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RILDA VERÔNICA CARDOSO DE ARARIPE

PALEOECOLOGIA, BIOESTRATIGRAFIA E PALEOBIOGEOGRAFIA DE MICROFÓSSEIS CARBONÁTICOS DA FORMAÇÃO ROMUALDO, APTIANO – ALBIANO, BACIA DO ARARIPE – NORDESTE DO BRASIL

Recife
2023

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Tese apresentada ao Programa de Pós-graduação em Geociências do Centro de Tecnologia e Geociências da Universidade Federal de Pernambuco como preenchimento dos requisitos para a obtenção do grau de Doutora em Geociências

Área de concentração: Geologia Sedimentar e Ambiental

Orientadora: Prof.ª Dra. Alcina Magnólia da Silva Franca

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RESUMO

Este trabalho tem por objetivo fornecer novas contribuições bioestratigráficas, paleoecológicas e paleobiogeográficas para a Formação Romualdo, Bacia do Araripe, através da análise integrada de foraminíferos associada a outros grupos de microfósseis carbonáticos (ostracodes e nanofósseis calcários). Para o estudo, foram selecionados quatro afloramentos baseando-se na presença de invertebrados marinhos (equinodermatas, gastrópodes, bivalvios e crustáceos). Foram elaboradas seções estratigráficas e coletadas 103 amostras nas porções centro-sul da bacia nos sítios Santo Antônio (6m) e Cedro (22m), Exu, PE, e a leste, em Sobradinho (50m), Jardim, e Serra do Mãozinha (28m), Missão Velha, CE. No total, foram identificadas 29 espécies de foraminíferos bentônicos, 5 planctônicos, associados a uma inédita e diversificada fauna de ostracodes marinhos e a primeira ocorrência de nanofósseis calcários para a Bacia do Araripe. Para os foraminíferos, foram identificadas três assembleias (*Quinqueloculina*, *Conorboides* e *Bathysiphon*). O paleoambiente deposicional das seções estudadas sugere diferentes subambientes (laguna hipersalina com conexões de mar aberto, plataforma rasa e, ambiente estuarino) formados por incursões marinhas ocorridas ao longo da deposição da Formação Romualdo. Quanto a bioestratigrafia, com base nas associações de microfósseis carbonáticos, a seção Santo Antônio foi dividida em duas biozonas, que compreende ao Aptiano superior, com a ocorrência do ostracode *Damonella grandiensis* (biozona-O11) e dos foraminíferos planctônicos *Hedbergella aptiana* e *Pseudoguembelitria* sp. (biozona *P. rohri*), e o Albiano inferior pela presença do nanofóssil *Hayesites albiensis* (biozona CC8). Nos afloramentos Cedro, Sobradinho e Serra do Mãozinha a ocorrência do ostracode *Damonella grandiensis* (biozona-O11) indica idade Aptiano superior para as seções. Muitas das espécies de foraminíferos encontradas na Bacia do Araripe são cosmopolitas, com alguns gêneros de ocorrência endêmica para a região. Os foraminíferos planctônicos estão correlacionados com a regiões do Oeste da África e América do Norte com forte influência Tetiana (*Hedbergella*, *Globigerinelloides*). Já as associações bentônicas (*Lingulogavelinella*, *Pseudonodosaria*, *Agathammina*), indica latitudes médias a baixas e uma bioprovincia Tetiana/Transicional.

Palavras-chave: incursão marinha; Aptiano-Albiano; foraminíferos; ostracodes; nanofósseis

ABSTRACT

This work aims to provide new biostratigraphic, paleoecological and paleobiogeography contributions to the Romualdo Formation, Albian-Aptian of the Araripe sedimentary basin, through the integrated analysis of foraminifera with others carbonate microfossil (ostracods and nannofossils). Four outcrops were selected based on the presence of marine invertebrates (echinoderms, gastropods, bivalves, and crustaceans). A total of 103 samples were collected from outcrops located in the central-southern and eastern portions of the basin: Santo Antônio (6m), Cedro (22m), Sobradinho (50m) and Serra do Mãozinha (28m). Twenty-nine species of benthic foraminifera, five species of planktonic foraminifera, an unique and diverse association of marine ostracods and the first occurrence of calcareous nannofossils for the Araripe Basin were recovered. Regarding foraminifera, three assemblages (*Quinqueloculina*, *Conorboides* and *Bathysiphon*) were identified among the four outcrops. The paleoenvironment suggests different subenvironments (hypersaline lagoons with open sea connections, shallow platform and estuarine) formed by incursions that occurred in that interval. Based on the carbonate microfossil associations, the Santo Antonio section was divided into two biozones, which comprise the upper Aptian, with the occurrence of the ostracode *Damonella grandiensis* (biozone-O11) and of the planktonic foraminifera *Hedbergella aptiana* and *Pseudoguembelitria* sp. (biozone *P. rohri*). And the lower Albian by the presence of the nannofossil *Hayesites albiensis* (biozone CC8). In the Cedro, Sobradinho and Serra do Mãozinha the occurrence of *Damonella grandiensis* (biozone-O11) suggests an upper Aptian age for the sections. Many of the foraminiferal taxa found in the Araripe Basin are cosmopolitan, with some genera endemic to the region. The planktonic foraminifera association are correlated to Western Africa and North America with strong Tethyan influence (*Hedbergella*, *Globigerinelloides*). In addition, the benthic associations (Lingulogavelinella, Pseudonodosaria, Agathammina), indicate medium to low latitudes and a Tethyan/Transitional bioprovince.

Keywords: marine ingression; Aptian-Albian; foraminifera; ostracods; nannofossils.

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1 INTRODUÇÃO

As discussões acerca do ambiente deposicional da Formação Romualdo têm crescido bastante nos últimos anos (Fursich et al. 2019; Goldberg et al. 2019; Arai e Assine, 2020; Bom et al. 2021; Kroth et al. 2021). Apesar da inquestionável influência marinha, citada pela primeira vez por Beurlen (1966), pela presença de equinóides irregulares, no Município de Araripina, PE, os diferentes ambientes de sedimentação encontrados na Formação Romualdo são ainda controversos. A idade da Formação Romualdo também é outro tópico importante que vem sendo alvo de diversas discussões científicas (Braun, 1966; Heimhofer e Hochuli, 2010; Melo et al. 2020; Arai e Assine, 2020; Barreto et al. 2022).

Os microfósseis fornecem uma riqueza de informações paleoambientais e bioestratigráficas que são utilizadas tanto para o reconhecimento de sistemas deposicionais, como para a datação e reconhecimento de biozonas com correlação internacional. Por muitos anos os estudos com microfósseis na Bacia do Araripe foram restritos aos ostracodes e palinomorfos (Krommelbein e Weber, 1971; Bate, 1971, 1972, 1973; Lima, 1978; Silva, 1978; Regali, 2001; Coimbra et al., 2002). No entanto, estudos recentes discutem através da ocorrência dos foraminíferos a bioestratigrafia e paleoecologia da Formação Romualdo (Melo et al., 2020; Araripe et al., 2021), fazendo com que a utilização de outros grupos de microfósseis como foraminíferos e nanofósseis, e novas metodologias sejam eficazes para enriquecer o estudo paleoambiental e paleoecológico da bacia.

Diante disso, o estudo da fauna de foraminíferos integrado a outros grupos de microfósseis carbonáticos pode contribuir para a melhor interpretação dos diferentes ambientes e subambientes registrados da Formação Romualdo. Além disso, a identificação de microfósseis marcadores de biozonas internacionais (como por exemplo, foraminíferos planctônicos e nanofósseis calcários) e, o melhor entendimento dos seus aspectos paleobiogeográficos podem ser fundamentais para as discussões acerca da idade e reconstrução de paleobiogeográfica da formação em questão. Nesse trabalho, é proposto investigar esses aspectos, a partir de uma análise taxonômica mais detalhada, aliado ao estudo de novos sítios fossilíferos da Bacia sedimentar do Araripe.

1.1 Objetivos

O objetivo geral do trabalho é realizar o estudo integrado de foraminíferos e outros grupos de microfósseis carbonáticos (ostracodes e nanofósseis calcários) da Formação Romualdo para o melhor estabelecimento da sua idade e o entendimento da transgressão marinha Aptiana-Albiana na Bacia do Araripe.

Como objetivos específicos o trabalho propõe:

- Identificar e descrever as principais associações de foraminíferos bentônicos e planctônicos da Formação Romualdo;
- Baseado nas principais assembleias de microfósseis definir biozonas com base em bioestratigrafia e critérios quantitativos.
- Buscar elementos guia para correlação internacional entre o Aptiano-Albiano e o Andar local Alagoas;
- Identificar o padrão de distribuição paleobiogeográfica dos foraminíferos bentônicos e planctônicos da Bacia do Araripe e correlacionar com outras bacias brasileiras.
- Integrar os dados levantados e subsidiar informações para a interpretação paleoceanográfica da transgressão marinha registrada na Formação Romualdo, Bacia Sedimentar do Araripe.

2 CONTEXTO GEOLÓGICO

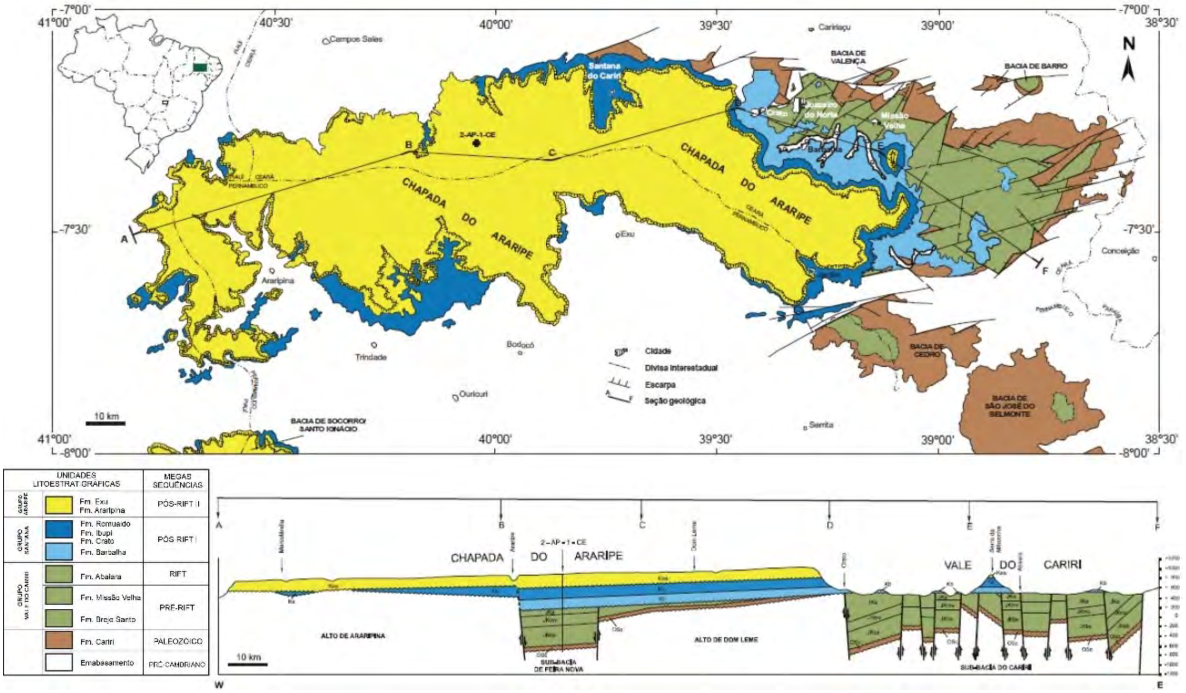
2.1 A Bacia do Araripe

A Bacia do Araripe é a maior entre as bacias interiores do Nordeste, com extensão de mais de 9.000 km², localizada entre os estados de Pernambuco, Piauí e Ceará, compreendendo toda a Chapada do Araripe e se estendendo pelo Vale do Cariri. Exibe estruturação alongada com maior eixo na direção E-W e mergulho suave da chapada para oeste (Ponte, 1996; Fambrini et al., 2020) (Figura 1).

As bacias interiores do Nordeste são fortemente controladas pelas estruturas do embasamento pré-cambriano/ Eopaleozoico, reativadas ao longo do Fanerozoico, em especial durante os eventos tafrogênicos do Eocretáceo (Almeida, 1967). Entre o Neojurássico e o Eocretáceo o consequente rifteamento do Supercontinente Gondwana causaram diversas transformações estruturais iniciando a formação dessas bacias interiores (Matos, 1992).

Pelo seu arcabouço estratigráfico constituído de megassequências geradas em regimes tectônicos distintos, a Bacia do Araripe é tida como uma bacia de evolução poligenética (Assine, 1990, 1992, 2007; Ponte e Appi, 1990; Ponte e Ponte Filho, 1996). As diferentes sequências foram formadas em cenários paleogeográficos diferentes, integrando o contexto da evolução geológica regional das bacias do Nordeste do Brasil (Assine, 1994).

Figura 1 - Mapa geológico da Bacia do Araripe



Fonte: Assine, 2014

2.2 Estratigrafia

Segundo Assine (2007), a Bacia do Araripe constitui-se pelas megassequências Pré-Rifte, Rifte que afloram somente na porção leste da bacia (região do Vale do Cariri), onde os estratos se encontram movimentados por falhas associadas aos *horstes* e *grabens* da Sub-bacia do Cariri, e pelas megassequências Pós-Rifte, subdividida nas megassequências pós-rifte I e pós-rifte II que afloram nas escarpas e sopé da Chapada do Araripe e descontinuamente, ao longo do Vale do Cariri (Assine, 2007; Bagni, 2010).

Várias propostas estratigráficas foram lançadas ao longo dos anos no que se refere à estratigrafia da Bacia do Araripe. Os primeiros trabalhos foram realizados por Small (1913) e Spix e Martius (1828-31). Porém, a nomenclatura por muitos anos utilizada foi proposta por Beurlen (1971) que subdividia a Formação Santana nos membros Crato, Ipubi e Romualdo, baseada em critérios ambientais (Assine, 1992). Posteriormente, Neumann e Cabrera (1999) e Assine (1992, 2007) propuseram a elevação de hierarquia de forma ampliada, dado que ambos os membros da Formação Santana possuem características sedimentológicas e ambientais próprias, e extensão em área que permitem individualizá-los como formações dentro do Grupo Santana. Neste trabalho, adotou-se a nomenclatura proposta por Assine et al., (2014) que inclui dentro do Grupo Santana todo registro estratigráfico da supersequência pós-rifte de Assine (2007).

A megassequência pós-rifte I, cronoestratigraficamente pertencente ao Andar Alagoas (Aptiano superior / Albiano inferior), é composta pelo Grupo Santana, constituído, da base para o topo, pelas formações Barbalha, Crato, Ipubi e Romualdo (Figura 2).

A Formação Barbalha é formada essencialmente por arenitos, compreende dois ciclos fluviais com granodecrescência ascendente, cujos topos são marcados pela presença de intervalos pelítico-carbonáticos lacustres (Assine, 2007). O primeiro se encerra com intervalo de folhelhos ricos em lâminas carbonáticas onde se encontra inserida uma camada de calcário com aspecto brechoide chamada de Camadas Batateiras (Hashimoto et al., 1987), que devido à sua grande extensão lateral é considerada um marco estratigráfico pertencente à biozona P-270 de importância regional da Bacia do Araripe (Assine, 2007).

Nos folhelhos é comum a presença de ostracodes, conchostráceos, restos de peixes e fragmentos vegetais carbonificados (Assine et al., 2014). A associação de fácies é típica de sistemas transgressivos, materializado por fácies de canais fluviais, que gradativamente perdem energia e são recobertos por fácies pelíticas lacustres (Assine et al., 2014).

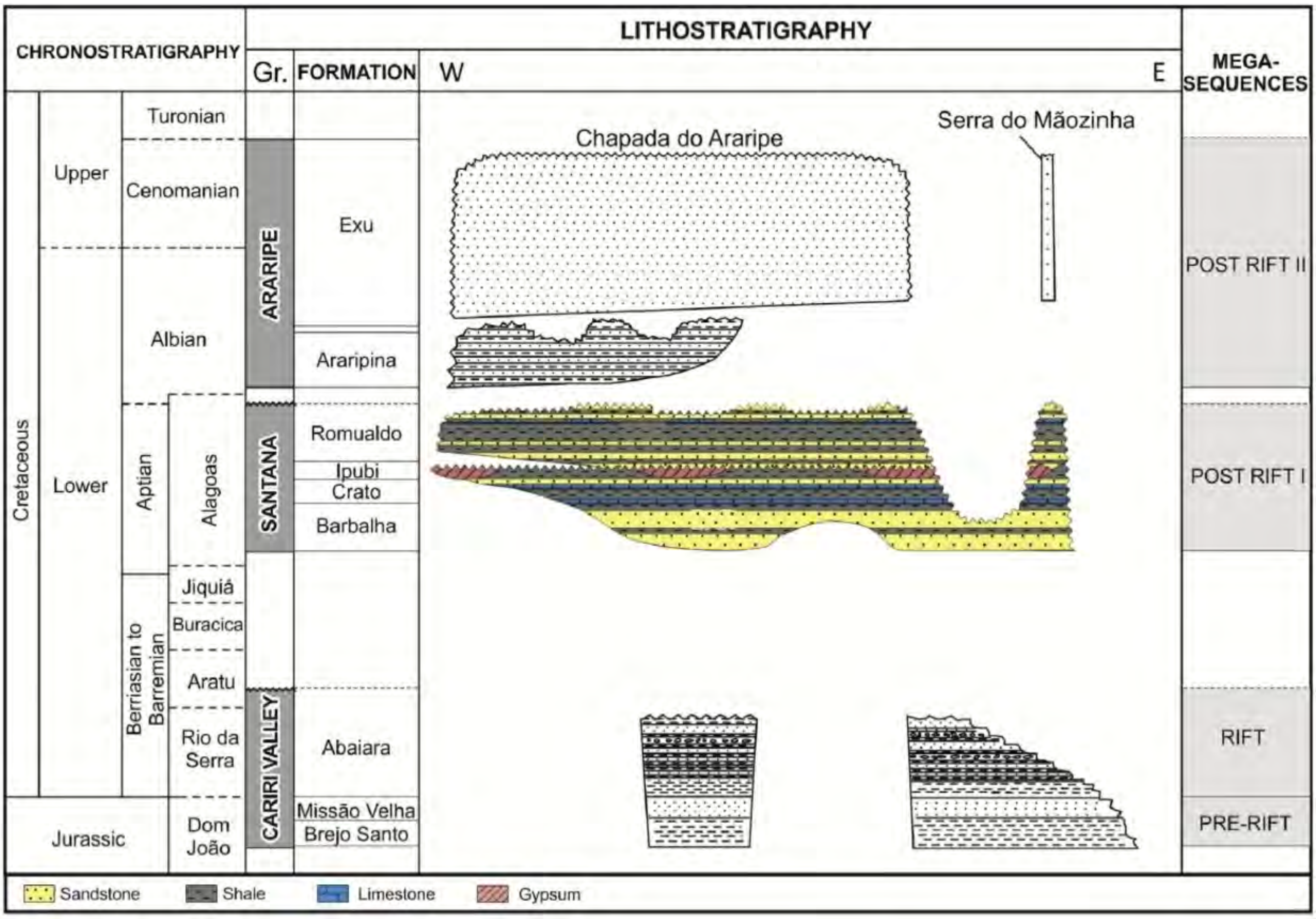
A Formação Crato é formada por folhelhos calcíferos interestratificados com calcários laminados, que se sobrepõe à Formação Barbalha. São representadas por folhelhos papiráceos calcíferos, interestratificados com calcários micríticos laminados, argilosos (Pons et al., 1990). A associação faciológica indica condições de baixa energia no ambiente deposicional com influxo de terrígeno, sendo comum a presença de filamentos algálicos (Assine, 1992). Por apresentar um diverso e abundante registro fossilífero com espécimes excepcionalmente bem preservados (Maisey, 1991) é considerado um depósito excepcional (*Konservat-Lagerstätten*). São encontrados ostracodes, conchostráceos, insetos, aracnídeos, biválvios, gastrópodes, peixes, pterossauros, quelônios, crocodilianos, aves, anuros, algas, gimnospermas, angiospermas e palinomorfos (Maisey, 1991; Kellner, 2002; Tomé et al., 2014; Teixeira et al., 2017). Tido como uma sedimentação em ambiente lacustre por vários autores (e.*g.*, Assine et al., 2014; Carvalho et al., 2020; Catto et al., 2016; Heimhofer et al., 2010; Neumann, 1999; Neumann et al., 2003; Warren et al., 2017). No entanto, Goldberg et al., (2019) através de análises palinológicas sugere a primeira incursão marinha para a Bacia do Araripe na formação. Onde foram registrados palinoforaminíferos em amostras imediatamente subjacentes a Formação Ipubi sugerindo que a parte superior da Formação Crato teria sido depositada sob condições marinhas.

Na Formação Ipubi são encontradas camadas de gipsita associadas a folhelhos, carbonatos e arenitos. Embora ocorra na porção leste da bacia, os níveis evaporíticos, em grande parte gipsíticos, não se estendem lateralmente e ocorrem intercalados com folhelhos verdes e pretos e delgadas camadas arenosas finas e calcário laminado (Assine, 2007; Fabin et al., 2018; Menor et al., 1993). A Formação Ipubi concentra-se sobretudo na porção oeste da bacia, onde é lateralmente contínua (Assine, 1992). O conteúdo fóssil é representado por ostracodes, vegetais, peixes e coprólitos (Barros et al., 2016). A associação de fácies sedimentares e geometria dos evaporitos indicam sedimentação em ambientes costeiros (supramaré) sujeitos a variações relativas do nível do mar, em condições de clima árido e semiárido, similares as atuais salinas do sul da Austrália (Assine,1992; Assine et al., 2014).

