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**ANÁLISE ICNOLÓGICA DO TESTEMUNHO ITAMARACÁ-1IT-03-PE NO
INTERVALO MAASTRICHTIANO-DANIANO DA BACIA PARAÍBA**



Recife

2023

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Dissertação apresentada ao Programa de Pós-Graduação em Geociências da Universidade Federal de Pernambuco, como requisito parcial para a obtenção do título de Mestre em Geociências.

Área de concentração: Geologia Sedimentar e Ambiental.

Orientador: Prof. Dr. Mário Ferreira de Lima Filho.

Coorientadora: Biol. Dra. Sônia Maria Oliveira Agostinho da Silva.

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RESUMO

A faixa costeira da Bacia Paraíba ocupa uma estreita faixa ao longo do litoral dos Estados de Pernambuco e Paraíba. Esta bacia marginal possui uma área continental de aproximadamente 7600 km² e mais 31400 km² de área oceânica, ao longo da plataforma continental. Sua coluna sedimentar é constituída por cinco unidades principais: formações Beberibe, Itamaracá, Gramame, Maria Farinha e Tambaba depositadas entre o Coniaciano e o Eoceno. Esse trecho do Nordeste oriental foi o último a se separar da contraparte africana, e os depósitos basais nesta faixa costeira possivelmente se iniciaram no Coniaciano. O objetivo principal desse trabalho foi identificar e descrever os icnofósseis na Formação Gramame e Maria Farinha, do Cretáceo Superior e Paleoceno da Bacia Paraíba, determinar suas icnofácies, e interpretar o paleoambiente durante o intervalo Maastrichtiano-Daniano na Bacia Paraíba. Este estudo icnológico foi conduzido no poço Itamaracá-1IT-03-PE, localizado na Ilha de Itamaracá, com extensão total de 82,7 metros. As descrições se concentraram na sequência carbonática característica das formações. A sequência estudada abrange uma espessura de 68 metros, composta por calcários bioclásticos (wackestone-packstone) intercalados com margas. Os calcários, predominantemente maciços, variam de cinza a cinza muito claro, exibindo bioturbação e intraclastos. As camadas de margas, mais finas, são em grande parte maciças, com menos bioclastos e bioturbação. Foram identificadas duas icnofábricas compostas: *Palaeophycus-Asterosoma* e *Asterosoma*. A seção do poço Itamaracá-1IT-03-PE exhibe vários icnogêneros, como *Palaeophycus*, *Planolites*, *Asterosoma*, *Teichichnus* e *Taenidium*. Esses icnogêneros diferem em diversidade de áreas carbonáticas similares, e em outras localidades que registraram o evento K-Pg. As icnoassembleias sugerem predominantemente um ambiente marinho de baixa energia, com pequenas variações de taxa de sedimentação. A baixa diversidade pode indicar um ambiente com variações de oxigenação e salinidade. Essas icnofábricas são caracterizadas por estruturas horizontalizadas de alimentação e moradia, com diversidade e abundância reduzidas produzidas por organismos escavadores que migraram verticalmente no substrato, sugerindo uma icnofácies *Cruziana*. Além disso, esta região do Nordeste oriental foi a última a se separar da África, com depósitos sedimentares a partir do Coniaciano, especialmente os do intervalo Maastrichtiano-Daniano estudados aqui. Neste mesmo período, na Bacia de Douala e Rio Muni se depositaram formações que exibem intervalos geradores com querogênio tipo II e III, com pacotes de areia atuando como reservatórios. Essa configuração levanta a possibilidade de intervalos geradores nos folhelhos offshore da Bacia Paraíba e na formação Gramame como potencial reservatório. Desta forma, a investigação das formações Gramame e Maria Farinha na Bacia Paraíba assume importância para compreender o preenchimento da bacia e prever os ambientes deposicionais offshore.

Palavras-chave: traços fósseis; icnofábricas; plataforma carbonática; limite k-pg

ABSTRACT

The Paraíba Basin occupies a narrow strip along the coast of the States of Pernambuco and Paraíba. This marginal basin has a continental area of approximately 7600 km² and a further 31400 km² of oceanic area, along the continental shelf. Its sedimentary column is made up of five main units: Beberibe, Itamaracá, Gramame, Maria Farinha and Tambaba formations deposited between the Coniacian and Eocene. This stretch of the eastern Northeast was the last to separate from its African counterpart, and basal deposits in this coastal strip possibly began in the Coniacian. The main objective of this work was to identify and describe the ichnofossils in the Gramame and Maria Farinha Formation, from the Late Cretaceous and Paleocene of the Paraíba Basin, determine their ichnofacies, and interpret the paleoenvironment during the Maastrichtian-Danian interval in the Paraíba Basin. This ichnological study was conducted in the Itamaracá-1IT-03-PE well, located on Itamaracá Island, with a total length of 82.7 meters. The descriptions focused on the characteristic carbonate sequence of the formations. The studied sequence covers a thickness of 68 meters, composed of bioclastic limestones (wackestone-packstone) interspersed with marls. The limestones, predominantly massive, vary from gray to very light gray, exhibiting bioturbation and intraclasts. The thinner marl layers are largely massive, with fewer bioclasts and bioturbation. Two composite ichnofabric were identified: *Palaeophycus-Asterosoma* and *Asterosoma*. The Itamaracá-1IT-03-PE well section exhibits several ichnogenera, such as *Palaeophycus*, *Planolites*, *Asterosoma*, *Teichichnus* and *Taenidium*. These ichnogenera differ in diversity from similar carbonate areas, and from other localities that recorded the K-Pg event. The ichnoassemblages predominantly suggest a low-energy marine environment, with small variations in sedimentation rates. Low diversity may indicate an environment with variations in oxygenation and salinity. These ichnofabric are characterized by horizontalized feeding and dwelling structures, with reduced diversity and abundance produced by burrowing organisms that migrated vertically in the substrate, which suggests a *Cruziana* ichnofacies. Furthermore, this region of the eastern Northeast was the last to separate from Africa, with sedimentary deposits from the Coniacian onwards, especially those from the Maastrichtian-Danian interval studied here. During this same period, formations were deposited in the Douala and Rio Muni Basins that exhibit generating intervals with type II and III kerogen, with sand packages acting as reservoirs. This configuration raises the possibility of generating intervals in the offshore shales of the Paraíba Basin and in the Gramame formation as a potential reservoir. Therefore, the investigation of the Gramame and Maria Farinha formations in the Paraíba Basin is important to understand the filling of the basin and predict the offshore depositional environments.

Keywords: trace fossil; ichnofabric; carbonate platform; k-pg boundary

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1 INTRODUÇÃO

Ichologia é o estudo de vestígios produzidos por organismos (animais, plantas e micróbios) sobre ou dentro de um substrato. Ele lida com todos os aspectos relacionados a traços modernos (neoichologia) e fósseis (paleoichologia) e é interdisciplinar na combinação de métodos sedimentológicos, paleontológicos, biológicos e ecológicos, assim complementando as interpretações paleoecológicas (Bromley, 1996).

A paleoichologia estuda os vestígios fósseis (ou icnofósseis), que são estruturas fossilizadas produzidas em substratos que vão desde sedimentos não litificados até rochas sedimentares ou matéria orgânica (incluindo conchas, ossos e madeira) pela atividade de organismos. Essas estruturas estão diretamente ligadas as interações dos organismos com o substrato e de que forma isso é condicionado pelas características paleoambientais. A análise ichológica permite inferir parâmetros paleoecológicos como salinidade, oxigenação, taxa de sedimentação, energia hidrodinâmica, consistência do substrato, fonte de alimentos e paleobatimetria relativa.

Dois conceitos da ichologia são importantes para o estudo paleoambiental, são eles as icnofácies e as icnofábricas. Icnofácies como conceito foi estabelecido por Seilacher (1967), e representam a prevalência no tempo e no espaço das comunidades de vestígios fósseis (ou icnocenoses) que apresentam parâmetros ligadas a um perfil ambiental geral, principalmente relacionadas à resposta comportamental dos animais da fauna bentônica a um gradiente batimétrico ou suprimento de alimentos. A icnofácies representa uma ferramenta poderosa ao trabalhar em uma escala maior (por exemplo, escala da bacia) e na correlação com novas áreas, onde uma interpretação aproximada do paleoambiente em termos das fácies pode ser obtida. O conceito de icnofácies tem sido continuamente atualizado (Buatois e Mángano 2011, MacEachern et al., 2012), refinado e estendido para ambientes continentais e (Melchor et al., 2012).

Já o conceito de icnofábrica diz respeito a todos os aspectos da textura e estrutura interna de uma camada sedimentar que resulta da bioturbação em todas as escalas (Ekdale e Bromley 1983, 1991; Bromley e Ekdale, 1986). São representadas pelo icnogênero mais abundante e representa as diferentes relações transversais que podem estar relacionadas à colonização sucessiva ou à hierarquização e a mudança do grau de bioturbação. Comparado com o conceito de icnofácies, que enfatiza o reconhecimento de icnocenoses

recorrentes e características das fácies, o objetivo do conceito da icnofábrica é principalmente a análise de diferentes estágios contidos em um determinado pedaço de rocha bioturbada (Taylor et al. 2003; Ekdale et al., 2012).

