Seismic facies characterization of carbonates of the Macaé Group in Campos Basin using acoustic seismic inversion

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Abstract

The Campos Basin is located on the north coast of the state of Rio de Janeiro and the south of the state of Espírito Santo. Seismic inversion is one of the methods used for the characterization of lithologies and to differentiate the lithostratigraphy, because it presents distinct impedance values capable of making the identifications of the lithologies. This work aims to characterize the different seismic facies of the carbonates present in the Macaé Group in Campos Basin through the model-based seismic inversion. The inversion was performed in the 2D seismic line 0258-3145 and in an arbitrary line obtained from the 3D seismic volume. The results showed the characterization of three seismic facies in both data, identified lithologically as a) calcirrudites and calcarenites; b) calcilutites, shales, and marls; and c) marls, and from this characterization, it was possible to interpret the lithology of the studied area. Thus, the methodology applied was fundamental for the identification of the carbonates of the Macaé Group and demonstrates how seismic inversion is an efficient method for this characterization.

Introduction

In recent decades, the oil industry has focused on the development of new methods to obtain models of the physical characteristics of rock and fluid. Therefore, it is crucial to have reliable subsurface information to reduce exploratory risk. Carbonate reservoirs are important worldwide in the hydrocarbon scenario because 60% of oil reserves are found in these rocks, in addition to 40% of natural gas reserves (Milani et al., 2000).

There are several obstacles in exploring carbonate reservoirs due to the complexity of identifying the properties of carbonate rocks in unsampled sites, mostly because of its extensive and complex lateral and vertical variation of facies and porosity (Maucec et al., 2011). Therefore, the seismic method has great importance for understanding these reservoirs.

The seismic method is a reference among geophysical techniques for being able to identify the reflectivity of subsurfaces, resulting in the production of a high-resolution structural image. Seismic exploration techniques are being increasingly improved over the years, especially when it comes to more complex subsurface geological structures, such as in the pre-salt. This case requires a greater technological demand for the prospecting and production of hydrocarbons, thus demanding better geophysical techniques for imaging and inversion of properties (Carneiro, 2017).

Seismic inversion combines geological, petrophysical, and geophysical measurements and knowledge. This technique can be used in the characterization of seismic facies by building a more accurate model of them, which makes it possible to better identify the geometry of the reservoirs, thus reducing the uncertainties of the exploratory risk. The model-based seismic inversion is quite popular in the geophysical world because it estimates acoustic impedance quickly and reliably. In this method, a forward modeling technique is used to generate a seismic data based on an acoustic impedance model of the subsurface (Maurya et al., 2019; Kushwaha et al., 2021).

The Campos Basin is located on the north coast of the state of Rio de Janeiro and the south of the state of Espírito Santo (Figure 1). This basin is bordered by two structural highs: to the south, Alto de Cabo Frio, and to the north, Alto de Vitória, which separate it, respectively, from the Santos and Espírito Santo basins. The basin covers an area of 100.000 km², from the outcrops of the basement on the continent to its limit with international waters (Winter et al., 2007).

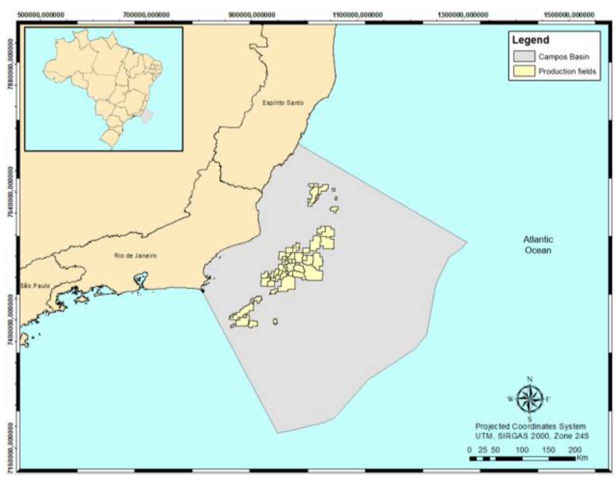


***Figure 1** – Regional map indicating the location of the Campos Basin and the production fields.*

The Macaé Group has a large albo-turonian carbonate section and characterizes the beginning of the implantation of the South Atlantic (Drift Supersequence). The stratigraphic landmark known as chalk, formed by calcilutites and marls, is found in the Upper Macaé (Neoalbian-Eoturonian age). This landmark was deposited in response to sea level rise, with the drowning of shallow water carbonates from the Lower Macaé (Eo-Mesoalbian) (Spadini et al., 1987).

