Porosity Determination by 3D High-Resolution X-Ray Computed Microtomography and Its Correlation with Gas Adsorption Technique*

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Abstract

In order to evaluate the productivity performance of the oil reservoir, it is necessary to investigate how easily the fluid can flow into the pore system. Several reservoir rock and fluid properties can be determined from petrophysical parameters, such as, porosity which is the ratio of pore volume to the total bulk volume of the formation. This parameter can be presented as an absolute or as an effective value. The effective porosity is the fractional volume of pore space that permits fluid to flow in a rock and it is lower than the absolute porosity which is related to all connected void spaces, regardless of whether the pores are connected or dead-ended. The porosity can be determined in laboratory routines using cores from the formation, but all the techniques used in conventional petrophysical studies require sample preparation which leads, in most cases, to a destruction or modification of the used material. The unique technique that can determine some petrophysical parameters without sample preparation is the X-ray computed microtomography. This is a non-destructive test, resolution of microns and becomes a useful tool in study of internal characteristics of geological samples. This was to investigate cores from the reservoirs of Resende Formation which were collected in Porto Real, RJ/Brazil. This formation is characterized by sandstones and fine conglomerates, with associated fine siliciclastics; the paleoenviroment is interpreted as a braided fluvial system. The purpose of this study was to estimate the total core porosity by microtomography and to correlate it with the gas adsorption porosimetry technique. The microtomography was acquired using a 3D high-resolution microtomography system which has a microfocus X-ray and a CCD camera fiber-optically coupled to scintillator operated at 100 kV and 100 μA. Thirty-six samples at different depths of three oils wells were analyzed and a total of 961 2D slices were made with a resolution of 14.9 μm. The porosity was estimated from the 3D analysis of binary images. The correlation between the conventional and microtomography techniques demonstrated that the porosity values were in the same range, but the latter has an advantage of being non-destructive and more sensitivey to changes in 3D microstructures. It was also possible to perform a 3D visualization of the size and shape of pore volume present in the rock used in the tests without destroying the samples.

Introduction

The applications of 3D High-Resolution X-ray microtomography (μ-CT) in geosciences became widespread because it is a non-invasive technique that has several advantages. μ-CT is a nondestructive technique that allows 2D and 3D visualization of the internal structure of rocks. Many studies have demonstrated the power of μ-CT with respect to classical petrography in geological research (Van Geet et al., 1999); μ-CT can be used for quantitative and qualitative analysis of internal characteristics of geological materials (Mees, 2003). The 3D characterization of porous medium from the core plug evaluation leads to petrophysical properties, such as porosity, pore distribution, and permeability.

Most of all oil and gas produced comes from accumulations in the pore spaces of reservoir rocks. The amount of oil or gas contained in a unit volume of the reservoir is the product of its porosity and the hydrocarbon saturation. Therefore, porosity is a very important petrophysical parameter of rocks (Schlumberger, 1991). It is defined as the ratio of the volume void or pore space to the total or bulk volume of the rock and is the result of various geological, physical and chemical processes.

Porosity can be classified according to the petrographic fabric, and to the type and degree of interconnection between the individual pores (Schon, 2004). The μ-CT can estimate the total porosity which is related to all the void spaces between the solid components.

The aim of this work was to estimate the total core porosity by microtomography and to correlate them with the gas-adsorption-porosimetry technique. The porosimetry measures the effective porosity related only to those spaces which are connected.

Materials

The estimate of porosity presented in this work refers to core withdrawn from three boreholes called GPR1, GPR2 and GPR3, with 50.9 m, 60.0 m and 50.0 m of depth respectively, located in Resende Basin. This basin belongs to part of the taphrogenic basin group, “The Continental Rift of Southeastern Brazil” (Riccomini, 1989), which joins the geological evolution of the Serra do Mar and the Cenozoic part of the Santos basin, in the continental margin of the Brazilian southeastern region. The boreholes are located in an outcrop at "Ponte dos Arcos" in the Resende basin (Ramos, 2003), in Porto Real, Rio de Janeiro State with coordinates UTM 765.140 NS and 7.681.984 EW (Figure 1). The boreholes were witnessed with material recovery estimate of around 66%.

