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Characterization of a Carbonate-Basement System with Elastic Multi-Parameter FWI on OBN Data

Øystein Korsmo, TGS, Oslo, Norway; John Brittan, TGS, Weybridge, UK; Mokhtar Raafat, TGS, Cairo, Egypt

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Abstract

This study presents an elastic Full Waveform Inversion (FWI) workflow applied to an Ocean Bottom Node (OBN) dataset, with the aim of generating reliable velocity models for accurate structural depth imaging and geological interpretation. The important elements of the geology in the study area a carbonate-basement system with shallow gas accumulations and fractured basement structures. A secondary objective is to evaluate elastic multi-parameter FWI (eMP-FWI) as an extension of the workflow, targeting the recovery of additional subsurface properties: P-wave impedance, absolute density, and Vp/Vs ratio. The derivation of these properties is a key element of using eMP-FWI for seismic attribute analysis and integrated interpretation.

The elastic FWI workflow updates P-wave velocity (Vp) using an elastic modelling engine, with initial shear wave velocity (Vs) and density models derived from well log data and Gardner's equation. A phase-driven dynamic matching objective function, combined with a quasi-Newton L-BFGS optimizer, drives stable convergence while reducing sensitivity to amplitude mismatches and cycle skipping. A data reconstruction approach is applied to suppress unmodelled wave phenomena (e.g., Scholte waves, attenuation effects) as this improves the utilization of the full dataset in the inversion. The eFWI workflow used multiple frequency stages up to 25 Hz. The eMP FWI stage then simultaneously inverted Vp, Vs, and P-wave impedance, using an inverse scattering imaging condition to decouple kinematic and dynamic sensitivities.

Introduction

Traditional full-waveform inversion (FWI), solving for P-wave velocity only, has become as a core component of velocity model building (VMB) workflows in seismic exploration. As computational power has grown and with the widespread use of cycle-skip- resistant misfit norms, it has become common to use FWI on both low frequencies and high frequencies from the recorded data, with the aim of directly updating reservoir properties from the inversion. Reflectivity images that result from FWI are now widely used for structural interpretation, particularly when converted into seismic-like images, these are sometimes referred to as FWI Image, FWI- derived reflectivity (FDR), or pseudo-reflectivity; these all assume that density is constant or directly correlated with velocity. The approach can be extended further to generate partial-

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angle or partial-offset stacks: near, mid, and far data subsets are selected and inverted independently and in parallel once a best-fitting model has been established from the full shot record. However, these approaches do not address directly the issue of amplitude fidelity, largely because such a single-parameter inversion cannot separate the competing influences of density and velocity on the data.

MPFWI is alternative formulation that offers velocity model estimation (FWI) and non-linear, data domain, least-squares imaging (LS- RTM) simultaneously through an innovative and extended implementation of the FWI framework. Here we refer to the FWI velocities as the background model required for correct structural imaging and LS-RTM as the process that corrects for limited resolution and illumination artefacts seen with conventional imaging. The concept is based on seismic scale separation, full wavefield modeling and the shared sensitivity kernels between RTM and FWI. Firstly, scale separation refers to de-coupling of the kinematic and dynamic effects observed in the data. This separation is achieved with an Inverse Scattering Imaging Condition (ISIC), which decomposes the FWI kernel into a tomographic and impedance kernel (Whitmore and Crawley 2012; Ramos-Martinez *et al*., 2016). Secondly, full wavefield modeling is achieved with a vector reflectivity formulation of the wave-equation (Whitmore *et al*., 2020). This generates both reflections and refractions (the full acoustic wavefield), not limited by the Born approximations. Finally, these two elements combined, enables the simultaneous and iterative inversion for the FWI velocity model and the LS-RTM (Yang *et al*., 2021). The inversion workflow is shown in Figure 1.

