Multi-Parameter FWI for Velocity, Attenuation, and Angular Impedance: A Case Study, Outer Vøring Basin

Introduction

Accurate seismic imaging in geologically complex areas relies on the availability of high-resolution subsurface models. While velocity models play a central role in improving structural imaging, velocity alone is insufficient to fully account for amplitude distortions arising from absorption, acquisition footprint, and geological heterogeneity. These effects can significantly degrade amplitude fidelity and limit the reliability of quantitative interpretation, particularly in challenging overburden settings.

Full-waveform inversion (FWI) has become a key technology for building detailed velocity models and enhancing seismic images. Approaches such as FWI Derived Reflectivity (FDR) utilize directional derivatives to extract reflectivity information directly from the inverted velocity. Early implementations produced a single pseudo-reflectivity volume, which was subsequently extended to partial-angle imaging through multiple parallel inversions. However, these angle-dependent products typically rely on predefined angles in pre-migration space, introducing uncertainty due to inaccurate angle estimation and non-uniform illumination. Recent developments in inversion methodology now enable the estimation of multiple physical parameters, including velocity, attenuation (Q), and angular impedance. This multi-parameter framework provides a more physically consistent description of the subsurface and improves both structural imaging and amplitude preservation. The resulting parameter sets also form the basis for deriving additional attributes, such as relative density and Vp/Vs ratios, which are important for amplitude-versus-angle (AVA) analysis and reservoir characterization. In parallel with these advances, the underlying modelling engine has been enhanced through the implementation of an elastic wave-equation solver.

The dataset considered in this study was acquired in 2016 in the Norwegian Sea, in water depths of approximately 800–1500 m. The target area is located on the Nyk High, a structural feature with proven Upper Cretaceous hydrocarbon potential, including the Aasta Hansteen field. Imaging in this region is complicated by fault shadows, igneous intrusions, and remobilized ooze in the overburden, which can obscure seismic signals and mask direct hydrocarbon indicators. These challenges make the area well suited for evaluating advanced Multi-Parameter FWI (MP-FWI) approaches.

Theory

Conventional FWI formulates the inverse problem as the minimization of residuals between recorded and modeled seismic data through iterative updates of a velocity model. In this study, the approach is extended to MP-FWI, in which velocity, impedance, and Q are inverted. This extension is enabled by two key components: a vector reflectivity formulation and the Inverse Scattering Imaging Condition (ISIC), which together allow kinematic and dynamic subsurface properties to be recovered within a unified inversion framework.

A central element of the methodology 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 the more conventional velocity–density parameterization. By expressing reflectivity explicitly, the need for density assumptions is removed, reducing parameter trade-offs and model bias. Whitmore et al. (2020) showed that this formulation produces modeling results equivalent to conventional approaches while offering greater flexibility for multi-parameter inversion.

The second methodological pillar is the ISIC, originally developed in the context of reverse time migration (RTM) and later adapted for FWI by Ramos-Martinez et al. (2016). ISIC separates the tomographic (low-wavenumber) and impedance (high-wavenumber) components of the inversion by decoupling the corresponding sensitivity kernels. This separation allows the background velocity model to be updated without contamination from migration isochrones, which can otherwise introduce premature high-wavenumber updates and lead to mispositioned velocity contrasts. As a result, velocity and impedance updates can be introduced in a more physically consistent and stable manner. Together, the vector reflectivity formulation and ISIC define a unified MP-FWI workflow capable of jointly updating kinematic properties, such as velocity, and dynamic properties related to reflectivity and attenuation. Early implementations of this approach produced a single impedance volume that depended on approximate angle selection in pre-migration space. The formulation used in this study extends the method to the pre-stack domain, enabling the recovery of angular impedance. As demonstrated by Chemingui et al. (2023), angular information is obtained by mapping the reflectivity vector into angle bins using the local propagation direction of the forward-modeled wavefield, avoiding reliance on predefined angles and improving the robustness of amplitude-versus-angle analysis.

Examples

The area of interest, located within production license PL1234, is covered by a multisensor streamer seismic survey that has been subjected to multiple imaging and processing workflows, including Q-Kirchhoff pre-stack depth migration (Q-Kirchhoff PSDM), Q wave-equation migration (Q-WEM), and reverse time migration (RTM). Despite these efforts, several key imaging challenges persisted, particularly in areas affected by complex overburden and variable illumination. An MP-FWI test conducted in 2021, although limited at the time to a single impedance output, indicated significant potential for improved subsurface characterization and motivated the present study.

