Carbonate microporosity aspect ratio and S-wave velocity prediction using 2D/3D digital image analysis and inclusion theory

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Abstract

The methodology of this study aims to characterize carbonate pore system applying velocity-porosity-pressure relationship, digital image analysis (DIA) from thin-section and X-ray microtomography (µCT), and effective elastic media theory. The method assumes three pore-spaces in two representative inclusion scenarios: 1) a macro-mesopore median aspect ratio from DIA and 2) a microporosity aspect ratio predicted from measured P-wave velocity. Rock physics Differential Effective Medium (DEM) theory is applied to predict microporosity aspect ratio in the suggested methodology. The Albian carbonate core samples from the Campos Basin are studied, aiming to predict the amount of microporosity and the representative aspect ratio of pore inclusions. P- and S-wave velocities (Vp and Vs) are evaluated at effective pressures, including the textural impact on the pore system. The results of macro-mesopore characterization by 2D thin-sections and 3D µCT scan are discussed and correlated with efficiency of the methodology to estimate the microporosity aspect ratio inverted from Vp and predict Vs with good agreement.

Introduction

Carbonate rocks have great economic significance and hold more than 50% of the oil and gas reserves worldwide (e.g., Burchette, 2012). Carbonates commonly display heterogeneities due to diagenesis and exhibit complicated mineral composition, pore structure, and texture variations that may cause low hydrocarbon recovery (Xu et al., 2007). According to Sun et al. (2006), for a given reservoir, e.g., with a porosity of ~25%, the permeability can vary by more than four orders of magnitude, which is caused by pore structure changes. Thus, pore type variations can also produce seismic velocity changes at a given porosity, a similar behavior that is observed in the Albian carbonates.

Rock physics studies show that moldic and vuggy pore spaces tend to be rounded and enhance rock stiffness, inducing faster seismic wave propagation. However, interparticle or microcrack pore spaces tend to be flat and make the rock softer (Kumar and Han, 2005). Therefore, the pore aspect ratio is a textural parameter that contributes for stiffness or softness of carbonate rocks. Additionally, studies between pore shape and the elastic properties are important to develop realistic rock physics models.

DIA methods can be applied to evaluate mineral structures and pore system. For example, Weger (2006) and Weger et al. (2009) show that carbonate rocks have pore structures constructed of macro-, meso-, and micropores. Macro- and mesopores can be detected in thin-section images, or other accurate techniques as µCT scan that express better resolution, which contribute to quantify pore structure properties as size, shape, distribution of grains, cementation, and porosity.

This study proposes a methodology to characterize Albian grainstones, aiming to predict microporosity parameters as aspect ratio. Thin-section images and µCT analysis are performed to verify median aspect ratio of macro-mesopore. The suggested methodology uses rock physics DEM theory under ultrasonic and dry conditions to evaluate 10 core samples, considering three pore-spaces in two representative inclusion scenarios: macro-mesopore median aspect ratio from DIA and predicted microporosity aspect ratio. After the aspect ratio prediction, the textural properties may be applied to estimate Vs from Vp measurements.

Data set

Albian carbonate reservoirs from Campos basin are located in southeastern Brazil, which are composed mostly of grainstones and packstones containing oncolites, peloids, oolites, and rare bioclasts. In this study, grainstone samples were selected from two cored wells, Early to Middle Albian age.

The data set (Tab. 1) includes oncolite/oolite grainstones with good porosity and permeability from Well 1, and oncolite/oolite grainstones with calcite cementation occurrence from Well 2 (see Archilha et al., 2013; Lima Neto et al., 2013, 2014). The mineralogical characterization was performed using X-ray diffractogram (XRD) analysis and Rietveld method, that showed calcite predominance (>95%). Thin-sections show interparticle pore predominance, texture complexities, and pore fabric. Grainstones of Well 1 exhibited better permeability, and grainstones of Well 2 presented more calcite cementation causing reduction of permeability. Vp and Vs were measured under dry and ultrasonic conditions at effective pressures. The stress measurements are performed with strain gauges and radial deformation by LVDTs (Linear Variable Differential Transformers), allowing us to evaluate the volumetric deflections of core at effective pressure induced during the triaxial tests. The effective pressures during triaxial tests were limited to 10 MPa for dry conditions because the core samples have heterogeneities, such as vugs and microfractures, which cause brittleness.