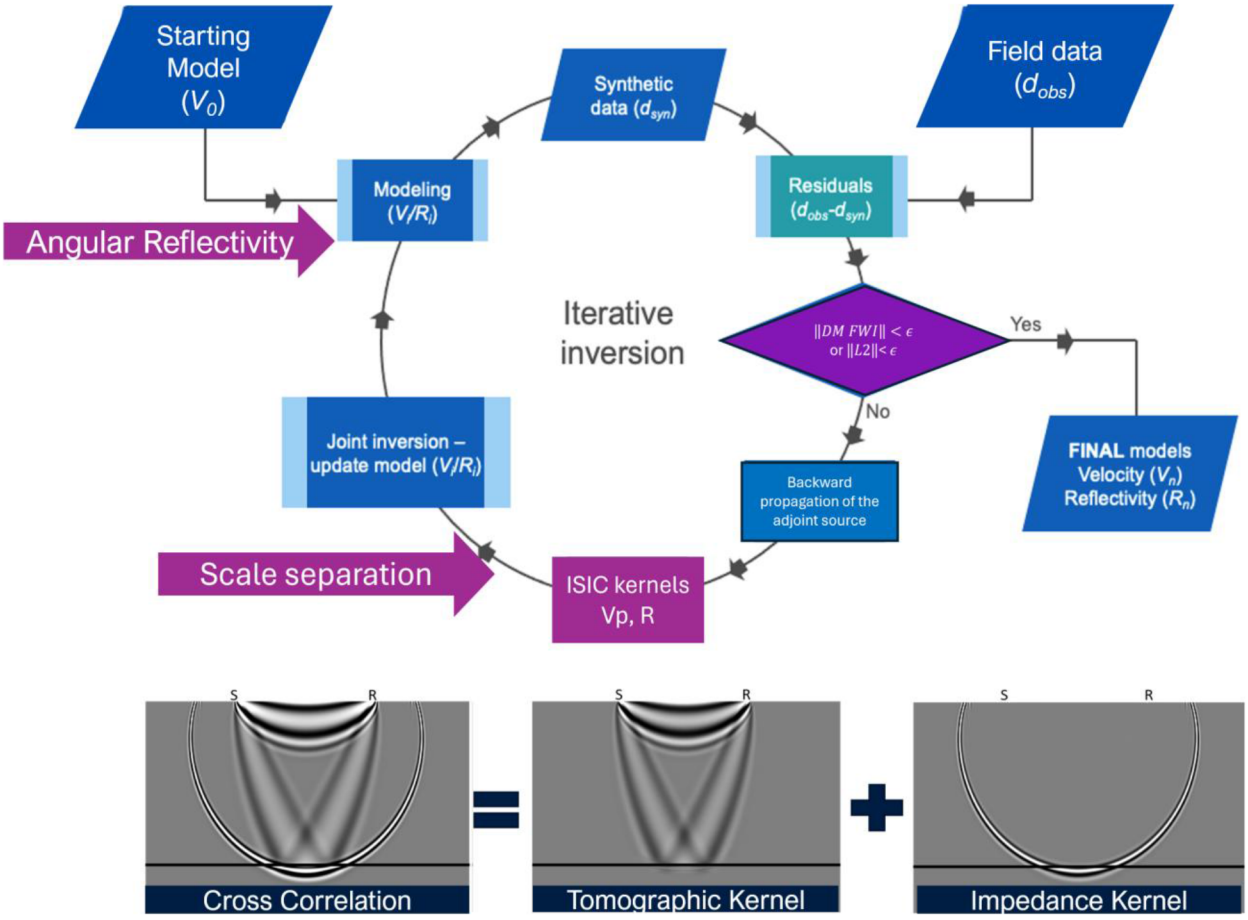


Figure 1—Schematic representation of the multi-parameter (MP-FWI) process. The key elements are that at each loop of the inversion, the algorithm updates both the velocity model and the vector reflectivity volume. The objective function is common between single-parameter and multi-parameter FWI and utilizes a Dynamic Matching approach. The lower part of the figure illustrates the ISIC kernels used in the scale separation.

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Vector Reflectivity

The vector reflectivity modeling engine makes use of a reflectivity volume as a proxy for density to initiate reflections during forward modeling. If no initial reflectivity is supplied, the first iteration of the inversion will be essentially an RTM process. In the second iteration, this image will be an auxiliary input to the modeling engine. Later, throughout the inversion, both the velocity and the reflectivity volume will be refined with FWI, eventually providing a FWI velocity model for accurate structural imaging and a nonlinear LS-RTM that represents an estimate of the earth reflectivity. As the reflectivity improves throughout the inversion, the modeling will improve, resulting in better velocity predictions and vice versa. This approach avoids the requirement of building speculative density models or introducing hard boundaries in the velocity model to initiate reflections during forward modeling.

