POROUS MICROSTRUCTURE CHARACTERIZATION OF A SANDSTONE RESERVOIR USING HIGH-RESOLUTION X-RAY MICROTOMOGRAPHY

Carlos Roberto Appoloni(1), Carlos Rogério Oliveira Rodrigues(2) and Celso Peres Fernandes(3)

(1) Applied Nuclear Physics Laboratory (LFNA), Physics Department, State University of Londrina, Paraná, Brazil
(2) PETROBRÁS Research and Development Center (CENPES), Rio de Janeiro, RJ, Brazil
(3) Porous Media and Thermophysical Properties Laboratory (LMPT), Mechanical Engineering Department, Federal University of Santa Catarina, Florianópolis, SC, Brazil

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ABSTRACT

This paper presents the pore space characterization of a sandstone reservoir rock carried out with a microfocus X-ray computed tomography (μ-CT) scanner using a cone-beam (Feldkamp) reconstruction algorithm. The sandstone sample was roughly cylindrical, 3 mm wide and 5 mm high. The resulting spatial resolution of the image was 3.8μm, which allowed a very good visualization and enabled a geometric quantification of grains and pores. A total of 956 cross-sections were taken to render a 3D volume of the specimen. These cross-sections were processed in order to characterize the geometrical microstructure of the sample. Total porosity, pore size distribution and the two point correlation functions were measured after segmenting images. The pore size distribution was obtained through morphological operations performed using the appropriate structuring element based in chamfer metrics. A 3D microstructure of the sample was modeled based on the two point correlation function data using a truncated Gaussian method in the Fourier space. The geometrical parameters (porosity, pore size distribution and two point correlation function) were then measured in 2-D image slices from the Gaussian 3D model in order to compare with the same parameters from the 2D μ-CT images. This approach shows promise in allowing a thorough evaluation of the 3D model quantifying its resemblance with the real pore space depicted by the μ-CT 3D volume.

INTRODUCTION

Understanding and digitally characterizing the petrophysical parameters of reservoir rocks is essential to their appraisal and to the computer aided prediction of their quality and behavior during production. This knowledge is usually obtained from the core plug evaluation where several parameters are analyzed such as: porosity, pore size distribution, absolute permeability, formation factor, capillary pressure, relative permeability, etc. These properties are measured on appropriate rock samples (which are, in some cases, not easy to obtain), by laboratory experimental testing that may sometimes be laborious, time consuming and very expensive.

The present improvement of image acquisition equipments and computer technology are both favoring the implementation of very sophisticated 3D porous media models that allow the use of complex simulation methods. These methods appear to open a promising scenario for new techniques to estimate petrophysical properties promptly and at low costs using solely the knowledge of the 3-D pore geometry of reservoir rocks.

The 3-D characterization of a porous medium is most commonly achieved using one of the following two methods: microstructural modeling, also known as image reconstruction procedure, and direct determination of a 3-D volume. The first method is based on measurements of geometrical parameters and the spatial organization of the porous medium in 2-D images obtained by optical microscopy or scanning electron microscopy. Mathematical models that honor these measurements are used to reconstruct the 3-D volume of the pore space, such as the truncated Gaussian stochastic model [1, 2, 3] or simulated annealing [4, 5]. The 3-D reconstruction is an interesting method since it provides fast and inexpensive results. However, it presents pitfalls when dealing with long-range connectivity, such as in rocks with low porosities where only the use of higher order statistics (multiple-point function) can achieve the goal, as demonstrated by Okabe and Blunt (2004) [6]. The second approach uses serial sectioning [7] or microfocus X-ray computed tomography (μ-CT) to assess the porous media of the rocks [8, 9, 10]. Serial sectioning is not often used since it demands the acquisition of hundreds of 2-D images of polished sections for each sample, resulting in a delicate and time consuming technique. Although μ-CT scanners are not routinely available yet, they grant the acquisition of 2-D images with a spatial resolution of a few micrometers that can be rendered as a 3-D volume detailed enough to characterize the pore structure. This is a powerful non-destructive technique that allows visualization of the internal structure of the porous media and will help understand the petrophysical properties of reservoir rocks.

