Accurate Structural Imaging with Elastic FWI and Multi-Parameter Inversion for Seismic Attribute Estimation

Introduction

In recent years, Full Waveform Inversion (FWI) based on elastic wave propagation has gained preference over acoustic implementations for complex imaging projects. When significant mode conversions occur during seismic acquisition (typically associated with strong velocity contrast) an acoustic modeling engine cannot reproduce these observed effects. This limitation often prevents the inversion from converging unless specific data selections, pre-processing steps, or inversion constraints are applied to mitigate the impact of missing physics. A robust modeling engine is essential for successful FWI; however, the choice of objective function, optimization strategy, and parameterization (e.g., Vs, density, impedance, or reflectivity) is equally critical.

In this paper, we demonstrate how elastic FWI enables accurate structural imaging at the correct vertical depth and supports geological interpretation, from shallow gas accumulations to lateral velocity variations within fractured basement rocks. The case study is based on an Ocean Bottom Node (OBN) survey from the North Sea. Furthermore, we investigate elastic multi-parameter FWI (eMP-FWI) to derive additional attributes such as density, impedance, reflectivity, and the Vp/Vs ratio.

Methodology - Elastic FWI

In the first phase of this case study, we employ an elastic FWI engine (Liu *et al.*, 2024) to update the pressure-wave velocity (Vp) model. The initial shear-wave velocity (Vs) model and density field were built based on a linear and empirical relationship to Vp from well log information and Gardner's equation. These parameters were subsequently updated during the inversion process based on changes in the Vp model. The FWI objective function is based on Dynamic Matching (Mao *et al.*, 2020), which maximizes the local windowed cross-correlation between observed and modeled data. This norm has proven robust against cycle-skipping and low signal-to-noise ratio (SNR), while being less sensitive to amplitude variations, making the inversion primarily phase-driven. The optimization leverages a quasi-Newton (L-BFGS) method, which enhances convergence, particularly when improved physics (elasticity) is incorporated into the modeling.

Although elastic modeling is utilized, certain wave phenomena observed in the field data may not be fully reproduced. These discrepancies can arise from effects such as Scholte waves, attenuation, or other mechanisms not accurately represented in the modeling engine or in "passive model parameters" (parameters not actively inverted during FWI). To mitigate these effects, we apply a data reconstruction approach (Zuberi *et al.*, 2023), computing and applying a global matching filter for each node using synthetic data as the target. This process does not alter the kinematics of the observed data since the same filter is applied to all traces within the node. Furthermore, it will address uncertainties in the source wavefield.

The inversion was performed in frequency stages up to 25 Hz, with most stages utilizing the full dataset without mute functions. The data reconstruction approach was applied from frequencies above 10 Hz to enable improved utilization of the complete dataset (see Figure 1).

Inversion results – elastic FWI

Figure 2a-d shows the initial velocity model and the corresponding imaging results; a) Vp model, b) Kirchhoff PSDM stack, c) Vp model and image overlay, d) 3D view of the image through the well location and Top Chalk surface interpretation. Figure 2e-h shows the corresponding results after elastic FWI. The initial model captured the background trend, facilitating a stable inversion process, but did not contain any details apart from the velocity boundary at the Chalk/Basement interface (approx. 1.9 km depth).

As shown in figure 2e-h, the inversion has captured significant number of geological details; from shallow gas pockets (yellow arrows), stratigraphic layering and lateral velocity variations in the Chalk/Basement structure correlating to the basement faulting (black arrows). The sequence was purely data-driven, without any manual editing, and did not involve any reflection tomography. Most importantly, the seismic structure changes drastically with the inversion, comparing figure 2b and 2f. The geological expectations in this area support a simplistic Chalk/Basement structure, as seen in the inverted results, which has been confirmed through horizontal drilling (Dhelie *et al*., 2022). Vertical depth mispositioning at the well location has been reduced to practically zero (~1 meter) for the key markers after elastic FWI, see figure 2h.

Further work - elastic multi-parameter FWI (eMP-FWI)

Based on the encouraging elastic FWI results, further investigations were done with elastic multi-parameter FWI (eMP-FWI). The purpose of this test was to evaluate if eMP-FWI could resolve additional earth properties that could lead to a better description of the subsurface geology.

The aim of eMP-FWI is to resolve two (or more) model parameters that can explain the observed data. This can be achieved through an alternative formulation of the wave equation combined with the deployment of seismic scale separation. In practice, we make use of an elastic wave equation parametrized with variable Vp, Vs and P-wave reflectivity/impedance and utilize the inverse scattering imaging condition (ISIC) to de-couple the tomographic kernel from the impedance kernel in FWI (Whitmore and Crawley 2012, Ramos-Martinez *et al*. 2016, Yang *et al*. 2021 and Huang *et al*., 2025). This leads to an inverted Vp model that primarily explains the kinematic effects and an impedance model that explains the dynamic effects in the data. The two products can be directly used to build a detailed absolute density model by combining the relative density product with a background trend from an empirical relation (like Gardner's relation). The new detailed absolute density model can further be utilized in elastic FWI with the conventional cross-correlation kernel to bring the resolution up further and still avoid density effects leaking into the velocity model (Korsmo *et al*., 2022).

