Multi Parameter Elastic FWI for Reliable Depth Imaging and Seismic Attribute Analysis

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Summary

Full waveform inversion (FWI) has become a central component of modern velocity model building workflows, particularly in areas characterized by complex geology and strong velocity contrasts. In such settings, acoustic assumptions are often insufficient to reproduce key wave phenomena observed in seismic data, including mode conversions and guided wave energy. Elastic FWI provides a more complete physical description of wave propagation and has demonstrated improved robustness and accuracy in these environments.

This abstract presents an elastic FWI case study based on a North Sea Ocean Bottom Node (OBN) survey. The workflow produces a reliable velocity model that enables accurate structural imaging at the correct vertical depth and supports geological interpretation from shallow gas accumulations to basement related velocity variations. The inversion is performed using a phase driven dynamic matching objective function combined with a quasi-Newton optimization strategy. To mitigate discrepancies between observed and modeled data caused by wave phenomena not fully captured in the modeling engine, a data reconstruction approach is applied, allowing improved utilization of the full dataset.

Building on the elastic FWI results, elastic multi parameter FWI (eMP FWI) is evaluated to recover additional subsurface properties. The eMP FWI workflow provides direct access to seismic attributes such as P wave impedance, absolute density, and Vp/Vs ratio. These attributes show good agreement with well data and complement conventional imaging products, contributing to an enhanced understanding of the subsurface.

Introduction

Velocity model building remains one of the most critical steps in seismic imaging, particularly in regions where complex geology introduces strong lateral velocity variations, significant velocity contrasts, and mode converted energy. Conventional ray-based methods and acoustic FWI approaches often struggle in such settings, as acoustic modeling cannot reproduce key elastic wave phenomena present in the recorded data. These limitations frequently lead to cycle skipping or require extensive data conditioning, restrictive muting strategies, or additional inversion constraints to stabilize the process.

Elastic full waveform inversion addresses many of these challenges by incorporating a more complete physical description of wave propagation. By accounting for both compressional and shear wave effects, elastic FWI improves data fitting in areas with strong contrasts and complex overburden and has shown increased robustness compared to acoustic formulations. However, successful elastic FWI does not depend solely on the modeling engine. The choice of objective function, optimization strategy, inversion parameterization, and data conditioning remains critical to achieving stable convergence and geologically meaningful results.

In this study, elastic FWI is applied to a North Sea OBN dataset to generate a velocity model that supports accurate structural imaging and geological interpretation. The area is characterized by a chalk–basement system with localized shallow gas accumulations and fractured basement structures. These features present challenges for conventional imaging workflows but provide an ideal test case for elastic FWI.

Beyond velocity model building, there is growing interest in extending FWI toward the recovery of additional subsurface properties that can support interpretation. Elastic multi parameter FWI (eMP FWI) aims to simultaneously invert multiple earth parameters, separating kinematic and dynamic effects in the data. In this work, eMP FWI is evaluated as a follow up to elastic FWI to assess its ability to deliver interpretable seismic attributes that complement conventional imaging results.

Elastic FWI Workflow

The elastic FWI workflow (Liu *et al*., 2024) updates the P-wave velocity (Vp) model using an elastic modeling engine. Initial shear wave velocity (Vs) and density models are constructed from empirical relationships to Vp, derived from available well log information and Gardner's equation. These initial models provide a smooth and geologically reasonable starting point that captures the large-scale background trend required for stable inversion. As the inversion progresses, Vs and density are updated indirectly in response to changes in the Vp model.

The objective function is based on dynamic matching (Mao *et al*., 2020), which maximizes localized, windowed cross correlation between observed and modeled seismic data. Unlike conventional least squares formulations, dynamic matching is less sensitive to amplitude mismatches and focuses primarily on phase alignment. This phase driven behavior improves robustness against cycle skipping, particularly at early inversion stages and in the presence of noise. The objective function has proven effective in elastic FWI applications where amplitude fidelity is difficult to achieve due to incomplete physics or uncertainties in source and receiver responses.

Optimization is performed using a quasi-Newton L-BFGS algorithm. Compared to steepest descent approaches, L-BFGS accelerates convergence by approximating second order curvature information while maintaining manageable memory requirements. The combination of elastic modeling, dynamic matching, and L-BFGS optimization results in a stable and efficient inversion workflow.

