An OBN multiparameter FWI case study from Santos Basin

Abstract

A multiparameter inversion workflow that jointly estimates velocity and reflectivity was applied to an ocean bottom node (OBN) dataset from the deep-water Santos Basin, offshore Brazil. The complex geology—featuring layered evaporites above pre-salt reservoirs—poses significant imaging challenges due to salt-related illumination issues and resolution loss. Starting from minimally processed hydrophone data, the inversion improved structural imaging and amplitude fidelity by integrating velocity modeling and least-squares migration in a unified framework. The results highlight the workflow's value in resolving subsurface complexity and informing exploration and reservoir development in pre-salt environments.

Introduction

Advanced seismic imaging methods such as full waveform inversion (FWI) and least-squares reverse time migration (LS-RTM) have proven effective in addressing the challenges posed by complex subsurface geology. These techniques aim to deliver high-fidelity structural images and stable pre-stack amplitude and phase information, which are critical for accurate reservoir characterization, quantitative interpretation, and time-lapse (4D) analysis.

In recent years, multiparameter inversion workflows have gained traction as an integrated approach that unifies FWI and LS-RTM within a single framework. In this formulation, the velocity model—primarily influenced by FWI—captures kinematic effects, while the reflectivity model—estimated through LS-RTM—captures dynamic amplitude behavior. Grounded in the principle of seismic scale separation (Claerbout, 1985), this joint inversion approach enhances stability and reduces crosstalk between model parameters, ultimately improving the reliability of both structural imaging and amplitude information.

This case study applies a multiparameter inversion workflow to a 2015 ocean bottom node (OBN) survey acquired over the Tupi Field in the deep-water Santos Basin, approximately 280 km offshore Rio de Janeiro. The acquisition included 954 nodes across 36 lines, covering 111 km² with a 345 km² source carpet, targeting complex pre-salt reservoirs of the Barra Velha Formation beneath a thick, laterally variable salt canopy. The geological setting—shaped by rift, post-rift, and drift tectonic phases—features layered evaporites and carbonates that introduce significant imaging challenges, including velocity complexity, internal multiples, and illumination loss in the pre-salt interval. Starting from minimally processed hydrophone data, the multiparameter inversion workflow demonstrated improved structural imaging and amplitude stability, supported by well calibration and enabling more informed exploration and reservoir decisions.

Method

Full waveform inversion (FWI) and reverse time migration (RTM) have traditionally served distinct roles in seismic imaging—FWI for velocity model building and RTM for reflectivity imaging. However, their shared mathematical foundations allow them to be combined within a single framework that simultaneously solves for both parameters. This joint approach, demonstrated by Yang et al. (2021), leverages the physical relationship between wavefield kinematics and dynamics to improve image accuracy and amplitude fidelity.

The methodology is built around two key components: the Inverse Scattering Imaging Condition (ISIC) (Whitmore and Crawley, 2012; Ramos-Martinez et al., 2016) and a two-way acoustic wave equation modeling engine parameterized with velocity and vector-reflectivity (Whitmore et al., 2020). Vector-reflectivity removes the need for a separate density model, simplifying the inversion while preserving amplitudes. Unlike conventional LS-RTM based on Born modeling, this approach uses full-wavefield modeling to capture multi-scattering effects, offering a more complete description of subsurface interactions.

To reduce parameter crosstalk, the method applies seismic scale separation via ISIC, isolating low-wavenumber velocity updates and high-wavenumber reflectivity components. This ensures robust, interpretable inversion results even in complex geological settings.

The workflow uses a multi-scale strategy, beginning with low frequencies (typically below 4 Hz) to recover large-scale velocity trends. As the model converges, higher frequencies are introduced to refine velocity and enhance reflectivity resolution. Early iterations focus on background model accuracy, while later stages sharpen structural details and amplitude fidelity.

The multiparameter inversion framework delivers a data-domain LS-RTM solution in which velocity and reflectivity are jointly updated through nonlinear optimization. Unlike traditional least-squares migration—where velocity is fixed and only the migrated image is refined—this approach iteratively refines both parameters, improving convergence and model accuracy. This simultaneous estimation proves particularly advantageous in regions affected by complex illumination and resolution loss due to salt heterogeneity, as it better resolves kinematic and dynamic aspects of the wavefield. Moreover, the vector-reflectivity formulation, used in lieu of explicit density modeling, effectively reduces parameter leakage and stabilizes amplitude recovery, further enhancing image fidelity.

The early implementation of this method was based on an acoustic approximation of wave propagation, which has yielded high-quality images in many geological settings (e.g. Chemingui et al., 2023; Korsmo et al., 2022; Pankov et al., 2023; and, Yang et al., 2021). However, this acoustic formulation has some limitations—blurred velocity boundaries, and subtle imaging artifacts around high-contrast media. Huang et al. (2025) introduced an evolution of the multiparameter inversion that incorporates elastic wavefield propagation which highlights the importance of considering elastic effects in more complex environments.

Results

The multiparameter inversion workflow began with raw hydrophone data corrected for clock drift and water column velocity variations, followed by minimal denoising. A legacy velocity model—originally constructed for conventional imaging, and verified against well data—served as the starting background model. The inversion followed a multi-scale frequency strategy, initiating with a narrow band from 2–5 Hz to resolve long-wavelength velocity features. As convergence was achieved, the frequency band was gradually expanded to 25 Hz, enabling the recovery of fine-scale structural details and reflectivity.

Figure 1 show snapshots from different inversion stages, where increasing frequency bandwidth progressively enhances resolution and structural clarity. Figure 2 compares the final inverted reflectivity (2a) with a conventionally processed image-domain LS-RTM result (2b). The inverted reflectivity not only exhibits amplitude consistency with LS-RTM but also demonstrates superior fault delineation and structural continuity, particularly in the pre-salt interval.