A Bacia da Paraíba tem o início de sua formação durante o processo tafrogenético entre as placas Sul-Americana e Africana. A bacia é limitada, a sul, pela Zona de Cisalhamento Pernambuco e, a norte, pelo Alto de Mamanguape, um prolongamento da Zona de Cisalhamento Patos. A Bacia da Paraíba está sobreposta a rochas supracrustais, graníticas e ortognaisses, do Paleo- ao Neoproterozoico, que constituem os terrenos Rio Capibaribe (TRC), Alto Moxotó (TAM) e Alto Pajeú (TAP). Se comportando como uma rampa estrutural que mergulha suavemente na direção leste, apresentando blocos falhados com baixo gradiente de rejeito. É dividida em três sub-bacias: Olinda, Alhandra e Miriri (Lima Filho et al., 1998, 2005; Barbosa et al., 2003, 2004).

A estratigrafia da Bacia Paraíba é iniciada pela Formação Beberibe, que se estende de forma erosional e discordante sobre o embasamento cristalino (Nóbrega e Alheiros, 1991). É composta de uma sequência arenosa, de granulação grossa a fina, mal selecionada, com coloração variando de cinza clara a creme, tendo, na base, o predomínio de leitos arenosos conglomeráticos, estas camadas se intercalam com a Formação Itamaracá, constituída por camadas bem estratificadas, de arenitos finos de coloração creme, além de siltitos cinza esverdeados, com manchas avermelhadas, e ricamente fóssilífero (incontáveis conchas de bivalves mal preservados), caracterizando um ambiente lagunar (Kegel et al., 1953; Tinoco & Siqueira 1976; Menor & Amaral, 1979; Amaral et al., 1997; Souza, 1998, 2006).

Logo acima se encontra a Formação Gramame que está em contato gradacional ou interdigitado sobre sedimentos siliciclásticos e distais da Formação Beberibe (Nascimento, 2003). Depositada durante o Maastrichtiano, a formação é caracterizada por calcários margosos e margas sem influência siliciclásticas, depositados em plataforma rasa com baixa ou moderada energia e sob a ação periódica de tempestades (Nascimento, 2003), retratando o estágio de instalação definitiva da transgressão marinha durante o maastrichtiano. A mudança para os calcários da Formação Maria Farinha, limite superior, é marcada por contatos gradacionais (Menor et al., 1977).

Oliveira (1940) denomina de Formação Maria Farinha os calcários fóssilíferos encontrados a norte de Recife. A Formação Maria Farinha repousa diretamente sobre a

Formação Gramame, sem nenhuma discordância ou hiato, mergulhando para leste e mostrando uma suave ondulação no sentido N-S (Oliveira & Ramos, 1956). A porção basal está em contato com a Formação Gramame através de “calcário vidro”, de cor creme, homogêneo, compacto, utilizado como uma camada-guia (Kegel, 1955).

Sobreposta a Formação Maria Farinha, encontra-se em contato discordante erosional a Formação Barreiras, com a maioria das camadas são constituídas de material silico-argilosos, com predominância de areias quartzosas, arcoseanas e argilas, às vezes, com ocorrência de seixos, como citado anteriormente. Geomorfologicamente, é dominada por tabuleiros costeiros de grande extensão recortados por grandes vales de rios na zona costeira proximal.

Esse trecho do Nordeste oriental foi o último a se separar da contra-parte africana, tendo seus sedimentos depositados a partir do Coniaciano, principalmente os sedimentos aqui estudados de idade Maastrichtiano-Daniano. Nesse mesmo intervalo na Bacia de Douala, Cretáceo Superior ao Cenozóico inferior, corresponde ao período de deposição das formações Logbaba (Maastrichtiano) e N'kapa (Paleoceno-Eoceno) (por exemplo, Mfayakouo et al, 2021). Os sedimentos consistem principalmente de arenito de granulação grossa, folhelhos fossilíferos, margas e calcário.

Assim, o estudo das formações Itamaracá e Gramame poderá ajudar a entender seu preenchimento e predizer os ambientes deposicionais localizados em offshore. Para essa análise foi utilizada a identificação dos icnofósseis, como uma importante ferramenta para a interpretação paleoambiental. Embora a Formação Gramame apresente elevado conteúdo de icnofósseis, poucos trabalhos com ênfase em dados desse tema foram publicados (BARBOSA et al., 2006), menos ainda para dados de subsuperfície. Além disso, o estudo dos icnofósseis permite a reconstrução paleoambiental e, se disponível, a correlação com outros testemunhos.

Dessa forma, o reconhecimento dos icnofósseis e do grau de bioturbação podem auxiliar nessa caracterização. Os icnofósseis representam o resultado da atividade biológica dos organismos, e são registrados em rochas, sedimentos e grãos. Normalmente, os traços fósseis refletem o comportamento dos organismos a certas condições ambientais (e.g. resistência do substrato, taxa de sedimentação, energia do sistema, oxigenação, salinidade). A associação de icnofósseis formam as icnofácies que podem refletir

variações na batimetria, associados com fatores químicos, físicos e biológicos (SEILACHER, 1964; BROMLEY, 1996; MACEACHERN et al., 2007).

1.1 OBJETIVOS GERAIS

O objetivo principal é identificar e descrever os icnofósseis em testemunho (Itamaracá - 1IT-03-PE) das Formações Gramame e Maria Farinha, Cretáceo Superior e Paleoceno da Bacia Paraíba; e determinar as icnofácies dessas formações. E desse modo, interpretar e reconstruir o paleoambiente do Maastrichtiano e Daniano da Bacia Paraíba e permitir a correlação com bacias da margem oeste africano.

1.1.1 Objetivos específicos:

- Identificar e descrever os icnofósseis em testemunho das Formações Gramame e Maria Farinha, Cretáceo Superior da Bacia Paraíba;
- Determinar as icnofácies (associações de icnofósseis) das Formações Gramame e Maria Farinha, Cretáceo Superior da Bacia Paraíba;
- Interpretar e reconstruir o paleoambiente da Bacia Paraíba durante o Cretáceo Superior e Paleoceno.
- Comparar a estratigrafia das Formações Gramame e Maria Farinha com Formações correlatas no oeste africano.

2 RESULTADOS

2.1 ARTIGO - ICHNOLOGICAL ANALYSIS OF THE MAASTRICHTIAN-DANIAN INTERVAL IN THE PARAÍBA BASIN: PALEOENVIRONMENTAL INSIGHTS FROM THE ITAMARACÁ-1IT-03-PE WELL

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Ichnological analysis of the Maastrichtian-Danian interval in the Paraíba Basin: Paleoenvironmental insights from the Itamaracá-1IT-03-PE well

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Cruziana ichnofacies

ABSTRACT

The Gramame and Maria Farinha formations were deposited in the Paraíba Basin during the Maastrichtian-Danian interval, recording the paleoenvironmental evolution during the opening of the Atlantic Ocean. Despite well-investigated, there is still a need to better understand the bioturbation record and the represented ecological conditions during the deposition of these units. This study investigates the ichnofauna of the carbonate facies recorded in the Itamaracá-1IT-03-PE well in the Paraíba Basin, Brazil, focusing on the paleoenvironmental characteristics that influenced this carbonate ramp. The ichnologic analysis allowed to identify environmental stress based on the limited variation in the diversity and complexity. The identified *Palaeophycus-Asterosoma* and *Asterosoma* suites suggest low to moderate energy levels, minimal fluctuations in sedimentation rates, and a relatively stress in salinity that persisted for a long period. Variations in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values during the Maastrichtian interval corroborates changes in temperature and bioproductivity, reflecting an increase in freshwater influx during this period, which affected paleoenvironmental conditions and trace fossil diversity mainly due to changes in salinity.

1. Introduction

Ichnological research has proven very useful to characterize and interpret carbonate sedimentary systems and past bio-events (Abdulsamad et al., 2021; Bádenas and Aurell, 2010; Benyoucef et al., 2019; Benyoucef and Meister, 2015; Carmeille et al., 2018; El-Kahtany et al., 2024; Olóriz and Rodríguez-Tovar, 2002), with special attention placed on the Cretaceous-Paleogene (K/Pg) boundary (Rodríguez-Tovar and Uchman, 2004, 2006, 2008; Rodríguez-Tovar et al., 2002, Rodríguez-Tovar et al., 2006, 2010, 2011; Rodríguez-Tovar, 2005). The Gramame and Maria Farinha formations were deposited in carbonate environments that have been extensively studied from various perspectives, including this section (Barbosa et al., 2006; Barros et al., 2018; Nascimento-Silva et al., 2011, 2013; Neumann et al., 2009; Topan

and Lima Filho, 2018).

Sedimentary deposits with low ichnodiversity and the prevalence of poor development of tiering structure suggest stressed conditions impacting colonization, such as nutrient fluctuations, variable oxygen levels, and physical disturbances (Buatois and Mángano, 2011; Knaust and Bromley, 2012). Oxygenation reductions and salinity changes, for example, were key factors controlling the low diverse trace fossil suites in Eocene deposits (e.g., Villegas-Martin et al., 2014), while changes in sedimentation rates further influenced bioturbation and the complexity of suites, as seen in the Sinop-Boyabat Basin (Turkey) (Uchman et al., 2004; Knaust and Bromley, 2012). Ichnofossils in low-energy settings displayed varying bioturbation intensities, reflecting environmental cycles and substrate conditions that influenced ichnofaunal distribution (Pemberton and Wightman, 1992; Bromley, 1996; Savrda and Nanson,

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2003; Nascimento-Silva et al., 2011).