Scale Separation

Scale separation in MP-FWI is an inversion strategy designed to decompose the FWI gradient into distinct spatial wavelength (or wavenumber) bands. This approach enables the simultaneous estimation of different subsurface physical properties (typically background velocity and high-resolution reflectivity or impedance). When FWI is expanded to invert for multiple earth parameters, a major challenge is crosstalk (parameter leakage). For instance, using reflected wavefields to update velocities can cause high-wavenumber reflectivity features to imprint on the low-wavenumber background velocity model. The approach is based on inverse scattering theory and reformulates the wave equation and decomposes the FWI gradient into decoupled sensitivity kernels targeting different spatial scales:

1. **Long-Wavelength (Low-Wavenumber) Sensitivity Kernel:** This kernel isolates propagation velocity updates. It filters out high-frequency reflection isochrones and reflectivity imprints, utilizing both transmitted/diving waves and pre-critical reflections to build a smooth, macro-velocity model.
2. **Short-Wavelength (High-Wavenumber) Sensitivity Kernel:** This kernel isolates earth reflectivity or impedance. It functions equivalently to Least-Squares Reverse Time Migration (LS-RTM) to map sharp interfaces and fine structures.

The seismic scale separation takes place during the imaging condition. From a single set of back-propagated data-residuals (difference between observed and modeled data), the ISIC will decompose the FWI kernel and produce two gradients: one for the background velocity model and one for the reflectivity. The tomographic sensitivity kernel, commonly referred to as the "banana and rabbit ears", resolves the long-wavelength kinematic component needed for accurate structural positioning, while a separate migration-isochron- based kernel derives reflectivity through what is effectively a non-linear, data domain, least-squares reverse-time migration (LS-RTM). Fully decoupling these two parameters offers several benefits: density variations are no longer misinterpreted as velocity interfaces; the background velocity model can be updated without being overwhelmed by the strong migration/impedance-driven kernel; and reservoirrelevant attributes, such as impedance and density, can be computed directly on a relative basis. The term "relative" is used here to mean that the resolution is bounded by the acquisition geometry itself, whereas deriving absolute values would require calibration against well-log data. This framework can also be extended to generate angle-dependent reflectivity gathers, in principle as an alternative to pre-inversion angle-domain data selection and the subsequent unconstrained, independent inversions for near, mid, and far angle stacks (Chemingui *et al*., 2023). Generating these pre-stack inversion involves the integration of angle-domain common-image gathers (ADCIGs) into the inversion loop, reconstructed in a full 5D pre-stack domain with binning in azimuth, and reflection angle. This framework enables accurate modeling of AVA effects while enhancing illumination balance through iterative data matching and back projection of 5D pre-stack reflectivity. The inversion process progressively refines both velocity and reflectivity models, with regularization ensuring stability across poorly illuminated regions.

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Elastic Formulation

Multiparameter elastic FWI (MP-EFWI) simultaneously inverts for P-wave velocity and reflectively (Huang *et al*., 2025, Macesanu *et al*., 2025). In this approach, the elastodynamic equations are formulated in terms of velocities and P-wave reflectivity. Density is not a required parameter for modelling and inversion although its relative changes can be estimated from reflectivity, which is iteratively updated within the same FWI framework. To minimize the crosstalk between background velocity and reflectivity in our MP-EFWI framework, we applied an effective scale separation of the FWI gradient.