Data Reconstruction

Despite the use of elastic modeling, certain wave phenomena present in the field data are not fully reproduced by the modeling engine. These include guided waves such as Scholte waves, attenuation effects, and other phenomena linked to passive model parameters that are not explicitly inverted during FWI. If left unaddressed, these mismatches can degrade inversion performance and limit the usable portion of the dataset.

To mitigate these effects, a data reconstruction approach (Zuberi *et al*., 2023) is applied. In this workflow, a global matching filter is computed for each node using synthetic data as the target. The same filter is applied to all traces within a given node, ensuring that the kinematics of the observed data are preserved. This approach reduces discrepancies between observed and modeled data while addressing uncertainties in the source wavefield and receiver response.

The effect of data reconstruction is illustrated in Figure 1, which compares the P-total field data before and after reconstruction, alongside elastic modeling. The reconstruction suppresses coherent linear noise and improves data quality near the apex, enabling more complete use of the dataset in the inversion. Data reconstruction was applied from frequencies above 10 Hz, where the impact of unmodeled wave phenomena becomes more pronounced.

Inversion Strategy

The inversion is performed in multiple frequency stages, progressing up to 25 Hz. Most stages use the full dataset without muting, reflecting the robustness of the dynamic matching objective function and the data reconstruction strategy. By minimizing reliance on data selection and manual intervention, the workflow remains largely data-driven and reproducible.

Examples

The initial velocity model captured the regional background trend but contains limited structural detail, apart from the pronounced velocity contrast at the chalk–basement interface at approximately 1.9 km depth. Imaging results obtained with this initial model are shown in Figure 2a–d, including the Kirchhoff PSDM image and a 3D view through the well location. While the initial model supports basic imaging, significant structural complexity and lateral variations are not resolved.

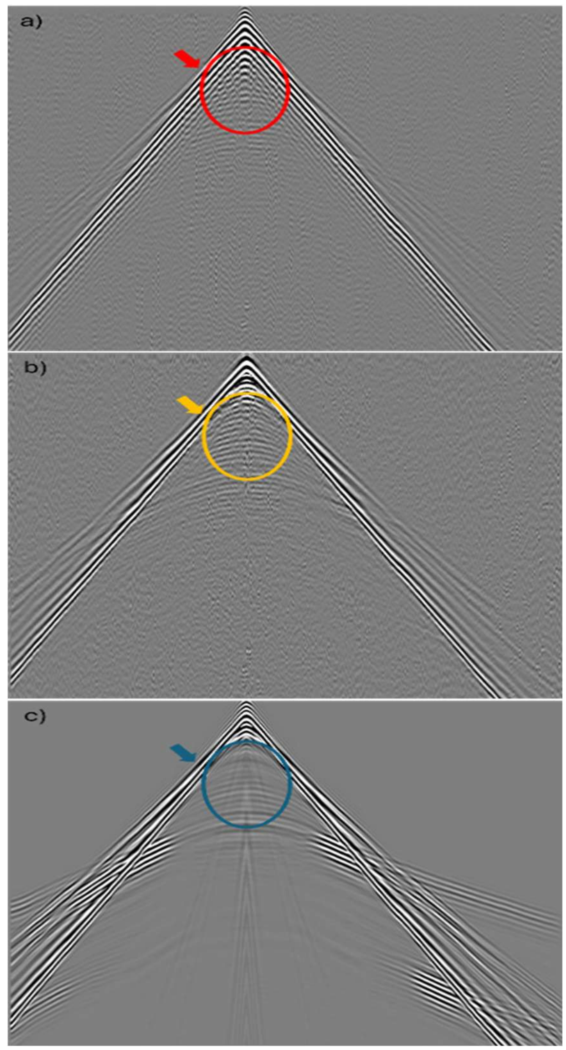

Figure 1: P-total field data at 25Hz before (a) and after (b) data reconstruction compared to elastic modeling (c). Notice how the reconstruction suppresses the parallel linear events and cleans the data near the apex (annotated by the arrow and ellipse) and enables FWI to utilize the full dataset in the inversion process.

