CILAMCE 2017
Florianópolis - Santa Catarina - Brazil

NUMERICAL SIMULATION AND EVALUATION OF ABSOLUTE PERMEABILITY IN CARBONATES USING 3D DIGITAL MODELS

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Abstract. *Pre-Salt carbonate reservoirs are one of the most important subjects for oil and gas research in Brazil. They often exhibit multiscale heterogeneities that make the understanding of fluid flow dynamics and production optimization a challenge. Digital Rock Physics technology associated to experimental core analysis have been widely used to investigate and compute physical properties and fluid flow characteristics of the pore structure. In this approach, this work uses micro-CT high resolution images and a proposed 3D model of rock porous media to perform a single-phase numerical simulation and predict permeability in Pre-Salt analogue coquinas, from Morro do Chaves Formation, northeast Brazil. This paper highlights the challenges faced during the flow simulation and analyze the computed permeability, which are in good agreement with the results from the routine core analysis.*

Keywords: *Pre-Salt Carbonate, Coquina, Digital Rock Physics, Numerical Simulation, Permeability.*

1 INTRODUCTION

Over the past few years, the destructive nature of most experimental tests has led to a significant development of the concept of Digital Rock Physics (DRP). In general, DRP investigates and calculates the physical and fluid flow properties of the porous media. It has been used as a methodology that complements the experimental routine and special core analysis (SCAL). Some authors, such as Masalmeh et al. (2015), have already used digital image techniques to predict multi-phase flow in rock porous media, but there is still a lot of work to be done to improve the basis and the predictive capability of this emerging technology. DRP is based on image acquisition, digital reconstruction of the pore network, image processing and numerical simulation to predict petrophysical parameters and fluid flow properties. However, the prediction becomes even more challenging for Pre-salt carbonate reservoirs known by their huge heterogeneity and complex pore structure.

The X-ray computed microtomography (micro-CT), also known as high resolution computed tomography, can be defined as a non-destructive technique that allows the acquisition and analysis of hundreds of sections or images. This technique enables subsequent digital reconstruction and visualization of three-dimensional internal regions of rocks samples, in addition to automated quantification of area and/or volume (Neto et al., 2011).

After the step of data acquisition using micro-CT and digital reconstruction of the generated images, through specific software or well-defined programming routines, the stage of image processing begins. One of the most important steps for the analysis of 3D reconstructed images is the segmentation process.

Segmentation can be understood as a process of converting a grayscale or even color image to a binary image. This process is possible by identifying two populations present in the image, based on the intensity of their values obtained during the data acquisition (Al-Raoush & Willson, 2005). In studies involving the analysis of rocks and their porous systems, for example, these two populations refer to the porous and the solid phases. The simplest segmentation techniques employ the use of a global value (threshold value) in such a way that, based on the chosen value, one phase is associated with all values below this chosen one and other to all values above this same value. The selection of the threshold value is based on 8-bit images, which is associated with a range of grayscale varying between 0 and 255 (2^8 possible grayscale values). For example, in a 3D reconstruction of a rock sample, by setting a threshold value, all values below this chosen one will be associated with the porous phase, and all values above this threshold value will correspond to the solid phase. These phases are related to the gray scale generated image obtained from the interaction of the sample with the X-ray beam from the micro-CT.

Some segmentation techniques are part of an ongoing research, but two methods were briefly described and used to extract the interconnected porous system in a previous work (see Silveira et al. (2017)), which objective was to propose a 3D model of rock porous media for coquinas samples and predict their petrophysical parameters.

In this approach, the main objective of this present work is to perform a numerical simulation of a single-phase fluid flow using the proposed 3D digital model of Pre-Salt analogue carbonates (coquinas from Morro do Chaves Formation, northeast Brazil) to compute and evaluate absolute permeability. In addition, this paper highlights the challenges faced during the flow simulation and shows that the computed permeability is in good agreement with the results from the routine core analysis. Hence, this paper is the second part of the work described in Silveira et al. (2017), an outline of workflow for prediction of petrophysical parameters and analysis of fluid flow.

2 METHODOLOGY

The carbonate samples used in this study are coquinas from Morro do Chaves Formation, from Sergipe-Alagoas Basin, northeast Brazil. The coquina reservoirs are grainstones composed essentially of bivalve shells accumulated in bars in high-energy lacustrine environments, affected by several stages of diagenesis, which entailed a complex porous system (Corbett et al., 2016; Kattah, 2015).

