Porosity and Permeability upscaling in a Lagoa Salgada Stromatolite and Codó Formation Stromatolite

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Abstract

There is a shortage of petrophysical studies in microbialite facies and more importantly, the absence of these studies has created confusion over how industry and researchers should approach sampling these kinds of reservoirs. This work sought to define petrophysical properties in a Lagoa Salgada (Holocene) and Codó formation (Aptian) stromatolite by way of investigating petrophysical properties from each growth structure. Primary computations presented in this paper include porosity and permeability on sub samples imaged at multiple scales with a micro computed tomography (CT) scanner to attain the adequate Representative Elemental Volume (REV). Computations of porosity and permeability were performed at the pore scale and upscaled to the growth structures and finally to the whole stromatolite. Calculation of porosity and permeability trends revealed that sub sampling growth structures is not the most efficient way to investigate petrophysical properties, but a refined approach would precisely target different segmented CT phases. It also revealed how important REV and location are when extracting MICP samples in highly heterogeneous reservoirs.

Introduction

Lacustrine Stromatolites along with Travertines in offshore Brazil have received a lot of industry and research attention, but what is principally lacking from the body of knowledge is a petrophysical characterization that can serve as a guide for a petro-seismic distinction of similar pre-salt rock elsewhere in the reservoir Rasmussen et al. (2011).

This work sought to define petrophysical properties, namely porosity and permeability, associated with the growth structures of a 'modern' Lagoa Salgada stromatolite and then related these to the petrophysical properties from the growth structures of an 'ancient' Codó formation stromatolite rock sample. This objective was achieved by delineating the boundaries of growth structures contained within the stromatolites first (Figure 1b) and then targeting multiple sub samples in each growth structure (Figure 1c), precisely at locations relating to different segmented phases (Figure 2b). The true REV of each sub sample was determined with a Digital Rock Physics (DRP) multi-scale imaging approach and computed petrophysical properties were then upscaled to the growth structures and lastly to the whole stromatolite.

Lagoa Salgada (Holocene) and Codó formation (Aptian) in Brazil were chosen because they represent a modern and ancient analogue respectively, to the Brazilian pre-salt Silva and Silva et al. (2004); Bahniuk et al. (2013).

The Lagoa Salgada is located in the terrestrial part of the Campos basin, northern coast of Rio de Janeiro and is a shallow water hyper-saline lacustrine environment. It is a member of the deltaic river complex, Paraíba do Sul. Its formation, according to Martin et al. (1993), took place after a phase of erosion of the coastal plain of the Rio Paraiba do Sul and during rising sea levels between 3,600-3,900 years ago. During this time, the Lagoa Salgada transitioned from a marine to a lagoonal environment. This was confirmed by an analysis of foraminifera (Rodrigues et al. 1981). The microbialites formed only on the west side of the lagoon Silva e Silva *et al.*, (2007), where low slope angle and relatively higher energy supported the microbiological activity.

The Aptian deposits corresponding to the Codó Formation in the Parnaíba basin Pazet al. (2006) in the north east of Brazil are of interest due to their economic production of gypsum and because they are the best outcropping record of the early stages of the opening of the Equatorial Atlantic Ocean Bahniuk et al. (2013). This flat lying stromatolite biostrom is formed in marginal saline pans or lakes and mudflats that consist of a variety of shallow water to subaerially exposed facies including massive pelite with pedogenetic features, fenestral calcarenite, ostracodal wackestone to packstone, pisoidal packstone, gipsarenite, tufa, rhythmite of limestone, argillite, and microbial mats. There is an underlying basement of basalt that is faulted and is surrounded by nearby volcanics Rossetti et al. (2004).

Method

To quantify porosity and permeability in these stromatolites, each one had physical sub samples selected and removed from each of the growth structures (Figure 1).Multi scale imaging, through the use of high resolution X-ray Computed Tomography (CT) was done to specify the resolution and dimensions of the REVs used for porosity and permeability calculations.