A Formação Romualdo compreende a última unidade do Grupo Santana, composta por arenitos interestratificados com intervalos de folhelhos cinza-escuros a pretos, ricos em matéria orgânica, folhelhos esverdeados e margas, localizados na base da formação. Logo acima, as concreções frequentemente fossilíferas que ocorrem em meio a folhelhos esverdeados ricos em ostracodes (Arai e Coimbra, 1990; Mabesoone et al., 1999). Os fósseis são encontrados tanto nos nódulos quanto nos folhelhos que envolvem os nódulos. Para o topo, encontram-se camadas de calcário com invertebrados sotopostas às camadas de arenito fino com intercalações de siltitos e folhelhos contendo fósseis de água doce e mixohalina, como conchostráceos e moluscos (Beurlen, 1971; Assine, 2007).

Assim como a Formação Crato, a Formação Romualdo é considerada um *Konservat Lagerstätten*, conhecida internacionalmente por abrigar fósseis excepcionalmente bem preservados na maioria dos casos (Maisey, 1991). A fauna representada por peixes ósseos e cartilaginosos, dinossauros, pterossauros, moluscos, equinoides, crustáceos, foraminíferos, dinoflagelados e vegetais (Mabessone e Tinoco, 1973; Arai e Coimbra, 1990; Berthou et al., 1990; Kellner, 2002; Bruno e Hessel, 2006; Lima et al., 2012) é típica de ambiente transicional a marinho raso, sendo os equinoides, foraminíferos e dinoflagelados os principais indicadores de sedimentação marinha franca (Beurlen, 1963, 1964; Arai et al. 1994; Prado et al., 2015, 2018ab; Melo et al., 2020; Araripe et al., 2021). Custódio et al., (2017), a partir da análise da estratigrafia de sequência, caracterizaram a Formação Romualdo com um ciclo transgressivo-regressivo delimitado por duas inconformidades regionais, estendendo a deposição marinha para toda a unidade.

Figura 2 - Carta estratigráfica da Bacia do Araripe



Fonte: Arai e Assine, 2020

2.3 Microfósseis carbonáticos da Formação Romualdo

Os primeiros estudos sobre os microfósseis carbonáticos da Bacia do Araripe, datam da década de 70 e estão relacionados principalmente com a fauna de ostracodes, sua diversidade e taxonomia (Krommelbein e Weber, 1971; Bate, 1971, 1972, 1973; Silva, 1978). Os primeiros registros de foraminíferos para a bacia foi feito por Lima (1978) que identificou a espécie *Rhodonascia bontei* Deak 1964, em lâminas palinológicas, da Formação Romualdo, e considerada pelo autor como espécie marinha não costeira.

Nas décadas seguintes, as pesquisas passaram a abordar outros aspectos, como paleoecologia, bioestratigrafia, e correlações com outras bacias adjacentes (Arai e

Coimbra, 1990; Berthou et al*.,* 1990; Silva Tales Jr. e Viana, 1990; Colin e Depèche, 1997; Coimbra et al., 2002; Gobbo, 2006).

Arai e Coimbra (1990), em estudo paleoecológico de amostras de poço no município de Araripe, Ceará, mencionaram a presença de ostracodes, palinoforaminíferos e foraminíferos indeterminados juntamente com uma assembleia de microfósseis composta por grãos de pólen, esporos, dinoflagelados e micromoluscos. A fauna representaria um ambiente tipicamente costeiro mixohialino e com a ocorrência dos gêneros de dinoflagelados *Spiniferites* (Mantell) e S*ubtilisphaera* (Jain e Millepied) indicaria a inquestionável influência marinha para a Formação Romualdo.

No mesmo ano, Berthou et al., (1990) registraram uma abundância de ostracodes e no mínimo duas formas de foraminíferos bentônicos, entre eles miliolídeos e formas calcário-hialinas, provenientes de estratos da Formação Romualdo, considerando-os como de origem marinha. Destacam-se também o trabalho de bioestratigrafia baseada em ostracodes e palinomorfos de Coimbra et al., (2002) e os estudos paleoambientais das formações Crato e Romualdo de Gobbo (2006).

Com o surgimento de novos grupos de pesquisa voltados à micropaleontologia brasileira e incentivos oferecidos pelas empresas de petróleo, nos últimos anos ocorreram importantes avanços no conhecimento dos microfósseis da Bacia do Araripe (Tomé et al., 2014; Goldberg et al., 2019; Melo et al., 2020; Almeida-Lima e Piovesan. 2020; Bom et al., 2021; Araripe et al., 2021; Piovesan et al., 2022; Tomé et al., 2022; Guzmán et al. 2022).

Os trabalhos tem enfoque principalmente paleoecológico a partir das interpretações das condições paleoambientais durante a deposição da Formação Romualdo, além da busca pela datação relativa da idade (bioestratigrafia).

Almeida-Lima et al., (2020) mostraram que a deposição da Formação Romualdo ocorreu em ambiente salino com base na ocorrência de *Pattersoncypris minima*, com influência marinha, corroborando com trabalhos prévios (Assine 2007; Assine et al., 2014; Fürsich et al., 2019; Prado et al., 2018ab; Varejão et al., 2019).

Melo et al., (2020) analisaram a seção tipo da Formação Romualdo localizada no sítio Sobradinho (CE), fazendo um estudo bioestratigráfico e paleoecológico. Os autores reconheceram uma fauna de ostracodes de ambiente mixohalino e registraram a ocorrência de foraminíferos bentônicos e planctônicos. Ainda segundo os autores, a fauna de foraminíferos planctônicos seria característica do Aptiano superior e possui uma afinidade tetiana.

Ainda na seção Sobradinho, Bom et al., (2021) realizaram a análise de macro e microfósseis. Os autores identificaram pulsos de abundância de ostracodes, e a ocorrência de foraminíferos bentônicos aglutinantes reconhecendo três intervalos de influência marinha.

Araripe et al., (2021) fizeram estudo taxonômico e paleoecológico de ostracodes e foraminíferos bentônicos em seções na parte sudoeste e centro-sul da bacia, no estado de Pernambuco e identificaram uma fauna característica de ambiente mixohalino a marinho raso e afinidade com associação tetiana de algumas espécies.

2.3.1 *Bioestratigrafia*

Inúmeros trabalhos discutem a idade da Formação Romualdo, porém a maioria tende a posicioná-la no Cretáceo Inferior (Braun, 1966; Mabesoone e Tinoco, 1973; Lima, 1978). No entanto, existem divergências sobre o refinamento cronoestratigráfico da formação, que têm o seu posicionamento entre o Aptiano superior ao Albiano inferior.

Os microfósseis são uma importante ferramenta biocronoestratigráfica para a datação relativa. Para a Formação Romualdo, os microfósseis (palinomorfos, ostracodes e foraminíferos) têm sido amplamente utilizados no refinamento e a atribuição de idade (Tabela 1).

Braun (1966) atribui idade Aptiano-Albiano para o Grupo Santana, baseado em dados de microfauna de ostracodes (*Candonopsis sp., paraschuleridea sp., heterocypris sp., bisulcocypris*), fauna similar a registrada na Formação Riachuelo (Bacia de Sergipe/Alagoas), pertencentes a paleozona Z-7.

Baseados em dados de palinomorfos Lima (1978) posiciona a formação no Albiano inferior a médio, Zona *Complicatisaccus cearensis*, o autor ressaltou a dificuldade que encontrou para correlacionar seu biozoneamento da então, Formação Santana, com aquele proposto por Regali et al. (1974).

Brito (1984) analisou a influência marinha da Formação Romualdo durante o Eocretáceo (Neoaptiano / Eoalbiano). Segundo o autor, o limite inferior do Andar Alagoas é marcado por uma associação de ostracodes não marinhos de difícil classificação (? *Cytheridae*). A parte superior da formação, a qual é marcada por equinoides e moluscos marinhos, corresponde ao Aptiano superior alcançando o Albiano inferior (Brito, 1984). Tais dados corroboram com Regali (1990) que estudou a palinologia de amostras provenientes da borda oriental da Bacia do Araripe e as atribuiu à Biozona P-270 (Aptiano superior) através da ocorrência da *Sergipea variverrucata.*

As bacias do Nordeste do Brasil foram caracterizadas como de idade Aptiana-Albiana, pela ocorrência da Ecozona *Subtilisphaera*. Arai (2000), apresentou dados paleontológicos das bacias do Nordeste do Brasil (São Luís, Potiguar, Araripe e Ceará) delimitando a ecozona no limite Aptiano superior.

Em contraponto, Coimbra et al., (2002) propõem uma idade albiana para a Formação Romualdo, baseada na análise bioestratigráfica de conjuntos de pólens, esporos e ostracodes. Heimhofer e Hochuli (2010), também afirmam ser improvável uma extensão do Aptiano ao topo da Formação Romualdo, pois tal idade não corresponde aos agrupamentos palinomórficos (pólen e esporos *Stellatopollis barghoornii*, *Dichastopollenites* cf. sp. 1 e *Retimonocolpites* aff. sp. 7) encontrados pelos autores, caracterizando como idade Albiano inferior para a formação. Outros autores também inferem idade albiana para a Formação Romualdo (Beurlen, 1964; Coimbra et al., 2002, Valença et al., 2003).

Rios-Netto et al., (2012) posicionaram a Formação Romualdo no Aptiano, pela ocorrência de *Sergipea variverrucata,* analisando testemunhos de 14 furos de sondagem perfurados na borda leste dessa bacia. Tais dados foram corroborados mais recentemente por Arai e Assine (2018; 2020).

Tomé et al., (2014) descreveram associação de ostracode não-marinhos do Andar Alagoas. Composta principalmente por espécies do gênero *Pattersoncypris* (*P. angulata, P.micropapillosa* e *P. salitrensis*) e *Damonela grandiensis* (ostracode-207) caracteriznando a biozona *Damonella grandiensis* do Aptiano-Albiano.

Em estudos mais recentes, Melo et al., (2020) reforçaram a idade aptiana da Formação Romualdo através da associação de foraminíferos planctônicos e o caráter marinho inequívoco na porção superior da unidade. Barreto et al., (2022), por meio da técnica radiométrica do U/Pb, analisado em dentes do peixe *Cladocyclus gardneri* da Formação Romualdo, na seção de Santo Antônio (PE), obtiveram o resultado de 110 ±7,4 Ma, datando a formação no Aptiano superior, podendo se estender até o início do Albiano.

Tabela 1 - Microfósseis da Formação Romualdo com o posicionamento biocronoestratigráfico.

Idade	Autores	Argumentos
Albiano inferior	Beurlen, (1964)	*Gastrópodes (Cassiopinae*) Nova subfamília dos *Turriteliidae*
	Lima, (1978)	Palinomorfos: Zona *Complicatisaccus cearensis* (espécies *Stellatopollis*; *Dicotetradites sp*; *Gnetaceaepollenites ornatus*; *G. perforatus*)
	Coimbra et al., (2002)	Palinomorfos e ostracodes
	Valença et al., (2003)	Biozona *Elaterosporites protensus*
	Heimhofer e Hochuli (2010)	Pólen e esporos: *Stellatopollis barghoornii*, *Dichastopollenites* cf. sp. 1 e *Retimonocolpites* aff. Sp. 7
Aptiano/Albiano	Barreto et al., (2022)	Datação U/Pb
	Braun (1966)	Paleozona Z-7: Dentes e fragmentos de ossos de peixes; Ostracodes *Candonopsis sp.*
	Brito (1984)	Biozona Vinctifer (*Aspidorhynchus*); Ostracode *Cytheridae ?*
	Arai et al., (1994)	Ecozona *Subtilisphaera*
	Tomé et al., (2014)	Ostracode *Damonela grandiensis (*O-11)
Aptiano superior	Regali (2001)	Palinozona *Complicatisaccus cearenses* (*S. variverrucata*)
	Rios-Netto et al., (2012)	Palinozona *Complicatisaccus cearensis* (*S. variverrucata*)
	Melo et al., (2020)	Foraminíferos planctônicos: Zona *Microhedbergella miniglobularis*
	Arai e Assine (2018; 2020)	Palinozona – P 270 *Sergipea variverrucata*

2.3.2 *Paleobiogeografia*

O intervalo Aptiano – Albiano representa um período importante de mudanças climáticas/oceânicas. Pelo aumento da crosta oceânica juntamente com as ações de vulcanismo ativo (Skelton et al., 2003), pela deposição cíclica e preservação de folhelhos negros, alguns deles relacionados a Eventos de Anoxia Oceânicos (EAOs) (Schlanger e Jenkyns, 1976; Arthur et al., 1990), mudanças periódicas nas condições redox no fundo do oceano (Oceanic Red Beds, ORBs) (Wang et al., 2009) e as rápidas irradiações bióticas e turnovers (Leckie et al., 2002).

Nesse intervalo, uma grande transgressão marinha atingiu várias bacias brasileiras, incluindo a Bacia do Araripe, e diversos estudos discutem suas afinidades paleobiogeográficas e as diferentes caminhos em relação às rotas das ingressões marinhas

(Beurlen, 1963; Beurlen, 1966; Mabesoone et al. 1999; Valença et al. 2003; Arai, 2014; Assine et al. 2014; Prado et al. 2015; Assine et al. 2016; Pereira et al. 2016; Araripe et al. 2021; Barreto et al. 2022). Dentre os microfósseis, os palinomorfos e foraminíferos tem mostrado uma afinidade com a fauna de Tétis. De acordo com Arai (2014), a distribuição do gênero *Subtilisphaera* nas bacias do nordeste do Brasil representa uma ecozona de afinidade tetiana, e sendo ela menos notável na Bacia Potiguar, indicaria também uma ingressão marinha através da Bacia do Parnaíba, onde a ecozona é mais proeminente.

Outros autores correlacionam a fauna de foraminíferos bentônicos (*Agathammina*) e planctônicos (*Gorbachikella*, *Blesfucuiana* e *Pseudoguembelitria*) com a região de Tétis. Principalmente as espécies planctônicas, que possuem uma faixa latitudinal muito restrita, no Norte da África, Europa Oriental, América Central (incluindo o Caribe e México) e o Atlântico Norte, todas estas regiões cobertas pelo antigo mar de tétis (Melo et al., 2020; Araripe et al., 2021).

3 MATERIAL E MÉTODOS

3.1 Etapas de campo

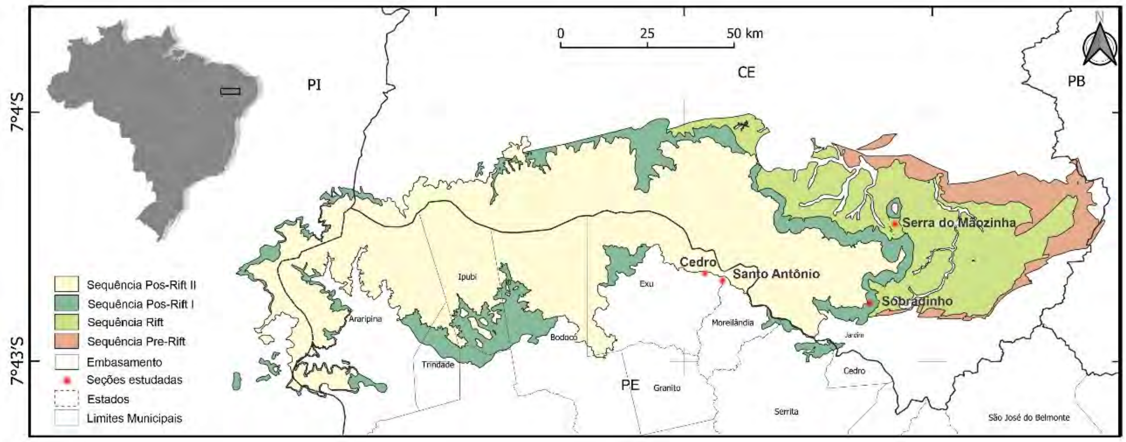
Foram realizadas 3 etapas de campo, nos anos de 2019 e 2020, seguindo o protocolo padrão de atividades (pesquisa cartográfica e geologia da área), e foram selecionadas 4 seções estratigráficas para o estudo de microfósseis carbonáticos. Os afloramentos Santo Antônio e Cedro foram coletados na porção centro-sul da bacia, munícipio de Exu, Pernambuco. Os afloramentos Sobradinho e Serra do Mãozinha foram coletados na porção leste da bacia, nos municípios de Jardim e Missão Velha (Figura 3).

Os afloramentos de Pernambuco foram selecionados para estudo de microfósseis, pela presença marcante de macrofósseis de preferências ecológicas marinha, como os equinóides irregulares, gastrópodes e bivalves, tendo sido estudado por Pereira et al., 2015; 2016, Prado et al., 2018 a, b. Quanto às seções do Ceará, foram priorizadas por serem afloramentos clássicos da Formação Romualdo (Maisey, 1991; Custódio et al., 2017; Fürsich et al., 2019).

Nas áreas de estudo, foram realizadas descrições dos afloramentos e a elaboração das seções estratigráficas. Foram coletadas um total de 167 amostras, com base em intervalos padronizados e/ou diferenciação litológica (Tabela 2).

A análise de fácies sedimentares da Formação Romualdo observados nos perfis aqui levantados, segue Custódio et al., (2017), onde foram descritas as fácies FA-1, arenitos e conglomerados (*fácies aluvial a costeira*); FA-2, arenitos intercalados por finas camadas de folhelho (*fácies costeira dominada por marés*); FA-3, folhelhos cinzas com invertebrados (*fácies de plataforma interna*); FA-4, folhelho escuro com abundantes concreções calcárias (*fácies de plataforma interna e externa*); FA-5, arenito bioclástico, formando ocasionalmente coquinas (*fácies marinha dominada por tempestades*).

Figura 3 - Mapa de localização dos afloramentos Santo Antônio e Cedro na porção Centro-sul, Sobradinho e Serra do mãozinha, localizados na porção leste da Bacia do Araripe.



Fonte: A Autora (2022)

Tabela 2 - Lista de afloramentos coletados e quantidade de amostras.

Afloramento	Amostras	Coordenadas	Profundidade
Santo Antônio	51	39° 32' 57"W/7° 30' 53"S	6,3 m
Cedro	34	39° 35' 21" W/ 7° 29' 17"S	22 m
Sobradinho	50	39° 09' 47"W/ 7° 34' 18"S	51 m
Serra do mãozinha	32	39° 05' 56" W/ 7°21' 45" S	42, 5 m

3.2 Etapas de Laboratório

Para recuperação das carapaças dos microfósseis carbonáticos de acordo com Do Carmo et al., (2008), as amostras foram mergulhadas em uma solução de peróxido de hidrogênio (H_2O_2) a 26%, durante 24 horas. Em seguida, foi realizado o peneiramento sob água corrente com peneiras sobrepostas de aberturas de 250 µm, 120 µm, 63 µm e 45 µm. Após a lavagem, as amostras foram secas em estufa a 60º C.

Após a secagem, foi realizada a triagem sob lupa binocular (SteREO Discovery V8, ZEISS), para a recuperação dos microfósseis carbonáticos, entre eles: foraminíferos (bentônicos e planctônicos), ostracodes e demais elementos do conteúdo biótico das amostras (bivalves, gastrópodes, fragmentos de decápodas e fragmentos de equinóide).

A sistemática adotada para os foraminíferos seguiu a descrição feita por Leoblich e Tappan, (1988) e Ellis e Messina, (1940-2006). Para os ostracodes, a sistemática supragenérica segue a mesma adotada por Liebau (2005). Em paralelo a triagem das amostras, foram elaborados *stubs* para a realização de fotomicrografias dos espécimes de ostracodes e foraminíferos em Microscópio Eletrônico de Varredura (MEV) no Laboratório de Dispositivos e Nanoestruturas (LDN) da UFPE.

Para os nanofósseis calcários foram utilizadas quatro metodologias de preparação: decantação (Antunes, 1997), esfregaço (*Smear Slide*, Bown, 1998), centrifugação, confeccionada a 15 segundos/1000 r.p.m (*short centrifuging,* Bown e Young, 1998) e lâmina delgada (Erba et al., 2010). Após a etapa de processamento, o conteúdo de nanofósseis de cada lâmina foi investigado e descrito com o auxílio de um Microscópio Óptico Zeiss (Axion Vision Imager A2), com sistema de polarização. Exemplares das principais espécies foram fotografados com a câmara (Camera AxioCam MRc) e por meio do software/aplicativo AxioVision foram transferidas para o computador.