Three outcrop core samples (named PET-01, PET-02 and PET-04), considered here as analogue of the Santos Basin Pre-Salt carbonates, were selected for this work. The proposed 3D model of rock porous media of each sample were used to generate image-based meshing which can be used for a wide range of simulations (Fig. 1). For more details on the rock properties, the carbonate analog samples and 3D model, see Silveira et al. (2017), Camara et al. (2014) and Corbett & Borghi (2013).

a)

b)

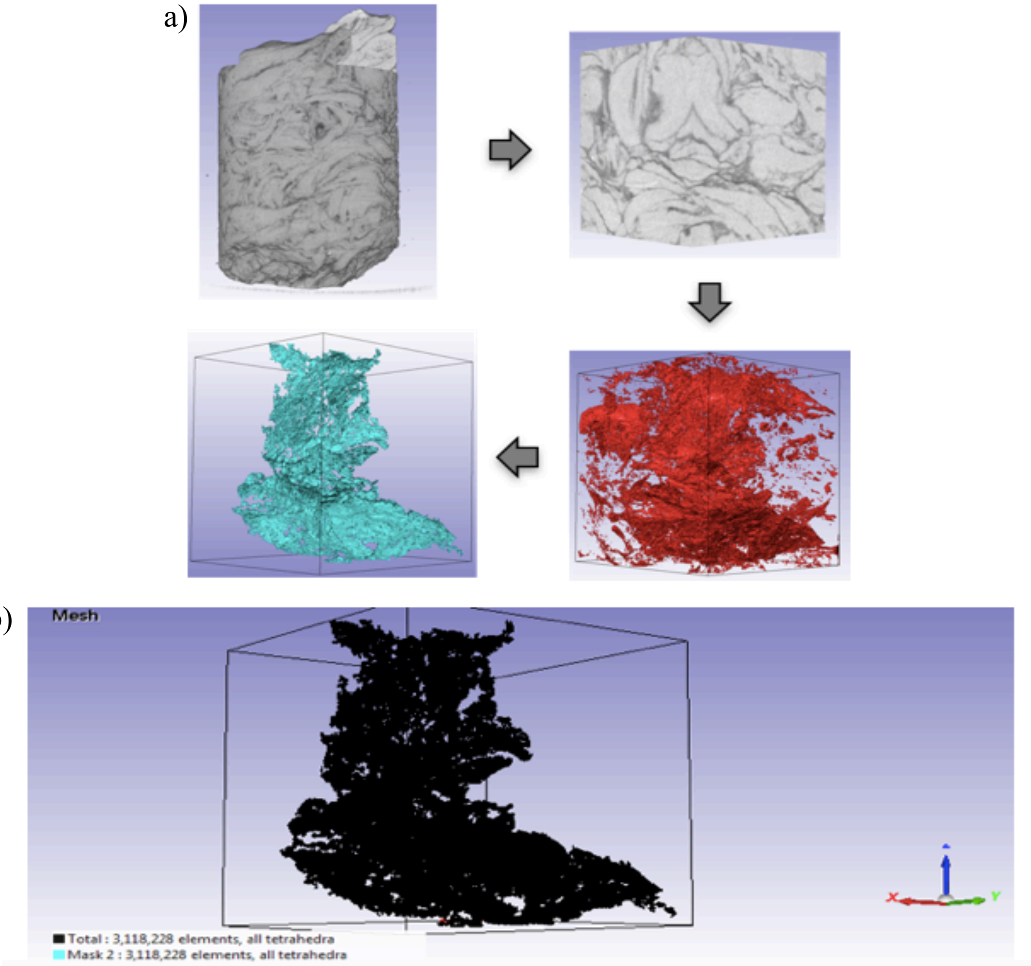

Figure 1 - Images from a coquina sample (PET-04) studied in this work: (a) 3D modeling process of carbonate rock porous media (b) detailed view of the mesh with tetrahedral elements

2.1 Mesh Generation and Numerical Simulation of Fluid Flow

The three-dimensional models generated are the domain in which the equations of fluid flow in pore scale are solved by the Finite Element Method (FEM).

There are two main specifications for this step: the degree of refinement of the desired mesh and the sample volume of a region of interest (ROI). Carbonate porous media are complex geometries that represent a challenge in generating meshes from 3D image data, such as micro-CT. Considering the heterogeneity and the high computational cost involved in this process, the coarser meshes were used in this work, in order to reduce the number of tetrahedral elements in the mesh and to decrease the computational effort required for the convergence of the numerical solution.

