# High resolution elastic full waveform inversion using ocean bottom nodes in Santos Basin, Brazil

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## Summary

The Santos basin, offshore Brazil, raises numerous challenges for any model building workflow, including significant lateral velocity variations emerging from layers of carbonates, complex series of evaporites, such as halite and anhydrites. This complexity intensifies when considering the pre-salt regime, featuring carbonate and deeper velocity inversions. These challenges are best tackled using broadband, long-offset, and full-azimuth data obtained with ocean-bottom node surveys. Full waveform inversion with this dataset type, is used to start building the velocity model from low frequencies, where the bigger kinematics changes occur. The higher frequencies gradually add geologically conformable details to the model, resulting in better images for interpretation and reservoir characterization. This work showcases a tilted transversely isotropic earth model building case study for a deep-water ocean bottom seismic acquisition in Santos basin, utilizing elastic propagation and enhanced-template-matching objective function in full waveform inversion combined with multiscale common-image-point tomography.

An extra step was taken to push elastic full waveform inversion up to 55 Hz. The high-resolution model achieved not only follows the underlying geology and matches the well logs, but also results in a full waveform inversion derived reflectivity that closely resembles the reverse time migration image and gives some uplift in the illumination challenged areas.

## Introduction

The challenges posed by complex seismic targets was effectively addressed using full-waveform inversion (FWI) in conjunction with ray-based tomography techniques. FWI originated in the early 1980’s (Lailly, 1983; Tarantola, 1984), and has evolved into a reliable tool over the last decade, enabled by an increase in computing power and acquisition of full azimuth broad band data. Recently, the elastic full-waveform inversion (EFWI) (Vigh et al., 2022) has become feasible in production size projects, and the geological complexity and pervasiveness of salt in the Santos basin makes it well-suited -to become part of earth model building (EMB) workflow in this area.

To maximize the utilization of ocean-bottom node (OBN) data and enable the creation of high-resolution and geologically consistent earth model, we present a suitable model building strategy incorporating EFWI with enhanced-template-matching (ETM) objective function (Cheng et al., 2023; Vigh et al., 2022) in conjunction with multiscale common-image-point (CIP) tomography (Woodward et. al, 2008). The use of EFWI and multiscale tomography is aimed to effectively capture the high-contrast heterogeneity of the earth, assures the gather flatness, and improved well ties.

Considering this, we increased the frequencies gradually up to 55 Hz using EFWI on a smaller sample of data to derive a high-resolution earth model, striving to provide a more immediate lithological knowledge. Additionally, we generated its associated FWI derived reflectivity (FDR) to accompany the subsurface images from migration. FDR (Bai et al., 2020) is a product of a non-linear data fitting mechanism, and can compensate for illumination, resolution enhancement, improvements for interpretability and fault imaging, hence mimics the results from data domain least squares migration.

Therefore, the present work is divided in two complementary parts: the first involves the model building strategy workflow and the second is an application of high frequency EFWI and its FDR on a subset of data.

## Case study context

The survey is located in the deep-water Santos basin, the legacy model used as reference, was constructed using two perpendicular narrow-azimuth towed-streamer datasets. The objective is to formulate a workflow that leverages contemporary broadband processing technologies and model building workflows to improve upon the existing image and model. The acquired data covers about a 1000 km$^2$, using approximately 3,300 ocean-bottom nodes uniformly spaced on the seafloor at 400-m intervals, in about 2,000 m of water, with a nominal maximum offset of 10 km (with some central nodes having offsets > 20 km). The reservoir is set in the pre-salt carbonates at a depth of about 5 km. Hence, the main challenge of this EMB is to have a good model in the post salt, and complex salt to be able to image the target level correctly. With this, it becomes possible to precisely delineate the high-contrast heterogeneity of the target region, leveraging both OBN data and a tailored EMB workflow.

