Rock Physics Modeling Applied to Carbonates of Quissamã Formation in the Campos Basin: A Case Study

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Abstract

This work presents a case study on the application of Rock Physics Modeling to the carbonate rocks of the Quissamã Formation in the Campos Basin. The Quissamã Formation is of particular interest due to its geological characteristics, making it an important target for hydrocarbon exploration and production activities. Understanding these characteristics is essential for identifying potential reservoirs.

The study focuses on five wells located in the Marlim Field area that penetrate the carbonates of the Quissamã Formation. Advanced Rock Physics modeling can provide important insights into the physical and petrophysical properties of the rock and aid in the prediction of hydrocarbon reservoirs. Two contemporary Rock Physics models, namely the Xu-Payne and Vernik-Kachanov models, were calibrated for the study. Reliable knowledge of mineralogy and fluid content significantly affects the quality of predictions from Rock Physics Modeling and ultimately impacts oil & gas exploration and production.

Introduction

This paper presents a case study on the Rock Physics Modeling (RPM) applied to the carbonates of the Quissamã Formation in the Campos Basin. The Campos Basin is a sedimentary basin located along the southeastern coast of Brazil, containing a thick sedimentary succession, including the Albo-Aptian carbonate section of the Macaé Group. This carbonate section is characterized by the Drift Supersequence, marking the beginning of the South Atlantic Ocean.

The Quissamã Formation, which is part of the Macaé Group, is of particular interest due to its unique geological characteristics. This formation is influenced by a gentle carbonate slope formed as the basin gradually opened. The slope is characterized by a base composed of deposits from tidal flats, supratidal, intertidal, and lagoons. Moving up the slope, high-energy facies are predominant in banks of oolitic and oncolytic calcarenites. These facies are important for hydrocarbon exploration and production, as they can act as reservoirs or seals for oil and gas accumulations (WINTER et al., 2007).

Effective exploration and production in the Campos Basin require an understanding of the Quissamã Formation's geological characteristics. Advanced rock physics modeling can provide insights into the physical properties of the rock and aid in the prediction of hydrocarbon reservoirs. RPM combines theoretical models with empirical calibration and is commonly used to quality-check measured data, fill gaps in data where it is missing or damaged, and predict desired properties, such as seismic inversion for large-scale shale content or porosity and fluid type in some cases.

One Key difference between carbonate and siliciclastic RPM is the relatively greater stiffness implied by the carbonate mineralogy, the more advanced diagenetic cementation, and the more complex pore microstructure (BAECHLE et al., 2008). Geologically informed assumptions may be used when measurements are used to calibrate RPMs with amplitude variation with offset (AVO) and Prestack inversion attributes.

Therefore, the focus of this study is to apply RPM to the carbonates of the Quissamã Formation in the Campos Basin, to gain insights into the physical properties of the rock and improve the prediction of hydrocarbon reservoirs.

Dataset

This work focuses on five wells located in the Marlim Field area that penetrated the carbonates of the Quissamã Formation, specifically 1-BRSA-182-RJS, 3-BRSA-1020-RJS, 3-BRSA-468-RJS, 6-BRSA-517-RJS, and 6-BRSA-647D-RJS. Measured logs, including compressional velocity (Vp), shear velocity (Vs), and density (Rhob), were available for these wells, and the petrophysical analysis included porosity (Phit and Phie), water saturation (SW), and volume logs (Vcalcite, Vdolomite, Vsand, and Vclay). These data were interpreted by the LAMCE/COPPE/UFRJ research group, and they provide crucial inputs for RPM studies.

Table 1 presents the mineralogy and fluid properties used in this study. The mineralogy information was based on MAVKO et al. (1998), which distinguishes between different minerals based on their elastic properties. The fluid properties were estimated using the method developed by BATZE and WANG (1992), which utilizes acoustic velocities and density to calculate the properties of fluids in the reservoir.

It is worth emphasizing that reliable mineralogy and fluid property data are vital for successful RPM studies. The accuracy of these inputs can significantly affect the quality of RPM predictions and ultimately impact geologic modeling, reservoir characterization, and field development studies.

