Advances in OBN imaging for pre-salt fields

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Summary

Since the discovery of pre-salt oil fields offshore Brazil two decades ago, the Santos Basin has transitioned from an exploratory to a development phase. This requires a more comprehensive understanding of the reservoir physical properties. This study aims to demonstrate, on one of the biggest Brazilian oil fields, how five years of technological evolution for OBN processing can improve our understanding of the pre-salt reservoir. The Tupi producing field presents various imaging challenges due to its thick and stratified salt and complex pre-salt layer. The latest technologies, such as elastic Time-Lag FWI, RTM angle gathers using spherical binning and internal multiple attenuation, provide a more accurate velocity model, as well as better fault definition and AVA response. The impact on reservoir-based inversion of the Vp/Vs ratio shows decreased uncertainty at the target level.

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Introduction

Since the discovery of pre-salt oil fields offshore Brazil two decades ago, the Santos Basin has transitioned from an exploratory to a development phase. With this new stage, the primary objective is now to provide comprehensive knowledge of the reservoir and its surroundings. As seismic imaging methods evolve, new technologies can bring more insights to improve our understanding of the reservoir. Using an ocean bottom node (OBN) dataset acquired in 2015 and last processed in 2018, we demonstrate how five years of technological advancements can extract more value from the data compared to the legacy imaging. The new processing includes improved internal multiple attenuation (IMA), reverse time migration (RTM) 3D angle gathers, and elastic full-waveform inversion (FWI).

Data description and methods

This study uses a 2015 OBN acquisition, which covers 110 km² over the Tupi field, located 250 km south of Rio de Janeiro, in the Santos Basin. Data was acquired using a node carpet spread on a 375 m x 325 m staggered grid with shot intervals of 50 m x 50 m, providing a maximum offset of 16 km. The water depth is approximately 2100 m. A layer of stratified salt with thickness of around 1800 m to 2000 m covers the entire region. The reservoir is located in the pre-salt, at a depth of 5000 m. The pre-salt is characterized by a combination of fast carbonates, a slow Piçarras formation, and volcanic layers in a large faulted-block system.

The data was initially processed in 2015 and subsequently in 2018, focusing on 4D analysis (Cypriano et al., 2019). The 2018 processing used the state-of-the art imaging technology available at the time. The velocity model building used a 15 Hz acoustic Time-Lag FWI (TLFWI) (Zhang et al., 2018; Jouno et al., 2019). For pre-processing, internal multiple attenuation (IMA) using an overburden-target separation method (Pereira et al., 2019) was used. The final imaging was performed using 45 Hz least-squares RTM (LSRTM) with Surface Offset Gather (SOG) output.

In 2023, a new pre-processing flow was designed. The flow included small improvements to the de-ghost and directional de-bubble steps to enhance the preservation of low frequencies. The IMA was improved by using a synthetic dataset to compensate for the azimuthal limitation of the streamer data used for the modelling step. This synthetic was created by de-migrating the OBN image in a similar approach to Martinez et al. (2021). For the velocity model building flow, the main addition to the new processing is elastic TLFWI (Wu et al., 2022), which was run up to 20 Hz to add more definition to the pre-salt layers. For imaging, 3D RTM angle gathers were used. A spherical binning approach was utilized to achieve a more natural distribution of energy amongst subsurface azimuths and angles (Pereira et al., 2021).

The benefits of elastic TL-FWI

The velocity inversion used the raw OBN hydrophone data together with a simple smooth layer cake model as an initial velocity. The inversion globally updated the post-salt, salt, and pre-salt sections, using 20 Hz elastic TLFWI. The S-wave velocity was not inverted but kept to a simple ratio of the P-wave velocity.

