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Drill Cutting Samples Assessment for the Palynofacies Analysis and Paleoenvironmental Reconstruction: Codó Formation, São Luís-Grajaú Basin (Brazil)

Avaliação de Amostras de Calha na Reconstrução Paleoambiental e em Análises de Palinofácies: Formação Codó, Bacia de São Luís-Grajaú (Brasil)

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Abstract

The Codó Formation has 170.000 km² of extension and represents part of the Cretaceous Supersequence of the São Luís-Grajaú Basin, located in the northeastern part of Brazil. This formation is composed of shales, siltstones, limestones, sandstones, and some anhydrite levels. The marine influence in the Codó Formation is still being discussed in terms its geographic extension and time interval. Previous palynological studies on the 2-ANP-5-MA well and other sections have shown the presence of dinoflagellate cyst (*Subtilisphaera* genus) and fresh-water algae (*Scenedesmus*, *Pediastrum* and *Botryococcus*). This research aims to classify the sedimentary organic matter in drill cuttings of the 2-ANP-5-MA well. The drill cutting samples are from 2469–2559 m depth, and 25 slides were made with 3 m intervals between them. We applied the usual palynological method of preparation to identify the sedimentary organic matter (SOM) groups. Through the distribution analysis of the main groups and subgroups of the SOM, and application of the APP-diagram, four palynofacies were defined, as well as the redox conditions, the principal kerogen type generated and the depositional paleoenvironment. In addition, a statistical treatment with multivariate techniques (PCA and K-means clustering) and Fuzzy logic was used, aiming a better application of the drill cutting samples to paleoenvironmental reconstructions. In this stratigraphic section, the Codó Formation record is interpreted as a closed lagoonal system to a fluvial system passing through a marine incursion. The statistical and Fuzzy logic approaches appear as automated tools for grouping drill cutting samples, with a proposition of the PARE (Paleoenvironmental Reconstruction Ratio) that shows a good relationship with SOM data and previous works done in this stratigraphic section.

Keywords: Sedimentary Organic Matter; Fuzzy Logic; Paleoenvironment

Resumo

A Formação Codó possui uma extensão de 170.000 km² e representa parte da Supersequência cretácea da Bacia de São Luís-Grajaú, localizada na região nordeste do Brasil. Esta formação é composta por folhelhos, siltitos, calcários, arenitos e alguns níveis de anidrita. A influência marinha na Formação Codó ainda está em discussão em termos de sua extensão geográfica e intervalo temporal. Estudos palinológicos anteriores no poço 2-ANP-5-MA e em outras seções mostraram a presença de cistos de dinoflagelados (gênero *Subtilisphaera*) e algas de água doce (*Scenedesmus*, *Pediastrum* e *Botryococcus*). Esta pesquisa tem como objetivo classificar a matéria orgânica sedimentar em amostras de calha do poço 2-ANP-5-MA. As amostras representam as profundidades entre 2469–2559 m, das quais 25 lâminas palinológicas foram preparadas com intervalos de 3 m entre elas. Aplicou-se a metodologia padrão de preparação e análise para identificar os grupos da matéria orgânica sedimentar (MOS). Através da análise da distribuição dos principais grupos e subgrupos da MOS e da aplicação do diagrama APP, foram definidas quatro palinofácies, bem como as condições de redox, o principal tipo de querogênio gerado e o paleoambiente deposicional. Além disso, foi utilizado um tratamento estatístico com técnicas multivariadas (PCA e agrupamento por K-means) e lógica Fuzzy, visando uma melhor aplicação das amostras de calha para reconstruções paleoambientais. Nesta seção estratigráfica, o registro da Formação Codó é interpretado como um sistema lagunar fechado, passando a um sistema fluvial, com a ocorrência de uma incursão marinha. As abordagens estatísticas e de lógica Fuzzy mostram a automatização da utilização das amostras de calha através da aplicação da PARE (Índice de Reconstrução Paleoambiental), que mostra uma boa relação com os dados de MOS e trabalhos anteriores realizados nesta seção estratigráfica.

Palavras-chave: Matéria Orgânica Sedimentar; Lógica Fuzzy; Paleoambiente

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1 Introduction

Part of the Cretaceous Supersequence of the São Luis-Grajaú Basin is represented by the Codó Formation (Fernandes & Della Piazza 1978; Góes & Feijó 1994), which depositional condition is still being discussed, primarily due to the marine influence in geological and time interval. Based on sedimentary data, Messner and Wooldrifge (1964) considered three main environments for the Codó Formation. Thus, the Codó Formation was interpreted as a lagoonal and restricted marine environment, flowing to a fluvial-deltaic environment and then a lacustrine environment on the top, passing through a marine environment on the base of the upper members.

Based on the chemical stratigraphic analyses, Rodrigues (1995) separated the Codó Formation in five intervals and pointed out the marine influence in the lower members. Antonioli and Arai (2002) and Eneas et al. (2022) identified two distinct occurrences for the *Subtilisphaera* genus on the Codó Formation, one linked to the *Sergipea variverrucata* (upper Aptian) and *Complicatisaccus cearensis* (lower Albian) biozones.

Concerning the UN-24-PI and UN-37-PI wells data, Basin (2014) separated the Codó Formation into five intervals and interpreted, based on the organic components, that the marine intrusion in this formation was located in the lower member, despite non-marine palynomorph founds. In addition, Gonzalez et al. (2020) determined four palynofacies associations for the 2-ANP-5-MA well, despite the presence of dinoflagellate cysts (*Subtilisphaera* genus) and fresh-water algae (*Scenedesmus*, *Pediastrum,* and *Botryococcus)* in the Codó Formation, and considered the marine inclusion only for the overlapped sequence, the Itapecuru Formation.

Recently, an increasing number of researchers have come out to understand the limitations and uses for drill cutting samples, not only in the gas and oil systems but also in the geochemistry of igneous rock (Fontana et al. 2021; Szalak et al. 2021; Vaizman et al. 2020; Ayati et al. 2019; Fowler & Zieremberg 2016; Mostavi et al. 2015). Focusing on data integration, we show a new approach for analyzing drill cutting sample data using the palynofacies and fuzzy logic techniques to associate the hydrodynamic equivalence and the preservation ratio between the granulometric class and the components of SOM (Wentworth 1922; Tyson 1989; 1993; 1995; Vincent 1995; Piper 1995; Mendonça Filho 1999; Dubois et al. 2012), which allows an overview of the inorganic and organic compounds in the sediments, during their transportation and deposition.

Concerning the extensive discussion about using drill cutting samples in reconstruction and biostratigraphic analyses for the oil industry (Mostavi et al. 2015; Fowler & Zieremberg 2016; Ayati et al. 2019; Vaisman et al. 2020; Fontana et al. 2021; Szalak et al. 2021), we propose an integrated way of lithological percentage data from drill cutting samples to facilitate and automatize the usual palynofacies analysis of Tyson (1995) and Mendonça Filho (1999) aiding the paleoenvironmental reconstruction stage.