Thus, several image-based meshes with tetrahedral elements were generated from different sample volumes of region of interest for each sample, varying from 0.6 to 4.9 cm^3, using a commercial software (Simpleware ScanIP + FE 6.0) and a computer with 32 GB RAM and fifth generation Core i7 (Intel) processor. Total porosity can be estimated through the relationship between the volume of the porous system and the total from the ROI. The effective porosity was estimated analogously, by selecting, this time, the volume of the interconnected pore structure. Figure 2 shows three meshes generated from three different ROIs (in Z axis) of PET-01.

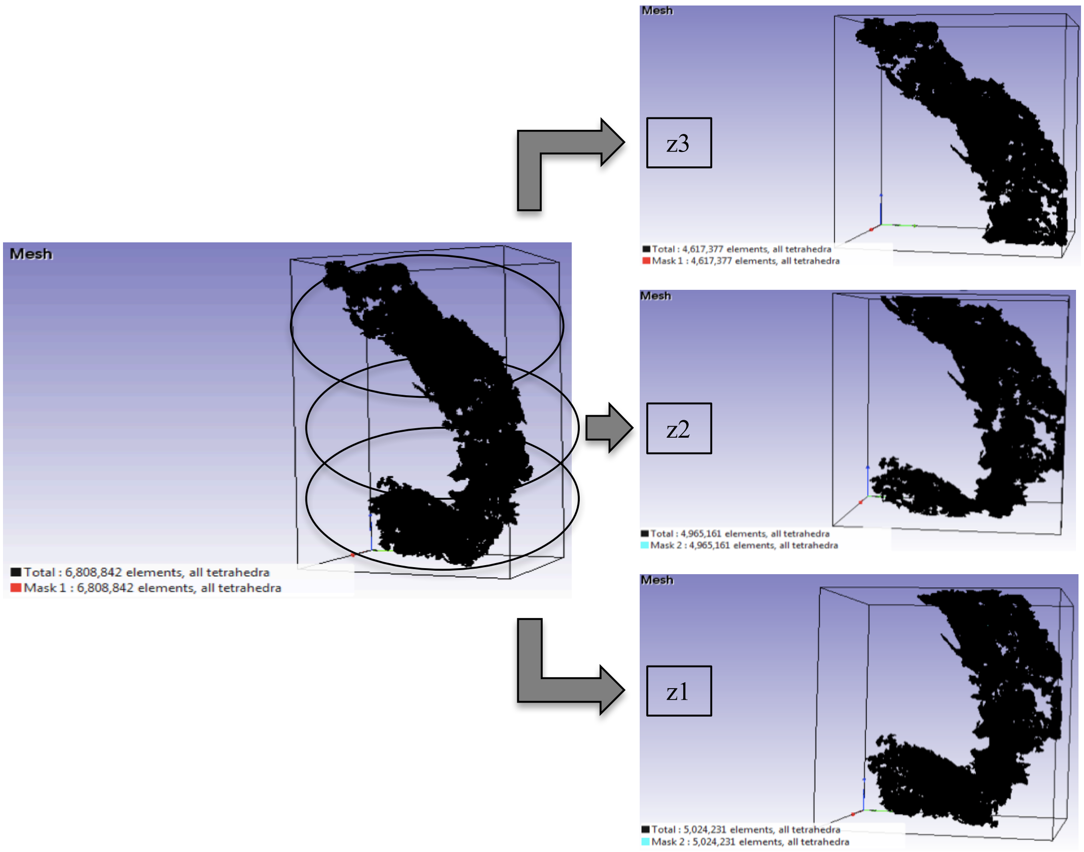

Figure 2 - The coarser image-based meshes from different regions of interest of sample PET-01.

For a comparative evaluation of the generated meshes, it was performed a numerical simulation of a single-phase fluid flow in the 3D coquina porous media. The numerical simulation was performed with a commercial software (Comsol Multiphysics 4.4) based on the FEM, assuming some premises to facilitate the resolution of the problem: all strains in the drainage field are related to the porous medium, the fluid in the pore system (liquid water) has constant temperature and density (simulated the single-phase fluid), laminar flow (Stokes flow or Creeping Flow) and stationary analysis was performed. The time required to achieve the convergence of the solution of the numerical simulation was used as a comparison parameter.