4 RESULTADOS E DISCUSSÃO

Os resultados e discussões obtidos são apresentados em uma primeira parte com a descrição dos afloramentos trabalhados, contendo a litologia, descrição de fácies e idade. E uma segunda parte dividida em três artigos científicos, são eles:

- Artigo 1 apresentado no APÊNDICE. Intitulado "Upper aptian–lower albian of the southern-central Araripe Basin, Brazil: Microbiostratigraphic and paleoecological inferences". **Publicado no Journal of South American Earth Science.**

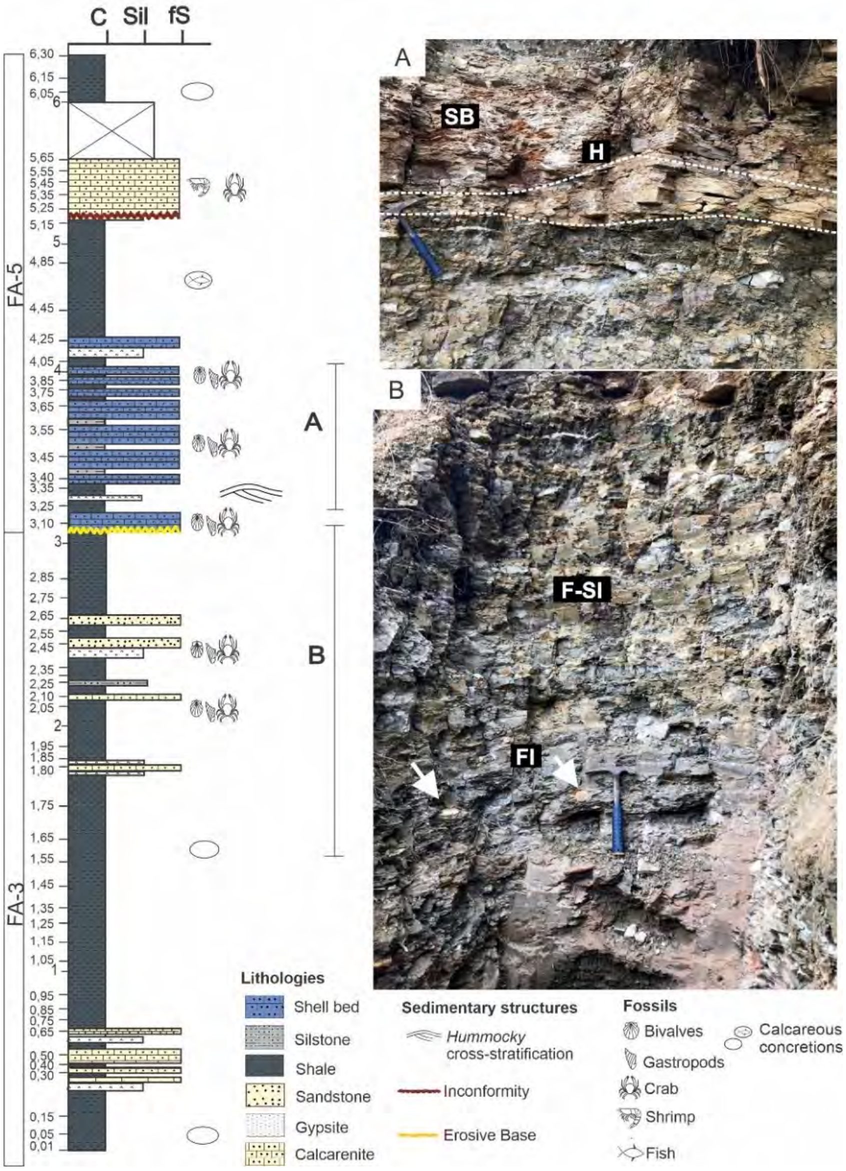
- Artigo 2 Aptian – Albian foraminifera from the Romualdo Formation, Araripe Basin, Brazil: Taxonomy and Paleoenvironmental reconstruction. **Submetido a Palaeobiodiversity and Palaeoenvironments**

- Artigo 3 Considerações Paleobiogeográficas de Foraminíferos do Aptiano - Albiano de Mares Epicontinentais do Nordeste Do Brasil. **A ser submetido a revista Palaeogeography, Palaeoclimatology, Palaeoecology.**

4.1 Perfis estratigráficos e análise de Fácies

A seção Santo Antônio está localizada no Sítio Santo Antônio próximo ao riacho Carrancudo, no município de Exu, Pernambuco, com aproximadamente 6,5 m de espessura (Figura 4). A partir da base até 3,0m a seção caracteriza-se pela presença de folhelhos cinza, com fósseis de invertebrados e poucas concreções, intercalado a finas camadas de calcário, siltito e arenito calcífero. Comparando-se a litologia, estruturas e conteúdo macrofossilífero, desse trecho da seção, com a análise de fácies de Custódio et al., (2017), pode-se correlacionar com a facies FA-3, folhelhos cinzas com invertebrados - *fácies de plataforma interna*. Já o trecho 3,0 – 4,25m da seção se caracteriza por apresentar camadas pouco espessas de folhelhos intercalados a arenito calcífero e calcário com concentração de conchas de moluscos (coquinas), nota-se estratificação cruzada do tipo *hummocky* e observa-se base erosiva na coquina da fácies FA-5, arenito bioclástico, por vezes, formando coquinhas – *fácies marinha dominada por tempestades*.

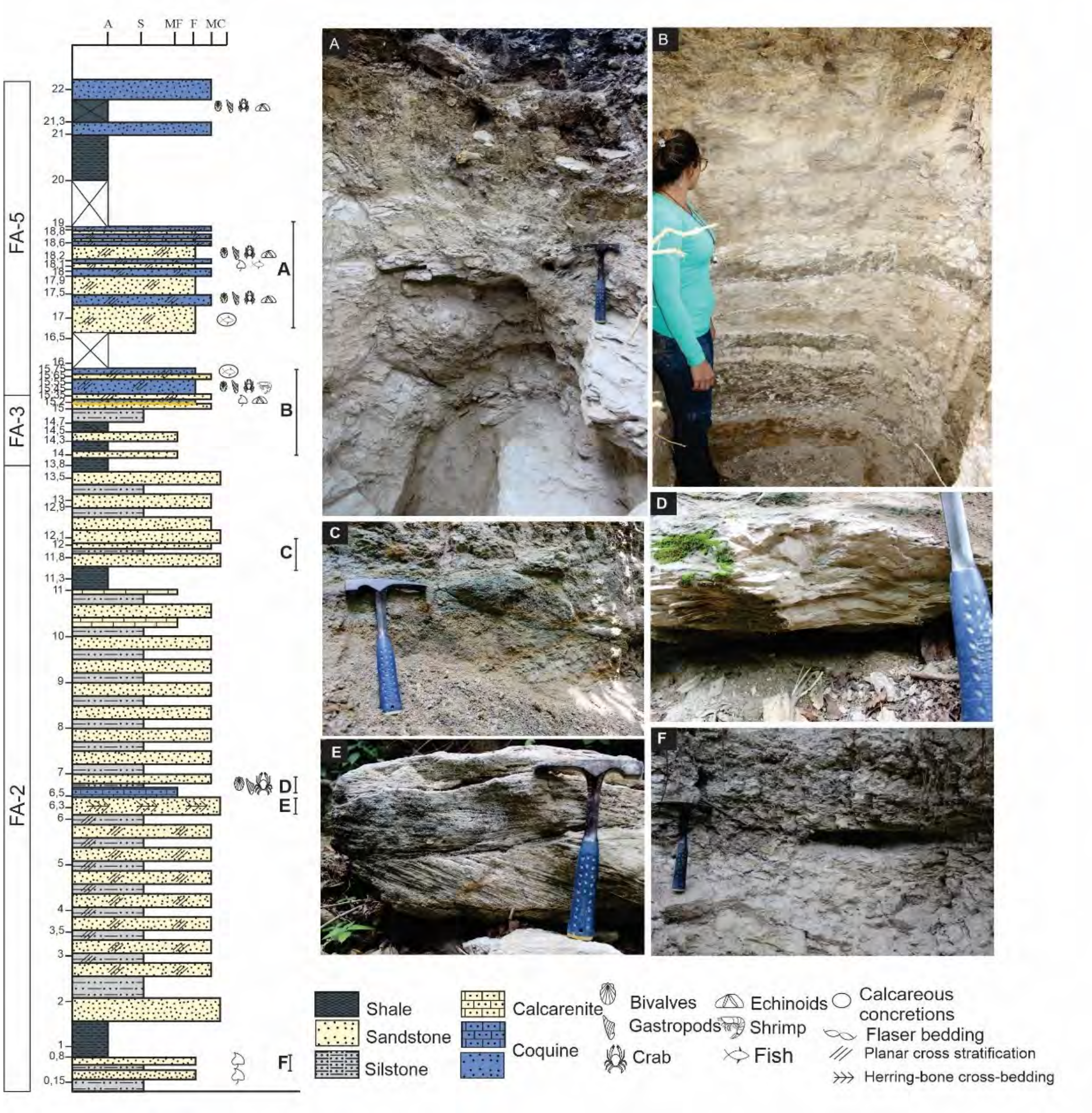
Figura 4 - Seção estratigráfica Santo Antônio, Munícipio de Exu (PE), com as associações de fácies (Adaptado de Custódio et al., 2017). A- Fácies FA-5, *fácies marinha dominada por tempestade*. B - Fácies FA-3, *fácies marinha de plataforma interna*



Fonte: A Autora (2022)

A seção Cedro localiza-se no Sítio Cedro, também no município de Exu (PE), porção centro-sul da Bacia do Araripe, com aproximadamente 22 m (Figura 5), abrange folhelhos, siltitos, calcários e arenitos calcíferos com a presença de macrofósseis, em especial equinóides irregulares, bivalves e gastrópodes. A base da seção (0 –11 m) é marcada pela presença de argilitos e siltitos intercalados por camadas centimétricas de arenitos com estratificação cruzada de baixo ângulo (FA-2, *fácies costeira dominada por marés*). Estratificações cruzadas do tipo *flaser* e espinha de peixe também estão presentes. Nessa fácies, os macrofósseis são raros e representados por fragmentos vegetais e invertebrados. Nota-se níveis de erosão e estrutura acanalada. Entre 13,8 m e 15,3 m são encontrados argilitos intercalados por arenitos calcíferos, sem observação de macrofósseis (FA-3, *fácies de plataforma interna)*. No intervalo de 13,5 m a 22 m ocorre uma sucessão de camadas de arenitos e siltitos, de cimento calcífero, com estratificação cruzada planar e laminação horizontal, por vezes formando coquinas (FA-5, *facies marinha dominada por tempestades)*. Os macrofósseis presentes são fragmentos vegetais, peixes e invertebrados.

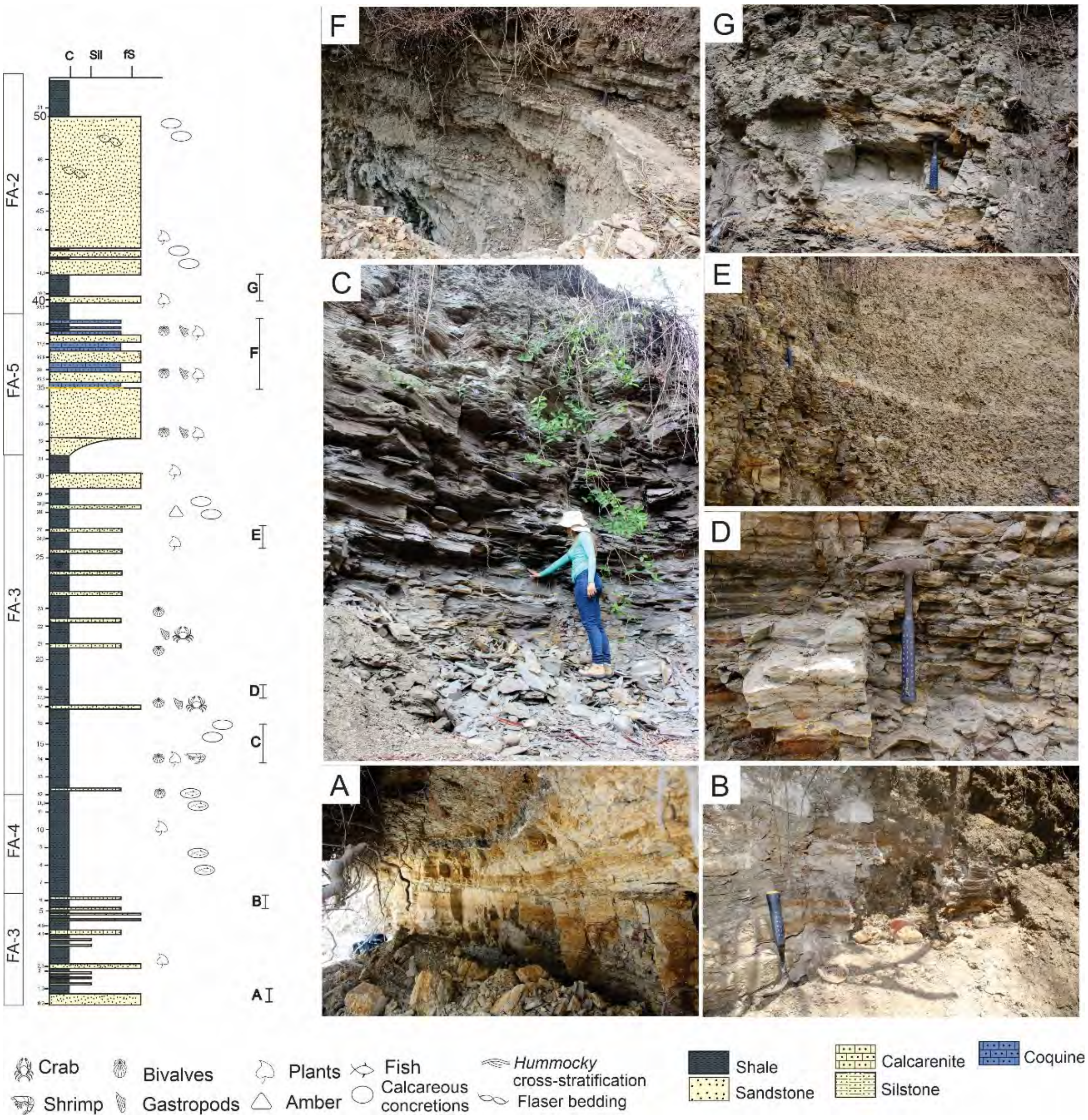
Figura 5 - Seção estratigráfica Cedro, município de Exu, PE. A. 13-16 m; B. 15-16,0 m; C. 13,5-14,5 m; D. 11,0-13,5 m; E. 6, 3 m; F. 3,5 m; G. 1,8 m. FA-2, *fácies costeira dominada por marés*, FA-3, *fácies marinha de plataforma interna* e, FA-5, *fácies marinha dominada por tempestades.*



Fonte: A Autora (2022)

Na Seção Sobradinho, localizada no sítio Sobradinho, município de Jardim, CE, foi levantada uma seção de 51 m de um total de aproximadamente 100 m aflorantes (Figura 6). Os primeiros 49 m não foram amostrados pela dificuldade de acesso, porém, correspondem a uma sequência, de pacotes de arenito estratificados e ondulados, de espessura variável, alternando com folhelhos (*fácies costeira dominada por marés,* FA-2). Apenas o último metro superior dessa sequência foi amostrado (0,2 m). Acima, camadas centimétricas de silte, arenito e calcarenito são encontrados intercalados a argilitos e folhelhos (*fácies marinha de plataforma interna,* FA-3*;* 1,3 a 6,0 m). Nos oito metros superpostos (7,0 a 13 m), ocorre um homogêneo intervalo de folhelho escuro com muitas concreções com vertebrados (*fácies marinha de plataforma interna e externa,* FA-4). Acima, entre os níveis 14,0 a 31,0 m, há o retorno a fácies FA-3, de águas mais rasas, e agora com numerosos invertebrados (gastrópodes, biválvios, camarões e caranguejos). Embora os restos vegetais predominem no topo desta fácies (26,5 a 30 m), eles estão presentes ao longo de todo o perfil. Próximo ao topo (32,0 e 38,6 m) ocorre sequência de arenitos e arenitos calcíferos coquinoides (*fácies marinhas dominadas por tempestades,* FA-5*)*. O topo da seção é marcado pela presença de arenito estratificado, na base, com estruturas do tipo *flaser*, intercaladas ao folhelho (*fácies costeiras dominadas por marés,* FA-2).

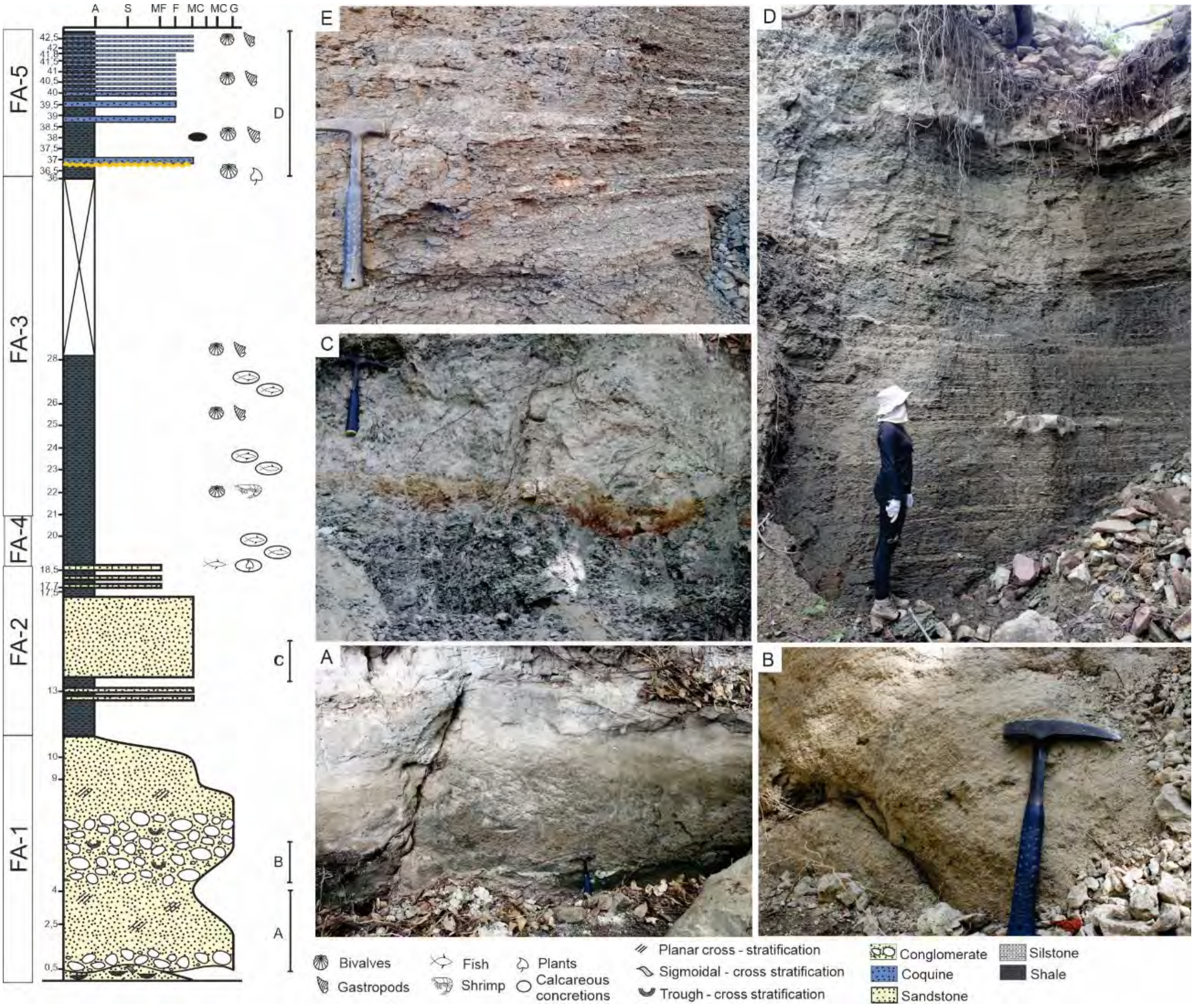
Figura 6 - Seção Sobradinho, município de Jardim, Ceará, com as associações de fácies (Adaptado de Custódio et al., 2017). A-B; fácies FA-3, *fácies marinha de plataforma interna*. C; fácies FA-4 *fácies marinha de plataforma interna a externa*. D-E; fácies FA-3. F; fácies FA-5, *fácies marinha dominadas por tempestades*. G; FA-2, *fácies costeiras dominadas por marés.*



Fonte: A autora (2022)

Na seção Serra do Mãozinha, localizada no sítio Serra do Mãozinha, aflora aproximadamente 43 m da Formação Romualdo. Foi identificada na base a fácies FA-1 (*fácies aluvial* a *costeira*), composta por arenitos e conglomerados, seguida de camadas de arenitos intercalados por camadas de folhelhos representando a fácies FA-2 (*fácies costeira dominada por marés*). Entre 18,5 a 21 m ocorre um folhelho escuro com abundantes concreções calcárias (FA-4 *fácies de plataforma interna e externa*); logo acima, os folhelhos contêm uma grande quantidade de fósseis de invertebrados (FA-3 *fácies de plataforma interna*); e no topo da seção é registrado um arenito bioclástico formando coquinas (FA-5 *fácies marinha dominada por tempestades*).

Figura 7 - Seção Serra do Mãozinha, município de Missão Velha, Ceará, com as associações de fáceis (Adaptado de Custódio et al., 2017). A-B; fácies FA-1, fácies aluvial a costeira. C; fácies FA-2, fácies costeiras dominada por marés. D-E; fácies FA-5, *fácies marinhas dominadas por tempestades*. E; detalhe da fácies FA-5.



Fonte: A Autora (2022)

4.2 Idade

Os microfósseis encontrados neste estudo são típicos do Cretáceo Inferior, porém algumas espécies se estendem até o Cretáceo Superior (Maastrichtiano). Nos quatro afloramentos estudados foi identificado a Biozona O11 sendo, tal biozona, caracterizada pelo aparecimento da espécie *Damonella grandiensis* (= Ostracode 207, Weber, 1964 in: Brito, Viana & Praça, 1984) e considerado como fóssil- guia do Andar Alagoas, Aptiano – Albiano, (Brito, Viana & Praça, 1984).