2 Geological Setting

The São Luís-Grajaú Basin is located in the northeast of Brazil, and it has 2500 m thickness of sedimentary rocks and 500 m thickness of igneous rocks, with the sedimentary covers dating from the Silurian to the Cretaceous (Caputo et al. 2005; Vaz et al. 2007). Its formation is related to the opening of the Atlantic Ocean, surrounded at the north by the Ilha Santana Platform and at the south by the Ferrer-Urbano Arch (Zalan 2007). The basin can be divided into three interior units: (a) the Silurian, Devonian, and Carboniferous-Triassic sequence, corresponding to the Serra Grande, Canindé and Balsas groups; (b) the Jurassic sequence represented by the Mearim Group; (c) and the Cretaceous sequence comprising the Grajaú, Codó, and Itapecuru formations (Figure 1), followed by the Mesozoic magmatic sequences related to the Mosquito and Sardinha formations (Góes & Feijó 1994).

The Serra Grande Group (Ipu, Tianguá, and Jaicós formations) composes the Silurian Supersequences. The Canidé Group is separated into Pimenteiras, Itaim, Cabeças, Longá and Poti formation, a Mid-Devonian-Carboniferous sequence (Góes & Feijó 1994; Vaz et al. 2007). The Upper Carboniferous–Lower Triassic and Jurassic sequences are formed by Balsas Group, divided into Piauí, Pedra de Fogo, Motuca, Sambaíba, and Pastos Bons formations. The Balsas Group is overlapped by the basalts from the Mosquito Formation (Lima & Leite 1978; Góes & Feijó 1994; Vaz et al. 2007).

In the São Luís-Grajaú Basin, the Grajaú, Codó, and Itapecuru formations are the Cretaceous Supersequence, associated with the transgressive and regressive system during the Atlantic Ocean opening (Góes & Feijó 1994). The Codó Formation, superimposed on the Grajaú Formation and overlapped by the Itapecuru Formation, comprises shales, siltstones, limestones, sandstones, and some anhydrite levels (Paz & Rossetti 2005; Vaz et al. 2007; Rossetti et al. 2004). The Codó Formation has a maximum thickness of 237 m and has 170.000 km² of extension (Fernandes and Della Piazza 1978; Góes & Feijó 1994).

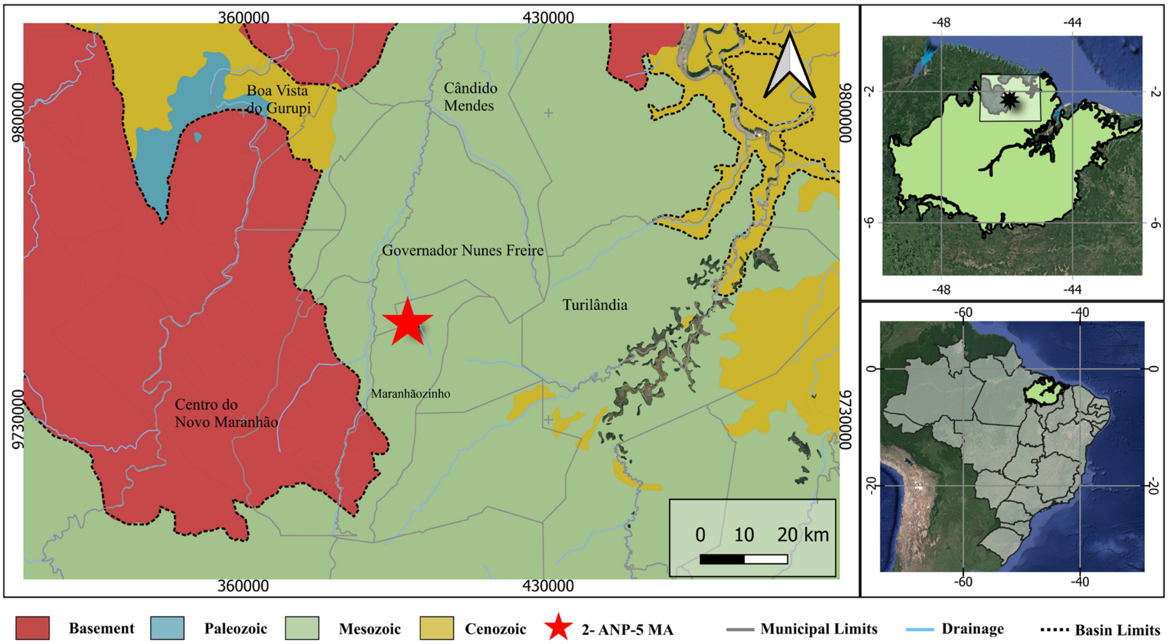

Figure 1 Map of part of the São Luís-Grajaú Basin, NE Brazil, with the location of the 2-ANP-5-MA well. Available on the CPRM (Brazilian Geological Survey) at 1:1,000,000 scale.

3 Material and Methods

3.1 Samples and Palynofacies Preparation

The drill cutting samples from this study are from a Petrobras S.A. well, disposed of by the Brazilian National Petroleum Agency (ANP) for the PRH 47.1 project, and storage at the Applied Micropaleontology Laboratory (LMA) in the Sedimentary Geology Laboratory (LAGESE) from the Department of Geology, Federal University of Pernambuco (Brazil). For the analysis of organic matter, 25 slides were made on the drill cutting samples of the 2-ANP-5-MA PETROBRAS's well, located at UTM zone 23 south, 9751725.8N and 398247.9E, embracing the Codó Formation (2469–2559 m). The sampling selection was made using the ANP-Terrestre data, that corresponds to the lithological (anhydrite, shale, siltstone and sandstone. See Supplementary Materials 1 and 2) percentage in each drill cutting samples. The slide confection was done according to the usual palynofacies preparation (Tyson 1995; Mendonça Filho et al. 2002; 2011), differing only by washing the samples with a degreaser to remove any oil residue on the samples. The silicates were separated using hydrofluoric acid (HF) at 40% concentration and the carbonates by hydrochloric acid (HCl) at 37%. The residue was sieved in a 10 μm opening net with distillate water every 24 hours after an acid attack. The organic content was aggregated to the slides using a polyvinyl Alcohol (PVA) and Norland Optical Adhesive cured under ultraviolet light.

3.2 Microscopy Analyses

In each slide, 300 particles of organic matter were counted (Tyson 1995; Mendonça Filho et al. 2011) using white light microscopy in a Zeiss microscope (Axio Imager A.2) with 20X air objective and 100X oil immersion, coupled with a digital Axiocam 503 camera. The particles were separated into the main kerogen groups (Amorphous organic matter, phytoclast and palynomorphs) and subgroups (opaques phytoclast, non-opaques phytoclast, pollen and spores grain, resin, freshwater and marine microplankton) being grouped for the analysis of the palynofacies, redox and proximal-distal conditions of the deposition, and kerogen generation potential.

3.3 Statistical Approach

The organic components of each sample were cataloged, and the association of the SOM was plotted in the RiojaPlot site, using the separation of the main groups of the kerogen (Mendonça Filho et al. 2011; 2014; Tyson 1995) to correlate its abundance along the 2-ANP-5-MA drill cutting samples. The APP-Diagram (Amorphous Organic Matter-Phytoclast-Palynomorphs Diagram; Tyson 1995) expresses the different conditions of deposition, paleoenvironment, and kerogen from the samples considering only the three main groups of the kerogen (Phytoclast, Amorphous organic matter and Palynomorphs).

