Challenges for petrophysical characterization of presalt carbonate reservoirs

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Abstract

We discuss the petrophysical challenges for interpretation of presalt carbonate rocks that constitute the main reservoirs in the recently discovered hydrocarbon accumulations in the Santos Basin. These rocks are described as microbialites and have become one of the main exploratory targets in several basins worldwide, resulting in giant discoveries in the South Atlantic (Brazil, Angola) and in the Caspian Sea (Kazachstan). The origin of these rocks is still controversial, and several carbonate rock outcrops have been proposed as possible analogs for the presalt microbialites, including stromatolites, travertine deposits, and carbonate tufas. The distribution of porosity and permeability in the microbialite reservoirs are important parameters for building up reservoir models and optimization of the hydrocarbon production strategy. Petrophysical parameters may also be obtained by reconstruction of microtomography binary images obtained from reservoirs plugs. The quantitative analysis is based on an innovative numerical simulation software that uses a pore network algorithm. This tool is under development and aims at providing a 3-D visualization of the rock framework and yielding reliable evaluations of porosity and permeability factors that can be compared with traditional laboratory measurements.

Introduction

In the 2000's the largest petroleum accumulations discovered in the world are concentrated in the region north of the Arabian Peninsula, particularly in the northern Caspian Sea, and in the salt basins of the South Atlantic (Brazil and Angola). The Kashagan Complex in Kazachstan and the presalt oil fields in the Santos Basin (Lula, Libra, Franco, etc.) and Kwanza Basin (Caimea, Lontra, Bicuar) are all characterized by carbonate reservoirs with evaporites as the top seal (Mohriak, 2015). The productivity of some of these wells is extremely high, reaching more than 20,000 bbl/d per well. However, the production forecast for this type of reservoir is challenging because of the complex and heterogeneous network of pores and flow regimes. The permeability distribution in these carbonate reservoirs is extremely variable depending on the different lithologic facies, which includes grainstones, boundstones, calcilutites, carbonate breccias, microbialites, coquinas, etc. (Mohriak, 2015). The characterization of the petrophysical properties of the presalt carbonate reservoirs in the Santos Basin and other areas with similar lithotypes is thus critical for the optimization of the hydrocarbon production strategy, for the selection of best methods for enhancing primary and secondary recovery, and for the performance prediction of individual wells in the production area.

The presalt carbonate lithofacies variability results in extremely heterogeneous reservoir properties varying both in the vertical and horizontal directions. Consequently, the 3D distribution of the reservoir rocks is difficult to simulate by interpretation of seismic data. Usually the petrophysical parameters are also constrained by well log interpretation and by petrographic analysis of cores and plugs. Samples of the presalt carbonate rocks are rather difficult to obtain in exploratory wells and even when available they may not be representative of the overall properties of the main reservoir rocks that contribute to the oil production. Several companies and research groups thus make use of carbonate rock analogues obtained from field outcrops to investigate the possible sedimentological correlations with the reservoir rocks in the subsurface. In the case of the presalt microbialites in the Santos Basin, several investigations carried out so far have indicated that carbonate rocks such as stromatolites, travertines and tufas might correspond to end-members of the reservoir lithotypes. The reservoir characterization workflow often includes measuring the porosity and permeability by conventional methods in petrophysical laboratories. In this work we discuss some of the similarities and differences between the carbonate rock analogues and the presalt microbialites. We also show preliminary results of the application of numerical simulation methods to determine petrophysical parameters from digitally reconstructed binary images obtained by microtomography of carbonate rock plugs.

Geological and geophysical characteristics of presalt carbonate reservoirs

Presalt microbialites are registered in the North Caspian Basin (Kashagan Complex) and in the South Atlantic (Brazilian and West African margins). The pre-salt carbonate reservoirs in the Kashagan Complex in Kazachstan are characterized by diverse lithotypes including calcilutites, grainstones, boundstones, microbialites, and carbonate breccias (Ronchi et al., 2010; Kent et al., 2012; Collins, 2014; Searle et al., 2014). The Kashagan oil field corresponds to a reef buildup measuring 75 km x 35 km, with the top of the Carboniferous reservoir approximately 4.5 km below sea-level. The oil column in the trap exceeds 1000 m, with very light oil (45^o API) and a high Gas-Oil Ratio. The presence of H_2S in the reservoir (reaching almost 20% of the volume) is a major concern for the exploitation of the field. Production in Kashagan has started in 2013 but many reservoir issues exist concerning the best strategy for oil recovery (including a future 4D acquisition). Production was halted in 2014, and given the high production cost for this field, it will only resume when the international price for oil compensates the huge investments necessary for the primary and secondary recovery of the hydrocarbon volumes. This field represents the largest oil discovery in the world in the past decade, with estimates reaching more than 40 billion barrels of oil in place.