Our eMP-FWI test started with an intermediate model from the elastic FWI process, allowing the inversion to fit the two model parameters as required. Figure 3 shows the different seismic attributes derived directly from the eMP-FWI process. Figure 3a shows the inverted Vp-model and its comparison with the sonic trend. Figure 3b displays the relative P-impedance. Figure 3c shows the absolute density model as described in the section above and its comparison with the log density. Figure 3d displays the Vp/Vs-ratio based on the linear relationship between Vp and Vs as outlined previously. The inverted Vp-model captures correctly the trend seen in the sonic log and the detailed absolute density model shows high correlation to the log density at the well location. The eMP-FWI process gives directly access to 3D attributes as shown in Figure 3, which can be complementary to the traditional imaging products and thus increase the understanding of the seismic subsurface.

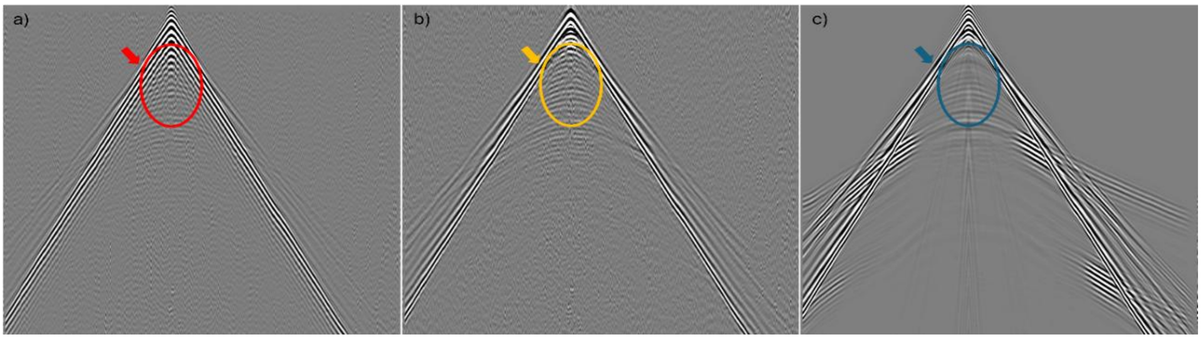

Figure 1 *P-total field data at 25Hz before (a) and after (b) data reconstruction compared to elastic modeling (c). Notice how the reconstruction suppresses the parallel linear events and cleans the data near the apex (annotated by the arrow and ellipse) and enables FWI to utilize the full dataset in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

