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Application of Multi-wavelets Elastic Attributes for the Reservoirs Characterization in the Brazilian Pre-Salt of Santos Basin

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Summary

The Santos Basin Pre-Salt province, located offshore Brazil, has significantly accelerated E&P activities due to its vast hydrocarbon reserves. These carbonatic reservoirs are typically overlain by a complex salt sequence, with thicknesses ranging from a few meters to over 3 km, featuring structures like salt walls and canopies. Above this salt layer lies a thick siliciclastic section, imposing several challenges regarding the seismic amplitude response. Consequently, the seismic signal at the reservoir level is affected by shadow zones and energy loss, particularly in far offsets. Additionally, seismic inversion processes face uncertainties when adopting just a single global wavelet for wavelet estimation. To overcome this issue, we introduce a methodology to generate 3D P-impedance and VP/VS ratio throughout seismic elastic inversion using a non-unique wavelet estimated from wells. The inverted elastic attributes calculated with this methodology incorporates the inhomogeneity of seismic energy arriving at the reservoir level, matching both well and seismic data rather than that traditional methodology that uses a single and global wavelet in the seismic elastic inversion. The results after employing this approach illustrate that mismatches in estimating 3D VP/VS ratios are minimized, leading to improved reservoir characterization workflows including geological, geophysical and geomechanical aspects, because it is well-designed for porosity prediction, facies modeling, fluid saturation analysis, and elasticity modulus estimation.

Introduction

Seismic data is essential for advancing oil and gas fields development projects, supporting activities such as qualitative and quantitative interpretation, facies modeling, geomechanical analysis, and uncertainty assessment (Meneguim et al., 2016; Meneguim et al., 2023). Despite its importance, seismic amplitudes at depths exceeding 5 Km (Figure 1) often suffer from signal degradation in several ways. Imaging challenges arise from uneven illumination caused by the significant variability in salt thickness and its internal mineral composition, as well because the presence of a siliciclastic Albian wedge, which can lead to shadow zones across offset angles (Maul et al., 2015; Camargo et al., 2022).

While halite dominates the salt composition in the salt section, other evaporites such as anhydrite, tachyhydrite, and carnallite also contribute to the inherent complexity (Yamamoto et al., 2016). Furthermore, seismic frequency bandwidth is impacted by low-frequency loss during acquisition (source and receiver noise like ghosts) and high-frequency attenuation due to absorption within the salt layer and Albian wedge. Figure 1 illustrates these effects, showing variations in seismic energy between wells, despite similar reservoir property contrasts observed in well logs.

To properly address these challenges, a tailored multi-wavelet strategy for P-impedance and VP/VS ratio estimation is essential in the study area. This method accounts for spatial variations in seismic energy at well locations, enabling the generation of more representative wavelets compared to the use of a single global wavelet across the entire region. By employing this approach, errors in estimating 3D VP/VS ratio and P-impedance are minimized, leading to improved reservoir characterization workflows such as porosity prediction, facies modeling, fluid saturation analysis, and elasticity modulus estimation (Grana et al., 2021).

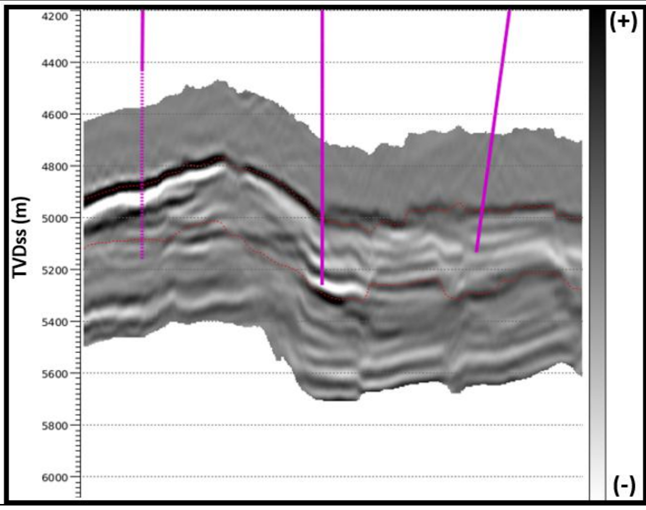

Figure 1: Pre-Salt migrated seismic amplitude in a full stack reservoir section. It illustrates the significant variation in seismic energy at the leftmost well, when compared to the two rightmost wells. The distance between the center well and the rightmost well is 1.5 km.

The results illustrate that mismatches in estimating 3D VP/VS ratios are minimized when adopting this methodology. It led to improvements in reservoir characterization workflows, covering geological, geophysical and geomechanical studies.

Method

The seismic inversion processes use reflection seismic data stacked in the offset angle (near, mid and far, at least) to estimate VP/VS ratio and P-impedance, enabling quantitative calculation of rock properties. It involves the straightforward convolution of a reflectivity model with an estimated wavelet to produce synthetic traces, which are then compared to the input seismic traces for each offset angle range, and the reflectivity model is updated to ensure careful matching between the synthetic and seismic data, as well as lateral/vertical smoothness and sparsity.

For this study, the wellbore VP/VS ratio and P-Impedance log data from 29 drilled wells were used for seismic-well tie, thus the main difference between wavelets is related to energy variation in the seismic data. Given this variation among the wavelets for each sub-stack angle (near, mid and far), they were reorganized by peak amplitudes into three groups: low, medium, and high. Figure 2 shows these three groups of wavelets for the near (left side) and for the far (right side).

