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COMPARATIVE ANALYSIS OF PETROGRAPHIC DATA AND GEOLOGICAL INTERPRETATION FROM GEOPHYSICAL LOGS FOR PRE-SALT CARBONATES RESERVOIR CHARACTERIZATION, IN THE SURURU FIELD, SANTOS BASIN

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ABSTRACT. The understanding of petrophysical characteristics, such as porosity and permeability, is a target in the reservoir characterization task, and understanding the behavior of these parameters is paramount for the exploration of hydrocarbons. The focus of this work was the characterization of the Barra Velha Formation, in Sururu Field, from a qualitative integrated analysis of geophysical data from two exploratory wells and petrographic data, in order to verify how they are corroborative. By using porosity-related well logs, i.e., density, nuclear magnetic resonance, neutron, and sonic logs, three groups of electrofacies were generated, representing high, medium and low porosity rocks. Besides, the wells could be correlated by the recognition of three main intervals according to their electrofacies distribution. With the description of thin section images (photomicrography), thirteen groups of distinctive microfacies, i.e., floatstone, stromatolite, spherulite, laminite, grainstone / microcrystalline limestone and packstone, differing in texture and pore size, were identified within the three electrofacies, allowing inferences about environmental energy for the study area. Qualitative microfacies analyses corroborate the electrofacies interpretation regarding porosity characteristics of the rocks.

Keywords: Barra Velha Formation; Santos Basin; electrofacies; petrophysics.

RESUMO. O entendimento de características petrofísicas, como porosidade e permeabilidade, é alvo no processo de caracterização de reservatórios e entender o comportamento desses parâmetros é fundamental para a exploração de hidrocarbonetos. Este trabalho buscou caracterizar de forma qualitativa o principal intervalo reservatório do pré-sal, a Formação Barra Velha, no Campo de Sururu da Bacia de Santos, a partir da análise integrada de dados geofísicos de dois poços exploratórios e dados petrográficos. Através do uso de perfis geofísicos de dois poços, i.e., perfis de densidade, ressonância magnética, nêutron e sônico, foi possível a geração de três eletrofácies, que representam rochas de alta, média e baixa porosidade. Além disso, os poços puderam ser correlacionados através da identificação de três intervalos principais conforme a distribuição das eletrofácies. Através da descrição de imagens de lâminas petrográficas (fotomicrografias), treze grupos de microfácies distintas, i.e., *floatstone,* estromatolitos, esferulititos, laminitos*, grainstone/*carbonato microcristalino *e packstone*, diferindo em textura e tamanho de poro, foram reconhecidas dentro das três eletrofácies, possibilitando inferências sobre a energia do ambiente para a área de estudo. Por fim, a análise das microfácies corroboraram a interpretação das eletrofácies no que concerne as características de porosidade da rocha.

Palavras-chave: Formação Barra Velha; Bacia de Santos; eletrofácies; petrofísica

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INTRODUCTION

The Brazilian pre-salt play is one of the top five hydrocarbon provinces in the World. Its discovery was in 2006, but the first production started in September of 2008. By August of 2020, its production reached 2.776 BOE/d representing 70.7% of the Brazilian production (ANP, 2020). The main reservoir is formed by carbonate rocks of microbial origin being stratigraphically positioned in the so-called "post-rift phase" of the Santos and Campos basins (Moreira et al., 2007; Winter et al., 2007). Besides the high productivity of the pre-salt reservoirs, a consequence of their permoporous high quality, they also produce light oil. These aspects place the pre-salt reserves among the most profitable in the world.

The subject of this study consists of the carbonate rocks (stromatolites, microbial limestones and laminites) of the Barra Velha Formation, Guaratiba Group (Aptian age), of the pre-salt play of Santos Basin, located in Sururu Field. Such field showed in 2018, through a drilled well by Petrobras, the highest oil column ever found in Brazil, reaching the mark of 530 meters. Studies disclosed concerning the understanding of these carbonate rocks commonly focuses on Lula, Mero, and Sapinhoá fields (*e.g.*, Carlotto et al*.,* 2017; Jesus et al., 2019).

This present study proposes to expand the knowledge on the reservoir characteristics of the pre-salt section in the Sururu oil field (Fig. 1), Santos Basin, Brazil. This field is part of a cluster of other oil fields, which together are one of the most prolific production pole of the pre-salt play, located about 200 km off the coast of Rio de Janeiro state, at a depth of 2,300 m, in the eastern portion of Santos Basin.

The growing interest of studying the reservoir rocks of the pre-salt play is given by the lack of consensus about their origin and the complexity of their petrophysical characteristics (Farias et al*.,* 2019). Enhancing the understanding of the petrophysics properties, such as porosity and permeability, is one of the main purposes of reservoir characterization. Recognizing the behavior of these parameters is paramount in hydrocarbon investigation.