Understanding how to sub sample stromatolites and how do define the correct REV for a given technology or computation was the first step to understanding how these types of reservoirs produce. Sampling them in the presence of a matrix and underlying and overlying facies is a natural next step.

CT technology outputs volumetric data to be quantitatively analyzed for a determination of the dimensions associated with the REV. This analysis utilizes the multi-scale Digital Rock Physics (DRP) approach Dvorkin et al. (2008, 2009); Grader et al(2010); Sharp et al., (2009); Toelke et al. (2008); . With this approach it becomes possible to determine with confidence how much material is needed for the kind of technology or petrophysical property measurement required for characterizing the particular reservoir or rock type.

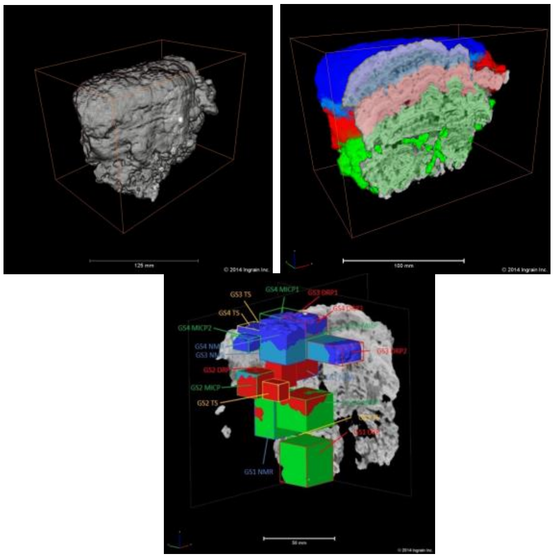


Figure 1: (A) Greyscale surface rendering of the Lagoa Salgada Stromatolite imaged at a resolution of 0.250mm per voxel. (B) Locations of the growth structures. (C) Grey scale YZ "slice" from the volume and the exact locations for sub samples used in multi-scale imaging.

Following the sub sampling program, multi scale imaging and determination of the REV's dimensions; the resultant REV's greyscale of the pore space and framework were then binarized (Figure 2). Horizontal and vertical permeability calculations were calculated on all of the subsamples. Permeability was derived by solving Brinkman-extended Darcy equations for multi-scale Stokes and Darcy flows using the lattice Boltzmann approach Dvorkin et al. (2008, 2009); Grader et al(2010); Sharp et al., (2009); Toelke et al. (2008);

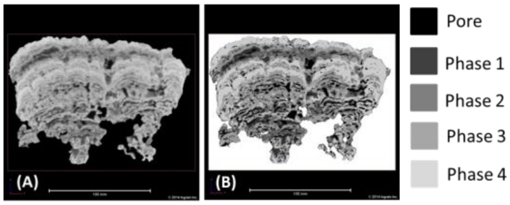


Figure 2: (A) is a greyscale XY "slice" through the entire volume of the Lagoa Salgada Stromatolite. (B) Is a segmented "slice" through the volume that has binarized the greyscale into CT Phases: 0 (pores) and 1-4 (framework).

Porosity and permeability sub sample trend analysis follows Sungkorn et al. (2014) general workflow and it operates by interrogating the starting volume to extract the building blocks that are defined by varying sizes and locations. Each building block will have a porosity and permeability calculation computed yielding a trend (Figure 4). Khalili et al. (2012) also discusses the approach.

Results

The results of this approach produced 10 sub sample REVs for the Lagoa Salgada, modern Stromatolite analogue and also for the Codó formation Stromatolite, ancient analogue.

The sub sample results for porosity and permeability (Figure 3a and b) demonstrate that if they are grouped according to their growth structure then it is hard to observe any trends or relationships. However, if grouped according to the phases, as defined based on their respective segmented greyscale phase from the whole stromatolite (figure 2 above), then the relationship is more apparent (Figure 3c and 3d).