In the proximal portion, the Macaé Group is composed of the Goitacás Formation, and in its distal portion, the Quissamã (calcarenites and calcirrudites), Outeiro (calcilutites, marls, and shales) and Imbetiba (marls) formations (Winter et al., 2007).

The Quissamã Formation is influenced by a smooth carbonate slope formed as the basin gradually opened, its base is composed of deposits of tidal plains, supratidal, intertidal, and lagoons, and from the middle to the top of the sequence, high-energy facies predominate in oolitic and oncolitic calcarenite beds (Winter et al., 2007).

The top of the Outeiro Formation has rhythmic rocks deposited during sea level rise, which happened during the Eo-Mesoalbian. Despite the hot and dry climate that prevailed during the deposition of the Quissamã Formation, the greater biodiversity in this stratigraphic interval is a response to desalination due to the gradual rise of sea level (Spadini et al., 1987).

The Imbetiba Formation is characterized by pelitic sediments, essentially marls, that record deep marine conditions, in a general sea-level rise context. These marls represent the drowning of the entire carbonate package (Winter et al., 2007).

The listric faults of this basin originated in the Albian and persisted until the Holocene and were extremely important for the control of sedimentary facies, causing them to contribute to the trampling in most of the hydrocarbon accumulations of Campos Basin. The first movements of salt formed salt pillows, which controlled the distribution of the carbonates of the Macaé Group (Figueiredo et al., 1984).

This study aims to improve the characterization of different seismic facies of the carbonates present in the Macaé Group in Campos Basin. This characterization occurs through the model-based seismic inversion using the 2D seismic line 0258-3145 and an arbitrary line drawn from the 3D seismic volume.

Method

The data used in this work were provided by the National Agency of Petroleum, Natural Gas and Biofuels (ANP), obtained from the Exploration and Production Database (BDEP), and correspond to the data of seismic surveys of Campos Basin: a 2D and 3D PSDM data (Post-Stack Depth Migration data). In this study, we used the 2D seismic line 0258-3145 and an arbitrary line obtained from the 3D seismic volume (Figure 2), in addition to the well 6-BRSA-517-RJS, which is located near them. The model-based seismic inversion was carried out in both lines.

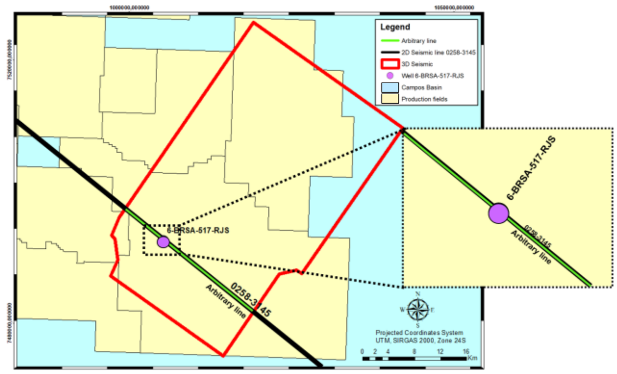


***Figure 2** – Map of the 2D seismic line, the arbitrary line obtained from the seismic volume 3D and the well 6-BRSA-517-RJS used in the work. The lines and where the model-based seismic inversions were carried out is highlighted.*

The work was developed in eight steps, demonstrated in the work flowchart in Figure 3: (1) Loading of the post-stacked seismic data; (2) Processing of post-stack seismic data using the filters Graphic Equalizer and Median; (3) Interpretation of horizons; (4) Loading of the well data; (5) Well-to-seismic tie; (6) Creation of the low-frequency model (initial model), (7) Model-based seismic inversion and (8) Characterization of seismic facies. In addition, a quality control was carried out for the updating and improvement of the well-to-seismic tie and, consequently, of the low-frequency model, the model-based inversion, and the characterization of the facies.

