Use of geometric parameters to understand acoustic velocities in bioclastic carbonate rocks

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Abstract

Porosity and pore types are very often factors applied to petroelastic interpretations. However, in carbonate rocks, the same pore types can be found at very different deposits, making assumptions about wave propagation very hard to find. In an attempt to understand pore geometry and pore parameters and their relationships within acoustic velocities, we took Morro do Chaves coquinas as an example to evaluate those aspects. Those bioclastic deposits are analog to the Aptian bioclastic deposit at Campos and Santos Basin. The scarcity of publications on this topic and the complexity of carbonate rock's diagenetic environments leads us to evaluate geometric parameters at Morro do Chaves Formation. This work evaluates the correlations between acoustic properties and four geometric parameters: Perimeter over Area, DomSize, Gamma, and the Aspect Ratio. Using those geometric tools was possible to explain why we have differences in Vp at the same porosity. The PoA and DomSize results were extremely helpful in understanding the existence of minor pore types at unusually low velocities. The association between pore type, Gamma, and the Aspect Ratio was very successful in understanding why we still have a variance in P-wave measurements at the same pore classification and porosity.

Introduction

Despite being calcite-dominated, reservoir carbonate rocks have a complex pore structure and depositional texture, resulting in different parameters affecting seismic waves velocities. Directly assumptions between acoustic proprieties and porosity could not appear very intuitive, especially because porosity alone does not provide any information about pore size distribution and connection degree between pores. Rocks with the same porosity may have completely different physical properties (Glover, 2007).

In carbonate rocks, both primary and secondary porosity are important to identify. However, secondary porosity has the greatest impact on the porous system, where diagenetic processes such as fracturing, dissolution, replacement, and cementation modify the original porosity by enlarging or reducing the primary porosity and creating new pore types (Ahr, 2008). In addition, the heterogeneities due to diagenesis can cause a variety of complex pore structures and laterally and horizontally porosity variations that may cause a velocity deviation (Anselmetti and Eberli, 1993,1999; Berryman and Blair, 1987; Mavko et al., 2009).

Because of the complicated porous structure, there are significant uncertainties in evaluating the petrophysical parameters of carbonate rocks. Elastic velocities of geological formations are influenced by pore texture-geometric factors such as shapes, sizes, distribution, and pore connectivity (Eberli et al., 2003; Lucia 2007, Vasquez et al., 2019), which are not directly interpreted by pore type classification.

Many studies have demonstrated that the diversity of pore morphologies, along with significant pore size variation in carbonate rocks, can have an influence on acoustic calculations, making assumptions extremely difficult (Assefa; Mccann; Sothcott, 2003; Fournier et al., 2014, 2018; Lima Neto et al., 2015; Weger et al., 2009). Because of the dependency between pore geometry and acoustic velocity in carbonate rocks, several publications emphasize the importance of pore geometry identification (Assefa; Mccann; Sothcott, 2003; Fournier et al., 2018; Li et al., 2021; Lima Neto et al., 2015; Tiab; Donaldson, 2015; Vasquez et al., 2019; Weger et al., 2009).

This study aims to evaluate the relationships between the P wave and porosity, focusing on geometric parameters. For this purpose, carbonate rock samples from Morro do Chaves Formation were used (Sergipe-Alagoas Basin), which have been used as an analog of pre-salt bioclastic deposits. For the pore geometric appraisal, four parameters were chosen, which are: Perimeter over area (PoA), Dominant pore size (DomSize), Gamma, and Aspect Ratio (AR). The first three parameters are proposed by Weger et al. (2009) and are defined as follows:

PoA: defines the ratio between the total perimeter that comprises pore space and the pore area. It describes how complex the porous system is independent of total porosity. Small values, in general, indicate a simple pore system;

DomSize: it is an indicator of a dominant pore-size range, defined by the number of pore sizes that comprise 50% of the thin section;

Gamma: the parameter Gamma is used to describe the roundness of pores and is obtained from the ratio between pore perimeter and area. It is a strong parameter to identify elongated pores and distinguish them from a perfect rounded circle.

The Aspect Ratio (AR) is frequently applied to rock physics models to predict pore inclusions and was first proposed by Kuster and Toksöz (1974). AR varies from 0 to 1. Low AR is related to micropores and low velocities. On the other hand, high AR (closer to 1) is linked with interparticle and vuggy porosity and high compressional wave values.

Thus, the present work presents possible interpretations using geometrical parameters to understand acoustic deviations in the same carbonate rock deposits.