Resende Formation is characterized by sandstones and fine conglomerates with associated fine siliciclastics, for this reason, it can be a similar model of the petroliferous reservoir. Thirty-six cores taken at different depths and identified five sedimentary facies, four sandstone facies (Acg, Amg, Amf, Amfs) and one silty facies (S). Figure 2 and Figure 3 show the cores plugs for each facies.

Methods

3D High-Resolution X-ray microtomography (μ-CT)

X-ray microtomography system allows us to visualize and measure complete three-dimensional object structures without sample preparation or chemical fixation. The μ-CT is based on the attenuation of X-rays emitted from an X-ray tube which produces a cone X-ray beam in the object area, as can be seen in Equation 1.

The simplest common elements of μ-CT are an X-ray source, an imaginary object through which the X-rays pass, and a detector that measures the extent to which the X-ray signal has been attenuated by the object.

$I = Io\ exp(-\mu x)$ (1)

In Equation 1, I_o is the X-ray incident; I is the X-ray transmitted by the samples; μ is the linear attenuation coefficient of the sample, and x is the sample width. For the measurement, a Skyscan 1172 X-ray computed microtomography was used as seen in Figure 4. All the samples were scanned using a tungsten anode and operating at 100 kV and 100 mA (spot size < 5μm). The samples were analyzed using filter Al+Cu and 10 Mp CCD camera. Total rotation angle was 360^o with rotation step size angle of 0.40^o. A total of 961 μ-CT slices were obtained with spatial resolution of 14.9 μm.

Usually, the porosity es timate is perf ormed using the im age trea tment sof tware CtanR®. The two-dim ensional im age is derived from the treatment of the region of interest (ROI) in the rocks. The image is binarised in grayscale in accordance with the determination of the optimal threshold.

The porosity is estimated from the 3D analysis of the binary image. It is the proportion of the volume of interest occupied by binarised porous sample; e.g., Equation 2, where BV is the volume of the rock matrix and TV is the total volume of the core.

$$\Phi = 1 - \frac{BV}{TV} \qquad (2)$$

Gas adsorption porosimetry

Gas adsorption porosimetry is based on a known volume of gas is isothermally expanded into an unknown porous volume. After the expansion, the result of pressure is measured, and this value depends on the unknown pore volume, which is obtained using Boyle'Law (Vidal, 2006). The porosity of the sample is calculated by Equation 3:

$$\Phi = \frac{\Delta V}{V} \quad (3)$$

Where ΔV is the volume of gas in the sample, or in other words, the volume of pore space in the sample in cm^3 and V is the total sample volume. To obtain the effective porosity, an Ultra-Poro-Perm's ® 500 equipment by Core Laboratories Inc. was used (Figure 5).

During the porosity measurement, the core must be submitted to a minimum pressure of 400 psi and the samples prepared in a 1-inch cylinder. The minimum pressure is required because the space between the core sample and the wall of the rubber cylinder must be eliminated. This procedure avoids the gas passing throughout this region and restricts it only to inside the core sample.

Results and Discussion

The main factors that influenced porosity in analyzed core plugs were degree of selection, compaction, size, and shape of grains. The more angular and rounded the grains were, the more the porosity values decrease. With increased sorting, the porosity values generally increase. When poorly sorted, the spaces between the grains with large diameters are filled with smaller grains. The compaction leads to a decrease in volume and porosity of rocks due to the effects of compression-superimposed materials.

Table 1 shows the porosity values obtained from the core plugs analyzed according to µ-CT and gas absorption porosimetry. µ-CT provides the total porosity for the cores, while the porosimetry measures the effective porosity. The main reason for the differences between porosity values is a result of the interconnected pores. The facies Acg and Amg are extremely friable. There are more partially isolated pores than facies Amfs, Amf, and S. These facies are more consolidated and these kinds of rocks have fewer isolated pores.

