Characterization of carbonate reservoirs based on Lithogeochemical and Thin Section data: A case study in the Atapu field, Santos Basin

Carlos Saraiva[1], Guilherme Oliveira[2], Leonardo Ventura[2,1], Gabriel Ribeiro[2], Bruno Valle[3], Filipe Vidal[1,4], Bruna Silva[1,4], Giovanni Stael[2,1];
[1]Universidade Federal Fluminense (UFF), [2]LabPetrON – Nacional Observatory (ON), [3]3R Petroleum, [4]Petrobras S.A.

Abstract

The Santos Basin is the largest offshore basin on the Brazilian southeastern margin and is currently the main oil producing basin in Brazil. The Atapu Field is located in the central portion of the Santos Basin. Its carbonate reservoirs under the salt layer estimate oil volumes that exceed between 2.5 and 4 billion barrels of oil equivalent. This work aims to characterize the pre-salt carbonate reservoirs on the BRSA-1284 well of the Atapu field, Santos Basin. The present work held an integrated geological and geophycal analysis with convencial and special well logs and thin sections. The use of thin sections contributed to the understanding of information obtained from conventional and special geophysical well logs, resulting in more robust interpretations. The petrographic description reports and the final drilling reports were fundamental for the interpretation of thin sections and well zoning, respectively. The integrated methodology results in a workflow to estimate the best intervals for production in the Atapu carbonates context.

Introduction

The Santos Basin is the largest offshore basin on the Brazilian southeastern margin and is currently the main oil producing basin in Brazil, accounting for around 73% of total production in the sector (ANP/SDP, 2023). Its huge oil reserves correspond to the complex carbonate reservoirs of the pre-salt play, discovered in 2006, and which are increasingly attracting investors willing to develop new technologies capable of exploiting the immense productive potential of these deposits.

However, the characterization of these reservoirs still presents great challenges to be studied due to the faciological complexities which results in high vertical and lateral heterogeneities of its reservoirs (Mohriak et al., 2015). These carbonate rocks generally have high permo-porous properties, nevertheless, they are often affected by diagenetic processes, which may impair their quality as an accumulation (Lebre et al., 2021). Dissolution, cementation and mineralogical replacement (silicification and dolomitization) are among the most common processes. (Lima and De Ros, 2019) observe that the deterioration in the porosity and permeability characteristics of these reservoirs, due to diagenesis, occurs in several fields of the basin (Lima and De Ros, 2019). In addition, these accumulations are located below thick layers of salt, often fractured and suffering from the influence of hydrothermal activities, making their exploration and production even more difficult.

The Atapu Field is located in the central portion of the Santos Basin, about 200km from the coast and under water depths ranging from 2,000 to 2,300m. Its carbonate reservoirs under the salt layer estimate oil between 2.5 and 4 billion barrels of oil equivalent (Ribeiro et al., 2022). Together with the Berbigão and Sururu fields, it covers an area of high exploratory potential known as *Iara Complex* (Vital et al., 2023).

Currently, the production in the Atapu field is assigned to two contracts, one under the onerous assignment regime (39.5%) and the other corresponding to the production sharing of its surplus volume (60.5%), with the participation of several consortium companies (ANP/SDP 03/2023). According to the ANP/SDP Monthly Production Bulletin (2023), the Atapu field has average total production greater than 140 Mboe/d (One thousand barrels of oil equivalent per day), placing it as the 6th largest pre-salt producing field and the 8th largest in Brazil.

Geological Context

Itapema Formation

The Itapema Fm. was deposited from the Neobarremian to the Eoaptian during the rift phase tectonic regime, and is bounded at the base by the Jiquiá-Buricica unconformity and at the top by the Pre-Alagoas unconformity. This formation is composed of conglomerates and sandstones in the proximal part and intercalations of carbonate rocks and dark. These carbonates are characterized by Moreira et al., (2007) as coquinas (bivalve grainstones, bioclactic wackestones and packstones) and carbonate shales.