The Santos Basin presalt oil accumulations have been discovered following the Tupi prospect successful result in 2006 (Azevedo, 2009). The exploration effort conducted by Petrobras and partners resulted in the discovery of several other oil fields in the ultradeep water province of the basin, including the Franco and Libra giant fields (Petersen et al., 2013). The application of the presalt play type to the conjugate margin (Kwanza Basin) resulted in equivalent discoveries (Caimea, Lontra, Bicuar) which are also characterized by carbonate rocks (microbialites) as the main reservoir (Cazier et al., 2014).

Microbialites are carbonate rocks that are registered in the geological history of sedimentary basins ranging in age from Neoproterozoic to Recent. They are recognized in diverse basin types formed in different tectonic regimes. Several sedimentologic models based on outcrop analogues have been suggested for the origin of these rocks in the South Atlantic presalt oil accumulations. Three carbonate rocks have been discussed as possible analogues for the presalt microbialites (Mohriak, 2015):

Reefs and carbonate buildups (stromatolites): these might have been formed during periods of sea-level rises in a desiccating basin.

Chemical abiotic precipitation of carbonates: these rocks occur in basins affected by volcanic or hydrothermal episodes, such as in the Yellowstone Park in the United States, or in the Tivoli region of Italy, with travertine deposits often associated with secondary biogenic growth.

Carbonate tufas: these are detrital carbonate rocks related to reworking of shells and chemical precipitates formed at low temperatures.

Examples of carbonate analogues

The presalt carbonates in the South Atlantic are characterized by lithotypes that show marked similarities (but also differences) with samples of carbonate rocks in diverse tectonic settings (Borghi, 2012). We discusss three possible analogues for the presalt microbialites:

(a) STROMATOLITES (LAGOA SALGADA, RIO DE JANEIRO): QUATERNARY

Lagoa Salgada, located in northeast Rio de Janeiro State, is a small salt lagoon in the Paraíba do Sul delta, measuring about 8.5 km in length by 2 km in width. It is possibly the only place in South America where Quaternary carbonate stromatolites, thrombolites and oncolites occur subaerially, providing an interesting analogue for the South Atlantic presalt microbialites (Srivastava, 2002; Azevedo, 2009; Borghi, 2012; Riccomini et al., 2012). These rocks have been intensively studied in the past 10 years by several sedimentology researchers focusing on petrographic description of thin rock slides. The shells at the base of the carbonate rocks (stromatolites) are dated between 4000 – 3600 ybp, and the carbonate deposition continued until about 300 ybp (Iespa et al., 2012). The sediments that occur at the base of the lagoon correspond to marine sands of the Paraíba do Sul delta, as indicated by abundant foraminifers. This stratigraphy suggests a transition from a marine siliciclastic environment to a saline lacustrine environment with carbonates fringing a shallowing and desicatting lagoon. Cyanobacteria incorporated into the stromatolites indicate high salinity, alkaline pH, high temperature, and a rather low oxygen content. Figure 1 shows an example of the stromatolite from Lagoa Salgada.

(b) TRAVERTINES (TIVOLY, ITALY): HYDROTHERMAL ORIGIN

The carbonate rocks that are mined in the Tivoly region of Italy since antiquity originate from chemical precipitation in lakes with warm to hot waters (Gandin and Capezzuoli, 2014). These hypersatured alkaline-sulphate waters form deposits of abiotic crystalline crusts of calcite minerals (similar to Yellowstone Park in USA), microbially mediated crusts (microbialites), and granular deposits of interbedded lime and mudstone. Some of the granular deposits and the microbialites are considered analogous to sediments that form in evaporitic environments (tidal flats/sabkhas). Figure 2 shows an example of the travertine carbonate from Tivoli.