Comparisons with trace fossil suites from regions such as the Muschelkalk and Khuff formations, and across distinct geological periods, including the K-Pg boundary, reveal varying depositional settings and biological responses. For instance, the ichnofauna from the Itamaracá-1IT-03-PE borehole shows limited similarity to those found in European carbonate ramps (Knaust, 1998, 2007, 2009). Despite the significant faunal turnover post-K-Pg event, trace fossil studies in the Paraíba Basin and other regions suggest some continuity in ichnodiversity and adaptations such as dwarfism linked to environmental stress (Rodríguez-Tovar et al., 2010, 2011; Wiest et al., 2015, 2016; Bromley, 1996; Łaska et al., 2017). This study aims to characterize the ichnofauna of carbonate ramps from the Gramame and Maria Farinha formations, Paraíba Basin, Brazil, and understand their paleoenvironmental controls.

2. Geological setting

The Paraíba Basin (Fig. 1) is situated along the northeastern coast of Brazil (Pernambuco and Paraíba states) and is bounded to the north by the Pernambuco Shear Zone and to the south by the Mamanguape High, an extension of the Patos Shear Zone. Covering approximately 7600 km² onshore and 31,400 km² on the continental shelf, the origin of the basin is associated with the opening of the South Atlantic Ocean during the Late Jurassic to Early Cretaceous (Mabesoone and Alheiros, 1988; Feijó, 1994; Barbosa et al., 2006; Barbosa et al., 2003; Barbosa, 2007). Structural elements, such as Precambrian Lineaments and basement structural highs, have profoundly influenced the Paraíba Basin, resulting in horsts and grabens. Three primary depocenters within the basin are identified as sub-basins: Olinda, Alhandra, and Miriri (Mabesoone and Alheiros, 1988; Feijó, 1994; Barbosa et al., 2006; Barbosa et al., 2003; Barbosa, 2007).

The basement of the Paraíba Basin has the shape of a structural ramp, gently dipping eastward. Carbonate formations in this region display a ramp-like depositional profile with a mild gradient. Basin subsidence facilitated the deposition of carbonate packages with thicknesses of a few hundred meters (Barbosa et al., 2003; Barbosa, 2007). Within the Olinda sub-basin, the Beberibe, Itamaracá, Gramame, and Maria Farinha

formations are present, deposited from the Maastrichtian to the Eocene. These formations indicate a transgressive system tract during the Santonian-Campanian and a highstand system tract during the Maastrichtian, followed by regressive pattern in Eocene (Barbosa et al., 2006; Barbosa, 2004, 2007). The Gramame Formation (Fig. 2), from Maastrichtian, comprises grayish limestones and marls and features wackestones and packstones microfacies with microfossils filled with calcite, as well as macrofossils (Nascimento-Silva et al., 2011; Lima Filho et al., 2006).

Overlying the Gramame Formation, the Maria Farinha Formation (Danian) displays alternating yellowish limestones and marls. Thicker marly layers with more terrigenous content are evident in proximal regions as effect of the regressive phase. These carbonates were deposited in a shallow platform to shoreface environment and contain foraminifera, ostracods, and macrofossils (Nascimento-Silva et al., 2011; Barbosa et al., 2006).

3. Material and methods

The ichnological description was conducted on a core sample from the Itamaracá-1IT-03-PE well (Fig. 1), acquired in Itamaracá Island (7° 44' 41.59" S, 34° 49' 41.59" W, WGS 84 datum), with a total length of 82.7 m. This core sample is stored at LAGESE (UFPE - Universidade Federal de Pernambuco). The descriptions primarily focused on the carbonate interval that characterizes the Gramame and Maria Farinha formations, from the basal portion to the contact with sandy sediments. Sedimentological descriptions involved recognizing texture, the presence of macrofossils and intraclasts, layer contacts, and sedimentary structures within the rocks.

The ichnological description was based on identifying trace fossils using ichnotaxobases and relevant literature (e.g., Bromley, 1996; Buatois and Mángano, 2011; Knaust, 2017) and estimating the bioturbation index (BI) as described by Taylor and Goldring (1993). This index proposes six degrees of bioturbation, from BI 0 indicating non-bioturbated layers to BI 6 indicating complete obliteration of sedimentary structures. Descriptions were conducted at a 1:20 cm scale to ichnofauna and lithofacies. To define the trace fossil suites, various aspects were considered, such as bioturbation index, ichnodiversity,

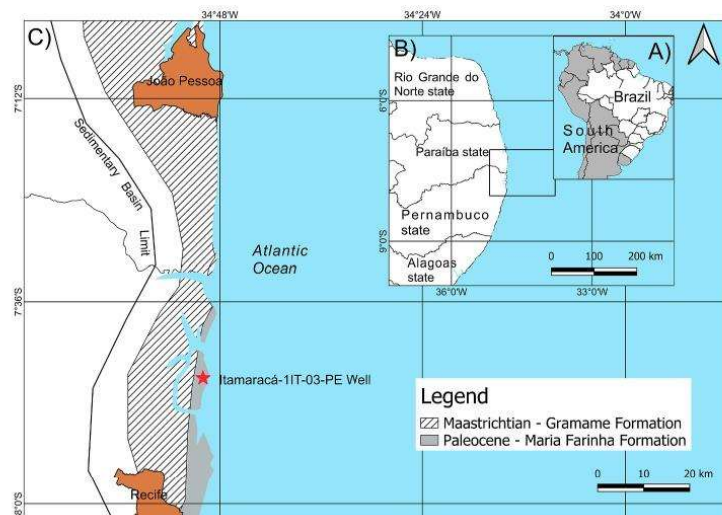


Fig. 1. Geology of the Paraíba Basin in Northeast Brazil, including its limits, subdivisions, and the location of Itamaracá Island. A. Position of Brazil in South America. B. Position of studied area in NE Brazil. C. Position of drill hole in NE Brazil. Modified from Nascimento-Silva et al. (2011).

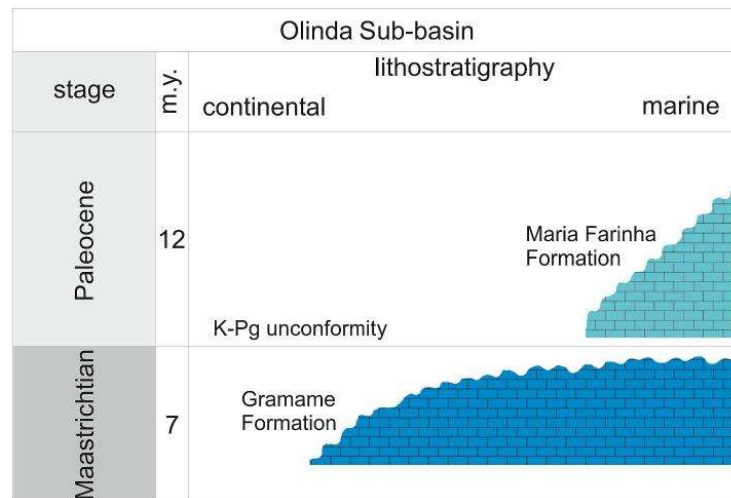


Fig. 2. Stratigraphy onshore of the Paraíba Basin. Modified from Neumann et al. (2009).

burrow size, general morphology, and recurrence (Knaust, 2009, 2017; Knaust and Bromley, 2012).

4. Results

4.1. Sedimentary facies and trace fossils

The studied interval corresponds to a 68-m-thick carbonate sequence composed of bioclastic limestones (wackestone-packstone) interbedded with mudstone (Table 1). The limestones are fine-grained, ranging from gray to very light gray, predominantly massive, with the presence of trace fossils and intraclasts. The marl layers are mainly massive, with less bioclasts and lower bioturbation index.

The observed sedimentary facies range from Mudstone to Packstone, each with distinct characteristics reflecting different depositional environments and energy conditions. The Mudstone facies, characterized by its dark gray to black, mud-supported texture, were deposited in low-energy environments. The bioclastic Wackestone facies is grain-supported, medium gray, and rich in intraclasts, pyrite nodules, and macrofossils of bivalves, echinoids, and annelids, and were deposited in restricted lagoons of low to moderate energy. The Wackestone facies, ranging from mud-supported to grain-supported with pyrite nodules, were deposited in similar low energy environments. Finally, the Packstone facies, also grain-supported and medium gray, with few macrofossils, intraclasts, and pyrite nodules, was deposited in moderate to relatively high-energy environments such as back-shoals (Fig. 4).

The analysis of facies, combined with available oxygen and carbon isotope curves, guided the identification of 3rd, 4th, and 5th order

cycles. The 3rd order cycle signifies a notable shift in the carbonate ramp, distinguishing the Gramame and Maria Farinha formations. Subsequent cycles reveal minor fluctuations in terrigenous sediment influx and corresponding sea-level fluctuations.

4.1.1. Lower interval

This interval has approximately 7 m thick (Fig. 4) and is a sequence of gray packstone with a fining-upward pattern, locally with concentrations of macrofossils. This interval is interpreted as reworked by storm waves in the predominantly carbonate mud substrate, enabling the accumulation of shells and carapaces, mainly of mollusks, echinoids, and decapods. The trace fossil content is characterized by dominance of simple horizontal burrows identified as *Palaeophycus* (Fig. 5A), and rarely concentric horizontal burrows identified as *Asterosoma* (Fig. 5E and H). This suite shows a moderate to high bioturbation index (BI 3–5).