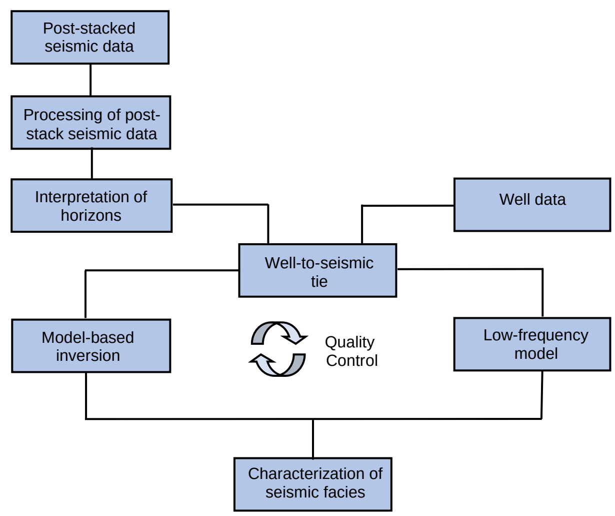


***Figure 3** – Flowchart used for the work.*

The very first step consists of the processing of the post-stack seismic data, in which were applied the Graphic Equalizer and Median filters. The migrated seismic data may present noises from the seismic migration stage, the use of these filters aims to increase the signal/noise ratio and, consequently, improve the continuity of the reflectors. After these applications, the horizons were interpreted, and the well-to-seismic tie was done. Next, a low-frequency model was created, and we performed the model-based seismic inversion on each data. Thus, it was possible to interpret the seismic inversions, compare the results and characterize the carbonates.

Results

Using the seismic data with post-stack processing, five horizons were interpreted in the two seismic lines: salt base (base of the Retiro Formation), salt top (top of the Retiro Formation), top of the Quissamã Formation, top of the Outeiro Formation and top of the Imbetiba Formation (Figures 4 and 5). This step is essential for an accurate well-to-seismic tie. The well-to-seismic tie is important in the process of seismic inversion, as it demonstrates the best correlation between the data and the well. For this process, the seismic data, the interpreted horizons, and the information on the profiles of the well were used.

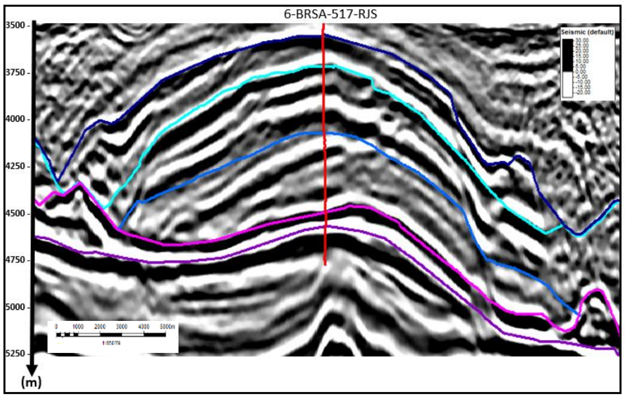


Figure 4 *– 2D Seismic line 0258-3145, with emphasis on the area of well 6-BRSA-517-RJS and the interpreted horizons. From the bottom to the top: salt base (base of the Retiro Formation) (purple), salt top (top of the Retiro Formation) (pink), top of the Quissamã Formation (light blue), top of the Outeiro Formation (green) and top of the Imbetiba Formation (dark blue).*

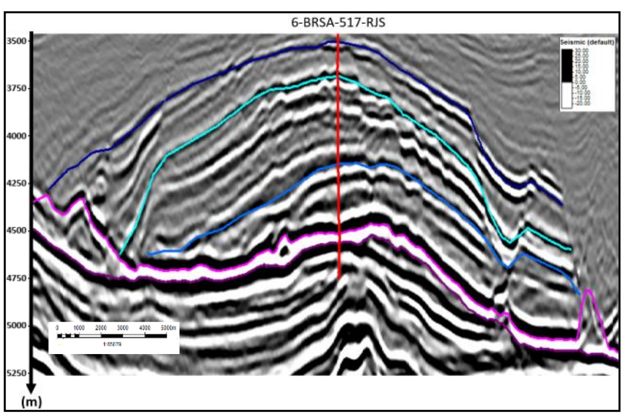


Figure 5 *– Arbitrary seismic line of the 3D seismic volume with emphasis on the area of well 6-BRSA-517-RJS and the interpreted horizons. From the bottom to the top: salt base (base of the Retiro Formation) (purple), salt top (top of the Retiro Formation) (pink), top of the Quissamã Formation (light blue), top of the Outeiro Formation (green) and top of the Imbetiba Formation (dark blue).*

To perform the inversions, the well 6-BRSA-517-RJS was chosen because it is the closest to the seismic lines and it also contains the necessary information (Vp and density) to undertake the seismic inversions. With the results, the initial low-frequency model of each data was generated based on the estimation of the impedance values of the well. As a result, the inversion of the well was carried out, so that it was possible to start the quality control process.

