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Application of Pre-Stack AVA-FWI Elastic Inversion for geological interpretation and reservoir characterization in a Pre-Salt field of the Santos Basin

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Abstract

This study applies Elastic Inversion methodology to characterize pre-salt carbonate reservoirs in the Santos Basin, southeast Brazil. Using pre-stack seismic data and three well data, we estimated elastic properties (Vp, Vs, Rho, Ip, Is, and Vp/Vs). The method provided reliable correlations with well logs, particularly for Vp and Ip, and revealed lateral variations and property contrasts within the Barra Velha Formation. Petrophysical analysis confirmed relationships between impedance and porosity. The results also suggest a reinterpretation of the Intra-Alagoas Unconformity, enhancing geological understanding and supporting reservoir characterization in complex carbonate settings.

Introduction

The pre-salt Lower Cretaceous carbonates on the southeast Brazilian margin have been the focus of many studies. Most of them concentrate on the seismic inversion and reservoir characterization, which is an important step to understand the reservoir properties. One way to perform a reservoir characterization is through the pre-stack elastic inversion, allowing for an estimation of not only the compressional velocity (Vp) but also the shear velocity (Vs) and density (Rho). Those elastic properties contribute to inferring various petrophysical properties such as porosity, volume of shale, etc, which are highly important to a better understanding of the reservoir.

Distinct methods have been applied in the past to perform an elastic seismic inversion in pre-salt carbonates, which are extremely difficult to characterize due to their complex properties and heterogeneities related to intense diagenesis, such as silicification and dolomitization (Penna et al., 2024), and also the existence of fractures in these reservoirs.

In this work, we apply the methodology of the Pre-Stack AVA-FWI Elastic Inversion proposed by Oliveira et al. (2019) to generate multiple elastic properties volumes in a pre-salt field in the Santos Basin. The dataset available for this work is: a 312.5 km^2 high-quality seismic database comprising Ocean Bottom Nodes (OBN) full-stack and angle-stack volumes and 4 wells with various well logs, including gamma ray and acoustic, and elastic. The main goal of this work is to estimate reservoir properties through these inverted volumes and gain insights into geological interpretation.

Method

The Pre-stack amplitude versus angle full-waveform elastic inversion (AVA-FWI) adopted here (Oliveira et al., 2019) employs optimized computational routines based on the reflectivity method to efficiently compute synthetic angle gathers and differential angle gathers. It operates on common-angle gather seismograms derived from image gathers obtained through migration. Like the reflectivity method, AVA-FWI assumes a locally 1-D Earth model, similar to conventional linearized AVA inversion. However, unlike traditional elastic AVA/AVA inversion, it avoids many of the common simplifying assumptions, resulting in improved accuracy.

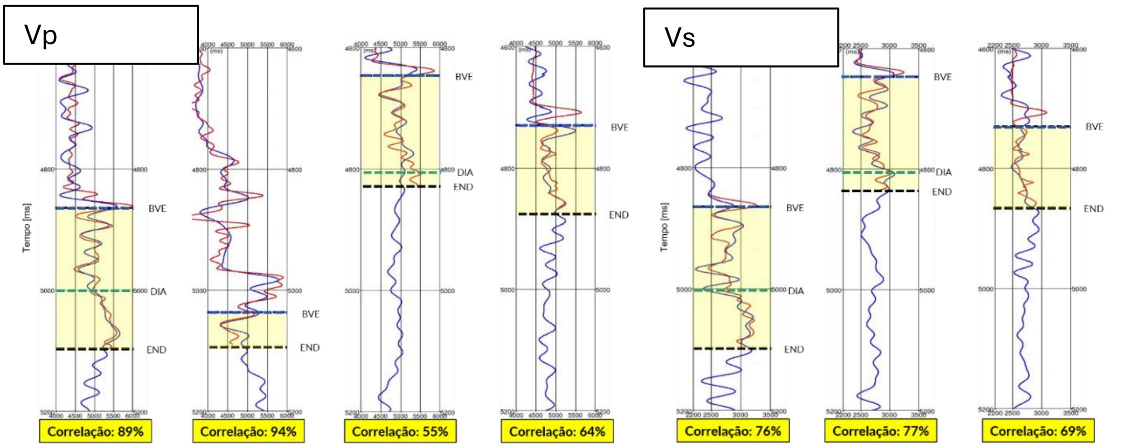
The method is capable of correctly handling seismic amplitudes from prestack data with a wide-angle range beyond 30° of angle of incidence, which is instrumental for density inverted computation. The method works under the local 1D assumption. Our AVA-FWI is a nonlinear inversion based on forward modeling by the reflectivity method, which substantially increases its computational cost with respect to conventional AVA inversion. To address this challenge, we developed an efficient routine for angle gather modeling and a new method for differential seismogram generation that reduces the amount of computation involved in this task (Oliveira et al., 2019).

