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Full-azimuth internal-multiple modeling and attenuation in a deep-water OBN setting

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Abstract Summary

A field-scale experiment was performed using a combination of 3D internal multiple attenuation (IMA) methods and the deterministic derivation of the generator of the internal multiple travel path in the convolutional process. This innovative approach in the deep-water Santos Basin proved to be beneficial not only for the interpretation of complex structures but also for reservoir monitoring and characterization in time-lapse seismic products, enabled by the improved signal-to-noise ratio (SNR) of the image in pre-salt areas.

Introduction

In deep-water environments such as the Santos Basin, the presence of thick-layered evaporites poses significant challenges for seismic data interpretation due to strong internal multiple contamination. These multiples, generated by the high acoustic impedance contrast between evaporites and surrounding sediments, can obscure true subsurface reflections and complicate the seismic interpretation process, as illustrated in several studies (Pereira et al. 2018; Xavier de Melo et al. 2020). Thus, effective IMA is crucial for mitigating these issues and enhancing the overall quality of seismic datasets, particularly those acquired using ocean bottom node (OBN) technology.

The Santos Basin has hosted one of the largest OBN surveys to date (Trezzi et al. 2024), followed by a time-lapse 4D seismic processing campaign for reservoir monitoring and characterization. Such a large acquisition effort underscores the importance of advanced IMA techniques in managing the vast and complex seismic data from this region as a crucial processing step for obtaining improved imaging and enhancements in the 4D seismic responses. These 4D seismic responses are crucial for monitoring reservoir changes over time. By attenuating internal multiples, not only is the signal-to-noise ratio increases, but also the true amplitude variations with angle can be better preserved, resulting in more reliable amplitude variation with angle (AVA) and inversion outcomes.

This study focuses on the full-azimuth internal multiple modeling methodology and its benefits for OBN datasets in the Santos Basin, highlighting its importance for accurate reservoir monitoring and management, particularly in the context of 4D seismic surveys.

Method

In this study, we incorporated two main factors to obtain higher fidelity internal multiple models. First, we utilized a combination of Jakubowicz and Marchenko-based modeling, providing a robust and comprehensive wavefield extrapolation framework when predicting all internal multiples observed in the field data. Second, we incorporated a deterministic operator referenced at the source acquisition surface as an additional component for OBN datasets, ensuring precise identification and attenuation of internal multiples generated by complex subsurface structures without relying on legacy towed streamer surveys. These combined approaches allowed for significant improvements in the accuracy and reliability of our internal multiple attenuation results.

Based on the principle that any internal multiple can be constructed from three observed subevents positioned at a known surface or subsurface recording datum, data-driven prediction methods employ convolution and cross-correlation operations over a defined and finite number of points grouped as multiple contribution gathers (MCGs). Model predictions are defined according to a common interface (Jakubowicz 1998), or boundary divisions, known as Marchenko-based methods (Van der Neut and Wapenaar 2016).

In this project, three models have been generated to better isolate the different internal multiples as a function of their generators. This alternative modeling strategy aims to reduce the main drawback when combining several formations as generators into a single and simultaneous prediction approach. When doing so, we can counteract the cumulative amplitude approximation errors when not fully considering the depth variant behavior carried out during the modeling process but not present in the observed internal multiple.

In this complex geological setting, the different multiple models are analyzed in the data domain and in the image domain, where the subtraction is performed to better understand their differences and consistency with the input data.

Data-driven multiple modeling algorithms are dependent on dual-datum information to be able to mimic the travel path of internal multiples present in OBN scenarios, where the receivers are stationary on the seafloor and the sources are being towed by a boat on the sea surface.

The asymmetry created by the dual-datum character of OBN breaks the reciprocity assumption of most data-driven modeling solutions, requiring different strategies to reproduce the actual condition of the OBN acquisition setting.

A conventional solution is to use existing legacy streamer data that might be available in the survey area. This data can be used as input to the source side and generator component of the convolution and correlation scheme to be able to compose the full travel path expected by the internal multiple propagation theory.

The limitation of the conventional approach is that such data (legacy streamer) that are needed to construct the internal multiple model might not be always available. Moreover, the limited azimuthal coverage commonly associated with towed streamer data may limit the accuracy of multiples predicted for full-azimuth OBN data, especially in highly complex geological scenarios and deep targets such as the Brazilian pre-salt.

In this project, a new implementation was developed that takes advantage of the OBN data itself to derive the multiple models, without using any *a priori* streamer information. The source-side and generator-side components of the internal multiple prediction process engine were deterministically derived using a high-resolution full waveform inversion (FWI) velocity model (Casado et al. 2024), and a migrated image posed as reflectivity model as input to a one-way wavefield-extrapolation algorithm at given target locations. These modeled datasets were directly used in our data-driven IMA algorithm and provided an unbiased outcome, free of directional imprints associated with the limited azimuthal coverage originating from the legacy towed streamer acquisition.

Results

Following the modeling steps of our IMA workflow, adaptive subtraction of these three models is performed. To allow better discrimination between primary and multiple energy, as reported by Xavier de Melo et al. (2020), image domain subtraction of IMA models is preferred. In this study, a first pass of global matching of the models was performed in the data domain to better balance the amplitudes between predicted models and recorded data prior imaging. After imaging, both the input data and multiple models are projected into the 3D curvelet space, where a m where a soft and variable thresholding masking operation was computed and applied to the data. The sparsity promotion representation of the data as 3D curvelet coefficients promotes better separation between primaries and multiples, resulting in an effective masking computation.