Sample	Porosity		Microporosity (%)	Permeability (mD)	Matrix		
	Helium-gas (%)	Thin-section (%)			Bulk modulus (GPa)	Shear modulus (GPa)	Density (g/cm^3)
W1-Im1	23.03	14.1	8.93	9	76.85	32.03	2.71
W1-Im2	25.71	13	12.71	221.6	74.65	31.86	2.709
W1-Im3	22.07	11	11.07	31.9	76.33	32.09	2.712
W1-Im4	22.28	8	14.28	13.5	75.1	31.8	2.709
W1-Im5	28.51	11	17.51	126.6	76.47	32.44	2.72
W1-Im6	22.2	19	3.2	9.8	76.16	32.16	2.711
W1-Im7	26.42	6	20.42	4.4	75.63	31.98	2.71
W1-Im8	27.96	19	8.96	8.2	75.9	32.07	2.711
W2-Im1	21.94	12	9.94	2.03	76.55	32.08	2.71
W2-Im2	19.72	9	10.72	0.88	76.8	32.16	2.711

Table 1: Albian grainstones data set.

Sample		W1-Im1	W1-Im2	W2-Im2
Helium-gas porosity (%)		23.03	25.71	19.72
Thin-section images	**Porosity (%)**	14.1	13	9
	AR Macro-meso	0.51	0.51	0.51
	Microporosity (%)	8.93	12.71	10.72
	AR Micro	0.04	0.05	0.03
	DomSize (μm)	78.13	77.94	17.39
	PoA (mm^{-1})	112.59	142.85	1418.31
	Gamma	2.5	2.37	2.16
μCT	**Porosity (%)**	16.5	19.3	6.8
	AR Macro-meso	0.54	0.54	0.55
	Microporosity (%)	6.53	6.41	12.92
	AR Micro	0.02	0.02	0.03
	DomSize (μm)	37.4	38.83	34.05
	PoA (mm^{-1})	145.68	136.47	401.33
	Gamma	-	-	-

Table 2: Results of the macro-mesopore inclusions from DIA: thin-section and μCT. The aspect ratio (AR) of the micropore inclusion was predicted applying the methodology of study (Fig. 1).

Methodology and Results

The methodology is summarized in Fig. 1, it considers three pore-spaces in two representative inclusion scenarios: 1) the macro-mesopore median aspect ratio, and 2) the microporosity aspect ratio predicted by the Vp measurements. The textural and elastic input parameters were evaluated based on laboratory measurements (Tabs. 1 and 2). The microporosity aspect ratio is quantified at the minimum error ($e_{\min}$) and maximum adjustment coefficients (R), given by:

$$e_{\min} = \frac{|Vp_{Measured} - Vp_{DEM}|}{Vp_{Measured}}, \quad (1)$$

$$R = 1 - e_{\min}. \quad (2)$$

In this work, DEM theory was assumed to predict microporosity inclusion aspect ratios to characterize the complex constituents and pore geometries with elastic properties of the Albian grainstones. The DEM model was evaluated as suitable model according to the previous study (Lima Neto et al., 2013). However, other inclusion (or effective elastic media) approaches as Kuster-Toksöz or Self-consistent approximations of effective moduli could be applied to characterize distinct carbonate texture cases. Bulk and shear moduli of dry core samples were estimated using the input parameters: macro-mesopore properties from DIA (Fig. 2), microporosity inclusion weight calculated by the difference between helium-gas and image porosities, Vp, density and elastic moduli of mineral matrix (Tab. 1). Thus, the calculated Vp-DEM was compared to the Vp measurements, and the results exhibited $R \simeq 1$ for all core samples as expected, and the aspect ratio of microporosity was determined (Fig. 3).

