Evaluation of Microstructural Parameters of Reservoir Rocks of the Guarani Aquifer by Analysis of Images Obtained by X-Ray Microtomography

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Abstract. Microstructural parameters evaluation of porous materials, such as, rocks reservoir (water, petroleum, gas...), it is of great importance for several knowledge areas. In this context, the X-ray microtomography (µ-CT) has been showing a technical one quite useful for the analysis of such rocks (sandstone, limestone and carbonate), object of great interest of the petroleum and water industries, because it facilitates the characterization of important parameters, among them, porosity, permeability, grains or pore size distribution. The X-ray microtomography is a non-destructive method, that besides already facilitating the reuse of the samples analyzed, it also supplies images 2-D and 3-D of the sample. In this work samples of reservoir rock of the Guarani aquifer will be analyzed, given by the company of perforation of wells artesian Blue Water, in the municipal district of Videira, Santa Catarina, Brazil. The acquisition of the microtomographys data of the reservoir rocks was accomplished in a Skyscan 1172 µ-CT scanner, installed in Applied Nuclear Physics Laboratory (LFNA) in the State University of Londrina (UEL), Paraná, Brazil. In this context, this work presents the microstructural characterization of reservoir rock sample of the Guarani aquifer, analyzed for two space resolutions, 2.8 µm and 4.8 µm, where determined average porosity was 28.5 % and 21.9 %, respectively. Besides, we also determined the pore size distribution for both resolutions. Two 3-D images were generated of this sample, one for each space resolution, in which it is possible to visualize the internal structure of the same ones.

1. Introduction
The characterization of the pore space geometry and the determination of microstructural properties of the reservoir rock are extremely important for determining the capacity of a water, oil or gas reservoir. The porous rocks system has a complex geometry, involving aspects of pore shape (morphology) and the pores connection (topology). The macroscopic physical properties of these materials are strongly dependent on their microstructure. The intrinsic permeability, for example, depends on the effective porosity, the distribution of pore size and the interconnection degree between the pores. Thus, the quantitative description of the microstructure of porous materials is of fundamental importance, allowing a better understanding of how the microstructure influences physical phenomena occurring within the material, as well as the numerical determination of their microstructural properties.
The recent development of microtomograph allows characterization of porous materials with a spatial resolution between 0.5 to 5 micrometers using an X-ray tube. It makes possible to have a Synchrotron accelerator results, however, in a conventional laboratory.

The Guarani Aquifer occupies a total area of 1.2 million square kilometers and is located in the central western region of South America, being inserted within the boundaries of four countries, namely: Brazil, Argentina, Paraguay and Uruguay. Within the State of Santa Catarina it occupies an area of approximately 49,200 km². As the average thickness of the aquifer is 228 m, the approximate volume of the aquifer in Santa Catarina is 11,218 km³ [1].

The City of Videira is located on the region of the aquifer. This aquifer is considered one of the largest underground freshwater reservoirs in the world, consisting basically of Botucatu sandstone formation.

The conservation of groundwater is crucial to mankind, due to the increasingly polluted and scarce of surface water present in rivers and lakes, a situation aggravated by deforestation and overuse of pesticides. Becomes therefore of the utmost importance to study the storage capacity of aquifers by population.

In this context, this article quantify the porosity of the rocks that forms the Guarani aquifer through X-ray microtomography, it made possible to estimate the amount of water the aquifer can store, because by determining the porosity of the rock and knowing the total volume of these rocks, it's possible to estimate the amount of water.

2. Material and methods
The X-ray microtomography technique is an inspection method that allows obtaining data from the internal microstructure of materials, as cross sections images from the external irradiation of the samples [2]. This technique requires the use of appropriate software for processing and analysis of images, which enable the determination of important parameters for better understanding of the material analyzed. From the cross sections images of the rocks, holds up a rendering process, obtaining three-dimensional images (3-D) [3,4,5]. These images are originally used for the characterization of properties such as pore and grains size distribution, specific surface area and connectivity of the pore system, effective porosity and permeability. An illustrative diagram of the acquisition, reconstruction and generation of image and 3-D models is shown in Figure 1.

![Illustrative diagram of the acquisition, reconstruction and generation of image and three-dimensional models.](image-url)
Furthermore, the 3-D images are used directly in numerical simulations of physical phenomena of equilibrium and transport of fluids, to determine their microstructural properties. In this procedure, fundamental physical laws are applied in the pore scale. This technique aims to characterize the geometry of the pore system and the determination of some microstructural properties.

2.1. Equipment used
For these results, a Skyscan microtomograph model 1172 was used, at the Applied Nuclear Physics Laboratory (LFNA), in the State University of Londrina (UEL), in the state of Paraná, Brazil. The microtomography images were reconstructed by NRecon software. The porosity and pore size distribution were obtained by Imago, developed by the Laboratory of Porous Media and Thermophysical Properties of Materials (LMPT) of the Department of Mechanical Engineering of the Federal University of Santa Catarina, Florianópolis, SC, in association with the Brazilian software company ESSS (Engineering Simulation and Scientific software). Figure 2 shows a picture of microtomograph Skyscan 1172.