***Table 1** - Elastic Properties used in RPM calibration, forward modeling (orange), and fluid substitution (blue).*

Mineral/Fluid	Vp (km/s)	Vs (km/s)	Rho (g/cm3)
Calcite	6.253	3.42	2.71
Dolomite	7.347	3.96	2.87
Clay	3.539	1.784	2.67
Anhydrite	6.106	3.367	3
Water	1.735		1.063
Oil	1.224		0.792

Rock Physics Model

The purpose of RPM is to establish the relationship between the geophysical properties and the physical and petrophysical characteristics of rocks. To achieve this, RPMs must be calibrated using empirical data. In this study, we calibrated two contemporary RPMs, namely XU AND PAYNE (2009), and VERNIK AND KACHANOV (2010) models, with the specific goal of evaluating their performance in predicting elastic properties, including Vp, Vs, and Rhob.

The Xu-Payne model is an extension of the Xu-White method (1995) that utilizes the Kuster-Toksöz (1974) differential effective-medium theory. It employs two mineral fractions and the ellipsoidal inclusions with specified aspect ratios (α) that are partitioned between the minerals, such as quartz and clay or calcite and clay, depending on the case. The total porosity of the rock is attributed to the ellipsoidal inclusions. In this study, we used a stiff inclusion (α = 0.20) and a compliant inclusion (α = 0.02) for the calcite and clay mineralogy, respectively, with a calcite volume variation from 100% to 90% of the solid rock volume (Figure 1).

Although the Xu-Payne model effectively captures the relationship between compressional velocity (Vp) and total porosity (Phit), it overpredicts the shear velocity (Vs) values in the entire porosity range, from low to high porosity.

This is evident in Figure 1(B), which shows a variable density plot of shear velocity versus total porosity superimposed by the Xu-Payne model.

The Vernik-Kachanov model is based on the non-interaction approximation method combined with the Mori-Tanaka-Benveniste approach. Pore geometries are modeled by their departure from sphericity and represented by pore shape factors. In carbonate rocks, the pore shape factors are greater due to the greater Poisson´s ratio of the mineral matrix. The model also includes normalized compliance due to cracks, and zero-stress crack density in the model is empirically computed as a function of porosity. The matrix coefficients A (νm) and B (νm) are known functions of the matrix Poisson´s ratio.

