Stromatolite Investigation by 3D X-ray Microtomography

Inayá Lima, Nuclear Instrumentation Laboratory – PEN/COPPE/UFRJ
Leonardo Malouf, Sedimentary Geology Laboratory – IGEO/UFRJ
Leonargo Borghi, Sedimentary Geology Laboratory – IGEO/UFRJ
Ricardo Lopes, Nuclear Instrumentation Laboratory – PEN/COPPE/UFRJ

This paper was prepared for presentation during the 12th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 15-18, 2011.

Abstract

The knowledge of internal structure and pore space 3D distribution of stromatolites are fundamental in order to understand the petrophysical properties, which are very important in oilfield behavior. The X-ray Imaging development such as 3D X-ray Microtomography provides the ability to characterized complex objects with excellent 2D and 3D high spatial resolution on the order of microns. This paper provides a brief reservoir rock application of the possibilities offered by 3D x-ray microtomography.

Introduction

Stromatolites are layered structures formed in shallow waters, in most cases in hypersaline environments where other animals usually cannot survive. They are formed by trapping or binding and cementation of sedimentary grains by biofilms of microorganisms called microbial mats. These microbial mats are one of the oldest ecosystems on the planet and are formed from the oldest kinds of unicellular microbes, each of these have their own specific function.

The most commons organisms founded in the mats are the cyanobacteria, fermenters, sulfate reducers and sulfur oxides, the repeated life cycle of these bacterial community form the stromatolite layered structure. In order to understand the process of stromatolite genesis it is necessary to comprehend better the metabolic functions of the most important microbial group in the doormats, the Cyanobacteria. These primitive cells have the ability to store substances they need to maintain their vital functions in their external cellular wall, in association with the ability of secreting a polymeric extracellular material these bacteria tend to precipitate and trap calcium carbonate and even other minerals, thus, the mineralization occurs and the rock starts to grow, layer after layer (Riding, 2000).

Although stromatolites were the most abundant life form on earth for nearly 2 billion years, modern stromatolites are very difficult to find and tend to grow only in very specific environments, such as hypersaline lakes and marine lagoons. They are unable to grow in acid environments because the calcium carbonate dissolute and the structures start to suffer chemical erosion.

Because of this complex process of genesis, the stromatolites tend to have a very complex porous space, moreover, their primary porosity is almost irrelevant and the secondary porosity is due to bioerosion or dissolution, processes that are really hard to predict.

This subject is quite important because in the past few years it was discovered one great oilfield in Brazil, which is called pre-salt. This expression is because it forms a rock interval that ranges under an extensive layer of salt. The pre-salt reservoir facies is reported to consist predominantly of microbialites of either stromatolites precipitating in a lacustrine setting or travertine (Toledo et al, 2009).

Stromatolities reservoir properties depend strongly on their pore space geometry, which is a very complex media. Traditional manual point counting, used for describing pores in thin sections, is tedious, time consuming, and too imprecise to solve many problems that involve reservoir studies. Pore space must be defined and classified in terms of rock fabrics and petrophysical properties in order to integrate geological and engineering information.

Over the past few years, traditional reservoir characterizations have advanced into multidisciplinary processes in order to development accurate reservoir description (Sutton, 2008; Rosenberg, 1999).

With the advance of X-ray imaging technique the 3D X-ray microtomography (µCT) becomes one of the great practices used in geological field. The data contained in µCT refers to the amount of X-ray attenuation factors and it is related to the sample density, according to the Beer's law for monochromatic x-ray beam through a homogeneous material:

$$I = I_o \exp(-\mu x)$$

In the equation, I and I_o are the final and initial x-ray intensity, μ is the material's linear attenuation coefficient and x is the length of the x-ray path.

If a polychromatic source is used, the equation becomes a little different because the relation between the attenuation coefficient and the x-ray energy.

$$I = \int I_o(E)exp\left[\sum_i (-\mu_i(E)x_i\right]dE$$

µCT allows non-destructive imaging of internal structures and is very helpful in order to study pores space. It is a representation of 3D structure as a series of 2D images recorded for different angular positions of the rock, which is, rotates around an axis perpendicular to the radiation beam (Fig. 1).