Studies carried out in the Coqueiros Fm., analogous to Itapema Fm. from Campos Basin (Moreira et al., 2007), attribute a river-lacustrine environment with a strong influence of faults, on low-angle slopes cut by normal faults (Thompson et al., 2015; Pietzsch et al., 2018), which would have suffered considerable water level fluctuations due both to tectonic variations and to the influence of waves and currents generated by storms (Carvalho et al., 2000). Pietzsch et al., (2018) highlight a more humid environment with greater drainage influence at the time of Itapema Fm. deposition, and also indicate an expectation that its carbonates are more calcitic than those of Barra Velha Fm. Although the prominent role of Itapema Fm. is attributed to coquinas, which have excellent permoporous characteristics, the shales of Itapema Fm. also play an important role as source rock as these shales are rich in organic matter, with a TOC of 2 to 6% and a type I kerogen (Castro, 2019).

Barra Velha Formation

The Barra Velha Fm. was deposited during the Aptian Alagoas local stage, and occurs over the rocks of Itapema Fm. and below those of Ariri Fm. It may be bounded at its base by the Pre-Alagoas unconformity, at its top by the salt base, and internally divided in two by the Intra-Alagoas unconformity. This unconformity separates the carbonates deposited during the sag phase in its upper part, from those deposited during the upper rift phase, in its lower part (Wright & Barnett, 2015; Buckley et al., 2015), and can be characterized by a reflector positive seismic data (Moreira et al., 2007).

Rocks with composition similar to limestone stromatolites. microbial laminites, carbonate shales, and microbialites rich in talc and magnesian clays, with subordinate occurrence of coquinas and basalts of Barra Velha Fm. (Moreira et al., 2007), are associated with a shallow lake environment, hyper-alkaline and prone to evaporation (Wright & Barnett, 2015), with diagenetic facies commonly presenting replacement/cementation by dolomite and quartz (Arienti et al., 2018). The Barra Velha Fm. represents the main pre-salt reservoir of the Santos Basin (Szatmari & Milani, 2016), and its thickness can vary from more than 500m to less than 55m on top of faulted blocks, where it can even be locally absent (Wright & Barnett, 2015).

Method

This work aims to characterize the pre-salt carbonate reservoirs of the Atapu field, Santos Basin on the BRSA-1284 well. This characterization was done through the use of data from conventional and special geophysical well logs and thin sections. Saraiva et al. (2022) proposed a work flowchart for the formation evaluation in the same well where different clay volume calculation methodologies were proposed to estimate three scenarios for NetPay. In the present work, the clay volume estimated using the spectral Gamma-Ray has been chosen, which more coherently showed zones with lower permo-porous properties.

In figure 1 it is possible to observe the workflow used by Saraiva et al. (2022) with the addition of the stages of analysis of the Lithogeochemistry logs, the Nuclear Magnetic Resonance (NMR) and the Petrographic thin sections and finally the indication of the probable best production intervals.

All data were made available by the ANP, including images of the slides, petrographic reports and well reports. Data interpretation was developed using the Interactive Petrophysics (IP) software provided by Lloyd's Register.

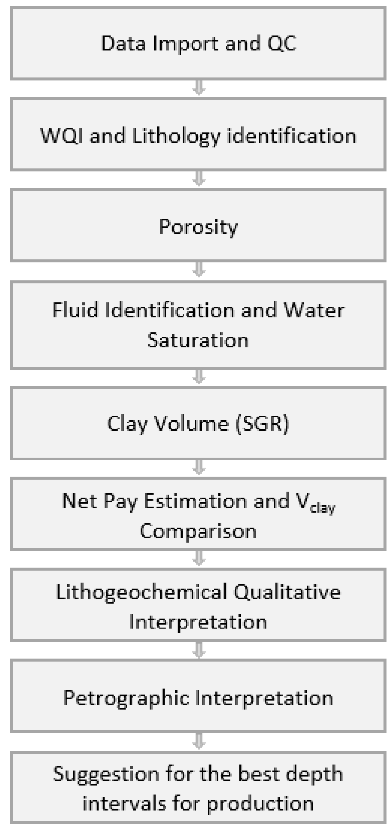

Figure 1 *– Applied work flowchart for the Atapu carbonate reservoirs*

Lithogeochemical Qualitative Interpretation

One of the first points to be verified through the analysis of the lithogeochemical well logs is the fact that metallic elements (Al, Fe and K) along with silica have considerably higher levels in two intervals of the well. These two intervals coincide with high values of the gamma-ray curve. These intervals are called A and C of figure 2, where smaller values for the resistivity curves and the T2 distribution and higher values for absolute acoustic impedance can also be observed. It is interesting to note that in these two intervals the density log tends to the right (with higher values) while the neutron log tends to the left (also with higher values), causing a crossover that can be interpreted as a greater presence of clay content.