The multiparameter elastic FWI (MP-EFWI) utilizes the reformulated system of elastic wave equation in term of velocity and reflectivity as follows (Huang *et al*., 2025):

$$\begin{cases} \frac{\partial \tilde{v}_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} \\ \frac{\partial \sigma_{ij}}{\partial t} = \tilde{c}_{ijkl}\frac{\partial \tilde{v}_k}{\partial x_l} - \tilde{c}_{ijkl}\left(2r_l^p - \frac{1}{V_p}\frac{\partial V_p}{\partial x_l}\right)\tilde{v}_k \end{cases}$$

where $\tilde{v}_i(i = 1, 2, 3)$ are the weighted particle velocity wavefields; σ_{ij} represents the stress tensor, and $\tilde{c}_{ijkl}$ is the weighted stiffness tensor. In an isotropic case, the weighted stiffness tensor is given by

$$\tilde{c}_{ijkl} = \frac{1}{2}\left(V_p^2 - 2V_s^2\right)\delta_{ij}\delta_{kl} + V_s^2\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right),$$

where its components are functions of P- and S-wave velocity and independent of density. In anisotropic media, the weighted stiffness tensor components additionally depend on the Thompsen parameters. The P-wave reflectivity is represented by r_l^p and can also be derived from the derivative of the log of the P-wave impedance. Thus, the approach can be formulated to invert for either P-wave reflectivity or impedance (Macesanu *et al*., 2025).

This paper presents an example of the use of elastic MP-FWI as a decoupled, simultaneous inversion for both velocity and reflectivity models in a OBN survey of a carbonate-basement system from the North Sea. We show that this yields more dependable attributes suited for quantitative interpretation (QI), and that the methodology can be pushed into the prestack domain to unlock additional reservoir characterization capabilities, including elastic property estimation.

Methodology

An elastic FWI methodology was initially used to update the pressure-wave velocity (Vp) model. The initial shear-wave velocity (Vs) model empirical relationship to Vp from well log information and the density model was generated using Gardner's equation. The Vs and density parameters were subsequently updated during the inversion process based on changes in the Vp model. The FWI objective function is based on Dynamic Matching, which maximizes the local windowed cross-correlation between observed and modelled data (Mao *et al*., 2020). 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 modelling (Liu and Nocedal, 1989).

Although elastic modelling is utilized, certain wave phenomena observed in the field data may not be fully reproduced. These discrepancies can arise from effects such as surface-waves, visco-elastic effects, or other mechanisms not accurately represented in the modelling engine or in parameters not actively inverted during FWI. To mitigate these effects, we applied a data reconstruction approach, computing and applying a global matching filter for each node using synthetic data as the target (Zuberi *et al*., 2023). 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 allows for any acquisition-related variation in the source wavefield.

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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 2).

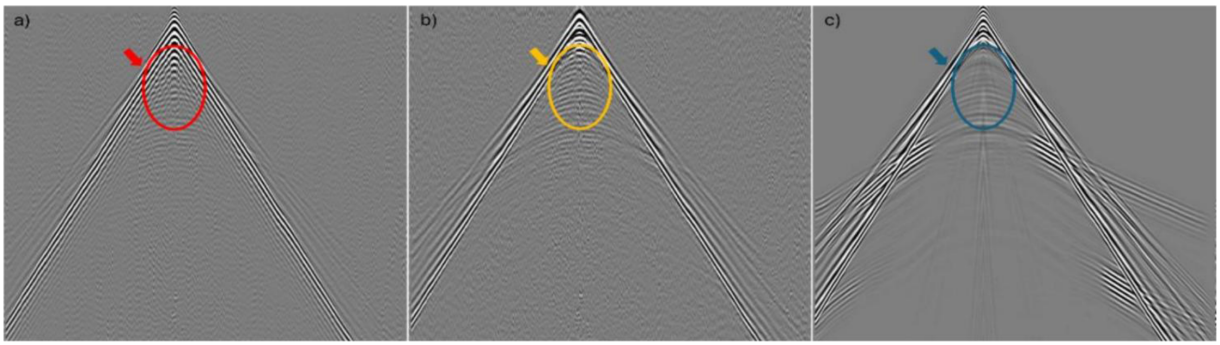


Figure 2—Comparison of field data with and without the reconstruction methodology applied. The hydrophone (pressure) field data is shown at 25Hz before (a) and after (b) data reconstruction compared to elastic modeling (c). Notice how the reconstruction methodology suppresses the parallel linear events 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.

Inversion results - elastic FWI

Figure 3a–d shows the starting 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 3e–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 3e–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 significantly, the inversion considerably changes the structural seismic image, this can be seen by contrasting figure 3b and 3f.