After elastic FWI, the inverted velocity model and corresponding images (Figure 2e–h) show a substantial increase in geological detail. Shallow gas accumulations are clearly visible as localized low velocity anomalies, while stratigraphic layering within the chalk becomes more coherent. Lateral velocity variations within the basement correlate with known faulting patterns, providing additional insight into the fractured basement structure.

A key observation is the structural simplification of the chalk–basement interface after inversion, which has been validated via horizontal drilling (Dhelie *et al*., 2022). Compared to the initial PSDM image, the inverted results exhibit a geometry that is more consistent with geological expectations for this area. This simplification is achieved without reflection tomography or manual model editing, highlighting the data driven nature of the elastic FWI workflow.

Vertical depth mis ties at the well location are significantly reduced after elastic FWI. As shown in the 3D views in Figure 2d and 2h, key geological markers align closely with the inverted image, with residual depth errors on the order of one meter. This improvement is critical for well planning and reservoir characterization, particularly in areas where small depth errors can have significant operational implications.

Building on the elastic FWI results, elastic multi parameter FWI (eMP FWI) was applied to recover additional subsurface properties. The eMP FWI workflow started from an intermediate elastic FWI model, providing a well-conditioned starting point for simultaneous inversion of multiple parameters.

The wave equation is parameterized in terms of Vp, Vs, and P-wave reflectivity/impedance. An inverse scattering imaging condition is used to decouple the sensitivity kernels associated with kinematic (velocity) and dynamic (impedance) effects (Whitmore and Crawley 2012, Ramos-Martinez *et al*., 2016, Yang *et al*., 2021 and Huang *et al*., 2025). This separation reduces parameter tradeoffs and allows the inversion to recover a Vp model that primarily explains kinematic effects, while the impedance model captures amplitude related information.

Relative density estimates obtained from the inversion are combined with an empirical background trend to construct a detailed absolute density model. This approach allows density variations to be resolved at seismic scale while maintaining consistency with well log information. The resulting density model can be reintroduced into subsequent elastic FWI runs without causing density leakage into the velocity updates (Korsmo *et al*., 2022).

The eMP FWI inversion products are shown in Figure 3. The inverted Vp model (Figure 3a) follows the sonic log trend at the well location, confirming the kinematic consistency of the inversion. The relative P-impedance (Figure 3b) highlights lateral variations associated with stratigraphy and basement structure. The absolute density model (Figure 3c) shows strong agreement with the density log, indicating that the inversion successfully captures meaningful density variations. The derived Vp/Vs ratio (Figure 3d) provides additional information relevant for lithological interpretation.

These attributes are obtained directly from the eMP FWI process and are available in 3D, offering complementary information to conventional imaging products. When used together, velocity, impedance, density, and Vp/Vs ratio enhance the interpretability of the seismic data and support integrated subsurface characterization.

Conclusions

This abstract demonstrates that elastic full waveform inversion provides reliable velocity models and accurate structural imaging at the correct vertical depth in a North Sea OBN setting. The elastic FWI workflow resolves key geological features, including shallow gas accumulations, stratigraphic layering, and lateral velocity variations within fractured basement rocks. The inversion is fully data driven and does not rely on reflection tomography or manual model intervention.

The use of a phase driven dynamic matching objective function, combined with an efficient L BFGS optimizer, ensures stable convergence and robust performance. A data reconstruction strategy mitigates the impact of wave phenomena not fully captured by the modeling engine, enabling improved utilization of the full dataset.

Elastic multi parameter FWI extends the workflow beyond velocity model building by providing additional seismic attributes, including P wave impedance, absolute density, and Vp/Vs ratio. These attributes show good agreement with well data and complement conventional imaging products, contributing to an enhanced understanding of the subsurface. Together, elastic FWI and eMP FWI form a powerful framework for seismic imaging and interpretation in complex geological environments.