The intervals B and D are characterized by lower values of gamma-ray, metallic elements and silica, in addition to having a smaller proportion of fines, according to the density and the neutron well logs. In addition, these intervals present the highest values of the permo-porous properties of the pre-salt interval of the well in that study.

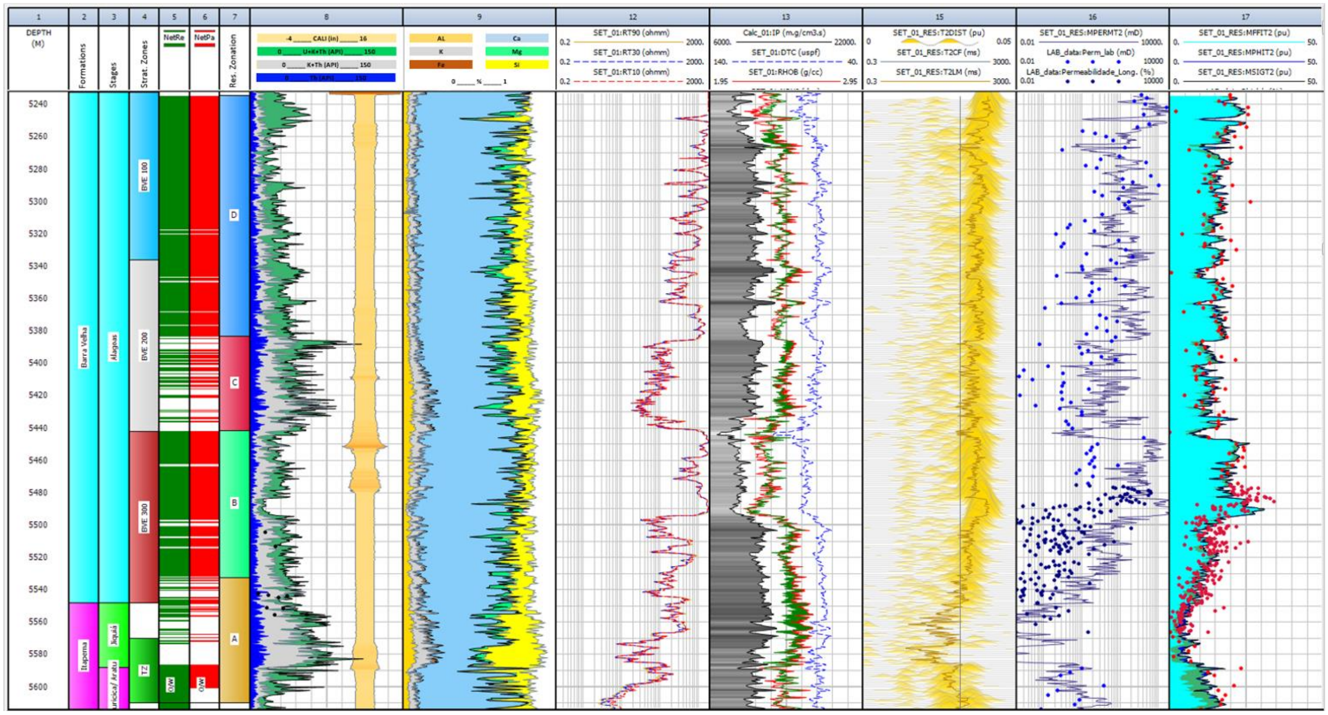

Figure 2 *– Well log analysis for BRSA-1284 Atapu well.*

Petrografic Interpretation

The studied well was zoned into 4 different parts, called A, B, C and D, with zone A being the deepest, as is has been discussed in this work. As identified in the well logs analysis, it is possible to observe that zones A and C have a higher content of fine-grained rocks, and therefore worse permo-porous properties.

For Zone A, the ANP petrographic reports characterize the thin sections 1, 2 and 3 as laminite composed of calcite, organic matter, microcrystalline rhombohedral dolomite, peloids and siliciclastic grains (figure 3A). In sample 3, phosphate fragments that are interpreted as vertebrate fragments.