## EMB workflow Methodology

The first part of this work consists in a combination of ETM-EFWI and multiscale CIP tomography. The model building starts with a smoothed version of the legacy tilted transversely isotropic (TTI) model calibrated with the latest well information available. The model updates with FWI start with low-frequency ETM-EFWI from 3 Hz and increasing gradually to 12 Hz peak frequency. Early in the model building phase we observed that the elastic propagation was needed to correctly account for the phase and amplitude complexities posed by the presence of shallow salt, carbonates, and anhydrites, not captured by acoustic wave propagation. EFWI was further run to higher frequencies to add resolution to the model and tackle small scale kinematic challenges.

The elastic propagation approach and the ETM objective function, which matches the local templates between the observed and predicted shot record for temporal and spatial displacements (Vigh, 2023). This approach enables more accurate updates at high-contrast boundaries in the model, such as those related to salt and carbonates as the use of elastic propagation ensures a closer match to the wave propagation in the earth, providing improved amplitude and phase modelling, particularly for high contrasts features. Moreover, elastic modelling better handles post-critical propagation, yielding a more accurate kinematic estimation.

One of the primary benefits of FWI is the capability to initiate model building from early-stage using raw pressure (P) data as recorded by the hydrophones. Deriving a robust low wavenumber is crucial to achieve a kinematically accurate imaging. The P component encompasses abundant transmitted waves, attributed to the long-offset acquisition geometry (refraction and diving waves). This proves advantageous to build the low-wavenumber earth model with significant depth of penetration, despite the steep velocity gradient and the prevalence of shallow layered salt.

The multiscale CIP tomography updates were interleaved, integrating joint velocity and epsilon inversions in the intermediate updates. This process employs structure-guided solution to shape the updates with steering filters (Bakulin et al., 2010). The workflow incorporates residual moveout (RMO) multi-parameter picks from down going wavefield with 12 azimuth ranges covering the full 360 degrees. To accurately capture moveout, we rely on the Kirchhoff offset-azimuth gathers in the post-salt and layered salt section of the image (where the signal is coherent and robust). In the pre-salt sections, where ray-based Kirchhoff gathers alone may not be sufficient, we leverage reverse time migration (RTM) dip guided subsurface azimuth and angle gathers (Du, Xiang 2021). The final stage deployed a multilayer CIP tomography with well constraints.

## EMB workflow Results and discussions

Figure 1 illustrates the resulting model, with a closer look at the pre-salt target level. Notably, a higher resolution Vp achieved by the EFWI at 12Hz is evident, showcasing an improved correlation with the overlayed sonic logs. Arrows highlight a closer match with the sonic profiles. Additionally, the stack response reveals finer geological definition, displaying enhanced structural response and simplification in the pre-salt. These improvements are observable in superior focusing and fault delineation, as indicated by the white dashed circle.

Moreover, the significant decrease in average misties error, from 0.93% to 0.01% at top of salt and from 0.21% to 0.07% at base of salt confirms the robustness of our workflow. Despite the limited angles at the depths of the pre-salt targets, the EFWI and tomography driven workflow markedly improves the gather flatness, bolstering our confidence in the final model. These findings substantiate the reliability in our pre-salt model building workflow and underlying structures.

## FDR derivation and comparisons

Once the earth model building satisfied its requirements of having the optimal image, minimal residual moveout, and misties within 0.5%, we pushed the EFWI to higher frequencies to build a high resolution (broad band) earth model, as developed by the second phase of this work. We took a representative subset of our data, using down-going wavefield, and pushed the frequencies gradually higher up to 55Hz and derived its reflectivity.

We benchmark the updated model with an equivalent RTM ensuring a consistent comparison.

Figure 2 displays the EFWI 55Hz results comparing them with the legacy and EMB from part 1 of this work. Notably, there is a distinct delineation of strong velocity in sediment, layered salt, and pre-salt, exhibiting an even closer match with lithological events found in sonic logs.

In Figure 3 illustrate the reflectivity derived from EFWI, benefits are noticeable in terms of improved illumination and possibly superior wavelet deconvolution, less side lobes are observed. Yielding to an enhanced and cleaner image.