In this context, to scan the sample, it must be placed between the source and the detector. As the beam passes through the object, the lower energy photons are preferentially absorbed. X-rays emitted from the source are attenuated through scattering or absorption before being recorded by the detector, which records a larger series of radiographies as the sample rotates incrementally on this stage. µCT algorithms are applied to these data to reconstruct the internal structure of the sample and preserve its scale in three dimensions.

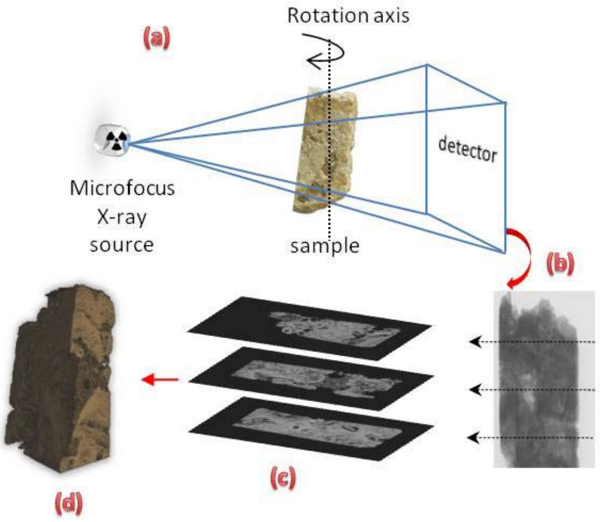

Fig.1 - *µCT principle: (a) scan process (image acquisition), (b) example of one radiogram, (c) reconstruction process (example of three 2D µCT images), (d) 3D µCT generated image.*

This work intend to improve the knowledge about stromatolities in order to provide the necessary tools to understand the porous space of the rock and make it possible to determine, for a microbialite reservoir with similar features, the flow pattern inside of it. Herein, we report a preliminary characterization of the internal microstructure from stromatolites collected from a coastal laggon (Lagoa Salgada), Brazil through µCT.

Method

"Lagoa Salgada'' is a hypersaline lagoon that occupies an area of about 16 km^2 near the coastal town of Cape of São Tomé on ''São João da Barra'' county, on the north coast of Rio de Janeiro state (Brazil) (Silva e Silva, et al, 2007). It is a unique occurrence of recent columnar carbonate stromatolites of whole of Brazil. It is situated on the terrestrial part of Campos's basin and its geological history is associated with the fluctuations of the sea level of the Late Quaternary and the formation of the delta of Paraiba Do Sul River (Iespa et al, 2008). At that place it is possible to find five predominant microfacies on local microbialites, which correspond to different phases of the growing structure (Silva e Siva et al, 2005). In order to study stromatolites microestructure, were selected 2 samples that are shown in Fig. 2.

Fig.2 - *Photography of one stromatolite sample used in the µCT scan.*

It was used an X-ray microfocus source and a flat panel detector in order to scan rock plugs. The system uses a stable 8W source with spot size smaller than 6 µm, which allows investigating rock samples in detail. It was used 120 kV at 61 µmA with 1.0 mm Al filter in combination of 0.5 mm Cu filter in order to cut off the lower energy part of the X-ray spectrum and reducing beam hardening artifacts. As the beam passes through the object, the lower energy photons are preferentially absorbed.

The X-ray sensor was set to the highest resolution (2240 x 2240 pixels) with 18 µm pixel size. It was also used a frame averaging of 5, a rotation step of 0.5^o and the sample was rotated over 180^o. The reconstruction procedure was performed based on Feldkamp's algorithm (Feldkamp et al, 1984) using asymmetrical boxcar smoothing kernel filter (order equal to 3) and a beam hardening correction of 35 % which is based on the second order polynomial function. Transaxial reconstruction formed by combining many of these slices is shown in Fig.1c and a series of 2D images can be used to construct 3D image (Fig. 1d).