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 3h.

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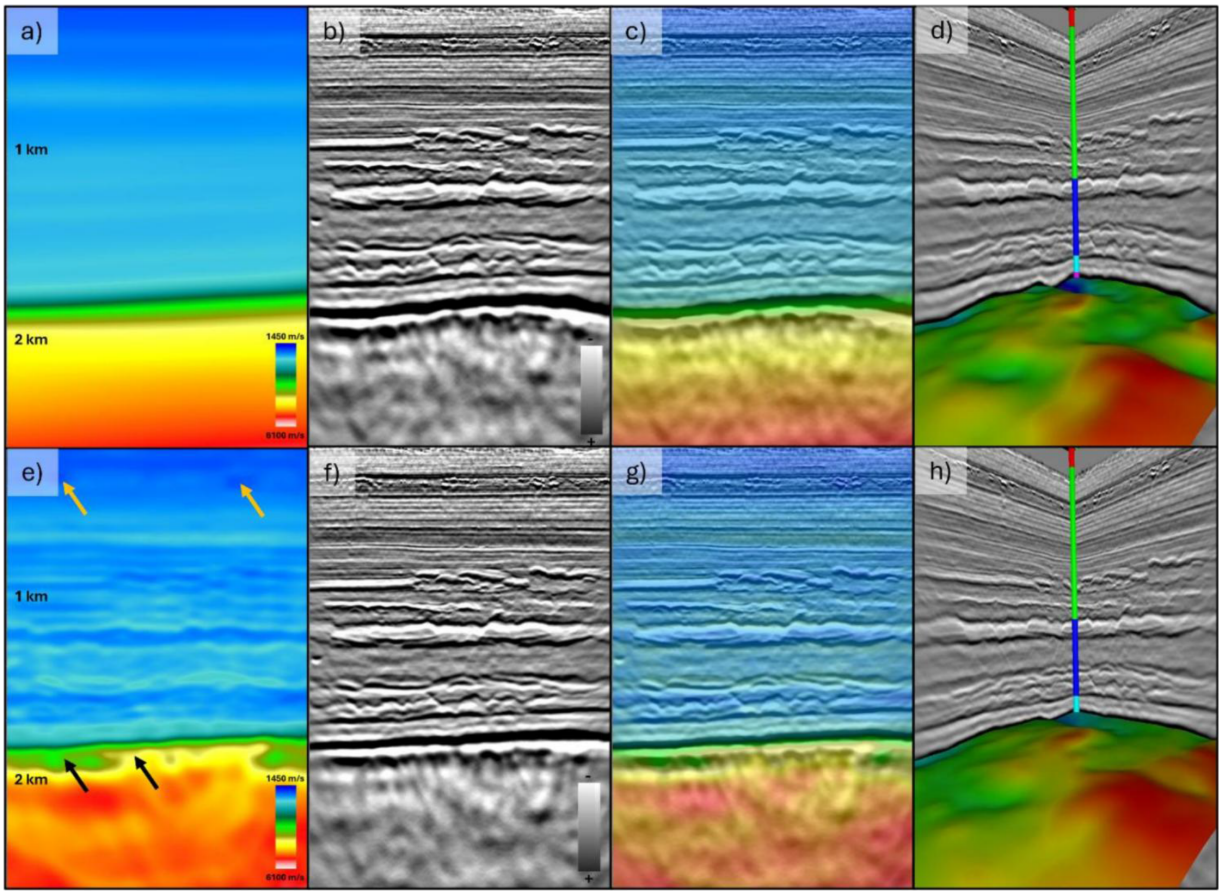


Figure 3—a) Starting velocity model, b) Initial Kirchhoff PreSDM image, c) starting model with seismic image overlay, d) 3D-view of initial image through the well location with markers and Top Chalk interpretation as per the initial image. The corresponding results after elastic FWI shown in e) to h). Note the important information captured in the inverted velocity model (gas pockets, stratigraphic layering and lateral variations in the basement structure). Furthermore, the structural simplification of the Chalk/Basement layer, which agrees with the geological expectations is now clear, and the vertical depth mistie is reduced to practically zero after inversion.