## Conclusions

The presented EMB workflow, showcases the effectiveness of elastic FWI in resolving carbonate reservoirs below thick stratified evaporites in Santos Basin, offshore Brazil. We demonstrate that this methodology produces robust low wavenumber earth models, enhancing horizon continuity and imaging accuracy. By elevating frequencies, we extend the model resolution, which is validated through well log measurements. This contributes to a more reliable subsurface image, emphasizing the crucial role of elastic FWI in seismic processing applications.

The implementation of EFWI to high frequencies led to a notable enhancement to the model resolution. Significant indicators of lateral velocity variations have emerged, overcoming previous unclear delineation. This breakthrough closely aligns with the sonic well data and introduces the potential for obtaining direct lithological information. Moreover, the FDR exhibits an improvement over RTM image benefiting from the embedded least square approach in EFWI, offering a valuable complementary product to validate and extend the regional and stratigraphic interpretations.

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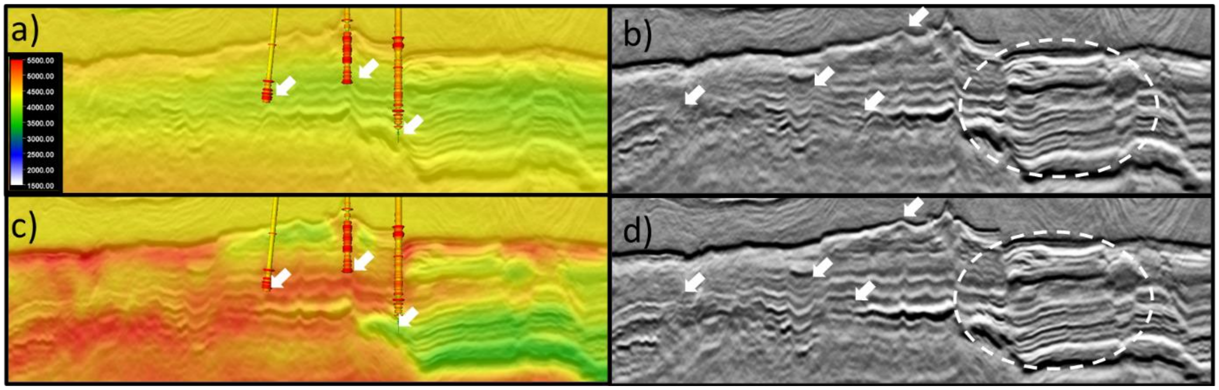

Figure 1: Legacy vs Final velocity: On the left are the KDM images overlaid with velocities, being a) legacy velocity model, c) final velocity model. On the right are, respectively, KDM images produced using b) legacy and d) final model. The white arrows and dashed circle indicate areas of significant improvement.