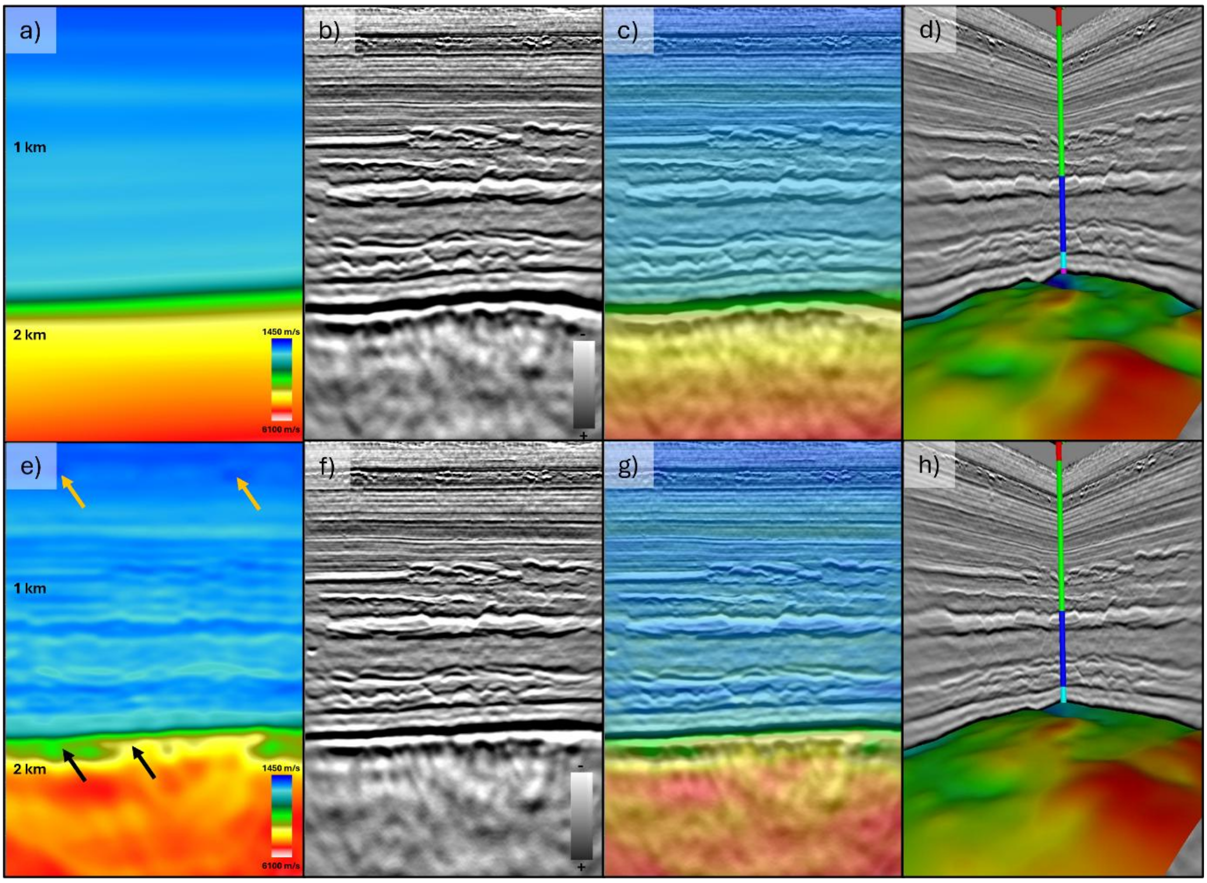

Figure 2 *a) Initial velocity model, b) Kirchhoff PSDM image, c) initial model and image overlay, d) 3D-view of initial image through the well location with markers and Top Chalk interpretation snapped to the initial image. The corresponding results after elastic FWI shown in e) to h). Notice the details 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.*

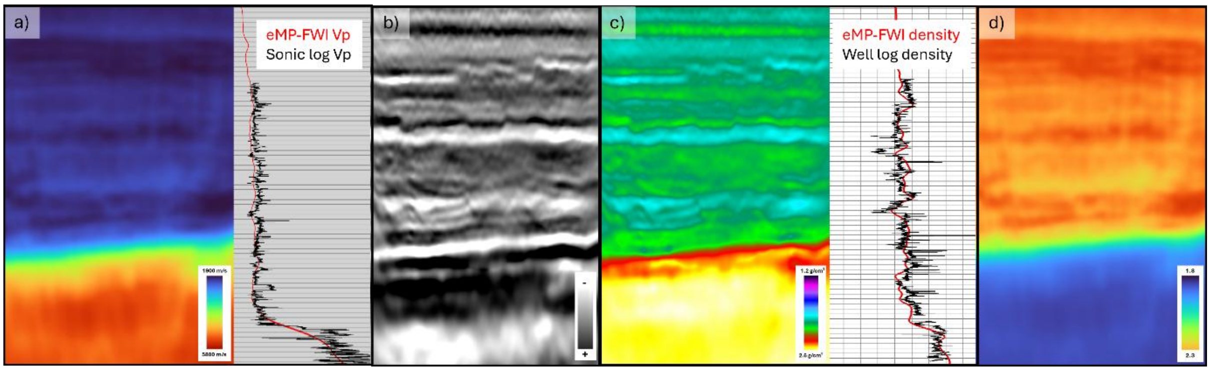

Figure 3 *Inversion products from eMP-FWI: a) Vp model and sonic log, b) relative P-impedance, c) absolute density and density log and d) Vp/Vs-ratio. Notice how both the inverted Vp and absolute density captures the measured variations at the well. The eMP-FWI gives direct access to 3D attributes like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

Conclusions

In this case study we have demonstrated how elastic FWI can provide a reliable velocity model that leads to correct structural imaging at the right vertical depth over a typical North Sea geology. The details in the velocity field can be used to map out geological features like shallow gas-pockets, stratigraphic layers and lateral velocity variations in the fractured and faulted basement. Our implementation utilizes a robust and phase-driven dynamic matching objective function and an efficient quasi-Newton (L-BFGS) solver to accelerate the convergence. Furthermore, we have shown that elastic multi-parameter FWI can provide additional attributes such as Vp, P-wave impedance, absolute density and Vp/Vs-ratio. Results are validated by the good match of these attributes with the measured values at the well location. Our implementation makes use of an elastic wave equation formulated in terms of Vp, Vs and P-wave reflectivity/impedance, combined with the inverse scattering imaging condition for sensitivity kernel de-coupling (kinematics, dynamics).

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