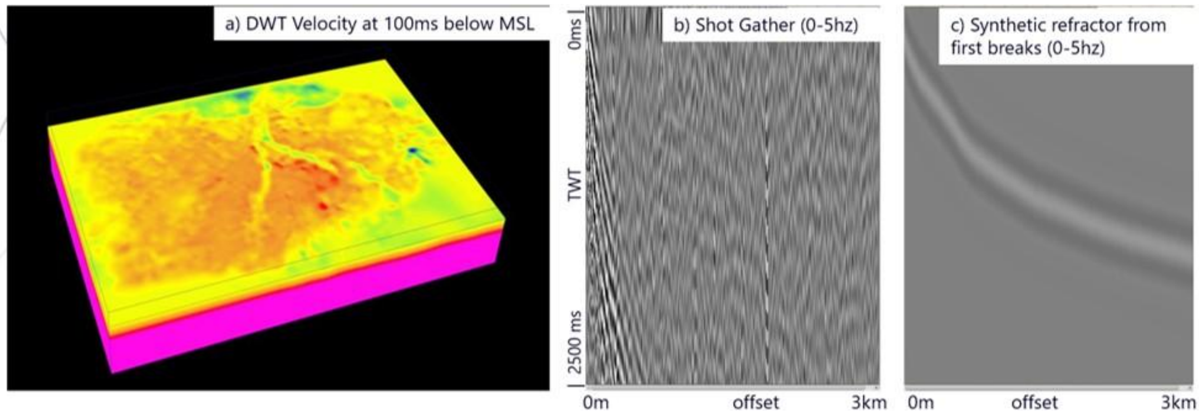

Figure 4 *a) Depth slice of Diving Wave Tomography Velocity Model, b) Shot gather filtered 0-5hz, c) shot gather with synthetic refractor from first breaks.*

Results

After applying the workflow, the FWI update to the TTI PSDM velocity model exhibits noticeably improved vertical and lateral resolution, as illustrated in the section comparison in Figure 5. The introduction of velocity inversions in the vertical profile aligns well with available well-velocity data, while enhancements in lateral continuity and horizon consistency are most evident in depth slices, an example of which is shown in Figure 6.
The low-frequency stabilisation provided by synthetic data proved critical to achieving these results. Tests demonstrated that without this component, the shallow velocity updates became unstable and risked introducing errors into the model, errors that could propagate downward and create misleading structural features in the deeper target intervals.