No afloramento Santo Antônio, a presença de *Hedbergella aptiana* associada a outras formas planctônicas como *Pseudoguembelitria* sp. e *Lililiputianella* sp. sugerem idade Aptiano superior para a seção. Com base nos bioeventos identificados, a primeira ocorrência do *Hayesites albiensis* e a última ocorrência *Hedbergella aptiana*, foi delimitado o intervalo entre o Aptiano superior e o Albiano inferior para a seção. O gênero *Hedbergella* encontrado também na seção Sobradinho possui range estratigráfico que compreende quase todo o Cretáceo Inferior, Valanginiano ao Aptiano (entre outros BouDagher-Fadel et al., 1997; Huber e Leckie, 2011; Petrizzo et al., 2012; Premoli Silva et al., 2018), porém estudos anteriores realizados indica idade Aptiano superior para a seção Sobradinho (Arai e Assine, 2020; Rios-Netto et al. 2012; Melo et al. 2020).

No afloramento Cedro, os nanofósseis calcários identificados (*Biscutum constans, Biscutum* sp., *Nannoconus* sp., *Thoracosphaera* sp.,) possuem grande amplitude estratigráfica, que corresponde o Aptiano – Cenomoniano, bioestratigraficamente equivalente as biozonas CC7 a CC10 de Sissingh (1977) ou N240 a N260.1 de Antunes (1997).

Baseado nessas informações, a seção Santo Antônio possui idade Aptiano – Albiano e as seções Cedro, Sobradinho e Serra do Mãozinha podem ser colocadas no Aptiano superior.

4.3 Artigo 1 - Upper Aptian–lower Albian of the southern-central Araripe Basin, Brazil: Microbiostratigraphic and paleoecological inferences

Publicado na revista Journal of South American Earth Science, no dia 13 de Abril de 2022. O artigo I encontra-se completo anexado no Apêndice A desta tese.

Figura 8 - Captura de página do artigo 1.

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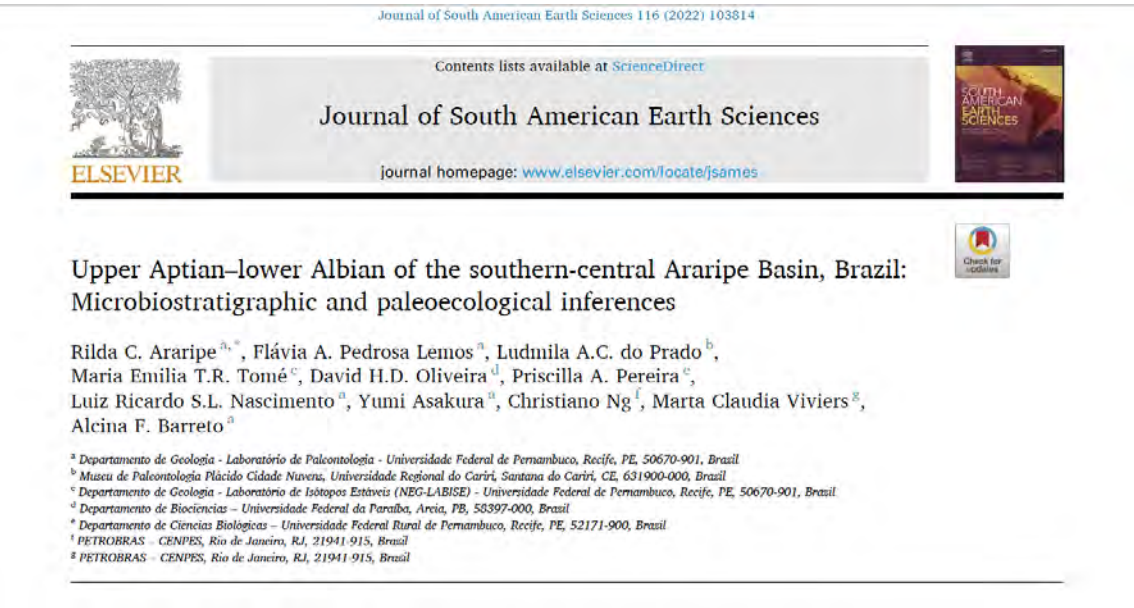

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Upper Aptian–lower Albian of the southern-central Araripe Basin, Brazil: Microbiostratigraphic and paleoecological inferences

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Fonte: A Autora (2022)

4.4 Artigo 2 – Foraminiferal paleoecology of the Aptian/Albian deposits of the RomualdoFormation (Araripe Basin) in Northeastern of Brazil

FORAMINIFERAL PALEOECOLOGY OF THE APTIAN/ALBIAN DEPOSITS OF THE ROMUALDO FORMATION (ARARIPE BASIN) IN NORTHEASTERN OF BRAZIL

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Author Contribution

Rilda Araripe - conceived and designed the experiments, analyzed the data, prepared figures and tables, authored and reviewed drafts of the paper, and approved the final draft.
David Oliveira - Foraminifera specialist, data analysis and interpretation.

Marta Claudia Viviers - Critical revision of the taxonomy and foraminifera specialist and approved the final draft.

Renata Moura de Mello - Foraminifera specialist, data analysis and critical revision of the article

Anne Montenegro - Performed the experiments and acquisition of the data

Bruno Fernandes - Performed the experiments and acquisition of the data

Rizoaldo do Espírito Santo - Performed the experiments and acquisition of the data

Anny Carvalho - Performed the experiments, analyzed the data and prepared figures

Maria Emília Tomé - Data analysis and interpretation, reviewed drafts of the paper

Flavia Pedrosa - Data analysis and interpretation and approved the final draft.

Ludmila Prado – Data analysis and interpretation, reviewed drafts of the paper

Ricardo Nascimento – Data analysis and interpretation, reviewed drafts of the paper

Alcina Barreto - Conception of the work and Critical revision of the article

Data Availability Statement

The authors confirm that the data supporting the findings of this study, demonstrated in figures 6, 7 and 8 are available within the article its supplementary materials. Data on Cluster analysis, relative abundance, richness, epifauna/infauna ratio and percentage of foraminifera type shell were used to support this study. The authors used PAST program version 4.04 to perform the dataset.

Acknowledgements

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Abstract

The Romualdo Formation is the sedimentary succession of the Araripe Basin of northeastern Brazil that best records the marine incursion of an epicontinental sea during the Aptian–Albian transition. While the characteristics of the paleoenvironment of the Romualdo Formation have long been the subject of debate, detailed data on the composition of its microfauna can provide important insights for the understanding of the formative processes. In the present study, the benthic and planktonic foraminifera of four sections of the Araripe Sedimentary Basin were analyzed in order to reconstruct the paleoecological and paleoenvironmental conditions of the Romualdo Formation. The foraminifera identified in the present study belong to 16 families, with a predominance of benthic taxa. The families Hauerinidae and Conorboididae were the most abundant overall. The other principal families included the benthic Spirillinidae, Ammodiscidae, Hemigordiopsidae, Vaginulinidae, Ellipsoidinidae, Nodosaridae, and the planktonic family Hedbergellidae were much less abundant. Four assemblages (*Quinqueloculina*; *Quinqueloculina*–*Conorboides*; *Quinqueloculina*–other groups, and *Bathysiphon*) were identified here. These assemblages were composed primarily of epifaunal species characteristic of stressful conditions related to marginal marine environments. These assemblages indicate poorly oxygenated environments with low sedimentation rates, associated with the marine transgression that occurred during the upper Aptian. The distribution of the foraminiferal assemblages in the Romualdo Formation of the Araripe Basin indicates a progressive shift in environmental conditions as the area evolved into a marine ecosystem.

Keywords: Benthic foraminifera; Lower Cretaceous; Paleoecological inferences; Epicontinental sea

1. Introduction

Foraminiferal assemblages provide an important analytical tool for the reconstruction of marine paleoenvironments. The distribution of both benthic and planktonic species is related systematically to environments conditions, and the analysis of the variation in species composition permits relatively accurate inferences on nutrient availability, oxygen concentrations, and sedimentation rates (e.g., Jorissen et al., 1995; Van der Zwaan et al., 1999; Fontanier et al., 2002 Caratelli and Archuby, 2023). Marginal marine environments, which may include habitats ranging from coastal salt marsh to the inner continental shelf, tend to have high levels of organic productivity, which favor the establishment of foraminiferal communities, as well as considerable heterogeneity (Sen Gupta, 1999).

The Araripe Basin is a major area of sedimentary deposition (9,000 km^2) and is considered to be the largest inland sedimentary basin in northeastern Brazil (Fambrini, 2020). The sedimentary succession of the Santana Group, in the Romualdo Formation, registers a marine transgression that occurred at the time of the breakup of the Gondwana supercontinent and the expansion of the South Atlantic Ocean (Neumann and Assine, 2015). The sedimentary layers that compose the Romualdo Formation are observed in many areas of the Araripe Basin, recording the different phases of the ancient marine environments. The exact extension of the flooding episodes is still unclear, however. Divergences have been observed between the sedimentary patterns and the macro- and microfossil records of the Romualdo Formation at distinct geographic locations, in fact, and the exact configuration of the paleoenvironments is still not fully understood.

Both marine and non-marine faunas have been described from the Romualdo Formation, although its microfossils (foraminifera, nannofossils, and dinoflagellates) constitute one of the principal pieces of evidence of marine deposition (Arai and Coimbra, 1990, Berthou et al., 1990; Melo et al., 2020; Araripe et al., 2021;2022; Pedrosa et al., 2023). For many years, however, research on the microfossils of the Araripe Basin were very limited in their scope. More recent studies have provided more detail, both by increasing the resolution of their samples, and by deciphering the response of the associated fauna to prevailing paleoenvironmental conditions.

Understanding the factors that influence the distribution of the foraminifera in marginal marine environments will provide important insights into the evolution of the paleoenvironments of the Romualdo Formation. The present study is based on the analysis of foraminifera from four sites in the Araripe Basin – Santo Antônio and Cedro, in the southern-central basin, and Sobradinho and Serra do Mãozinha in the eastern extreme – to provide more detailed paleoenvironmental information and a better understanding of the dynamics of the marine incursions recorded in the sedimentary deposits of the Romualdo Formation.

2. Geological setting

The Araripe Basin is filled with stratigraphic units associated with the fragmentation of Gondwana, and is the only basin located in the interior of northeastern Brazil that records the marine transgressions of the Lower Cretaceous (Assine, 1992; 2007; Ponte and Filho, 1996). The Romualdo

Formation is a post-rift I sequence (the Alagoas local stage), which records this transgression, a process derived from the evolution of the Atlantic Ocean (Assine et al., 2014).

The Romualdo Formation is composed of interbedded sandstones with intervals of dark gray shales, which are rich in organic matter, with greenish shales or marls at the base. Much of the upper portion is composed of fossiliferous concretions found within greenish shales rich in ostracods (Arai and Coimbra, 1990; Berthou et al., 1990; Colin e Depèche, 1997; Mabesoone et al., 1999; Coimbra et al., 2002; Tomé et al., 2014). On the top, there are layers of limestone with invertebrates, overlain by thin layers of sandstone with interlayers of siltstone and shale, which contain mixohaline and marine fossils, such as mollusks and foraminifera, both benthic and planktonic (Beurlen, 1971; Assine, 2007; Pereira et al. 2015; Prado et al., 2015, 2018; Araripe et al., 2021).

The most studied sites of the Romualdo Formation are located in the Sobradinho and Serra do Mãozinha sections (Fig. 1), in the eastern portion of Araripe basin (Custódio et al., 2017; Fursich et al., 2019; Arai and Assine 2020; Melo et al., 2020; Bom et al., 2021; Kroth et al., 2021). In addition to these sites, the present study focuses on two other sections – Santo Antônio and Cedro – which have received much less attention, despite having a high diversity of marine invertebrates (Prado et al., 2018; Pereira et al., 2015; Araripe et al., 2022). Some of the best records of marine influences in the Araripe Basin can be found in the exposed outcrops of the Santo Antônio and Sobradinho sections (Melo et al., 2020; Araripe et al., 2021; 2022) (Fig.1).

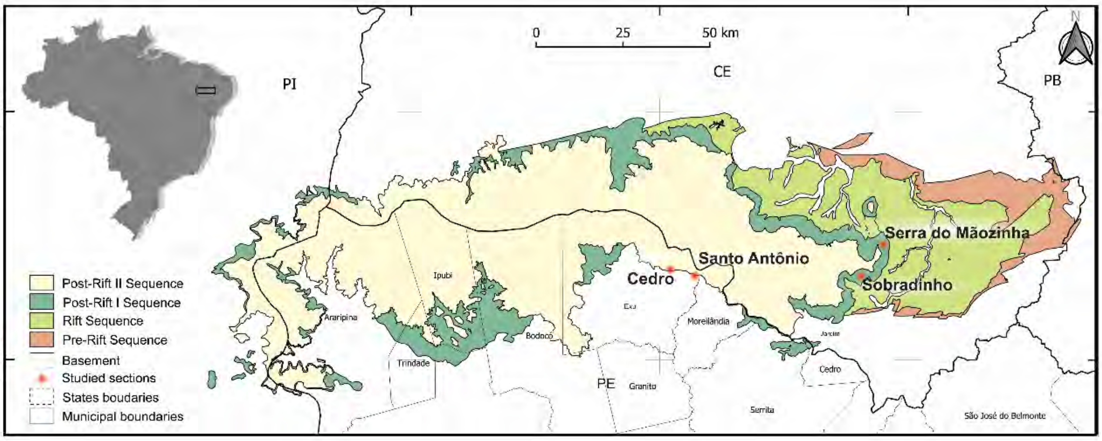

Fig 1 Location of the sections analyzed in the present study: Santo Antônio and Cedro, in Pernambuco state (PE), in the central-southern portion of the Araripe Basin, and Sobradinho and Serra do Mãozinha, in Ceará (CE), in the eastern portion of the basin. PB = Paraíba state, PI = Piauí state.

The fauna of the Romualdo Formation is typical of a transitional coastal to shallow marine environment (see Mabesoone and Tinoco, 1973; Arai and Coimbra, 1990; Berthou et al., 1990; Kellner, 2002; Bruno and Hessel, 2006; Lima et al., 2012, Melo et al., 2020; Araripe et al., 2021; 2022). Even so, the presence of echinoids and foraminifera is the principal evidence of the marine sedimentation that characterizes the Romualdo Formation, with a transgressive-regressive cycle delimited by two regional unconformities, which extend the marine deposition throughout the entire unit (e.g., Beurlen, 1963, 1964, Prado et al., 2015, 2018; Custódio et al., 2017; Melo et al., 2020; Araripe et al., 2021; 2022).

2.1 *Age assessment*

A number of studies (e.g., Braun, 1966; Mabesoone and Tinoco, 1973; Lima, 1978) have discussed the age of the Romualdo Formation, although there are profound disagreements on it chronostratigraphy, especially in terms of the position of the Aptian–Albian boundary (Fig 2). The formation has been biozoned based on its ostracods and palynomorphs. The *Sergipea variverrucata* palynozone, which has been described in a number of studies (Regali, 2001; Rios-Netto and Regali, 2007; Texeira et al., 2017; Arai and Assine, 2020), defines the upper Aptian for the entire succession of the Romualdo Formation. Melo et al. (2020) analyzed the foraminifera and ostracods from the Sobradinho section, and established a *Cyteridea* spp. ostracod biozone. These authors identified a typical Aptian assemblage in the intermediate portion of the section, characterized by the presence of species of the family Hedbergellidae (*Hedbergella aptiana*, *Hedbergella praelippa*, *Hedbergella sigali*, *Blesfucuiana* cf. *cumulus*, and *Microhedbergella miniglobularis*), as well as other, planktonic forms (*Gorbachikella* cf. *kugleri, Pseudoguembelitria blakenosensis, Globigerinelloides clavatus*, *Globigerinelloides* aff. *aptiensis*, *Gubkinella* sp., and *Loeblichella* sp). The foraminiferal *Microhedbergella miniglobularis* biozone was also identified within this interval. The absence of *Microhedbergella ranileavis* from this section led the authors to infer an upper Aptian age for the entire section, which was corroborated by previous studies of palynomorphs (the *Sergipea variverrucata* biozone) in the Sobradinho section (Arai and Assine, 2020; Rios-Netto et al., 2012; Texeira et al., 2017).

By contrast, in their biostratigraphic proposal for the Santana Group, Coimbra et al. (2002) identified the ostracod *Cytheridea* spp. biozone 201/218 and two palynozones, *Sergipea variverrucata* and *Cicatricosisporites avnimelechi.* According to these authors, the *C. avnimelechi* palynozone attributes a lower-middle Albian age to the Romualdo Formation. Heimhofer and Hochuli (2010) provide similar conclusions based on the comparative stratigraphic assessment of a dinoflagellate cyst assemblage (*Subtilisphaera perlucida*, *Dingodinium albertii*, and *Leptodinium cancellatum*), which excluded an age younger than the early Albian for the Romualdo Formation. Nannofossil biozone CC8 was recognized in the Santo Antônio section by Araripe et al. (2022) and Pedrosa et al. (2023). Based on the chart compiled by Sissingh (1977), the first appearance of *Hayesites albiensis* would correspond to the earliest Albian. The last appearance of the foraminiferal species *Hedbergella aptiana* and the occurrence of *Pseudoguembelitria* sp., restrict the interval to between the upper Aptian and the lower Albian in this section. (Araripe et al., 2022) (Fig 2).

3. Material and Methods

Foraminiferal assemblages were obtained from four outcrops in the Araripe Basin – Cedro, Santo Antônio, Serra do Mãozinha, and Sobradinho (Table 1; Fig 2). For the analysis, 103 samples of foraminifera were disaggregated in a 28% hydrogen peroxide solution, washed under running tap water, and sorted using sieves of three mesh sizes (250, 125, 63µm), before being dried at 60°C. The foraminifera were observed under a Zeiss SteREO Discovery V8 stereomicroscope. Thin sections were obtained from some specimens of the order Miliolida, given that some miliolid species can only be diagnosed by their typical internal coiling pattern, which is not visible externally.

The specimens were photographed using a scanning electronic microscope in the Laboratory of Nanostructure at the Federal University of Pernambuco, with photomicrographs being obtained using Axion Vision Release v.4.8. All the thin sections and slides used in this study were deposited in the Ivan de Medeiros Tinoco Microfossil Collection in the Paleontological Laboratory of the Department of Geology, in the Center of Technology and Geosciences at the Federal University of Pernambuco (PALEOLAB-DGEO-CTG-UFPE) in Recife.

Quantitative analyses of the benthic and planktonic foraminifera were used to document shifts in the configuration of the assemblages across the study sections. Samples with less than 10 specimens were excluded from the statistical analyses. The foraminifera were divided into three groups according to the type of the test (agglutinated, porcelaneous or hyaline). The relative abundances of the species was calculated for each sample. A Q-mode cluster analysis using UPGMA was applied to identify the benthic assemblages (Bocard et al., 2018), based on Euclidian distance, with the species being classified as (i) rare (≤5% of the individuals identified), (ii) common (5–20%) or (iii) abundant (≥20%). The planktonic forms were counted and the Planktonic/Benthic ratio was calculated to provide the percentage of planktonic foraminifera. The interpretation of the paleoenvironment was based on these statistical analyses, which were run in PAST (version 4.04; Hammer et al., 2001).

The original descriptions of the foraminiferal genera and species can be found in Loeblich and Tappan (1988) and the Ellis and Messina Catalogue (1940 *et seq.*). The systematics of the planktonic foraminifera follow microtax.org. The following abbreviations of bodily dimensions were used in the taxonomic descriptions of the benthic and planktonic foraminifera: H = Height of the test in µm; L = Length of the test in µm, and W= Width of the test in µm.

Table 1 Number of samples collected from the different sections analyzed in the present study.