It is important to note that the computational cost necessary to perform the numerical simulations is directly dependent on the number of degrees of freedom (DOF) of the geometry of interest and the computer hardware. The degrees of freedom correspond to the physical unknown values of the problem to be solved (pressure and velocity, in this case), which are used for the assembly of a large system of equations, directly based on the geometry and generated mesh of each model. Therefore, the higher the number of elements used, the greater the system of equations and the higher the computational cost required to solve it. Regarding the computer hardware, the resolution of the equations associated with each problem requires a lot of RAM and a large processing capacity. For the numerical simulations, it was used a computer with 128 GB RAM and a processor Intel® Xeon® CPU ES-2690 v2.

So, for this work, several numerical simulations were performed and the predicted absolute permeability values were evaluated considering the variation of the threshold value and the volume of ROI, i.e. the number of degrees of freedom for each carbonate geometry.

3 RESULTS AND DISCUSSION

It is worth mentioning that the estimated time for mesh generation is related to the degree of refinement defined and to the complexity of the 3D model geometry. Figure 3 shows the example of coarse and ultra-fine mesh from a ROI of PET-04 for a mesh sensitivity study. The coarser mesh was generated in approximately 6 hours and 25 minutes and consists of 1,643,296 tetrahedral elements; the ultra-fine mesh has 7,393,717 tetrahedral elements and needed more than 29 hours to be generated. The prediction of permeability was performed successfully in the coarser image-based mesh. Nevertheless, due to the high computational cost, it was unfeasible to achieve the convergence of the numerical simulation in the ultra-fine mesh. Hence, for all the numerical simulation cases of this work, it was generated the coarser mesh for each ROI of the carbonate geometry.

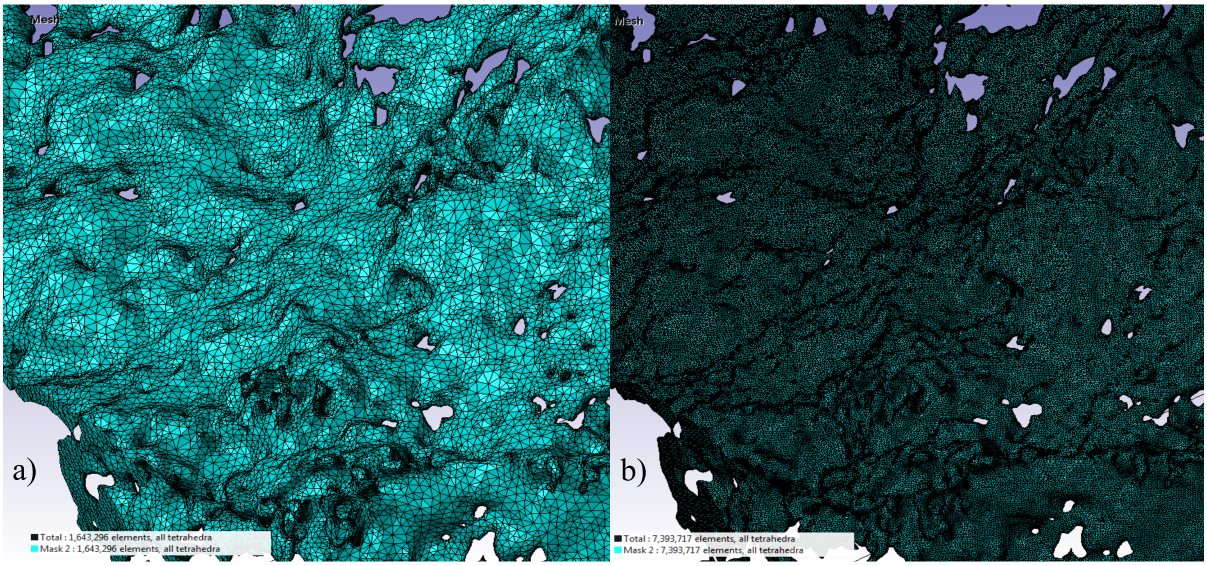

Figure 3 - Image-based mesh for PET-04 sample: a) coarse mesh and b) ultra-fine mesh

The coquina sample named PET-04, with the lower porosity and permeability, was chosen to evaluate the impact of the threshold value on the predicted absolute permeability. Based on the threshold values between 96 and 118 generated by different segmentation methods for PET-04 (Silveira et al., 2017), four digital models of the rock porous media (with the same volume 4.9 cm^3) were proposed in order to perform the numerical simulation of a single-fluid flow using a FEM-based software. Table 1 shows the duration of meshing process, the number of tetrahedral elements and the number of degrees of freedom linked to each threshold value. Furthermore, the table shows the predicted value of absolute permeability. As the threshold value increases, the time for simulation convergence and the permeability values becomes higher. For the highest threshold value, it was not possible to perform the simulation because of the computer limitations.

