Influence of pore geometry on the velocity-porosity analysis in carbonates using effective elastic medium theory: a case of Morro do Chaves Formation

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Abstract

Velocity-porosity analysis is widely explored by rock physics to understand the reservoir system. In this regard, can be used laboratory measurements performed on samples and empirical methods. To predict some parameters empirically, such as velocity, it is possible to use the effective elastic medium theory. However, without pore geometric details the best that can be estimated are the upper and lower bounds of the rock modulus. Thus, the velocity will be a rough estimate. It is known that formation and diagenetic processes in carbonates could change the pore structure and mineralogy, resulting in rocks with complex heterogeneity and influencing the elastic properties. In Brazil, carbonate rocks are considered important reservoirs, and the sucession named coquinas in these basins has an important outcropping chronocorrelate named Morro do Chaves Formation, which facilitates the study of rock physics. This work estimates the velocity with effective elastic media bounds and compare with laboratory measurements and Digital Image Analysis from samples of Morro do Chaves Formation to bring some light in how the pore geometry influences the effective elastic medium and petrophysical properties of carbonate rocks.

Introduction

Developing accurate relationships between porosity and velocity in porous rocks has been an important area of interest in rock physics for decades. Such relationships are crucial to connect laboratory measurements with data from seismic velocity and better understand porosity in situ. Present porosity-velocity relationships are based on theoretical formulae, rigorous bounds, or empirical relationships.

To predict the effective elastic moduli of a rock without pore geometric details, the best that can be done is to predict the upper and lower bounds. The effective modulus will fall between the bounds at any given volume fraction of constituents, but its precise value depends on geometric details (Mavko et al., 1998). Thereafter, the estimated elastic moduli can predict the rock velocity but this will be a rough estimate.

In the Campos and Santos Basins located in the Margin of Brazil, carbonates are considered important reservoirs. The succession named Coquinas Sequence in these basins are carbonate rocks with variable content of siliciclastics and have a complex pore framework that implies an issue for their reservoir characterization. These Coquinas Sequence has an important chronocorrelate named Morro do Chaves (MC) Formation, outcropping in the Sergipe-Alagoas Basin (Thompsom et al., 2015), which facilitates the study of rock physics.

Formation and diagenesis processes in carbonates are responsible for pore network and mineralogy modifications, resulting in complex heterogeneity and significantly influencing elastic properties. Many previous works have recognized and verified that pore features like size, shape, aspect ratio, and pore type strongly affect the elastic behavior of rocks (Anselmetti et al., 1998; Anselmetti and Eberli, 1993).

Digital Image Analysis (DIA) is a well-established method of quantifying pore features from images (Anselmetti et al., 1998; Lima Neto et al., 2015). This method allows to use images of thin sections to separate the rock into a pore and solid phase, quantify the pore size distribution and calculate geometric parameters (Anselmetti et al., 1998; Weger et al, 2009; Lima Neto et al., 2015; Fournier, 2018). Due to image resolution, DIA only considers the macro-mesoporosity of the rock, but still provide an adequate analysis of the pore system.

This work estimates the velocity with effective elastic media bounds and compare with laboratory measurements and Digital Image Analysis from samples of Morro do Chaves Formation to bring some light in how the pore geometry influences the effective elastic medium and petrophysical properties of carbonate rocks.

Method and Theory

In this work were used thirty samples of coquinas from Morro do Chaves Formation for the laboratory measurements.

The analysis of the mineral composition of the samples was determined by X-ray diffractometry (XRD) based on the Rietveld method. This method adjusts different XRD patterns and obtains the best fit between the experimental measurement and the fitted equation.

The simplest method to predict the upper and lower bounds of the effective elastic moduli of a rock are the Voigt and Reuss (VR) bounds (Mavko et al., 1998).

The Voigt upper bound (M_v) and the Reuss lower bound (M_r) of effective elastic moduli, is given by the Equations 1 and 2 respectively.

$$M_v = \sum_{i=1}^{N} f_i * M_i \quad (1)$$

$$1/M_r = \sum_{i=1}^{N} f_i / M_i \quad (2)$$

Where N is the number of phases in the mixture, f_i is the volume fraction of the $_i$th phase and M_i is the elastic modulus of the $_i$th phase.