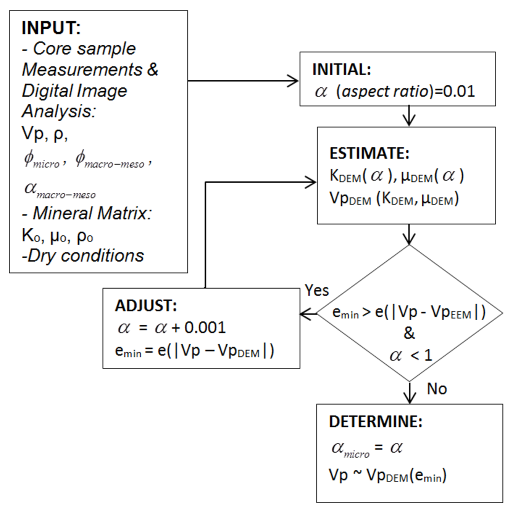


Figure 1: The methodology suggested to predict micropore aspect ratio (α_{micro}). Input parameters: porosity (ϕ), density (ρ), bulk and shear moduli (K and μ, respectively).

Thin-section images versus μCT scan

The representative macro-mesopore properties was estimated by Digital Image Analysis (DIA) from 2D thin-sections and 3D μCT. The resolution of thin-section images: W1 (~16.32 μm^2/pixel), W2 (~0.28 μm^2/pixel) (Tab. 1), and μCT: W1-Im1, W1-Im2 and W2-Im2 (~11.39 μm^3/pixel). Both DIA methods are compared using this three core samples (Tab. 2). After establishing the geological setting with measurements and mineral information, the physical properties of the Albian grainstones can be linked to DIA parameters through thin-section micrographs and μCT scan, allowing the characterization of macro- and mesopores. Representative median macro-mesopore inclusions were identified from thin-section images and µCT scan, in Fig. 2. We suppose that microporosity may occur at nanometer scale, justifying the porosity difference between the helium-gas and DIA methods, from thin-section and µCT resolutions. Therefore, the microporosity was calculated from porosity difference, assuming that the helium-gas is able to fill the whole connected pore system (see Tabs. 1 and 2).

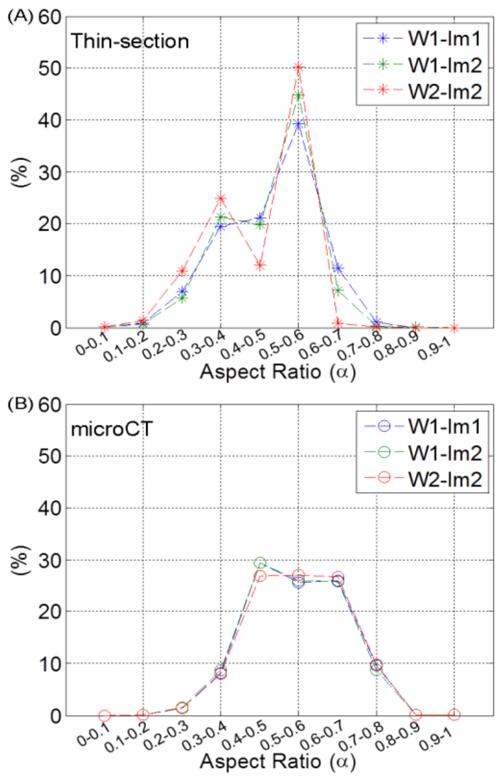


Figure 2: Representative pore inclusions identified from thin-section (A) and µCT scan (B). The pixel resolution reached in this study was limited to identify macro-mesopore.

Effects of effective pressure on core sample texture

The Vp, Vs and porosity of core samples were evaluated during triaxial tests. The volumetric reduction was assumed to be caused by microporosity diminishing when an effective pressure is applied, which leads to an increase Vp by increasing the predominance of rounded macro-mesopores and reducing bulk porosity. The method depicted in Fig. 1 was applied at effective pressure conditions aiming to evaluate the resulted porosity (see Fig. 3 – A). The results in Fig. 3 consider the macro-mesopore aspect ratio estimated from thin-section images at initial condition without loading for each core sample.