The advantage of implementing a 3-D reconstructed volume or a μ-CT 3-D volume is that they enable the computational simulation of fluid invasion phenomena based on very fundamental physical laws, which are not dependent on the porous structure, helping to estimate petrophysical properties of reservoir rocks [11].

METHOD

This paper presents the morphological characterization of an eolian sandstone sample from the Botucatu Formation, Parana Basin, Brazil, using a μ-CT facility. Further on, this paper presents details of the equipment, samples and procedures applied to perform the porous medium characterization as well as the theoretical discussion that support this study.

Studied samples

The Botucatu Formation is a Cretaceous continental red bed that occurs in the Parana Basin, central South America, covering the south and central regions of Brazil, the east of Paraguay and the northeast of Argentina [13]. These sedimentary rocks were deposited in an eolian environment where crescentic and complex linear sand dune morphologies were predominant [13]. These sediments were covered by the huge extrusion of basaltic lavas of the Serra Geral Formation, which helped preserve this vast dune field all over the Parana Basin.

The Botucatu sandstones are fine to medium in grain size, well rounded and highly spherical. They are quartzarenites in composition, presenting almost only detrital quartz grains, entirely coated with a fringe of microcrystalline quartz (small and discrete quartz crystals) and iron oxide cements. Some iron oxide concretions may form locally and they may interfere in the µ-CT analysis, causing some artifacts. The studied sample is moderately consolidated (disaggregates only after rubbed vigorously between fingers) and presents intense grain dissolution recognized by the occurrence of moldic pores delineated by the micro-quartz envelopes. This remarkable occurrence of moldic pores is related to intense percolation of meteoric water (telodiagenesis) that dissolved chemically unstable grains, such as potassium feldspars, for instance. However, the dissolution process did not influence the more stable quartz grains and micro-quartz cement, even when precipitated over the unstable grains. The Botucatu sandstone sample was selected to this study due to its excellent properties as a reservoir rock, presenting porosities that may vary in the 15–32 % range and permeabilities of dozens to thousands of mD. The scanned sample comes from a quarry and has a porosity of 30% and permeability of 5,000 mD.

Acquisition of µ-CT Images

The µ-CT images were obtained in a Skyscan 1072 µ-CT scanner (Fig. 1) with an air cooled sealed microfocus X-ray tube, using a tungsten anode and operated at 60kV and 165µA (spot size <5µm). This sample was analyzed using a 1mm Al filter and an 8-bit CCD camera (1K x 1K resolution) with on-chip integration mode and lenses coupled to a scintillator (28 to 65 mm field of view). The equipment detectability varies from 2 to 5 µm depending on sample size and composition (contrast resolution). Total rotation angle of the sample was 180.0^{o}, with rotation step size angle of 0.45^{o}. The images were generated using a cone-beam (Feldkamp) reconstruction algorithm.

Figure 1 – Skyscan 1072 µ-CT system used to study the sandstone samples. The equipment is simple to operate and the resolution depends on sample size and composition.

The sample shape was roughly cylindrical, about 3 mm wide and 5 mm high. It was taken from a larger sample (one half of a plug end) that did not achieve a suitable resolution for porous medium characterization (Fig. 2). The achieved spatial resolution of the image was 3.8µm, which allowed a very good visualization of microstructural details and enabled the geometric quantification of grains and pores.