For Zone B, the reports describe the thin section 4 as spherulitite composed of undifferentiated particles, siliciclastic grains and bioclasts, calcite matrix and dolomitic cementation (figure 3B). Thin sections 5 and 6 are characterized as laminite and have in their composition calcite, organic matter and microcrystalline rhombohedral dolomite. On slide 6, it is possible to observe the dissolution of what was interpreted as phosphate clasts and/or organic matter.

For Zone C, the reports describe thin sections 7 and 8 as laminite composed of calcite, organic matter, bioclasts, microcrystalline rhombohedral dolomite, peloids and siliciclastic grains (figure 3C). Thin section 9 is described as spherulitite composed of undifferentiated particles, siliciclastic grains and bioclasts. Calcite matrix and dolomitic cementation.

For Zone D, in this work it was decided to describe both thin sections 10 and 11 as grainstone composed of fragments of spherulitite and peloids with cementation varying between calcite and dolomite Thin section 12 is a crystalline limestone of probably dolomitic composition (figure 3D).

Discussions

Magnesian clays normally do not show good responses in Gamma-ray curves. However, the gamma ray logs and the lithogechemical logs marks some possible clay content rich intervals wich was interpreted as a potencial incursion of hydrothermal fluids in the area. For the typical environment of the pre-salt Itapema and Barra Velha formations, significant amounts of the elements Al, Fe, K and Si are not expected. It is then possible that these elements are of allochthonous origin and sometimes end up worsening the permo-porous properties of the reservoirs, as is the case of intervals A and C in the highlighted well.

It is still possible to see a good correlation between the gamma-ray potassium curve and the lithogeochemical potassium curve, both in gray, on tracks 8 and 9, respectively. The spectral gamma-ray curves were fundamental for the evaluation of intervals with lower reservoir qualities and were good indicators for possible intervals negatively affected by hydrothermal activities.

It is important to emphasize that the intervals are not necessarily dry (without the presence of hydrocarbons) but rather have lower porosity and permeability. These characteristics are fundamental for the production and flow of a well.

From the thin sections it's observed that intervals A and C intervals are muddy in comparison to the other two and they have lower porosity. It's possible to see (mainly in the B interval) that the permeability occurs in a horizontal way.