Figure 2 shows the application of the subtraction of the three internal multiple models in the curvelet domain post imaging (defined previously), showing a good attenuation of the internal multiples at the target interval.

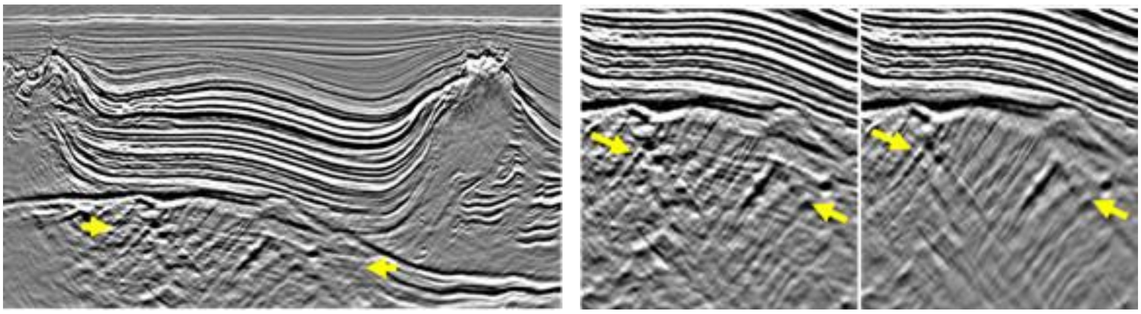

Figure 2: On the left, RTM image before IMA highlighting the multiple contamination. On the right, zoomed images of before (left) and after (right) curvelet domain subtraction showing the effectiveness of the subtraction flow on attenuating multiples overlaying pre-salt reflections.

To fulfill the project objectives, a time-lapse seismic acquisition initiative was started to track production, identify untapped oil, improve reservoir sweep, and calibrate water alternating gas (WAG) injection cycles. The program included a baseline survey (B) in 2015, followed by the first monitor survey (M1) in 2017, and the second monitor survey (M2) in 2023. Previous work published by Scapin et al. (2024) expands the discussion on the survey design and main processing strategies used to provide high-fidelity 4D products.

IMA provides several significant benefits in enhancing 4D seismic responses and signal quality. In this application, the aim is to improve the clarity of seismic data to facilitate more accurate detection of reservoir changes over time, enhance the reliability of AVA analysis, and increase the precision of inversion products, which is crucial for characterizing reservoir properties. These improvements collectively contribute to more reliable and precise monitoring of reservoir dynamics, demonstrating the critical role of IMA in 4D seismic applications.

The workflow above was applied to the three vintages (B, M1, and M2) using the same models to reduce variability associated with slight differences in the predicted multiple times.

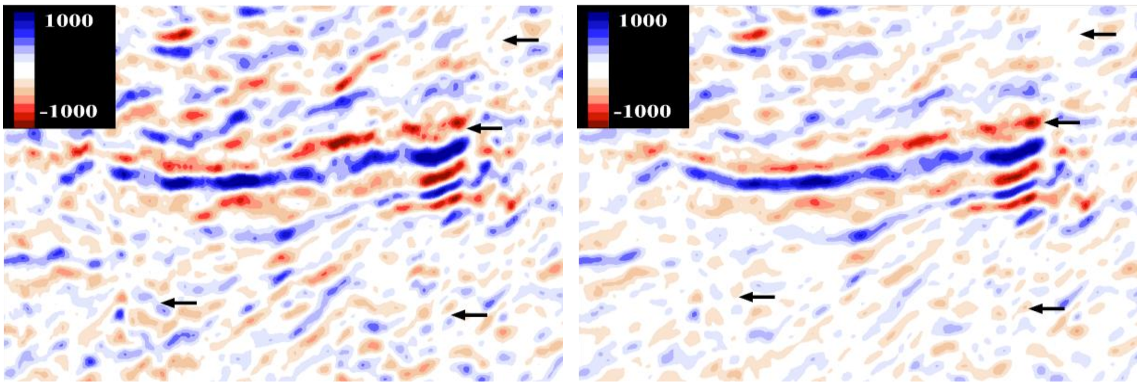

Figure 3: 4D quadrature difference before (left) and after (right) IMA. This composite inline view shows an increase in the SNR and better focusing of 4D responses after a consistent application of IMA over B and M2 surveys. The black arrows highlight the attenuation of interfering multiple energy over the signal.

The overall improvement of the continuity and simplification of post- and pre-salt imaging positively impacts the reservoir modeling due to the increase in SNR and the simplification of the structures through the attenuation of overlapping internal multiple imprint.

One of the main assessments for IMA implementation is to check the 4D difference between vintages for overall improvements in the SNR, and to observe better continuity after the attenuation of crossing multiple energy, mainly generated by the layered evaporites over the presalt events. Figure 3 highlights the beneficial aspect of the process in obtaining more clarity in the 4D responses consistently between B and M2.

Conclusions

We demonstrated a processing application scenario where both Jakubowicz and Marchenko modelling approaches are combined towards a complete internal multiple attenuation framework. We showed that the full-azimuth character of the internal multiple in an OBN dataset could be better represented when deriving the source-side component of the convolutional process from a data-driven deterministic forward modelling. All those insights culminate in a more robust IMA that considers the complexity of the multiple generation in a complex salt context and better represents its travel path along the subsurface. Results show a significant improvement in data quality, not only for interpretation, but also for reservoir characterization and time-lapse campaigns for reservoir monitoring.

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