The quality control process was performed by analyzing the correlations and accuracy of the seismic inversions of the 2D seismic line 0258-3145 and the arbitrary line presented, respectively, in Tables 1 and 2. The Tables represent the error between the impedance (Zp) of the well and the impedance of the inversion and the correlations between the impedance of the well and the impedance of the inversion. Above 70% of correlation, the inversion is considered satisfactory for a good seismic inversion result, and the lower the error between the well impedance and the inversion impedance, the more accurate the inversion will be.

Table 1 *– Correlation and error corresponding to the well referring to the 2D seismic line 0258-3145.*

Well	Error between well Zp and inversion Zp	Correlation between well Zp and inversion Zp
6-BRSA-517-RJS	1556.260	0.736488

Table 2 *– Correlation and error corresponding to the well referring to the arbitrary line.*

Well	Error between well Zp and inversion Zp	Correlation between well Zp and inversion Zp
6-BRSA-517-RJS	964.595	0.899603

By analyzing the results on Table 1 and Table 2, we observed that they were close and adequate for each line, and the model-based seismic inversion was performed for each of them, providing absolute acoustic impedance values for the seismic data. With these results, the seismic lines were interpreted, highlighting the formations of the Macaé Group. Through this analysis, it was possible to investigate and compare the results of the 2D seismic line 0258-3145 with the arbitrary seismic line of the 3D data, their similarities, and how much they complete each other (Figures 6 and 7).

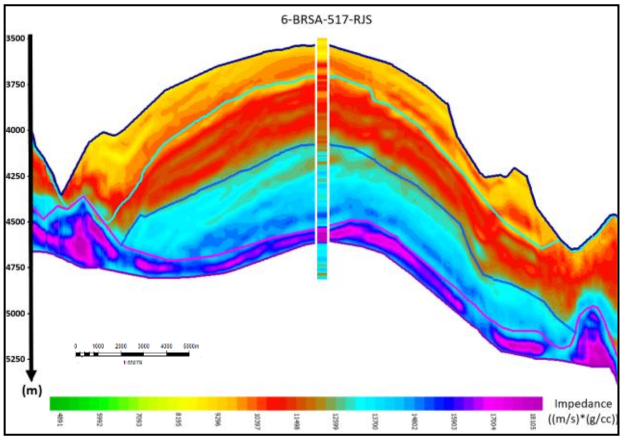


Figure 6 *– Model-based seismic inversion of the seismic line 0258-3145 and the well 6-BRSA-517-RJS.*

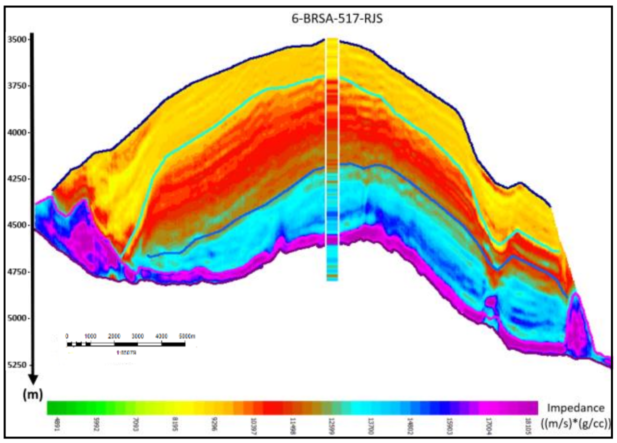


Figure 7 *– Model-based seismic inversion of the arbitrary line of the 3D volume and the well 6-BRSA-517-RJS.*

For the analysis of the facies, a comparison was made between the inversions generated. In general, it was possible to notice that the seismic inversion of the arbitrary line presented a slightly better result than that of the seismic line 0258-3145 because it presents greater details and a better resolution in the acoustic impedance. Besides, being an arbitrary line obtained from a 3D data, it usually presents more robust seismic data with higher quality compared to the 2D data and, consequently, better results in seismic inversion. This conclusion can also be corroborated by comparing the values in Tables 1 and 2. In addition, in the arbitrary line, it was possible to better observe the frequency amplitude and, consequently, the seismic inversion of this line.

According to Figures 8 and 9 and Table 3, it is possible to examine three distinct variations of the carbonates of the Macaé Group. First, from the bottom to the top, in the Quissamã Formation, carbonates are represented by calcirrudites and calcarenites. In the Outeiro Formation, the facies are thin and represented by calcilutites, shales, and marls. In the Imbetiba Formation, which bridges the carbonate sequence, the predominant lithology is marl. Thus, with the help of seismic inversions, it was also possible to observe that the carbonates follow the process of thinning from the base towards the top, in addition to having different acoustic impedances in each formation.