Based on the lithology description from each kind of sediment found in the drill cutting samples (sandstone, siltstone, and shale), the PCA (Principal Component Analysis) was employed to decorrelate the lithology information (Pearson 1901; Jolliffe & Cadima 2015; Hotelling 2016;). The results (Principal Components or PCs) were selected as input data to apply the K-means clustering technique (MacQueen 1965) for grouping similar samples, Orange Data Mining software was employed for this task. We considered the well-established statement of the kind of sedimentary organic compounds transported in each sedimentary fraction (Wentworth 1922; Tyson 1989; 1993; 1995; Vincent 1995; Piper 1995; Mendonça Filho 1999; Dubois et al. 2012). Thus, the reliability of each point of the well could be estimated based on the granulometric class and the hydrodynamic equivalence and preservation.

Fuzzy Logic (Zadeh 1965) was also applied to ponder the relation between the lithologies and the organic compounds. The procedure was based on the following stages: fuzzification, fuzzy membership identification, the application of fuzzy operators, and defuzzification. Three variables were considered (shale, siltstone, and sandstone), with the levels of anhydrite associated with the sandstone class due to the low probability of preservation of SOM in these levels. For each variable, a fuzzy membership function [$\mu(x)$] was applied, considering the hydrodynamic equivalence and the preservation ratio between the granulometric class and the components of the SOM proxies. The fuzzy membership functions used in this research are shown in equations 1 to 3.

Shale: positive linear function, $\mu(x) = x$ (1)

Sandstone: negative linear function, $\mu(x) = 1 - x$ (2)

Siltstone: positive linear function, $\mu(x) = 0.7x$ (3)

The data were integrated using fuzzy membership functions combination (Figure 2). Sand and the silt fraction variables were first matched by the fuzzy algebraic sum operator, and the result (decreasing material variable) was joined with the shale fraction variable using the gamma operator ($\gamma = 0.5$) (Zimmermann 1991).

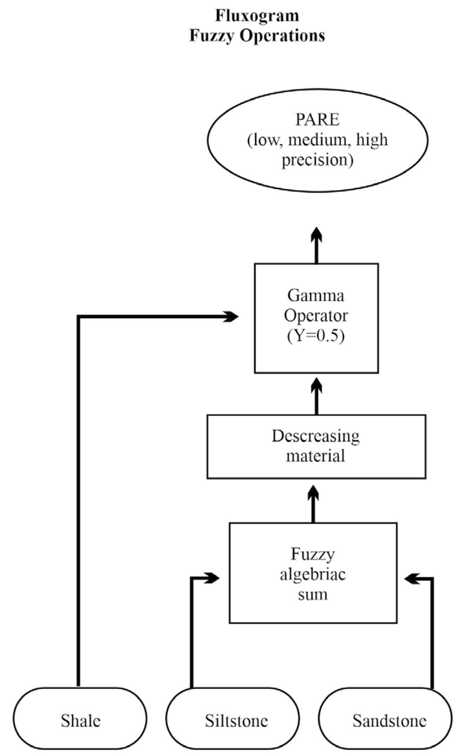

Figure 2 Sequence of fuzzy logic application, using different fuzzy operators to combine the shale, siltstone, and sandstone variables. The decreasing material refers to the siltstone and sandstone fractions in the samples since the high percentage of those materials has a decreasing effect on the final result (PARE).

4 Results

4.1 Palynofacies Association

Four palynofacies were identified by the abundance and distribution of SOM associations (Figure 3). Palynofacies I (2550-2559) is predominantly composed of high AOM (70.00%-90.67%). Palynofacies II (2526–2550 m) has a medium abundance of AOM (average 57.80%) and non-opaques phytoclast (20.00%-42.30%). Palynofacies III (2481–2526 m) is characterized by a high amount of opaques phytoclast (2.60%–35.60%), rare palynomorphs (basically 2.60% of the components), and the presence of dinoflagellate cyst (3.30%) of the genus *Subtilisphaera,* in the 2517 m sample. Palynofacies IV (2469–2481 m) is composed of non-opaques phytoclast, stripped and non-biostructed (max. 41.00%) and palynomorph (average 18.00%); in this palynofacies, freshwater algae (*Scenedesmus*, *Pediastrum* and *Botryococcus)* also occurs.

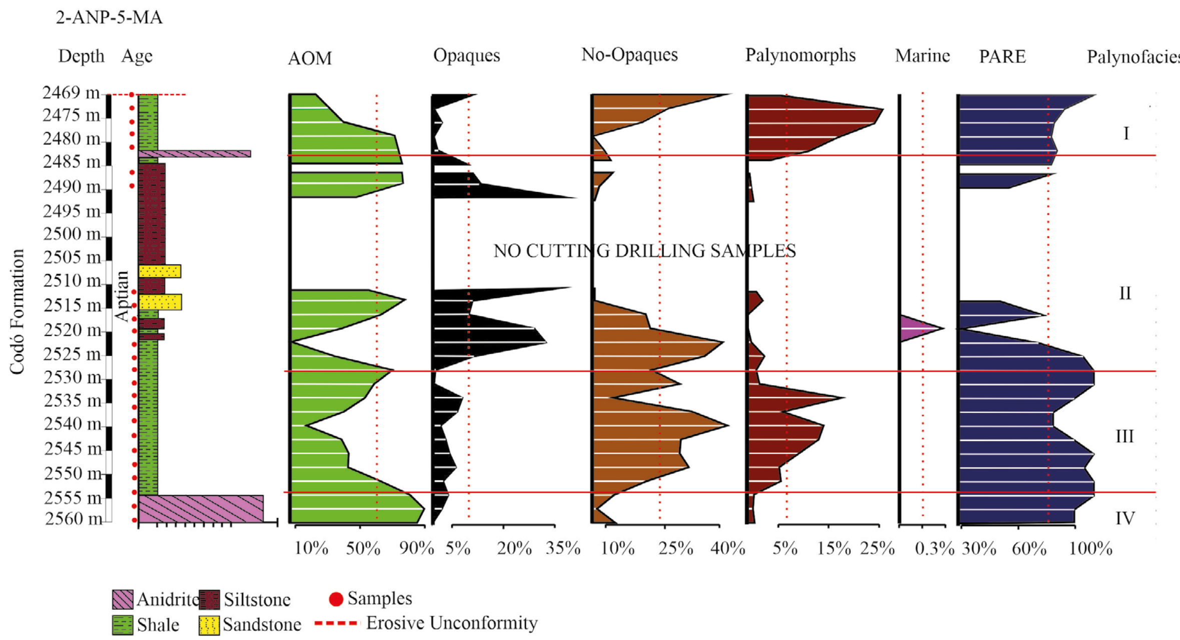

Figure 3 On the left, the composite profile from the 2-ANP-5-MA well, modified from the ANP Terrestre website. On the right, the distribution and association of the kerogen compounds of the samples are shown, including the PARE (Paleoenvironmental reconstruction ratio), are shown blue. The sedimentary distribution was made using the traditional palynological analyses (Tyson 1995; Mendonça 1999) and the PARE. The red horizontal bars represent the limits of each palynofacies interval, and the dotted vertical red lines indicate the medium values of each kerogen group and PARE.

4.2 Palynofacies Microscopy

SOM components from the 2-ANP-5-MA samples under white light and ultraviolet reflected light. Most palynomorphs fluoresce, but the AOM is mainly non-fluorescent, with the palynomorphs' fluorescence color ranging from an orange-yellow to a yellow-greenish color (Figure 4 A-E).