µ-CT detected all void spaces between the solid components with sizes lower than 14.9 µm. However, this technique is non-destructive and without sample preparation; this allows for making tests without material loss. This technique keeps the internal characteristics of the cores. The 2D and 3D images of the cores allows us to see the pore distribution, the size, and shape of pores volume. It is possible to see an example in Figure 6.

Conclusions

Porosity data obtained by gas absorption porosimetry and µ-CT have been compared, and it was possible to note the advantage and problems with µ-CT. The µ-CT measures all pore spaces between the solid components while gas absorption porosimetry measures only spaces which are connected. However, µ-CT make tests without sample destruction, it is important because there are rocks, such as the cores plugs analyzed, which are extremely friable, making it difficult to use conventional techniques. The results compared with gas absorption porosimetry showed that this technique is reliable and effective, principally with consolidated rocks, and becomes an important tool in studies of petrophysical parameters (e.g., porosity). The great advantage of µ-CT is the two-dimensional and three-dimensional visualization of the pore-size distribution without material damages. The combination of µ-CT with others techniques allows for the improvement of the quality of results about porosity.

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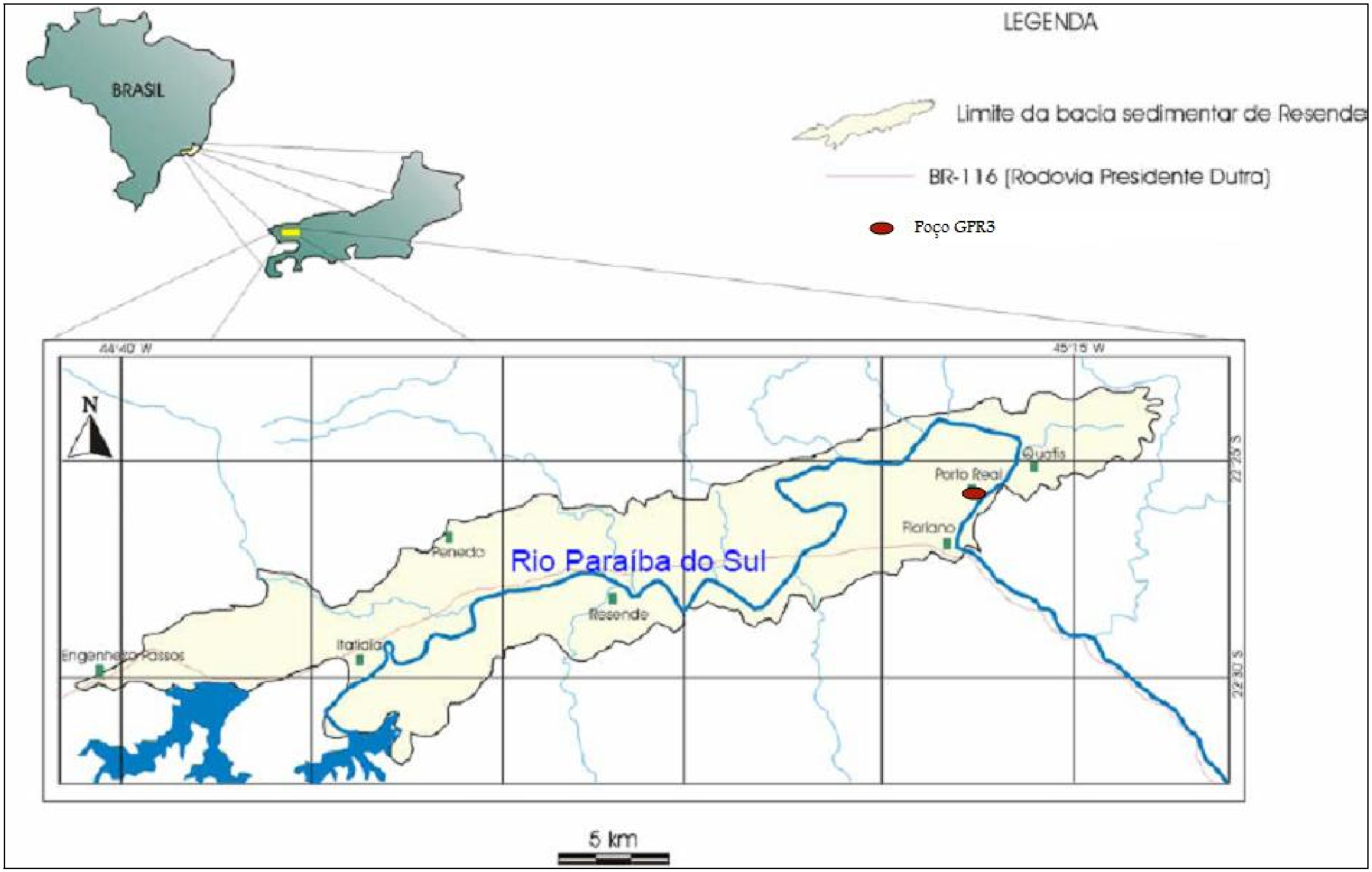