Table 1 – Evaluation of predicted permeability considering different threshold values, duration of meshing process, number of tetrahedral elements of mesh, number of degrees of freedom and time for single-phase simulation convergence

Threshold Value	Duration of Meshing Process	Number of Tetrahedral Elements of the Mesh	Number of Degrees of Freedom (millions)	Time for Convergence of the Single-phase Numerical Simulation	k (mD)
96	7h25min13s	2,425,868	13.19	9min04s	98.15
108 (average value)	10h22min37s	3,118,228	18.13	30min11s	481.61
111	8h56min57s	3,710,194	21.34	34min24s	612.98
118	29h02min52s	6,878,859	infeasible	infeasible	infeasible

These variations shown in Table 1 were expected, since higher threshold values correspond to models with greater number of tetrahedral elements in meshes, and hence a greater number of degrees of freedom. These greater meshes require longer times to solve and find the solutions of the numerical simulations of single-phase flow in pore-scale. However, the differences are considerable with significant changes in the number of degrees of freedom and time of numerical simulation convergence. Depending on the chosen threshold value, the convergence time of the numerical simulations varied between a few minutes and a few hours. The variations found in permeability are also representative (between 10^2 and 10^3).

Table 2 summarizes several numerical simulations performed for both samples of the coquinas, considering ROI volume and position in Z axis as variables. PET-01 and PET-02 were the samples which the maximum value of ROI were not able to be simulated.

Table 2 – Evaluation of predicted permeability considering ROI volume and position in Z axis, duration of meshing process and number of degrees of freedom

Sample	ROI Volume (cm^3)	ROI Position in Z axis	Duration of Meshing Process	Number of Degrees of Freedom (millions)	k (mD)
PET-01	3.4	-	18h27min41s	6,808,842	infeasible
	2.4	z1	12h48min12s	5,024,231	infeasible
		z2	17h50min04s	4,965,161	18.44
		z3	9h59min29s	4,617,377	40.49
	1.3	z1	1h45min15s	1,806,569	62.28
		z2	3h07min25s	2,941,750	1527.67
	0.9	z1	1h01min05s	1,575,271	5054.98
		z2	24min53s	794,377	52.12
		z3	1h43min39s	2,100,920	5321.02
	0.6	z1	46min15s	1,201,480	28754.08
		z2	8min30s	378,442	infeasible
		z3	52min59s	1,236,625	1438.99
		z4	46min30	1,373,003	4321.63
PET-02	3.4	-	18h22min18s	6,535,628	infeasible
	2.9	z1	8h49min59s	3,630,702	1472.80
	2.9	z2	4h28min39s	2,182,555	375.86
	2.9	z3	10h26min36s	4,147,748	256.60
	2.9	z4	28h22min18s	6,535,328	infeasible
	2.9	z5	9h19min24s	4,046,438	196.38
PET-04	4.9	-	10h22min37s	3,118,228	481.61
	2.5	z1	2h01min24s	2,267,962	470.37
		z2	1h01min05s	942,084	134.21
	1.6	z1	1h00min24s	1,629,641	583.03
		z2	24min40s	751,344	713.02
		z3	13min46s	523,335	95.35
	1.2	z1	9min29s	1,198,568	132.62
		z2	14min57s	1,548,894	644.74
		z3	29min35s	508,907	363.11
		z4	39min53s	387,301	76.02

It is possible to observe in Table 2 that 5 millions of degrees of freedom is a limiting factor for the numerical simulation convergence – lack of RAM to continue the convergence of the numerical equations. Although sample PET-01, ROI 0.6 cm^3, has few degrees of freedom, yet is infeasible, contradicting the proposed limit of 5 million DOF because the system lost the connection in Z axis. Besides that, with small ROI volumes, such as 0.6 cm^3, the predicted permeability value is 28 D, which can be explained by the dependency of tortuosity and absolute permeability in carbonates (Guo, 2012).