4.3 APP-Diagram (AOM-Phytoclasts-Palynomorphs Diagram)

The APP-Diagram has a proximal-distal feature from top to bottom and a redox-oxic environment from left to right (Figure 5). Each field (I-IX) in the diagram represents a palynofacies fields and paleoenvironment from Tyson (1995).

Four fields were determined (Figure 5): (a) palynofacies fields IX and VI, in red, with reducing conditions; (b) palynofacies fields VII and VIII, in greenish-blueish regions, with more oxidizing conditions, represented by the input of continental components; (c) palynofacies field VI (proximal suboxic-anoxic shelf), characterized by very good preservation of the AOM due the reducing conditions, with the average presence of phytoclast as a consequence of the proximity with the source; (d) palynofacies field IX (distal suboxic-anoxic shelf, carbonate shelf, restricted marine (proximal) or lagoon), with a high content of AOM and a low presence of palynomorphs, being related to stratified sea shelf deposits or deep basin. The palynofacies fields VI, VII, VIII, IX are oil-prone and produce kerogen II. The palynofacies fields VII and VIII represent the distal dysoxic-anoxic/suboxic-anoxic shelf, marked by good preservation of the AOM with few palynomorphs, as well as deposits of organic-rich shales and bituminous mudstones.

4.4 Multivariate Statistics and Fuzzy Logic

The results from the PCA technique in the lithology data, followed by the K-means classification, produced three clusters. Cluster 1 (C1) is marked by finer granulometry, with 70.00% ≤ clay ≤ 100.00%, 0.00% ≤ silt ≤ 20.00%, and 0.00 ≤ sand ≤ 20.00%. Cluster 2 (C2) is marked by coarser granulometry, with contents of sand fraction greater than or equal to 20.00%, and cluster 3 (C3) represents a mixture mainly of clay and silt fractions 30.00% ≤ clay ≤ 65.00%, 30.00% ≤ silt ≤ 70.00%, and 0 ≤ sand ≤ 10.00% (Figure 6A).

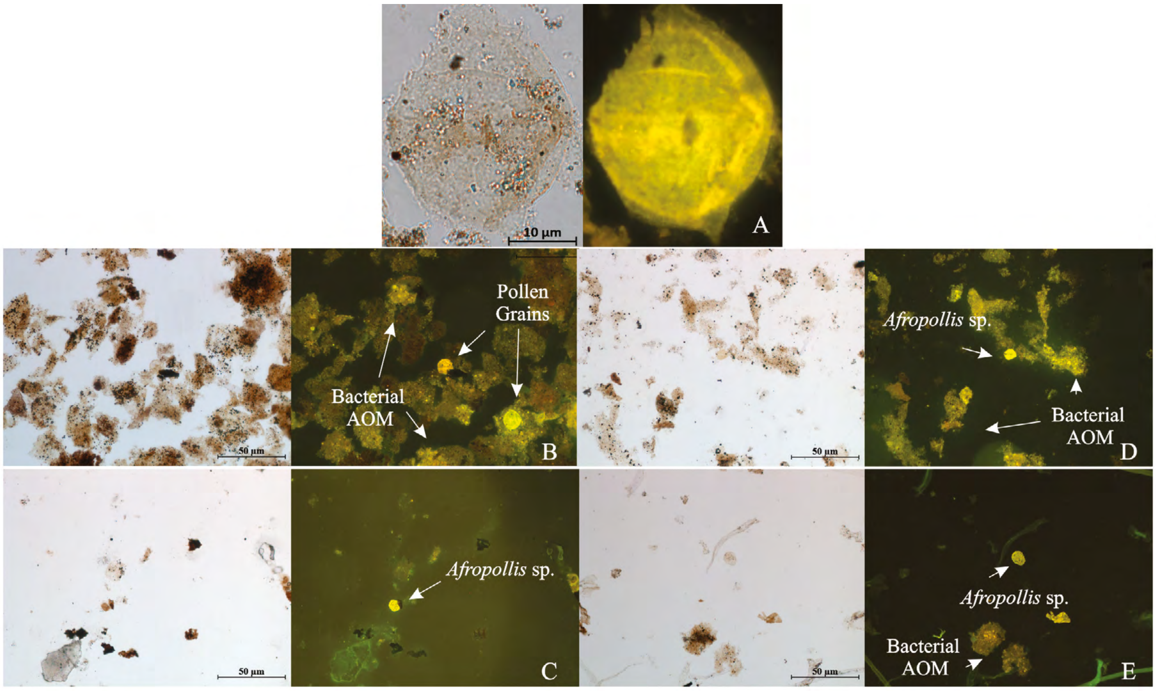

Figure 4 SOM from the 2-ANP-5-MA samples, under white light (on the left) and ultraviolet reflected light (on the right): A. Subtilisphaera sp.; B. Sample 2478; C. Sample 2535; D. Sample 2556; E. Sample 2523. On the right, the organic matter is under white light, and on the left, under fluorescence. The AOM is mainly not fluorescent and has mineral inclusions, while the sporomorphs have a greenish-orange-yellow color.

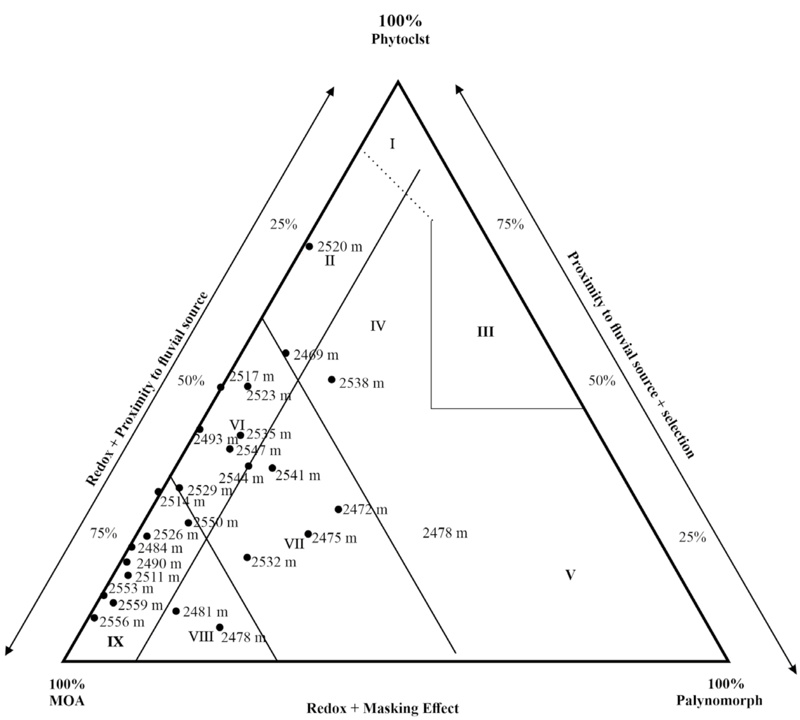

Figure 5 APP-Diagram modified from Tyson (1995) showing the distribution of samples from the 2-ANP-5-MA well. Each Roman numeral denotes the palynofacies' fields and environments from Tyson (1995).