4.1.2. Middle interval

Approximately 40 m-thick, the contact with the underlying interval is transitional and ranges from packstone to wackestone and bioclastic wackestone in light gray color. These rocks lack visible structures and exhibit an overall low bioturbation index (BI 0–1), characterized by simple horizontal burrows *Palaeophycus* (Fig. 5B). A layer of wackestone, with a slight increase in macrofossil content and bioturbation index (BI 3), occurs upward. Immediately above is a thin layer (15 cm thick) with a sharp base, containing a level of bioclasts (about 5 mm thick). The uppermost part of this interval is dominated by fine, light gray wackestone with massive structure, extending just beyond the K-Pg boundary. A marked change in the oxygen and carbon isotope

Table 1
Sedimentary Facies and ichnofossil distribution of well ITAMARACÁ-1IT-03-PE.

Facies	Texture and components	Ichnogenera	Energy	Depositional environment
Mudstone	Mud-supported, Grayish black (Fig. 3C)	<i>Palaeophycus</i> , <i>Taenidium</i> , <i>Teichichnus</i>	Low	Restricted Lagoon
Bioclastic Wackestone	Grain-supported, medium gray with intraclasts, pyrite nodule, bioclasts of bivalves, echinoids, and annelids. (Figs. 3A, 6C and 6E, 6G)	<i>Palaeophycus</i> , <i>Asterosoma</i> , <i>Planolites</i>	Low to moderate	
Wackestone	Mud to grain-supported, light to medium gray with pyrite nodule (Fig. 3D)	<i>Palaeophycus</i>	Low to moderate	
Packstone	Grain-supported, medium gray with bioclasts, intraclasts, pyrite nodule and hummocky-cross stratification. (Figs. 3B and 5A–B)	<i>Palaeophycus</i> , <i>Asterosoma</i> , <i>Planolites</i>	Moderate to high	Back-shoal

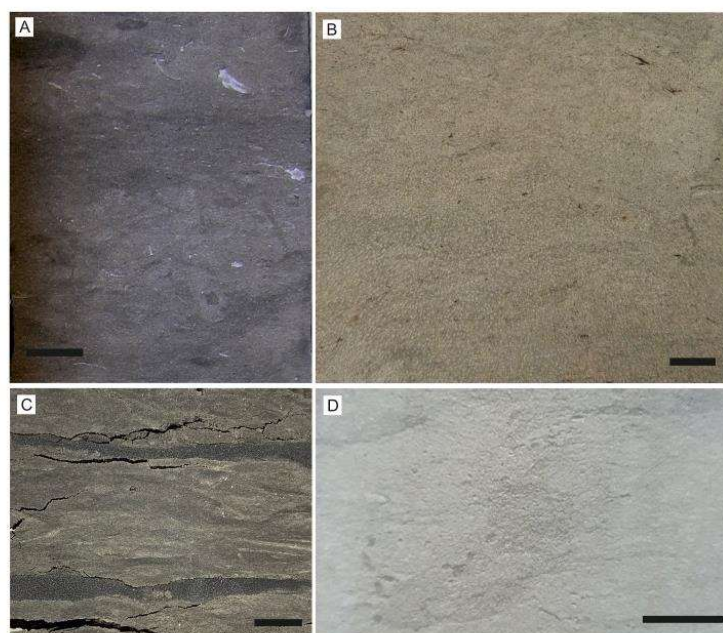


Fig. 3. Expressions of the facies. A) Bioclastic Wackestone. B) Packstone. C) Mudstone. D) Wackestone. Scale: 1 cm.

composition delineates the Cretaceous-Paleogene boundary (Nascimento-Silva et al., 2011, Fig. 4). Trace fossils in this interval include *Palaeophycus*, *Asterosoma*, and *Planolites* (Fig. 5).

4.1.3. Upper interval

Approximately 20 m thick, this interval consists of gray wackestone with an average thickness of 2 m, interspersed with thicker mudstone layers with an average thickness of 1 m. Trace fossils in this portion present two expressions: below, the recurrence of *Palaeophycus-Asterosoma* suite, with *Palaeophycus*, *Asterosoma*, and *Planolites* in low bioturbation index (BI 2), followed upward by a slightly higher ichnodiverse suite, the *Asterosoma* suite, including concentric-filled burrows identified as *Asterosoma*, simple horizontal burrows identified as *Palaeophycus*, meniscated, unwall burrows identified as *Taenidium*, and spreiten vertical burrows identified as *Teichichnus* (Fig. 6).

4.2. Trace fossil suites

4.2.1. *Palaeophycus-Asterosoma* suite

This suite is dominated by circular burrows, with a thin lining and passive filling, identified as *Palaeophycus* (Fig. 5), ranging from 3 to 8 mm in diameter, presenting an overall low bioturbation index (BI 1–3), but locally high bioturbated (BI 5 in the lower interval in fine mudstone, gray packstone). This suite is dominated by *Palaeophycus*, but is common to find associated some cylindrical, concentric-filled, horizontally-oriented structures, ranging from 7 to 9 mm in diameter, identified as *Asterosoma*. Less common, in this suite occurs simple horizontal burrows, actively-filled, with darker filling than the surrounding matrix, identified as *Planolites*. This suite is more common in wackestone layers, without visible sedimentary structure, with a low occurrence of echinoids and intraclasts, but locally can present several bioclasts.

4.2.2. *Asterosoma* suite

This suite is restricted to upper levels of the section and is dominated

by cylindrical, concentric-filled, horizontally-oriented structures identified as *Asterosoma*, ranging from 6 to 10 mm in diameter. Subordinated, it is present simple horizontal burrows, with a thin lining in the wall and passively-filled, identified as *Palaeophycus*, meniscated, unwall horizontal structures identified as *Taenidium*, and vertical-oriented burrows with spreiten, identified as *Teichichnus* (Fig. 6). The degree of bioturbation is low (BI 2–3). This suite is contained in dark gray mudstones and, unlike the previous packages, it does not contain bioclasts or intraclasts (Fig. 6).

5. Discussion

5.1. Paleoenvironmental context

The ichnological analysis conducted in this study was combined with established geochemical data provided in Nascimento-Silva et al. (2011, 2013). In general, the described facies indicate an inner ramp environment. The bioclastic packstone facies (lower interval) was interpreted as a back-shoal environment, while the wackestone facies (middle interval) and mudstone/wackestone (upper interval) were associated with a restricted lagoon environment (Table 1).

The *Palaeophycus-Asterosoma* suite (Fig. 5) is characterized by a moderate to locally high bioturbation index (BI 2–5) and reduced sizes of burrows (3–9 mm). This suite occurs in layers of bioclastic packstone that were heavily influenced by storms as evidenced by the presence of hummocky-cross stratification. *Palaeophycus* (Fig. 5A) is a facies-crossing ichnogenus, but the presence of *Asterosoma* indicates deposition in a subtidal environment (Knaust, 2009; Cross et al., 2010; Abdel-Fattah et al., 2018). The ichnofossils *Palaeophycus* and *Asterosoma* are mainly representing activity of arthropod crustaceans as well as polychaetes, indicating domicile and detritus-feeding habits (e.g., Frey and Howard, 1990; Bromley, 1996; Neto de Carvalho and Rodrigues, 2007). This suite occurs in a low energy depositional environment on the ramp, and the dominance of small trace fossils, associated with the

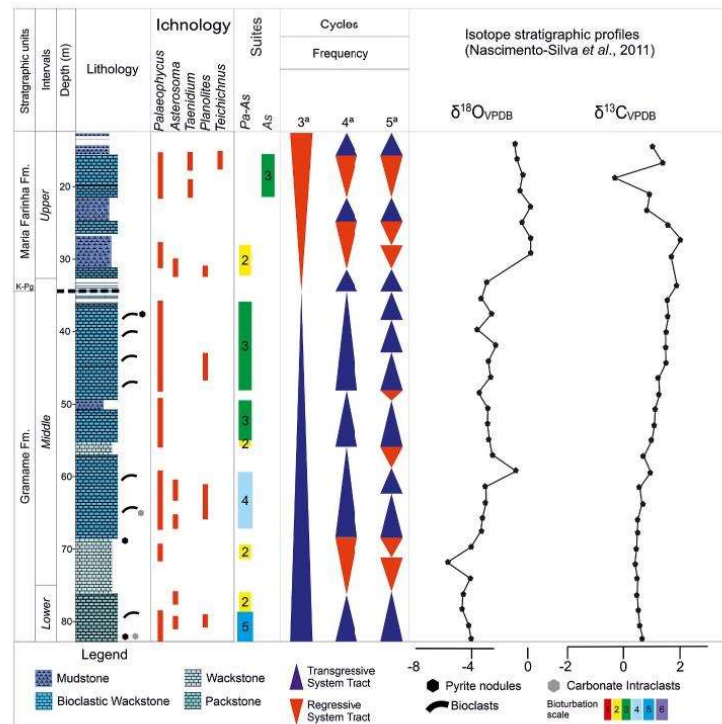


Fig. 4. Geological log of well-core 11T-03-PE with main sedimentary facies, trace-fossil distribution, bioturbation scale, stratigraphy cycles, geochemical logs, and sedimentary environment interpretation.