For the workflow, the following input data were used: angle gathers generated from partial stacks, the seismic wavelet, and the initial low-frequency models (Vp, Vs, and Rho):

1) The angle gathers employed were generated from partial stacks, starting with a mean incidence angle of 10 degrees and ending at 34 degrees, with a 6-degree interval.
2) The seismic wavelet used was statistically estimated by the AVA-FWI program within the inversion window. The target of the inversion window was defined between the top of the Piçarras Formation (PIC) and the top of the Barra Velha Formation (BVE).
3) The initial low-frequency models used in the AVA-FWI inversion, Vp, Vs, and Rho logs, were obtained from three wells. The logs were extrapolated using the interval velocity model (derived from seismic processing) to fill in regions where log data were not available. The VP logs were directly extrapolated using the interval velocity, while the Vs and Rho logs were adjusted through linear relationships, derived from crossplots between the interval velocity and well logs. Once extended, the well logs were filtered to retain only low-frequency content, limited to 8 Hz. Additionally, seismic horizons were used as guides during the interpolation process for generating low-frequency volumes. The horizons used as guides spanned from the top of the Piçarras Formation (PIC) to the top of the Barra Velha Formation (BVE).

Results

Figure 1 shows a comparison between Vp, Vs, and Rho obtained from the inversion and those from the wells (resampled to seismic scale at 65Hz), as well as the correlation coefficients between them. It is possible to note that Vp, Vs, and density (Rho) trends and overall could be fairly well estimated by inversion. The tendency of increase or decrease in various intervals was predicted by the AVA-FWI method, being especially well-correlated near the top of the reservoir on the BVE marker. The Vp has the highest correlations while Rho has the lowest.



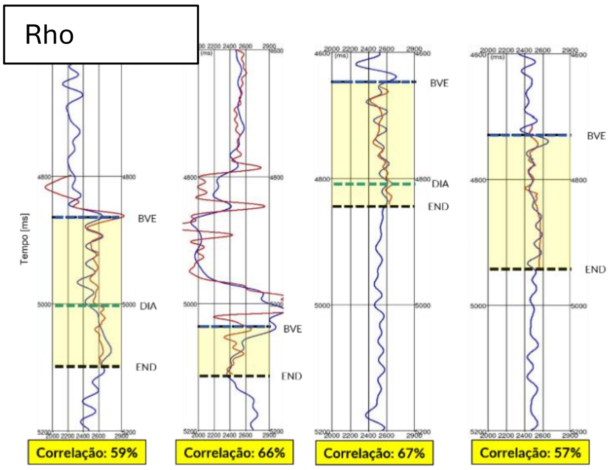


Figure 1: Elastic Vp, Vs, and Rho resulted from AVA-FWI inversion for the wells in comparison with those from well logs, correlated in vertical time (ms) scale. The inverted seismic data is on the interval marked by the yellow polygon. BVE = Barra Velha Fm. Top, DIA = Intra Alagoas Unconformity and END = end of the well data. The black and red curves represent the inverted and measured well-log data, respectively.

Figure 2 shows the results for the inverted compressional velocity (Vp), shear velocity (Vs), and density (Rho) along an arbitrary seismic line throughout the well's position. It is located longitudinally to the field structure and shows a good lateral correlation between the inverted traces and a decrease in the properties of the Barra Velha Fm. interval above the Intra Alagoas Unconformity (IAU). This decrease is higher for Vp, indicating better reservoir properties, especially in the central and southern areas.

Also, there are high values of Vp, Vs, and Rho in the interval below the Intra Alagoas Unconformity in the north and the south of the field. Nonetheless, in the central part, the surface is positioned below the high values, suggesting that the seismic horizon can be reinterpreted.