The first phase of the current work focused on the construction of a high-quality velocity model suitable for use as an FWI starting model. Given the geological complexity of the study area, this initial model was developed through multiple iterations of reflection tomography, repeated reinterpretation of key stratigraphic horizons, and extensive data-domain modeling quality control. Particular attention was paid to ensuring kinematic consistency across the dataset. This background model was subsequently updated using FWI, with an emphasis on recovering the low-wavenumber velocity component by exploiting the tomographic kernel described in the previous section. Once a stable background velocity has been established, higher-wavenumber updates were progressively introduced to enhance structural detail.

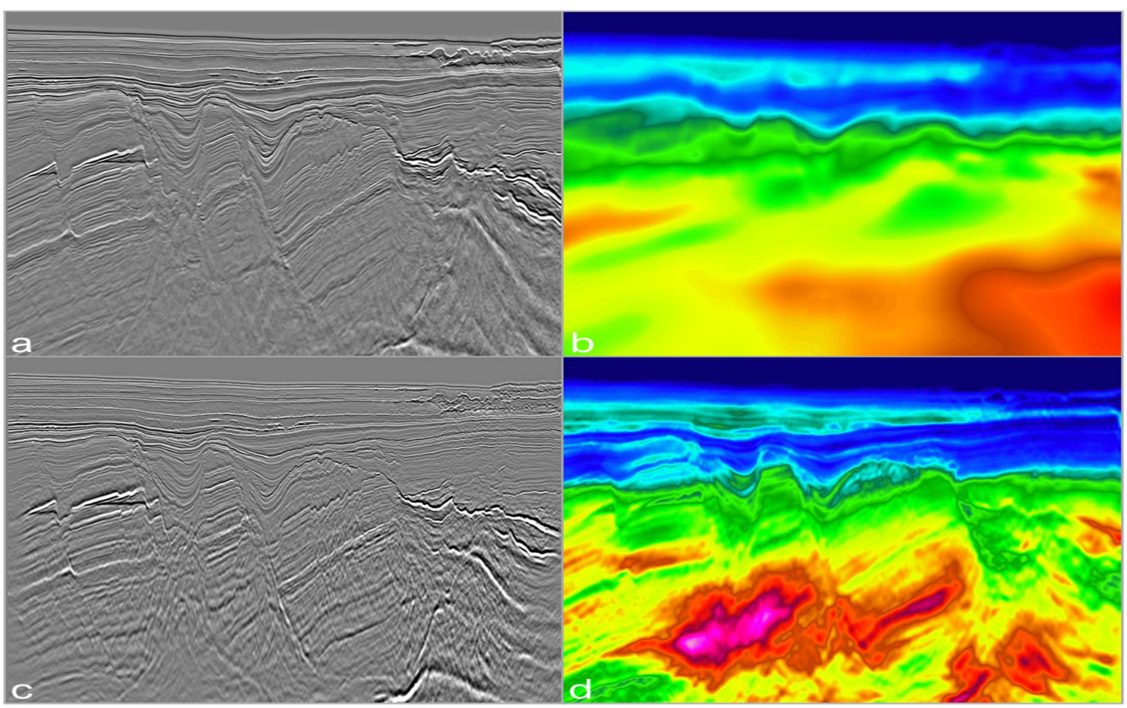

Figure 1 *Vintage KPSDM full offset stack (a) and its corresponding velocity model (b) which was the starting model for FWI. Final KPSDM full offset stack (c) and 20Hz FWI velocity model (d). Note the structural improvement.*

Figure 1 illustrates the improvement achieved through this process by comparing the initial velocity model with the final FWI result up to 20 Hz. The updated model exhibits sharper definition of shallow remobilized ooze bodies, clearer stratigraphic layering, and improved delineation of fault blocks. These velocity improvements translate directly into a better-focused and more geologically consistent migrated image.

In the second phase of the study, the velocity model was further refined using the full MP-FWI workflow, with simultaneous inversion for angular impedance. The maximum frequency was increased from 20 to 40 Hz. The resulting images were compared with conventional KPSDM and RTM outputs in both pre-stack and post-stack domains. Figure 2 shows full angle stack comparisons between KPSDM, RTM and MP-FWI reflectivity. This comparison demonstrates notable improvements in illumination, structural continuity, and fault definition, particularly in areas previously affected by shadow zones.