This work focused on the qualitative analysis and interpretation of well logs and petrographic data, which are considered one of the main tools applied to exploration and exploitation of hydrocarbon. Notwithstanding, this study attempted to describe, by the analysis of electrofacies identified through the geophysical well logs, the permo-porous characteristics of the Barra Velha Formation. The electrofacies were obtained through a unsupervised statistical method (K-means), and the results and hypothesis were validated by the description of thin section images (photomicrographs) obtained from core samples.

GEOLOGICAL SETTING

The Santos Basin is located in the southeast Brazilian margin, limited to the north by the Cabo Frio High and to the south by the Florianópolis High (Fig. 1). The development of the eastern Brazilian Continental Margin basins started with the Cretaceous taphrogenesis of the Gondwana paleocontinent, which resulted in the opening of the Atlantic Ocean (Kusznir & Karner, 2007; Mohriak *et al.,* 2008). The rift phase in Santos Basin started with massive tholeiitic basalt spills, with records recognized in Paraná, Pelotas, Santos, Campos and Espírito Santo basins, in descending order of occurrence (Mohriak *et al.,* 1995).

Moreira et al. (2007) divided the tectonostratigraphic development of the Santos Basin into three phases: Rift, Post-Rift, and Drift. The Pre-salt section encloses the Rift phase, which holds the sedimentary record deposited between the Hauterivian and the beginning of Aptian, including the Camboriú, Piçarras and Itapema formations of the Guaratiba Group; and the Post-Rift phase, which comprises the main Pre-salt play reservoir, the microbial carbonates of the Barra Velha Formation and the overlying seal, the evaporite rocks of Ariri Formation.

The Barra Velha Formation (Aptian), focus of this study, is composed by stromatolites and microbial limestones, whose origin (biotic or abiotic) is still intensely discussed (cf. Wright & Barnett, 2015; Gomes et al., 2020), laminites of the proximal portions and shales of distal ones. These deposits occur above the bioclastic calcarenites and

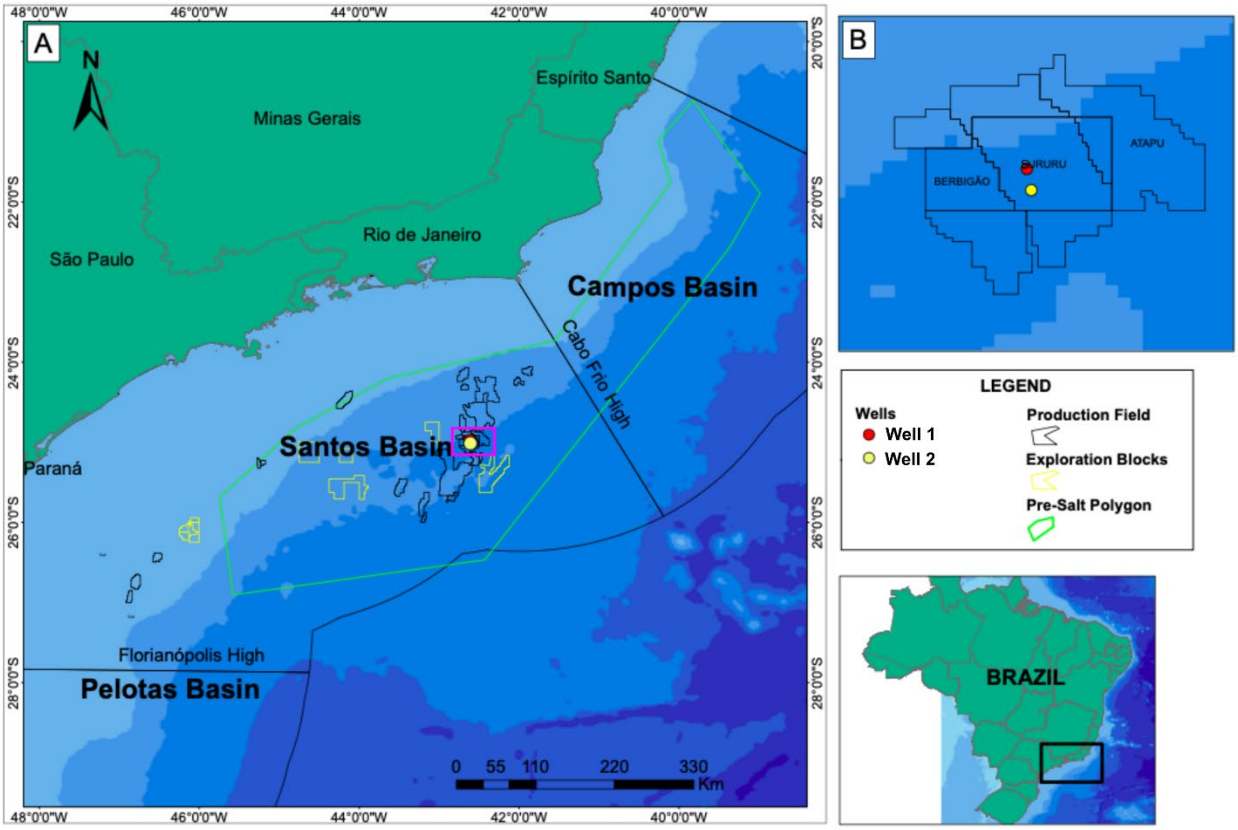

Figure 1 - A) Regional map of the offshore southeastern Brazil showing sedimentary basin limits (black lines); pre-salt polygon (green); oil field ring fences in Santos Basin (yellow: exploratory, black: exploitatory); purple square: study area expanded in B. B) Black polygons: oil field ring fences; yellow and red dots: wells analyzed in this work.