Sections	**Coordinates**	**Thickness (m)**	**Number of samples**
Santo Antônio	39° 32' 57"W/7° 30' 53"S	6.3	51
Cedro	39° 35' 21" W/ 7° 29' 17"S	22	34
Sobradinho	39° 09' 47"W/ 7° 34' 18"S	51	50
S. do Mãozinha	39° 05' 56" W/ 7°21' 45" S	42. 5	32

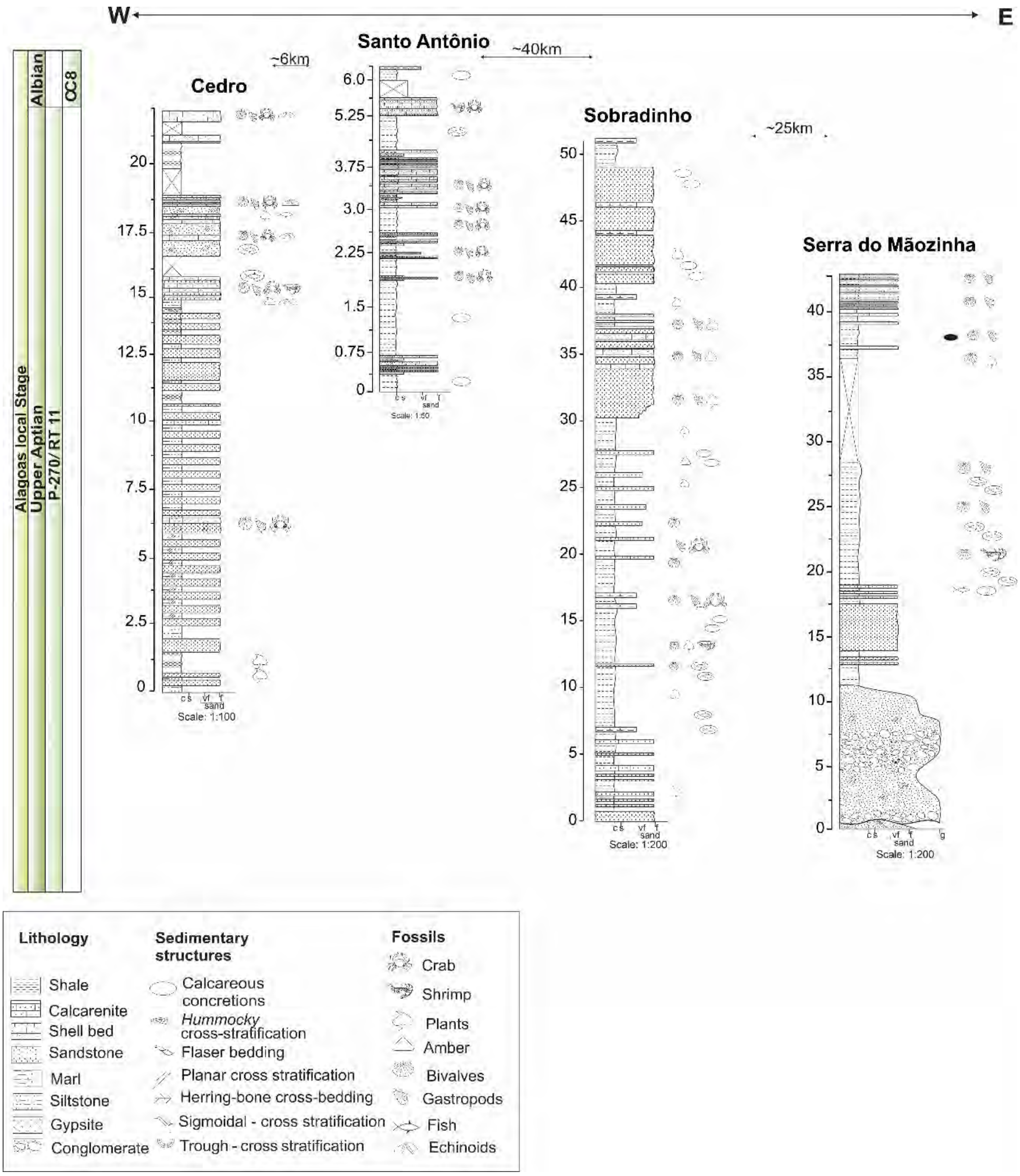

Fig 2 Lithostratigraphy of the study sections of the Romualdo Formation in the Araripe basin showing the lithological features and fossil content of the different strata. c = clay; s = silt; vf = very fine (sand); f = fine (sand).

4. Results and discussion

In a previous study of samples from Santo Antônio and Cedro, the outcrops located in the central-southern portion of the Araripe Basin, Araripe et al. (2021) recovered nine benthic foraminifera and five ostracod species. These authors concluded that the paleoenvironments of the Romualdo Formation range from transitional coastal to shallow marine, with a greater marine influence in the central portion of the Araripe Basin. Cedro and Santo Antônio were resampled in more detail in the present study, and investigated more thoroughly, revealing many new genera and species, primarily benthic taxa, that were identified in the Araripe basin for the first time. The species reported from the Santo Antônio section by Araripe et al. (2022) are described here in more taxonomic detail, and used as a diagnostic tool for the quantitative and qualitative analyses of the foraminifera identified in the other sections.

A total of 10,661 specimens were collected in the present study, representing 27 benthic and five planktonic taxa (Fig 3 and 4). Just over a third (37) of the 103 samples examined here yielded foraminifera, while the other 66 were unproductive. The foraminifera identified in the present study were distributed among 16 families, dominated by benthic taxa. The groups best represented, by either their abundance or species richness, were the calcareous benthic families Hauerinidae (abundance and species richness) and Conorboididade (abundance). The principal benthic families Spirillinidae, Ammodiscidae, Hemigordiopsidae, Vaginulinidae, Ellipsoidinidae, Nodosaridae, and the planktonic Hedbergellidae were secondary in their contribution. The most common species in the 37 samples analyzed here (Online Resource 1) were *Quinqueloculina* sp. 1. (42.5% of the individuals), *Conorboides minutissima* (20.0%), *Bathysiphon* sp. (9.4%), and *Spirillina minima* (6.6%) (Online Resource 1).

Systematic paleontology

Order LITUOLIDA Lankester, 1885

Suborder LITUOLINA Lankester, 1885

Family LITUOLIDAE Blainville, 1827

Subfamily AMMOMARGINULININAE Podobina, 1978

Genus *Ammobaculites* Cushman, 1910

Type species: *Ammobaculites aglutinans* (d'Orbigny, 1846)

Ammobaculites sp.

Fig. 3. (a-b) (c)

Illustrated material. Fig 3 (Nº DGEO-CTG-UFPE – 1477)

Description. Elongated test and large. initial portion rolled plane-spiral, then rectilinear. Coarsely agglutinated wall.

Dimension. L= 596.5 µm /H=1656.7 µm

Number of specimens. 22 specimens.

Observations. *Ammobaculites* sp. is compared to *Ammobaculites* ex. gr. *coprolithormes* (Schwager) from the Sergipe Alagoas Basin (Koutsoukos, 1989) however, it differs by the number of chambers.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Cedro section. Occurs with *Rhadammina* sp., *Hyperammina* sp. and *Bathysiphon* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Melo et al., 2020 and this work); Sergipe-Alagoas Basin, Riachuelo Formation, upper Aptian (Koutsoukos, 1989). Late Peleozoic and Mesozoic of Gondwanan/Australian interior basins (Scheibnerova 1976; Holbourn and Kaminski, 1997; Taylor and Haig 2001; Dixon et al 2003; Stilwell et al. 2012; Haig et al. 2017, 2018; Haig, 2020).

Order ASTRORHIZIDA Lankester, 1885

Suborder ASTRORHIZINA Lankester, 1885

Superfamily ASTRORHIZOIDEA Brady, 1881

Family RHABDAMMINIDAE Brady, 1884

Subfamily BATHYSIPHONINAE Avnimelech, 1952

Genus *Bathysiphon* Sars, 1872

Type species: *Bathysiphon filiformis* Sars, 1872

Bathysiphon sp.

Fig. 3. (d)

Illustrated material. Fig 3.d (Nº DGEO-CTG-UFPE – 1504)

Description. Elongate test, tubular, slightly curved, finely agglutinated wall, open at the both ends, in some cases with annular constrictions.

Dimension. L= 276.7 µm /H=828.3 µm.

Number of specimens. 694 specimens.

Occurrence and microfossil association. The occurrence of this species is abundant. Found at the Serra do Mãozinha and Cedro sections. Occurs with *Rhadammina* sp. *Hyperamina* sp. and *Ammobaculites* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Melo et al., 2020 and this work); Sergipe-Alagoas Basin, Riachuelo Formation, upper Aptian (Koutsoukos, 1989). Upper Triassic to Recent, locations around the Pacific (Miller, 1995; Hannah and Campbell 1996; Narayan et al., 2005), United States (Johnson et al., 2005), Europe (Crimes and Uchman, 1993; Bieda, 1948; Simpson, 1969; Malecki, 1973; Bak, 2004; Van den Akker et al, 2000; Mcllroy et al., 2001), and the eastern Indian Ocean (Bartenstein, 1974).

Subfamily RHABDAMMININAE Brady, 1884

Genus *Rhabdammina* Sars *em* Carpinteiro, 1869

Types species: *Rhabdammina abyssorum* Sars in Carpenter, 1869

Rhabdammina sp.

Fig. 3. (e)

Illustrated material. Fig 3.e (Nº. DGEO-CTG-UFPE – 1530)

Description. Test branched or tubular fragments, short, unilocular chamber. Open at both ends, coarsely agglutinated wall.

Dimension. L= 220 µm /H=776.3 µm.

Number of specimens. 5 specimens.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Serra do Mãozinha and Cedro sections. Occurs with *Bathysiphon* sp. *Hyperamina* sp. and *Ammobaculites* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Melo et al., 2020 and this work); Sergipe-Alagoas Basin, Riachuelo Formation, upper Aptian (Koutsoukos, 1989). North Germany, Upper Cretaceous (Hoffman, 2009).

Suborder HIPPOCREPININA

Superfamily HIPPOCREPINOIDEA Rhumbler, 1895

Family HYPERAMINIDAE Eimer e Fickert, 1899

Subfamily HYPERAMMININAE Eimer e Fickert, 1899

Genus *Hyperammina elongata* Brady, 1878

Type species: *Hyperammina elongata* Brady, 1878

Hyperammina sp.

Fig. 3. (f)

Illustrated material. Fig 3.f (Nº DGEO-CTG-UFPE – 1531)

Description. Elongate tubular test, unilocular chamber, annular constrictions, finely agglutinated wall, smooth surface.

Dimension. L = 328.5 µm /H= 660.6 µm.

Number of specimens. 610 specimens.

Occurrence and microfossil association. The occurrence of this species is common. Found at the Serra do Mãozinha and Cedro sections. Occurs with *Bathysiphon* sp. *Rhadammina* sp. and *Ammobaculites* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Melo et al., 2020 and this work); Sergipe-Alagoas Basin, Riachuelo Formation, upper Aptian (Koutsoukos, 1989). Angola, Kwanza Basin (Kochhann, 2013; 2014). Australia, Carnarvron Basin and Queensland (Haig, 1982; 2005).

Order SPIRILLINIDA Hohenegger e Piller, 1975

Suborder AMMODISCINA Mikhalevich, 1980

Superfamily AMMODSCOIDEA Chapman, Parr e Collins, 1934

Family AMMODISCIDAE Reuss, 1862

Genus *Glomospira* Rzehak, 1885

Type species: *Trochammina squamata* Jones e Parker var. *Gordialis* Jones e Parker, 1860.

Glomospira ? sp.

Fig. 3. (g-h)

Illustrated material. Fig 3 (g-h) (Nº DGEO-CTG-UFPE – 1531)

Description. A finely agglutinated form attributed with doubt to the *Glomospira* genus. Present initial streptospiral coiling followed by an irregular. Tubular chamber in the final portion of the test. The final portion of the chamber appears to be broken which makes it difficult to identify more precisely, even though this is the best-preserved specimen.

Dimension. L= 162.5 µm /H=201.6 µm.

Number of specimens: 6 specimens.

Observations. Species assigned to *Glomospira* have been described for the Cretaceous of the Brazilian basins. Two species of *Glomospira* have been recorded in the Upper Cretaceous of the Sergipe Basin: *Glomospira charoides* (Jones and Parker) e *Glomospira gordialis* (Jones and Parker) (Koutsoukos, 2000). A low frequency of *Glomospira charoides* was registered in Romualdo Formation strata at the Sobradinho section (Melo et al., 2020).

Occurrence and microfossil association. The occurrence of *Glomospira*? sp. is few at the Santo Antônio section. Occurs with *Quinqueloculina* sp., *Spirillina minima* and *Conorboides minutissima.*

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Melo et al., 2020); Sergipe-Alagoas Basin, Piaçabuçu Formation, upper Aptian to Maastrichtian (Koutsoukos, 1989) Italy, Parma, Monte Piano Formation, Early Cretaceous (Morlotti and Kuhnt, 1992). During the Aptian – Albian the genus is found in Western Africa: Ghana, Cote d'ivore Basin (Holbourn and Moullade, 1998; Bamba et al., 2017), Angola, Kwanza Basin (Kochhann, 2013; 2014). EUA, Blake Nose (Gradstein et al. 1978).

Suborder SPIRILLININA Hohenegger e Piller, 1975

Family SPIRILLINIDAE Reuss e Fritsch, 1861

Genus *Spirillina* Ehrenberg, 1843

Types species: *Spirillina vivipara* Ehrenberg, 1843

Spirillina minima Schacko, 1897

Fig. 3. (l-n)

1897 *Spirillina minima* Schacko – Schacko, pl. 1, fig. 4.
1982 *Spirillina minima* Schacko - Bartenstein and Kovatcheva, pl. 4, figs. 38-39; pl. 5, figs. 43-44.
1998 *Spirillina minima* Schacko - Holbourn and Moullade, pl. 1, figs. 7-10
1989 *Spirllina minina* Schacko. Koutsoukos, pl. 7, fig. 3-4.
2021 *Spirillina minima* Schacko. Araripe et al., fig. 4 (7a-b)

Illustrated material. Fig 3 (l-n)(Nº DGEO-CTG-UFPE – 1478)

Description. Test small discoidal, flat in lateral view, proloculus followed by five whorls of the tubular chamber with planispiral arrangement and terminal aperture. Wall calcareous hyaline. Surface with numerous pores or pseudo pores.

Dimensions. L= 223.1 µm /H=231.7 µm/W=37.5 µm.

Number of specimens: 105 specimens.

Observations. S. minima was previously recorded by Koutsoukos (1989) in the Sergipe-Alagoas Basin (Riachuelo Formation, Cenomanian to Turonian) and for first time in Aptian sediments of the Romualdo Formation (Araripe et al., 2021;2022).

Occurrence and microfossil association. The occurrence of this species is rare at the Santo Antônio, Cedro and Sobradinho sections). Occurs with *Quinqueloculina* sp. 1, *Conorboides minutissima* and *Pseudoguembelitria* sp.

Geographic and stratigraphic distribution. Brazil: Araripe Basin, Romualdo Formation, upper Aptian (Araripe et al., 2021 and this work); Sergipe-Alagoas Basin, Riachuelo Formation, Cenomanian to Turonian (Koutsoukos, 1989). Austria, Drusberg strata., middle Barremian (Fuchs, 1971); Egypt, Rizan Aneiza Formation, Aptian – Albian (Abu-Zied, 2007); Ghana, Cote d'ivore, Albian to Cenomanian (Holbourn and Moullade, 1998).

Family PATELLINIDAE Rhumbler, 1906
Genus *Patellina* Williamson, 1858
Type species: *Patellina corrugata* Williamson, 1858; OD(M).

Patellina subcretacea Cushman and Alexander, 1930

Patellina elliotti Stelck & Wall, 1956 pl. 3 (fig.7-9)
Patellina elliotti Araripe et al. 2022 fig 4 (8 a-b)
Patellina subcretacea Koutsoukos, 1989 pl. 7 9-12

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Fig. 3. (i-k)

Illustrated material. Fig 3 (i-k) (Nº DGEO-CTG-UFPE – 1479).

Description. Test small and discoidal with a convex arrangement. Low conical in lateral view, periphery narrowly rounded. Spherical proloculus followed by five whorls. Ventral side flat with terminal aperture.

Dimensions. L= 201.8 µm /H=192.3 µm/W=59.1 µm.

Number of specimens: 699 specimens.

Occurrence and microfossil association. The occurrence of this species is common. Occurs at the Santo Antônio and Cedro sections, com *Quinqueloculina* sp. e *Conorboides minutissima.*

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Araripe et al., 2022). Kwanza Basin (Kochhann, 2013; 2014). Genus widely distributed from the Lower Cretaceous.

Order MILIOLIDA Delege e Hérouard, 1896

Suborder MILIOLINA Delage e Hérouard, 1896

Superfamily MILIOLOIDEA Ehrenberg, 1839

Family HAUERINIDAE Schwager, 1876

Genus *Quinqueloculina* d'Orbigny, 1826

Type species: *Serpula seminulum* Linné, 1758 (1859), p. 786; SD Parker e Jones, 1859 (2345), p. 480.

Quinqueloculina sp. 1

Fig. 5 a

Fig. 3. (q-s)

Illustrated material. Fig 5, a; Fig 3 (q-s) (Nº DGEO-CTG-UFPE - 1480).

Description. Test ovate in shape with miliolid chamber arrangement, four chambers visible in side view, slightly inflated in the terminal portion, biconvex suboval in lateral view, aperture terminal with a small neck, with a lip. Wall calcareous porcelaneous. Transverse section with classic whorl of the genus *Quinqueloculina*, with an initial chamber in central portion and later overlapping chambers, totaling 5 external chambers (fig. 3 A). Inner construction of transverse section in quinqueloculine arranged, of 140°.

Dimensions. L= 167.1 µm/H=241.7 µm/W=98.3 µm.

Number of specimens. 4.457 specimens.

Observations. The genus *Quinqueloculina* has been recorded from the Lower Cretaceous of the Araripe Basin (Berthou et al., 1990; Martill, 2007; Custódio et al., 2017; Araripe et al., 2021). Most records indicate the presence of the group as miliolidae or porcelaneous foraminifera. This is a general form of classification that does not include genus/species specific characters, as well as the term miliolids includes a large number of taxa with diverse morphological characteristics. *Quinqueloculina* sp.1 and Q. sp. 2, was recorded and figd in strata of the Romualdo Formation. (Araripe et al., 2021; 2022).

Occurrence and microfossil association. The occurrence of this species is abundant and it was present in Santo Antônio, Cedro and Sobradinho sections. Occurs with several groups of foraminifera.

Geographic and stratigraphic distribution. Lower Cretaceous to Recent (Loeblich and Tappan, 1988). Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Araripe et al., 2021; 2022 and this work).

Quinqueloculina sp. 2

Fig. 5 b

Fig. 3 (t-u)

Illustrated material. Fig 2. (t-u) (Nº DGEO-CTG-UFPE - 1481)

Description. Test ovate to fusiform in outline with miliolid chamber arrangement, four chambers visible in side view, showing tubular development, rounded sub rectangular in lateral view, terminal aperture, rounded; wall calcareous porcelaneous. Longitudinal section (Fig 5B) with classic coiling of *Quinqueloculina*, with a macrospherical proloculus followed by 5-chamber overlapping. Chambers arrangement on a 60° axis.

Dimensions. L= 118,1 µm /H= 212,2 µm/W= 80 µm.

Number of specimens: 251 specimens.

Observations. It differs from *Quinqueloculina* sp. 1 by the outline fusiform and chamber arrangement.

Occurrence and microfossil association. The occurrence of this species is rare. Occurs in the Santo Antônio section associated with other porcelaneous forms (*Quinqueloculina* sp. 1, *Miliolinella* sp., *Sigmoilinita tenuis*, *Sigmoilinita* sp. 1, *Spirosigmoilina rajkae* and *Agathaminna pusilla*).

Genus *Miliolinella* Wiesner, 1931

Type species: *Miliolinella subrotunda* (Montagu, 1803)

Miliolinella sp.

Fig. 5 e

Fig. 3. (v-x)

Illustrated material. Nº DGEO-CTG-UFPE – 1482 (Fig. 4, 3 a-b *in* Araripe et al. 2022, re-illustrated in Fig 3. v-x).

Description. Test elongate ovate to fusiform, rounded in outline; biconvex in apertural view; Three and 1/2 chambers visible in lateral view; arrangement quinqueloculine. Proloculus prominent (macrospheric), last chamber rounded and curved at inferior portion with a terminal arch-shaped aperture. Wall calcareous, porcelaneous. Transversal section (Fig. 5 e) shows the initial coiling of the quinqueloculine type. Proloculus is located slightly away from the central axis, the chambers irregularly overlaps the following chambers, it has 4 external chambers, with one of the external chambers covering ⅓ of the entire carapace.

Dimensions. L= 164.3 µm /H= 336.9 µm/W= 81.2 µm.

Number of specimens. 86 specimens

Observations. According to Loeblich and Tappan (1988), the genus is poorly known and no sections have been illustrated to show the internal structure. The classification here follows the description by Franke (1928) for *Miliolina (Quinqueloculina) antiqua. S. antiqua* is similar to *Pseudosigmoilina* sp. A found by Koutsoukos (1989) in the Sergipe-Alagoas Basin.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Sobradinho sections. Occurs with *Quinqueloculina* sp. 1, *Spirosigmoilina rajkae*, *Agathammina pusilla*, *Spirillina minima* and *Spirillina* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Araripe et al., 2021; 2022 and this work). Australia, Eromanga Basin and Queenland, early Albian (Haig and Lynch, 1993).

Genus *Sigmoilinita* Seiglie, 1965

Types species: *Quinqueloculina tenuis* Czjzek, 1848 (866), p. 149); OD.

Sigmoilinita tenuis (Czjzek, 1848)

Fig. 5 c

Fig. 3 (y-z)

1848 *Quinqueloculina tenuis* Czjzek, p. 149, pl. 13, figs. 31-34.

1884 *Spiloculina tenuis* (Czjzek) - Brady, p. 152, pl. 10, figs. 7-8, 11.

1951 *Sigmoilina tenuis* (Czjzek) - Marks, p. 39, pl. 5, fig. 7.

1960 *Sigmoilina tenuis* (Czjzek) - Barker, pl. 10, figs. 7-8, 11.

1965 *Sigmoilinita tenuis* (Czjzek) - Seiglie, p. 72

1979 *Spirosigmoilina tenuis* (Czjzek) - Sztrakos, pl. 7, fig. 13

2021 *Spiroculina* sp. Araripe et al., pl. 3, KP

Illustrated material. Fig 3 (y-z) (Nº DGEO-CTG-UFPE – 1483)

Description. Test ovate in outline, compressed in lateral view; with seven rounded elongate chambers, rounded. Sightly depressed sutures; terminal aperture with a neck, wall calcareous, porcelaneous. In transversal section (Fig. 5 c) central axis formed by tiny chambers which increase laterally in size. Chambers inflate in the opposite direction to the central axis, turning the carapace flattened in longitudinal axis.

Dimensions. L= 201.8 µm /H= 383.2 µm/W= 45.7 µm.

Number of specimens. 327 specimens.