Results

Fig. 3 shows examples of coronal, transaxial and sagittal views of one stromatolite µCT scan. These images show the reliability of the reconstruction data and it can be notice some porosity, which are very low, are clearly visible (black pixels inside the images).

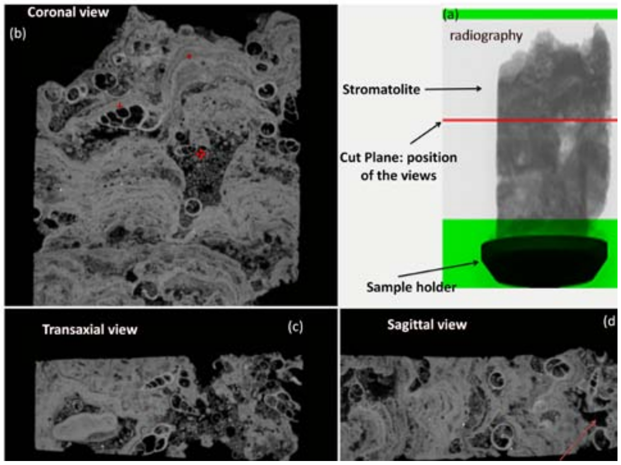

Fig.3 - *Stromatolite µCT views: (a) radiography image, (b-d) cut planes views, (*) carbonate matrix, (+) foraminifers (⁘) trapped grains.*

The tomographic image of the rock scanned with a resolution of 18 µm, shows a high concentration of carbonate matrix accompanied by some trapped grains along some parts of its interior, which appears together with certain density material. It is important to observe that lighter features represent higher CT values signifying different mineralogy or different amounts of microporosity. It is possible to notice foraminifero calcareous multilocular with shell ornamentation and some grains of higher density mineral (silica, for example).

Filamentous bacteria living in an alkaline and hypersaline environment can produced a well-defined calcite laminated structures which present different thickness, are clearly visualized by µCT imaging. It is also possible to see some trapping grains, which suggests that the growth surface was covered by the occurrence of extracellular polymeric secretions that are produced by cyanobacteria.

Fig.4 shows all the quantified volumes, which are the total volume of the volume of interest (VOI) (TV) and the total volume of all binarised pores within each discreet 3D object (OV). The total porosity that appears in the image is the volume of all open plus closed pores as a percentage of the VOI. PV and P represent the total volume of pore space and total porosity respectively. The 3D measurements are based on the marching cubes volume model, which creates triangle models of constant density surfaces from 3D data (Lorense et al, 1987).

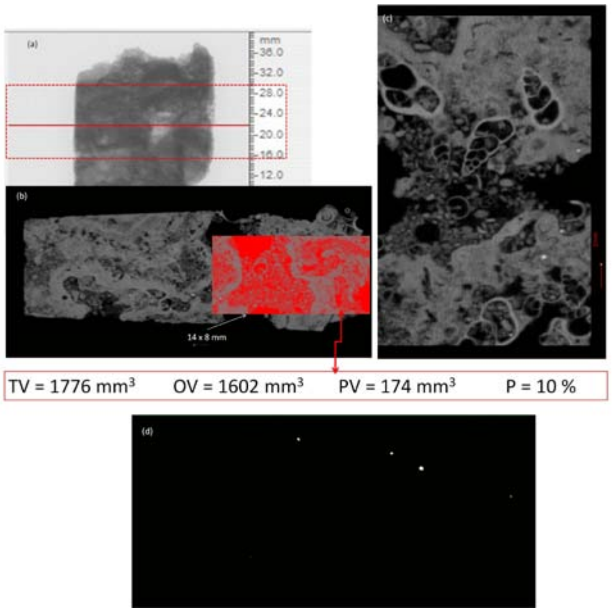

Fig.4 - *Detail of the quantified region of interest (ROI): (a) radiography and the ROI, (b) Geometry, dimensions and position of the ROI, (c) example of ROI cross-section, (d) binarised example of the same ROI cross-section (it shows only the density particles).*

Fig.5 shows external 3D stromatolite structure.