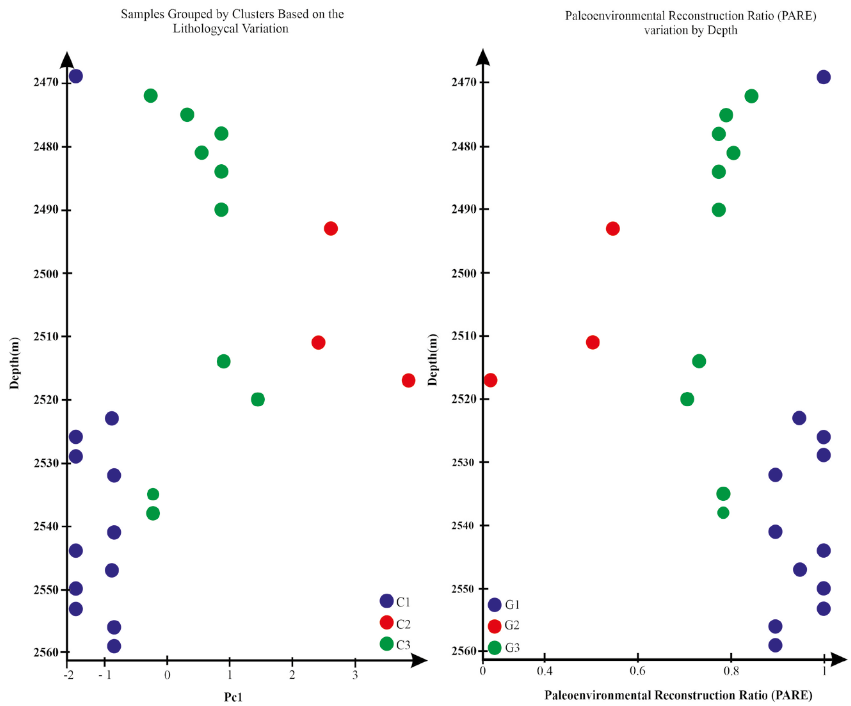

Figure 6 On the left, graph of PC1 versus depth, with clusters C1, C2, C3 grouping samples with similar granulometric associations. C1 indicates clay-rich samples, C2 is associated with sand-rich samples, and C3 shows clay and silt mixture samples. On the right, graph of PARE versus depth, with groups G1, G2, G3. Note that G1 group is related to clay-rich material, G2 indicates sand-rich samples, and a mixture of clay and silt samples marks G3. The results generated by PCA and fuzzy logic (PARE) are very similar.

Concerning fuzzy logic, the defuzzification stage was associated with interpreting the precision on each point of the drill cutting samples, called the Paleoenvironmental Reconstruction Ratio (PARE). The PARE is associated with the following significance: low, medium, and high precision for estimating the SOM preservation in each drill cutting sample based on the lithological mixture. In this paper, for example, low PARE values vary from 28.60% to 54.70%, while medium and high values of PARE comprise the interval of 54.70%-80.40% and 80.40%-99.80%, respectively.

The clustering of the samples based on the PARE results separates them into 3 groups (G1, G2, G3). G1 is composed of 12 samples with a high PARE (89.50%–99.80%). G3 has 10 samples that were interpreted as a medium PARE, from 70.60%-84.40%. G2 represents three samples with a low PARE (28.60% to 54.70% precision; Figure 6B).

Palynofacies I (2550-2559 m) has 94.60% of PARE average, the highest of the samples. Palynofacies II (2526-2550 m) is marked by a PARE average of 92.10%. Palynofacies III (2481–2526 m) has a PARE with an average of 69.64%. In the sample from 2517 m, the PARE has the lowest value from all the investigated samples (28.60% PARE), reflecting the high sand and silt fractions, despite a 51.60% AOM. Palynofacies IV (2469–2481 m) is associated with a PARE average of 84.50% (Figure 3).

5 Discussion

The palynofacies analysis from the 2-ANP-5-MA well section (Figure 3) points out two main phases from paleoenvironments for the Codó Formation. One phase is associated with the high preservation of non-opaques phytoclast, which can be related to higher energy environment (palynofacies II and IV; Figure 3). It could represent a shelf with high preservation of the AOM and reducing conditions, with abundant preservation of the allochthonous terrestrial material in close to a fluvial-deltaic source or turbidites (Tyson 1984; 1987; 1993).

The other phase is associated with the palynofacies I and III, with an interpreted lower hydrodynamics, as a lagoon or closed lake system due to the higher preservation of AOM and non-opaques phytoclast. The increase of the non-opaque phytoclast is proportional to the distal settings, as their size becomes smaller due to the prolonged transport and fragmentation (Tyson 1989; 1993; 1995; Vincent 1995; Piper 1995; Mendonça Filho 1999). Those data could be associated with more humid paleoclimate during the Brazil-Africa separation in the Cretaceous (Santos et al. 2022).

The palynofacies I is located on the top member of the drill core sample from this same well and was characterized by Santos et al. (2022) and is also could be related to a semi-arid climate considering a increasing on the abundance of the representatives of the genus *Classopollis* in comparison to the other sporomorphs from the assemble such as the genus *Araucaracites* and *Inaperturopollenites*; this same abundance is expressed in the palynofacies III from our interpretation (Figure 3), associated with a higher AOM preservation, and redox conditions. Both palynofacies II and IV determined in our study would represent, considering Santos et al. (2022) data, a less dry environment with the dominance of the genus *Araucaracites* and *Inaperturopollenites* in comparison to the genus *Classopollis*; and a high oxic feature with the presence of more phytoclasts amounts, showing the same cycles described by Santos et al. (2022), on the core samples of the 2-ANP-5-MA well, are kept on the drill cutting samples (a semi-arid to more humid paleoclimate).

The four palynofacies associations are related to the intervals for the Codó Formation defined by Rodrigues (1995; Figure 7), regardless the different methods used in the studies. Based on chemical-stratigraphic analyses, five intervals were considered in association with the chemical composition of the organic matter and paleoenvironmental interpretation by Rodrigues (1995). Interval 1 is located on the bottom of the formation and has a low concentration of COT, with the organic matter mainly derived from higher plants. Paleontological content and biomarkers indicate a marine environment ranging from a high salinity to brackish conditions. Interval 2 has a high COT, a lipidic-rich organic matter, reflecting a more restrictive environment, with dysaerobic-anoxic conditions. As the second interval, Interval 3 has high COT and a more lipidic composition. This interval represents the climax of the marine transgression during the Codó deposition. Interval 4 designates a hypersaline environment, dysaerobic with a layer of evaporites on the top of the interval. Interval 5, located at the top of the Codó Formation, has very similar features with interval 1, with higher plants dominance on the organic matter, ranging from a high salinity to brackish conditions.

Using the anhydrite level in a stratigraphic correlation, present in the 2-ANP-5-MA-well and 1-CL-1-MA, described by Rodrigues (1995), his interval 2-5 resembles our palynofacies I-IV, interpreted in this paper (Figure 7). Interval 2 from Rodrigues (1995), marked by a high COT and associated with a restricted kind environment with dysaerobic-anoxic condition, has the same depositional condition of the field IX defined by Tyson (1995) called distal suboxic-anoxic shelf, carbonate shelf, restricted marine (proximal) or lagoon; this interval 2 is linked to our palynofacies I, with a high presence of MOA.