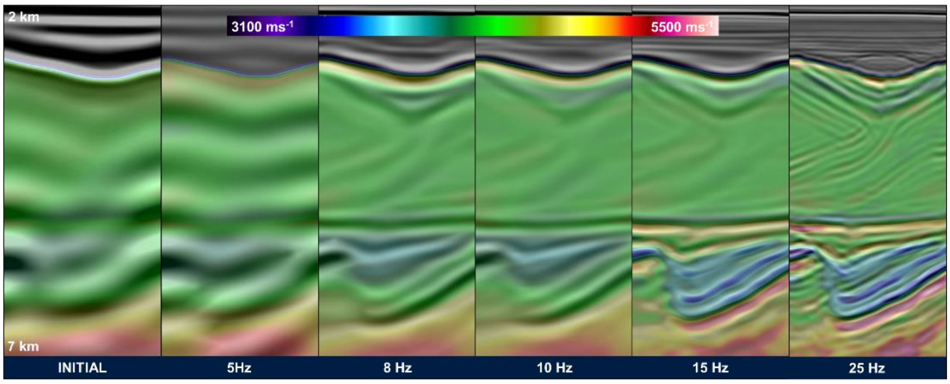

Figure 1: Inverted reflectivity overlaid with the inverted velocity field from different stages of the inversion, as the maximum frequency is progressively increased up to 25 Hz.

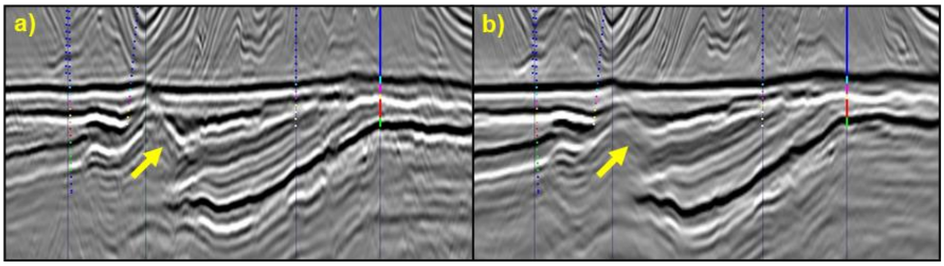

Figure 2: Comparison between a) the inverted reflectivity from the multiparameter inversion, and b) an image-domain LS-RTM.

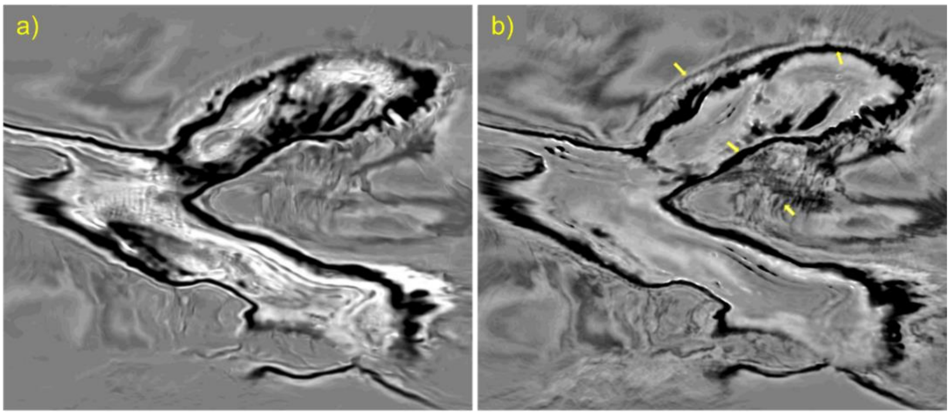

Figure 3: Depth slice of the inverted reflectivity using a) acoustic and b) elastic algorithms. The yellow arrows highlight enhanced imaging with better continuity and more focused salt boundary (adapted from Huang et al., 2025).

Figure 3 compares the reflectivity from acoustic inversion result (3a) with the elastic implementation (3b). The elastic inversion shows sharper definition at the salt interfaces and improved imaging of steeply dipping features, underscoring the value of elastic modeling in enhancing image resolution and interpretability in such settings.

One notable practical benefit of the multiparameter workflow used here is its operational efficiency. The inversion was performed using only minimally processed input data, bypassing much of the complex pre-processing, imaging, and post-processing typically required for LS-RTM. This streamlined workflow was enabled by the high-quality OBN acquisition and favorable deep-water conditions, which provided clean primary reflections and clear separation from free-surface multiples. The reduced processing footprint, combined with robust results, demonstrates the practical viability of this approach for large-scale offshore projects.

Conclusions

The application of a multiparameter inversion workflow to a deep-water OBN dataset from the Santos Basin has demonstrated the significant potential of integrated velocity and reflectivity inversion for improving seismic imaging in complex geological settings. By unifying full waveform inversion and least-squares reverse time migration within a single framework, this approach delivers structurally consistent images and amplitude-stable reflectivity estimates, even in the presence of challenging salt geometries and illumination variability. The methodology proved not only effective in recovering both large-scale velocity trends and fine-scale reflectivity features, but also operationally efficient—requiring minimal pre-processing compared to conventional LS-RTM workflows. While the acoustic formulation produced robust results, comparisons with elastic inversion indicate further benefits in resolution and interface sharpness when elastic effects are accounted for. Overall, the multiparameter inversion framework offers a scalable and reliable solution for subsurface characterization, supporting more informed exploration and development decisions in Brazil's pre-salt domain and beyond.

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