Mathematically, the M in the VR equation can represent any modulus. However, it makes the most sense to compute only shear (G) and compressional (K) moduli as used in this work.

The VR bounds were calculated to estimate: 1) a range of the effective compressional modulus considering the mixture of minerals in the rock; 2) a range of shear and compressional moduli for a mixture of mineral and pore fluid. For the mixture of mineral and pore fluid were considered a calcite variation from 95% to 45%, a quartz variation from 5 to 45%, and a porosity variation from 0 to 30%.

Utilizing K and G modulus from VR bounds was possible to calculate the p-velocities following the relationship of the Equation 3, where ρ is the mineral density of the mixture with calcite and quartz.

$$Vp = \sqrt{(K + \left(\frac{4}{3}\right) G)/\rho} \quad (3)$$

The p-velocity of the samples were also measured in laboratory under dry conditions and effective pressure of 20 MPa.

A transmitted light petrographic microscope coupled to a camera was used to evaluate the pore types and obtain petrographic images. These images were analyzed by DIA (Anselmetti et al., 1998) and the aspect ratio were extracted using Weger et al. (2009) and Lima Neto et al. (2015) methodology.

Aspect Ratio (AR) is the ratio between an ellipse's major and minor axis that encloses the pore. The AR describes the elongation of the pore-bounding ellipsoid. The arithmetic means of AR values for the entire thin section range from 0 to 1. (Weger et al., 2009).

Xu and Payne (2009) correlate aspect ratio and p-velocity in carbonates rocks and concluded that for a given porosity, rounded pores make the velocity faster, and microcracks make it slower.

Lima Neto et al. (2015) worked with the mean of macro-mesopores aspect ratio for prediction of microporosity aspect ratio in carbonates. It is possible to notice that the mean of aspect ratio used is almost similar for the samples.

In this work were evaluated the mean of aspect ratio and also the frequency of the aspect ratio. Most of the time, the aspect ratio behavior is a Gaussian distribution, which implies in coincident mean and median. Thus, the frequency of the aspect ratio could be an alternative way to analyze the influence of this pore parameter on the velocity-porosity analysis.

Results and Discussion

Although the high degree of heterogeneity of carbonates deposits, three principal minerals were detected at XRD. There are calcite, dolomite, and quartz. Figure 1 shows the ternary diagram illustrating the composition of the Coquinas samples measured at XRD. The mineralogical content of samples shows calcite with higher content and variations of quartz between 0 and 45%, and the dolomite content is less than 1%.

Figure 1 - Ternary diagram illustrating the composition of the coquinas samples measured at XRD

Considering a variation of quartz in the samples, a range of the effective compressional modulus were calculated using the VR bounds to analyze the behavior of MC Formation samples.

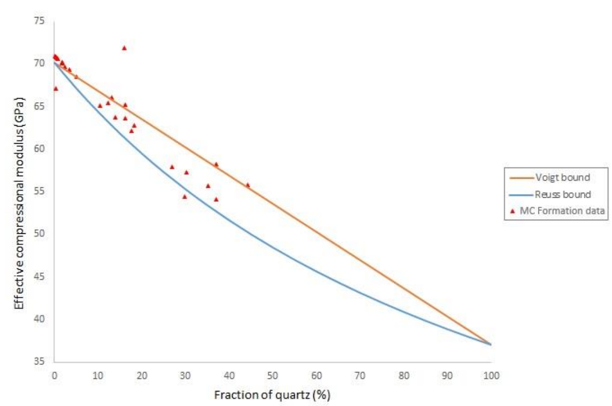

Figure 2 – Comparison between the effective compressional modulus (K) calculated using VR bounds considering a variation of quartz and calcite and the mineral content of MC Formation samples.

As shown in Figure 2, when comparing the effective compressional modulus (K) using VR bounds considering a variation of quartz and calcite and the data of MC Formation samples, the expected behavior is followed. The mostly samples fall between the VR bounds, showing that

Voigt and Reuss's bounds could be an important method important for analyzing the variation in mineral content and its influence on the compressional modulus of the rock.