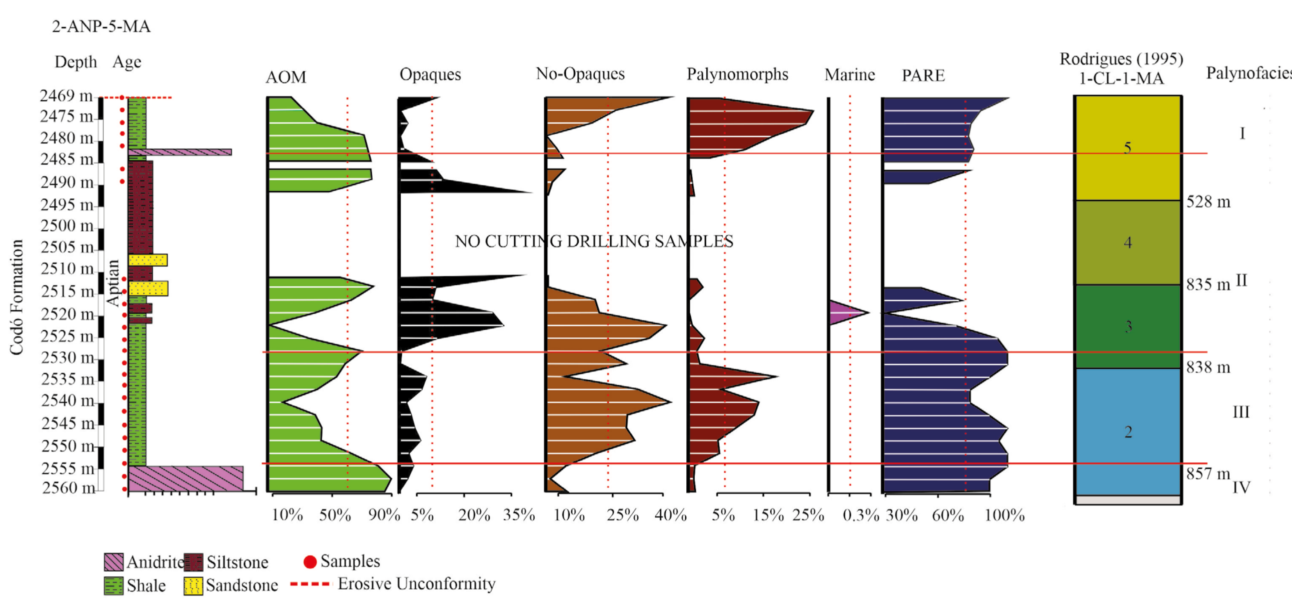

Figure 7 The 2-ANP-5-MA drill-cutting palynofacies interpreted in this research (I to IV), and Rodrigues (1995) intervals correlations.

Interval 3 (Rodrigues 1995) could be related with our palynofacies II. In palynofacies II, there is a balance of the MOA and terrigenous components, and non-marine palynomorph was found in it, so here, palynofacies II would be interpreted better as a fluvial or close to a fluvial-deltaic kind of environment (Tyson 1995). The disponibility of organic compounds during the deposition of this interval is better related to the Equatorial humidity belt defined by Santos et al. (2020), differently, as classified by Rodrigues (1995), which classified Interval 3 as the marine transgression climax.

Our palynofacies III and Interval 4 (Rodrigues 1995) are characterized by the high presence of opaques phytoclast, indicating a more oxide condition. The presence of the genus *Subtilisphaera,* in the 2517 m sample analyzed in this paper (Figure 4), would be related to marine waters on the Codó Formation (Regali 1989; Arai et al. 1994; Arai 2014). The deposition of an evaporite package represents the end member of this sequence or as determined by Rodrigues (1995), a dysaerobic environment with a layer of evaporites on the top of the interval, the huge difference, between Rodrigues's (1995) intervals and the palynofacies interpreted in this paper.

The presence *Subtilisphaera* in the 2517 m sample, is related to Mesner and Wooldrifge (1964), according to, interpreted as a lagoonal and restricted marine environment, flowing to a fluvial-deltaic environment and then a lacustrine environment on the top, passing through a marine environment on the base of the upper members. Antonioli and Arai (2002) classified for the upper units of the Codó Formation, a regression state, characterized by a ranging in dinoflagellates assemblage, ranging from the absolute abundance to a few representants, and based on this abundance and pollen grains association, divides two zones for genus *Subtilisphaera* occurrence the P-270 and P-280 Palynozones, nevertheless, as only one specimen from the dinoflagellate genus was found in this paper, it is not clear from each zone it would be better placed.

Lastly, the Interval 5 (Rodrigues 1995) and our Palynofacies IV, are both related to a proximal suboxic-anoxic shelf (Tyson 1995), are characterized by the high presence of terrigenous materials and sporomorphs on the sequence and marked by the main abundance of brackish water algae components and high presence of superior plants on the organic matter and brackish to saline conditions.

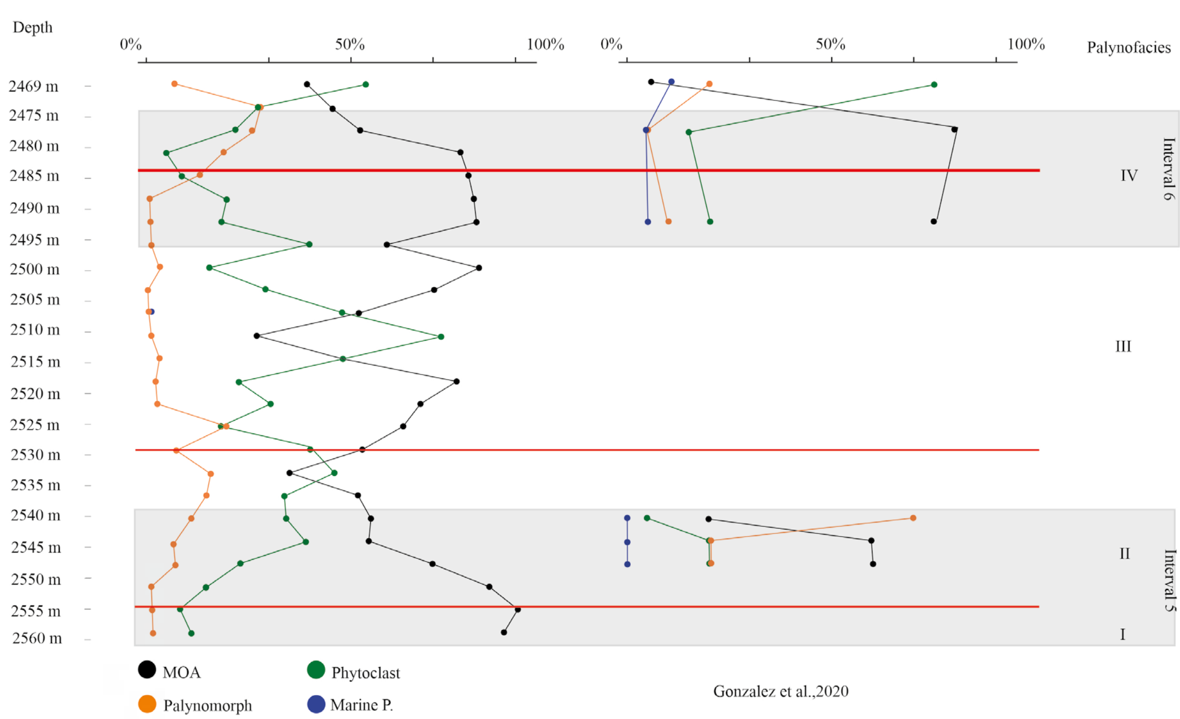

Figure 8 The 2-ANP-5-MA drill-cutting palynofacies interpreted in this research (on the left) and sedimentary organic matter distribution from Gonzalez et al. (2020; on the right). The colored dots on the bottom-left represent the three main component from the SOM and the marine palynomorph's occurrence.