Considering that, according to Camara et al. (2014), the experimental routine core analysis of these coquina samples, from Morro do Chaves Formation, shown absolute permeability variation from 10 to 10^3, it can be said that the prediction of absolute permeability of several ROIs, through DRP technology, is in good agreement with the experimental values. Figure 4 presents that, as in Pre-Salt carbonates, the main variation of the permeabilities of 2 or 3 orders of magnitude, occurs in coquinas analog.

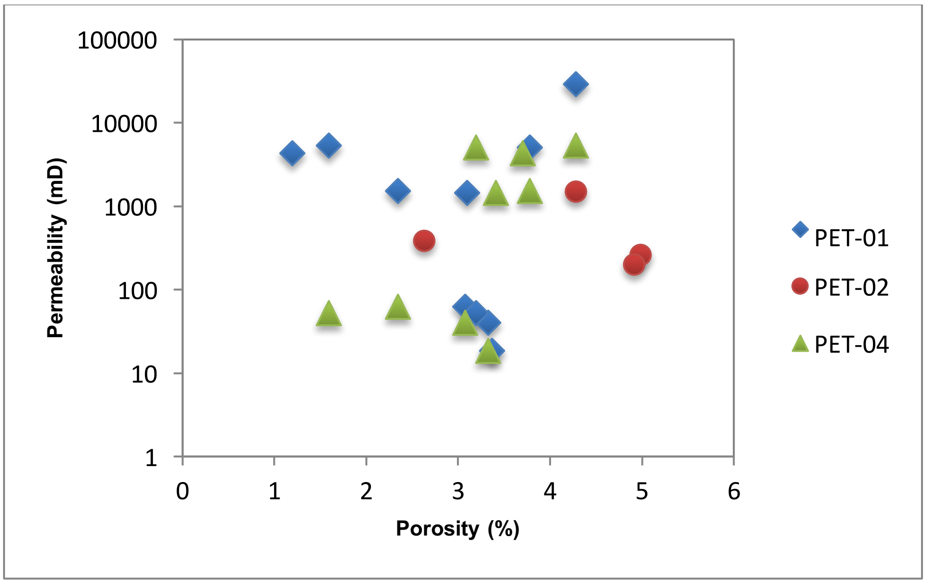

Figure 4 - Porosity vs Permeability of the samples used in the study

4 CONCLUSIONS

The results show that the selection of a segmentation method during the digital rock analysis is extremely important when working with complex carbonates. Small variations in the threshold value generate different porous systems and, consequently, the numerical simulation is also affected by these variations: the 3D model geometry and the required time to solve the single-phase fluid flow problem are sensitive to small modifications.

This paper is the second part of the work developed as an outline of workflow for prediction of petrophysical parameters and analysis of fluid flow. Several numerical simulations of single phase fluid flow at pore scale using the 3D models of analog coquinas were performed and experimental data from routine core analysis was used to validate the predictions of absolute permeability. In general, the results of the study suggest that the higher the resolution of computed microtomography images, the higher the number of pore pixels, the better pore connectivity, the higher the 3D model complexity, the greater the system of equations and thus, the higher the computational cost required to solve the fluid flow simulation. The mesh refinement, i.e. the variation in the number of degrees of freedom, is related to the number of elements within the 3D model of rock porous media and it is a key process to more accurately resolve the numerical simulation. The number of DOF and the time required to solve the finite element model were used to compare the achieved values of absolute permeability.

Through this work we suggest and encourage the development of news studies using DRP technology as a methodology to complement the routine and SCAL analysis. The predicted values for absolute permeability in some subsamples are not completely in accordance with the experimental and measured values. It can be verified in some small volumes a variation of more than 3 orders of magnitude for this property. However, as the absolute permeability varies according to the analyzed ROI that is different from the representative elementary volume (REV), these higher values are justifiable. Besides, highly heterogeneous carbonates have microporosity, which is below the resolution of the micro-CT image used for this study. Research is still ongoing, while there have been improvements in imaging acquisitions, pore-scale modeling and petrophysical and fluid flow modeling

ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from Shell, CNPq and CAPES. We thank LRAP and LAMCE teams in UFRJ for their support; and professor Leonardo Borghi (LAGESED/UFRJ) and Patrick Corbett (Heriot-Watt University) for useful discussions.

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