Figure 3 shows the P-velocity calculated by K and G moduli calculated by VR bounds for the mixture of minerals and porosity. The VR bounds changes according to the proportion of elements in the equation. It is possible to note, that when porosity is added to the mixture of minerals, the coquinas samples doesn't follow the expected behavior. Coquinas samples does not fit between the calculated bounds, which may be related to other factors than mineralogy, such as diagenetic processes pore geometry.

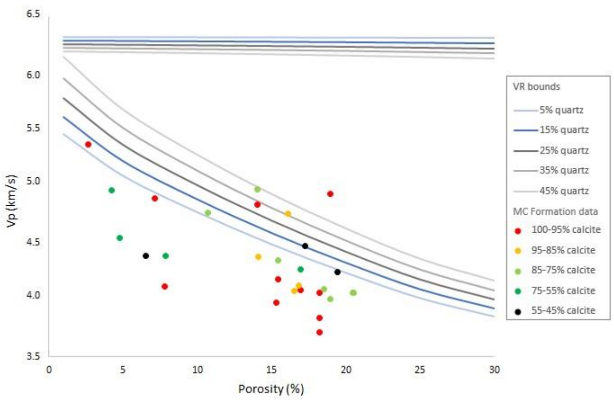

Figure 3 - Comparison between p-velocity (Vp) calculated by the VR effective moduli bounds considering a variation of quartz, calcite and porosity and the laboratory measurements of coquinas samples.

To better understand the velocity-porosity relationship of MC Formation samples and its relationship with the VR bounds were selected for five samples to analyze the velocity-porosity relationship and aspect ratio from the Digital Image Analysis. The samples were chosen considering closer values of XRD, and variations of Vp velocities in the same porosity, as shown in the Figure 4. The table 1 sinthesizes the laboratory measurements and AR of the chosen samples.

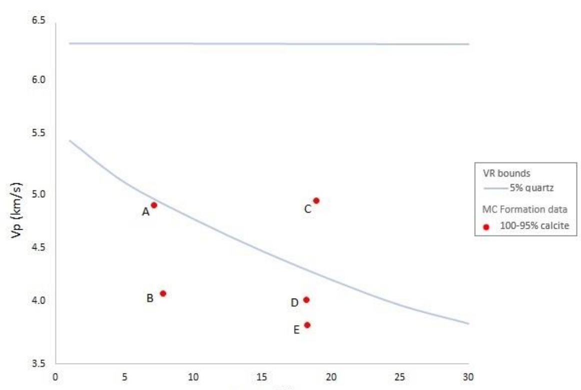

Figure 4 - Velocity-porosity relationship and the VR calculated bounds closely of XDR for the chosen samples

In the Figure 4 it's not possible to conclude the reasons of the variation of velocity in the same porosity values. according Mavko et al. (1998), in terms like stiff and soft pore shapes, stiffer pores cause velocity values to be higher and softer shapes cause the value to be lower within the bounds. Although the most values are out of the range of VR bounds. Thus, the Digital Image Analysis could be an adequate parameter to figure out the influence of pore geometry on the velocity-porosity analysis.

Table 1 – Synthesis of laboratory measurements and AR by DIA of the chosen samples.

Sample	Calcite (%)	Porosity (%)	Vp (km/s)	Mean AR
A	99.230	7.125	4.894	0.544
B	97.670	7.769	4.120	0.504
C	96.590	18.930	4.939	0.531
D	99.350	18.235	4.065	0.541
E	99.730	18.245	3.840	0.528

The Table 1 shows less variation of mean AR in the samples and it's not possible to conclude about the influence of pore geometry in the velocity-porosity analysis using the mean of AR. An analysis of the thin sections and the frequency of the aspect ratio emerges as an alternative. The Figure 5 shows the thin sections and respectively frequency of aspect ratio for the chosen samples

From the Figure 4 and 5 jointly it's feasible make notes about the influence of pore geometry in velocity-porosity analysis.

The thin section 5A shows more rounded pores and most values of aspect ratio between 0.5 and 0.6, according Xu and Payne (2009) it make the velocity faster as shown in the Figure 4. The thin section 5B shows more small pores that can explain the lower velocity compared with the 5A, which has the same porosity. Beholding the aspect ratio frequency of the samples A and B, the relationship described by Weger et al. (2009) is maintained, were small pores are related to aspect ratio close to range 0.1-0.4 and big and more rounded pores are related to aspect ratio close to range 0.5-0.7.