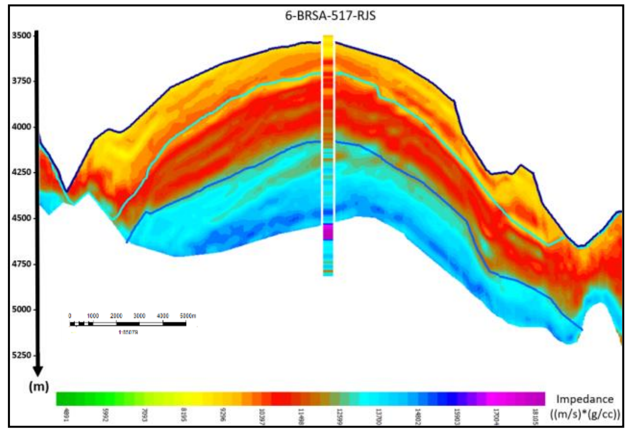


Figure 8 *– Model-based seismic inversion of the seismic line 0258-3145 and the well 6-BRSA-517-RJS with emphasis on the area where the different lithostratigraphic formations were classified.*

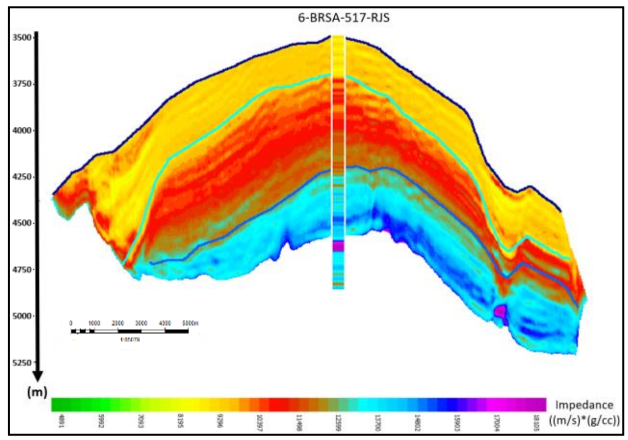
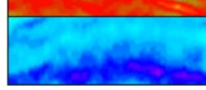


Figure 9 *– Model-based seismic inversion of the arbitrary line of the 3D volume and the well 6-BRSA-517-RJS, with emphasis on the area where the different lithostratigraphic formations were classified.*

Table 3 *– Classification of the main lithological components and the lithostratigraphic equivalences according to the regions represented in figures 8 and 9.*

Seismic texture on inversion	Main lithological components	Lithostratigraphic equivalence
	MARLS	Imbetiba Formation
	CALCILUTITES, SHALES AND MARLS	Outeiro Formation
	CALCIRRUDITES AND CALCARENITES	Quissamã Formation

Therefore, with the distinct impedance values present in the seismic inversions, it was possible to identify the differentiation regarding the definition of the carbonates of the Macaé Group interpreted in the seismic sections, allowing better separation of the carbonate lithologies.

Although the result of the seismic inversion of the arbitrary line from the 3D seismic volume presented a more sensible result, the pattern of the classification of lithologies is repeated. In other words, both the 2D seismic line 0258-3145 and the arbitrary line separate the seismic facies in the same way. Thus, with the methodology presented, using only the 2D seismic line 0258-3145 would be enough to classify the three seismic facies in this area of study, because they are coherent with each other.

Conclusions

This work contributes to a better understanding of the characterization of the seismic facies of carbonates of the Macaé Group in Campos Basin using acoustic seismic inversion. The results showed that there are three different seismic facies with different impedance values.

With the seismic inversions of the 2D seismic line 0258-3145 and the arbitrary line drawn from the 3D seismic volume, it was possible to notice that, in addition to contributing to the characterization of seismic facies, they have similarities, reinforcing the idea that there is a distinct variation in the carbonate sequence, following the same characteristics in both seismic lines. It is also possible to conclude that, even if the arbitrary line presented a better result, only the 2D seismic line 0258-3145 would be enough for classifying seismic facies in this study area because the classification pattern of lithologies reproduces the same result in both lines.

Therefore, the seismic inversions helped in the identification and the characterization of the carbonates of the Macaé Group, as well as the understanding that these carbonates follow the process of fining up from the base towards the top.

Acknowledgments

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