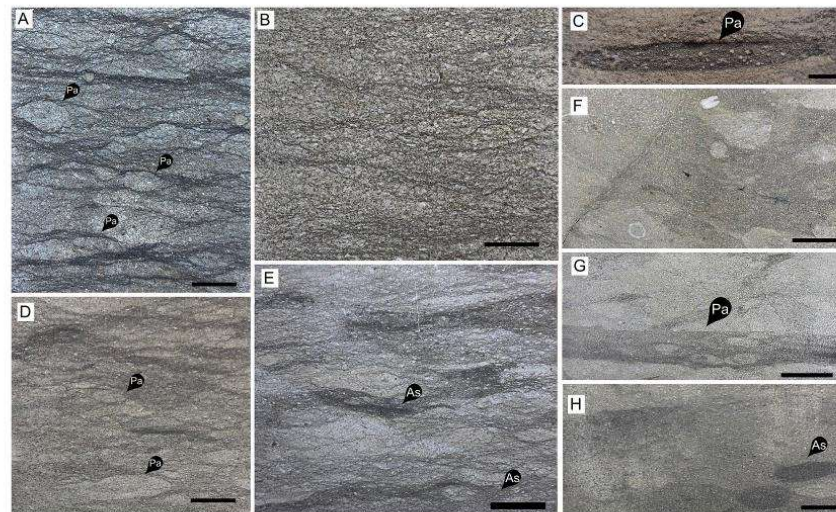


Fig. 5. Expressions of the *Palaeophycus-Asterosoma* suite. A), C), D) and G) Examples of *Palaeophycus*. B) Facies characteristic of the interval 82.7 to 75.1 m. E) and H) Examples of *Asterosoma*. F) Facies characteristic of the interval 75.1 to 35 m. Scale: 1 cm.

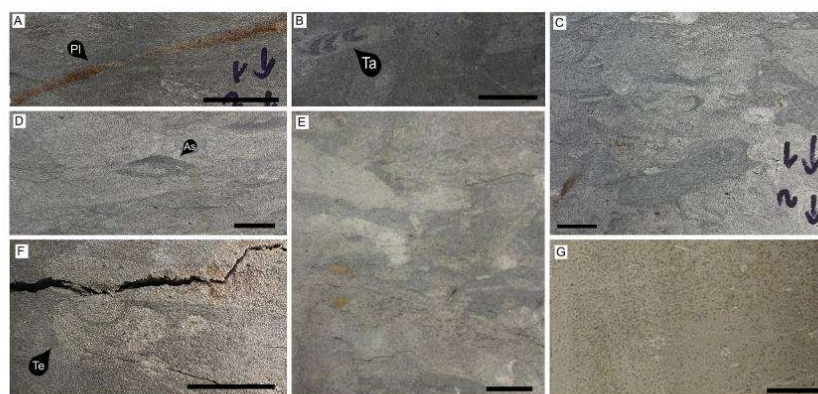


Fig. 6. Expressions of the *Asterosoma* suite. A) *Planolites*. B) *Taenidium* C) and E) Facies characteristic of the bioclastic Wackestone facies with bioturbated texture D) *Asterosoma* F) *Teichichnus* and G) Facies characteristic of the bioclastic Wackestone facies. Scale bar: 1 cm.

overall low diverse ichnoassemblage indicates high oscillations in the salinity (Buatois and Mángano, 2011).

Asterosoma is a concentric-filled, generally star-shaped burrowing system, with some bulbs or arms connected to a higher center, being very common in shallow water conditions (e.g., Farrow, 1966; Howard, 1975; Gowland, 1996; MacEachern and Bann, 2008; Joseph et al., 2012; Pemberton et al., 2012). The presence of the relatively higher diverse *Asterosoma* suite in the carbonate beds, containing the associated ichnogenera *Palaeophycus*, *Taenidium*, *Teichichnus*, and *Planolites*, indicates a decrease in sedimentation rates. Low-diversity *Asterosoma* suites, as well as trace fossil assemblages dominated by crustacean arthropods and vermiform organisms, are commonly reported in shallow marine deposits (e.g., Buatois et al., 2005; MacEachern et al., 2005; Coates and MacEachern, 2007; Alonso-Muruaga et al., 2013). *Teichichnus* occurs associated in the *Asterosoma* suite, and suggests adaptation of the tracemaker to varying depositional rates (Buckman, 1996). *Teichichnus* can occur in different zones and facies associations of the shelf (e.g., Bland and Goldring, 1995), although is a typical component of the *Cruziana* ichnofacies (e.g., Buatois and Mángano, 2011). *Teichichnus* tracemaker may not only respond to high deposition but also to erosion, forming protrusive or retrusive spreiten (e.g., Knaust, 2018). *Teichichnus* preferably occurs in local high sedimentation rate environments, as is the case of the here reported protrusive spreiten (Bromley and Ekdale, 1984; Savrda and Bottjer, 1986, 1989; Martin, 2004).

In outcrop, it was described for the Itamaracá section beds with *Thalassinoides*, with well-preserved burrow networks both in limestone and marly tempestite levels (Barbosa et al., 2006). These outcrops correspond to the middle and upper Maastrichtian and exhibit very similar characteristics throughout the entire coastal range, where it is common to find an abundance of callianassid remains, echinoids, and shark teeth (Barbosa et al., 2006). The absence of *Thalassinoides* in the studied well core is probably result of lateral facies variation, with absence of proximal facies in the correlated upper Maastrichtian beds.

The *Palaeophycus-Asterosoma* and *Asterosoma* suites present within the sedimentary sequence constitute a paleoichnocoenosis that represents impoverished *Cruziana* ichnofacies. The archetypal expressions of this ichnofacies are formed due to the exploitation of the substrate over an extended period, suggesting a relatively stable paleoenvironmental setting, with variable bioturbation index (BI 1–5), representing entirely marine origin (Bromley, 1996; Bromley and Ekdale, 1984; Knaust, 2017). In comparison to its archetypal models, however, the ichnodiversity in the studied well core is low, allowing the assumption of an impoverished *Cruziana* ichnofacies (Bromley, 1996; MacEachern et al., 2007; 2012; Sedorko et al., 2018, 2019, 2021).

The trace fossil suite from Itamaracá section consist of an association of horizontally burrowed structures, which are used for feeding and dwelling, with reduced diversity, abundance, and limited overlap of ichnofossils. The fine-grained sediment composition of these deposits, the predominance of overall marine macrofossil assemblages, and evidence of wave action reinforce the interpretation of colonization within a carbonate inner ramp environment (Fig. 7) (Buatois et al., 2005; Buatois and Mángano, 2011).

The *Cruziana* ichnofacies has a relatively wide depositional distribution, from distal platforms to nearshore or lagoon regions. The shift from platform to nearshore environments is marked by the gradual replacement of trace fossils suites that gradually present more proximal elements, linked to the *Skolithos* ichnofacies (Bromley and Ekdale, 1984). This transition suggests an increase in energy within the environment as one move from the zone occasionally influenced by storm wave action to that zone influenced by fair-weather wave action (Scasso et al., 1991; Brian et al., 1998; Buatois et al., 2002; Malpas et al., 2005).

The low ichnodiversity, scarcity of ichnofossils and predominance of intermediate-tier ichnofossils suggest an environment that may have experienced stress or limitation, such as variations in nutrient availability, fluctuations in oxygenation levels, or periodic physical disturbances. Those factors could have impeded more intensive colonization by a diverse ichnofauna (Bromley and Ekdale, 1984). The ichnological record indicates intermittent episodes of stress that restricted colonization. The bioturbation index between 2 and 4 indicates moderate disturbance of the substrate, suggesting high depositional rates, but considering the low ichnodiversity it is more plausible that the main controlling factor was oscillations in salinity rates (Buatois and Mángano, 2011; Knaust and Bromley, 2012).

Changes in salinity due to freshwater influxes influenced the distribution of bioturbating organisms, contributing to the impoverished nature of the *Cruziana* ichnofacies (Bromley, 1996). As observed in the alternation between calcarenites and marls, a characteristic of the Gramame Formation, the input of fine continental material and freshwater was not intense enough to avoid bioturbation but limited the formation of more complex tier structures (Uchman et al., 2004; Neumann et al., 2009; Knaust and Bromley, 2012).

In the lower section, there high bioturbation activity is likely associated with colonization post storm events, as corroborated by hummocky-cross stratification. The basal suite primarily consists of simple horizontal burrows, reflecting the reworking by infauna within the substrate during lower energy periods (Savrda and Nanson, 2003). The intermediate interval points to a low-energy environment with increased sediment production, as attested by overall low bioturbation

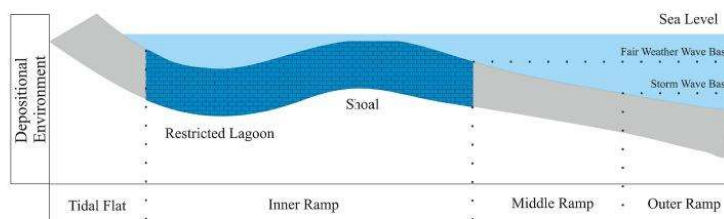


Fig. 7. Depositional model for the Maastrichtian-Danian carbonate ramp of the Gramame and Maria Farinha formations in the Olinda Sub-basin (Adapted from Hussein et al., 2017).

index (BI 1–2). The composition of the suites resemble that described in the basal portion, indicating similar depositional setting in an impacted brackish depositional setting (Buatois and Mángano, 2011). Finally, the upper interval presents an increase in marly and continental influx layers for its basal portion, although higher in the section the ichnodiversity is slightly increased. In these layers, freshwater impact was potentially lower, although the signature of an impoverished *Crustacea* ichnofacies persisted. Regarding the substrate characteristics, in the Itamaracá section the recognized suites occur on softgrounds (Bromley, 1996; MacEachern et al., 2007; MacEachern and Bann, 2008).