Observations. According to Czjzek, 1848 "the more spiroloculine-like shape, the great compression of the shell, its narrow chambers and the shape of the elongated opening distinguish it from the other numerous species from the Hauerinidae family". It is important to emphasize that this group is difficult to identify, since *Spiroloculina* and *Sigmoilinita* are similar in test shape, chamber arrangement. The authors of the present work believe that due to the preservation of the carapaces found in Araripe et al., (2021) the species attributed to *Spiroloculina* spp. actually belong to the genus *Sigmoilinita*.

Occurrence and microfossil association. The occurrence of this species is common. Found at the Santo Antônio and Sobradinho sections. Occurs with other porcelaneous forms (*Quinqueloculina* sp. 1, *Miliolinella* sp., *Spirosigmoilina rajkae* and *Agathamina pusilla*).

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (this work). Vima Formation, Romania, Oligocene (Székely and Filipescu, 2015).

Genus Spirosigmoilina Parr, 1942

Type species: *Spiroloculina teteana* Howchin, 1889 (1561), p. 3; OD

Spirosigmoilina rajkae Chiocchini, 2008

Fig. 5 f

Fig. 3 (aa-ab)

2008 *Spirosigmoilina* cf. *rajkae* - Chiocchini, pl. I, figs. 14-17; pl. VI, figs. 1-22.

Illustrated material. Fig 3 (aa-ab) (Nº DGEO-CTG-UFPE - 1485)

Description. Test rounded subrectangular in outline and flat in lateral view, six narrow and elongate chambers, aperture terminal compressed, wall calcareous porcelaneous. In transversal section, central axis is formed by tiny chambers that increase laterally in size. The chambers inflate in the opposite direction to the central axis, turning the carapace flattened in longitudinal axis. It is possible to observe a gradual distancing between the anterior and posterior chamber walls. (Fig. 5 f). It differs from the *Sigmoilinita tenuis* by having the central axis of the carapace a little broader, almost flat.

Dimensions. L= 256.4 µm /H= 297.9 µm/W= 73.9 µm.

Number of specimens. 16 specimens

Observations. Hofker (1971) has described in the Upper Albian of France an orthogenetic evolution from *Quinqueloculina* to *Spirosigmoilina* through a *Sigmoilina* stage. The presence of these three genera in the lower Cretaceous of Araripe Basin shows the occurrence of the *Quinqueloculina – Sigmoilina – Spirosigmoilina* evolutive trends.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Cedro sections. Occurs with other porcelaneous forms (*Quinqueloculina* sp. 1, *Miliolinella* sp. *Sigmoilinita tenuis, Sigmoilinita* sp. and *Agathamina pusilla*).

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (This work). Italy, Cenomanian (Chiocchini, 2008).

Spirosigmoilina sp. 1

Fig. 3. (ac-ad)

Illustrated material. Nº DGEO-CTG-UFPE – 1484 (Fig. 4, 5 a-b *in* Araripe et al. 2022, re-illustrated in Fig 3. ac-ad).

Description. Test ovate in outline, broad with milioliform shape, flat in lateral view; five to six chambers per half whorl, terminal aperture rounded with a neck, wall calcareous, porcelaneous.

Dimensions. L= 229.1 µm /H= 387.8 µm/W= 74.3 µm.

Number of specimens. 197 specimens.

Observations. Differs from *Sigmoilinita tenuis* by the rounded outline and chamber arrangement.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Cedro sections. Occurs with other porcelaneous forms (*Quinqueloculina* sp. 1, *Miliolinella* sp., *Sigmoilinita tenuis*, *Sigmoilinita* sp. and *Agathamina pusilla*).

Superfamily CORNUSPIRACEA, Schultze, 1854

Family HEMIGORDIOPSIDAE Nikitina, 1969

Subfamily HEMIGORIOPSINAE Nikitina, 1969

Genus *Agathamina* Neumayr, 1887

Type species: *Serpula pusilla* Geinitz, em Geinitz and Gutbier, 1848 (1214), p. 6; SD Cushman, 1927 (746), p. 188. *Agathamina* Neumayr, 1887 (2252), p. 171.

Agathamina pusilla (Geinitz, 1848)

Fig. 5 d

Fig. 3. (o-p)

1848 *Serpula pusilla* Geinitz - HB Geinitz, Die Versteinerungen, p. 6, pl. 1, fig. 3-6.

1959 *Agathamina pussilla* Geinitz Wolonska 1959 p. 27-59, pl. I, II, III.

1986 *Agathamina* sp.? - Bartenstein and Bolli, pl.2, fig. 26-27.

2021 *Agathammina pusilla*, Geinitz - Araripe et al., pl. 3, figs. CD.

2022 *Agathammina* sp 2. - Araripe et al., pl. 3, E. F.

Illustrated material. Fig 3. (o-p) (Nº DGEO-CTG-UFPE – 1486)

Description. Test ovoidal elongated with a single tubular chamber with flat-spiral coiling; organization similar to *Quinqueloculina* but without separations; periphery flattened with rounded outline; last whorl larger than the others, which overlaps in part the anterior whorl. Aperture terminal. In transversal section a circular chamber becoming gradually inflating and oval to the semilunar type, increasing the angularity towards to the periphery (Fig. 5d).

Dimensions. L=165.3 µm /H= 277.6 µm.

Number of specimens. 71 specimens.

Observations. One of the most representative families of this order is Haurenidae characterized by test with proloculus followed by two chambers per whorl and chambers added in one to five or more planes of coiling. *Agathammina pusilla* is included on the Hemigordiopsidae family, characterized by test free, proloculus followed by undivided enrolled tubular second chamber coiling streptospiral in at least the early stage but may later become planispiral.

Cushman (1929-1948) suggest the *Agathammina* genus as the initial form for the family Miliolidae (order Miliolida). The stratigraphic range of this genus extends, in his opinion, from the Carboniferous to the Jurassic, and has been widely recorded in Paleozoic deposits (Kobayashi, 2012; Sudar et al., 2018). *Agathammina pusilla*, under various generic names, has been reported from the Permian of eastern European Russia (Branson, 1948), from the Carboniferous and Permian of Texas (Cushman and Waters, 1927), and from the Permian of Poland (Czarnocki, 1923; 1924; Samsonowicz, 1953). However, more recently it has been recorded in Mesozoic deposits on the South America equatorial margin (Trinidad) in strata assigned to the late Aptian (Bartenstein and Bolli, 1986). For the Romualdo Formation *Agathammina* was previously identified as *Agathammina pusilla* and *Agathammina* sp. (Araripe et al., 2021). Benthic associations dominated by forms attributed to *Agathammina* were identified in southern and central portion of Araripe Basin (Cedro, Canastra, Arrojado and Santo Antonio outcrops) (Araripe et al., 2021).

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Cedro sections. Occurs with other porcelaneous forms (*Quinqueloculina* sp. 1, *Miliolinela* sp., *Sigmoilinita tenuis*, *Sigmoilinita* sp. and *Spirosigmoilina rajkae*).

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (Araripe et al., 2021 and this work). *Agathaminna* has been recorded since the Paleozoic in several regions (e.g., Poland, Permian, Wolanska, 1959); Lituanian, upper Permian, (Miklukho-Maklay and

Ukharskaya, 1975); Transcaucasia, Late Permian (Pronina and Gubenko, 1990); New Mexico, upper Permian, (Nestell and Nestell, 2006). *Agathaminna* sp. has been recorded in Mesozoic deposits on the South America equatorial margin (Trinidad), assigned to the late Aptian *Paraticinella rohri* biozone (Bartenstein and Bolli, 1986).

Class NODOSARIATA Mikhalevich, 1992,
emendar. Rigaud *et al.*, 2015
Subclass NODOSARIANA Mikhalevich, 1992
Order NODOSARIIDA Calkins, 1926
Suborder NODOSARIINA Calkins, 1926
Superfamily NODOSARIOIDEA Ehrenberg, 1838
Family NODOSARIIDAE Ehrenberg, 1838
Genus *Pseudonodosaria* Boomgaart, 1949
Type species: *Glandulina discreta* Reuss, 1850 (2573), p. 366; OD.
Pseudonodosaria sp.
Fig. 3. (ae-af)

Illustrated material. Fig 3. (ae-af) (Nº DGEO-CTG-UFPE – 1487)

Description. Test small, elongate, cylindrical, uniserial; increasing slowly in size, the last chamber inflated. Sutures straight weakly marked; wall calcareous; smooth surface; aperture terminal radiate.

Dimension. L=141 µm /H= 353.1 µm

Number of specimens: 34 specimens.

Observations. Species of this genus have been recorded previously in the Brazilian basins (Sergipe-Alagoas Basin, Lower Cretaceous; Pernambuco-Paraiba Basin, Upper Cretaceous). Tinoco, (1978) identified *Pseudonodosaria manifesta* (Reuss) as a rare species for Gramame Formation, Upper Cretaceous. Koutsoukos (1989), identified two species of this genus for the Sergipe-Alagoas Basin, *Pseudonodosaria* ex gr. *humilis* (Roemer) and *Pseudonodosaria obesa* (Loeblich and Tappan, 1988), and describes as a long ranging species-group. When compared, *Pseudonodosaria* sp. has a larger number of chambers and the last chamber is quite inflated, differentiating those figurate in Koutsoukos (1989).

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio, Sobradinho and Cedro sections. Occurs with *Quinqueloculina* sp. 1, *Lingulina* sp., *Astacolus gratus*, *Astacolus howchini* and *Pseudosaracenaria* ? sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, Upper Aptian (this work). This genus is cosmopolitan. Cretaceous to Holocene.

Subfamily LINGULININAE Loeblich and Tappan, 1961

Genus *Lingulina* d'Orbigny 1826

Lingulina sp.

Fig. 3. (aj-ak)

Illustrated material. Fig 3 (aj-ak) (Nº DGEO-CTG-UFPE – 1493).

Description. Elongate test, tapered; biserial in early portion, later becoming uniserial, with 4-6 chambers; sutures depressed, slightly curved; aperture terminal slit-like.

Dimension. L= 147,9 µm /H= 469,8 µm.

Number of specimens: 25 specimens

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Sobradinho sections. Occurs with *Spirillina minima*, *Spirillina* sp., *Glomospira*? sp., *Pseudosaracenaria*? sp. and *Conorboides minutissima.*

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, Upper Aptian (this work). Lower Cretaceous, Cosmopolitan (Loebich and Tappan, 1988).

Order VAGINULINIDA Mikhalevich, 1993

Family VAGINULINIDAE Reuss, 1860

Subfamily LENTICULININAE Chapman, Parr e Collins, 1934

Genus *Pseudosaracenaria* Venkatachalapathy, 1968

Type species: *Pseudosaracenaria truncata* Venkatachalapathy, 1968

Pseudosarcenaria ? sp.

Fig. 3. (as-at)

Illustrated material. Fig 3 (as-at) (Nº DG-CTG-UFPE – 1488)

Description. Test elongate, subtriangular, arched outline, slightly curved in the early portion, early chambers showing a partial astacoline coil, uniserial, with overlapping chambers, oblique sutures; terminal aperture rounded, smooth test surface.

Dimension. L=132.6 µm /H= 270.5 µm.

Number of specimens: 79 specimens.

Observations. The specimens found in this study resemble the description of the genus proposed by Loeblich and Tappan (1988) but without the carinate margin of the apertural view. *Pseudosaracenaria*? sp. is morphological comparable with *Saracenaria* sp. cf. *S. crassicosta* identified in the Sergipe Basin (Koutsoukos, 1989) by the presence of the coiling in the initial portion and the number of chambers. And it differs from *Pseudosaracenaria truncata* Pathy by the opening in the terminal portion not visible in the specimen figd in Savelieva et al., 2014.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio section. Occurs with *Quinqueloculina* sp. 1, *Spirillina* sp. and *Conorboides minutissima.*

Geographic and stratigraphic distribution. Araripe Basin, Romualdo Formation, upper Aptian (this work). Sergipe-Alagoas Basin, Riachuelo Formation, late Aptian (Koutsoukos, 1989). Peninsula of Crimea, Berriasian (Savelieva et al., 2014).

Subfamily MARGINULININAE Wedekind, 1937

Genus *Astacolus* Montfrot, 1808

Type species: *Astacolus crepidulatus* de Montfort, 1808 = *Nautilus crepidula* Fichtel and Moll, 1798 (1124), p. 64; OD.

Astacolus howchini ? Ludbrook, 1966

Fig. 3. (an-ao)

1966 *Astacolus howchini* - Ludbrook, pl. 7, fig. 27

1982 *Lenticulina* (*Astacolus*) *humilis* – Crittenden, pl. 6, fig. A

1989 *Astacolus* sp. A - Koutsoukos, pl. 9, fig. 9

2021 *Astacolus* sp. - Araripe et al., pl. 4, AB

Illustrated material. Fig 3 (an-ao) (Nº DGEO-CTG-UFPE - 1489)

Description. Test small, elongate, slightly arched in outline, lateral view flattened, periphery subangular, subovate in outline; early stage planispiral arrangement, later uncoiling uniserial, later chambers slightly inflated, increase in size without touch the early portion; sutures distinct, curved; subtriangular periphery. First chamber coiled, four latter's chambers uncoil, last two chambers turning toward the proloculus, aperture terminal.

Dimension. L=168,8 µm /H= 386,8 µm/ W= 93,7 µm.

Number of specimens: 5 specimens

Observations. This species differs from the original description by Ludbrook (1966) by not having a carinate dorsal side. However, the authors of the present study believe it is the same species, but these structures were not preserved. The specimens of the genus *Astacolus* found in this study have small carapaces, and resemble *Astacolus* sp. A found by Koutsoukos (1989) in the Sergipe Basin. In lateral view it is very similar to the species described here as *Palmula sagittaria*, but the shape of the last chambers and the less curved sutures differ between both species.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Sobradinho sections. Occurs with *Spirillina minima, Spirillina* sp.*, Glomospira* sp., *Pseudosaracenaria* ? sp. and *Conorboides minutissima.*

Distribuição geográfica e estratigráfica. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (This work). South Australia, Marree Formation, Lower Cretaceous (Aptian) (Ludbrook, 1966).

Astacolus gratus Reuss, 1863

Fig. 3. (al-am)

1863 *Cristellaria grata* Reuss, PI. 7, fig. 14.

1958 *Astacolus gratus* (Reuss) - Sztejn, p. 27, fig. 54.

1962 *Vaginulinopsis grata* (Reuss) – Tappan, p. 179, pl. 46, fig. 6-7.

1966 *Lenticulina* (*Astacolus*) *grata* (Reuss) - Bartenstein, Bettenstaedt and Bolli, pl. 2, fig. 130-133.

1973 *Astacolus grata* (Reuss) - Maync, pl. 2 fig. 13.

1989 *Astacolus* cf. *scitula* - Koutsoukos, pl. 9, figs. 7-8.

Illustrated material. Fig 3 (Nº DGEO-CTG-UFPE - 1491).

Description. Test free, suboval in outline, compressed in lateral view; five chambers visible that increase rapidly in size, the last chamber reaching back to the spiral portion; Sutures slightly curved and depressed; aperture terminal.

Dimension. L= 146 µm /H=307.7 µm.

Number of specimens: 1 specimen.

Observations. The genus *Astacolus* belongs to a highly diverse group of different morphotypes, each designated with different specific names that may reflect dimorphism. Many forms documented as different species are probably ontogenetic stages of a single species. Due to the large variability and morphological intergradients, it may be preferable to include all similar forms in one overarching superspecific taxon or plexus (Maync, 1973). Other authors propose an even broader concept of the species, for example E. Michael (1967), who interprets *Astacolus calliopsis* (Reuss) as a junior synonym of *Astacolus compressus* (d'Orbigny), described from the Upper Cretaceous of Paris, and other quite different forms, such as *Vaginulinopsis matutina* (d'Orbigny) and *Vaginulinopsis schloenbachi* (Reuss) described by Maync, 1973) in Albian of Portugal.

Occurrence and microfossil association. The occurrence of this species is rare. Found at Santo Antônio section. Occurs with *Spirillina minima*, *Spirillina* sp., *Glomospira* sp., *Pseudosaracenaria* ? sp. and *Conorboides minutissima.*

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (this work). Isle of Wight (U.K.), lower Aptian (Crittenden, 1982). Trinidad, Barremian (Bartenstein et al., 1957). Austria, Early Barremian (Fuchs, 1971). Portugal, eastern North Atlantic, Albian (Maync, 1973).

Subfamily PALMULINAE Saidova, 1981

Genus *Palmula* Lea, 1833

Type species: *Palmula sagittaria* Lea, 1833

Palmula sagittaria Lea, 1833

Fig. 3. (aq-ar)

2017 *Palmula sagittaria* Lea; (Lea 1833, pl. 6, fig. 228) - Aly, 1-ac; 2 ac.

Illustrated material. Nº DGEO-CTG-UFPE – 1490 (Fig. 4, 12 a-b *in* Araripe et al. 2022, re-illustrated in Fig 3. aq-ar).

Description. Test free, oval, compressed in lateral view; early stage planispiral, later chambers increase in size in an astacoline arrangement, chevron shaped; chambers rounded a subangular, last chamber larger, giving the test an elliptical shape. Sutures flush. Terminal aperture.

Dimension. L= 181.5 µm /H= 363 µm/ W= 97.9 µm.

Number of specimens: 32 specimens

Occurrence and microfossil association. The occurrence of this species is rare. Found at Santo Antônio section. Occurs with *Nodosarella* sp., *Lingulina* sp. and *Pseudonodosaria* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (this work). Timber Creek, New Jersey, Cretaceous (Weller, 1907).

Order POLYMORPHINIDA Mikhalevich, 1980

Suborder PLEUROSTOMELLINA Reuss, 1860 emenda. Mikhalevich, 1993

Superfamily PLEUROSTOMELLOIDEA Reuss, 1860

Family ELLIPSOIDINIDAE Silvestri, 1923

Genus *Nodosarella* Rzehak, 1895

Type species: *Nodosarella tuberosa* (Gümbel, 1870)

Nodosarella sp.

Fig. 3. (ai)

Illustrated material. Fig 3 (ai) (Nº DGEO-CTG-UFPE – 1492)

Description. Test small, elongate, uniserial, six globular chambers; sutures straight and depressed.

Dimension. L= 61 µm /H= 393.3 µm.

Number of specimens: 1 specimen

Observations. Only a single specimen was found. It was not possible to observe the initial biserial stage, because the fragmentation of the test.

Occurrence e microfossil association. The occurrence of this species is rare. Found at Santo Antônio section. Occurs with *Spirillina* sp., *Glomospira* sp., *Pseudosaracenaria* ? sp. and *Pseudonodosaria* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (this work). Upper Cretaceous (Maastrichtian), Cosmopolitan (Loeblich e Tappan, 1988).

Family PLEUROSTOMELLIDAE Reuss, 1860

Subfamily PLEUROSTOMELLINAE Reuss, 1860

Genus *Pleurostomella* Reuss, 1860

Pleurostomella reussi Berthelin, 1880

Fig. 3. (ag-ah)

Illustrated material. Fig 3 (Nº DGEO-CTG-UFPE – 1494)

Description. Test small, tapered, elongate, about 8 chambers uniserial, sutures straight, horizontal, flush; Aperture terminal.

Dimension. L= 66.5 µm /H= 245.1 µm

Number of specimens: 3 specimens.

Observations. The genus *Pleurostomella* is widely distributed in the Upper Cretaceous and Paleogene of some localities of Tetian influence: North Atlantic (USA, Mexico, Caribbean), Europe (France, Poland, Italy, Hungary, Bulgaria, North Sea), North Africa (Tunisia, Egypt), Southwest Asia (Iraq, UAE), Indian Ocean (Pakistan) and the Atlantic Ocean.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio and Sobradinho sections. Occurs with *Quinqueloculina* sp. 1, *Spirillina* sp. and *Pseudoguembelitria* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (this work). Kwanza Basin (Angola) (Kochhann et al., 2013), Aptian-Albian. Cosmopolitan. Lower Cretaceous (Aptian) to Holocene.

Class GLOBOTHALAMEA Pawlowski, Holzmann e Tyszka, 2013

Order ROBERTINIDA Loeblich and Tappan, 1984

Suborder ROBERTININA Loeblich and Tappan, 1984

Superfamily CONORBOIDODEA Thalmann, 1952

Family CONORBOIDIDAE Thalmann, 1952

Genus *Conorboides* Hofker, 1952

Type species: *Conorboides mira* Hofker, 1952 p. 357.

Conorboides minutissima (Tappan, 1943)

Fig. 3. (aw-ay)

1943 *Discorbis minutissima* Tappan, p.511, pl, 82, figs5-6.

1970 *Conorboides minutissima* (Tappan) - Eicher and Worstell, p.295, pl. 6, figs, 9, 11, pl. 7, fig.1.

1989 *Conorboides* ex gr. *minutissima* (Tappan) - Koutsoukos, pl.10, figs. 24-2.

2021 *Conorboides minutissima* (Tappan) - Araripe et al., pl. 4, fig. F1.

Illustrated material. Fig 3 (Nº DGEO-CTG-UFPE – 1495)

Description. Test small, low trochospiral, subrounded peripheral view. Dorsal side convex, with four to six chambers, increasing gradually in size. Depending on the proloculus size, the specimen can be macro or microspheric. Ventral side planoconvex to concave-convex, sutures curved and depressed. wall calcareous fine punctate or perforate.

Dimension. L= 194.1 µm /H= 227.9 µm/ W= 39.8 µm.

Number of specimens. 860 specimens.