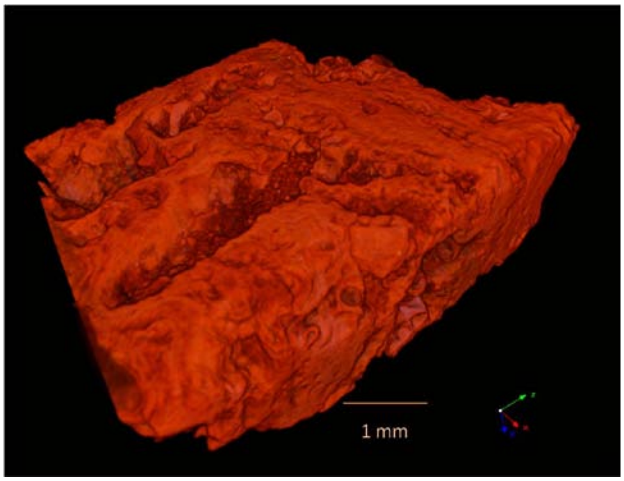

Fig. 5 - *3D visualization of stromatolite microstructure.*

It is possible to performance density line profile, longitudinal image cut through the dataset and maximum intensity projection (MIP) image generation from different angles. Fig.6 shows one MIP image in which a grey level profile along the red line that appears on the cross-section image is drawn. In each column of voxels orthogonal to the selected plane, the highest density value found is assigned to that position in the generated image. MIP images can visualize dense structures (white pixels) surrounded by lower density medium.

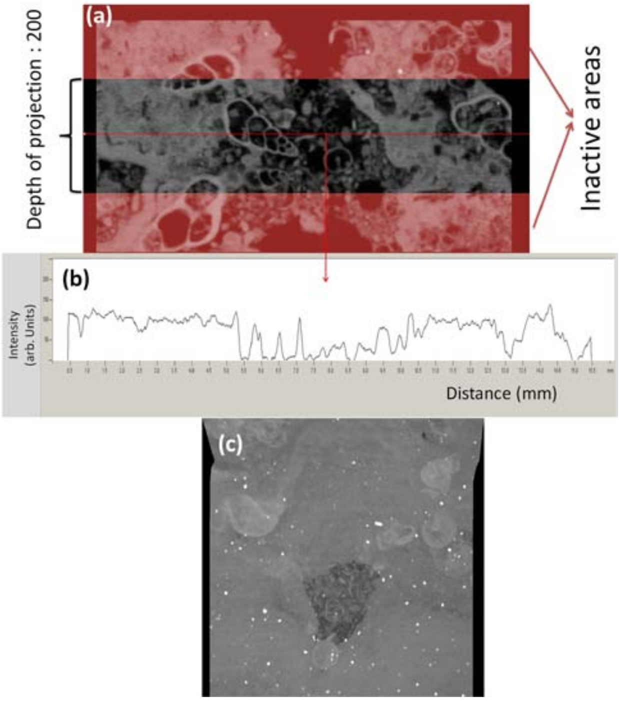

Fig.6 – *MIP image: (a) stromalolite µCT cross-section which shows the inactive area and the depth of projections used to produce the MIP image, (b) Profile of the red line, (c) MIP image (X plane, along profile, horizontal).*

The major advantage of µCT is the capability to examine the interior of the structure (Figs. 7-8), which can allow understanding the information of the pore and mineralogical spaces. Differences in X-ray attenuation throughout the sample indicate changes in density caused by porosity and various mineral constituents of the rock. Once mapped, these characteristics can be isolated for further inquiry this detailed analysis of rock space can reveal important signs to future performance of a reservoir.