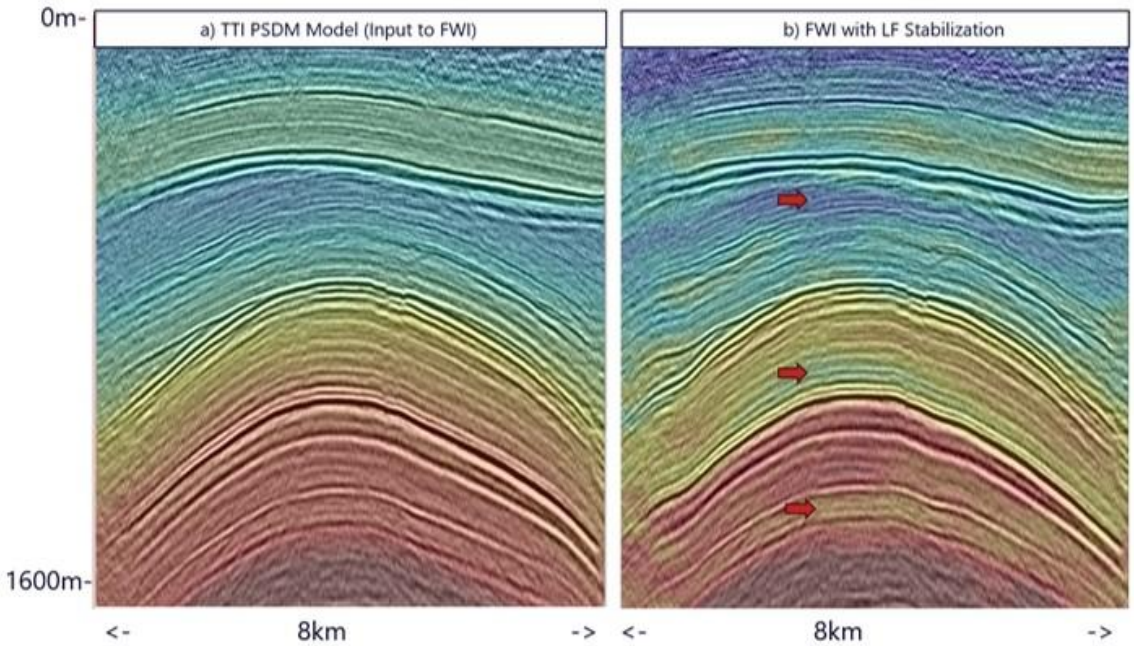

Figure 5 *a) TTI PSDM Model (input to FWI) overlain on PSDM, b) FWI model overlain on PSDM. Arrows indicate where inversion matches closely to well velocity profile.*

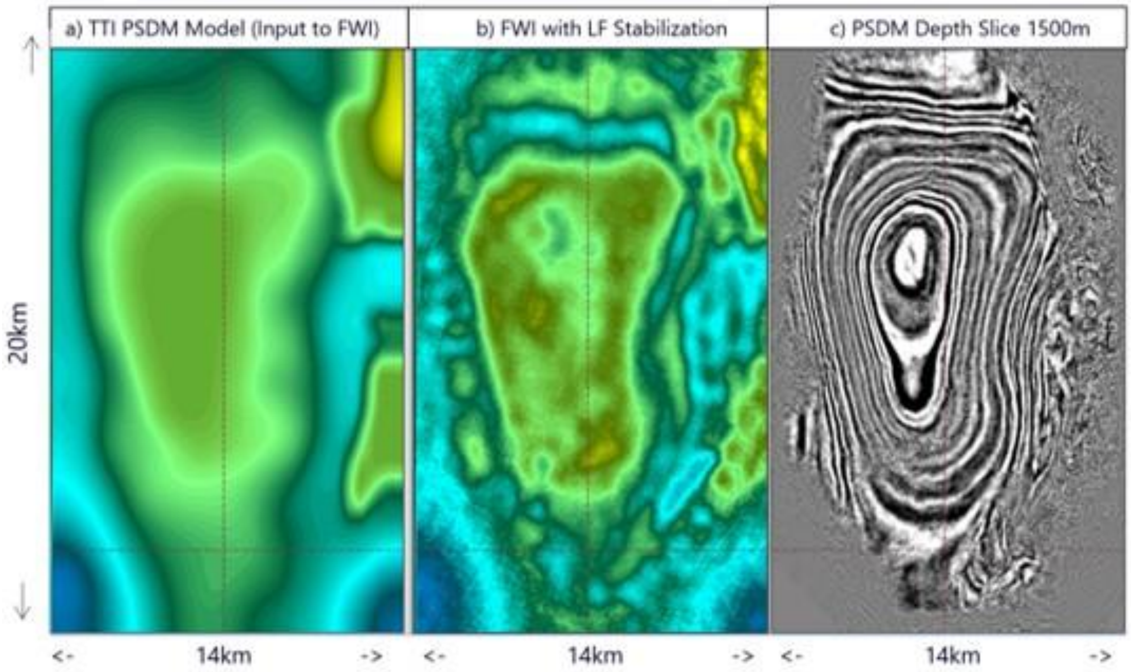

Figure 6 *Depth Slice at 1500m of a) TTI PSDM Model (input to FWI) b) FWI model c) PSDM (input to FWI velocity)*

Conclusions

This study shows that effective FWI updates are achievable even in sparse and noisy onshore acquisition environments when supported by a carefully structured velocity-model-building workflow. By combining detailed diving-wave tomography, 5D interpolation, and a well-constrained reflection-tomography starting model, the inversion remained stable despite the lack of usable low-frequency refraction energy. Synthetic first-breaks played a key role in preventing cycle skipping and enabling reliable long-wavelength updates. The resulting FWI model delivers improved vertical and lateral resolution consistent with well control, providing a more accurate foundation for imaging and CO_2 storage evaluation.

Acknowledgements

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