The thin section 5C shows big and rounded pore, making the velocity faster. Showing the Table 1, it is seen that sample 5 has the higher value of velocity, although the aspect ratio frequency is closer than a normal distribution.

From the aspect ratio frequency of sample D is noted more rounded pores than sample C. Despite the fact, the velocity of the sample C is higher than D. Looking at the thin sections, it is important to bring the diagenetic processes to the discussion. The thin section 5D has a micritization process, which is a process of alteration of original grain fabric that increase the micropores of the rock. Xu and Payne (2009) show that microporosity reduces the velocity of the carbonates rocks. The DIA considers only macro-mesopores, so it's not possible to detect micropores at aspect ratio frequency.

The Figure 5E shows the aspect ratio frequency closer than a Gaussian distribution. The thin section 5E shows small pores and micritization processes, two factors that decrease the p-velocity on the rock.

The Figure 4 and Table 1 also shows that samples B and C has closely values of velocity and distinguished porosities. The thin sections and respectively aspect ratio frequencies are also different between them. The thin section 5B shows blocky cementation, which increases the microfractures, decreasing the aspect ratio range. The thin section 5D, as previously metioned, show micritization processes that increases the microporosity and it's not possible to detected by DIA. The two diagenetic processes decrease the velocity, but is not enough to explain the proximity of the values of p-velocity.

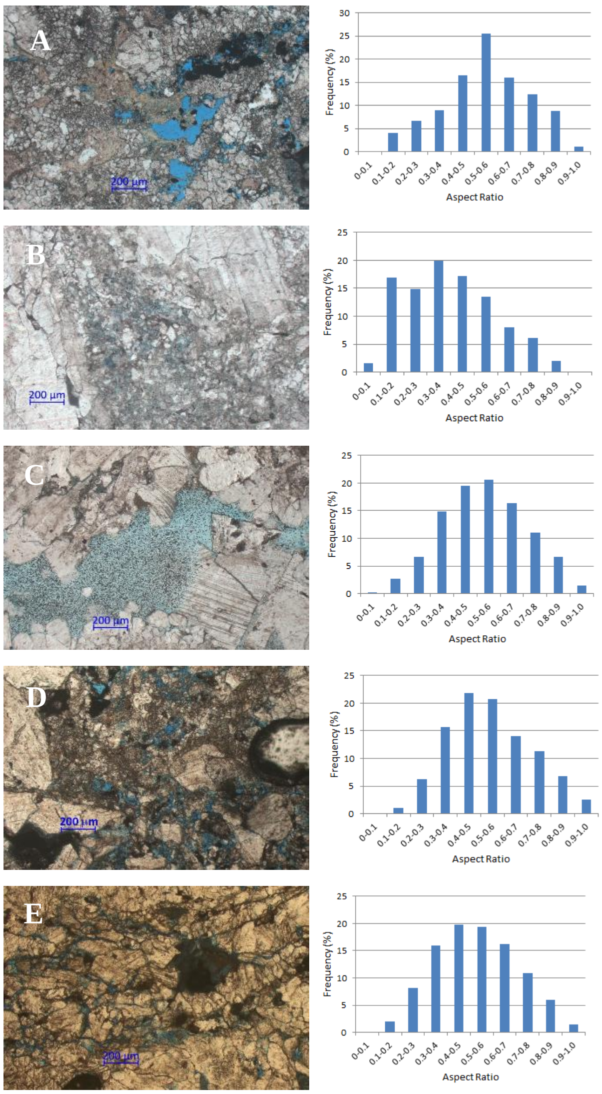

Figure 5 - Thin sections and respectively frequency of aspect ratio for the chosen samples

Conclusions

Voigt and Reuss's bounds are important for analyzing the variation in mineral content and its influence on the compressional modulus of the rock. Although these limits do not fit well with the porosity and quartz content variation of coquinas samples, they were important to understand how the pore system can influence the velocity of these carbonate rocks. The frequency of aspect ratio emerges as an important parameter for analysis between velocity and porosity because it highlights how the pore geometry influences the rock's velocity. In addition to mineralogical and pore geometry properties, diagenetic processes must be included in the analysis of the velocity-porosity relationship of carbonate rocks.

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