Figures 1a and 1b display the 15 Hz legacy acoustic TLFWI velocity and the 20 Hz elastic TLFWI velocity overlaid with a well sonic profile. The new velocity demonstrates increased resolution due the combination of its higher frequency content and the use of an elastic engine. The low velocity associated with the Piçarras formation is better delimited by the reflectors in the new model and its value is closer to the well sonic. The accuracy of elastic TLFWI can also be assessed by comparing its inverted velocity with well sonic data. When comparing the velocity profiles presented in Figure 1c, some details of the new velocity become apparent: with a frequency of 20 Hz, the elastic TLFWI starts to capture the stratification inside the salt; in the pre-salt, the new velocity model better represents the contrast between the high velocity of the Barra Velha formation (BVE) and the low velocity of the Piçarras formation when compared to the legacy model.

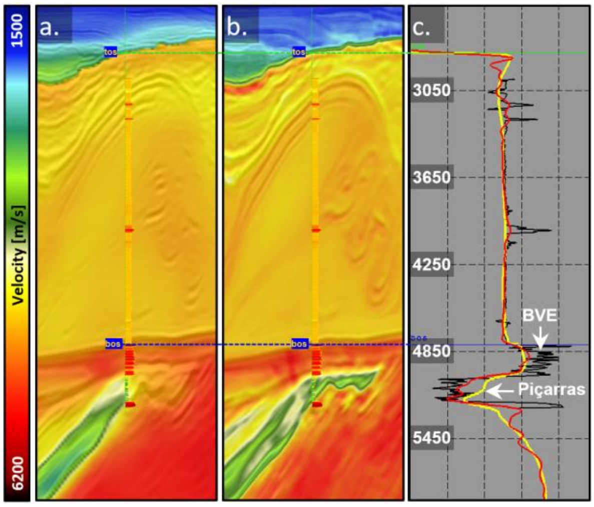

Figure 1 *a. Legacy acoustic velocity; b. New elastic velocity; c. Velocity profiles (yellow: legacy, red: new, black: well sonic).*

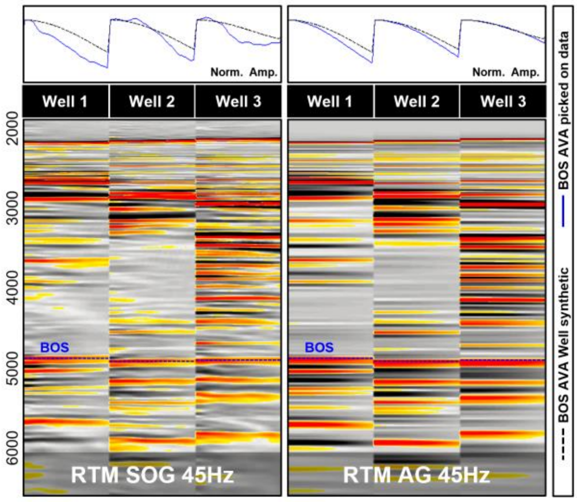

Figure 2 *Legacy and new ADCIGs at well positions. On top, AVA curves picked on base of salt (BOS, blue) and synthetic AVA (black) .*

RTM 3D angle gathers and the effect on AVA

Migration with the new velocity model was performed on the down-going wavefield using RTM, which remains the most effective approach for imaging pre-salt regions when pre-stack angle-dependent information is required. As previously discussed by Xu et al. (2011), the definition of common image gathers (CIGs) in a subsurface angle domain results in fewer migration artifacts when compared to surface offset gather (SOG) RTM, which was used in the legacy processing. This study employed a 3D angle gather (AG) RTM using an equal area spherical binning method (Pereira et al., 2021). This technique computes the gathers by binning different subsurface reflection angles in a more natural way for the Common-Offset-Vector (COV) geometry of OBN data. This avoids over- and under-sampling of near and far angles, respectively. The use of this method led to more continuity on the angle gathers, improving the amplitude versus angle (AVA) response, due to a better sampling of the near angles combined with the fact that no amplitude correction needs to be applied (Pereira et al., 2021).