Observations. Due to their instability, aragonitic tests are generally the first altered by diagenesis. The test of robertinids (aragonitic in composition), is metastable and thus particularly susceptible to dissolution. As a result, Robertinids test are strongly susceptible to diagenetic alterations and commonly recrystallized to calcisparite, making it difficult to identify (Rigaud et al., 2015). *Conorboides minutissima* has been recorded in strata of the Greenhorn Formation, U.S. Cenomanian, is distinguished by somewhat flatter spire and no perforations. The authors state that possibly due to a typically poor preservation of the aragonite wall. *C.* ex gr *minutissima* identified in Albian-Cenomanian intervals of the Sergipe-Alagoas Basin, (Koutsoukos, 1989) share the following characters: small size, number of chambers in the last whorl (4 to 5), strongly oblique sutures and sub rounded peripheral view.

Occurrence and microfossil association. The occurrence of this species is abundant. Found at the Santo Antônio, Sobradinho and Cedro sections. Occurs with *Quinqueloculina* sp. 1, *Spirillina* sp. and *Pseudoguembelitria* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, late Aptian (Araripe et al., 2021a and this work). Sergipe-Alagoas Basin, Riachuelo Formation and Cotinguiba Formation, late Aptian to early Coniacian. (Koutsoukos, 1989). United States, Great Plains, Greenhorn Formation, Cenomanian (Eicher and Worstell, 1970).

Superfamily DISCORBOIDEA Ehrenberg, 1838

Family ROSALINIDAE Reiss, 1963

Genus *Neoconorbina* Hofker, 1951

Type species: *Neoconorbina terquemi* (Rzehak, 1888)

Neoconorbina sp.

Fig. 3. (au-av)

Illustrated material. Fig 4 (Nº DGEO-CTG-UFPE – 1497).

Description. Test small, circular in outline; low trochoespiral; spiral side convex with four subglobular chambers, last chamber large, covering most of the test; Umbilical side flattened, two to three chambers can be observed; Aperture umbilical.

Dimension. L= 223.1 µm /H=228.7 µm.

Number of specimens. 2 specimens.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Sobradinho section. Occurs with *Spirillina minima*, *Lingulina* sp., *Conorboides minutissima, Pseudoguembelitria* sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, Romualdo Formation, upper Aptian (this work).

Suborder GLOBIGERININA Delage and Hérouard, 1896

Superfamily ROTALIPOROIDEA Sigal, 1958

Family HEDBERGELLIDAE Loeblich and Tappan, 1961

Subfamily HEDBERGELLINAE Loeblich and Tappan, 1961

Genus *Hedbergella* Brönnimann e Brown, 1958, emenda.

Huber and Leckie, 2011

Type species: *Anomalina lorneiana* d'Orbigny var. *trochoidea* Gandolfi, 1942, p. 9 *8.*

Hedbergella aptiana Bartenstein, 1965

Fig. 4. (a-c)

2012 *Hedbergella aptiana* Bartenstein, 1965, p. 347-348, texto-figs. 3-6.

1979 *Hedbergella aptiana* Bartenstein, Sigal, , p. 318, pl. 2, figs. 24, 25;

1988 *Blefuscuiana aptiana* (Bartenstein) - Banner and Desai, p. 158, pl. 5, figs. 1–3.

1994 *Hedbergella aptiana* Bartenstein, Coccioni and Premoli Silva, p. 671-672, figs. 10,4-9;

2005 *Praehedbergella aptiana* (Bartenstein). Moullade et al., p. 9, fig. 2

2011 *Hedbergella aptiana* Bartenstein - Huber and Leckie, p. 65, figs. 5,6, 5,7;

2012 *Hedbergella aptiana* Bartenstein - Petrizzo et al., pl. 1, fig. 1a–c.

2013 *Hedbergella aptiana* Bartenstein - Kochhann et al., Fig. 5.9

2018 *Hedbergella aptiana* Bartenstein. Premoli Silva et al., fig. 7.1-7 (7.1 holotype, 7.2, 3 paratype).

2020 *Hedbergella aptiana* Bartenstein. Melo et al., fig. 4, 32-33.

2022 *Hedbergella aptiana* Bartenstein. Araripe et al., fig 4, 20a-c.

Illustrated material. Nº DGEO-CTG-UFPE – 1498 (Fig. 4, 20 a-c *in* Araripe et al. 2022, re-illustrated in Fig 4. a-c).

Description. Test small, flat, trochospiral, final whorl with five globose chambers, the last chamber oval; sutures slightly depressed.

Dimension. L= 98,6 µm /H= 130,4 µm.

Number of specimens: 1 specimen.

Observations. The specimen recorded has only a single occurrence, although the small size has good preservation and it is possible to observe the characteristics that define the species. According to Premoli Silva et al., (2018), this species shows rather wide morphological variability, and may vary in the number of chambers and outline. *Hedbergella aptiana* has been previously recorded in the strata of the Romualdo Formation at Sobradinho section by Melo et al., (2020). These authors, cited an abundant and relatively diversified planktonic foraminifera assemblage and emphasized the small size of the specimens found. This species was also recorded in Aptian strata of the Kawanza Basin (offshore Angola) by Kochhann et al., (2013). *H. aptiana* identified in the present work resemble the number of globose chambers and their outline in lateral view, but differ in the shape of the last chamber.

Occurrence and microfossil association. The occurrence of this species is rare at Santo Antônio section. Occurs with *Pesudoguembelitria* sp. This same species assemblage is found by Melo et al., (2020) at the Sobradinho section.

Geographic and stratigraphic distribution. H. aptiana is a cosmopolitan species and the distribution ranges from the lower Barremian to the upper Aptian (among others BouDagher-Fadel et al., 1997; Huber and Leckie, 2011; Petrizzo et al., 2012; Premoli Silva et al., 2018). *H. aptiana* occur in late Aptian intervals of the Site 364, South Atlantic Kuanza Basin, (Kochhann et al., 2013) and in Brazil, Araripe Basin, Romualdo Formation (Melo et al., 2020 and this work). *H. aptiana* is frequent on late Aptian sections of Southeastern Brazilian basins (Viviers et al., 2018; Sanjinés et al., 2022).

Hedbergela aff. *daminiae* (Banner, Copestake and White, 1993)

Fig. 4. (f-h)

1993 *Blefuscuiana daminiae* Banner, Copestake and White, p. 10, pl. 3, fig. 6a–c

1997 *Blefuscuiana daminiae* Banner, Copestake and White. BouDagher-Fadel et al., p. 126, pl. 8.5, fig. 1a–c (holotype), pl. 8.12, fig. 4–6 (holotype *H. whittakeri*).

2018 *Hedbergella daminiae* (Banner, Copestake and White, 1993). Premoli Silva et al., Fig. 6.5-7 (6.5 holotype)

2022 *Hedbergela* aff. *Daminiae* Banner, Copestake and White. Araripe et al., p. 6, fig.4 21a-c.

Illustrated material. Nº DGEO-CTG-UFPE – 1499 (Fig. 4, 21 a-c *in* Araripe et al. 2022, re-illustrated in Fig 4. f-h).

Description. Test smooth, subquadrangular rounded in outline, trochospire very flat to depressed in lateral view; the outer whorl shows five globular chambers, with the first chamber smaller than the following chambers, umbilicus deep and large; sutures slightly depressed. The last chamber shows a malformation or an aggregated chamber.

Dimension. L= 243 µm /H= 408 µm.

Number of specimens: 1 specimen.

Observations. The specimen recorded has only a single occurrence, has a much larger test when compared to other associated planktonic species found, and the carapace wall is very smooth. *H. daminiae* have few mentions in the specialized literature (e.g., Premoli Silva et al., 2018). *H. daminiae* is characterized by five chambers in the last whorl, thereby giving an overall subquadrangular appearance to the test, and by a deep umbilicus, resulting from distinct overhang of the chambers in the last whorl (Premoli Silva et al., 2018). The only specimen studied shows the last whorl with 5 globular chambers, although the arrangement of the chambers differs from the original description. In addition, the wall of the studied specimen is very smooth, different of the *Hedbergella daminiae* (Banner, Copestake and White, 1993) indicated for the type species.

Occurrence and microfossil association. The occurrence of this species is rare. Found at Santo Antônio section. Occurs with *Pseudoguembelitria* sp., *Hedbergella* sp. and *Liliputinella* ? sp.

Geographic and stratigraphic distribution. Brazil, Araripe Basin, *H.* aff *daminiae* occurs in the Romualdo Formation, upper Aptian (this work). Forms attributed to *H. daminiae* has been recorded from upper Barremian to lower Aptian, (SW Crimea, Azerbaijan, Tunisia and Spain) (BouDagher-Fadel et al., 1997; Premoli Silva et al., 2018).

Hedbergella sp. 1

Fig. 4. (d-e)

Illustrated material. Nº DGEO-CTG-UFPE – 1500 (Fig. 4, 18 a-b *in* Araripe et al. 2022, re-illustrated in Fig 4. d-e).

Description. Test small, rounded in outline with three chambers; depressed and small umbilicus at the ventral side; sutures depressed; wall with smooth surface, finely perforate.

Dimension. L= 81.2 µm /H= 105.7 µm.

Number of specimens: 3 specimens.

Observations. Scarce material recovery, limited to a small interval. The first chambers of the first whorl are not visible. The form was assigned to *Hedbergella* sp. 1 for having a reduced number of chambers. Resembles other species of *Hedbergella* such as *H. tatianae, H. griegelisi* and *H. tuchepsensis* by the small number of chambers in the last whorl (4 and 3-4) and low trochospire, but in the specimens found in the present study, it is not possible to observe the chambers of the first whorl.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio section. Occurs with *Pseudoguembelitria* sp., *H.* aff. *daminiae* and *Liliputinella* ? sp.

Genus *Pseudoguembelitria* Huber and Leckie, 2011

Type species: *Pseudoguembelitria blakenosensis* Huber and Leckie, 2011.

Pseudoguembelitria sp.

Fig. 4. (k-l) (m)

Illustrated material. Nº DGEO-CTG-UFPE – 1501 (Fig. 4, 17 a-b *in* Araripe et al. 2022, re-illustrated in Fig 4. k-l, m).

Description. Test very small, globose, 3 chambers in apertural view; aperture low interiomaginal, sutures depressed; Initial chambers or first trochospiral stage, without definition or absent; wall perforate.

Dimension. L= 156 µm /H= 164.7 µm.

Number of specimens: 210 specimens.

Observations. According to Huber and Leckie (2011), *Pseudoguembelitria* differs from *Hedbergella* by having a higher trochospire, more weakly developed perforation cones on the test surface, and fewer chambers in the final whorl. It differs from *Guembelitria* Cushman,1933 (late Campanian–early Paleocene) and *Archaeoguembelitria* Georgescu, 2009 (late Albian–early Turonian) by the early hedbergellid stage and variable trochospire. It differs from *Gubkinella* — considered by Loeblich and Tapan (1988) to be a benthic foraminifer — in having perforation cones, more inflated chambers, and a higher-arched aperture, and in lacking a lip (Premoli Silva et al., 2018).

The specimens found in the present study, have a few number of chambers and apparent absence of the first trochospiral stage. Well preserved shells, show distinct types of preservation, in some specimens it has a glassy preservation (fig.5.6-8) and others show recrystallized appearance (Fig 5. 4). The forms differ from the species already described for the genus (*Pseudoguembelitria blakenosensis*) and may be a new species or a primitive form of guembelitrid (*Pseudoguembelitria* sp.) the highest abundance among planktonic foraminifera (up to 95% of the planktonic association), at Santo Antonio section, associated with few trochospiral hedbergellid species (*H. aptiana*, *Hedbergella* sp., *H.* aff. *daminiae*). The species studied here occurs in very shallow and stressed environments (Araripe et al., 2022). Forms attributed to *Pseudoguembelitria blakenosensis* has been previously recorded in strata of the Romualdo Formation at Sobradinho section (Melo et al., 2020). The forms differ in the number of chambers and it is not possible to observe the early hedbergellid stage characteristic of the type species.

Occurrence and microfossil association. The occurrence of this species is common. Found at Santo Antônio and Sobradinho sections. Occurs with *H. aptiana*, *Hedbergella* sp., *H.* aff. *daminiae e Liliputinella* ? sp.

Geographic and stratigraphic distribution. Brazil, Romualdo Formation, Araripe Basin (Melo et al., 2020 and this work). Blake Nose, western North Atlantic, upper Aptian (Huber and Leckie, 2011).

Family PRAEHEDBERGELLIDAE Banner and Desai, 1988

Genus *Lilliputianella* Banner and Desai, 1988

Type species: *Lilliputianella longorii* Banner and Desai, 1988

Liliputianella ? sp.

Fig. 4. (i-j)

Illustrated material. Nº DG EO -CTG-UFPE – 1502 (Fig. 4, 22 a-b *in* Araripe et al. 2022, re-illustrated in Fig 4. i-j).

Description. Test very small, five subglobosus chambers in the last whorl, radially elongate, last chamber turned to the umbilicus; sutures depressed; appears to be recrystallized.

Dimension. L= 140.2 µm /H= 142.9 µm.

Number of specimens: 5 specimens.

Observations. Due the poor preservation and scarce number of specimens, the generic attribution is inconclusive. Morfogroups of hedbergellidae with 5 small subglobosus radially elongate chambers, and depressed umbilicus were recently assigned transfered to the *Liliputianella* (Banner and Desai, 1988) by Premoli Silva et al., (2018).

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antônio section. Occurs with *Hedbergella* sp., *H.* aff. *daminiae* and *Pseudoguembelitria* sp.

Stratigraphic distribution. Early Cretaceous.

Gen. Indet.

Fig. 4. (n-o)

Illustrated material. Nº DGEO-CTG-UFPE – 1503 (Fig. 4, 19 a-b *in* Araripe et al. 2022, re-illustrated in Fig 4. n-o).

Additional material.

Description. Test large, very smooth wall, three globose chambers increasing in size; subquadrangular in lateral view; sutures marked and depressed.

Dimension. L= 716.2 µm /H= 904.5 µm/ MC= 457.7 µm.

Number of specimens: 1 specimen.

Observations. The specimen recorded has only a single occurrence, test much larger, standing out in relation to the other planktonic species, very smooth wall, without microperforations. Good preservation of the carapace.

Occurrence and microfossil association. The occurrence of this species is rare. Found at the Santo Antonio section. Occurs with *Hedbergella* sp., *H.* aff. *daminiae*, *Pseudoguembelitria* sp. and *Liliputianella*? sp.

Fig 3 Benthic Foraminifera from Romualdo Formation, Araripe Basin. **(a-b)** *Ammobaculites* sp. (Cedro outcrop); **(c)** *Ammobaculites* sp. (Cedro outcrop); **(d)** *Bathysiphon* sp. (Serra do Mãozinha outcrop); **(e)** *Rhabdammina* sp. (Serra do Mãozinha outcrop); **(f)** *Hyperammina* sp. (Serra do Mãozinha outcrop); **(g-h)** *Glomospira*? sp. (Santo Antônio outcrop); **(i-k)** *Patellina subcretacea* (Santo Antônio outcrop), **(i)** side view; **(j)** lateral view; **(k)** side view; **(l-n)** *Spirillina minima* (Santo Antônio outcrop), **(l)** side view, **(m)**

lateral view, **(n)** side view; **(o-p)** *Agathamina pusilla* (Santo Antônio outcrop); **(q-s)** *Quinqueloculina* sp. 1 (Santo Antônio outcrop), **(q, s)** side view; **(r)** lateral view; **(t-u)** *Quinqueloculina* sp. 2 (Santo Antônio outcrop), **(t)** side view; **(u)** lateral view; **(v-x)** *Miliolinella* sp. (Santo Antônio outcrop Fig. 4. 3a-b *in* Araripe et al. 2022); **(y-z)** *Sigmoilinita tenuis* (Santo Antônio outcrop), **(y)** side view; **(z)** lateral view; **(aa-ab)** *Spirosigmoilina rajkae* (Santo Antônio outcrop), **(aa)** lateral view; **(ab)** side view; **(ac-ad)** *Spirosigmoilina* sp. (Santo Antônio outcrop Fig. 4. 5 a-b *in* Araripe et al. 2022); **(ae-af)** *Pseudonodosaria* sp. (Santo Antônio outrocrop), **(ae)** side view **(af)** aperture view; **(ag-ah)** *Pleurostomella reussi* (Sobradinho outcrop); **(ai)** *Nodosarella* sp. (Santo Antônio outcrop); **(aj-ak)** *Lingulina* sp. (Santo Antônio outcrop); **(al-am)** *Astacolus gratus* (Santo Antônio outcrop), **(al)** side view **(am)** peripheral view; **(an-ao),** *Astacolus howchini* ? (Santo Antônio outcrop), **(an)** side view; **(ao)** peripheral view **(ap)** *Astacolus howchini* ? (Santo Antônio outcrop); **(aq-ar)** *Palmula sagittaria* (Santo Antônio outcrop Fig. 4. 12 a-b *in* Araripe et al. 2022), **(aq)** side view; **(ar)** peripheral view; **(as-at)** *Pseudosarcenaria* ? sp. (Santo Antônio outcrop) **(as)** side view **(at)** aperture view; **(au-av)** *Neoconorbina* sp. (Sobradinho outcrop), **(au)** dorsal view **(av)** ventral view; **(aw-ay)** *Conorboides minutissima* (Santo Antônio outcrop), **(aw)** dorsal view **(ay)** ventral view

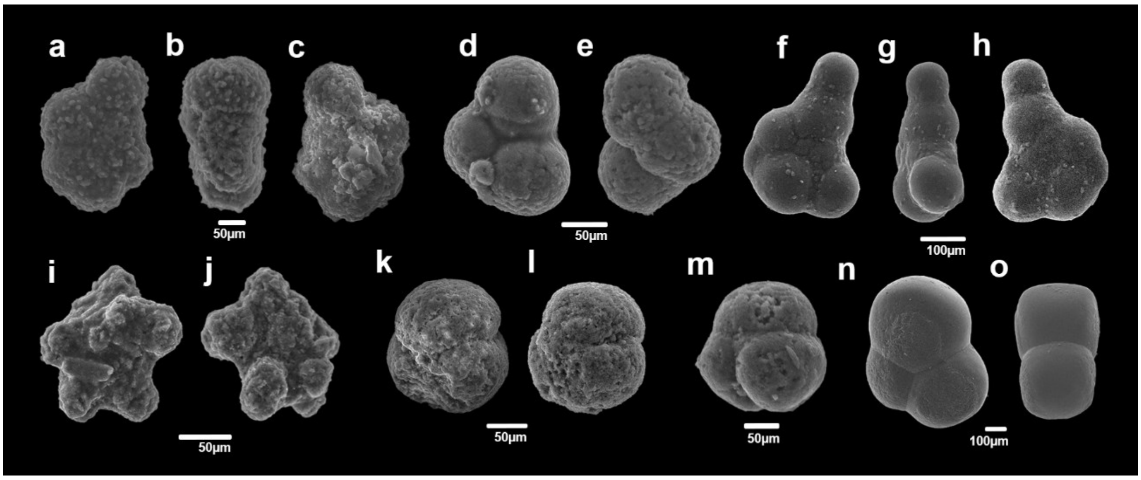

Fig 4 Planktonic Foraminifera from Romualdo Formation, Araripe Basin. **(a-c)** *Hedbergella aptiana* (Santo Antônio outcrop Fig. 4. 20 a-c *in* Araripe et al. 2022); **(d-e)** *Hedbergella* sp. (Santo Antônio outcrop Fig. 4. 18 a-b *in* Araripe et al. 2022); **(f-h)** *Hedbergella* aff. *daminiae* (Santo Antônio outcrop Fig. 4. 21 a-c *in* Araripe et al. 2022); **(i-j)** *Lilliputianella* ? sp. (Santo Antônio outcrop Fig. 4. 22 a-b *in* Araripe et al. 2022); **(k-l), m** *Pseudoguembelitria* sp. (Santo Antônio outcrop Fig. 4. 17 a-c *in* Araripe et al. 2022); **(n-o)** Gen. indet. (Santo Antônio outcrop Fig. 4. 19 a-b *in* Araripe et al. 2022)

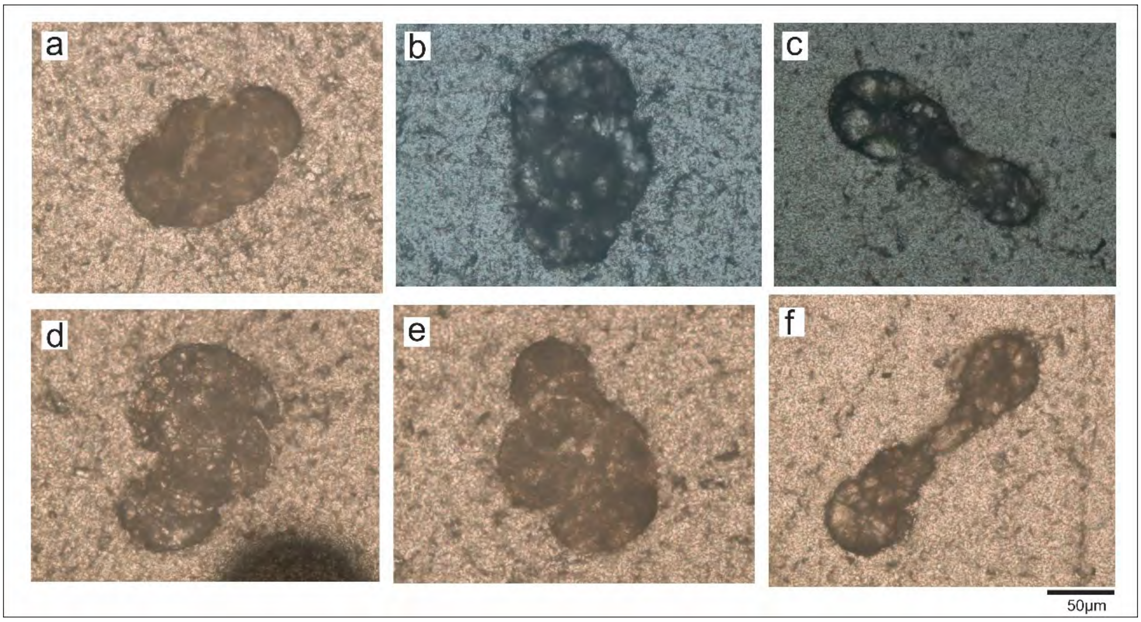

Fig 5 Thin section of benthic foraminifera tests from the Santo Antonio section (PE), Romualdo Formation, Araripe Basin. **(a)** *Quinqueloculina* sp. **(b)** Q*uinqueloculina* sp. 2 **(c)** *Sigmoilinita tenuis*; **(d)** *Agathammina* sp. **(e)** *Miliolinela* sp. **(f)** *Spirosigmoilina rajkae*.