The DIA parameters DomSize, PoA, gamma and aspect ratio (α) are parameters that describe textural characteristics of rock (Tab. 2). The DomSize provides an indication of a dominant pore-size, which is defined as the upper boundary of pore sizes of which 50% of the porosity in a thin-section is composed. The PoA is the ratio between the total pore-space area of a thin-section and the total perimeter that encloses the pore space. Generally, a small PoA value indicates a simple pore system. Gamma describes the roundness of pores as the perimeter over an area of an individual pore normalized to a circle, as discussed by Anselmetti et al. (1998). A perfect round circle would have Gamma=1. The aspect ratio (α) is the ratio between the major and minor axes of an ellipse that encloses the pore, and it describes the elongation of the pore-bounding ellipsoid. The aspect ratio can be estimated for macro-mesopore systems using the median of pores recognized from DIA (Fig. 2) (Weger, 2006). The equivalent 2D PoA was calculated from 3D µCT by specific surface area, the ratio between pore volume and pore surface. Gamma from µCT could be calculated from 2D slices that compose the cube 3D image, improving a statistical perimeter of pore. The textural parameters are dependent on the image resolution due to the detection of perimeter and shape in detail, and it may cause differences in the results. Although the common resolution troubles occur at each method, the aspect ratio predicted is consistent between the thin-section and µCT (see the estimated aspect ratio of macro-mesopore inclusions in Tab. 2).

Prediction of the microporosity aspect ratio and S-wave velocity

The methodology (Fig. 1) quantifies the microporosity aspect ratio at the minimum error calibrated using the laboratory Vp measurements. Vs measurements were not used in the methodology to predict the microporosity aspect ratio. However, we observed a high potential and good agreement for the method of using the microporosity aspect ratio inverted from Vp to predict Vs, from both DIA input parameters (Fig. 4). Vs was predicted for core samples using the calibrated shear modulus (µ) and bulk density (ρ), according to Eq. 3:

$$Vs = \sqrt{\frac{\mu}{\rho}} \cdot \tag{3}$$

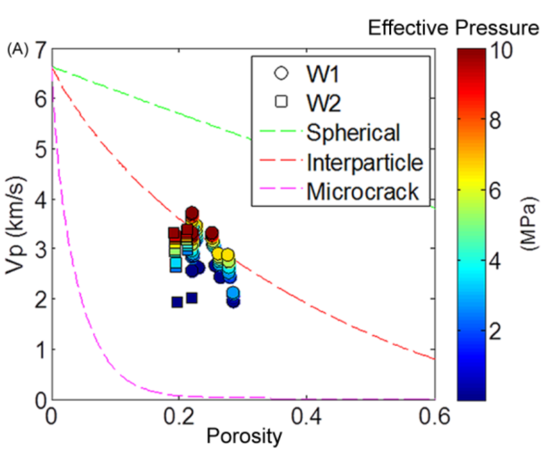
Fig. 4 shows the adjustment coefficients of thin-section and µCT results, and both are approximately equivalent ($R \simeq 0.9$). The good adjustment coefficient results are an indicative that the methodology works and contribute to evaluate the methodology efficiency. Although the common troubles of pixel resolution between the 2D thin-section images and 3D µCT scan, the macro-mesopore aspect ratio was efficiently estimated in both methods, and the low difference causes low impact in the suggested methodology for Albian grainstones.

Conclusions

This work evaluated Albian grainstones by laboratorial analysis of core samples, performing elastic and mineralogical measurements. Additionally, digital image analyzes (DIA) of thin-sections and µCT scans were employed to characterize macro-mesopore system (i.e., pores recognized in agreement with method resolutions), identifying the macro-mesopore aspect ratio. The amount of microporosity was assumed by the difference between helium-gas and image porosity. The microporosity aspect ratio was inverted by the proposed methodology, using Vp measurements as the main input parameter of calibration at minimum error to predict elastic moduli calculated by DEM inclusion model. Results of macro-mesopores from DIA and microporosity from methodology of study were considered suitable to characterize the Albian grainstone core samples. Although the low difference of macro-mesopore aspect ratio between thin-sections and µCT images, we consider that µCT scan method is more realistic to estimate pore system properties. However, µCT scan is expensive and thin-section image analysis can be a lower cost option.

Effective pressure effects on pore system were evaluated by crossplot analyzes (Fig. 3). Microporosity aspect ratio was predicted according to the proposed methodology (Fig. 1), using the porosity reduction and Vp evaluated in triaxial measurements. According to the results, microporosity is better expressed at low pressure loading and characterized by lower aspect ratio. In contrast, pressure loading induces a porosity reduction, probably caused by closing of micropores that expresses an increment of microporosity aspect ratio.