Figure 1. Location map of the Resende basin, middle course of the Paraíba do Sul River, and location in the city of Porto Real, the site of the boreholes GPR1 and GPR3.

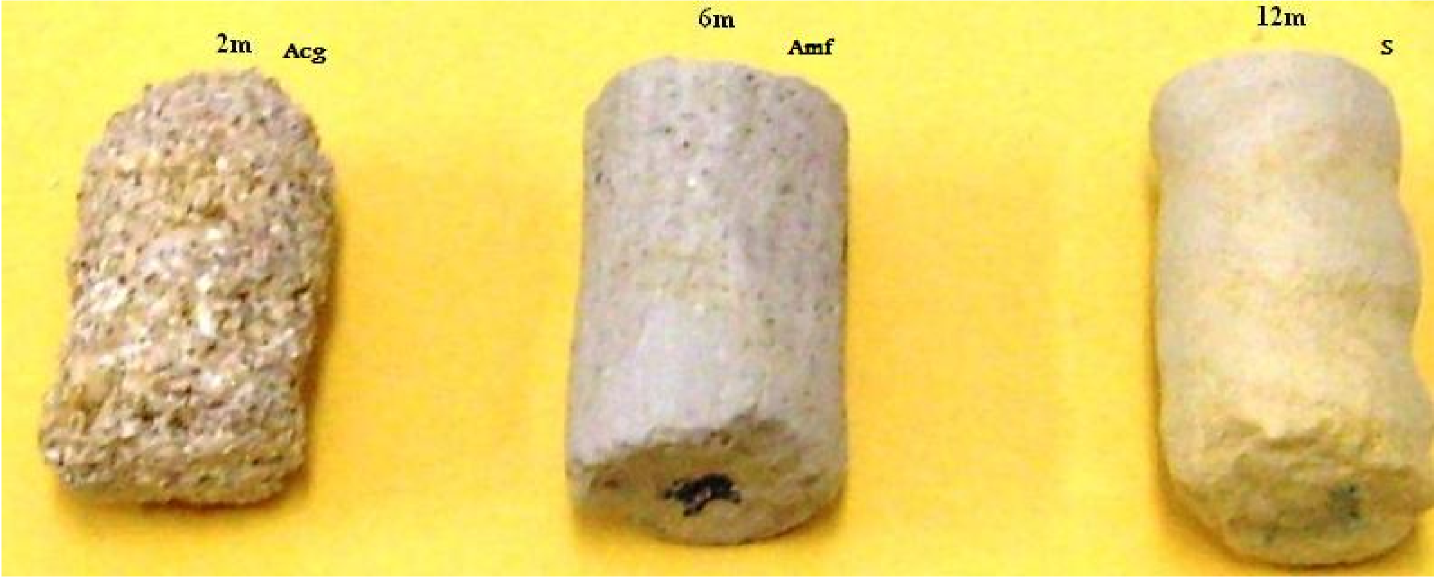

Figure 2. Facies Acg, Amf, and S in the GPR1 borehole.