Methodology

Petrographic analysis, pore type, and geometric parameters

A transmitted light petrographic microscope coupled to an AxioCam HRc camera with AxioVision software was used to evaluate the pore types and obtain petrographic images. The geometrics parameters were acquired from petrographic images using Weger et al. (2009) and Lima Neto et al. (2015) methodology.

Wave velocities determination

The international standard ASTM D2845-08 (2008) was applied to determine the seismic velocity waves (P- and S-waves). Therefore, P- and S-wave velocities were measured under dry and ultrasonic conditions using effective pressure of 20 MPa.

Mineralogy and porosity estimation

The analysis of the mineral composition of the samples was determined by X-ray diffractometry (XRD). X-ray diffraction analysis to mineral composition quantification is based on the Rietveld method (Rietveld, 1969). This method enables adjusting different XRD patterns and obtains the best fit between the experimental measurement and the fitted equation (Archilla et al., 2016).

Total porosity (ϕ), grain, and bulk densities were measured by a helium gas porosimeter (Ultrapore 300). This equipment performs measurements of matrix volume of samples through the gas expansion technique and Boyle's Law (Tiab and Donaldson, 2015), allowing to determine the porosity, bulk (Eq. 6), and mineral (grain) densities (ρbulk and Km, respectively).

$$\rho_{bulk} = (1-\phi)\rho_m + \phi\rho_{fl}(1)$$

were ρ_{fl} is the pore fluid density, in this case, air.

Results

Porosity types with mineralogy

From the nineteen thin sections, five pore types were recognized using the classifications of Choquette and Pray (1970). Interparticle porosity is the classification that most occurs in the data within seven rocks within this pore type. The other pore types that are classified are Vuggy, Intercrystalline, Moldic, and Microporosity (Figure 1).

Microporosity was defined in only one sample, and this specific pore type was chosen because gas porosity indicates 5% of porosity, but at thin-section recognition was not possible to see any pore in any given magnification.

It is noteworthy to mention that, from the nineteen samples analyzed, for each rock, the mineral occurrence was obtained using XRD. Calcite is the primary mineral (ranges from 45% to 99.5%), linked with bivalve clasts or as a diagenesis product (sometimes both). The mineral with the second-highest appearance is silica (ranges from 0.45 percent to 45 percent). Other minerals occur, but at the present data set, Calcite and Silica make up almost 100% of the mineral occurrence. So, for simplification purposes, when a sample has 75% of calcite content, the other 25% can be interpreted as silica content (poly and multicristallyne quartz grains)

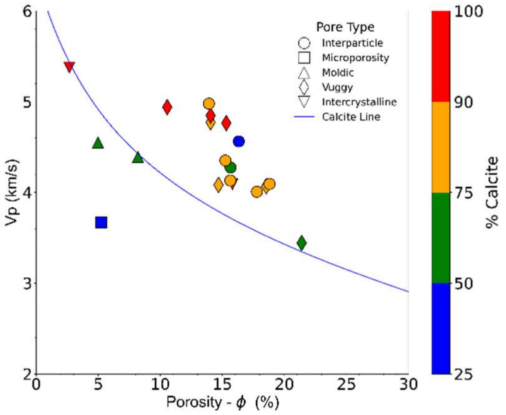

Figure 1: Vp-porosity-calcite correlations for pore type. The symbols indicate porosity type, and the color bar indicates calcite percentage. The solid line represents the time-average equation for calcite (Wyllie et al., 1956).

It is possible to identify that the lowest Vp value is related to the sample classified as having microporosity, which was expected. Another logical assumption is the very low amount of calcite in this particular sample, leading to lower bulk and shear modulus and lower P-wave value. On the other hand, the Intercrystalline pore type is related to the higher registered Vp, with high calcite content, associated with almost pure calcite and absent primary pore types, which have been replaced within crystalline calcite.

Even the assumptions made in Figure 1, the Vp-porosity associated with pore types cross plot makes inferences very difficult related to most pore types occurrences. Pore type is important for understanding a particular rock's geological and diagenetic history. Still, when dealing with links with acoustic properties and possible interpretations, relations are not that clear or intuitive, exemplified in the variety of P-wave values at the same porosity and pore type. For better understanding, the geometric parameter could be a useful tool.

Geometric Parameters

For each sample, were obtained PoA, DOMsize, Gamma, and Aspect Ratio values (Table 1). Both Gamma and Aspect Ratio are dimensionless.

Table 1: results of PoA, DOMsize, Gamma, and Aspect Ratio for the Coquinas from Morro do Chaves Formation.