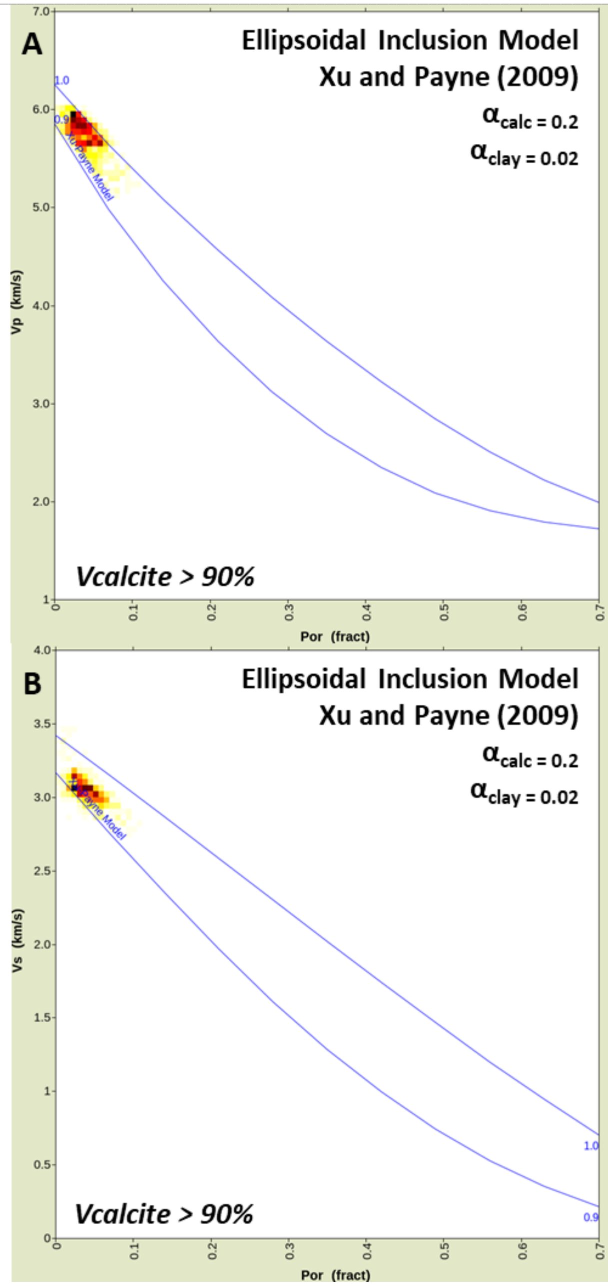

***Figure 1** - Xu-Payne model calibrated. Key parameters are calcite and clay inclusion aspect ratios α_{calc}, α_{clay} (A) Vp vs. Phit plot for brine-saturated carbonate, (B) Vs vs. Phit plot for brine-saturated carbonate.*

On our carbonate dataset, we used the following parameters to calibrate the Vernik-Kachanov model: effective stress is set to an average of 45 MPa, $b_p = 16$, and $b_q = 11$ are the slopes of the pore shape factor variation with porosity, c = 0.2 is the intercept of the crack density parameter as a function of porosity, $\Phi_{con} = 0.3$ and $\Phi_c = 0.62$ are the consolidation and critical porosity, and m = 2.2 and n = 1.8 are the exponents of the poorly consolidated leg of the model.

Figure 2 in the study shows that the Vernik-Kachanov model accurately predicts compressional and shear velocity for a range of porosity values in carbonate rocks. Compared to the Xu-Payne model, which overpredicts the shear velocity values across the entire porosity range, in this study the Vernik-Kachanov Model performs much better in predicting the elastic properties of carbonate rock.

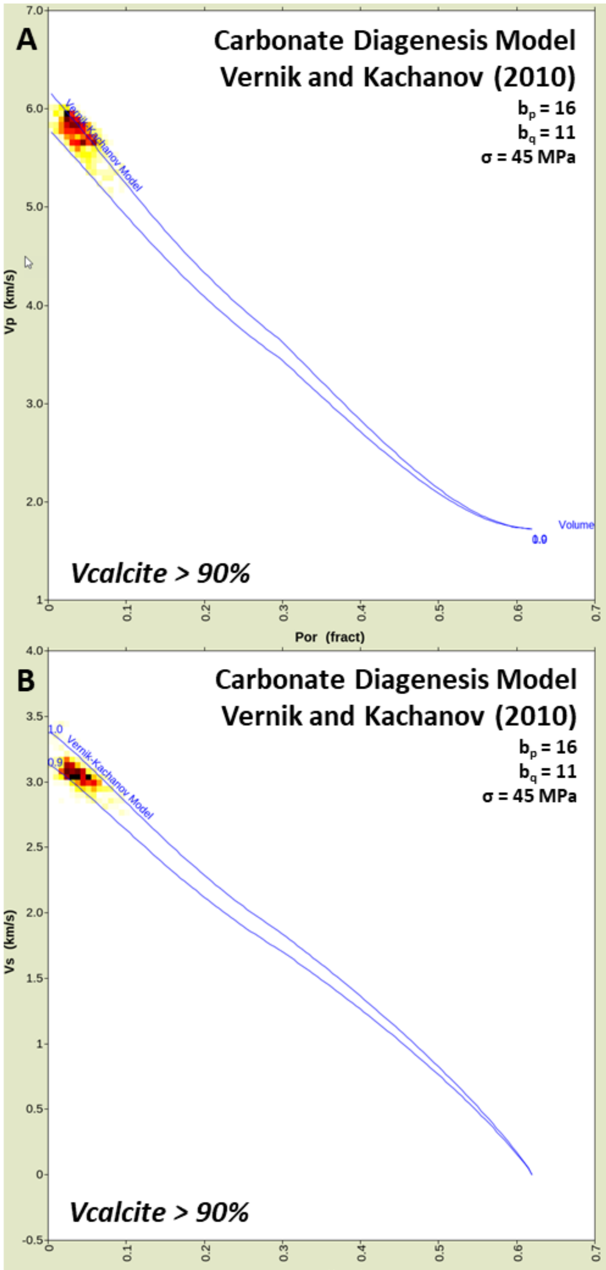

Figure 2 - *Vernik-Kachanov model calibrated. (A) Vp vs. Phit plot for brine-saturated carbonate, (B) Vs vs. Phit plot for brine-saturated carbonate.*