Figure 3. Facies Amg and Amfs in the GPR3 borehole.

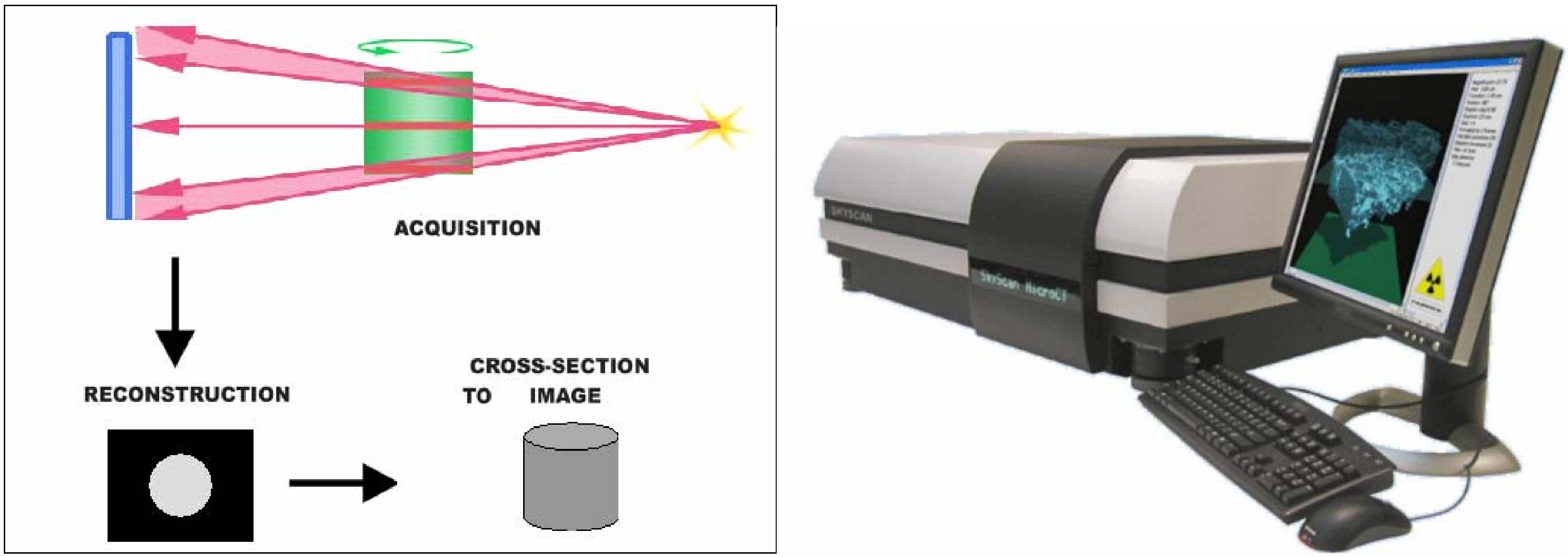

Figure 4. An illustration of the acquisition and reconstruction processes with cross-section to image in μ-CT and Skyscan 1172 X-ray computed microtomography.

Figure 5. Photograph of Ultra-Poro-Perm's ® 500.