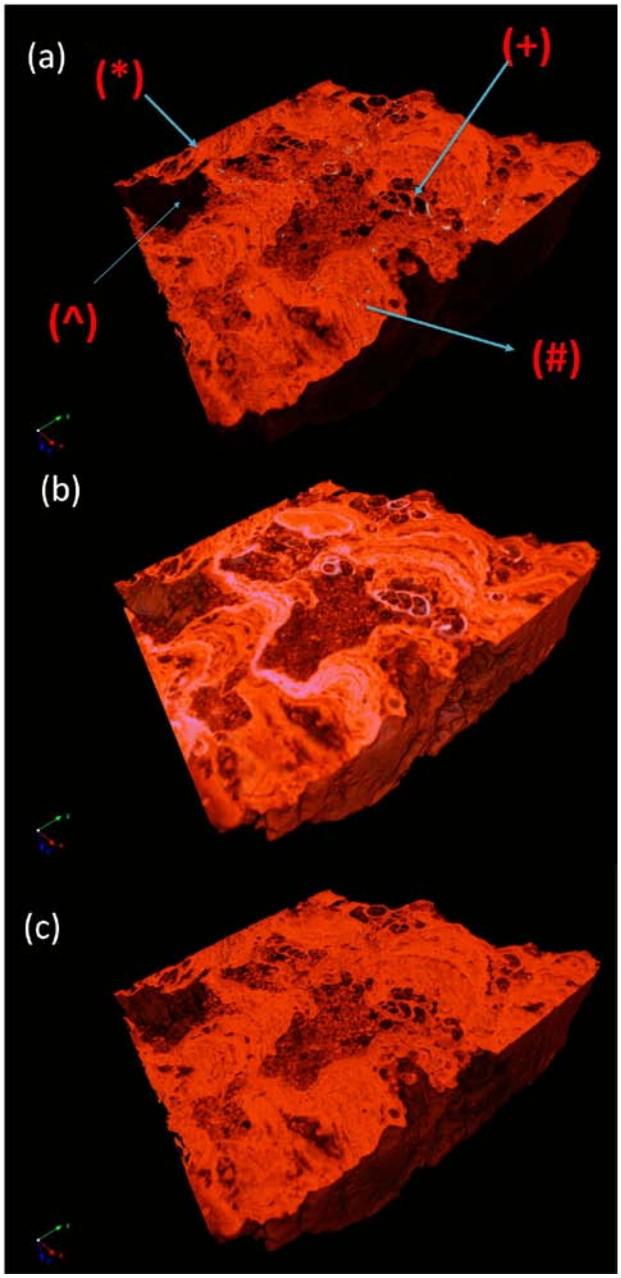

Fig.7 - *Details of the 3D visualization of stromatolite microstructure: (#) density grains particles, (+) foraminifers calcareous multilocular with shell ornamentation, (*) carbonate matrix and (^) pores.*