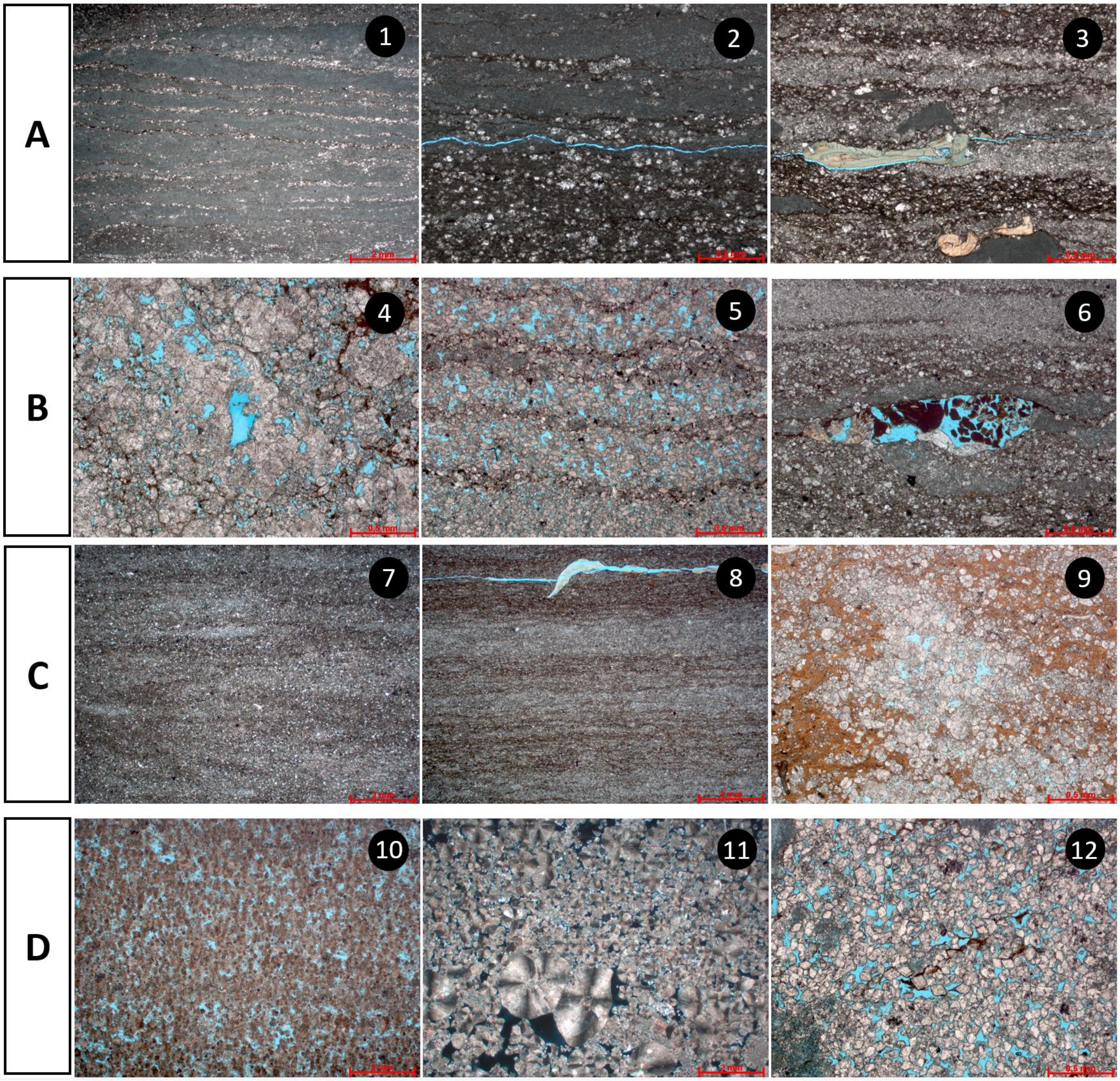

Figure 3 *– Thin sections from Atapu BRSA-1284 well.*

Conclusions

The integrative approach enabled the construction of more robust interpretations. The use of thin sections made it possible to limit the possibilities of interpretation brought by conventional and special geophysical well logs. The petrographic description reports and the final drilling reports were fundamental for the interpretation of thin sections and well zoning, respectively.

More specific conclusions are:

- In this work, the spectral gamma-ray curves Th and K can role as a quality indicator for the reservoirs that have suffer from hydrothermal fluid incursions. The bests production intervals (best permo-porous properties) are the ones with low gamma-ray values.
- The litogeochemical well logs have an important rule explaining Gamma-ray, Density/ Neutrons, Permeability and Porosity log answers.
- The thin section description/ analysis brought a refined explanation for the well log answers. The rock type and facies type clarify the interpretation of the low permo-porous intervals.
- Also, the thin section analysis played a rule for the hydrothermal interpretation as it’s possible to see some silicates in A and C intervals and the dissolution, as well.

Acknowledgments

First my thanks to my advisor Giovanni Stael for the infrastructure laboratory of the Petrophysics Laboratory in the Nacional Observatory (LabPetrON) and support.

To my laboratory colleagues, Guilherme, Leonardo and Gabriel that are also co-authors of this work. Thanks for the support and cowriting.

To Bruno Valle, that was my mentor at university and industry matters and helped me a lot with the thin section analysis.

To Filipe Vidal, that is one of my mentors at the university and helped me with well logs interpretation and the knowledge about the chemical elements and their geological role.

To Bruna Silva, for instigating creative thinking and also encouraging critical thinking about which geological processes can generate the responses seen in geophysical well logs.

Of course, thanks to the National Agency for Petroleum, Natural Gas and Biofuels (ANP) for providing data to this work.

And finally thanks to my professors Fernando Freire and Wagner Lupinacci that helped me in past academic works and also in the understanding of the Brazilian Pré-Salt geological and geophysical context.

References

ARIENTI, L.M.; SOUZA, R.S.; VIANA, S.; CUGLIERI, M.A.; SILVA, R.P.; TONIETTO, S.; PAULA, L.; GIL, J.A. Facies Association, Depositional Systems, and Paleophysiographic Models of the Barra Velha Formation, Pre-Salt Sequence – Santos Basin, Brazil. AAPG Annual Convention & Exhibition 2018, Salt Lake City, Utah, 2018.