Basin (2014), considering the UN-24-PI and UN-37-PI wells, and based on isotopic, geochemical, and lithological data, divided the Codó Formation into five intervals during the Aptian-Albian transition of the Parnaíba Basin: A) the base of the Codó Formation is characterized by a marine incursion, upping the sea level on the basin and allowing the black shales deposition; B) the input of the terrigenous material masking the marine provenient organic matter. C) a high evaporation cycle with restricted features; D) the normal salinity deposited shales and claystones; E) and predominant continental sediments. All those intervals are directly related to Rodrigues (1995) intervals, and the palynofacies identified in this paper. Intervals B-E are analog with palynofacies I-IV, respectively; the main difference is in the correlation with the Interval B and palynofacies I, where the AOM is derived from the decomposition of superior plants as defined by Mendonça (1999) and not from marine components. Interval A is not part of the cutting drill on the 2-ANP-5-MA well,

Our palynofacies IV and I have very close results with the palynofacies analysis of Gonzalez et al. (2020), on the core of the same well, specifically on intervals 5 and 6 defined in their paper (Figure 8). Our palynofacies I and the interval 5 from Gonzalez et al. (2020) have an average of 70.47% and 70.00% of the AOM content, respectively, less than 0.50% of the difference, on both the second most important compounder is the phytoclast, and palynomorph is the least representative group. In addition, our palynofacies IV and interval 6 from Gonzalez et al. (2020) (Figure 8) have similar average values of sporomorphs, 11.88% and 10.40%, respectively. Both share the same features, more oxidizing conditions, with a more abundance of sporomorph from the section, an abundance of freshwater algae, and a high abundance of non-opaque phytoclasts. The occurrence of the genus *Subtilisphaera* unravels a marine influence on the section, related to the marine transgression on the São Luís Basin in the Aptian (Regali 1989; Arai et al. 1994; Arai 2014).

Based on the APP-diagram, all palynofacies fields analyzed (VI, VII, VIII, IX) are oil-prone and produce kerogen II (Tyson 1995), considering the mixture of AOM, the lipidic component with terrigenous materials that was also characterized by the *Van Krevelen* graphic from the geochemical analyses made by Alvarenga (2010) that also indicates, an excellent organic matter for the hydrocarbon generation on the Codó Formation.

6 Conclusions

Considering the main groups and subgroups of the SOM described from the cutting drilling samples of the 2-ANP-5-MA well, in the 2469 to 2559 m interval, two main paleoenvironments and depositional conditions were interpreted: (a) a closer to a fluvio-deltaic source environment, with high energy and more oxic conditions, due to the presence phytoclasts (palynofacies II and IV); and (b) a more redox system, with lower energy and high AOM preservation (palynofacies I and III), represented by a semi-closed to closed environments. In this section, the Codó Formation was interpreted as a non-marine environment on the lower unit, specifically a lagoonal system close to a fluvial-deltaic source. On the middle members of the Codó Formation, the presence of the genus *Subtilisphaera* represents the incursion of marine water, interpreted as a semi-closed lagoonal system. In this section, the Codó Formation would generate kerogen type II.

The new methodological approach here presented with the integration of the lithological data from drill cuttings, and called paleoenvironmental reconstruction ratio (PARE), in general, showed a high precision with the SOM components contents/preservation, and aided the palynofacies determination, appearing as a powerful tool to automate and facilitate the paleoenvironmental reconstructions studies using drill cutting sample data. Based on the low, medium, and high precision of PARE, we demonstrate suitable results in the Codó Formation pilot case study, collaborating with the perspective of using cutting drilling samples for paleoenvironmental interpretation. However, as a starter method, it is essential to detach that more analyses on this type of data are necessary to understand its limitations fully.

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8 References

Antonioli, L., Arai, M. 2002, 'O registro da Ecozona Subtilisphaera na Formação Codó (Cretáceo Inferior da Bacia do Parnaíba, Nordeste do Brasil): seu significado paleogeográfico', *Boletim no 6° Simpósio sobre os Cratáceo do Brasil/2° Simposio sobre el Cretácico de América del Sur*, vol. 6, pp. 25-30.

Arai, M., Lana, C.C., Pedrão, E. 1994, 'Ecozona *Subtilisphaera* spp.: Registro cretáceo de um importante episódio ecológico do Oceano Atlântico primitivo', *Acta Geológica Leopoldensia*, vol. 17, pp. 521-38.

Arai, M., 2014. 'Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: A paleontological perspective', *Brazilian Journal of Geology*, vol. 44, pp. 339-350, DOI:10.5327/Z2317-4889201400020012.

Alvarenga, M.V.D.S. 2010, 'Fácies orgânica e evolução térmica de uma seção sedimentar da formação Codó, da Bacia do Parnaíba', Undergraduate thesis, Universidade Federal do Rio de Janeiro.

Basin, P. 2014, 'Estratigrafia química aplicada à Formação Codó nos furos de sondagem UN-24-PI e UN-37-PI (Aptiano/Albiano da Bacia do Parnaíba)', *Boletim de Geociências da Petrobrás*, vol. 22, no. 2, pp. 289-312.

Caputo, M.V., Iannuzzi, R., Fonseca, V.M.M. 2005, 'Bacias sedimentares brasileiras: Bacia do Parnaíba', *Fundação Paleontológica Phoenix*, vol. 81, no. 7, pp. 1-6.

Dubois, S., Savoye, N., Grémare, A., Plus, M., Charlier, K., Beltoise, A., Blanchet, H., 2012. 'Origin and composition of sediment organic matter in a coastal semi-enclosed ecosystem: An elemental and isotopic study at the ecosystem space scale', *Journal of Marine Systems*, vol. 94, pp. 64-73, DOI: 10.1016/j.envpol.2009.07.022>.

Eneas, G.O., Antonioli, L., Souza-Lima, W., Rodolfo, D.I.N.O., Soares, E.A.A. 2022, 'Palinologia Da Formação Codó, Bacia Do Parnaíba: Idade E Paleoambiente Deposicional', *Revista Geociências*, vol. 41, no. 3, pp. 845-56.

Fernandes, G., Della Piazza, H.D.O. 1978, 'Potential Oleogenítico da Formação Codó', *Boletim Técnico da Petrobras 21*, vol. 3, no. 16.

Fontana, K.B., Araujo, R.G.O., Oliveira, F.J., Bascuñan, V.L., Andrade Maranhão, T. 2021, 'Rare earth elements in drill cutting samples from off-shore oil and gas exploration activities in ultradeep waters', *Chemosphere*, vol. 263, 127984, DOI: .1016/j.chemosphere.2020.127984.

Fowler, A.P., Zierenberg, R.A. 2016, Geochemical bias in drill cutting samples versus drill core samples returned from the Reykjanes Geothermal System. Iceland, *Geothermics*, vol. 62, pp. 48-60, d DOI: 10.1016/j.geothermics.2016.02.007.