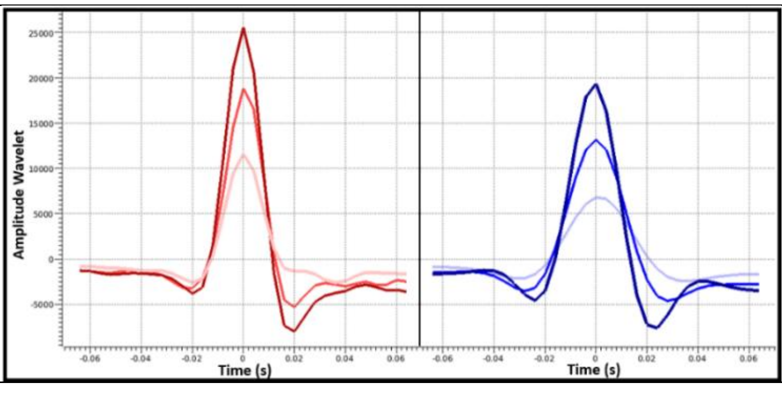

Figure 2: Wavelets Near (left side) in red color and wavelets Far (right side) in blue color organized into three amplitude groups (low, medium and high).

Three deterministic elastic inversion were performed with the same inversion parameterization, prior model, and input seismic data. The only difference between the three inversions was the wavelet group used in each inversion.

The multi-wavelets VP/VS ratio and P-impedance is a linear combination of the three inverted VP/VS ratio and P-impedances, with three appropriate weights for every spatial coordinate (x,y). The weight for each of the three inverted VP/VS ratio and P-impedance are based on the inverse square of the distance to the wells.

Results

Figure 3 presents the full-band VP/VS ratio sections, along with the corresponding well logs . There, the top panel displays the VP/VS ratio derived from elastic inversion using a single average global wavelet for each sub-stack angle (near, mid, and far), while the bottom panel shows the VP/VS ratio obtained using the multi-wavelet approach. Wells B and C required higher energy in the VP/VS ratio than what was provided by the single average wavelet, whereas wells A and D, in the other hand, required lower energy as indicated by the blacks arrows in figure 3. In the top panel, the single average global wavelet did not match well with the events. Conversely, in the bottom panel, the events are significantly better represented due to the application of the multi-wavelet approach.

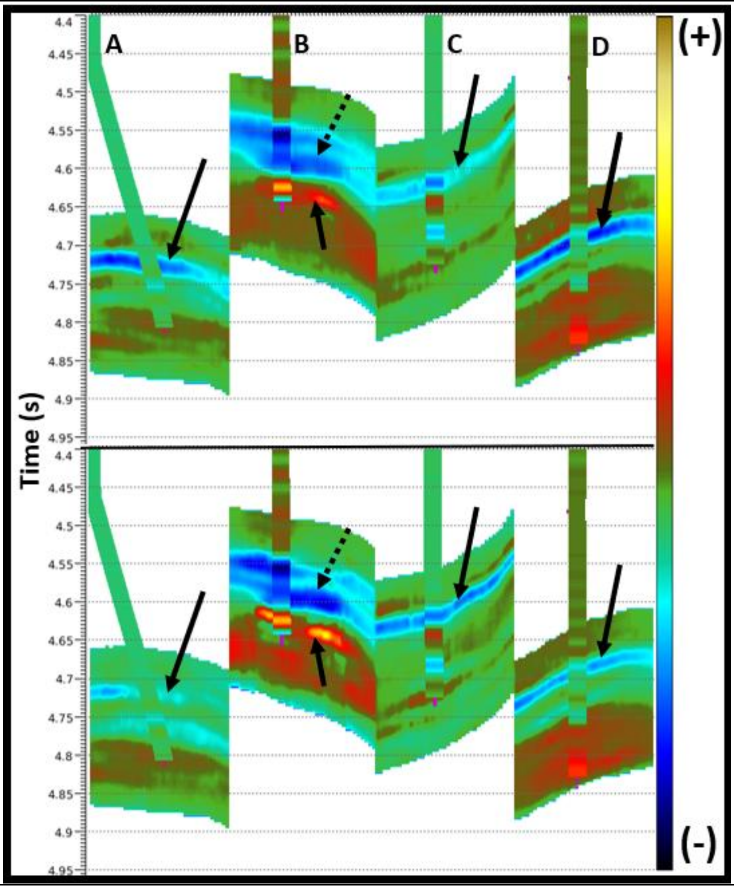

Figure 3: Comparison of the inverted VP/VS ratio using a single average global wavelet for each sub-stack angle (near, mid, and far) in the top panel, and the multi-wavelet VP/VS ratio in the bottom panel. A, B, C, and D represent drilled wells with their corresponding VP/VS ratio well logs.

A quantitative analysis of the multi-wavelet approach was also conducted for the VP/VS ratio within the seismic frequency bandwidth (referred to as band-pass VP/VS) for the four wells—A, B, C, and D—previously mentioned in figure 3. This analysis compared the seismically inverted VP/VS ratio obtained using a single average global wavelet for each sub-stack angle with the multi-wavelet VP/VS ratio cube.

The band-pass VP/VS ratio from the single average global wavelet has a correlation of 0.71 with the well's band pass VP/VS ratio. The band-pass VP/VS ratio derived from the multi-wavelet approach has a correlation of 0.79, much closer to the desired 1 correlation with the well's band pass VP/VS ratio.

Conclusions

The multi-wavelet approach for constructing 3D P-Impedance and VP/VS ratio cubes effectively compensates for non-homogeneous seismic illumination in the vicinity of each well, proving essential for the complex pre-salt reservoir case study in the Santos Basin. This methodology demonstrated improvements in matching well-log VP/VS ratio within the well sections, outperforming the results obtained with a single global wavelet.

Both qualitative and quantitative analyses indicate that elastic attributes derived from the multi-wavelet approach are more reliable for modeling porosity, geological facies, and mechanical properties.

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