Understanding the Relationship between Acoustic Impedance and Porosity in Presalt Carbonate Reservoirs of the Santos Basin using Probability Density Functions (PDF)

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Abstract

The carbonate reservoirs in the Santos Basin presalt are of great importance in the national oil production scenario, being currently the most prolific source of oil in Brazil, with accumulations of excellent production, quality and high commercial value. Quantitative seismic interpretation assists in the characterization of these reservoirs of high geological complexity and in the challenges related to seismic imaging, making the bridge between variations in seismic amplitude and changes in rock properties. The present work aims to understand the relationships between acoustic impedance, porosity and clay volume through the definition of electrofacies. The crossplots and probability density functions (PDF) built for the electrofacies from the well data with the upscale showed a good correlation between the values of acoustic impedance and effective porosity when considering the reservoir, tight carbonate and igneous electrofacies, but it is difficult to distinguish between muddy and reservoir electrofacies. This work intended to evaluate the feasibility of using an acoustic impedance volume for future modeling of reservoir properties, and to evaluate the types of electrofacies that can be distinguished in a future classification of multi-attribute seismic facies.

Introduction

The presalt of the Santos Basin is the most prolific source of oil in Brazil, with accumulations of excellent quality and high commercial value. In July 2020, the presalt reservoirs surpassed the mark of 70% of the national monthly production of oil, with more than 2.7 million boe/day (ANP, 2020). The increasing importance of the presalt interval in the national oil production scenario, together with the high geological complexity of its reservoirs, require increasingly accurate analyses and forecasts.

A series of recent articles uses quantitative seismic interpretation techniques to characterize presalt reservoirs. Acoustic and elastic inversions are recurrent themes, as well as the use of impedance volumes for modeling reservoir properties, such as porosity and facies classification (Teixeira et al., 2017; Dias et al., 2019; Peçanha et al., 2019; Penna et al., 2019; Penna and Lupinacci, 2021). Acoustic impedance data has also been frequently used for the classification of multi-attribute seismic facies in presalt carbonate reservoirs (Jesus et al., 2019; Ferreira et al., 2019; Ferreira et al., 2021).

A major challenge for the use of acoustic impedance is the difficulty of relating it concomitantly to the porosity and types of facies of the carbonate reservoirs. This is because lithologies with different porosities present, in many cases, similar values of acoustic impedance. Several works address this problem and discuss alternatives to get around it (Teixeira et al., 2017; Castro e Lupinacci, 2019; Dias et al., 2019; Mello, 2020; Penna and Lupinacci, 2020; Penna and Lupinacci, 2021).

This work aims to correlate the values of acoustic impedance with the values of effective porosity from well logs, in a scale compatible with the acoustic impedance volume, to evaluate the feasibility for future modeling of reservoir properties, and to evaluate the types of electrofacies that can be distinguished in a future classification of multi-attribute seismic facies.

Method

For the development of this work, we used data from 10 wells drilled in a presalt field of the Santos Basin. The objective is to evaluate the relationships of acoustic impedance and porosity, on the seismic scale, for different electrofacies in the two presalt producing formations: Barra Velha Fm. and Itapema Fm.

For this purpose, we constructed crossplots and probability density functions from the well logs. To carry out this analysis with a resolution compatible with seismic data, the well logs were upscaled using the Backus average (Backus, 1962; Tiwary et al., 2009). The sampling rate was set to 5m, equal to the sampling rate of the seismic volume. Figure 1 exemplifies the upscale process in a well.