Studies on microfossils have described foraminifera (Tinoco, 1971; Albertão, 1993) and ostracods (Fauth and Koutsoukos, 2002; Barros et al., 2018) for the studied units, revealing a gradual reduction in ostracod diversity during the Maastrichtian, suggesting a nearshore environment with warm and shallow waters. Towards the end of the Maastrichtian, the recorded assemblage is marked by the abundance of *Cytherella* sp. 2, *Schizoptocythere potyensis* (Fauth et al., 2005), *Paracosta recifeensis* (Fauth et al., 2005), and *Protobuntonia punctatum* (Barros et al., 2018). This ostracod association corroborates a shallow marine environment (Barros et al., 2018). In general, the fossil associations suggest that the Gramame Formation represents a shoal and restricted lagoon environment, while the Maria Farinha Formation indicates a restricted lagoon environment. Thus, based on the trace fossil suites, an inner shelf position for the carbonate ramp during the Maastrichtian is corroborated (see Fig. 7).

These paleoenvironmental interpretations are supported by the available geochemical data ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) (Nascimento-Silva et al., 2013). The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves record an initial increase in temperature and bioproductivity at the beginning of the Maastrichtian, followed by a gradual decline during the rest of the interval. There is also a positive $\delta^{13}\text{C}$ excursion (+2‰) near the Cretaceous-Paleogene boundary, followed by a decrease to values around +1‰ after this boundary. Positive $\delta^{13}\text{C}$ excursions can result from increased bioproductivity and/or increased evaporation in shallow, coastal, or temporarily restricted marine environments (Nascimento-Silva et al., 2013). An increase in freshwater influx was also recorded based on Al_2O_3 data. These freshwater inflows tend to increase organic supply but create stressful conditions such as salinity fluctuations, turbidity, and periods of oxygen depletion that affect benthic fauna, reducing fossil diversity. Thus, the here reported low diverse suites, with overall small diameters and predominance of shallow-to middle-tier trace fossils corroborates recurrent oscillations in the salinity rates (Ekdale, 1988; Ekdale and Mason, 1988; Buatois et al., 2005; MacEachern et al., 2005; Mángano and Buatois, 2007; Tonkin, 2012; Bosetti et al., 2021).

5.2. The K-Pg boundary

The trace fossil signature in the Itamaracá-1IT-03-PE borehole, represented by *Palaeophycus*, *Planolites*, *Asterosoma*, *Teichichnus*, and *Taenidium*, exhibit limited similarity to the signature of other carbonate environments. For example, in the Middle Triassic Muschelkalk region of Thuringia, Germany, is characterized by *Palaeophycus*, *Pholeus*,

Planolites, *Rhizocorallium*, *Thalassinoides*, firmground *Diplocraterion*, and *Trypanites* (Knaust, 1998, 2007). This succession primarily consists of carbonates and evaporites deposited in an intracratonic epic sea on a carbonate ramp. Similarly, in other successions like the Khuff Formation, ranging from the Middle Permian to the Early Triassic in the Middle East region, the carbonate platform presents an extensive belt of sand banks and a different trace fossil composition, with 22 ichnogenera including *Arenicolites*, *Asterosoma*, *Chondrites*, *Diplocraterion*, *Planolites*, *Rosselia*, *Thalassinoides*, *Skolithos*, and *Zoophycos* (Knaust, 2009). On the other hand, a simple suite, dominated by *Palaeophycus*, *Planolites*, and *Skolithos* were associated with facies associations indicating a restricted subtidal environment within a lagoon, indicating rapid drowning of the platform (Knaust, 2009).

In areas preserving the K-Pg boundary, various ichnogenera such as *Chondrites*, *Planolites*, *Thalassinoides*, *Zoophycos*, *Alcyonidiopsis*, *Ophiomorpha*, and *Skolithos* have been identified in outcrops in Spain and France (Rodríguez-Tovar et al., 2010; 2011). Ichnological analysis of these sections revealed a significant crisis in marine invertebrate fauna during the K-Pg event, with many species disappearing entirely. However, the presence of trace fossils in layers above the boundary suggests that paleoecologic conditions began to recover rapidly after the event, with new species emerging to fill the ecological niches left vacant by the mass extinction (Rodríguez-Tovar et al., 2010; 2011).

In the Itamaracá borehole, the composition of ichnoassemblages in the Late Maastrichtian and Early Danian limestones did not reveal significant changes in ichnodiversity, indicating that the K-Pg event did not significantly modify the previously impacted trace fossil composition in the Paraíba Basin. The main factors can be taphonomic, because the trace fossil assemblage was already low diverse due to the restrict depositional conditions, not revealing a shift or decrease in the K-Pg boundary. Similarly, there was no alteration in the size of ichnofossils before and after the K-Pg event, as observed in other locations in Europe (Łaska et al., 2017) and the United States where trace fossils are notably smaller in the layer just above the event. Studies conducted in outcrops of the Navesink, New Egypt, and Hornerstown formations in the United States identified a decrease of approximately 30% in tube diameter, primarily in *Thalassinoides* (Wiest et al., 2015, 2016).

According to Wiest et al. (2016), dwarfism may have been caused by environmental stress resulting from reduced food supply due to the collapse of primary production in later phases of the event. This decrease is evident in middle shelf environments dominated by siliciclastics, carbonates, and glauconite, which responded similarly. In other localities, the ichnofossil assemblage is also poorly diverse. Ichnological analyses of two K-Pg boundary sections in Bidart (SE France) and Sopelana (N Spain) show that the trace fossil assemblage is sparsely diversified, consisting of *Chondrites*, *Planolites*, *Thalassinoides*, *Trichichnus*, *Zoophycos*, and *Phycosiphon*, all attributed to the *Zoophycos* ichnofacies (Rodríguez-Tovar et al., 2011). In the Caravaca section (Spain), the K-Pg boundary did not cause a severe crisis for the burrowing macroinfauna. The similarity between pre- and post-event ichnotaxa reveals a rapid colonization phase. The minimal impact of the K-Pg boundary event on the benthic habitat were associated with the

near-instantaneous reestablishment of pre-impact oxygen conditions in bottom and intermediate waters (Rodríguez-Tovar et al., 2022; Rodríguez-Tovar, 2024).

Other studies have also shown that the trace fossil assemblage remained significantly constant before and after the K-Pg boundary (Wiest et al., 2015, 2016; Laska et al., 2017). These studies identified a significant temporary decline in the presence of trace fossils just above the K-Pg boundary, with a sterile layer a few centimeters thick. This decline suggests inhospitable environmental conditions for macrobenthic tracemakers, possibly due to temporary anoxia or a drastic reduction in food availability. However, the recovery of trace fossils was rapid, indicating that despite the initial severe impact, environmental conditions eventually stabilized, allowing the reestablishment of macrobenthic communities (Monaco et al., 2015; Sosa-Montes de Oca et al., 2016; Sosa-Montes de Oca et al., 2017). Geochemical analyses conducted by Sosa-Montes de Oca et al. (2016, 2017) also demonstrate a rapid return to pre-impact oxygenation conditions, which facilitated the quick recovery of the macrobenthic community, favored by the opportunistic behavior of some organisms.

6. Conclusions

This study provides a detailed analysis of ichnofossil suites and their paleoenvironmental implications in a Maastrichtian-Danian Interval in the Itamaracá-1T-03-PE Well. It identifies and interprets different trace fossils, conditions of energy, salinity, and food availability throughout the section were inferred. The *Palaeophycus-Asterosoma* and *Asterosoma* suites, are indicating paleoenvironments of low to occasionally moderate energy with few variations in sedimentation rate. The presence of these suites suggests relatively stressful paleoenvironmental conditions over a relatively long period, mainly related to impact in salinity. The colonization of softground substrates favored the activity of detritus-feeding organisms, expressing an impoverished *Cruziana* ichnofacies. Fluctuations in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values recorded during the Maastrichtian interval suggest changes in temperature and bioproductivity over time, corroborating the increase in freshwater input during this period that affected paleoenvironmental conditions and the trace fossil diversity.