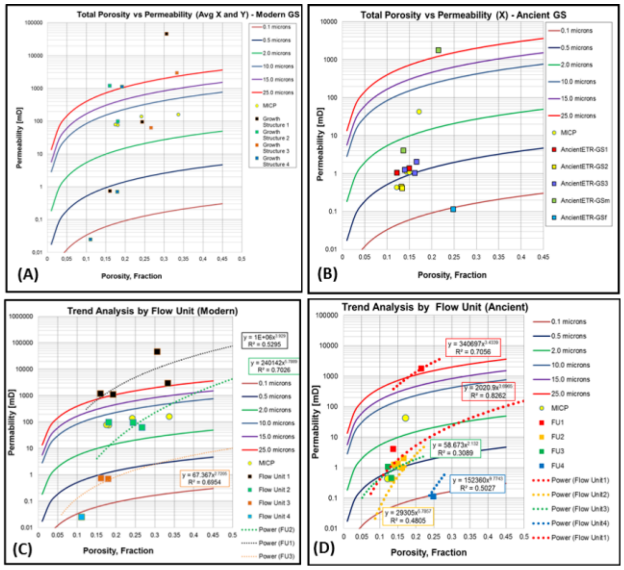


Figure 3:(A & B) Semi-log plots of totalporosity versus permeability relationships in the modern and ancient stromatolite respectively, do not follow a pattern if they are color coded based on growth structure. (C & D) demonstrates that color coding based on phases yield more distinct patterns.

In addition to these single deterministic points representing porosity and permeability for each sub sample, every sub sample had a porosity and permeability trend calculated. These trends further help to demonstrate that sub samples should target phases and not growth structures when investigating petrophysical properties (Figure 4).

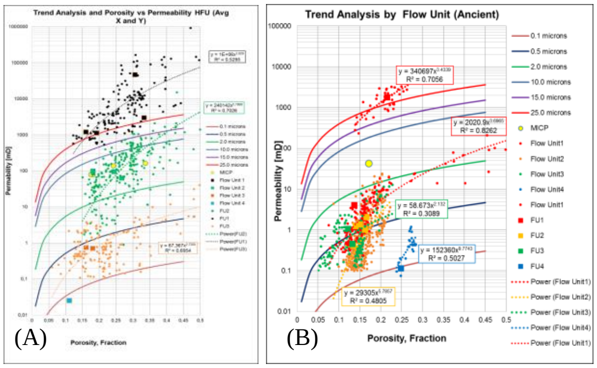


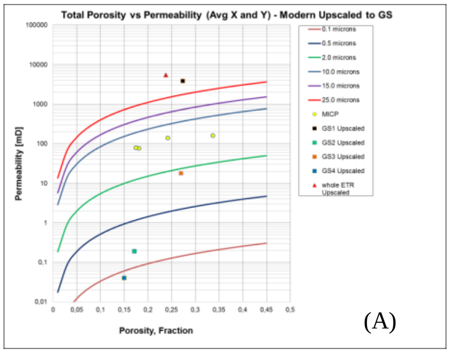
Figure 4: Each sub sample is digitally subdivided into many smaller cubes at varying sizes and locations from within the original volume to yield a porosity and permeability trend.

Mercury Injection Capillary Pressure (MICP) Sneider, et al. (2008) was done on each growth structure from both stromatolites to have a physical test for benchmarking the digital sub samples and upscaling.

Upscaling of the individual sub sample calculations to its respective growth structure and then to the whole stromatolite was done also using Lattice Boltzman. The final permeability's are a function of the volume fractions of segmented phases and their spatial distributions within the sample.

The results illustrate that if flowing horizontally through the stromatolite and that the most permeable phases that are in the growth structures are in pressure communication from one axis to the other, then the permeability of the growth structures will be controlled by the most permeable phases (Figure 5a). In this case, growth structure 1 from the modern stromatolite controls the horizontal permeability, as can be observed based on how close the result is to the whole stromatolite's upscaled permeability. Figure 6 shows that the volume fractions of the two most permeable phases and open pores in growth structure 1, when compared to the phases in the whole stromatolite correlate closely, which in part validates this statement.