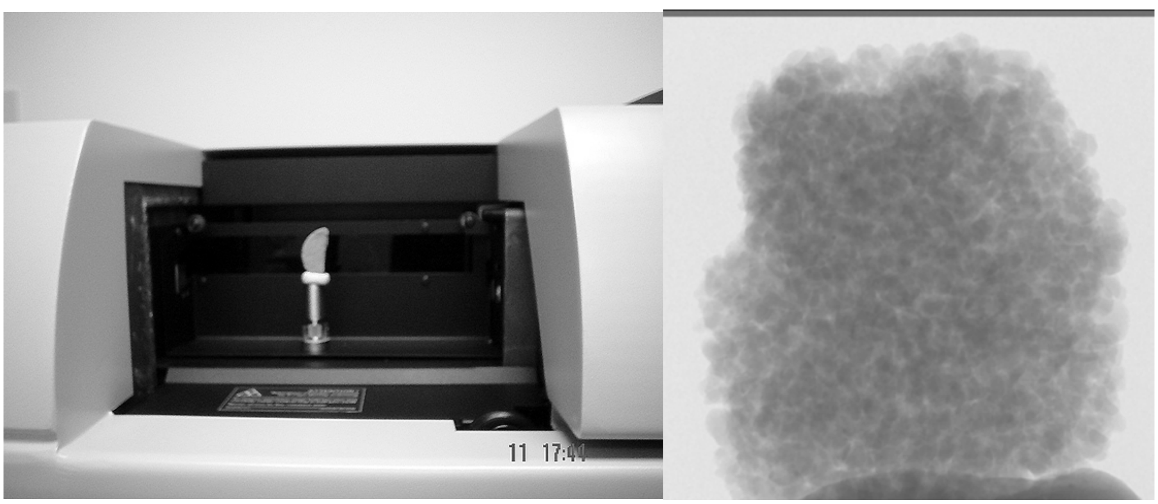

Figure 2 – Left: detail of the Skyscan 1072 µ-CT system showing sample chamber and holder with a half plug head. The best resolution was achieved using a smaller sample (bulk sample X-ray image to the right), about 1/5 in volume of the one shown to the left.

Image Processing

The porous medium characterization and 3-D modeling were performed using the Imago software: a program with tools to estimate petrophysical parameters using microstructural information. It was developed at the Laboratory of Porous Media and Thermophysical Properties (LMPT), Department of Mechanical Engineering, Federal University of Santa Catarina, Brazil, in association with the Brazilian software company Engineering

Simulation and Scientific Software (ESSS), and Petróleo Brasileiro SA (PETROBRAS) Research and Development Center (CENPES).

The 2-D set of Botucatu µ-CT cross-sections was first prepared using a cropping tool to select a region inside the rock to perform the characterization (determination of a region of interest - ROI). The resulting cropped images were then segmented into solid and porous phases based on a manual cutoff point determination using their gray level histogram. This cutoff point was chosen visually taking into account the gray level threshold which best separated the classes associated to solids and pores, creating binary black and white images. The binary image set was modeled to determine porosities, pore size distribution and autocorrelation function for each image and their respective mean values for the stack.

Geometrical Characterization

Phase Function And Its Moments

The porous medium represented in a 2-D µ-CT binary image can be characterized by the pore phase function Z**(x)** as follows:

$$Z(\mathbf{x}) = \begin{cases} 1 & \text{when } \mathbf{x} \text{ belongs to the pore space} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where **x** denotes the position with respect to an arbitrary origin. The porosity ϕ, the autocorrelation function C(**u**), and the normalized autocorrelation function R(**u**) can be defined, respectively, by the following statistical averages (denoted by $\langle\ \rangle$):

$$\phi = \langle Z(\mathbf{x}) \rangle \tag{2}$$

$$C(\mathbf{u}) = \langle Z(\mathbf{x}) Z(\mathbf{x}+\mathbf{u}) \rangle \tag{3}$$

$$R(\mathbf{u}) = \frac{\langle [Z(\mathbf{x}) - \phi][Z(\mathbf{x}+\mathbf{u}) - \phi] \rangle}{\phi - \phi^2} \tag{4}$$

where **u** is the displacement in the plane of the image. When the medium is homogeneous, the statistical parameters are independent of position **x** in space. Thus, the porosity is constant and $\mathrm{R}(\mathbf{u})$ depends only upon the vector **u** being independent of position **x**. Moreover, when the porous medium is isotropic, R_Z is a function only of $\mathrm{u} = |\mathbf{u}|$ and does not depend on the direction of **u**.

While the porosity ϕ is related to the probability of an arbitrary pixel of the image to belong to the pore phase, C(u) relates to the *probability* of finding two pixels separated by u and belonging to the pore phase. These relations constitute the first and second order statistics (or moments) of the image.

For an image f(x,y), the Fourier transform of the autocorrelation function is the power spectrum of f(x,y) (Wiener-Khinchin theorem). Thus, if the Fourier transform of the image is known, the correlation function can be obtained rapidly performing the inverse Fourier transform of the power spectrum. The 2-D autocorrelation function is calculated by using the Fourier transform [2].

