

FWI-driven Probabilistic Seismic Inversion: a carbonate case study in West Africa

Introduction

Seismic reservoir characterization in thin carbonate settings remains challenging despite advances in acquisition and imaging technologies. These difficulties mainly arise from strong velocity contrasts between the overburden and the carbonate reservoir, as well as from the limited thickness of the porous target layers. As a result, accurate velocity model estimation is critical, as it strongly influences seismic imaging quality and subsequent quantitative interpretation.

Full Waveform Inversion (FWI) is a key technique for deriving geophysically consistent velocity models by exploiting low-frequency and long-offset data, with particularly strong impact in complex geological settings.

Subsurface characterization using geophysical methods is increasingly adopting probabilistic frameworks (Penna et al., 2019), reflecting an industry-wide shift away from deterministic models, a trend that is particularly evident in modern Seismic Reservoir Characterization (SRC) workflows where Bayesian seismic inversion enables coherent uncertainty quantification while incorporating “prior” geological information (Grana et al., 2017; Paramo et al., 2023).

However, inconsistencies between velocity models used for seismic imaging and inverted elastic properties used for reservoir characterization can affect the effectiveness of the inversion-derived probabilistic petrophysical properties.

This study shows an integrated workflow in which imaging and inversion are tightly coupled through the direct use of FWI-derived velocity models within a probabilistic seismic inversion framework, improving the robustness of reservoir property estimation in a complex carbonate field in West Africa offshore.

Method

FWI estimates seismic velocity by minimizing the misfit between recorded and simulated seismic wavefields within a nonlinear least-squares optimization framework. Tarantola (1984) has formalized the theoretical formulation of seismic inversion as a nonlinear inverse problem, establishing the mathematical foundation for waveform-based parameter estimation. By leveraging low-frequency and long-offset data, FWI employs time-lag cross-correlation objective functions in the early stages to enhance robustness against cycle skipping (Z. Zhang, et al., 2018) and recover large-scale and geologically consistent velocity updates. Subsequent conventional L2-norm minimization is then applied to increase resolution. Progressively incorporating higher frequencies leads to a multiscale strategy that enables improved model details while preserving inversion stability.

The SRC technology used in this study is an integrated probabilistic workflow with the aim of characterizing reservoir properties according to the Bayesian inference (Buland and Omre, 2003) and the Chapman Kolmogorov framework (Grana and Della Rossa, 2010). The relationship between elastic properties, petrophysical parameters and facies, modeled as probabilistic variables, are described by prior distributions derived from well-log data and rock physics models. Elastic parameters are estimated analytically, producing posterior distributions defined by their statistical moments, including mean, variance, and correlation structure. Subsequently, petrophysical properties and facies are inferred through an iterative probabilistic updating scheme, yielding facies probability volumes and percentile-based uncertainty measures (e.g., P10 and P90) for key reservoir attributes such as porosity, shale content, and water saturation.

The integration of FWI with probabilistic seismic inversion leads to the creation of a hybrid workflow: FWI-derived velocity models and seismic data are used within an inversion Bayesian framework to minimize prior-driven subjectivity, reduce low-frequency model uncertainty, and support fully data-driven reservoir characterization.

Case Study

The integrated FWI–probabilistic inversion workflow was applied to a carbonate oil field in the deepwater of West Africa. The reservoir is a shallow-marine carbonate platform with inner neritic facies: reservoir quality is variable in the area, cementation and dolomitization play a significant role in reservoir properties degradation. In this area, the complexity of the velocity model and the occurrence of strong velocity contrasts among involved lithologies present significant challenges for seismic imaging and reservoir characterization, mainly focused detecting and properly describing fine-scale litho-petrophysical changes into reservoir.

The seismic exploration strategy in the area has progressed through several acquisition and imaging phases: the latest survey was designed with dense spatial sampling to improve lateral continuity and the interpretability of the main targets, with particular attention to preserving high-frequency content at reservoir depth. The acquisition geometry included sufficiently long offsets to enable both reflection and diving-wave FWI (13 streamers 7500m long plus 3 additional streamers extending to 10km of maximum offset). The input dataset available for this survey consisted of hydrophone data with minimal preprocessing, limited to mild denoising and shot-by-shot signature. This approach ensured a consistent zero-phase wavelet representative of each shot, while both source and receiver ghosts were explicitly modeled within the FWI process. A multiscale inversion strategy was adopted, starting from the lowest available frequencies and progressively extending the bandwidth up to 30 Hz. The workflow was implemented over an area exceeding 1000 km².