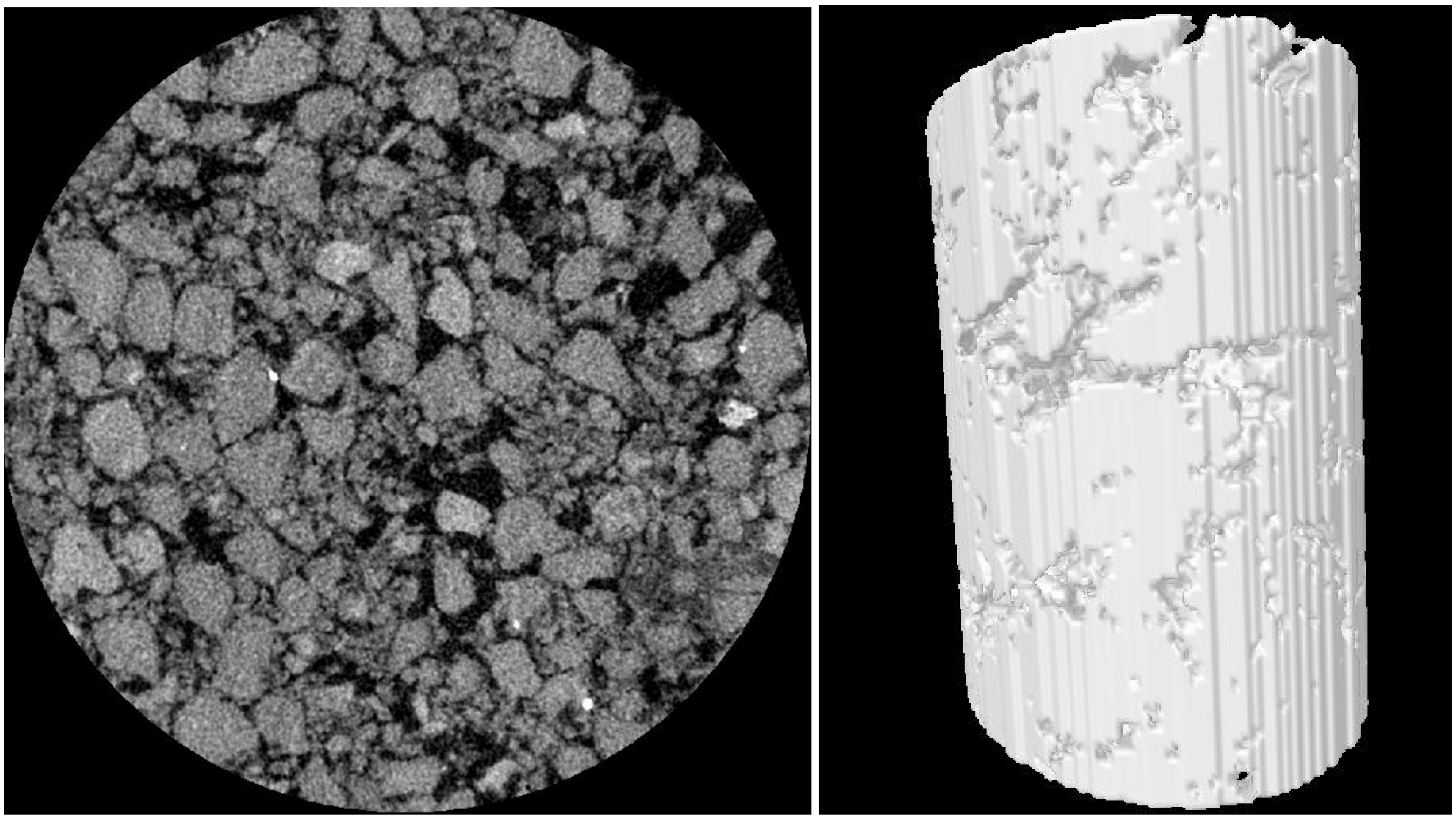

Figure 6. (a) One slice of 2-D μ-CT visualization and (b) 3-D μ-CT image with 14.9 μm resolution at 2 m of depth in the GPR1 borehole.

Facies	**Total porosity [%]** *µ-CT*	**Effective Porosity [%]** *Porosimetry*
Acg	32,6±6,4	27,3±2,6
Amg	31,1±4,2	26,7±7,4
Amfs	33,2±9,6	32,9±7,0
Amf	34,8±5,3	32,1±3,8
S	23,5±0,5	22,8±9,9

Table 1. Porosity values of Resende Formation core plugs.