Figure 2 shows a comparison of angle-domain CIGs (ADCIGs) at three well locations. It is noticeable that the legacy gathers – SOGs converted to angle domain – are noisier than the reprocessed ones. This can be corroborated by comparing AVA curves extracted at the base of salt (BOS). The new RTM angle gathers are more regular due to spherical-to-cylindrical domain interpolation and provide an improved fit to well synthetic AVA in both amplitude and trend along incidence angles. The residual mismatch in the far angles is commonly observed on BOS AVA for Brazilian pre-salt data and remains an active research subject. Further improvements on the final migrated image include IMA and additional post-migration enhancements. LSRTM was applied for each angle plane to mitigate imaging problems that arise from irregular or sparse wavefield sampling and improve the AVA response.

Imaging results and effects on inversion

The evolution of the pre-processing, velocity model building, and migration methods resulted in overall enhancements in imaging quality. Figure 3 shows the improvements in both velocity model and migrated image between the legacy and new processing. The use of elastic TLFWI improved the low-velocity halo near the top of salt, as highlighted by the yellow arrows. This effect was previously documented by Wu et al. (2022) and Brando et al. (2023). Moreover, elastic TLFWI contributed to recovering the pre-salt low velocities within the Piçarras formation, marked by the white arrows in Figures 3a and 3b. The uplift at the pre-salt can be explained by the strong impedance contrast seen at the steeply dipping reflectors with rapid changes in velocity, which intensifies the elastic effects of the wave propagation. Figures 3c and 3d reveal the flattening of the events below the Piçarras formation (blue arrow) and a reduction of the hockey-stick effect observed at the faults, as highlighted by the green arrows. Improvements due to the new IMA are also observable (red arrow).