(c) CARBONATE TUFAS (BONITO, MS) – REWORKED CARBONATES

These rocks are registered in the Bodoquena Range, a carbonate plateau located at the southeastern border of the Pantanal region in Mato Grosso do Sul, central Brazil. The carbonate deposits occur along the river drainage that cuts the Neoproterozoic carbonates (calcitic limestones of the Tamengo Formation of the Corumbá Group), which are exposed on the plateau (Boggiani et al., 2002). The rivers of the Bodoquena Plateau have clean, bicarbonate waters, which help in the formation of tufas associated with moss and algae. These fluvial carbonates are reworked and form blocks with concentric structures due to weathering as shown in Figure 3.

Figure 1: Stromatolites from Lagoa Salgada, Rio de Janeiro (sample and plug).

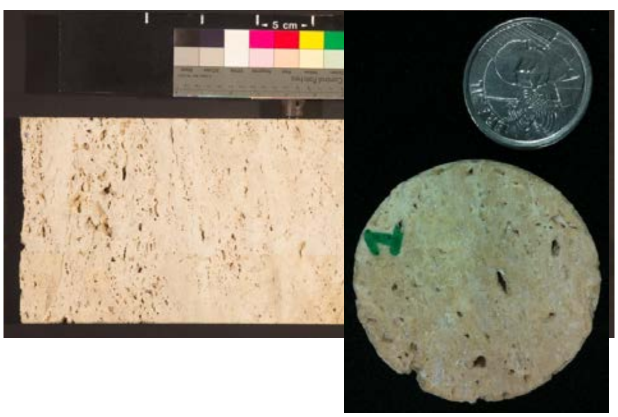

Figure 2: Travertine from Tivoli, Italy (sample and plug)

Figure 3: Carbonate tufa from Bonito, Mato Grosso do Sul (sample and plug)

Numerical Simulation Method

The numerical simulation technique employed to image the carbonate rock framework is based on the development of an innovative computational tool that will reconstruct the three-dimensional (3D) framework of the matrix and porous spaces in carbonate plugs by applying a binary renderization of the images obtained by microtomography. This new tool is under development and the preliminary results involving sandstone and carbonate samples are encouraging. The method uses the Pore Network algorithm, which is based on building up a voxel structure of pores and throats that is topologically equivalent to the porous system image, but with a simplified geometry consisting of spheres and linear connections. In the models both the connections and the pores have a constant cross-section and form factors, which are used to represent irregularities and the tortuosity of the structures in the real rock framework.

With the new tool, high-resolution 3D images and cube volumes can be built from the integration of the reconstructed 2D images obtained from the microtomography of rock plugs. The pore space geometry is mathematically simulated and quantitative analyses can be performed by statistical methods. This approach directly yields basic petrophysical properties (total and effective porosity, absolute and relative permeability, capillary pressure) and allows the simulation of fluid flow in the pore system. The challenge that has been faced so far is the upscaling from different pore geometries, which may range from nanometers to centimeters even in the plug scale. The carbonate rocks used as analogs for the presalt microbialites also display different scales for the pore sizes, and the connectivity of the multi-scale network is considerably higher than that obtained from the original network. This effect represents a natural feature that is often observed in carbonate rocks, where apparently disconnected pores are actually connected by microporous structures within the matrix. The results from the numerical simulations are also calibrated with the results of conventional petrophysical analyses conducted in laboratory, so that a quality check can be performed throughout the modelling process.

Results

The application of the method to a sample of a siliciclastic sedimentary rock (Figure 4) shows very good results for the simulation of the pore space framework by the Pore Network algorithm.

The total and effective porosity in the three directions (X,Y,Z) are shown in the table below, indicating a very good 3-D pore connectivity for this siliciclastic rock.

Absolute porosity	19.20%
Effective porosity (X-axis)	19.13%
Effective porosity (Y-axis)	19.13%
Effective porosity (Z-axis)	19.13%

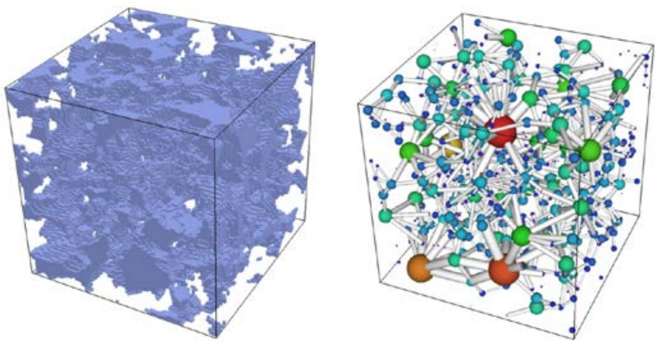

Figure 4: Pore Network extracted from microtomographic images of a plug from a siliciclastic sedimentary rock outcrop (sandstone). Left: reconstructed image of the pore distribution; right: pore network obtained by the method.

