Multiparameter inversion of velocity and reflectivity applied to ocean bottom node data from offshore Brazil

J. Burren[1] , E. Frugier[1] , Ø. Korsmo[1]

[1] TGS

Summary

A multiparameter inversion workflow that simultaneously estimates velocity and reflectivity was applied to ocean bottom node (OBN) dataset from the deep waters of the Santos basin, offshore Brazil. The survey encompasses a relatively thin post-salt section with a thick salt layer which includes layered evaporates, sat 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). Reliable imaging in this setting requires a combination of long-offset, full azimuth acquisition, accurate velocity estimation and least-squares migration.

This application of multiparameter inversion is one of the first test-cases in Brazil, working with 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.

Multiparameter inversion of velocity and reflectivity applied to ocean bottom node data from offshore Brazil

Introduction

High-end imaging methods such as full waveform inversion (FWI) and least-squares reverse time migration (LS-RTM) are used to solve imaging challenges in complex geological settings. They aim to provide reliable structural images and stable pre-stack phase and amplitude information for use in quantitative interpretation, reservoir characterization and 4D monitoring studies.

Recently, multiparameter workflows have begun to emerge as an alternative solution. These approaches combine FWI and LS-RTM into a single framework where kinematic effects are explained by the background velocity model (FWI) and dynamic effects by reflectivity model (LS-RTM). The concept of seismic scale separation (Claerbout, 1985) and the multiparameter inversion bring stability and robustness for both properties, minimizing leakage between the two terms.

In this paper, we show results from the application of multiparameter inversion applied to an OBN dataset acquired in the Santos basin.

Method

In recent years, some notable advancements have been made in the field of seismic imaging concerning the interplay between FWI and RTM. Previously, these two techniques have been used at different stages of the seismic imaging workflow – FWI for velocity model building, and RTM for the imaging stage. However, their formulation is fundamentally linked allowing them to be combined in the same inversion framework, solving for two unknown parameters simultaneously – velocity and reflectivity – as described by the pioneering work of Yang et al. (2021). The method comprises two fundamental elements for achieving this: an inverse scattering imaging condition (Whitmore and Crawley, 2012; Ramos-Martinez et al., 2016) with a full-wavefield modelling engine based on the two-way wave equation, parameterized in terms of velocity and vector-reflectivity (Whitmore et al., 2020). Importantly, the use of vector-reflectivity avoids the need for constructing an accurate density model. Furthermore, unlike the Born modelling generally used in the conventional data domain LS-RTM algorithms, the full-wavefield modelling approach simulates multi-scattering. Seismic scale separation helps to reduce parameter leakage using the inverse scattering imaging condition. The low-wavenumber component resolves the background model, necessary to create an accurate structural image structural image, while the high-wavenumber component brings resolution and fidelity.

The multiparameter inversion workflow uses a multi-scale approach, consistent with a typical velocity-only FWI application. The range of frequencies considered by the inversion starts low (typically less than 4Hz, depending on data quality) and is gradually extended to include higher frequencies as the long wavelength errors are resolved. The early stages use lower frequencies to resolve the background velocity trend (kinematic components) which are important for the structural image, and improve focusing of the reflectivity. Later updates use an increasingly broad range of frequencies and take advantage of the full wavefield to bring both detail to the velocity model and resolution to the reflectivity.

The approach has been extended to the pre-stack domain allowing reflectivity estimates to become angle-dependent (Chemingui et al., 2023). This integrated framework not only refines the velocity model but also yields high-fidelity seismic image angle gathers, making it a valuable tool in exploration and reservoir characterization.

Results from OBN dataset in Santos Basin

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.

