Multiparameter inversion applied to ocean bottom node data from Santos Basin

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Summary

A multiparameter inversion workflow that simultaneously estimates velocity and reflectivity was applied to an ocean bottom node (OBN) dataset from the deep waters of the Santos Basin, offshore Brazil. The geological setting includes a relatively thin post-salt section with a thick salt layer of varied composition, including layered evaporite deposits, situated above producing pre-salt reservoirs. The complexity of the varied salt structures creates imaging challenges at the pre-salt interval, notably variations in illumination and loss of resolution (blurring). Recovering stable amplitudes from reliable images requires a combination of long-offset, full-azimuth acquisition, accurate velocity estimation, and least-squares migration.

This dataset provides a good test case for the application of multiparameter inversion in Brazil. Starting from minimally processed hydrophone data, the results illustrate the potential of this technology to provide accurate imaging and reliable amplitude information in the region. By combining velocity and reflectivity estimation, this workflow can contribute to a deeper understanding of subsurface properties, aiding decision-making in exploration and reservoir management.

Introduction

Advanced imaging techniques like full waveform inversion (FWI) and least-squares reverse time migration (LS-RTM) address imaging challenges in complex geological environments. These methods aim to deliver reliable structural images and stable pre-stack phase and amplitude data, essential for quantitative interpretation, reservoir characterization, and 4D monitoring.

Recently, multiparameter workflows have emerged as a promising alternative. These approaches integrate FWI and LS-RTM into a unified framework, where the background velocity model (FWI) accounts for kinematic effects, and the reflectivity model (LS-RTM) addresses dynamic effects. By leveraging the concept of seismic scale separation (Claerbout, 1985) and multiparameter inversion, these workflows enhance stability and robustness, reducing leakage between the two terms.

This paper explores the application of multiparameter inversion to an OBN dataset from the Santos Basin.

Method

FWI and RTM have traditionally been applied at different stages of the seismic imaging process: FWI for building velocity models; and, RTM for imaging. Their underlying formulations are fundamentally connected, enabling them to be combined within a single inversion framework to simultaneously solve for velocity and reflectivity, as demonstrated by Yang et al. (2021). This method relies on two key components: an Inverse Scattering Imaging Condition (ISIC) (Whitmore and Crawley, 2012; Ramos-Martinez et al., 2016) and a full-wavefield modeling engine based on the two-way wave equation, parameterized by velocity and vector-reflectivity (Whitmore et al., 2020). Notably, using vector-reflectivity eliminates the need for an accurate density model. Additionally, unlike the Born modeling typically used in conventional data domain LS-RTM algorithms, the full-wavefield modeling approach accounts for multi-scattering. Seismic scale separation helps mitigate parameter leakage through the Inverse Scattering Imaging Condition. The low-wavenumber component refines the background model, essential for creating an accurate structural image, while the high-wavenumber component enhances resolution and fidelity.

The multiparameter inversion workflow employs a multi-scale strategy, similar to a typical velocity-only FWI application. The inversion process begins with low frequencies (usually below 4Hz, depending on data quality) and gradually incorporates higher frequencies as long wavelength errors are corrected. Initially, lower frequencies are used to resolve the background velocity trend (kinematic components), which are crucial for the structural image and focusing the reflectivity image. Subsequent updates utilize an increasingly broader range of frequencies and leverage the full wavefield to add detail to the velocity model and improve reflectivity resolution.

This approach has been adapted to the pre-stack domain, enabling angle-dependent reflectivity estimates (Chemingui et al., 2023). This integrated framework not only enhances the velocity model but also produces high-fidelity seismic image angle gathers, making it an invaluable tool for exploration and reservoir characterization.

Results

The dataset used is an OBN survey over the Tupi field situated approximately 280 km off the coast of Rio de Janeiro. The OBN survey was acquired in 2015, and comprised 954 stations over 36 lines, covering an area of around 111 sq.km with a 345 sq.km source carpet.

The OBN dataset utilized in this study is widely recognized and frequently cited in the literature. It is situated over a productive pre-salt reservoir in the deep waters of the Santos Basin (Figure 1). This basin is a typical distension-margin basin, with its sedimentary record divided into three distinct sequences that correspond to key tectonic phases: rift (Hauterivian to Aptian), post-rift (Aptian), and drift (Albian to present-day). The post-rift phase is characterized by carbonate and evaporite rocks, indicative of a tectonic regime with minimal fault activity and thermal subsidence. The primary reservoirs of the Tupi Field are located within these pre-salt carbonates, known as the Barra Velha Formation. Several wells in the study area provide crucial calibration points for velocity and reflectivity derived from seismic data.