	PoA (mm^-1)	DOMSize (microns)	Gamma	Aspect Ratio
Max. value	669,0707	384,5000	2,4179	0,5581
Min. value	52,8879	57,6875	1,7274	0,3075
Average	219,4959	134,8804	2,1601	0,5081

Perimeter over area is the parameter that shows the major difference between the minimum and maximum values at the data set. Such dispersion at those bioclastic deposits shows a wide range of pore sizes, which cannot be seen when looking solely at the pore type of a sample.

In Figure 2, DomSize is plotted against PoA within the measured acoustic velocity. This diagnostic plot proposed by Weger et al. (2009) aims to identify pore structure complexity.

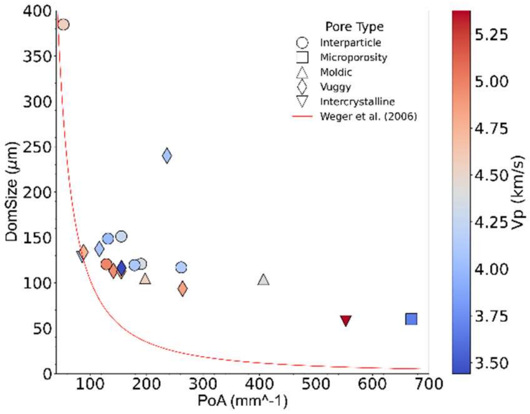

Figure 2: DomSize-PoA-Vp correlations for pore type. The symbols indicate pore type, and the color bar indicates Vp (km/s). The dashed line represents Weger et al. (2006) prediction trend.

Higher DomSize values matched with lower PoA indicate a simpler pore geometry associated with large pores and minor structure complexity. On the other hand, an increase in PoA with a decrease in DomSize expresses small pores with a complex pore structure. Those relationships can be observed in Figure 2. Pore types classification for the present data becomes easier to understand as we look at the Figure 2 plot, especially because microporosity and intercrystalline are associated with higher values of PoA and lower DomSize, with a good relationship between pore geometry, pore type classification, and the geological aspects.

Figure 3 presents Vp versus porosity and PoA and Calcite ranges. Small PoA's values mean an uncomplicated geometry, leading to an expected increase in velocity, which occurs in the present data. The majority of small PoA values are related to a higher Vp. Mineralogy also plays an important role, especially at the same porosity and PoA. Higher calcite contents make Vp higher at those points, as mentioned earlier. The maximum Vp at data is related to a PoA value of 669,0707. The sample in question has high calcite content, very low porosity, and intercrystalline pore type within a very small DomSize value (Figure 4), indicating a very tight pore system, where the acoustic propagation does not suffer a major dispersion at low porosity and reflects the dominance of the mineralogical content.

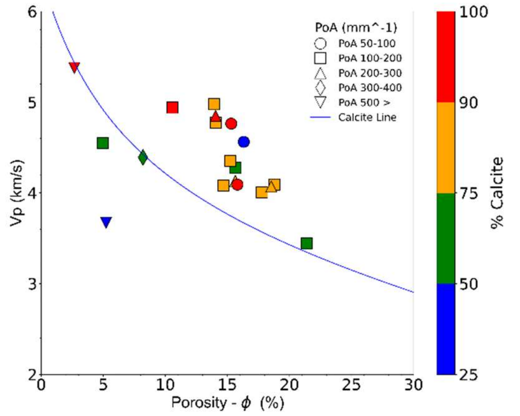

Figure 3: Vp-Porosity-Calcite correlations for PoA. The symbols indicate PoA (mm^-1) ranges, and the color bar indicates Calcite (%). The solid line represents the time-average equation for calcite (Wyllie et al., 1956).

In Figure 4, at DomSize relationships, as we increase DomSize values, we can understand the number of pore sizes that are dominant in a specific sample. Large pore by itself does not say a lot but is associated with the interpretation from Figures 2 and 3, and the percentage of calcite can give us a hint of what is happening with the data. Pores within small PoA and higher Domsizes also registered the higher Vp values at the same porosity percentages, which only do not occur with the sample having lower calcite content.

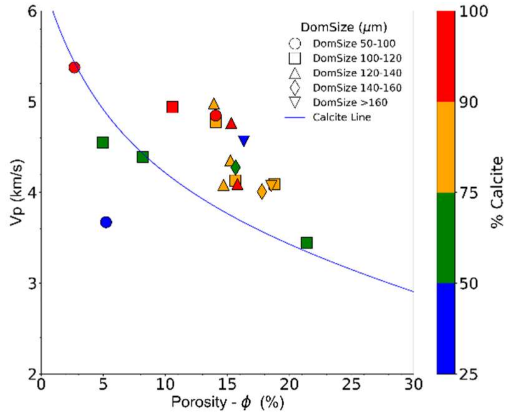

Figure 4: Vp-Porosity-Calcite correlations for DomSize. The symbols indicate DomSize (μm) ranges, and the color bar indicates Calcite (%). The solid line represents the time-average equation for calcite (Wyllie et al., 1956).

