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Acoustic Impedance Analysis of Pre-Salt Reservoirs in the Santos Basin: Insights into Faciological and Petrophysical Variability

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Abstract

The transitional Aptian carbonates of the Barra Velha Formation (BVF) in the Santos Basin exhibit significant facies and petrophysical variability, controlled by tectono-sedimentary factors, lake level fluctuations, climatic conditions, and volcanic activity. This study analyses acoustic impedance (AI) patterns from nine wells, integrating sonic, density, spectral gamma ray, and resistivity data. Three distinct AI trends were identified: (i) high values (14,000–14,681 kg/m²·s) in the Upper Barra Velha (BVU), related to high-energy carbonate facies; (ii) low values (~7,628–8,413 kg/m²·s) in the Middle Barra Velha (BVM), associated with stevensite-rich laminites deposited in low-energy settings with potential for organic matter preservation; and (iii) moderately high values (12,663–13,970 kg/m²·s) in the Lower Barra Velha (BVL), indicating more consolidated carbonates. This study suggests that structural position and depositional factors strongly influenced carbonate development and subsequent diagenetic pathways. Within this reversed trend, zones with low AI and high TOC may reflect favourable conditions for organic matter preservation and potential hydrocarbon generation. When integrated with geological models, AI analysis proves to be a powerful tool for characterising pre-salt reservoirs and optimising exploration strategies.

Introduction

The pre-salt reservoirs of the Santos Basin, especially those within the Barra Velha Formation, are characterized by high heterogeneity and challenging hydrocarbon exploration and development. This variability has been widely attributed to tectono-sedimentary controls such as the distribution of relative structural highs and lows, as well as subsequent diagenetic processes (Carvalho et al., 2021; Carvalho et al., 2024). Analog studies, such as those from the Kwanza Basin (Angola), show that structural position plays a major role in controlling carbonate facies distribution (Saller et al., 2016), while environmental and chemical conditions of lacustrine waters influence carbonate precipitation patterns (Wright & Barnett, 2015). This study adopts the term "Transitional Aptian Carbonates" to describe the pre-salt carbonate succession of the Santos Basin, subdivided into Upper Barra Velha (BVU), Middle Barra Velha (BVM), and Lower Barra Velha (BVL).

Previous works suggest that accommodation space variations, syn- and post-rift tectonic reactivations, and differential subsidence controlled the depositional architecture and reservoir quality (Moreira et al., 2007; Cainelli & Mohriak, 1999). Structural highs formed during the rift favoured shallow, high-energy settings with increased sunlight exposure and hydrodynamic agitation, promoting high-energy carbonate development. However, these conditions were modulated by lake level changes, climatic variations, and volcanic events, which influenced facies distribution throughout the pre-salt evolution. This study investigates petrophysical variability among nine wells in the Santos Basin by using acoustic impedance derived from well logs and correlating it with lithological properties, while also analysing the influence of intervals associated with organic matter preservation.

Method

Well log data from nine wells in the Santos Basin, provided by ANP (Agencia Nacional do Petroleo), were analysed across the Barra Velha intervals. The dataset includes sonic velocity (Vp, derived from compressional wave transit time - DT), bulk density (RHOB), spectral gamma ray (GR), resistivity, Nuclear Magnetic Resonance (NMR), and, when available, Total Organic Carbon (TOC) data.

Acoustic impedance (AI) was calculated as $AI = Vp \times \rho$, where $Vp = (10^6 / (DT \times 3.28084))$ (DT in µs/ft, converted to m/s) and $\rho = RHOB \times 1000$ (kg/m³). Lithological interpretation was based on log integration, distinguishing high- and low-energy carbonate facies. Variations in density and transit time helped infer potential diagenetic influences. One of the wells includes geochemical data that confirm conditions favourable to organic matter preservation and possible hydrocarbon generation.

Results

Three main AI patterns were identified in the transitional Aptian carbonates:

• BVU: High AI values (14,000 to 14,681 kg/m²·s), associated with high-energy carbonate facies in shallow settings.

• BVM: Lowest AI values (~7,628 to 8,413 kg/m²·s), corresponding to stevensite-rich laminites and microporous carbonates, deposited in low-energy lacustrine settings with potential for organic matter preservation.

• BVL: Moderately high AI values (12,663 to 13,970 kg/m²·s), indicating more consolidated carbonate deposition.

• In the BVM, thicker intervals (>20 m) tended to show even lower AI values, possibly reflecting enhanced organic matter preservation or greater compaction.

• One well with relatively homogeneous AI displayed subtle density variations that may indicate localised depositional or diagenetic alterations.

One of the most relevant findings of this study is the observation that intervals with good reservoir properties, such as the high-energy carbonates in the Upper Barra Velha (BVU), exhibit high acoustic impedance (AI) values. These high values would typically be expected if these high-energy carbonates underwent early diagenesis with cementation, which would increase AI values but result in sealed reservoirs due to reduced porosity and connectivity. In contrast, facies with poor reservoir quality, such as the stevensite-rich laminites in the Middle Barra Velha (BVM), show low AI (e.g., 7,628–8,413 kg/m²·s) due to microporosity and high organic content, challenging even more the reservoir prediction. Further studies involving a larger number of wells and core samples could provide a more in-depth analysis of these relationships in the future.

Conclusions

Acoustic impedance analysis proved to be a robust tool to characterize the petrophysical variability of pre-salt reservoirs in the Santos Basin. Key conclusions include:

• In some wells, BVM, possibly located in structural lows or low-energy lacustrine environments display low AI and elevated TOC, indicating favourable conditions for organic matter preservation and generation potential.

• Structural highs with high-energy facies exhibit high AI values. In some cases, this may reflect early diagenetic cementation and porosity reduction, but in others, good reservoir quality is preserved despite the high AI.

• Wells with homogeneous AI may reflect diagenetic homogenisation or facies reworking and require further petrographic validation.

The results also show that the traditional association between low acoustic impedance and good reservoir quality is not always valid for pre-salt carbonates in the Santos Basin. Diagenetic processes and facies composition exert strong control over petrophysical parameters and may lead to reversed impedance patterns. This factor should be considered in seismic modelling and exploration strategies to avoid decisions based on oversimplified assumptions.

Greater integration of core samples is recommended to refine the understanding of diagenetic effects and improve the calibration of current geological and geophysical models.

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