Rock Physics Templates

Rock Physics Templates (RPT) are a valuable tool for geoscientists to achieve the fundamental objective of reservoir characterization. RPTs serve as both a calibration method and a visual, multiscale integration platform. They generate dynamic graphical overlays of one or more rock physics models, accounting for variations in model constraints and reservoir properties, such as porosity, volume content, water saturation, effective stress, and others. RPTs provide access to model parameters and key reservoir property variables, enabling the creation of dynamic templates that highlight anticipated seismic attribute responses. These templates can be used to interactively calibrate key model parameters and covisualize data from various sources using a user-selected reservoir, rock physics, or seismic properties. RPTs simplify the complexity and detail of rock physics modeling, making calibrated model templates accessible to the larger geoscience and interpretation community.

Figure 3 shows two RPT plots: Vp vs. Rhob overlaid with the Xu-Payne template (Figure 3A) and the Vernik-Kachanov template (Figure 3B). The Xu-Payne template depicts the reservoir response based on the variation of volume content (calcite) and total porosity. The RPT was built with variations ranging from 100% to 70% volume of calcite and 0% to 30% porosity. Similarly, the Vernik-Kachanov template is overlaid on the Vp vs. Rhob plot. Both plots demonstrate the impact of variations in porosity and volume content on elastic properties.

Porosity is a crucial factor that drives RPM studies, given its significant impact on elastic properties compared to other parameters, such as volume content, in our case. In this study, we performed similar exercises to examine the effects of various variables on other elastics properties by plotting changes in the petrophysical template. This approach allowed for a better understanding of how different variables influence the overall behavior of the rock.

When comparing the results of both models, it is evident that they produce similar outcomes. However, the Vernik-Kachanov model exhibits superior performance to the Xu-Payne model in predicting volume and porosity properties using elastic properties, particularly for porosity values exceeding 5%. This is demonstrated in our example, where the Vernik-Kachanov model better predicts compressional velocity (Vp) against density (Rhob) as a function of porosity and volume content, highlighting its potential as a more reliable RPM tool for reservoir characterization in carbonate rocks.

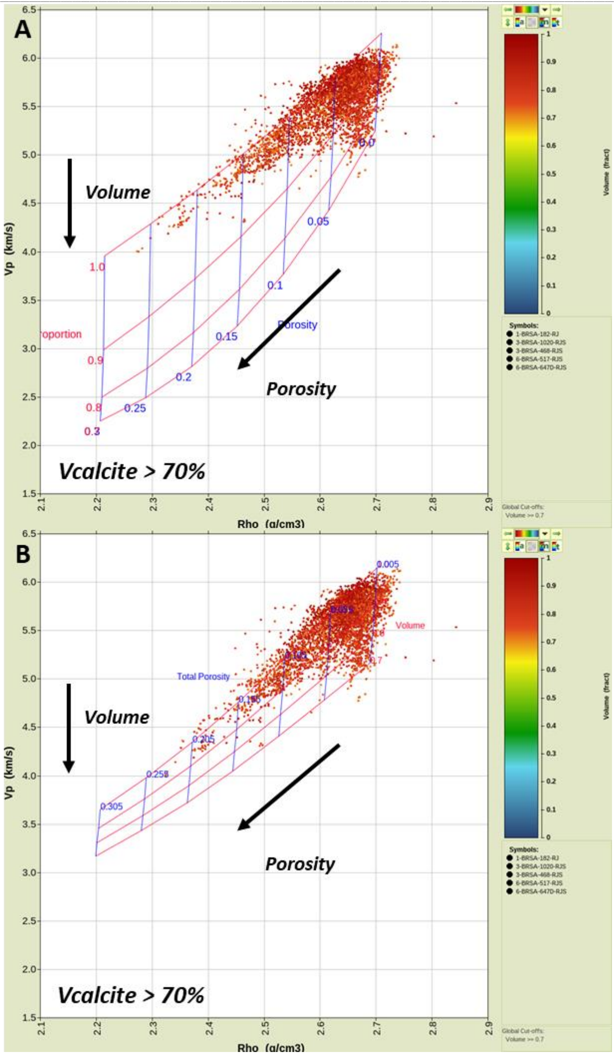

Figure 3 - *(A) Vp vs. Rhob plot for brine-saturated carbonate with the Xu-Payne RPT. (B) Vp vs. Rhob plot for brine-saturated carbonate with the Vernik-Kachanov RPT.*