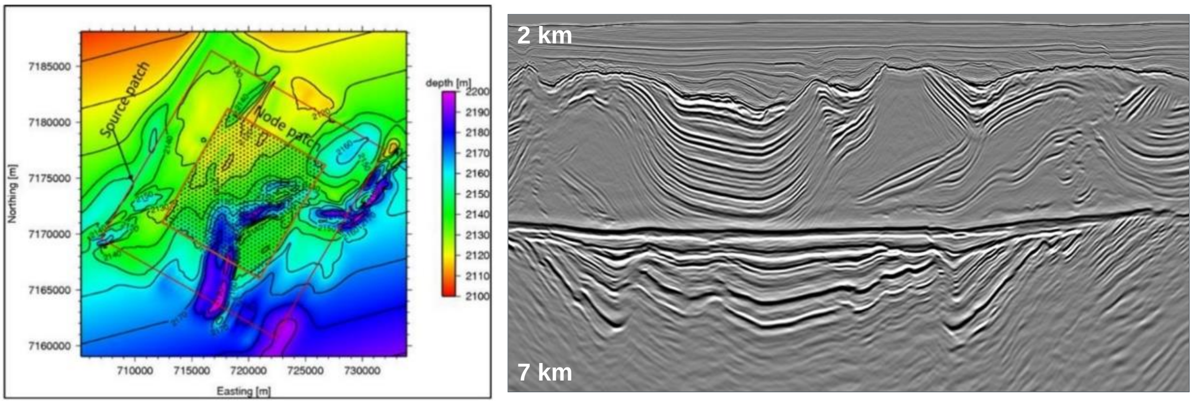

Figure 1 *Survey location map (left) showing extent of the node and streamer coverage, overlain on the bathymetry (image adapted from the acquisition report) and crooked line through the survey (right).*

The OBN dataset used for this study is well known, appearing many times in the literature, located over a producing pre-salt reservoir in the deep water of Santos basin (Figure 1). The basin is characterized as a typical distension-margin basin. The sedimentary record is divided into three distinct sequences, corresponding to key tectonic phases: rift (Hauterivian to Aptian); post-rift (Aptian); and drift (Albian to present-day). The post-rift phase is marked by carbonate and evaporite rocks, reflecting a tectonic regime with low fault activity and thermal subsidence. The primary reservoirs of the Tupi Field are found in these pre-salt carbonates, known as the Barra Velha Formation. Several wells cover the study area, providing important calibration points for velocity and reflectivity derived from the seismic data.

There are several imaging challenges associated with the large salt structure extending across the study area. Salt complexities create imaging challenges in the pre-salt interval, notably variations in illumination and loss of resolution (blurring). Also, strong internal multiples often contaminate the reservoir level, reverberating between the water bottom, salt and intra-salt reflectors.

A full suite of raw, pre- and post-migrated datasets was available from recent processing that included interbed multiple attenuation and an image-domain, pre-stack LS-RTM. The legacy velocity model was simple but still robust, providing good ties with the 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. Results from the simultaneous inversion are shown in Figure 2, compared to conventionally processed results.

Discussion

Observations – the reflectivity estimate from the multi-parameter inversion (Figure 2d) compares well to the image domain LS-RTM (Figure 2b). The inverted reflectivity exhibits consistent amplitude behaviour to the image-domain LS-RTM, but with improved structural continuity and imaging of faults. The inverted velocity model exhibits the expected variations through the pre-salt interval, including a known velocity increase below base of salt and slower dipping sedimentary packages (Figure 2c), while providing a reasonable match to the velocity trend measured at the wells (Figure 3).

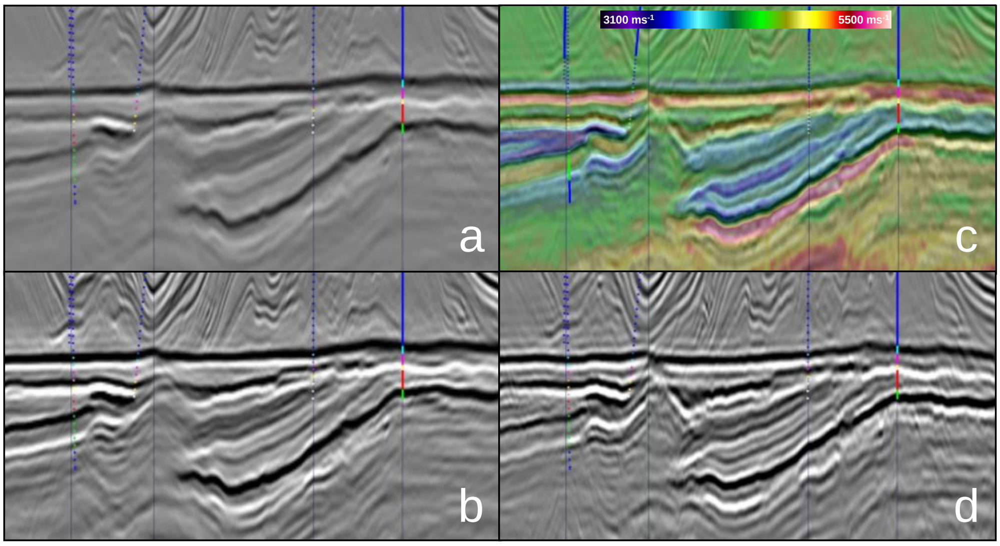

Figure 2 *Comparisons between a) raw RTM, b) image-domain LS-RTM. Panels c) and d) are results from the multiparameter inversion: c) shows the velocity overlaid on reflectivity, while d) shows just the reflectivity.*

The formulation of the multi-parameter inversion means the inverted reflectivity can be considered a non-linear, 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.