After the upscale, we defined four electrofacies based on the identification of the igneous rock intervals, and on the effective porosity and clay volume values. For the zoning of the igneous rocks, we used lithological logs from composite logs, together with a well log evaluation. We use the effective porosity log from nuclear magnetic resonance (NMR), and where it was affected by washovers, we estimated the effective porosity from the sonic log. The clay volume (Vclay) was calculated from the Gamma Ray (GR) log using the Larionov method (1969) for ancient rocks:

$$\mathrm{V_{cl_{GR}}} = 0.33\left(2^{2\mathrm{xIGR}} - 1\right), \quad (1)$$

where IGR is the gamma ray index:

$$\mathrm{IGR} = \frac{\mathrm{GR} - \mathrm{GR_{min}}}{\mathrm{GR_{max}} - \mathrm{GR_{min}}}. \quad (2)$$

After these calculations, we segmented the electrofacies according to Table 1 to assess the main lithologies found in the wells and to discuss the relationship between porosity and acoustic impedance. The minimum porosity cutoff value used to define the reservoir electrofacies was 6%. Below this, the cutoff value of 20% in Vclay was used to differentiate tight carbonates (Vclay <20%) from muddy facies (Vclay> 20%).

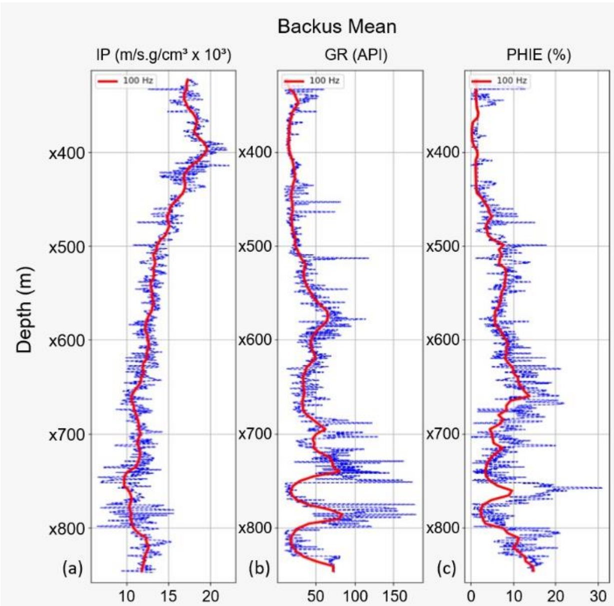

Figure 1: Example of the logs upscale in a well of the study area, using the Backus average (red line) at a cutoff frequency of 100Hz. (a) Acoustic impedance log (Ip); (b) Gamma ray log (GR); c) Effective porosity log (PHIE).

Table 1: Criteria for segmentation of electrofacies after *upscale*.

Criteria	Electrofacies
Lithology from composite and log interpretation	Igneous
PhiE > 6%	Reservoir
PhiE < 6% & Vclay < 20%	Tight carbonate
PhiE < 6% & Vclay >20%	Muddy facies

After the upscale and the definitions of the electrofacies, we built crossplots of effective porosity by acoustic impedance. These crossplots were built for each formation (Barra Velha and Itapema) and with the two formations simultaneously. Finally, we estimated the probability density functions (PDF) of acoustic impedance for each electrofacies by formation and for the entire reservoir interval. The PDF estimation was performed using the kernel density estimation method (Hastie et al, 2008).

Results

To exemplify the data upscale used to carry out this work, **Figure 2** shows the logs of well A, both in the original scale and using the upscale, considering a cutoff frequency equal to 100Hz and a sampling rate of 5m. We can notice that the main electrofacies are well represented in the upscale, but it is not possible to represent very thin layers.

In this well, the Itapema Fm. shows intercalations of reservoir electrofacies with muddy electrofacies. In the Barra Velha Fm. is observed a decrease in porosity and an increase in acoustic impedance from the base to the top, when the 4 electrofacies of the study area are present. This decrease in porosity, associated to a high content of silica and dolomite (confirmed in the descriptions of lateral samples and other well logs), possibly associated with diagenetic processes. This indicates that diageneses were more intense in the proximity to the base of the igneous intrusion (igneous electrofacies), where occur a change from reservoir to tight carbonate electrofacies.
Crossplots and PDF (**Figure 3** and Figure 4) show data from the 10 wells used in this work. In the crossplot with data from both Itapema and Barra Velha formations (**Figure 3**-a) there is a good correlation between acoustic impedance (IP) and effective porosity ($\Phi_{e,NMR}$) when considering igneous electrofacies, tight carbonate and reservoir. On the other hand, the muddy electrofacies hinder this correlation. It is observed that both the reservoir and muddy electrofacies are in the same acoustic impedance range: between 8,000 and 12,000 (m/s.g/cm3). This represents a major challenge for the use of porosity modeling techniques and classification of facies based solely on the IP volume as a constrain. This overlapping of IP values in the presalt carbonates between reservoir and non-reservoir rocks has also been reported in the work of Teixeira et al. (2017); Castro and Lupinacci (2019); Dias et al. (2019); Mello (2020); Penna and Lupinacci (2020); Penna and Lupinacci (2021).