calcirrudites (coquinas) of the Itapema Formation (late Aptian) and the lower limit given by the contact with the evaporites of the Ariri Formation (late Albian) (Moreira et al., 2007).

DATASET AND METHODOLOGY

The analyzed dataset comprises two exploratory wells, designated in this work as well 1 and well 2[1], and their respective well logs: DT – Compressional Slowness, RHOB –density, NPHI – Neutron; and porosity that were obtained by applying cutoff values in the NMR relaxation curve T2. The values were 100ms separating CMFF (Free Fluid) from CBF (Capillary Bound Fluid), and 3ms separating CBF from CBW (Clay Bound Water). The former value is an approximate default cutoff for carbonate rocks (Minh *et al*., 1997); the RCAL (Routine Core Analysis - porosity and longitudinal permeability) and photomicrography data were provided only for well 2.

The k-mean cluster analysis was used to obtain the electrofacies along the whole depth interval of the Barra Velha Formation, by using the HRA module in the Techlog software platform (Schlumberger), whose workflow can be consulted in Lis-Śledziona (2019). The K-means is an unsupervised method and comprises a widely utilized cluster separation algorithm due to its efficiency, feasibility and speed when working with large data. This algorithm works by generating k randomly groups from log samples, with a subsequent reorganization of each group composition, minimizing internal variability and maximizing variability among the groups (Soares, 2005). The mathematical notation is shown below:

$$J = \sum_{n=1}^{N} \sum_{k=1}^{K} r_{nk} \|\mathbf{x}_n - \boldsymbol{\mu}_k\|^2 \qquad (1)$$

where J is the objective function, K the number of clusters, n is the number of cases, r_{nk} is the binary

[1]Phase drilled with 10 lb/gal of synthetic-based mud

indicator, x_n is the case I and u_k is the centroid for cluster j. This objective function represents the sum of the squares of the distances of each data point to its assigned vetor u_k. The purpose is to find values for r_{nk} and u_k to minimize J (Bishop, 2006).

Usually, the methodology applied for the clustering determination is that proposed by Soares (2005) and adopted by several works such as Lisboa (2013) and Grou (2015), where the classes are defined in function of the reservoir quality (e.g., reservoir, non-reservoir and possible reservoir, focusing on lithofacies attributes). In this work, the approach was focused on the porosity, regardless the fact that the lithofacies as the carbonate rocks of the Barra Velha Formation reveal a high complex framework and lithology (e.g., Wright & Barnett, 2015; Saller et al., 2016; Farias et al., 2019; Lima & De Ros, 2019), and hence it would not be expected that the logs would present a differential response among the lithofacies.

The final steps targeted the correlation of the RCAL data, obtained from well 2, associating each sample to the three groups of electrofacies generated, for validation of the initial hypothesis concerning porosity. Finally, a microfacies analysis was executed using the photomicrography data, aiming to access the porosity characteristics for final electrofacies validation.

As shown in Figure 2, the electrofacies in the two wells reveal a similar trend, being possible to divide the Barra Velha Formation into three different intervals named I1, I2 and I3. In both wells it is noticed that the basal portion of the Barra Velha Formation is dominated by eletrocfacies E3, named as interval I1. The interval I1 transits upwards to interval I2, the middle portion of the Barra Velha Formation. Such interval comprises repeated intercalation of electrofacies E2 and E1. In the upper portion of the Barra Velha Formation, the electrofacies E3 reappear, establishing the interval I3. It is also noticed that interval I2 is thicker in well 2 than in well 1. There is no way to evaluate the thickness of interval I1 in well 2, since the latter did not cross the whole extension of the Barra Velha Formation.

The intended goal for the cluster analysis with the K-means method, from which it was expected three different classes of porosity, was satisfactorily reached. The method was able to show a common trend in the two wells, and a similar range of values for each electrofacies.

RESULTS

Electrofacies characterization

From a prior analysis of histograms and cross-plots from the two analyzed wells in this work, it was defined that the method is best adjusted into tree clusters of porosity (low, medium and high) using logs that better respond to porosity characteristics, as follow: RHOB, DT, NPHI, CMFF, CBW and CBF (Avalone, 2019). The electrofacies of wells 1 and 2, as well as the logs addressed to them, can be consulted in Figure 2. Table 1 presents the values of the mean, median and standard deviation of each log and electrofacies. The porosity categories *high, medium and low,* defined in this work, are arbitrary, given by relative comparison among them.