The resulting velocity model provides a high-resolution and geologically consistent representation of the subsurface, showing a clear improvement over the legacy velocity model (Figure 1 and Figure 2).

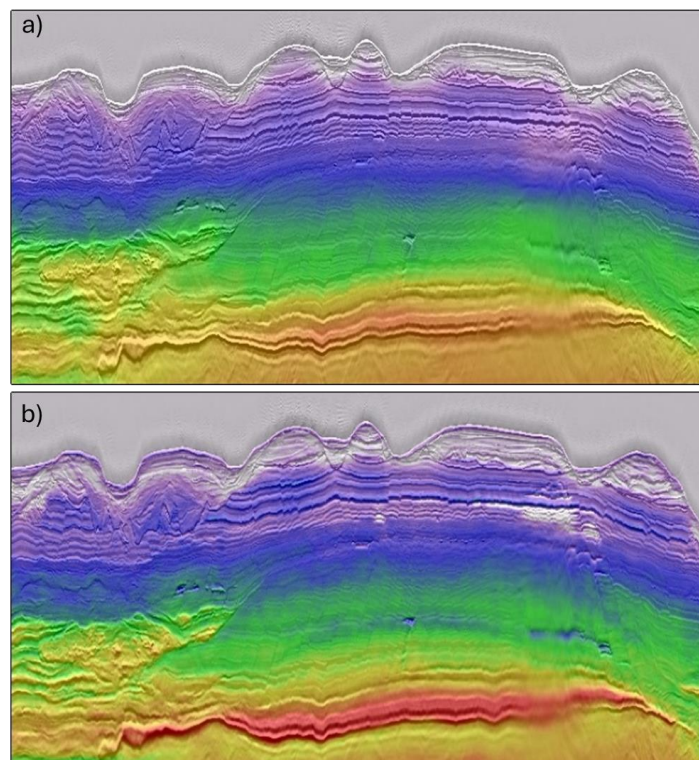


Figure 1 Comparison between: a) legacy and b) FWI 30Hz velocity model overlaid on Kirchhoff migrated seismic (TGS preprocessing input to migration data).

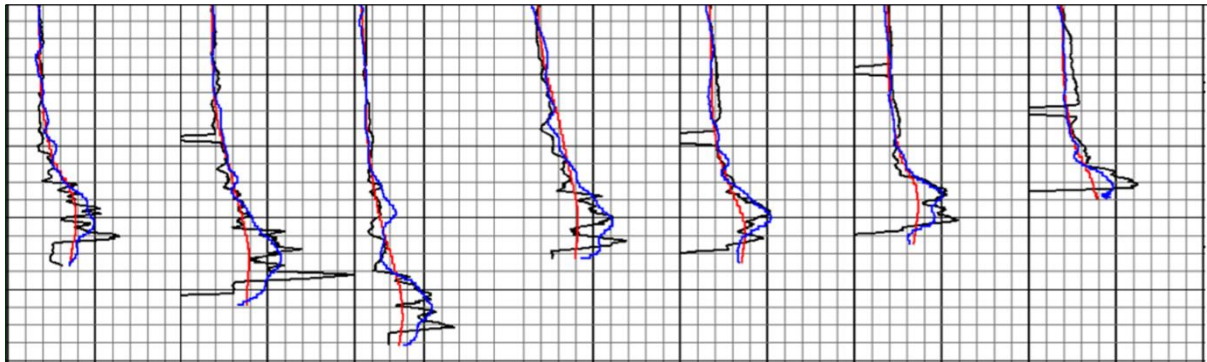


Figure 2 Comparison between sonic well log available in area at target level. In red legacy velocity and in blue FWI 30Hz velocity. FWI was able to introduce low velocities details and high velocity at target level.

Initially, in order to enhance resolution in areas of limited detectability and support continuous updates of the seismic-driven reservoir model through progressive well calibration, SRC performed in this area relied, firstly on deterministic seismic inversion calibrated with rock-physics relationships and then it was applied a single-loop geostatistical inversion constrained by well variography.

The novel hybrid workflow was designed to enhance the unbiased description of internal reservoir heterogeneities: it benefits from a more stable velocity model derived from FWI, resulting in a more reliable low-frequency model (LFM), ready to use in the probabilistic elastic inversion procedure. The inversion method was described by Paparozzi et al. (2011) and is based on a full Bayesian approach: the derived LFM is used as input to the first inversion step to obtain a set of volumes of posterior distribution of elastic properties (velocities or impedances) starting from Kirchhoff migrated angle stacks. Then, in the second step those probability volumes and a reference rock physics likelihood function represent the input information to generate as output probabilistic petrophysical properties in the whole 3D volume and, optionally, probabilistic facies model classifying reservoir facies.