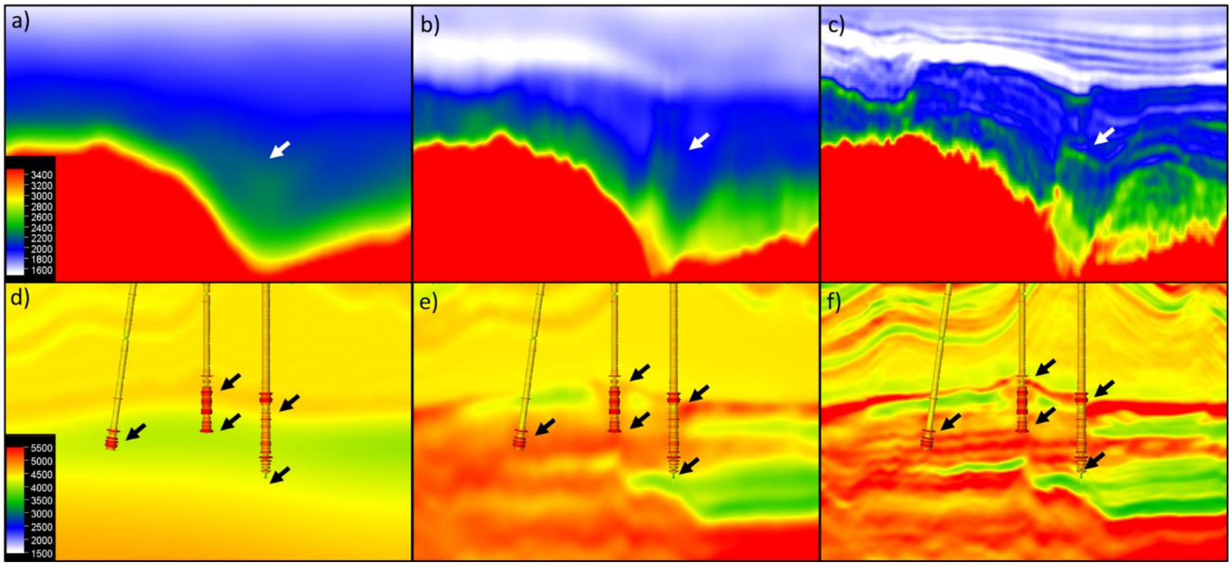

Figure 2: Velocity models comparison. Above is the post-salt region (a) Legacy, (b) EMB workflow, (c) Subset of data EFWI 55Hz, and below is the pre-salt (d) Legacy, (e) EMB workflow, and (f) Subset of data EFWI 55Hz. White arrows highlight faults being enhanced and black arrows the closer match with the sonic logs.

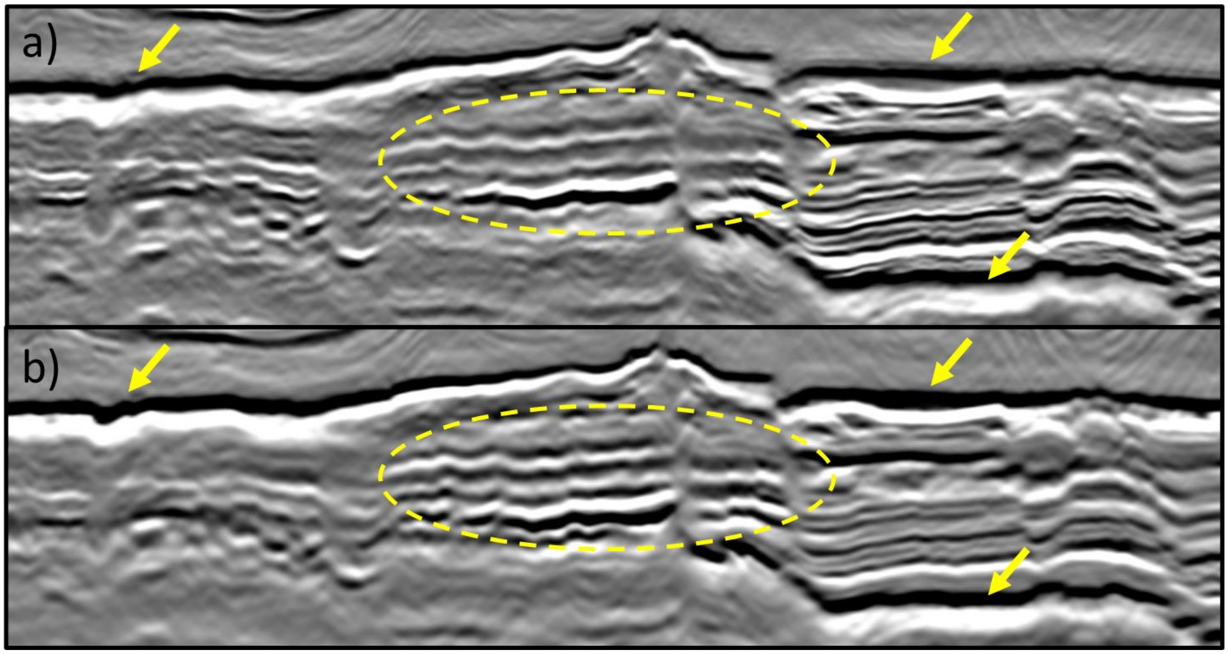

Figure 3: (a) RTM image 55 Hz with inverse Q amplitude applied and (b) Subset of data FDR 55 Hz, both generated using same velocity model. Yellow arrows show better deconvolved FDR's wavelet (sharper) and dashed circle highlights enhanced delineation and illumination.