BUCKLEY, J. D.; BOSENCE, D. W.; ELDERS, C. F. Tectonic setting and stratigraphic architecture of an Early Cretaceous lacustrine carbonate platformSugar Loaf High, Santos Basin, Brazil. Geological Society, Special Publications, vol. 418, pag. 1–17, 2015.

CARVALHO, M. D.; PRAÇA, U. M.; SILVA-TELLES JR., A. C.; JAHNERT, R. J.; DIAS, J. L. Bioclastic carbonate lacustrine facies models in the Campos Basin (Lower Cretaceous), Brazil. In: Gierlowski Kordesch, E. H. & Kelts, K. R. (ed.) Lake basins through space and time. Tulsa, AAPG, (Studies in Geology 46), pag. 245-256, 2000.

CASTRO, T. M. Avaliação dos Reservatórios Carbonáticos do Pré-Sal no Campo de Búzios, Bacia de Santos. Dissertação de Mestrado em Dinâmica dos Oceanos e da Terra (Universidade Federal Fluminense) 2019.

LEBRE, MARIANA & LUPINACCI, WAGNER. (2021). ANALYSIS OF FLOW FACIES IN THE PRE-SALT INTERVAL OF THE SANTOS BASIN. Thesis for: Master of ScienceAdvisor: Wagner Lupinacci.

LIMA, BRUNO EUSTÁQUIO & DE ROS, LUIZ. (2019). Deposition, diagenetic and hydrothermal processes in the Aptian Pre-Salt lacustrine carbonate reservoirs of the northern Campos Basin, offshore Brazil. Sedimentary Geology. 383. 10.1016/j.sedgeo.2019.01.006.

MOHRIAK, W. U.; PERDOMO, L. V.; PLUCENIO, D. M.; SAAD, J. L. Challenges for petrophysical characterization of presalt carbonate reservoirs. 14th International congress of the Brazilian Geophysical Society & EXPOGEF, Rio de Janeiro, Brazil, pag. 623-627, 2015.

MOREIRA, J. L. P.; MADEIRA, C. V.; GIL, J. A.; MACHADO, M.A.P Bacia de Santos. Boletim de Geociências da Petrobras 15, 531–549, 2007.

PIETZSCH, R.; OLIVEIRA, D.M.; TEDESCHI, L.R.; QUEIROZ NETO, J.V.; FIGUEIREDO, M.; VAZQUEZ, J.C.; SOUZA, R.S. Palaeohydrology of the Lower Cretaceous pre-salt lacustrine system, from rift to post-rift phase, Santos Basin, Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology 507, pag. 60−80, 2018.

RIBEIRO, G.S.S. Avaliação Petrofísica dos Reservatórios Carbonáticos do Pré-Salno Campo de Atapu, Bacia de Santos / Gabriel Sousa Dos Santos Ribeiro; Wagner Moreira Lupinacci, orientador; Giovanni Chaves Stael, coorientador. Niterói, 2022.121 f.: il.

SARAIVA, CARLOS & RIBEIRO, GABRIEL & RAMOS DOS SANTOS, GUILHERME & SILVA, BRUNA & FREIRE, FERNANDO & STAEL, GIOVANNI. (2022). Proposal for Formation Evaluation Based on Different Scenarios for Clay Volume Calculation in the Atapu Field, Santos Basin, Brazilian Pre-Salt. 10.3997/2214-4609.202288039.

SZATMARI, P. & E. J. MILANI. Tectonic control of the oil-rich large igneous-carbonate-salt province of the South Atlantic rift: Marine and Petroleum Geology, vol. 77, pag. 567–596, 2016. Doi:10.1016/j.marpetgeo.2016.06.004

THOMPSON D. L.; STILWELL J. D.; HALL M. Lacustrine carbonate reservoirs from Early Cretaceous rift lakes of Western Gondwana: pre-salt coquinas of Brazil and West Africa. Gondwana Res. 28, pag. 26–51, 2015.

VITAL, S., J. C., ADE, M. V. B., MORELATTO, R., LUPINACCI, W. (2023). Compartmentalization and stratigraphic-structural trapping in pre-salt carbonate reservoirs of the Santos Basin: A case study in the Iara complex. Marine and Petroleum Geology, 106163.

WRIGHT, V. P.; BARNETT, A. J. An abiotic model for the development of textures in some South Atlantic early Cretaceous lacustrine carbonates. Geological Society, London, Special Publications, vol. 418, n. 1, pag. 209-219, 2015.