CRedit authorship contribution statement

Carlos Alves Moreira Júnior: Conceptualization, Data curation, Investigation, Software, Writing – original draft, Writing – review & editing. **Sonia Agostinho:** Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing. **Edilma de Jesus Andrade:** Conceptualization, Methodology, Writing – review & editing. **José Antônio Barbosa:** Data curation, Investigation, Resources. **Emmanuel Franco Neto:** Investigation, Methodology, Writing – review & editing. **Mário Lima Filho:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing. **Daniel Sedorko:** Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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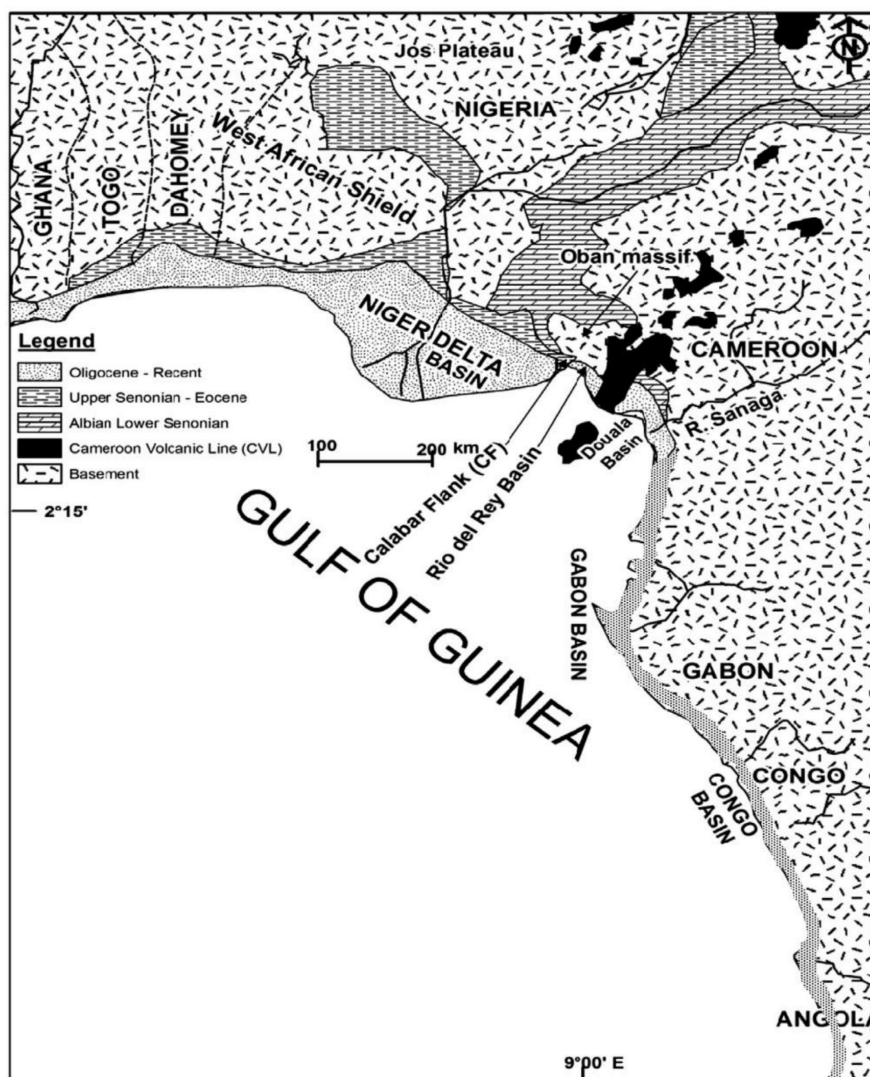
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2.2 ESTRATIGRAFIA DAS BACIAS CORRELATAS DO OESTE AFRICANO

A evolução das duas bacias sedimentares distribuídas ao longo da costa de Camarões está intimamente ligada ao processo de separação da África e da América do Sul e à subsequente formação da margem continental passiva (Brownfield; Charpentier, 2006; Yugye et al., 2021).

Essas bacias são separadas por uma cordilheira vulcânica: A Bacia do Rio Del Rey que representa a extensão sudeste do Delta do Níger e a Bacia de Douala / Kribi-Campo. Estas duas bacias estendem-se ao longo do Golfo da Guiné e pertencem ao grupo de bacias da África Ocidental, dentro da Província da Costa Centro-Oeste, de acordo com as suas características estruturais, que se estende desde os Camarões até à Namíbia (Brownfield; Charpentier, 2006) (Figura 1).

Figura 1. Mapa do golfo da guiné, mostrando as bacias sedimentares de Angola a Senegal.



Fonte: Anonh; Peters, 2014

Devido ao sistema de falhas presentes dentro do oceano atlântico e ao posicionamento geográfico as Bacias de Rio del Rey e Douala são possíveis bacias correlacionadas a Bacia da Paraíba. Os falhamentos que deram origem ao Rift durante o Aptiano-Albiano foram orientadas pela reativação de grandes falhas datadas da orogenia panafricana (650 a 450 Ma), incluindo o sistema de falhas Pernambuco-Tiko-Adamaoua que separa a futura margem passiva em duas áreas, a futura Bacia do Rio Del Rey ao norte, e a Bacia de Douala/Kribi-Campo ao sul (Nguimbous-Kouoh et al., 2018).

A história evolutiva tectônica e estratigráfica da Bacia do Rio del Rey, está intimamente ligada aos processos de rifting que levaram à abertura do Atlântico Sul. Njoh; Taku (2016) e Nguimbous-Kouoh et al., 2018, entre outros descreveram os

processos tectônicos que começaram ao final do Jurássico até o Cretáceo Inferior, incluindo; a sequência sin-rifte (Barremiano-Aptiano), a fase de transição rifte-deriva (Aptiano superior) e uma fase pós-rifte (Albiano - Presente) que compreende três estágios drift; Drift I (Albiano - Coniaciano, Drift II (Santoniano-Eoceno) Drift III (Eoceno - Pleistoceno) A bacia acumulou mais de 6000 m de espessura de sedimentos clásticos e biogênicos, marinhos e não marinhos que variam em idade de Neocomiano a Recente. Rochas predominantemente cretáceas afloram na parte onshore da bacia, enquanto as rochas terciárias cobrem o cretáceo principalmente como sequências progracionais deltaicas em direção a bacia. A estratigrafia da bacia (Figura 2) ainda é muito incompleta. No entanto, diretamente sobrejacente ao embasamento pré-cambriano está uma camada de conglomerados continentais neocomianos-albianos continentais e flúvio-lacustres. Sobrepostos a estes estão camadas finas de calcário datados do Albiano ao Cenomaniano intercaladas com folhelhos predominantemente cinza-escuros a pretos na parte norte da bacia. A unidade sedimentar Turoniano-Coniaciana foi descrita como folhelhos calcários cinzento-escuros, frequentemente intercalados por margas, calcários e siltitos. Estudos recentes estabeleceram a unidade Campaniana-Maastrichtiana que é chamada de “Formação Kita”. Já no Paleoceno a Formação Akata é constituída por folhelhos marinhos. Sendo sobreposto por areias do Oligoceno-Mioceno a Recentes e uma unidade de folhelhos, a Formação Agbada. A Formação Benin depositada no Plioceno-Recente é a unidade superior, que compreende arenitos de planície continental a costeira nesta bacia (Figura 2).

Figura 2. Estratigrafia da Bacia de Rio del Rey.

EON	ERA	PERIOD	EPOCH	LITHOLOGY	FORMATION
	Cenozoic	Tertiary	PLIOCENE-RECENT		BENIN
			Miocene		AKATA
			Oligocene		
			Eocene		
			Paleocene		
			Maastrichtian		KITA SHALE (Informal Name)
			Campanian		Njoh <i>et al.</i> 2013
			Santonian	??	??

Fonte: Retirado de Njoh; Taku, 2016

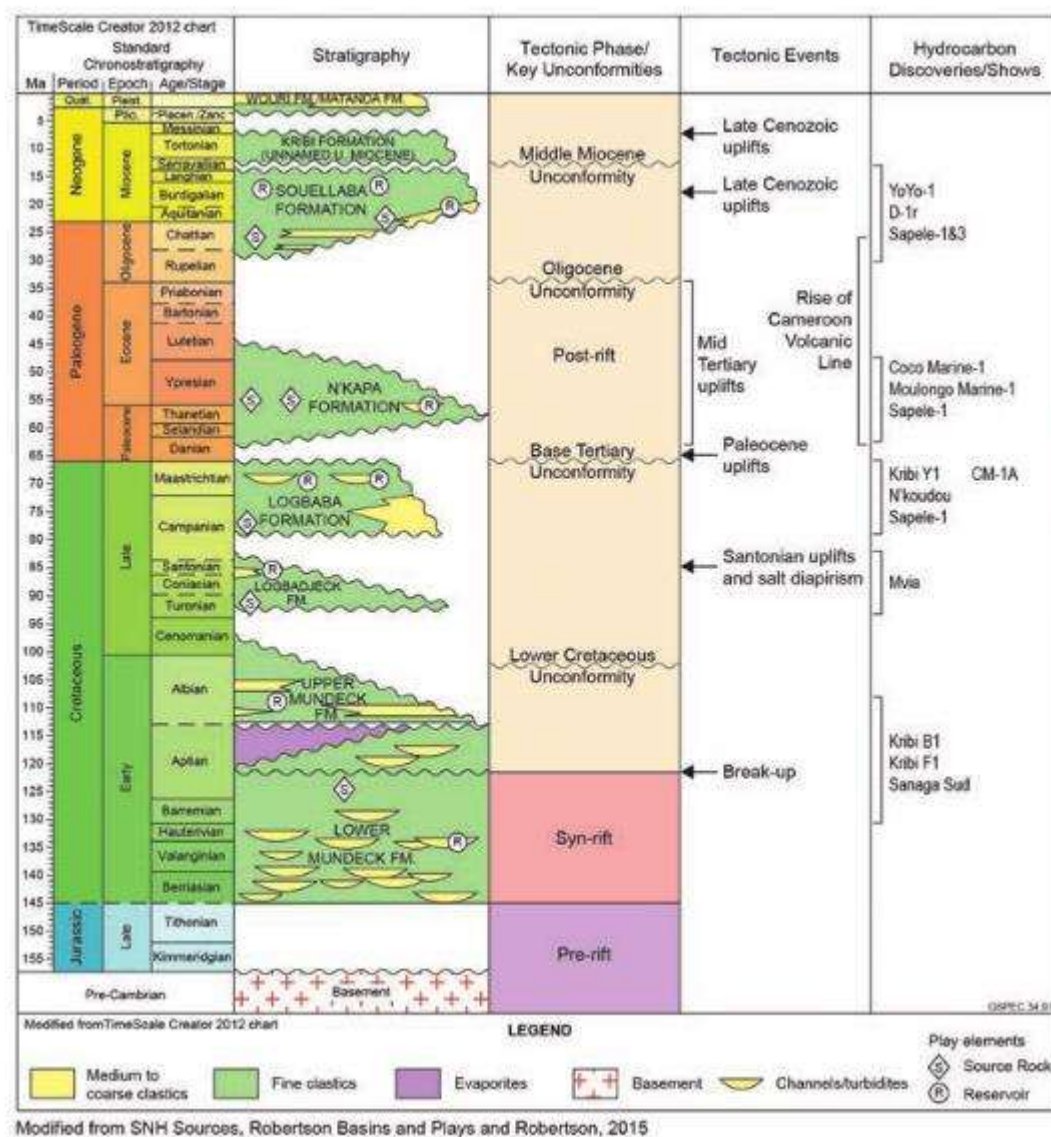
A Bacia de Douala / Kribi-Campo é maior que a Bacia do Rio del Rey e contém uma seção estratigráfica mais contínua. As areias continentais basais do Cretáceo são cobertas por calcários marinhos rasos, arenitos e folhelhos do Cretáceo Superior, Paleógeno e Neógeno. Na margem ocidental da bacia, essas formações são cobertas por lavas basálticas do centro vulcânico de Camarões. Na porção offshore, as formações se espessam acentuadamente desde o Cretáceo. Há mais areias e menos folhelhos do que na bacia do Rio del Rey, e falhas de crescimento e diapirismo devido a folhelhos estão praticamente ausentes (Brownfield e Charpentier, 2006).