The application of the method to a sample of the stromatolite from Lagoa Salgada (Figure 5) shows very good results for the simulation of the pore space framework by the Pore Network algorithm.

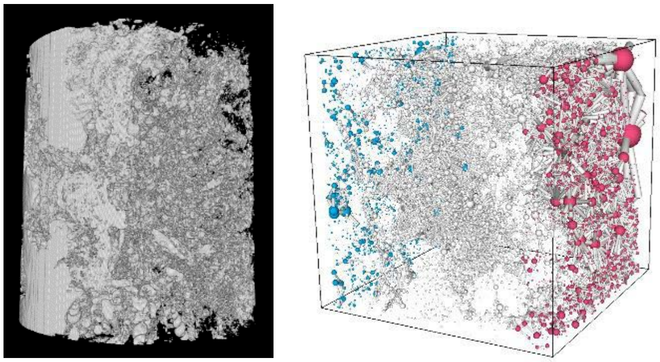

Figure 5: (left) microtomography image of the stromatolite sample from Lagoa Salgada, reconstructed after image binarization; (right) pore network extracted from the reconstructed images by the CONCREMAT-ESSS software (under development).

The values for the total and effective porosity for the Lagoa Salgada carbonate rock sample (Figure 6) are shown below:

Absolute Porosity	15.90%
Effective Porosity (Z-Axis)	10.28%

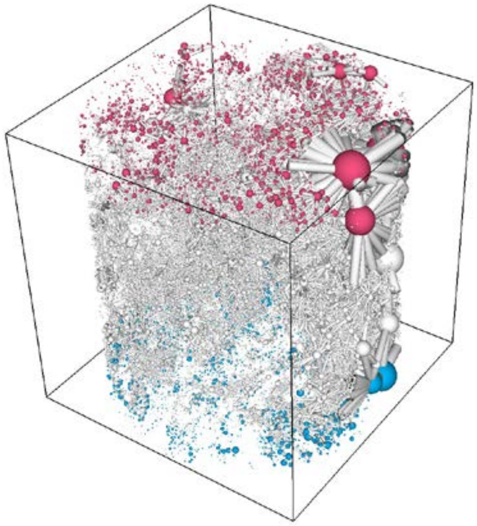

Figure 6: Pore Network extracted from the reconstructed images of the whole Lagoa Salgada stromatolite plug by the CONCREMAT-ESSS software (under development).

The application of the method for the Lagoa Salgada stromatolite indicates that in this case the pores are not as interconnected as in the sandstone sample. There are many isolated pores and the hydrocarbons that might be stored in this pore network configuration might not be recovered from the reservoir.

Conclusions

Presalt microbialites correspond to a complex carbonate rock lithotype that has been identified in several giant hydrocarbon accumulations worldwide. The characterization of the petrophysical properties of these rocks can be conducted by conventional methods in laboratories but may also be numerically simulated using microtomography images of rock plugs (outcrop samples, cores and plugs). The reconstruction of the 3D network of the rock (matrix, throats and pores) is based on binarization of the images and building up of a 3D volume by the Pore Network method. This method allows the determination of the static petrophysical properties (porosity, permeability, capillary pressure) by numerical simulation of flow in one or more stages through the network. The development of this innovative software is also calibrated by physical measurements in the Concremat Petrophysics Laboratory to obtain an accurate validation of the numerical simulation results. The application of the method to carbonate analogues will evolve into the application to presalt carbonate rocks. Eventually, these studies will be expanded from the plug to the core and well scale, based on correlation of the petrophysical parameters with well logs.

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References

Azevedo, R.L.M., 2009. O pré-sal: oportunidades para o Brasil. Simpósio de Geologia do Sudeste, Estância de São Pedro, São Paulo, 17 de outubro de 2009, 56p.

Boggiani, P. C., Coimbra, A. M., Gesicki, A. L., Sial, A. N., Ferreira,V.P., Ribeiro,F.B. and Flexor, J. M., 2002. Tufas Calcárias da Serra da Bodoquena, MS - Cachoeiras petrificadas ao longo dos rios. In: Schobbenhaus, C., Campos, D. A., Queiroz, E. T., Winge, M. and Berbert-Born, M. L. C. (eds.), Sítios Geológicos e Paleontológicos do Brasil. DNPM/CPRM - Comissão Brasileira de Sítios Geológicos e Paleobiológicos (SIGEP), 2002, v.01, p.249-259.