Pore Size Distribution

The pore size distribution is obtained by successive openings derived from mathematical morphology, using balls with increasing radius [12]. After an opening operation with a given r-radius ball, the resulting image can be viewed as the union of r-radius balls completely enclosed in the porous phase. In this way, after an opening, the porous phase loses all features that can be eroded by the given r-radius opening ball. The cumulative porous distribution is given by:

$$F(r) = \frac{\phi - \phi(r)}{\phi} \tag{5}$$

where ϕ is the total porosity of the original image and $\phi(r)$ is the volume fraction of the porous phase after the opening with a r-radius ball.

To reduce processing time, the opening operation is not applied directly to the binary image, but to a transformed image called background distance image**.** In this image, each pixel is labeled with the smallest distance from it to the neighbor background. This labeling technique uses a sequential algorithm [14], where the Euclidean distance is approximated by a discrete integer distance. The most commonly used discrete distance is the chamfer distance known as $d_{3\text{-}4}$, where each neighbor from a given point and following only the horizontal and vertical coordinate directions, is considered to be 3 measuring units apart from the starting point. The diagonal neighbors are considered to be at 4 measuring units from that point. Thus, this discrete distance gives the numerical approximation of $4/3$= 1.333...to the square root of 2 (1.4142...). The main advantage of using this discrete distance is related to the lower computer storage required for calculations when only integers are stored in resident memory. Balls generated using the $d_{3\text{-}4}$ distance and that are used to perform openings are octagonal in shape.

Three-Dimensional Reconstruction

The truncated Gaussian method can model a 3-D binary microstructure based on the first and second order porous media statistics, i.e. porosity and two-point autocorrelation function. The original conception of this method [15, 16] was modified by using discrete Fourier transform [2, 3]. This is, perhaps, the most frequently used method for 3-D reconstruction and the Imago software code is based in the approach presented by Liang et al. (1998) [3]. The main limitation of this method is related with the conservation of long-range connectivity since it is limited to the second order statistics. Thus, the truncated Gaussian method is always inadequate when dealing with any microstructure presenting a high degree of spatial organization, either in carbonatic or siliciclastic rocks.

The present paper presents a 3-D model of the Botucatu sandstone porous medium obtained using the truncated Gaussian method derived from the 2-D µ-CT cross sections first and second moments. In order to evaluate the statistical model accuracy, the same parameters, i. e. porosity and two-point correlation function (as well as pore size distribution), were also measured in the 2-D µ-CT cross-sections. This procedure allowed the numerical comparison between porous volumes, the 3-D µ-CT volume and 3-D reconstructed model.

RESULTS AND DISCUSSION

µ-CT Images

A total of 956 cross-sections were obtained from the sample and they were used to render a representative 3-D volume of the Botucatu sandstone (Fig. 3). The sample was roughly cylindrical, about 3 mm wide and 5 mm high, with images achieving a resolution of 3.8 µm. The rendered 3-D image of the sample can be seen as a solid showing the interlocking grains or as its complementary porous medium, resembling a 3-D pore cast of the sample (Fig. 3).