Firstly, from an overall analysis, both wells show low values for GR, a typic pattern of carbonate sections with low interference of terrigenous material. According to the logs that may present a correlation to porosity properties (RHOB, NPHI, DT, and NMR), the Barra Velha Section shows a preponderance in low values for RHOB and high values of NPHI, DT and CMFF logs, suggesting a predominance of rocks of high porosity.

Disregarding the effects of fluids or difference of lithology or matrix among the electrofacies, and analyzing the statistical result for each electrofacies, presented in Table 1, the trend values are considerably similar for both wells. This means that, for example, the DT values have a median that decreases from electrofacies E1 to E3 in both wells. It may suggest that the electrofacies E1 has better porosity quality than E2 and E3, respectively. The same reasoning can be applied to the RHOB, however, for this case, the increase in the RHOB values from E1 to E3 suggests, conversely from the DT values, a decreasing in porosity quality.

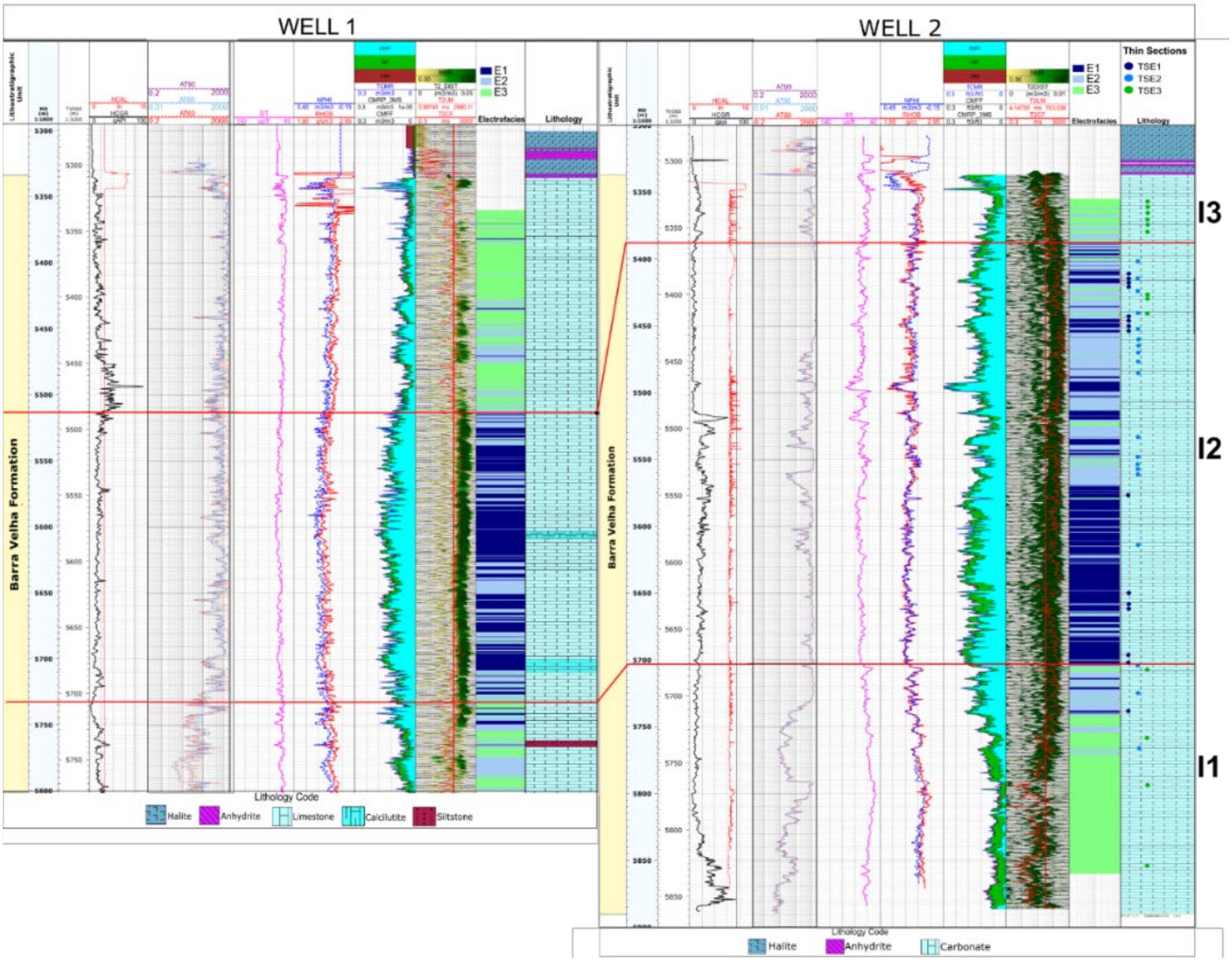

Figure 2 - Composite log showing the electrofacies model for the Barra Velha Formation in wells 1 and 2. From track 4 to track 7 the following logs are presented: caliper/gamma ray minus uranium contribution, resistivity (shallow, medium and deep), sonic, neutron/density, and the porosity logs (CMFF/CBF/CBW). Track 8 shows the NMR relaxation curve T2, along with its cutoff at 100 ms (T2CF) and its logarithmic mean (T2LM). The codes E1, E2 and E3 represent, respectively, the Electrofacies 1, 2 and 3. TSE1, TSE2 and TSE3 represent the thin sections, interpreted in this study, associated to their relative electrofacies. The red line marks the interval partition given by the electrofacies correlation. I1, I2 and I3 represent, respectively, interval 1, 2 and 3.

Cross plot permeability vs porosity from well 2

From the values of porosity and longitudinal permeability obtained by the RCAL analysis, it was possible to show to which group of electrofacies these samples belong.

As it can be observed in Figure 3, the clustered group shows consistency with the initial predictions concerning porosity (Fig. 2). This means that the permo-porous condition of electrofacies 1 (E1) is the best, while the condition of electrofacies 3 (E3) is the worst. The electrofacies E2 shows a wide range of values, showing no trend or specific values compared to electrofacies E1 and E3.

Microfacies characterization