![Skyscan 1172](image)

**Figure 2.** Skyscan 1171, X-ray source 20-100 kV, maximum power of 10 W.

The X-ray tube has a maximum power of 10 W. For this application the voltage used was 80 kV and a current of 124 μA. The sample was placed between the X-ray tube and a CCD camera of 2000 x 1048 pixels at a distance of 5.9 cm from the tube and 15.1 cm from the CCD.

2.2. Analyzed samples
The samples used were sandstones of the Botucatu formation, from two wells drilled in the region of Videira – SC, with UTM coordinates of 0551412, 7022236 for depth of 250 meters and the coordinates of 0487041, 7013997 for depth of 400 meters. The sample of sandstone collected at depth 250 m (sandstone250) has dimensions of 4 x 5 x 10 mm and the sample collected at depth of 400 m (sandstone400) has dimensions of 6 x 6 x 14 mm. The samples were rotated from 0° to 180°, with angular steps of 0.25°, totaling 1442 projections. These projections were reconstructed by NRecon software, resulting in 900 two-dimensional images for each sample. To acquire these data was used an Aluminum filter of 1 mm thick, to minimize the beam hardening effect in the sample [6].
2.3. Images processing

Figure 3 shows two longitudinal projections of the sample, 0 and 180 degrees, formed on the CCD camera. These projections are reconstructed by NRecon software using a cone beam reconstruction algorithm [7], resulting in 2-D images of the cross sections of the sample, in grayscale, as can be seen in figures 4a and 5a. After the generation of 2-D images, they are analyzed by Imago software, which is defined a region of interest (ROI) and held the binarization, transforming the image into black and white, where black represents the solid phase and white the porous layer, as can be seen in figures 4b and 5b. These images have a spatial resolution of 4.8 µm.

Figure 3. Projections of the Botucatu formation sample - sandstone400. (a) Image obtained at 0° position; (b) image obtained at position 180°.

With 2-D images was also possible to reconstruct a 3-D image, where the CTAN software was used to reconstruct the solid phase (figure 6a and 7a) and the porous phase (figure 6b and 7b) of the sandstone250 and of sandstone400 samples, respectively.
Figure 5. Images of sandstone400 rebuilt by NRecon software; (a) 2-D image in grayscale; (b) 2-D image binarized, black represents the solid phase and the white porous phase.

Figure 6. 3-D reconstructed volume the sandstone250; (a) solid phase reconstructed; (b) porous phase reconstructed.

Figure 7 - 3-D reconstructed volume of sandstone400; (a) solid phase reconstructed; (b) Porous phase reconstructed.
3. Discussion and results
The porosity of the samples sandstone250 and sandstone400 obtained by Imago software for each 2-D section, are shown in the graph of figures 8 and 9, respectively, where the black lines indicate the average porosity (18.8 ± 0.6 % and 20.8 ± 0.7 %, respectively) and the red bars indicate the statistical deviation of ± 3.2 % for each section, with 95 % of confidence.

One of the advantages of microtomography methodology is the generation of 3-D images, which beyond the images presented in this article; several were generated for visualization, where the internal navigation in the samples was possible, through specific software, which allowed monitoring/mapping porous network in greater detail. It’s not enough the rocks have porosity; it is necessary that their pores are interconnected and allow the water to drain.

![Figure 8](image1.png)

**Figure 8.** Porosity of 900 sections 2-D to the sample of sandstone to a depth of 250 meters and spatial resolution of 4.8 μm.

![Figure 9](image2.png)

**Figure 9.** Porosity of 900 sections 2-D sample of sandstone to a depth of 400 meters and spatial resolution of 4.8 μm.
4. Conclusions
After analyzing the results was possible to verify that the average porosity of these rocks ranged between 18.8 and 20.8 %. As the volume of the aquifer is estimated at 272,460 km³ may suggest a volume of stored water in the range of 51,222 to 56,671 km³. However it is important to observe that this study examined only rocks of two wells, so these results should be ratified by analyzing more samples, so will be possible to have a more accurate conclusion as to the porosity of these rocks, and also its storage capacity.

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References
[1] Rosa Filho E F 2003 Sistema aquífero guarani – considerações preliminares sobre a influência do arco de ponta grossa no fluxo das águas subterrânea. Rev. Águas Subterrâneas, 17 91–112.
[2] Appoloni C R, Fernandes C P, Innocentini M D M and Macedo A 2004 Ceramic foams porous microstructure characterization by X-ray microtomography Mater. Res. 7 n. 4, 557-64.
[3] Appoloni C R, Macedo A, Fernandes C P and Philippi P C 2002 Caracterização de Microestruturas Porosas por Microtomografia de Raios XVII Seminário Latino Americano de Análises por Técnicas de Raios X (Brazil: São Pedro, SP) pp 419-24.
[4] Appoloni C R, Rodrigues C R O and Fernandes C P 2005 Reservoir Sandstone Porous Microstructure Characterization By High-Resolution X-Ray Microtomography 19th Int. Symp. of the Society of Core Analysts (Toronto) pp 21-25.
[5] Appoloni C R, Fernandes C P and Rodrigues C R O 2007 X-ray microtomography study of a sandstone reservoir rock Nucl. Instrum. Meth. A 580, Issue 1, 629-32.
[6] Ketcham R A and Carlson W D 2001 Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences Comput. Geosci. 27 381–400.
[7] Feldkamp L A et al 1984 Practical cone-beam algorithm J. Opt. Soc. Am. 1 612-19.