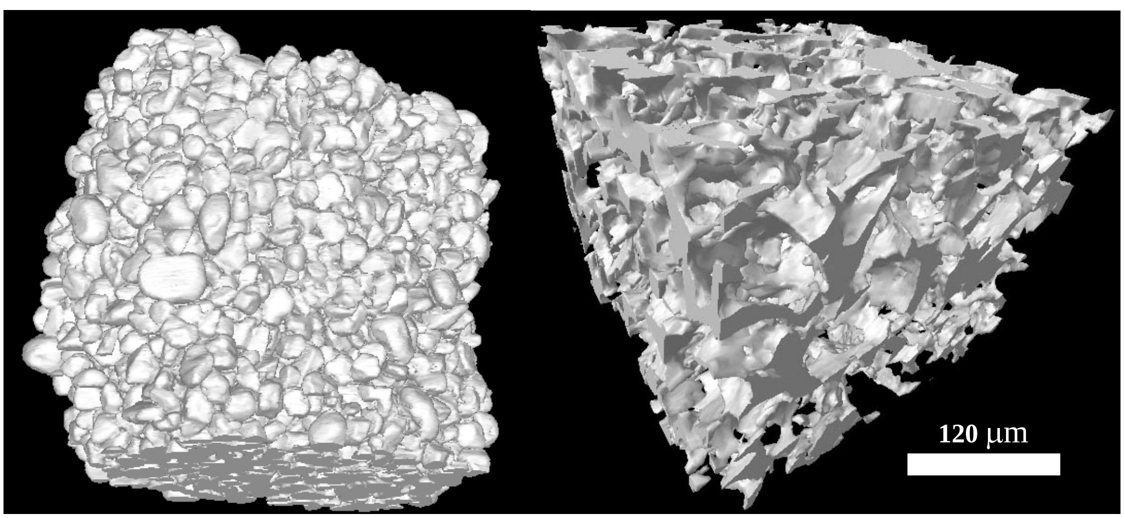

Figure 3 – Left: 3-D µ-CT image showing part of the sample grains in light gray. Right: a cubic section of the same µ-CT volume showing the pore space in light gray. The pixel resolution in both images is 3.8 µm. Average grain size fraction is fine to medium sand.

The accuracy of the µ-CT images was certified by the observation of petrographic thin sections under polarized light microscopes. Both methods presented the same features, such as grain size and shape, as well as the fringing silica cement precipitated over the grains and that delineated the remarkable moldic pores (Fig. 4). These moldic pores are clearly seen in the µ-CT images while the occurrence of the cement fringe over the grains is too subtle to be observed. Nevertheless, this feature can be easily detected during image segmentation since it presents a different shade of gray, a lighter gray level than the shades representative of grain nuclei (Fig. 4). Therefore, after comparing both pictures, the µ-CT images can be considered to achieve the same quality of details as those presented in polarized light photomicrographs.