Kenfack et al. (2012a, b) descreveram cinco eventos tectônicos que contribuíram para a formação desta Sub-Bacia: Fase Pré-rifte (Jurássica): Caracterizada por sedimentos continentais jurássicos, que foram depositados em uma depressão afro-brasileira que se estendia sobre esta sub-bacia. Fase de Rift (Jurássico-Barremiano): Caracterizada por uma sequência estratigráfica controlada por falhas lítricas e anticlinais roll-over associados. Fase Syn-rift: Caracterizada por uma intensa atividade de erosão das terras altas e deposição no graben formado anteriormente. Fase de transição rifte-deriva (meio-final do Aptiano): marcada pela deposição de sal e pela direção de transformação, resultando em uma série de falhas cruzadas que segmentaram a estrutura rifte. Fase pós-

rifte (Albiano-Presente): cuja sedimentação foi dominada por sedimentação clástica marginal com acúmulos esporádicos entre o Albiano e o Paleoceno.

O preenchimento da bacia começa no Barremiano na sub-bacia de Kribi-Campo e no Aptiano na sub-bacia de Douala. A Sub-Bacia de Douala é subdividida em sete Formações (Fig. 3). Estas formações, conforme descritas em Brownfield; Charpentier, 2006; Nguimbous-Kouoh et al., 2018; Yugye et al., 2021, consistem em: Formação Mundeck (Barremiano-Albiano) formada por arenitos; A Fm. Logbadjeck (Cenomaniana-Campaniana) composta por arenitos, calcários e conglomerados; A Fm. Logbaba (Maastrichtiana), formada por arenitos e folhelhos com intercalações de arenitos e rara ocorrência de calcários; A Fm. Nkapa do Paleoceno ao Eoceno Médio é composta por margas, folhelhos e arenitos calcários; A Fm. Souellaba do Eoceno Superior ao Oligoceno, composta por arenitos e margas, folhelhos, areias argilosas, areias e cascalhos; A Fm. Miocênica Matanda, formada por fácies deltaicas entremeadas por depósitos vulcânicos; A Fm. Wouri do Plioceno-Pleistoceno é composta por cascalhos e areias argilosas.

Figura 3. Estratigrafia da Bacia de Douala, com as rochas geradoras e reservatórios descritos para a bacia.



Fonte: Retirado de Loule et al., 2018

A Formação Logbaba que é a formação de idade correlacionada a Formação Gramame, foi depositada entre o Campaniano até o Maastrichtiano e pode alcançar até 4000m de espessura. Caracterizada por um ambiente marinho de águas rasas com canais e leques submarinos depositados na borda da plataforma. Apresenta uma possível rocha geradora os folhelhos Souellaba em offshore, com os canais e leques servindo de reservatório e folhelhos do Membro Logbadjeck como selantes (Nguimbous-Kouoh et al., 2018).

A litologia e as estruturas geológicas presentes na bacia de Douala sugerem a existência de rochas geradoras, rochas selantes, armadilhas estratigráficas, estruturais e mistas; com o melhor potencial de petróleo identificado na porção oriental. Por outro lado, os níveis arenosos são abundantes, limpos, espessos e com grande porosidade, o que os torna excelentes reservatórios de hidrocarbonetos.

A estrutura da bacia de Douala é caracterizada por uma densa rede de falhas sin-sedimentares e pós-sedimentares mais ou menos paralelas à costa com numerosas compensações ou anticlinais roll-over que são características das províncias deltaicas e apresentam bons fechamentos estruturais favoráveis à acumulação de hidrocarbonetos. Existem também cúpulas e domos de argila que se sucedem de leste a oeste e alongadas de norte a sul: elas resultam da compressão vertical contínua das argilas da formação Akata (Mfayakouo et al., 2021).

Ao contrário da Bacia de Douala, o melhor potencial petrolífero da Bacia do Rio Del Rey está nas formações de “alternância deltaica” datadas do final do Mioceno ao Plioceno. Esses sedimentos mostram intercalação entre níveis arenosos e argilosos. O dobramento dessas formações sugere a existência de potenciais armadilhas estratigráficas e estruturais. Por outro lado, camadas de folhelhos intensamente fraturadas facilitam a migração de hidrocarbonetos para armadilhas potenciais. A matéria orgânica tem uma origem marinha e a maturidade das rochas geradoras é atingida a partir dos 3000 metros de profundidade, estando as principais camadas descobertas entre os 1000 a 2000 metros de profundidade (Mfayakouo et al., 2021; Nguimbous-Kouoh e al., 2018).

As formações Gramame e Maria Farinha são as unidades correspondentes as formações africanas e são fundamentais na compreensão da evolução paleoambiental da Bacia Paraíba. A Formação Gramame, é caracterizada por wackestone a packstone, e é interpretada como um ambiente de plataforma interna. Por outro lado, a Formação Maria Farinha é caracterizada por mudstone e margas e é interpretada como de deposição em um ambiente raso a shoreface, indicativos de condições de maior energia no ambiente deposicional.

A evolução da sequência sedimentar nas formações Gramame e Maria Farinha revela importantes aspectos sobre a geometria da rampa carbonática na bacia. Essa rampa é composta por blocos falhados que se inclinaram suavemente em direção leste.

A transgressão marinha, que marcou o início da deposição dessas formações, está associada à incursão do Oceano Atlântico na bacia a partir do Santoniano-Campaniano. Esse evento teve início provavelmente no norte da bacia, onde preencheu inicialmente a porção correspondente às sub-bacias Miriri e Alhandra, para posteriormente avançar em direção à sub-bacia Olinda. A presença de sedimentos clásticos na sub-bacia Olinda e de sedimentos transicionais e marinhos na sub-bacia Miriri são reflexos diretos desse processo transgressivo. A subsequente regressão, que teve início no Maastrichtiano Superior, sinaliza um evento de reativação e soerguimento tectônico na bacia, acelerando a desocupação marinha (Barbosa, *et al.*, 2003; Barbosa; Lima Filho, 2006).

O paleoambiente discutido para as formações Douala e Kribi-Campo, são equivalentes temporalmente e desenvolveram um paleoambiente próximo a não ser pela ausência da entrada de siliciclásticos no lado brasileiro. Dessa forma, os sistemas petrolíferos encontrados na parte africana podem indicar que a porção offshore da Bacia Paraíba também poderia conter um sistema petrolífero. Contudo, devido à baixa quantidade de estudos na Paraíba, é necessária a realização de investigações detalhadas, estudos sedimentológicos, petrográficos e bioestratigráficos a fim de estabelecer melhor essa correlação e estabelecer possíveis alvos de prospecção de petróleo.

3 CONCLUSÕES

Foram identificadas duas icnofábricas compostas: *Palaeophycus-Asterosoma* e *Asterosoma*. Essa seção exhibe vários icnogêneros, como *Palaeophycus*, *Planolites*, *Asterosoma*, *Teichichnus* e *Taenidium*. Essa icnoassembleia difere de outras descritas para ambientes carbonáticos, e de outras localidades que registraram o evento K-Pg. Os icnofósseis descritos sugerem um icnofácies Cruziana e, de maneira geral, as icnofábricas indicam um ambiente marinho raso de baixa energia, com flutuações de salinidade e oxigenação.

As flutuações nos valores de $\delta^{13}\text{C}$ e $\delta^{18}\text{O}$ registradas no período Maastrichtiano sugerem mudanças na temperatura e na bioprodutividade ao longo do tempo, indicando que o suprimento de água doce aumentou durante esse período, afetando as condições paleoambientais e a diversidade fóssil.

Nas bacias da margem de Camarões foram identificados cinco eventos tectônicos que contribuíram para a formação desta sub-bacia, desde a fase pré-rifte até a fase pós-rifte. A Bacia de Douala possui um bom potencial de petróleo devido à presença de rochas geradoras, reservatórios de areias abundantes e estruturas favoráveis à acumulação de hidrocarbonetos. O potencial de petróleo está concentrado nas formações de "alternância deltaica" datadas do final do Mioceno ao Plioceno, com dobramento dessas formações sugerindo potenciais armadilhas estratigráficas e estruturais.

As características das formações revelam informações importantes sobre a geometria da rampa carbonática na bacia, com eventos de transgressão e regressão marinha. A semelhança temporal e paleoambiental entre as formações Douala e Kribi-Campo indicam que a porção offshore da Bacia Paraíba também pode conter um sistema petrolífero, embora sejam necessários estudos mais detalhados para confirmar essa correlação.

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