Borghi, L., 2012. Presalt carbonates: microbial or not ? ICCR-SCTC Workshop in Brazil, UFRJ, Rio de Janeiro, 10-13 December 2013, 66 p.

Cazier, E.C.,Bargas, C., Inman, I., Olson, C., Shinol, J., Nicholson, T., Ferreira, H., Lopes, A., Cardoso, S. and Buambua, L., 2014. Petroleum Geology of Cameia Field, Deepwater Pre-Salt Kwanza Basin, Angola, West Africa. AAPG Search and Discovery, Article #90194.

Collins, J.F., Katz, D., Harris, P.M. and Narr, W., 2014. Burial Cementation and Dissolution in Carboniferous Slope Facies, Tengiz Field, Kazakhstan: Evidence for Hydrothermal Activity. AAPG Search and Discovery Article #20234.

Iespa, A. A. C., Iespa, C. M. D. and Borghi, L, 2012. Evolução paleoambiental da Lagoa Salgada utilizando microbialitos, com ênfase em microfácies carbonáticas. UNESP, Geociências, v. 31, n. 3, p. 371-380.

Gandin, A. and Capezzuoli, E., 2014. Travertine: Distinctive depositional fabrics of carbonates from thermal spring systems. Sedimentology, v. 61, p. 264-290.

Kenter, J.A.M., Harris, P.M. and Collins, J.F., 2012. The Microbial-Dominated Slopes of Tengiz Field, Pricaspian Basin, Kazakhstan. AAPG Hedberg Conference “Microbial Carbonate Reservoirs Characterization”, June 4-8, 2012 – Houston, Texas, Abstracts, 4p.

Mann, J., 2013. Broadband Technology: New Benefits for Pre-Salt Exploration. GeoExpro, v. 10, n. 5, p. 77 – 78.

Mohriak, W.U., 2015. Pre-Salt Carbonate Reservoirs in the South Atlantic and Worldwide Analogs. AAPG Geosciences Technology Workshop “Carbonate Plays around the World - Analogues to Support Exploration and Development”, 4-5 February 2015 - New Orleans, Louisiana.

Mohriak, W.U., Szatmari, P., & Anjos, S.M.C., 2008. Sedimentação dos evaporitos. In: Mohriak, W., Szatmari, P. & Anjos, S. M. C., 2008, Sal: Geologia e Tectônica, Editora Beca, p. 64-89.

Petersen, E., Abelha, M. e Pedrosa, L., 2013. Brasil Pré-Sal-1: Libra – avaliação geológica e diretrizes ambientais. ANP, 17/09/2013, 90p.

Riccomini, C., Sant’Anna, L.G. and Tassinari, C.C.G., 2012. Pré-sal: geologia e exploração. Revista USP, São Paulo, n.95, p.33-42.

Ronchi, P., Ortenzi, A., Borromeo, O., Claps, M. and Zempolich, W.G., 2010. Depositional setting and diagenetic processes and their impact on the reservoir quality in the late Visean–Bashkirian Kashagan carbonate platform (Pre-Caspian Basin, Kazakhstan). AAPG Bulletin, v. 94, p. 1313–1348.

Searle, A., Xing, H., Iskakov, E., Jazbayev, K., Jenkins, S.D., Lee, K.S. and McLean, N., 2014. A Comprehensive Anisotropic Velocity Model Building Case Study - Tengiz Full Azimuth Land TTI PSDM. 76th EAGE Conference and Exhibition 2014, Session: Improvements in Velocity Model Estimation, Publication date: 16 June 2014; DOI: 10.3997/2214-4609.20141105

Srivastava ,N.K., 2002. Lagoa Salgada, RJ - Estromatólitos recentes. In: Schobbenhaus,C.; Campos,D.A. ; Queiroz,E.T.; Winge,M.; Berbert-Born, M.L.C. (eds.) Sítios Geológicos e Paleontológicos do Brasil. Brasilia: DNPM/CPRM - Comissão Brasileira de Sítios Geológicos e Paleobiológicos (SIGEP), 2002. v. 01, p 203-209.