Elastic multi-parameter FWI (eMP-FWI)

Although the elastic FWI results showed good improvement from the initial model, it was decided to take the next step and utilise elastic multi-parameter FWI (eMP-FWI). The reasoning was to understand if eMP-FWI could resolve additional earth information that would add to the understanding of the subsurface in this region.

The aim of eMP-FWI is to resolve two (or more) model parameters that can explain the observed data. In this case we utilized an alternative formulation of the wave equation combined with the deployment of seismic scale separation. In more detail, 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 effectively separate the tomographic kernel from the impedance kernel in the inversion process (Whitmore and Crawley 2012, Ramos-Martinez *et al*. 2016, Yang *et al*. 2021 and Huang *et al*., 2025). The result of this process is 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 well data or from an empirical relation (like Gardner's formula). 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).

The eMP-FWI test was initiated with an intermediate model from the elastic FWI process. The inversion was set to fit two model parameters (Vp and P-wave reflectivity - from which P-wave impedance can be

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derived). Figure 4 shows an example of the different seismic attributes derived directly from the eMP-FWI process. Figure 4a shows the inverted Vp-model and its comparison with the sonic trend. Figure 4b displays the relative P-impedance. Figure 4c shows the absolute density model derived as above and its comparison with the log density. Figure 4d 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 4, which can be complementary to the traditional imaging products and thus increase the understanding of the seismic subsurface.

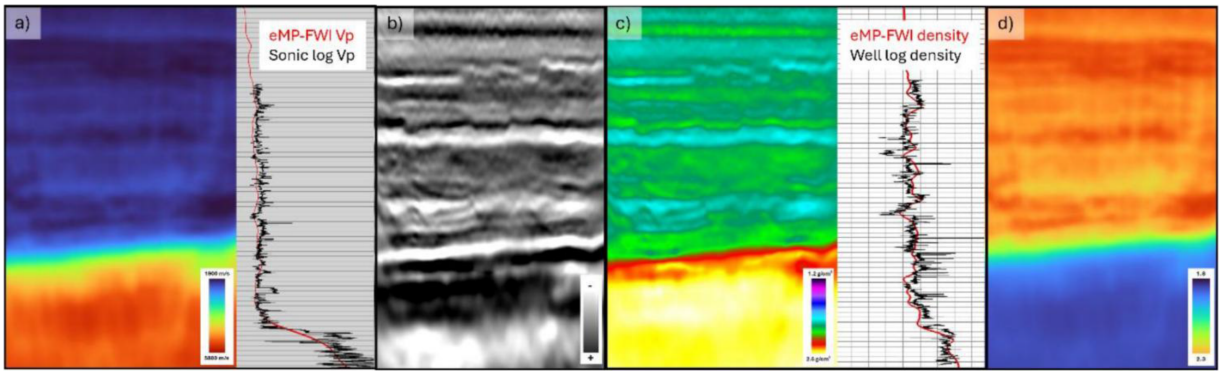


Figure 4—Inversion products from eMP-FWI: a) Vp model and sonic log, b) relative P-impedance, c) absolute density and density log and d) Vp/Vs-ratio. It can be noted that the inverted Vp and absolute density captures the measured variations at the well. The eMP-FWI gives direct access to 3D attributes such as Vp, impedance, density and Vp/Vs-ratio that supplement the conventional imaging products.

Conclusions

The results indicate that Elastic FWI alone substantially improved geological detail in the velocity model. The results resolved shallow gas anomalies, highlighted the stratigraphic layering within the carbonate, and found lateral basement velocity variations consistent with known faulting. When compared with logs, it was seen that vertical depth mis-ties at the well were reduced to approximately one metre. Structural geometry at the carbonate-basement interface was simplified in agreement with geological expectations which have been validated by horizontal drilling. The eMP FWI produced a number of output volumes: Vp, relative P-impedance, absolute density, and Vp/Vs ratio. These all showed strong agreement with well logs, confirming the reliability of the multi-parameter inversion. Together, elastic FWI and eMP FWI form a powerful framework for seismic imaging and interpretation in complex geological environments.

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