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Title:

MP-FWI, the key to unlock potential prospects in the Norwegian Sea - A case study from the Outer Vøring Area

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Summary

The Outer Vøring area in the Norwegian Sea has attracted increasing exploration interest in recent years. However, the region presents several challenges, including volcanic intrusions, remobilized ooze, and fault shadows. In this paper, we present a case study from the Outer Vøring area where we applied a Multi-Parameter Full Waveform Inversion (MP-FWI) workflow to derive a detailed velocity and Q model, along with a reliable angular impedance estimation. Furthermore, we demonstrate the advantages of a least-squares based imaging algorithm compared to a standard approach, both for structural imaging and quantitative interpretation (QI) purposes.

Introduction

Accurate imaging in complex geology requires a high-resolution velocity model, but velocity alone cannot correct amplitude distortions from absorption, acquisition footprint, or geological heterogeneity. Traditional FWI has been used to build detailed velocity models and structural images (e.g., FWI Imaging or FDR) by computing directional derivatives. Early implementations produced a single pseudo-reflectivity volume, later extended to partial-angle imaging through multiple parallel inversions. However, these angle stacks depended on predefined angles in pre-migration space, introducing uncertainty due to inaccurate angle estimation.

Recent advances now allow simultaneous inversion for velocity, Q, and angular impedance, providing more reliable subsurface characterization for both structural and amplitude-based interpretation. The resulting parameters can also be used to derive additional properties such as relative density and Vp/Vs ratios. The dataset in this study was acquired in 2016 in the Norwegian Sea in 800–1500 m water depth. The target area lies on the Nyk High, a structural feature with proven Upper Cretaceous hydrocarbons (e.g., Aasta Hansteen). Imaging is complicated by fault shadows, igneous intrusions, and remobilized ooze in the overburden, which can obscure signals and mask DHIs.

Theory

Conventional FWI minimizes residuals between recorded and modeled data by iteratively updating the velocity model. In this work, MP-FWI extends that approach to a multi-parameter inversion that simultaneously solves for velocity, impedance, and Q, enabled by two core components: vector reflectivity and the Inverse Scattering Imaging Condition (ISIC).

A key element is the modeling engine, which inverts the full recorded wavefield using a reformulated wave equation parameterized in terms of velocity and vector reflectivity rather than velocity and density. This eliminates the need for density assumptions, and Whitmore *et al.* (2020) demonstrated that it delivers equivalent modeling results.

The second pillar is ISIC, originally developed for RTM and later adapted for FWI by Ramos-Martinez *et al.* (2016). It decouples the tomographic and impedance kernels, allowing the inversion to recover the low-wavenumber background model without contamination from high-wavenumber migration isochrones, which can misplace velocity boundaries if introduced too early. Combined, these elements create a unified workflow that updates both kinematic (velocity) and dynamic (amplitude) properties. Earlier implementations produced a single impedance volume dependent on approximate angle selection, but the version used here extends the method to the prestack domain. As demonstrated by Chemingui *et al.* (2023), angular impedance is derived by mapping reflectivity into angle bins using the reflectivity vector and the direction of the forward-propagated wavefield.

Field data example

The area of interest in production license PL1234 is covered by a multisensor streamer survey that has undergone multiple processing efforts, including Q-Kirchhoff PSDM, Q-WEM, and RTM. Despite these attempts, key imaging challenges remained unresolved. However, a 2021 MP-FWI test—limited at the time to a single impedance output—demonstrated the strong potential of the approach.

The first phase of the current study focused on building a detailed velocity model suitable as an FWI starting point. Given the geological complexity of the area, the initial model was constructed through several iterations of reflection tomography, reinterpretation of key reflectors, and data-domain modeling QC. The model was then updated with FWI, emphasizing the low-wavenumber component by leveraging the tomographic kernel described earlier. After stabilizing the background velocity, higher-wavenumber details were introduced. Figure 1 compares the initial model with the 30 Hz FWI result, highlighting sharper definition of shallow ooze bodies, clearer stratigraphic layering, and better delineation of fault blocks—all contributing to improved migrated images.

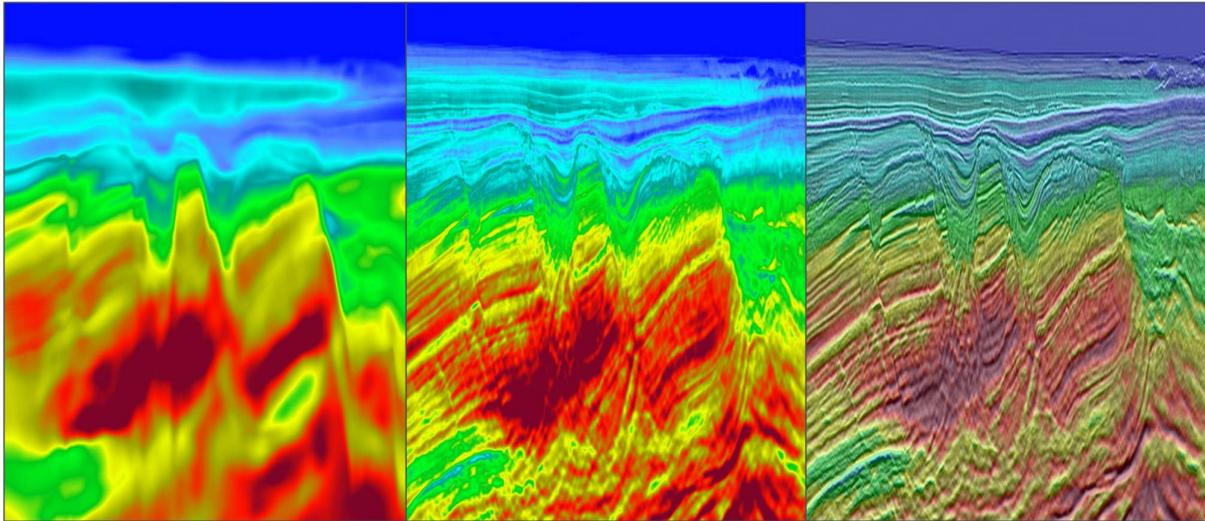


Figure 1: Initial velocity (left) in comparison to a 30Hz FWI model (middle) and its derived impedance (right)

In the second phase, the model was further refined using the MP-FWI workflow while simultaneously inverting for angular impedance. Comparing the MP-FWI-derived results with an RTM output, both in pre- and post-stack domains, shows an enhanced image in terms of illumination and structural imaging.

Conclusions

MP-FWI uses vector reflectivity and ISIC to simultaneously invert velocity and reflectivity, eliminating the need for a density model. By integrating tomographic and migration kernels within one framework, it enhances imaging in complex geology while mitigating illumination and blurring artifacts. Field results further demonstrate that the prestack implementation delivers higher-quality angle gathers than conventional migration approaches.

References

- Whitmore, N., Ramos-Martinez, J., Yang, Y. and Valenciano, A.A. [2020] Seismic modeling with vector reflectivity. 81st Annual International Meeting, SEG, Expanded Abstracts.
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