A similar behavior can be seen in the porosity and acoustic impedance crossplots for the Barra Velha Fm. (**Figure 3**-b) and the Itapema Fm. (**Figure 3**-c). However, it is possible to make some important analyses regarding the type of lithology from the different IP values found for the muddy facies and the igneous facies in each of the two formations. At the Itapema Fm., IP values for muddy facies are lower and are associated mainly with shales, while the Barra Velha Fm. presents higher IP values for these facies, and are associated with clay carbonates, such as laminites. When analyzing the igneous rocks, at the Barra Velha Fm. the IP values are higher and they are classified as diabase (igneous intrusions), while in Itapema Fm. there are lower IP values and facies are described as basalts (igneous extrusions).

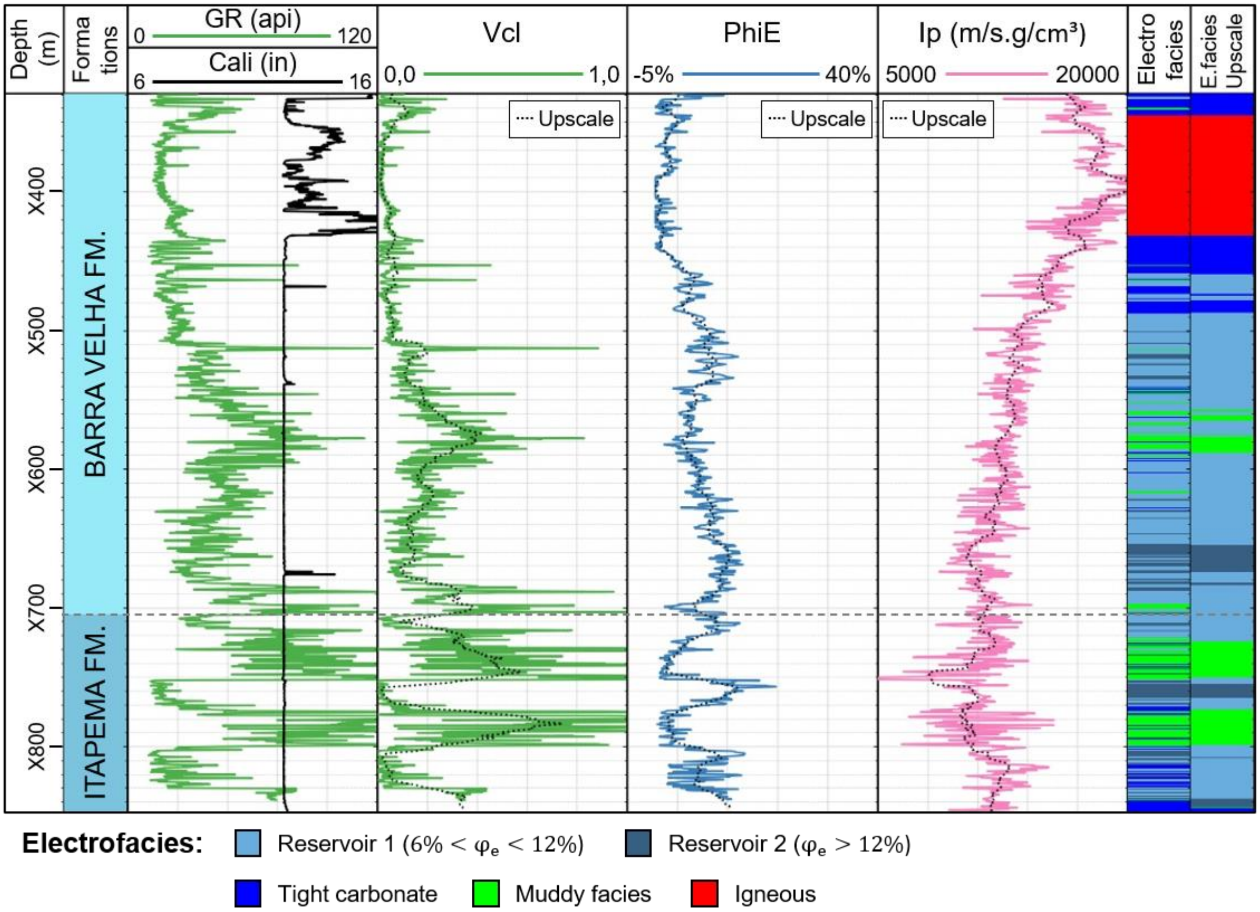

Figure 2: Well logs from Well A to exemplify the upscale of the data used to carry out this work. From left to right: depth; formations; caliper (CAL) and gamma ray (GR); clay volume (Vcl); effective porosity of nuclear magnetic resonance (φ_{e_NMR}); acoustic impedance (Ip); original electrofacies from the well; electrofacies after the upscale. The Vcl, φ_{e_NMR} and Ip logs are presented in the original scale (continuous line) and using the upscale (dotted line), considering a cutoff frequency equal to 100Hz and a sampling rate of 5m.

The PDF (Figure 4) allow us to assess whether it is possible to separate the different electrofacies in a classification of seismic facies based on acoustic impedance. The PDF of the whole presalt reservoir interval (Figure 4-a) show an overlap between reservoir electrofacies with muddy facies, and an overlap between tight carbonate electrofacies with igneous. The overlap between the tight carbonate and igneous electrofacies ends up not being as problematic as in the first case for modeling reservoir properties, as both proved to be non-reservoir, due to the low porosity that they present in the upscale. The possibility of unconventional fractured igneous reservoirs is not contemplated is this study.