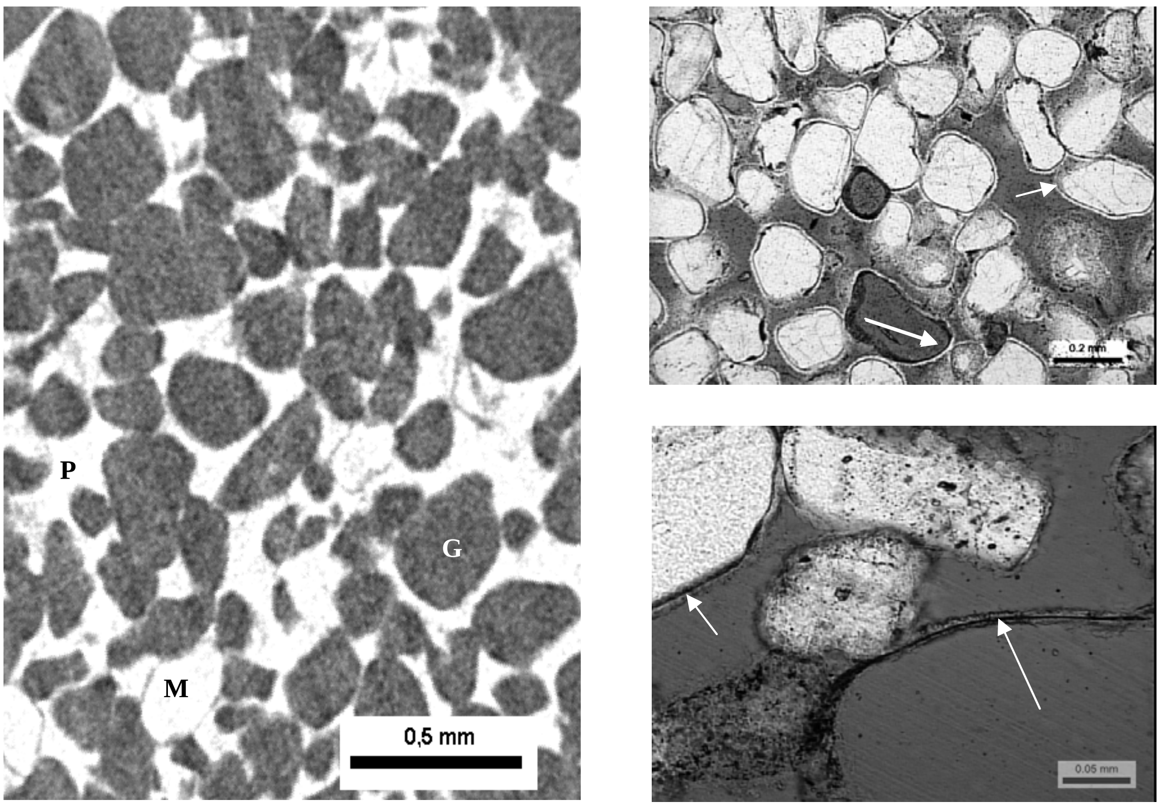

Figure 4 – Left: µ-CT cross section of the Botucatu sandstone showing grains (G-dark gray), moldic pores (M) delineated by micro quartz cement (lighter gray) and pores (P-white). Top right: petrographic thin section of the same sample (solid in light gray) showing the ubiquitous occurrence of fringing micro quartz cement moldic pores (arrows) and enhanced (secondary) pores (dark gray due to low density resin impregnation). Bottom right: detail of the micro quartz cement that fringes grains and delineate moldic pores (arrows). Note that all images present the same quality of porous media characterization.

Comparison between µ-CT Images and the stochastic model

In order to numerically compare the resemblance of a truncated Gaussian stochastic model with the µ-CT 3-D rendered image, the µ-CT cross-sections and the 2-D images of the stochastic model were geometrically characterized. Both sets of images had their porosity, pore size distribution and autocorrelation functions measured. The cropped µ-CT cross-sections were grouped in 14 sets of 50 images due to software limitations. Measurement results for 700 images are presented in figures 5, 6 and 7. The top 98 images and the bottom 155 cross-sections were discarded due to their small sample area and the occurrence of artifacts.

The measurement in groups of 50 slices, representative of about 190 µm, allowed tracing a porosity profile for the sample (Fig. 5). The porosity values range from 28.7 to 33.6% and the global average porosity is 30.2% while the experimental porosity measured by the gas expansion method (Boyles Law) is 30.0%.

The pore size distribution was measured by morphological opening operations performed with octagonal balls. The measurement in groups of 50 µ-CT cross-sections (190 micron width) was selected because most Botucatu sandstone pores are in the 10 to 55 µm range, with a frequency peak in the 30 µm size (Fig. 6).

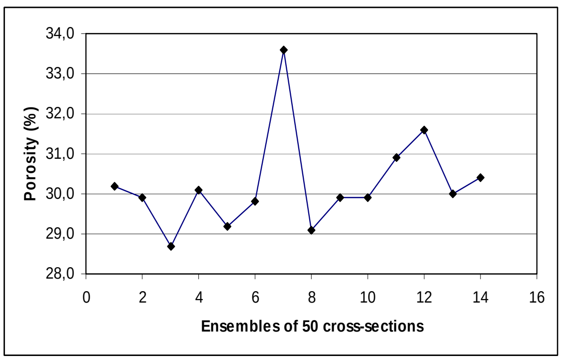

Figure 5 – Porosity profile of groups with 50 cross-sections of the Botucatu sample (190 µm intervals) showing a porosity total average of 30.2%.

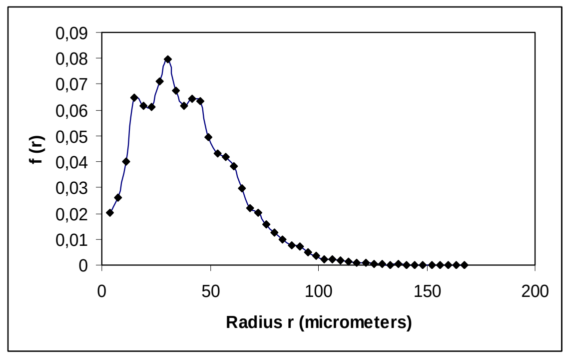

Figure 6 – Average pore size distribution of the 50 groups of µ-CT cross-sections, showing a frequency peak in the 30 µm size.