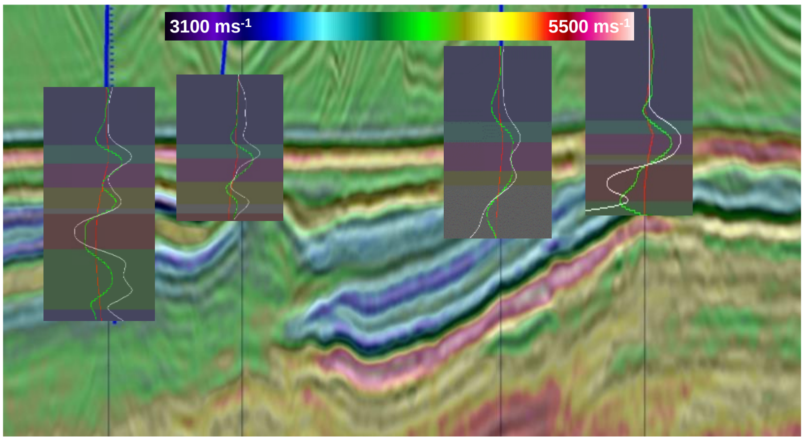

Figure 3 *Comparisons of velocity profiles at well locations: white = filtered sonic logs, red = legacy velocity model and green = velocity from multiparameter inversion.*

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 – this experiment was run under acoustic assumptions of wavefield propagation through the earth, providing a robust and efficient result. Contemporary FWI implementations incorporate elastic assumptions which are particularly important in correctly describing wavefield propagation in the regions characterized by strong impedance contrasts (Plessix and Krupovnickas, 2021). Evidence of the limitation of the acoustic assumptions are observed in the results, notably the subtle halo around the top and base salt interface. (The multiparameter inversion described here has now been extended to an elastic implementation; results are discussed in Huang et al. (2025).)

Conclusions

A multiparameter inversion workflow that simultaneously estimates velocity and reflectivity was successfully applied to an OBN datasets from the Santo basin, offshore Brazil. 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.

Acknowledgements

The authors would like to thank TGS for permission to publish this paper. We also acknowledge Petrobras' permission to use the Tupi OBN dataset in technology development.

References

Chemingui, N., Yang, Y., Ramos-Martinez, J., Huang, G., Whitmore, D., Crawley, S., Klochikhina, E. and Arasanipalai, S. [2023] Simultaneous inversion of velocity and angle-dependent reflectivity. IMAGE23, *SEG Technical Program Expanded Abstracts*: 625-629.

Claerbout, J. F. [1985] *Imaging the earth's interior*: Blackwell Scientific Publications.

Huang, G., Macesanu, C., Liu, F., Ramos-Martínez, J. Whitmore, D. and Calderon, C. [2025] Multiparameter elastic FWI for joint inversion of velocity and reflectivity. *86th EAGE Annual Conference and Exhibition*, submitted.

Plessix, R.-E., and Krupovnickas, T. [2021] Low-frequency, long-offset elastic waveform inversion in the context of velocity model building: *The Leading Edge*, 40, 342–347.

Ramos-Martinez, J., Crawley, S., Zou, Z., Valenciano, A.A., Qui, L. and Chemingui, N. [2016] A Robust Gradient for Long Wavelength FWI Updates. *78th EAGE Annual Conference and Exhibition.*

Whitmore, D., Ramos-Martinez, J., Yang, Y. and Valenciano, A. [2020] Seismic modelling with vector reflectivity. *81st Annual International Meeting, SEG,* Expanded Abstracts.

Whitmore, D. and S. Crawley [2012] Application of RTM inverse scattering imaging conditions. *82nd Annual International Meeting, SEG,* Expanded Abstracts

Yang, Y., Ramos-Martinez, J., Huang, G., Whitmore, D. and N. Chemingui [2021] Simultaneous velocity and reflectivity inversion: FWI + LSRTM. *82nd EAGE Conference & Exhibition*, Extended Abstracts.