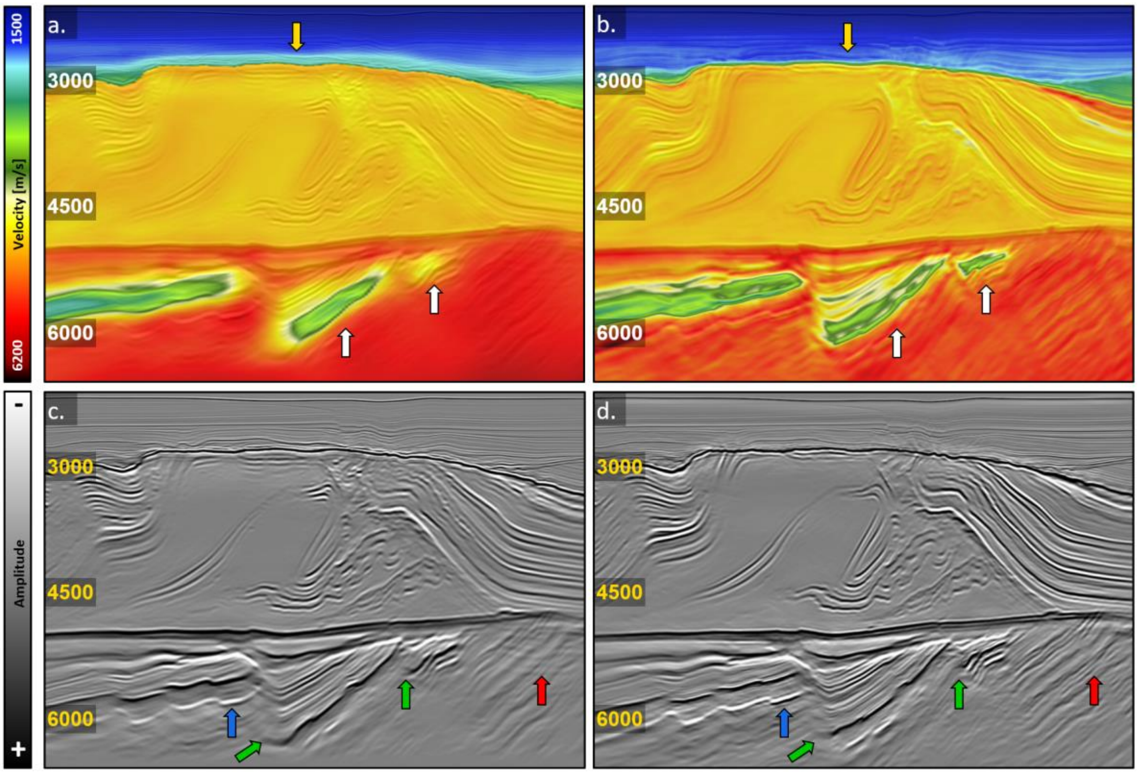

Figure 3 *a. Legacy 15 Hz acoustic TLFWI velocity; b. New 20 Hz elastic TLFWI velocity; c. Legacy 45 Hz SOG-LSRTM; d. New 45 Hz AG-LSRTM.*

The combined effect of the re-processing was evaluated using the final LSRTM partial-stacks for reservoir-based inversion for the Vp/Vs ratio. Figure 4a shows the result obtained with the new data overlaid with well data. There is an accurate match between inverted Vp/Vs ratio and the measured values. Inversion has effectively captured the BVE's low Vp/Vs ratio associated with the reservoir, while also capturing the high Vp/Vs values within the Piçarras. Figure 4b compares the normalized error of the inverted Vp/Vs ratio within the BVE formation, computed at each well position and interpolated to cover the entire BVE horizon. The new data globally reduces the error at the reservoir layer, which can decrease uncertainties when distinguishing between clean and argillaceous carbonate. This result can be attributed to two key factors: 1) a good starting Vp given by the elastic TLFWI velocity, and 2) the improved AVA response driven mainly by the AG-RTM using spherical binning.

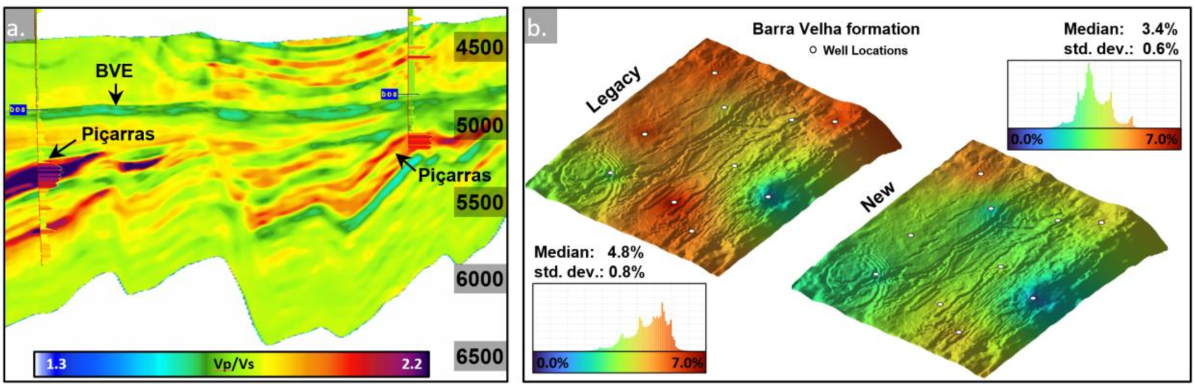

Figure 4 *a. Vp/Vs inverted using new LSRTM partial-stacks, overlaid with Vp/Vs from well data; b. Normalized error of the inverted Vp/Vs ratio within the BVE formation.*

Conclusions

This study presents the outcome of five years of seismic processing evolution on Brazilian OBN pre-salt data. Technological improvements, such as elastic TLFWI and LSRTM using spherical binning, can significantly enhance image resolution, fault definition, deliver better AVA, and provide a more accurate velocity model. This directly impacts the reservoir-based inversion of the Vp/Vs ratio, reducing uncertainties at the target level. In the future, FWI multi-parameter joint inversion of Vp and Vs may replace the need for reservoir-oriented inversions. For the time being, re-imaging legacy OBN datasets is providing uplifts to reduce uncertainties of developing fields.

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