The nomenclature adopted in this study for the classification of the pre-salt carbonate rocks followed that proposed by Terra et al. (2010), which blends the classic classifications of Dunham (1962), Folk (1962), Embry & Klovan (1971), Pettijohn (1975) and Riding (2000). The porous size classification followed that established by Choquette & Pray (1970).

The location of the sidewall core photomicrography, in well 2, interpreted in this study, can be found in Figure 2. In each electrofacies it was observed groups of

Table 1 - Mean, Median and Standard Deviation (SD) of well log reading (DT - compressional slowness, RHOB - density, NPHI - Neutron, CBW - Clay Bound Water, CBF- Capillary Bound Fluid, CMFF- Free Fluid). E1, E2 and E3 are the electrofacies individualized in wells 1 and 2.

		E1			**E2**			**E3**		
	Log/statistics	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Well 1	DT	61	62	5	61	61	2	57	57	3
	RHOB	2.4	2.45	0.04	2.6	2.6	0.04	2.7	2.6	0.06
	NPHI	0.20	0.20	0.02	0.14	0.14	0.02	0.09	0.09	0.02
	CBW	0.0045	0.0029	0.0049	0.0056	0.0041	0.0055	0.0053	0.0039	0.0052
	CBF	0.025	0.025	0.0069	0.0266	0.0245	0.01	0.0195	0.0188	0.0067
	CMFF	0.1204	0.1215	0.0214	0.0703	0.0722	0.0234	0.0333	0.0319	0.0184
Well 2	DT	73	73	5	67	67	4	57	57	5
	RHOB	2.4	2.4	0.05	2.5	2.5	0.04	2.6	2.6	0.05
	NPHI	0.2	0.2	0.02	0.1	0.1	0.02	0.1	0.1	0.03
	CBW	0.0054	0.0033	0.0059	0.0042	0.0024	0.0047	0.0063	0.0045	0.0060
	CBF	0.0426	0.0397	0.0180	0.0296	0.0283	0.0107	0.0380	0.0374	0.0139
	CMFF	0.1418	0.1450	0.0407	0.1042	0.1045	0.0252	0.0301	0.0246	0.0219

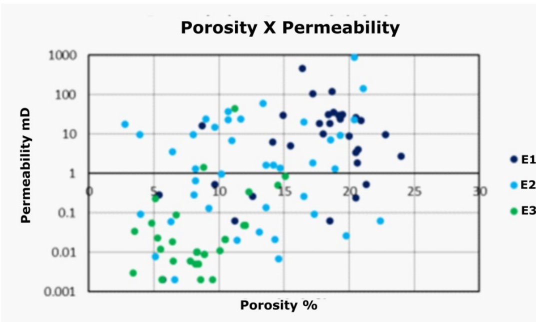

Figure 3 - Cross plot of porosity *vs* longitudinal permeability (RCAL analysis) with the points distributed according to the groups of electrofacies generated for the Barra Velha Formation interval in well 2.

microfacies that could only be described in a broad mode, since it is not possible to observe features in great detail in the photomicrography data. The three electrofacies enclose groups of characteristic microfacies that show different porosity and texture features. Figure 4 illustrates the microfacies described and Table 2 provides their general description.

The photomicrography analysis revealed that the porosity, the arrangement type connected to the degree of dissolution and cementation influenced the segregation of the three electrofacies (Table 2). Within the electrofacies E1, the microfacies show the highest porosity, independently of the porous size. The stromatolite-type arrangement is predominantly open, with a lack of cementation. The electrofacies E2 show intermediated porous size, compared with electrofacies E1 and E3.