At Barra Velha Fm. (Figure 4-b), there is a better separation of the tight carbonate and igneous electrofacies, as the igneous have higher IP values in this interval. In this formation, it is more difficult to separate the muddy and reservoir electrofacies, as is observed in the crossplots of **Figure 3**-b. On the other hand, Itapema Fm. (Figure 4-c) shows a better separation between the PDF of the reservoir electrofacies and the PDF of muddy facies (shales), as the muddy facies have a lower IP value. PDF of igneous and tight carbonate electrofacies have greater overlap in this formation, and it is possible to identify a bimodal behavior in tight carbonates. This bimodal behavior is also observed in the Barra Velha Fm., and it is associated with the higher heterogeneity of the presalt carbonates, due to the diagenetic processes, since many samples and geochemical logs indicate high silicification and/or dolomitization. Mello (2020) shows how the mineralogical composition of carbonates from Barra Velha Fm. impact on the elastic parameters of these rocks and finds that rocks with a considerable content of dolomite have higher values of elastic parameters than rocks with a elevated quartz content.

The overlapping of PDF, especially of reservoir electrofacies and muddy facies, is a challenge for the modeling of reservoir facies when this is done using only an acoustic impedance volume. When the overlap is large, it becomes impossible to define which IP values correspond to each facies. As an alternative, it is possible to condition facies modeling with *a* priori information. For the case of overlapping of muddy electrofacies and reservoir in the Itapema Fm., we can, for example, consider that in structural lows, shales are more likely to occur.