Figure 5 shows the same Vp and porosity plot within Gamma ranges. Weger et al. (2009) use the Gamma parameter to indicate how spheric the pores are. As a result, lower Gamma's closer to 1 is assumed to be perfectly rounded pores. Rounded pores contribute to higher P-wave values because they behave as stiff pores.

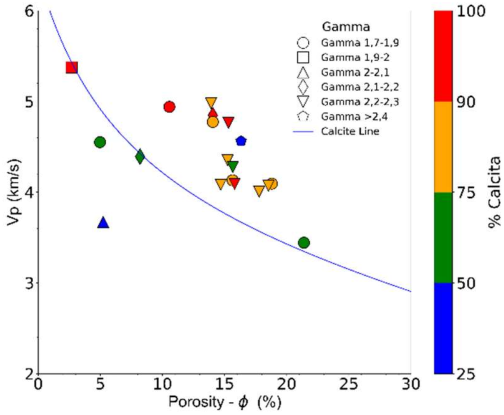

Figure 5: Vp-Porosity-Calcite correlations for Gamma. The symbols indicate Gamma ranges, and the color bar indicates Calcite (%). The solid line represents the time-average equation for calcite (Wyllie et al., 1956).

In this study, interparticle porosity does not occur as a rounded pore, as expected for oolitic limestones and most siliciclastic reservoirs (which also can be seen in Figure 6 below). Instead, interparticle pores in our data reflect more elongated and oblique void space between shells, resulting in Gamma values a little higher than 2. Even so, interparticle pores are associated with higher acoustic velocities, followed by Vuggy porosity.

Gamma does not show a big variance between minimum and maximum values in our data, and possible interpretation using this parameter needs to be followed by PoA, DomSize, and AR. (Figure 6). Mineralogy has its impact on velocity scattering, but it is possible to say that at the same porosity and calcite content, small and oblique pores (higher Gamma), with complex pore structure, have lower P-wave velocities, and the geometric factors play an important role.

In Figure 6, the Aspect Ratio (AR) enables some reliable assumptions. As expected, the higher AR values are, the higher velocities we have. Same pore types at the same porosity values have different AR values and, as a result, different Vp's. Greater AR reflects stiffer pores which tend not to attenuate P-wave propagation as microporosity within lower AR, as observed for one sample of our data.

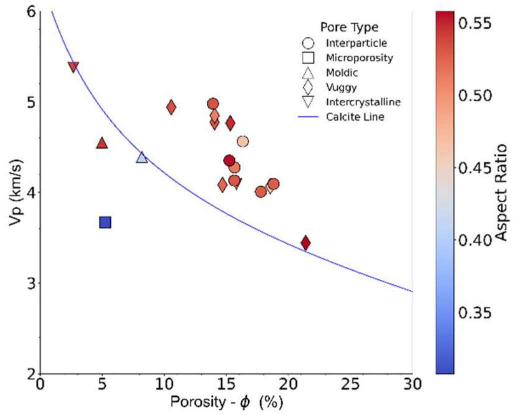

Figure 6: Vp-Porosity-Aspect Ratio correlations for pore type. The symbols indicate pore type classifications, and the color bar indicates the Aspect Ratio. The solid line represents the time-average equation for calcite (Wyllie et al., 1956).

Interparticle, vuggy, and intercrystalline porosity are linked to high AR in our data. Even so, most of the samples appear dislocated from the predicted calcite line proposed by Wyllie. When we look at our data in an integrated way, a possible explanation for that is the samples that follow above the line have low PoA and high DomSize. At the same time, those samples registered the higher AR measures indicate low complexity of pore frame structure, rigid pores, and larger pores, resulting in higher Vp measures in contrast to what was expected from Wyllie equations.

Conclusions

The coquinas from Morro do Chaves have different pore classifications, and only looking at pore type classification, it is difficult to make some conclusions. Anomalous velocity behaviors are easier to understand when geometric parameters are present and associated with mineralogy percentage. PoA and DomSize data were very useful in comprehending the existence of minor pore types at anomalous behaviors in very low velocities. Pore type associated with Gamma and the Aspect Ratio was very useful to explain why we still have a delta in P-wave measures at the same pore classification and same porosity. For further studies, mercury injection for pore throat recognition and an extensive data set will be very helpful in evaluating if those bioclastics deposits do have the same behavior in different mineralogic and diagenetic content.

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