The average normalized autocorrelation function R(u) for the 700 µ-CT cross-sections (Fig. 7) was used to generate a 3-D microstructural image of the Botucatu sandstone. The truncated Gaussian reconstruction method generated a cube with 250^3 voxels, spatial resolution of 3.8 µm/voxel and total porosity of 30.26% (Fig. 8 left).

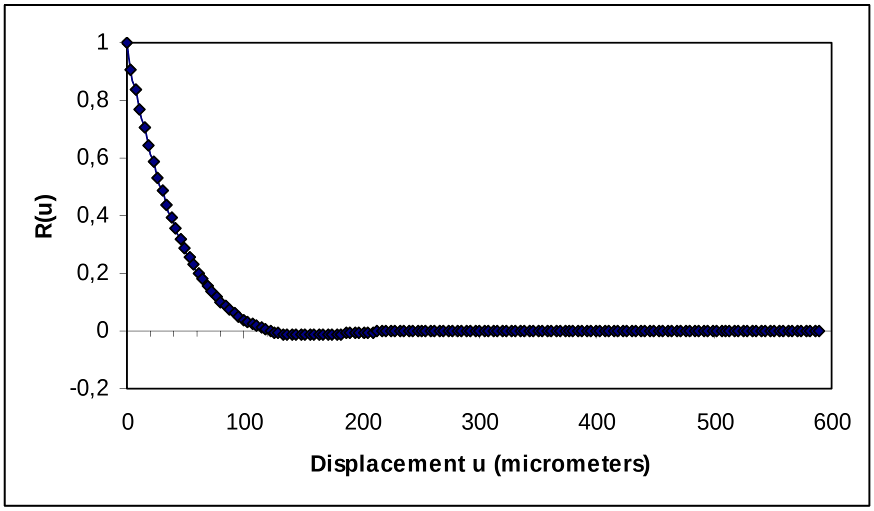

Figure 7 – Average normalized autocorrelation function R(u) for the 700 µ-CT images of the Botucatu sandstone used as input to the stochastic reconstruction model.

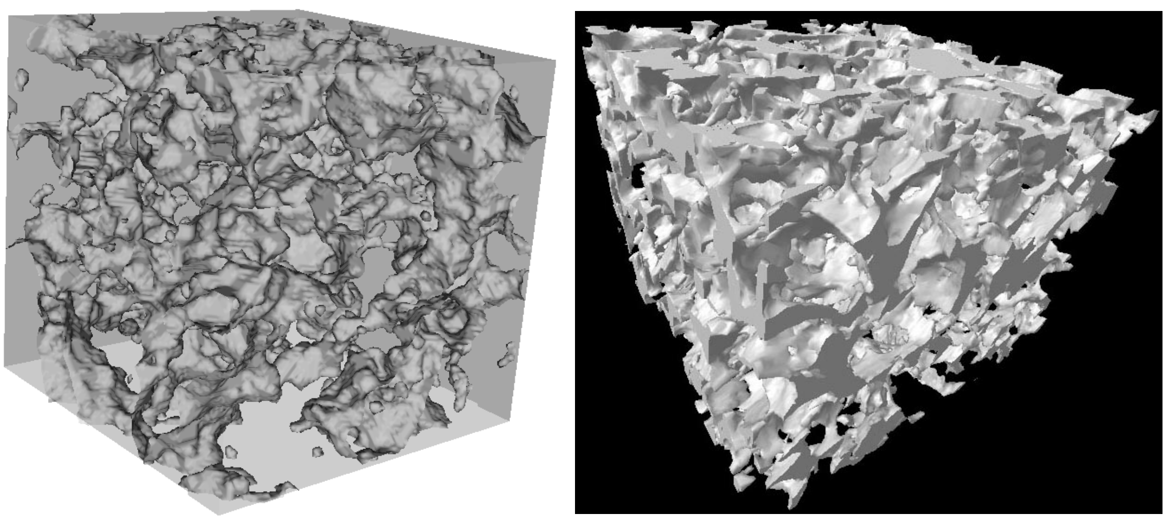

Figure 8 - Visualization of the porous medium as a result of the 3-D stochastic reconstructed model (left) and as depicted by the µ-CT analysis (right).