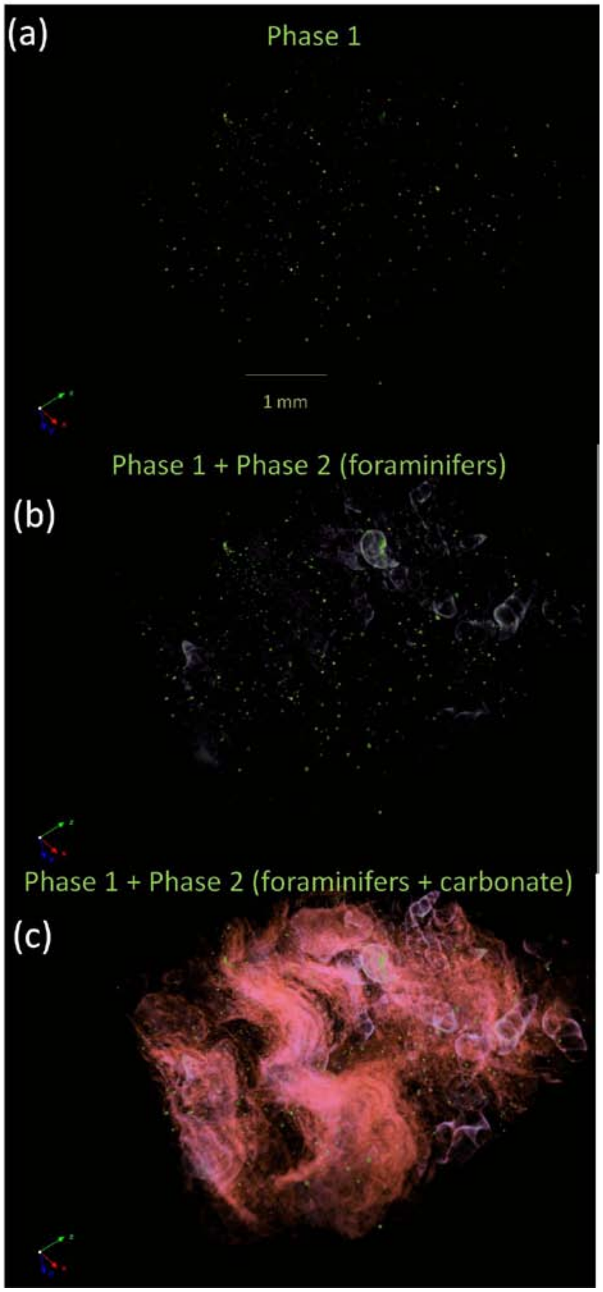

Fig.8 – *Detail of the 3D visualization of stromatolite microstructure: (a) density grains particles, (b) density grains particles plus foraminifers calcareous multilocular with shell ornamentation, (c) density grains particles plus foraminifers calcareous multilocular with shell ornamentation and carbonate matrix.*

Conclusions

3D X-ray Microtomography provides high spatial resolutions information crucial to understanding stromatolities internal structures. It was possible to demonstrate the power of this technique in order to investigate heterogeneities in this reservoir analogous which can help to solve many problems in oilfield studies.

Acknowledgments

This work was partially supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), FAPERJ (Fundação de Amparo à Pesquisa do Rio de Janeiro).

References

Riding, R., 2000, Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. *Sedimentology*, 47 (1), 179-214.

Toledo, M., Barth, O., Silva, C, Barros, M., 2009. Testing multivariate analysis in paleoenvironmental reconstructions using pollen records from Lagoa Salgada, NE Rio de Janeiro State, Brazil. An Acad Bras Cienc, 81, 757-768.

Sutton, M., 2008. Tomographic techniques for the study of exceptionally preserved fossils. Proc. R. Soc. B, 275, 1587-1593.

Rosenberg, E., Ferreira De Paiva, R., Guéroult, P., Lynch, J., 1999. Microtomography applications in rock analysis and related fields. DGZfP-Proceedings BB 67-CD, 9-18.

Silva e Silva, I., Rivastava, N., Iespa, A., Iespa, C., 2007. Evidência de oncóides recentes na lagoa salgada, norte do estado do rio de janeiro, sudeste brasileiro. *Revista UnG – Geociências*, 6(1), 201-206.

Iespa A., Iespa, C., Borghi, L., 2008. Microestratigrafia do Complexo Estromatólito, Trombólito e Oncoide Holocênico da Lagoa Salgada, Estado do Rio de Janeiro, Brasil. *Revista de Geologia*, 22, 7-14.

Silva e Silva, L., Iespa, Anderson, Damazio, C., Carvalhal, S., Alves, S., 2005. Confronto entre estruturas estromatolíticas domais (composição cianobacteriana) das lagoas Pernambuco e Salgada, Brasil. *Revista de Geologia*, 18, 159 – 164.

Feldkamp, L. A., Davis, L. C., Kress, J. W., 1984. Practical cone beam algorithm. *J. Opt. Soc. Am. A*, 1, 612–619.

Lorensen, W. E. , Cline, H. E., 1987. Marching cubes: a high resolution 3D surface construction algorithm. *Computer graphics*, 21 (4), 163-169.