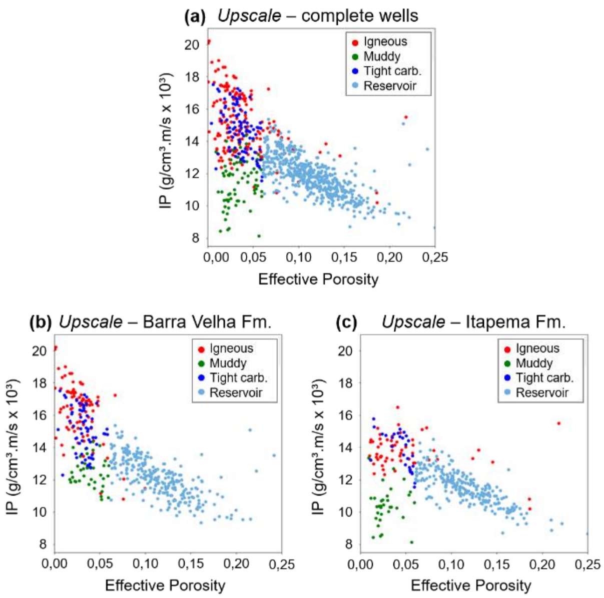

Figure 3: Crossplots of acoustic impedance (IP) vs. effective porosity from 10 wells in the study area. (a) Presalt reservoir interval; (b) Barra Velha Fm.; (c) Itapema Fm.

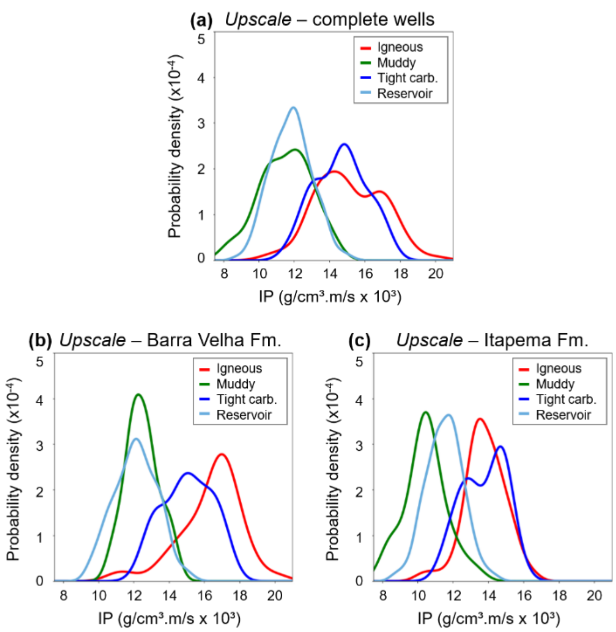

Figure 4: Probability density functions from 10 wells in the study area. (a) Presalt reservoir interval; (b) Barra Velha Fm.; (c) Itapema Fm.

Conclusions

The analysis of crossplots helped to understand the correlation between acoustic impedance and effective porosity. The igneous electrofacies, tight carbonate and reservoir showed a good correlation between IP and effective porosity. The muddy electrofacies have porosities lower than 6%, but they still hinder this correlation, as their IP values are within the same range as the IP values of the reservoir facies. This results in a big challenge for the use of techniques of porosity modeling and classification of facies that have as constrain only one volume of IP.

The probability density functions (PDF) of the acoustic impedance, together with the crossplots, helped in a better understanding of the behavior of the electrofacies in the study interval. When we consider the data from both Itapema and Barra Velha formations, the PDF showed overlaps between the reservoir electrofacies with the muddy facies, and between the tight carbonate electrofacies with the igneous ones. Separately, the two formations showed different behaviors. At the Itapema Fm., PDF referring to muddy facies have lower IP values and, therefore, are more easily separated from reservoir electrofacies. In the Barra Velha Fm., it is more difficult to separate PDF referring to muddy and reservoir electrofacies, due to the close values of IP. This overlap is a challenge for the modeling of reservoir facies, as it becomes difficult to define which IP values correspond to each facies. As an alternative, it is possible to condition facies modeling with a priori information.

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