Acknowledgments

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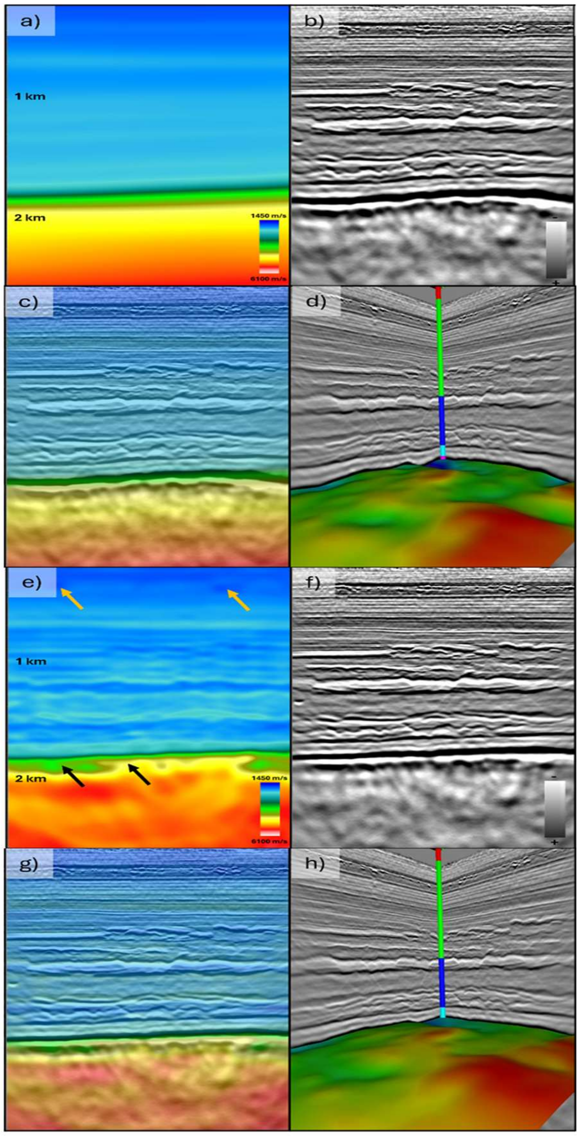

Figure 2: a) Initial velocity model, b) Kirchhoff PSDM image, c) initial model and image overlay, d) 3D-view of initial image through the well location with markers and Top Chalk interpretation snapped to the initial image. The corresponding results after elastic FWI shown in e) to h). Notice the details captured in the inverted velocity model (gas pockets, stratigraphic layering and lateral variations in the basement structure). Furthermore, notice the structural simplification of the Chalk/Basement layer, which agrees with the geological expectations, and the vertical depth mistie reduced to practically zero after inversion.

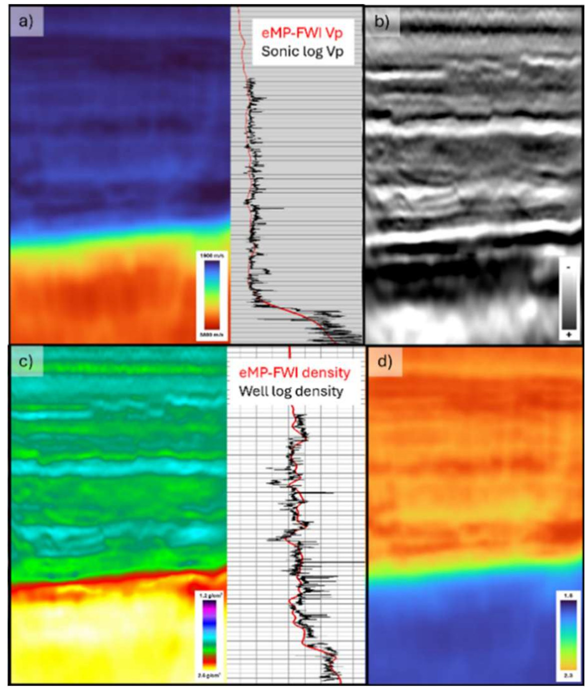

Figure 3: Inversion products from eMP FWI: a) Vp model and sonic log, b) relative P-impedance, c) absolute density and density log and d) Vp/Vs-ratio. Notice how both the inverted Vp and absolute density captures the measured variations at the well. The eMP FWI gives direct access to 3D attributes like (Vp, impedance, density and Vp/Vs-ratio) that could supplement the conventional imaging products.