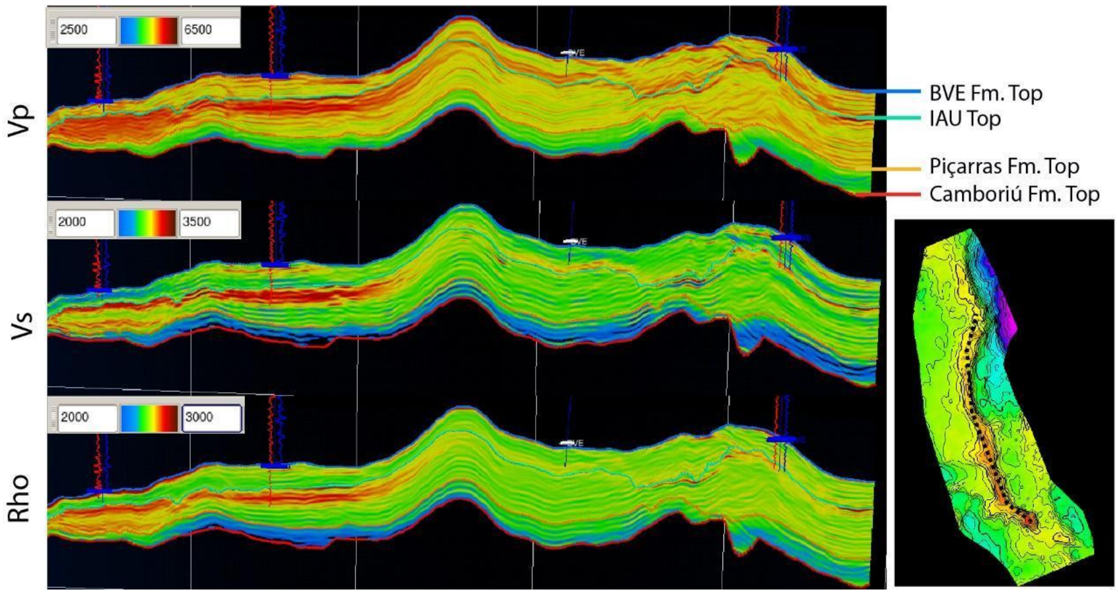


Figure 2: Inverted compressional velocity (Vp), Shear velocity (Vs), and density (RHO) on the left, with the map of the base of the salt on the right. Note the substantial lateral and vertical variation in elastic parameters along the sections, especially the decrease of compressional velocity on the reservoir interval between IAU and BVE tops. Seismic sections in time and map in depth.

The petrophysical crossplots, colored by effective porosity, of P-Impedance and S-Impedance to rock property (NMR-log derived effective porosity) show that most of these reservoir properties are linearly correlated (Figure 3a). Also, a good correlation (inverse relation) is computed between these properties and the porosity; that is, higher impedance values correspond to lower porosity, and conversely, lower impedance values indicate higher porosity. However, the Vp/Vs ratio (Figure 3b) has a different behavior. That is, for the same range of P-Impedance, a wider range of Vp/Vs ratio occurs.

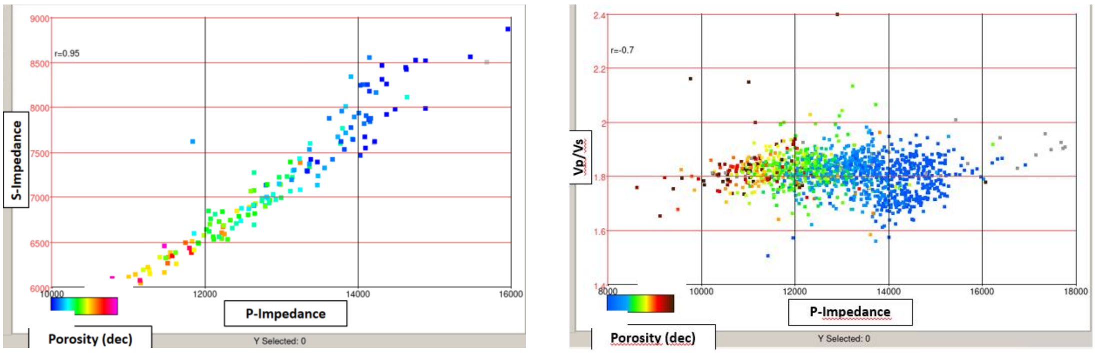


Figure 3: a) P-Impedance versus S-Impedance and b) P-Impedance versus Vp/Vs ratio crossplots from the well logs from tree wells, colored by NMR effective porosity filtered to the seismic sampling. Note the linear relation between P and S impedance and the higher porosity values related to low impedances.

Conclusions

Through Elastic pre-stack Inversion Vp, Vs, Ip, Is, and Vp/Vs were computed. Inverted Vp and Ip have the highest correlations with the measured field log data, with the highest values in the south portion of the field, allowing higher confidence on the inversion in this area. Considering the well data, there is a high degree of correlation between Ip, Is, and porosity, while Vp/Vs ratio shows a wider value range for the same interval of Ip or Is values. Seismic inverted data indicate substantial vertical and spatial variation in reservoir elastic properties over the field area. Furthermore, the Intra-Alagoas Unconformity (IAU) appears, in some areas, shallower than initially mapped using seismic amplitude data. Hence, suggesting that the seismic interpretation and mapping of this surface should be refined.

Acknowledgments

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