Although the microfacies E1b and E2c display the same arrangement type, the microfacies E2c are more cemented, a factor that decreases the porous size. Another remarkable feature is the dense and closed arrangement observed on stromatolites-type microfacies E2a and E3d, separated into different electrofacies due to a greater or lesser degree of dissolution.

DISCUSSION

In the first analysis of the NMR porosity logs, it was possible to identify a cyclicality of increase and decrease of their values (Fig. 5). Works such as those published by Dias (2005), Wright & Barnett

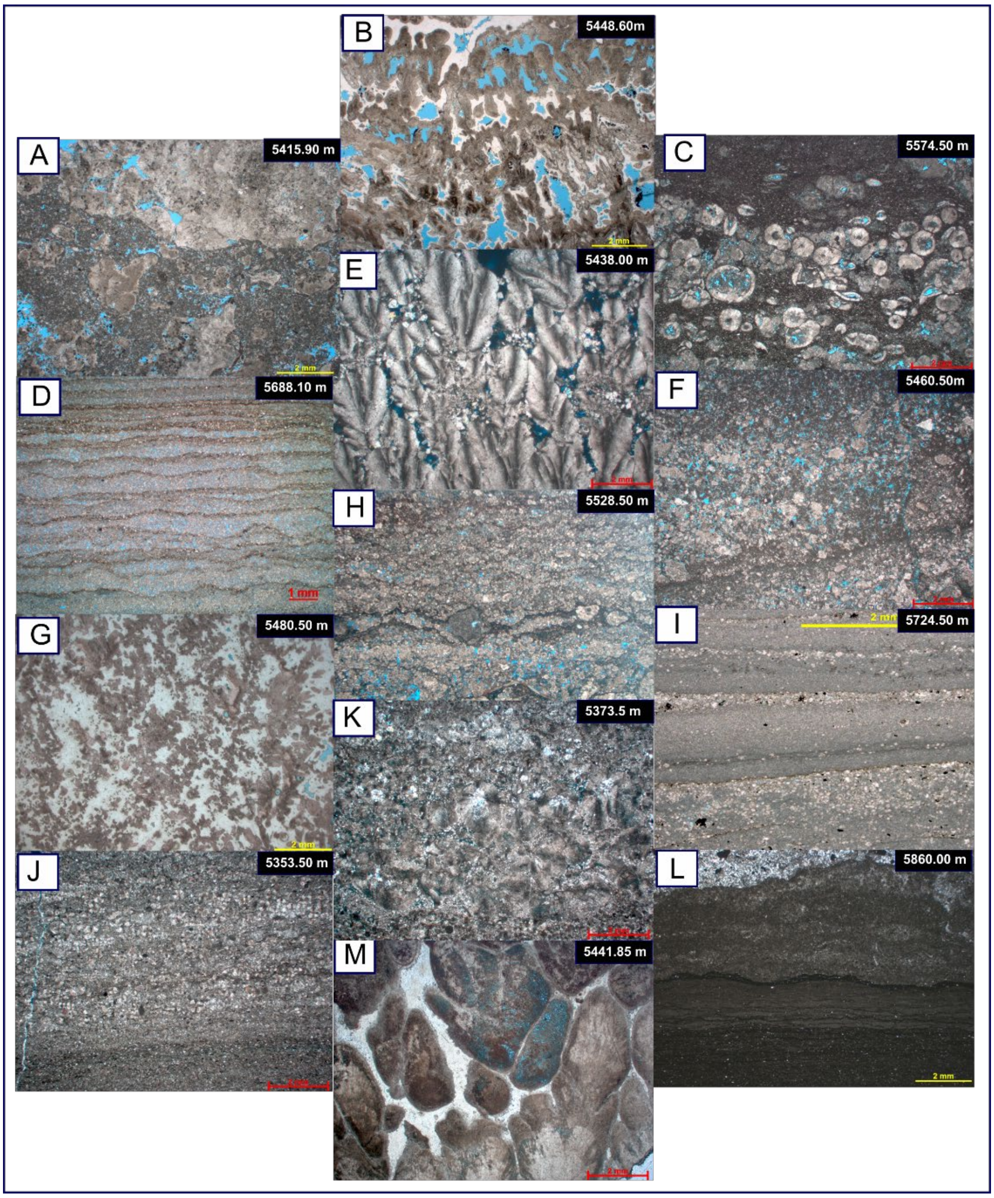

Figure 4 - The microfacies described in well 2: A) Microfacies E1a; B) Microfacies E1b; C) Microfacies E1c; D) Microfacies E1d; E) Microfacies E2a; F) Microfacies E2b; G) Microfacies E2c; H) Microfacies E2d; I) Microfacies E2e; J) Microfacies E3a; K) Microfacies E3b; L) Microfacies E3c; M) Microfacies E3d. For microfacies description, see Table 2.