Góes, Á.M.O., Feijó, F.J. 1994, 'Bacia do Parnaíba. Boletim de Geociências da Petrobras', vol. 8, no. 1, pp. 57-67, viewed 11 October 2024, <https://bgp.petrobras.com.br/bgp/article/view/581.

Gonzalez, L.D.C., Mastalerz, M., Mendonça Filho, J.G. 2020, Application of organic facies and biomarkers in characterization of paleoenvironmental conditions and maturity of sediments from the Codó Formation in the west-central part of the São Luís Basin, Brazil, *International Journal of Coal* Geology, vol. 225, 103482, DOI: 10.1016/j.coal.2020.103482.

Hotelling, H. 2016, 'Analysis of a complex of statistical variables into principal components', *Journal of Educational Psychology,* vol. 24, no. 6, pp. 417-441, DOI: 10.1037/h0071325.

Jolliffe, I.T., Cadima, J. 2015, 'Principal component analysis: a review and recent developments', *Philosophical Transactions of the Royal Society A*, vol. 374, 20150202, DOI: .1098/rsta.2015.0202>.

Lima, E.A.M., Leite, J.F. 1978, *Projeto estudo global dos recursos minerais da Bacia Sedimentar do Parnaíba: integração geológico-metalogenética: relatório final da etapa III,* Companhia de Pesquisa de Recursos Minerais, Recife.

Macqueen, J. 1965, *Some methods for classification and analysis of multivariate observations*, University of California, Los Angeles.

Mendonça Filho, J.G. 1999, 'Aplicação de estudos de palinofácies e fácies Orgânica em rochas do Paleozóico da Bacia do Paraná, Sul do Brasil', PhD thesis, Universidade Federal do Rio Grande do Sul.

Mendonça Filho, J.G., Carvalho, M.A., Menezes, T.R. 2002, 'Palinofácies', in Dutra, T.L. (ed.), *Técnicas e Procedimentos para o Trabalho com Fósseis e Formas Modernas Comparativas*, Unisinos, São Leopoldo, pp. 20-4.

Mendonça Filho, J.G., Menezes, T.R., Mendonça, J.O. 2011, 'Organic composition (palynofacies analysis)', in *4th ICCP Training Course on Dispersed Organic Matter*, pp. 33-81.

Mendonça Filho, J.G., Menezes. T.R., Mendonça, J.O. 2014, 'Organic composition (Palynofacies analysis)' in *7th ICCP training course on dispersed organic matter*, GFZ Potsdam, Germany, pp. 36-89.

Messner, J.C., Wooldridge, L.C.P. 1964, 'Maranhao Paleozoic basin and Cretaceous coastal basins, northern Brazil', *AAPG Bulletin*, vol. 48, pp. 1475-512.

Mostavi, E., Asadi, S., Ugochukwu, E. 2015, 'Feasibility study of the potential use of drill cuttings in concrete', *Procedia Engineering*, vol. 118, pp. 1015-23, DOI: 1016/j.proeng.2015.08.543.

Paz, J.D.S., Rossetti, D.F. 2005, 'Linking lacustrine cycles with synsedimentary tectonic episodes: An example from the Codó Formation (Late Aptian), northeastern Brazil', *Geological Magazine*, vol. 142, pp. 269-85, DOI: 10.1017/S0016756805000488.

Pearson, K. 1901, 'On lines and planes of closest fit to systems of points in space', *Philosophical Magazine,* vol. 2, pp. 559-572.

Piper, A.T. 1995, 'Evaluation of palynofacies analysis in the interpretation of depositional environment in the Middle Jurassic of Yorkshire', PhD thesis, Newcastle University, Newcastle.

Regali, M.S.P. 1989, 'Primeiros registros da transgressão neoaptiano margem equatorial brasileira', *CONGRESSO BRASILEIRO DE PALEONTOLOGIA 11*, vol. 1, Curitiba, Anais... SBP., pp. 275-293.

Rodrigues, R.A. 1995, 'Geoquímica Orgânica na Bacia do Parnaíba', DSc thesis, Universidade Federal do Rio Grande do Sul.

Rossetti, D.F., Paz, J.D.S., Goés, A.M. 2004, 'Facies analysis of the Codó Formation (Late Aptian) in the Grajaú Area, Southern São Luís-Grajaú Basin', Anais da Academia Brasileira de Ciência, vol. 76, no. 4, pp. 791-806, DOI: 10.1590/S0001-37652004000400012.

Santos, A., Mota, M.A.D.L., Kern, H.P., Fauth, G., Paim, P.S., Netto, R.G., Vieira, C.E.L. 2022, 'Earlier onset of the Early Cretaceous Equatorial humidity belt', *Global and Planetary Change,* vol. 208, 103724, DOI: 10.1016/j.gloplacha.2021.103724.

Szlazak, N., Korzec, M., Piergies, K. 2021, 'The determination of the methane content of coal seams based on drill cutting and core samples from coal mine roadway', *Energies,* vol. 15, no. 1, 178, DOI: .3390/en15010178.

Tyson, R.V. 1984, 'Palynofacies investigation of Callovian (Middle Jurassic) sediments from DSDP Site 534, BlakeBahama Basin, western Central Atlantic', *Marine and Petroleum Geology*, vol. 1, pp. 3-13, DOI: 10.1016/0264-8172(84)90116-8.

Tyson, R.V. 1989, 'Late Jurassic palynofacies trends, Piper and Kimmeridge Clay Formations, UK onshore and northern North Sea', in D.J. Batter & M.C. Keen (eds), *Northwest European Micropalaeontology and Palynology*: *The British Micropalaeontological Society Series*, Ellis Horwood, Chichester, pp. 135-172.

Tyson, R.V. 1993, 'Chapter 5: Palynofacies analysis', in D.G. Jenkins (ed.), A*pplied Micropaleontology: Kluwer Academic Publishers*, The Netherlands, Amsterdam, pp. 153-191.

Tyson R.V. 1995, *Sedimentary Organic Matter. Organic facies and palynofacies,* Chapman and Hall, Londres.

Vaisman, Y.I., Plugin, K.G., Vlasov, A.S. 2020, 'Using the resource potential of drill cuttings in road construction', *IOP Conference series: Earth and Environmental science*, vol. 459, no. 2, 022078.

Vaz, P.T., Rezende, N.G.A.M, Filho, J.R.W., Travassos, W.A.S. 2007, 'Bacia do Parnaíba', *Boletim de Geociências da Petrobras,* vol. 15, no. 2, pp. 253-263.

Vincent, A.J. 1995, 'Palynofacies analysis of Middle Jurassic sediments from the Inner Hebrides'. PhD Thesis, University of Newcastle upon Tyne.

Wentworth, C.K. 1922, 'A scale of grade and class terms for clastic sediments', *The Journal of Geology*, vol. 30, no. 5, pp. 377-392, DOI: 10.1086/622910.

Zadeh, L.A. 1965, 'Fuzzy sets', *Information and control,* vol. 8, no. 3, pp. 338-353, DOI: 10.1016/S0019-9958(65)90241-X.

Zalan P.V. 2007, 'Bacias de Bragança-Viseu, São Luís e Ilha Nova', *Geociências da Petrobras*, vol. 15, pp. 341-345.

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Conflict of interest

The authors declare no conflict of interest.

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