Seismic AVO Modeling

After calibrating and testing the RPMs, we applied the Vernik-Kachanov model to investigate the impact of porosity changes on the elastic properties of the reservoir. We kept the fluid content constant at 100% Brine and the mineral content at 90% calcite and 10% clay. For the overburden layer, we maintained a mineral content of 60% clay and 40% calcite with a total porosity of 10%, and for the underburden layer, we set the mineral content to 100% anhydrite with a total porosity of 0.5%. These conditions were similar to those found in the well 1-BRSA-182-RJS, which we used for this simulation exercise.

To generate synthetic data, we used the ZOEPPRITZ (1919) model, convolved with a zero-phase wavelet with a dominant frequency of 40Hz and range a of incident angles. Figure 4 displays the results of our simulation, showing the facies of the overburden (gray), reservoir (cyan), and underburden (purple), as well as acoustic impedances and Vp/Vs ratio from left to right. We compared in-situ data with synthetic data for three scenarios: 5%, 10%, and 15% total porosity.

Our study reveals the significant seismic impact of changing porosity on the top of the reservoir. The synthetic gather (in-situ) closely resembles the synthetic gather for 5% porosity. However, as we increase the porosity to 10% and 15%, we observe a reversal of the polarity, from positive to negative, on the top of the reservoir. We did not observe any significant effects on elastic properties when replacing fluids, such as brine with oil, in this study. Nonetheless, it is worth noting that the presence of oil in the reservoir early in the system can contribute to preserving porosity in carbonate reservoirs (SPADINI ET AL., 2005). Therefore, in some cases, high porosity may indicate a higher probability of oil content.

Moreover, scenario exercises can be a valuable tool in seismic interpretation studies, aiding in the better evaluation of potential exploration wells.

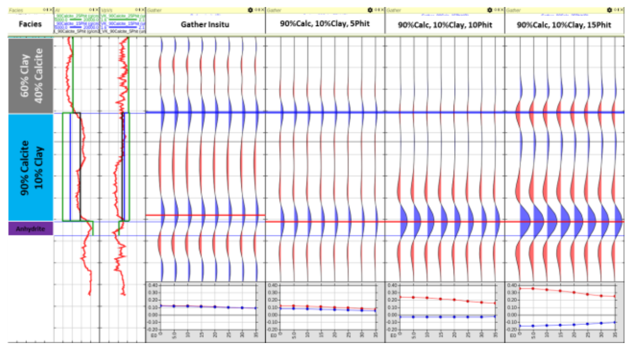

Figure 4 – *Synthetic gathers derived from the Well 1-BRSA-182-RJ. Reservoir calcite with porosity varying from 5 - 15%.*

Discussion and Conclusions

In this study, we conducted a comparative evaluation of the Xu-Payne and Vernik-Kachanov Rock Physics Models when applied to carbonate rocks in the Quissamã Formation, Campos Basin. RPMs are valuable tools for predicting the elastic and petrophysical properties of reservoirs, and the selection of the appropriate model depends on the study´s objectives, as each model has its advantages and limitations.

The Xu-Payne model is relatively simple and easy to implement, accurately capturing the relationship between Vp and porosity, making it ideal for a wide range of carbonate rocks. However, it tends to overestimate the Vs values, which can limit its accuracy.

In contrast, the Vernik-Kachanov model can account for the effect of microcracks on the elastics properties of rocks, accurately capture the relationship between velocities (Vp and Vs) and porosity, and can handle a wide range of pore shapes. Yet, it is more complex and computationally demanding than the Xu-Payne model, requiring more input parameters to model the elastic properties of rock.

Through different approaches, we demonstrated that the RPMs are valuable tools for predicting the elastic and petrophysical properties of reservoirs. They are particularly useful in dealing with carbonate reservoirs, which are known to be complex due to advanced diagenetic processes.

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