(2015); Muniz & Bosence (2015), Arienti et al. (2018), Artagão (2018), Farias et al. (2019), Lima & De Ros (2019) have already recognized this kind of cyclicity related to the lithofacies of the Barra Velha Formation. In a first analysis, this log behavior was interpreted as a result of an increase and decrease in porosity.

Some inferences could be drawn through an integrated analysis of the microfacies and electrofacies of the Barra Velha Formation from well 2. In the basal portion, comprising the interval I, it is possible to recognize a predominance of the electrofacies E3. This electrofacies is associated with fine-grained microfacies, apparently composed of microcrystalline carbonates, laminated spherulites, and laminites. The microfacies suggests a low energy environment, possibly in the distal lacustrine portions. In the middle portion of Barra Velha Formation, comprising the interval I2, intercalations between electrofacies E1 and E2 are recognized associated with reworked spherulites showing dissolution features, which may indicate the proximal part of a lacustrine system, since it offers

Table 2 - A general summary of microfacies with their relative electrofacies in well 2.

Electrofacies	Microfacies	General Description
E1	E1a	Floatstone (?), 25% large mesopores, weak carbonate cementation
	E1b	Stromatolite-type open arrangement or travertine (?), >25% large mesopores, low silicification present in some thin sections
	E1c	Spherulite (?), ~10-25% large mesopores, apparently they appear as reworked particles, and in some cases it is possible to observe lamination
	E1d	Laminite, ~25% small mesopores, high dissolution porosity
E2	E2a	Stromatolite-type (?), dense arrangement, <20% large mesopores, weak carbonate cementation and low to moderate silicification
	E2b	Grainstone or microcrystalline limestone (?), > 25% small mesopores, rock masked by intense diagenesis
	E2c	Stromatolite-type open arrangement or travertine (?), < 15% large mesopores, high silicification
	E2d	Spherulite (?), 10-25% small mesopores, moderate cementation low dissolution
	E2e	Laminite (?), <10% small mesopores, with porosity by dissolution and fracture
E3	E3a	Spherulite (?), > 5% small mesopores, in microcrystalline limestone matrix, apparently laminated
	E3b	Packstone (?), 5-10% small mesopores, with small particles, microcrystalline limestone matrix
	E3c	Laminite (?), 0-5% small mesopores, presence of fractures.
	E3d	Stromatolite-type dense (?), 0-5% small or large mesopores, with pores intensely cemented (by carbonate and silica).

a high energy setting. At the top of interval I2, it occurs stromatolite-type microfacies, locally and intensively cemented, associated with the electrofacies E2, which registers a decrease in the energy of the depositional environment. Finally, in the upper portion of the Barra Velha Formation, the electrofacies E3 reappears associated with laminated spherulites and packstones, *in situ*, indicating the return of a low energy condition in the depositional environment. It is also noticed that the microfacies described does not repeat over the stratigraphic column of the analyzed section, except the microfacies E2a, which occurs in two different intervals. In this sense, different cycles of a decrease / increase of porosity might be related not only to diagenetic factors, but also to depositional changes given by variations on a lacustrine base level, since it implies on the type of carbonate deposits that will be developed.

In light of all above considerations, it is possible to recognize a clear correlation between the electrofacies hypothesis and the microfacies description, concerning porous attributes. In spite of the absence of further data to validation, such as photomicrography or RCAL data, the interpretation of the electrofacies from well 1 could be estimated by its proximity and similarity in values with the electrofacies from well 2. Moreover, it is an important find that the analysis of microfacies from rock samples corroborates the interpretation made upon indirect methods like those derived from well logs. Rock samples such as side well core are not ordinary data from well, conversely, electric logs are. Hence, it is important to reinforce that porosity characteristics assessed from these indirect methods are reliable and may be estimated since they are confirmed by direct data from rocks as it was demonstrated in this work.

CONCLUSION

Due to the high complexity presented by the Pre-Salt carbonates, a rising attempt to bring answers about the depositional context and the response of