To mitigate the interpretation bias and reduce the process work cycle, maximizing project time, the building of the LFM from FWI within the Bayesian inversion workflow uses directly statistical relations derived by well data (considering the parametrized elastic properties in the inversion procedure, as P-, S-Impedances, P-, S-Velocities, etc.), thanks to the robustness and stability of FWI model previously calibrated by all the available field-scale well markers dataset.

The porosity represents the most sensitive petrophysical variable on elastic attributes and the key remarkable property to robustly model the target reservoir and correctly assess volumetrics and take development decisions. For these reasons the generation of the seismic porosity volume, including the estimation of its uncertainty, represents the main drivers to address the positioning of future wells and to identify best potential high reservoir quality areas.

The presence of multiple wells, combined with reliable velocity models from FWI and the resulting improved seismic imaging, led to a good agreement between predicted properties and well observations at borehole locations. Moreover, the resulting probabilistic elastic volumes show greater spatial continuity and improved geological consistency, thereby supporting more reliable reservoir interpretation and uncertainty-informed decision making (Figure 3).

Conclusions

This study demonstrates that the integration of Full Waveform Inversion and probabilistic seismic inversion significantly enhances reservoir characterization. In the target area a lot of geological and geophysics studies were performed using different approaches (from deterministic to geostatistical inversion), but this hybrid and integrated workflow based on FWI and Bayesian inversion reduces strongly the uncertainty in the subsurface description that represents a key to mitigating the geological risk during the operation phase.

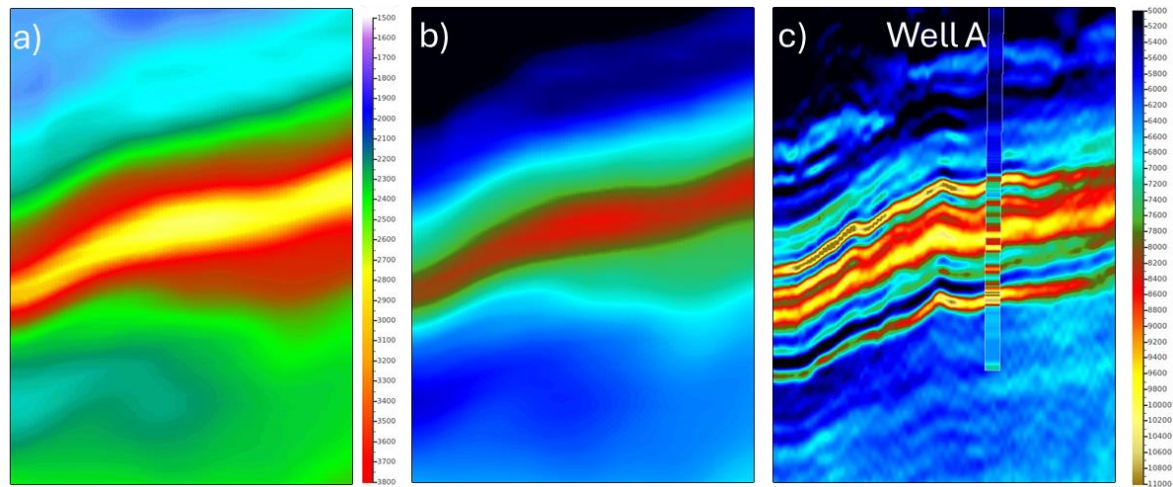


Figure 3 Comparison of results at a reference well location. The log plotted is *P*-Impedance filtered to match seismic frequency, using the same colormap scale: a) FWI 30Hz velocity stretched in time (zoom at target level); b) LFM derived from FWI 30Hz velocity; c) Acoustic impedance from seismic inversion.

The multiscale FWI-inversion provided a robust low-frequency model and reduced non-uniqueness in elastic property estimation while integrated into a unified Bayesian inversion framework. This integration results in more stable posterior distributions of elastic properties, enhanced consistency between well data and seismic observations, and more reliable probabilistic estimates of petrophysical parameters. Furthermore, it is important to emphasize that FWI should not be viewed solely as a tool for velocity model building in support of seismic imaging, but also as a key enabler for reservoir-scale characterization, providing significant added value for quantitative interpretation.

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