Prediction of Vs was evaluated using the macro-mesopore aspect ratio estimated from DIA, Vp measurement as the main input parameter and the respective microporosity aspect ratio result. The calculated Vs was compared with measured Vs, and the results showed a good adjustment coefficient (Fig. 4). Thus, the methodology could be applied to evaluate Vs on unknown Albian grainstone areas.



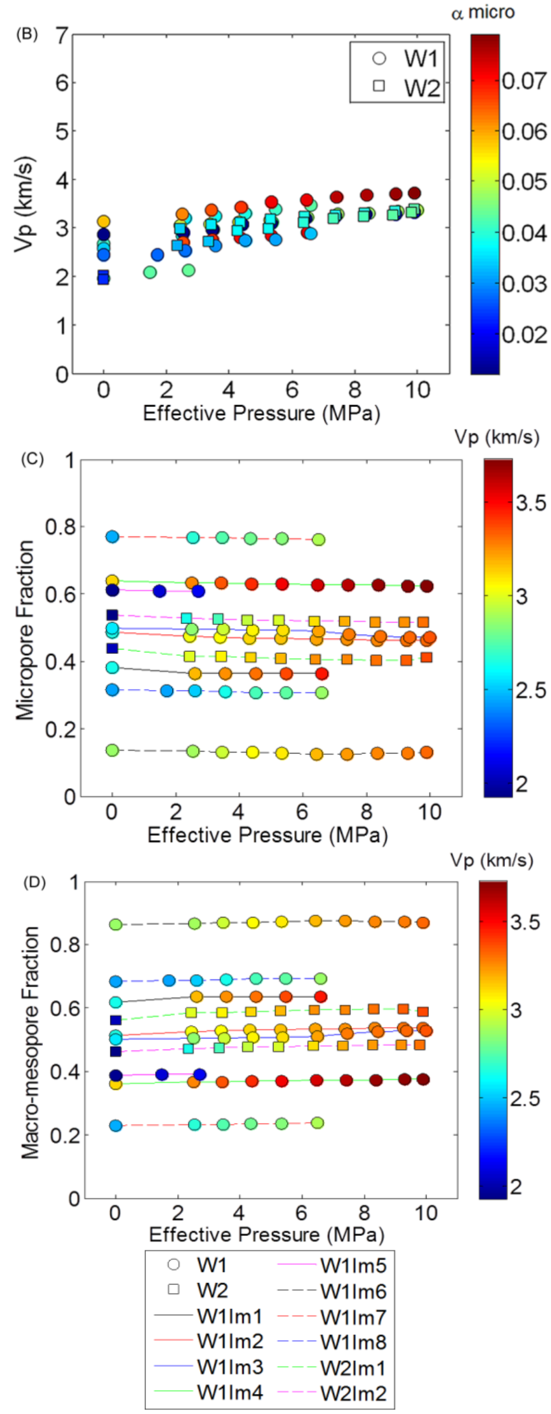


Figure 3: Vp versus porosity. The results reflect the slight porosity volume reduction by effective pressure loading. (A) Effective pressure, (B) Aspect ratio of microporosity inclusion, (C) and (D) microporosity and macro-mesopore fractions from thin-sections, respectively, at different Vp and effective pressures.

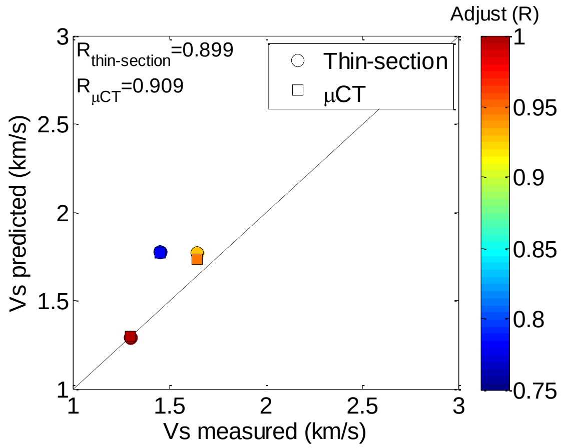


Figure 4: The Vs difference evaluated using input values predicted from thin-section images and µCT scan, calibrated by Vp measured at each core sample condition, according to the suggested methodology (Fig. 1).

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