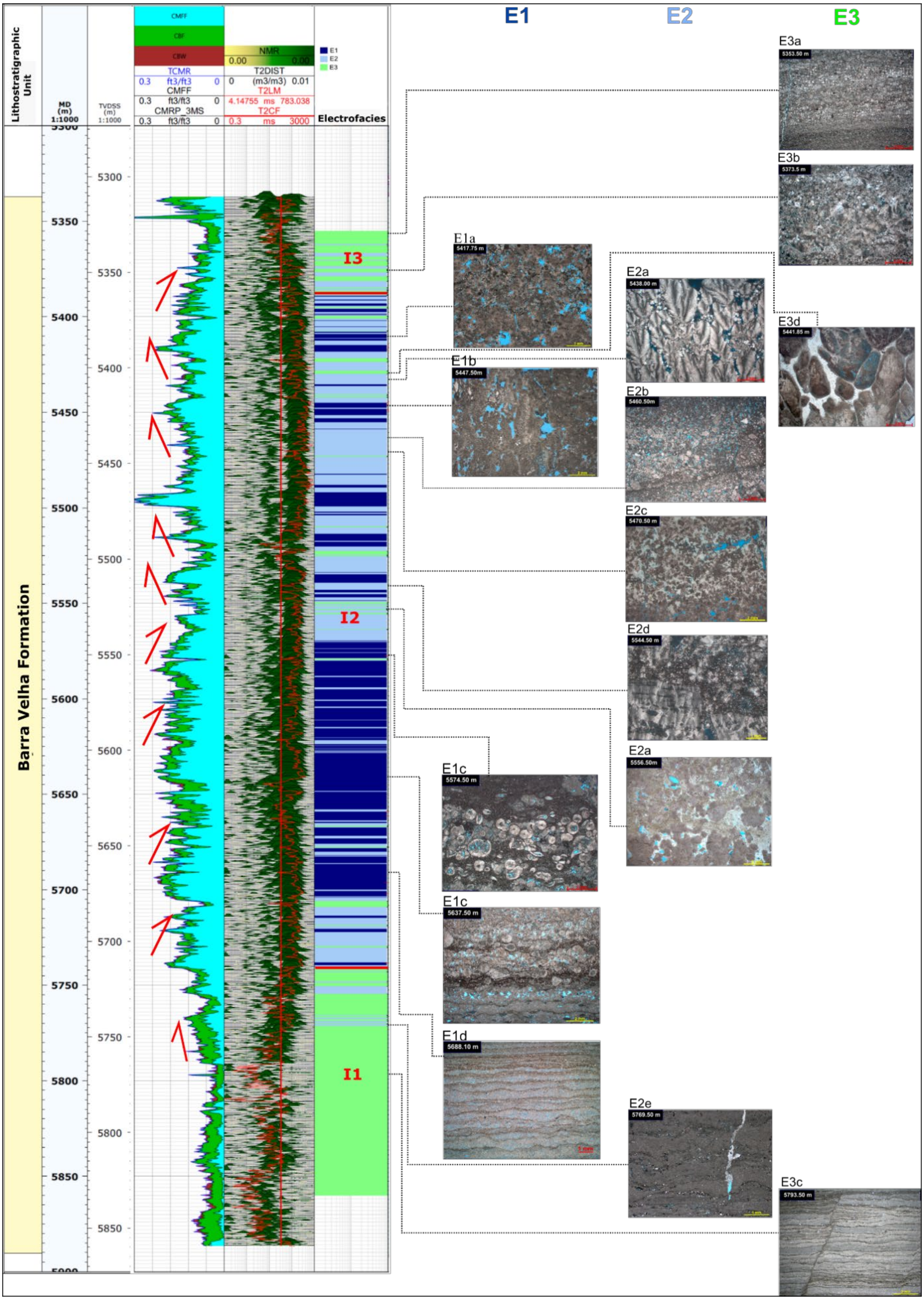

Figure 5 - Electrofacies model associated to the described microfacies (well 2), in stratigraphic order of occurrence. The red arrows point out to cycles of increase / decrease of the porosity, following the NMR log. The red bars into track 6 mark the limit of the intervals I1, I2 and I3.

these rocks upon the use of different exploration tools has been observed in several works. This work, although the paucity of data, aimed to shed some light on that effort by correlating responses given by two ordinary tools used in geological analysis in the Oil Industry: well data and petrography.

By the electrofacies modeling, it was possible to test and validate a method of clustering normally used in machine learning, the K-means. Such a method proved to be reasonable for the division of electrofacies, creating expected groupings, when considering the logs used to their generation. For instance, disregarding environmental conditions, the electrofacies E1 on both wells presented features of high porosity associated with low values of density and velocity of acoustic waves, while the electrofacies E3 encloses intervals of low porosity, being associated to higher values of the sonic and density logs.

From the photomicrography interpretation, groups of characteristics microfacies were described for each electrofacies. Within the electrofacies E1, high porosity microfacies were recognized, however, this does not mean only big pores. The electrofacies E3, on the other hand, is related to microfacies of low porosity, while the electrofacies E2 relates to intermediate microfacies, in spite of the large range of values presented by the cross plot of the RCAL data. High spikes in the NMR logs, specifically in the CMFF log, are not always related to big primary pores. High values of CMFF can be a result of microfractures in microporous rocks.

Depositional cycles / packages are recognized from the NMR log behavior, and when associated with the microfacies, it is possible to assume that this cyclicity might be related to not only diagenetic factors but also to periods of lower and higher energy.

Although it was not the goal of this work, there is no correlation between the electrofacies and a characteristic lithofacies. Each electrofacies showed different groups of microfacies, which in turn indicates different environmental systems (higher and lower energy). In this sense, it can be concluded that only the diagenetic factor (e.g., dissolution, cementation) is responsible for the electrofacies segregation.

Finally, the common analysis of the two methods (well logs / electrofacies and petrography) proved to be satisfactory, being possible to make inferences not only to log responses according to different classes of porosity but also in respect to the depositional context of the section investigated.

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