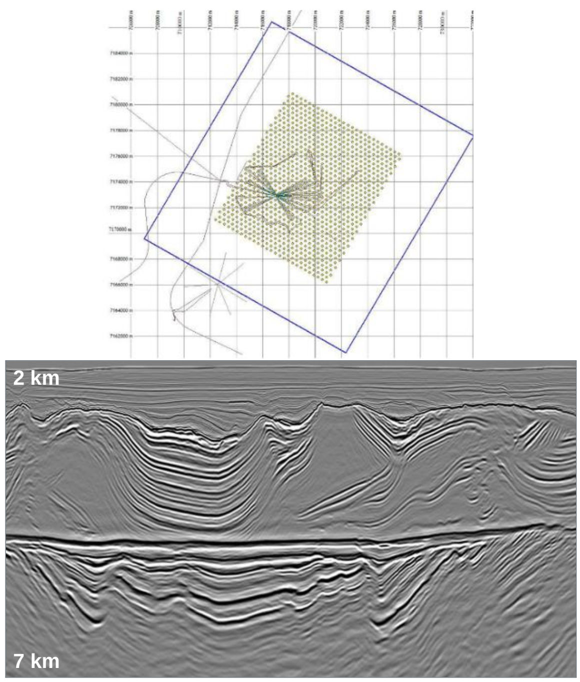

Figure 1: Survey location map (left) showing extent of the node and source coverage (image adapted from the acquisition report) and crooked line extracted from a migrated volume.

Imaging challenges arise due to the extensive salt structure spanning the study area. These complexities in the salt create difficulties in imaging the pre-salt interval, particularly in terms of variations in illumination and resolution loss (blurring). Additionally, strong internal multiples often contaminate the reservoir level, reverberating between the water bottom, salt, and intra-salt reflectors.

Recent processing provided a comprehensive suite of raw, pre-, and post-migrated datasets, including interbed multiple attenuation and image-domain, pre-stack LS-RTM. Despite its simplicity, the legacy velocity model was robust, offering good correlations with well information across the study area.

Input to the simultaneous inversion workflow used the legacy velocity model along with raw hydrophone data after corrections for clock drift and water column velocity variations and simple denoising. The inversion started with a frequency band from 2 to 5 Hz and progressively broadened the bandwidth as the long wavelength errors were resolved. Figure 2 shows some snapshot of the inverted reflectivity overlaid with the associated velocity field from different stages of the inversion. It illustrates how the structural image improves, and resolution is enhanced as the maximum frequency of the inversion is gradually increased up to 25 Hz. Figures 3 compares the inverted reflectivity (3a) to a conventionally processed LS-RTM (3b).

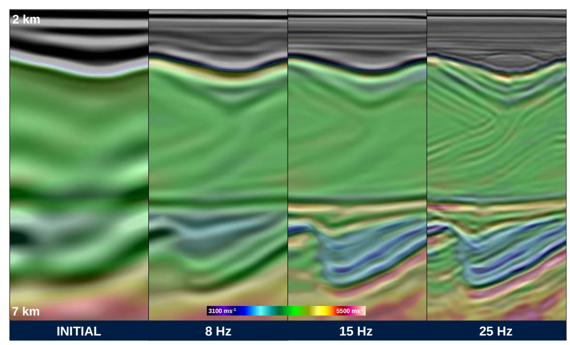

Figure 2: Inverted reflectivity overlaid with the inverted velocity field from different stages of the inversion, as the maximum frequency is progressively increased up to 25 Hz.

Observations – the reflectivity estimate from the multiparameter inversion (Figure 3a) compares well to the image domain LS-RTM (Figure 3b). The inverted reflectivity exhibits consistent amplitude behavior to the image-domain LS-RTM, but with improved structural continuity and imaging of faults.