If the upscaled growth structures do not have a good match l with the MICP, which serves as a bench mark for quality control, then it means that either (a) the volume fractions of each phase are not relatively equal between the MICP and the upscaled growth structure or (b), the spatial distributions of each phase in the MICP and the upscaled growth structure are sufficiently heterogeneous to create a porosity and permeability discrepancy, or (c) the permeability on the DRP sample or MICP sample itself was not an REV. The REV for permeability in growth structure 1 was larger than the sample used for MICP and is a common conundrum faced in microbialite reservoirs. The upscaled growth structure 2 and 3 permeability calculations are less than the MICP samples (Figure 5a) because the volumes used for upscaling are much larger than the volumes used for MICP and because there is less volume fraction of the permeable phases controlling the permeability (Figure 7.). The GS4 MICP sample included a large portion of GS3 and is not a fair comparison to draw any conclusions.



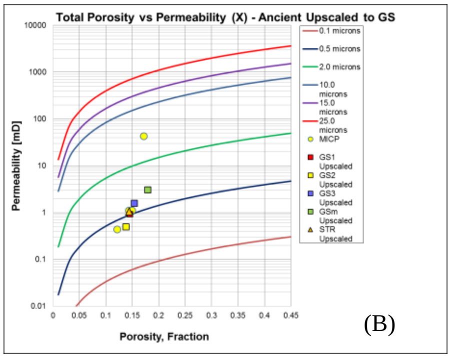


Figure 5: Upscaling sub samples to growth structures and then to the whole stromatolite identifies which part of the stromatolite is most relevant for understanding permeability.

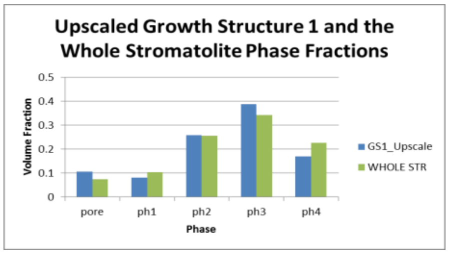


Figure 6: Similar phase fractions and spatial distributions allowed for similar permeability measurements.

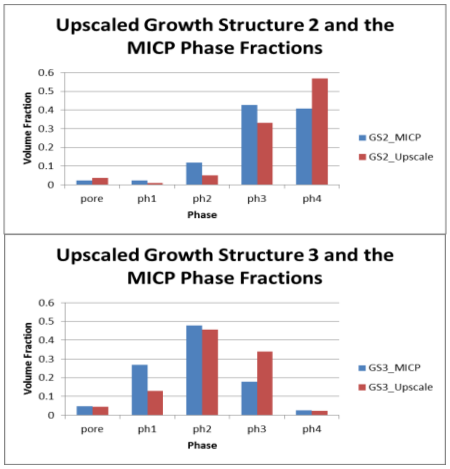


Figure 7. Permeability of both growth structures are controlled by phase 1 and 2 because open pores are isolated at this scale.

In the ancient Stromatolite, the high MICP permeability in GSM compared to the upscaled growth structure is due to the small sample volume used for the MICP which over characterized the largest pore throats from that growth structure (Figure 5b). The rest of the calculations are within a tolerable level of error.

Conclusions

Growth structures do represent different growth architecture and in some cases pore fabric in these stromatolites, but are not necessarily controlling porosity and permeability relationships. In conclusion, when investigating for petrophysical properties in stromatolites, sub sampling every growth structure is not necessary. A recommended approach would involve selecting sub samples at locations representing different rock fabrics as identified by the 3D digital binarized images.

This strategy of sampling and this approach to calculating porosity and permeability could be used in conjunction with most classic reservoir rock typing methods including Ameufelle's Hydraulic Flow Units Amaefule et al., (1993), Ahr's Genetic Pore Types Ahr et al. (2005), Gunther's Flow Zone Indicators Gunter et al. (1997), etc. . Even better would be to integrate these approaches to greatly enhance porosity permeability transforms used in reservoir simulators which rely on total porosity from openhole logs to be converted to permeability for each identified reservoir rock type.

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