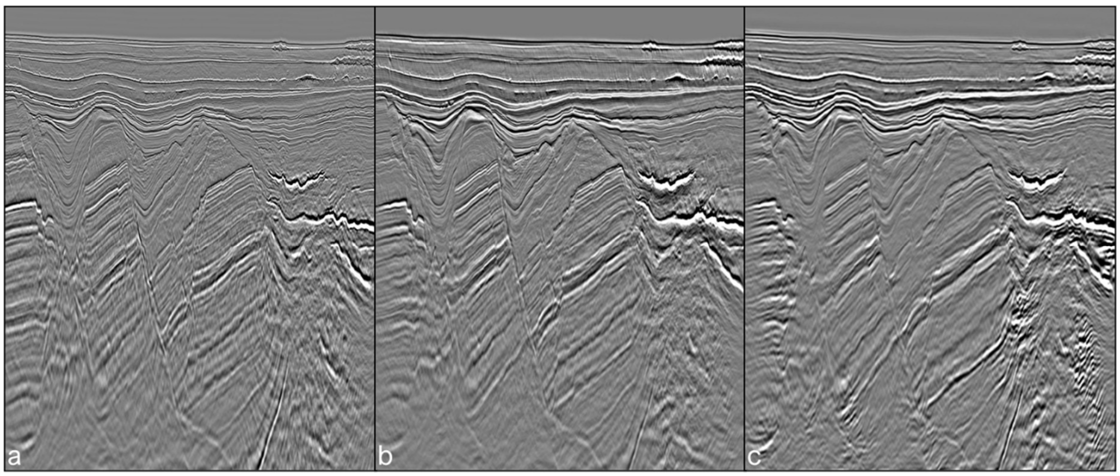

Figure 2 *Comparison between full angle stacks from KPSDM (a), 50Hz RTM (b) and 40Hz MP-FWI reflectivity (c).*

Figure 3 presents Amplitude Versus Angle (AVA) quality control (QC) at the well A location. The preliminary MP-FWI angle gathers are compared against full Zoeppritz modelling using pre-stack statistical wavelets focused on the Shetland Group. Amplitude extraction is performed at two key sand reservoirs: the in-situ gas-bearing Nise Formation (light blue level) and the water-bearing Kvitnos Formation (purple level). Amplitude values are shown in black for seismic data and blue for synthetics. A two-term Shuey approximation was fitted to the data, restricting input angle information to the 5°–30° range. Preliminary results at well A are promising, supporting further amplitude-based interpretation.

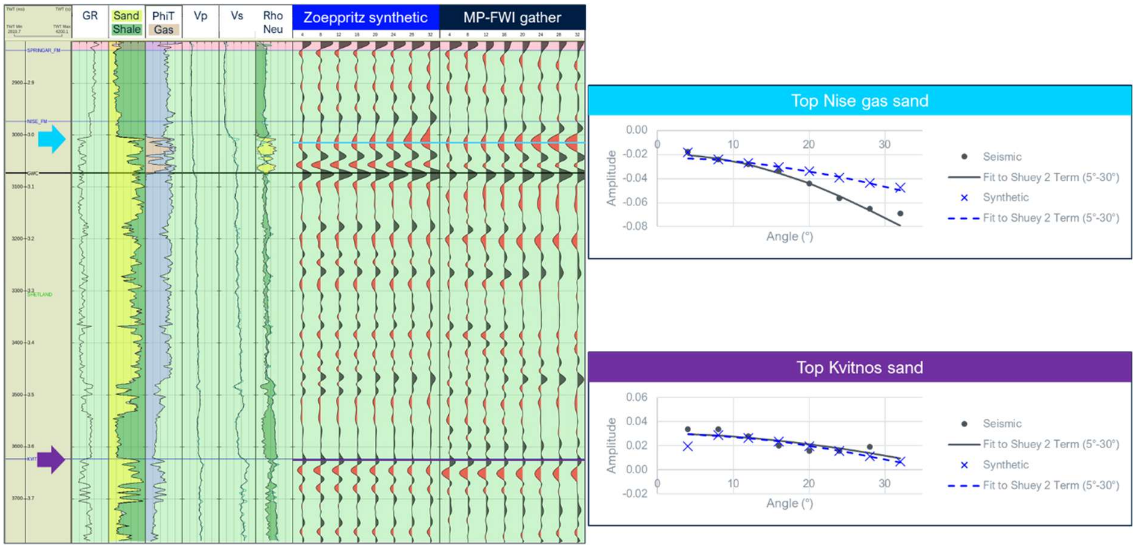

Figure 3 *AVA (Amplitude Vs. Angle) analysis at well A location focusing on Shetland Group. Amplitudes are extracted along Top Nise gas-bearing (light blue) sand and Top Kvitnos sand (purple).*

Conclusions

This study shows that MP-FWI can significantly improve seismic imaging in geologically complex areas. By jointly inverting for velocity and angular impedance using vector reflectivity and the Inverse Scattering Imaging Condition, MP-FWI produces clearer velocity models and better-focused images. Key features such as shallow ooze bodies, stratigraphy, and fault blocks are more sharply resolved, and pre-stack angular impedance improves the reliability of amplitude-versus-angle analysis. The inclusion of an elastic modeling engine further strengthens the workflow and minimized the requirement of additional processing of the field data. Overall, MP-FWI provides a robust and practical approach for improving both structural imaging and amplitude-based interpretation in complex geological settings.

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