The formulation of the multiparameter inversion means the inverted reflectivity can be considered a nonlinear, data-domain LS-RTM. Each iteration optimizes the velocity whilst refining the reflectivity (unlike the conventional image-domain solution which holds the velocity constant and works to resolve the migrated image). This simultaneous update of both properties through many iterations is better suited to resolve complexities in velocity, illumination and blurring effects compared to the image-domain LS-RTM.

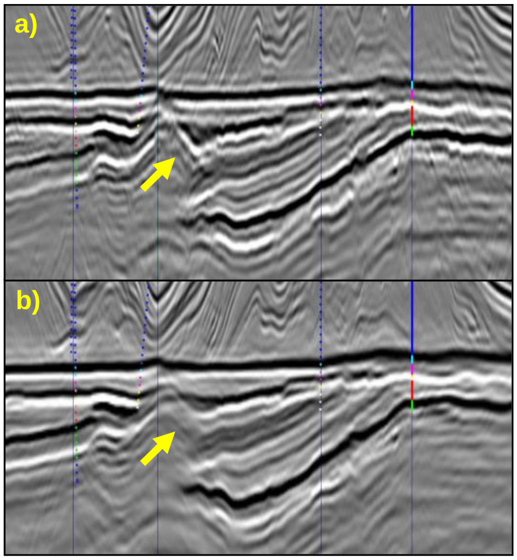

Figure 3: Comparison between a) the inverted reflectivity from the multiparameter inversion, and b) an image-domain LS-RTM.

Processing effort – it is noteworthy to comment on the processing effort behind the results. The multiparameter inversion started from minimally processed hydrophone data and was completed with far fewer processing steps and in less time than the traditional pre-processing, imaging and post-processing needed for the LS-RTM. This is facilitated by the quality of the acquired data, and by the deep-water setting which provides a clear separation between primary and free-surface multiples.

FWI implementation – the results shown in Figures 2 and 3 were produced based on acoustic assumptions of wavefield propagation through the earth, and they clearly provide a robust and efficient result. Contemporary FWI implementations incorporate elastic assumptions which are particularly important in correctly describing wavefield propagation in regions characterized by strong impedance contrasts (Plessix and Krupovnickas, 2021). Evidence of the limitation of the acoustic assumptions are observed in the results, notable the subtle halo around the top and base salt interface.

Figure 4 compares the inverted reflectivity from acoustic (4a) with an elastic implementation (4b) described by Huang et al. (2025). The result illustrates how some of the expected short comings of acoustic propagation are addressed by the elastic formulation, providing a sharper, better resolved image.

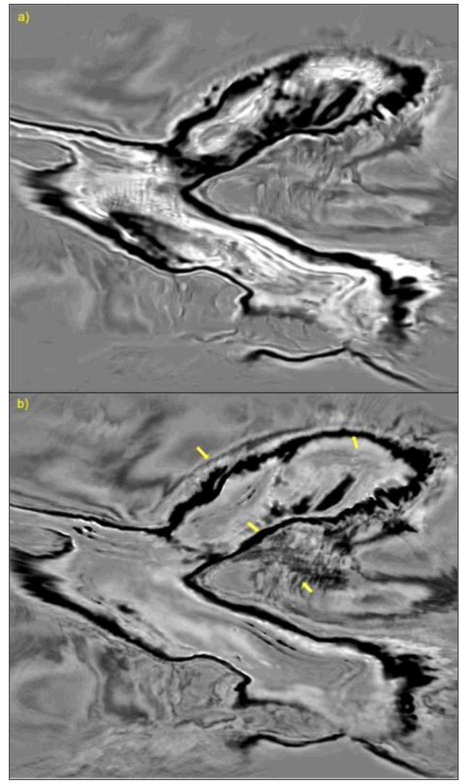

Figure 4: Depth slice of the inverted reflectivity using a) acoustic and b) elastic algorithms. The yellow arrows highlight enhanced imaging with better continuity and more focused salt boundary (adapted from Huang et al., 2025).

Conclusions

A multiparameter inversion workflow, which simultaneously estimates velocity and reflectivity, was successfully applied to OBN datasets from the Santos Basin, offshore Brazil. The results demonstrate the technology's potential to deliver accurate imaging and reliable amplitude information in this region, using far fewer steps than a traditional processing sequence. Incorporating elastic propagation can further enhance these outcomes. By integrating velocity and reflectivity estimation, this workflow contributes to a deeper understanding of subsurface properties, supporting decision-making in exploration and reservoir management.

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