The comparison of pore size distribution curves and normalized autocorrelation functions for the stochastic reconstructed model against the µ-CT analysis show that both parameters are quite similar to each respective counterpart, with minor differences (Figs. 9 and 10).

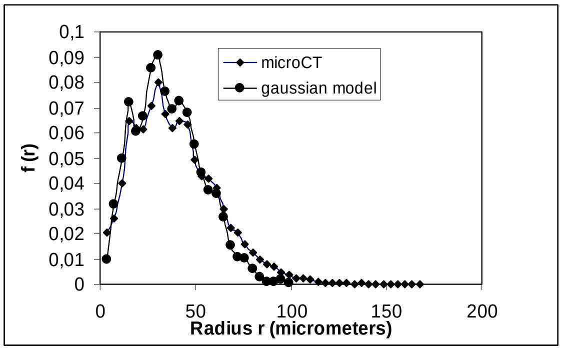

Figure 9 – Comparison of pore size distribution between μ-CT analysis and stochastic reconstructed model.

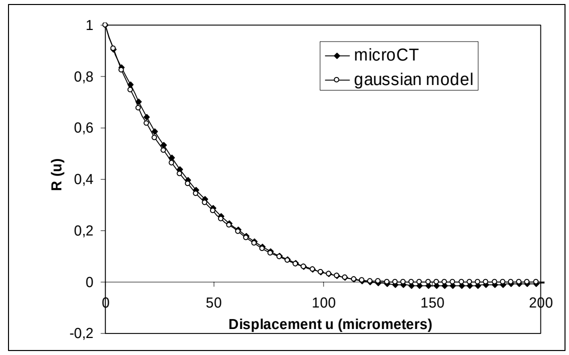

Figure 10 – Comparison of normalized autocorrelation functions for μ-CT analysis and stochastic reconstructed images.

One difference is that the pore size distribution curve of the stochastic reconstructed model does not reproduce pore sizes bigger than the 100 μm pores that were measured in the 2-D μ-CT images. Another difference observed is that the volume fraction of pore sizes smaller than 50 μm (radius) are overestimated in the reconstructed model when compared to what was measured in the μ-CT volume. The latter mismatch is related to the nature of autocorrelation functions for displacements smaller than about 150 μm, where the porous medium is spatially correlated, the stochastic model correlation is smaller than that in the μ-CT image.

Moreover, the stochastic model effective porosity obtained after filtering isolated pores, which is the set of connected pores that actually participate in fluid invasion, is 29.98%, a value slightly smaller than the total porosity measured in the μ-CT image, which is 30.26%.

CONCLUSIONS AND FURTHER DEVELOPMENTS

A sandstone sample has been analyzed using microfocus X-ray computed tomography (μ-CT), allowing the acquisition of images with a spatial resolution of 3.8μm. These high resolution images, comparable in quality to those obtained by optical petrographic microscopes, allowed the visualization of microstructural details. These details were used for the quantification of amount, size and spatial distribution (two-point correlation function) of the Botucatu sandstone porous medium.

This geometric characterization performed in 2-D μ-CT cross-sections allowed the generation of a truncated Gaussian stochastic 3-D model for the sandstone microstructure and its visual and numerical comparison with the μ-CT volume. Even for a relatively simple microstructure, like the Botucatu sandstone, there are differences between the μ-CT volume and the truncated Gaussian reconstructed model that emphasize the weaknesses in the stochastic reconstruction method. Such problems include the failure in reproducing long-range connectivity and the overestimation of small pores with the consequent reduction of effective porosity. This is shown to be a problem with fairly simple sandstone; it should be amplified for carbonates and complex sandstones.

The possibility of having a high resolution 3-D µ-CT image reveals a promising scenario for studies and applications in porous media characterization. It is possible to simulate fluid invasion in these µ-CT structures and estimate their petrophysical properties. The research presented in this paper will focus, in the future, on the development of tools for: morphology and topology measurements directly in 3-D porous media; verification of the accuracy of 3-D statistical models using µ-CT volumes; estimation of petrophysical parameters of the 3-D porous media through simulation of fluid flow in µ-CT volumes.

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