4.1 *Foraminiferal assemblages*

The variation found in the composition and stratigraphic distribution of the foraminiferal assemblages (i.e., abundance, species richness, dominance, and the composition of the morphogroups) throughout the study sections not only provide evidence of a marine environment in the Romualdo Formation, but also reflect modifications in the intensity of the primeval sea level changes occurring during the Aptian–Albian.

Based on the Q-mode cluster analysis of the relative abundance of foraminiferal species and morphotypes, it was possible to define the benthic and planktonic assemblages that are characteristic of the different sub-environments in the transitional shallow water systems developed within the Romualdo Formation (Fig 6). These assemblages were differentiated by the presence of one of two predominant genera, *Quinqueloculina* and *Bathysiphon*. Three *Quinqueloculina* sub-assemblages were recognized – (i) the *Quinqueloculina* sp. (“QuinSP”) assemblage, (ii) the *Quinqueloculina – Conorboides* (“Quin-Con”) assemblage, and (iii) the *Quinqueloculina* – other groups (“QuinOG”) assemblage.

The QuinSP assemblage includes the samples collected from the limestones of the Santo Antônio (in the 2.1 m, 3.1 m, 3.4 m, 3.45 m, 3.55m, 3.85 m, 4.05 m, 5.25 m, and 5.35 m levels), Cedro (6.3–22 m), and Sobradinho (23 m) sections. This assemblage is characterized by low species richness and a predominance of porcelaneous benthic foraminifera, represented by two families – the abundant and more diverse hauerinids, dominated by *Quinqueloculina* sp. 1 (with up to 82.2% of the individuals), associated with the much rarer *Sigmoilinita*, *Miliolinella*, and *Spirosigmoilina* (2.7%), and hemigordiospids, represented by the genus *Agathammina* (0.1%). The generally low number of species and the dominance of one opportunistic taxon (*Quinqueloculina* sp. 1) may reflect an environment with prohibitively limiting conditions.

The QuinCon assemblage is composed of samples from the Santo Antônio (at the 0.3 m, 5.55 m, and 5.56 m levels) and Sobradinho (16–17 m) sections (Figs 8 and 9), which were present in calciferous sandstone and shales. This assemblage is based on the presence of two taxa (*Conorboides minutissima* and *Quinqueloculina* sp. 1), which vary in dominance according to the interval or section. At the 0.3 m level in the Santo Antônio section, *Conorboides minutissima* (36.8%) is a secondary component of this assemblage, while *Quinqueloculina* sp. 1 is dominant (50.1%). Toward the upper part of this section, however, at levels of between 5.55 m and 5.56 m, there is a reversal in dominance, with the miliolid becoming the secondary component of the assemblage. At 16 m and 17 m in the Sobradinho section, in turn, a distinct configuration is observed, with a monospecific association of *Conorboides minutissima* (89.1%). Planktonic foraminifera also occur in some levels (5.65 m at Santo Antônio and 16 m at Sobradinho), where they are represented by *Pseudoguembelitria* (0.5%) and hedbergellids (0.4%). A total of 17 species were found in this assemblage, including *Patellina subcretacea*, *Spirillina* sp. 1, and *Nodosarella* sp. The tests are well preserved. The assemblage is characterized by a relative abundance of hyaline and porcelaneous species, with a reduced percentage of agglutinated species, which indicates a continental shelf type of environment (Brasier, 1975; Ruckheim et al., 2006; Grunert et al., 2015).

The QuinOG assemblage is composed of samples from the Santo Antônio section (at the 2.25 m, 2.65 m, and 5.45 m levels), present in calciferous sandstone. Miliolids prevail, once again, with *Quinqueloculina* sp. 1 predominating (55.6%), followed by *Quinqueloculina* sp. 2 (3.9%), although these values are relatively low in comparison with the other assemblages, given the more prominent presence of other taxa. Other benthic hyaline groups make up the remaining 21.6% of the assemblage, with *Pettelina subcretacea* (14.2%), *Conorboides minutissima* (4.7%), and coiled vaginulinids and nodosariids (2.7%). Planktonic foraminifera are also found in the assemblage, being represented primarily by *Pseudoguembelitria* (0.7%) and hedbergellids (0.8%).

The *Bathysiphon* assemblage includes samples collected from the lower levels of the Serra do Mãozinha (at 0.5 m) and Cedro (3.5–6.0 m) sections, where it is present in calciferous sandstone. This agglutinated foraminifera assemblage is dominated by tubular epifaunal forms that peak in abundance (> 1500 specimens) in the Cedro section. *Bathysiphon* sp. is by far the most common agglutinated species (80.2%), followed by *Hyperammina* (18.3%). *Rhabdammina* sp. and *Ammobaculites* sp. together represent 1.3% of the assemblage. While the *Bathysiphon* assemblage had the smallest number of species, it had the highest abundance of foraminifera, and may indicate an estuarine environment or proximal marine conditions (Tibert et al., 2003).

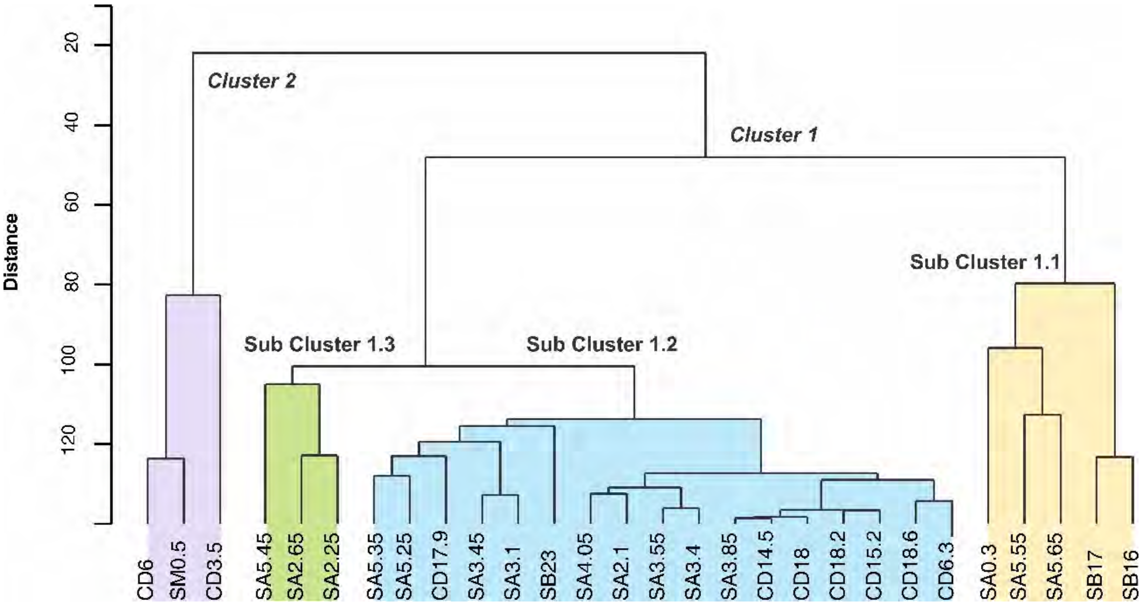

Fig 6 Q-mode cluster dendrogram made with UPGMA linkage. Assemblages are indicated with colors. Purple = *Bathysiphon* assemblage; green = *Quinqueloculina – other groups* assemblage; blue = *Quinqueloculina* assemblage; yellow = *Quinqueloculina – Conorboides* assemblage

4.2 *Studied sections and distribution of foraminifera assemblages*

Previous research on macroinvertebrates and carbonate microfossils (ostracods, foraminifera, and nannofossils) in the Santo Antônio section (Araripe et al. 2021; Araripe et al. 2022; Pereira et al., 2017; 2022) have demonstrated the value of this section for paleoenvironmental studies in the Araripe Basin. This was confirmed further in the present study, which focused only on the foraminiferal assemblages.

The foraminiferal fauna is relatively well preserved at Santo Antônio (Fig 7), where it is present primarily in the limestone and silt layers. The QuinCon assemblage is found in the lower part (0.3 m) of the section, where it is represented by the epifaunal benthic foraminifera *Quinqueloculina*, *Conorboides minutissima*, and *Patellina subcretacea*. Moving up (2.25–3.55 m), species richness increases through the addition of relatively rare infaunal species (*Pseudonodosaria* sp. – 1.4% *Palmula sagittaria* – 0.4%). Planktonic foraminifera also occur in these intervals, where they are represented by the globular forms, with the most common species being *Pseudoguembelitria* sp. (2.9%) and hedbergeliids (0.3%). The QuinSP assemblage is present at specific levels throughout the section (2.1 m, 3.85 m, 4.05 m, and 5.35 m), where the porcelaneous species *Quinqueloculina* sp. 1 (>70%), *Quinqueloculina* sp. 2 (2.9%), and *Spirosigmoilina* sp. (1.9%) predominate. The QuinCon assemblage is found in the upper part of the section (5.55–5.65 m), where the greatest abundance of foraminifera was found. The species richness was highest in this section in comparison with the other three (S=25; benthic species = 20, planktonic species = 5). The most abundant species were *Quinqueloculina* sp. 1 (65.7%), *Cornoboides minutissima* (9.6%), *Patellina subcretacea* (6.8%), *Sigmoilinita tenuis* (3.3%), *Quinqueloculina* sp. 2 (2.8%), and *Spirosigmolina* sp. (1.6 %).

The Cedro section contained only benthic foraminifera, which were recovered from only certain specific intervals (Fig 7). The QuinSP and *Bathysiphon* assemblages are present in the lower part of the calciferous sandstone, at 1 m, 3.5 m, and 6 m. At the base of the interval (1 m), the QuinSP assemblage is represented by rare *Quinqueloculina* sp. 1 and *Spirosigmoilina* sp. 1 (both less than 0.2%). The *Bathysiphon* assemblage (3.5–6 m) is represented by abundant agglutinated foraminifera (*Bathysiphon* sp., *Hyperammina* sp., and *Rhabdammina* sp.). Epifaunal tubular agglutinated species prevail in the assemblage dominated by *Bathysiphon* sp. (76.8%), *Hyperammina* sp. (22.9%), and *Rhabdammina* sp. (0.2 %), with a total of more than 1500 specimens. Further up, porcelaneous benthic foraminifera (the QuinSP assemblage) predominate in the 6.3–7.1 m, 14.5–15.2 m, and 17.9–22.0 m intervals, where they are abundant, but poorly diversified, basically including *Quinqueloculina* sp.1 (92.3%) and *Spirosigmoilina* sp.1 and sp. 2 (4.2%). The hyaline benthic foraminifera are represented by very rare infaunal (*Pseudonodosaria* sp. 0.04%, at 22 m) and epifaunal forms (*Spirillina minima* 0.08%, at 15.2 m). Despite the large quantities of mostly agglutinated species, species richness is low in the Cedro section (S=9). The most abundant species overall were *Quinqueloculina* sp. (67.4%), *Bathysiphon* sp. (15.3%), and *Hyperammina* sp. (4.5 %).

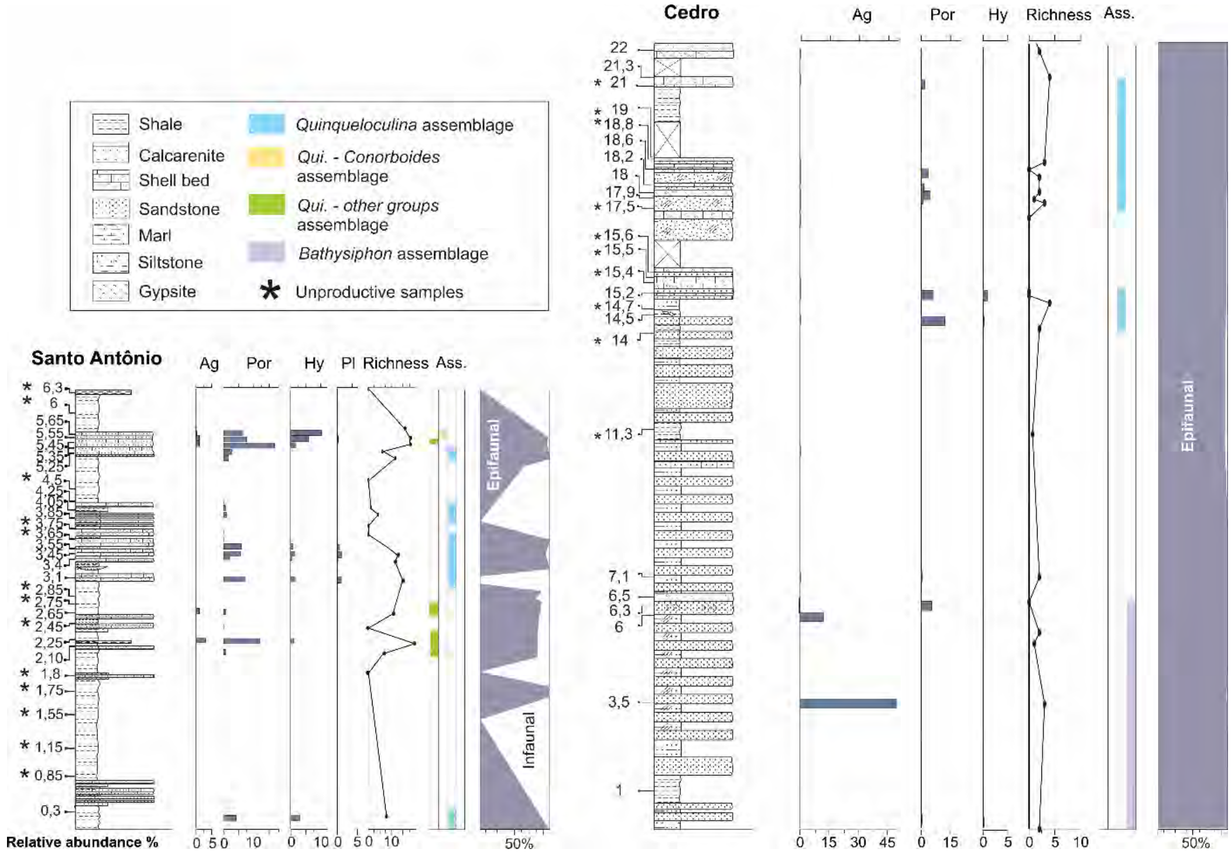

Fig 7 Distribution of the foraminiferal assemblages in the Santo Antônio and Cedro sections, showing the relative abundance, species richness and epifaunal ratio of the benthic foraminifera. Ag = Agglutinated, Por = Porcelaneous, Hy = Hyaline, Pl = Planktonic, Ass = Assemblage

Sobradinho section is one of the best exposure of Romualdo Formation in the Araripe basin, with numerous macro- and micropaleontological studies to date (Custódio et al., 2017; Arai and Assine, 2020). In the specific case of the foraminifera, previously studies have described assemblages composed of agglutinated foraminifera, milliolids, and a diverse planktonic fauna (Melo et al. 2020; Bom et al., 2021). In the present study, however, foraminifera were recovered only from the 16–23 m interval of the Sobradinho section (Fig 8). Both the benthic and the planktonic foraminifera are moderately well preserved, although the specimens are very small in size, and are present primarily in the calciferous sandstone and shales. The QuinCon assemblage is present in the middle portion of the section, at 16–17 m with a predominance of *Conorboides minutissima* (89.1%), followed by *Spirillina minima* (4.5%) and *Lingulonodosaria nodosaria* (3.5%). Planktonic foraminifera occur at 16 m, but are relatively rare (*Hedbergella* sp. and *Pseudoguembelitria* sp. – 0.3%). Porcelaneous and agglutinated benthic foraminifera (the *Quinqueloculina* assemblage) are found further up (17.5 m, 18 m, and 23 m), but they are also very rare, with 1.4% and 0.1% of the individuals, respectively. This section contains a total of 17 foraminifera species (benthic = 15, planktonic = 2), with a predominance of epifaunal forms, represented by the hyaline foraminifera of the families Conorbodidae (59.4%) and Miliolidae (4.7 %).

Benthic foraminifera are abundant in the calcareous sandstone at Serra do Mãozinha (Fig 8), in the 0.5 m interval, where they are represented exclusively by epifaunal tubular agglutinated benthic foraminifera (the *Bathysiphon* assemblage). Species richness is the lowest of any section (S=3), with a predominance of *Bathysiphon* sp. (87%), followed by *Hyperammina* sp. (9.2%) and *Rhadammina* sp. (3.7%).

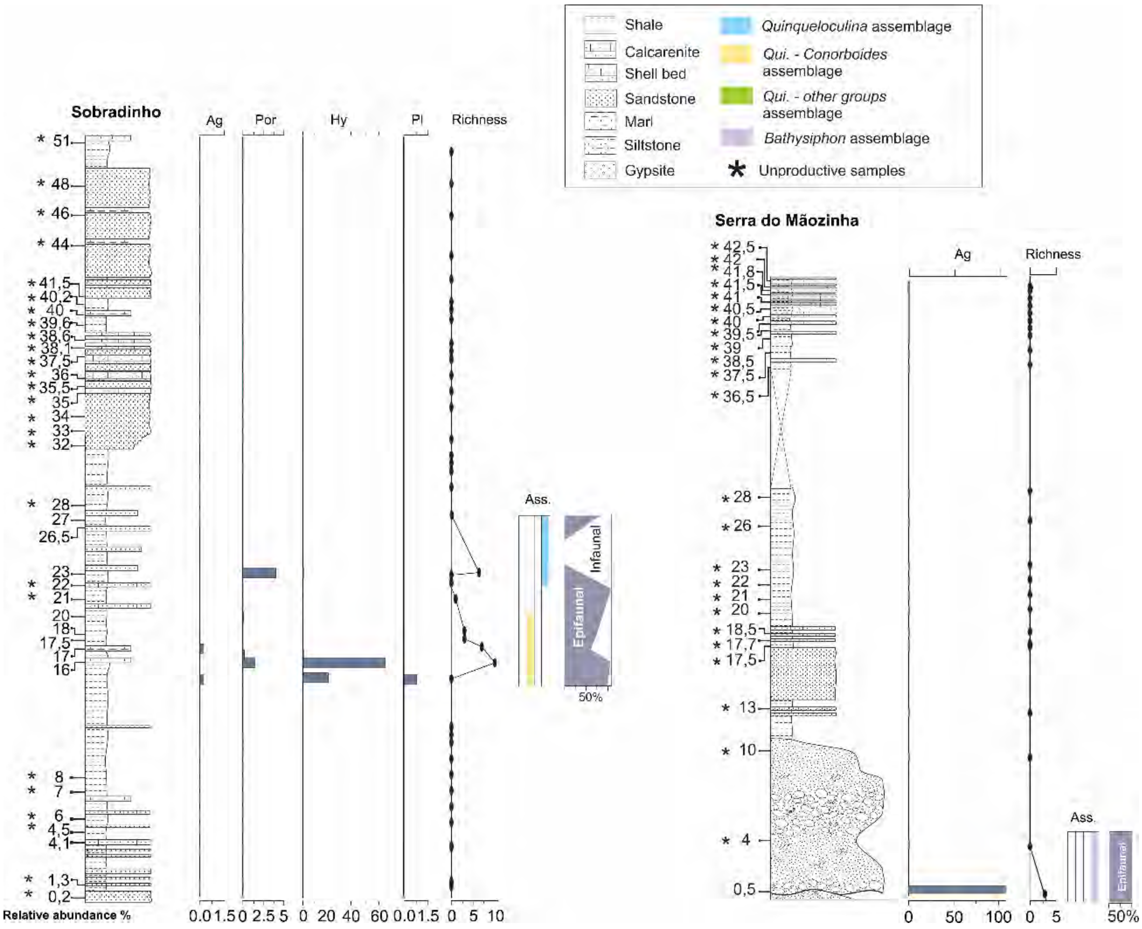

Fig 8. Distribution of foraminifera assemblages in Sobradinho and Serra do mãozinha sections, with values of relative abundance and species richness. Ag: Agglutinated, Por: Porcelaneous, Hy: Hyaline, Pl: Planktonic, Ass: Assemblages

4.3 *Paleoecological implications*

The foraminifera from the Romualdo Formation are represented primarily by abundant, but poorly diversified benthic species (porcelaneous and hyaline) and rare planktonic forms. Foraminiferal assemblages adapted to limited oxygen availability and variable salinity indicate a marginal marine environment. An abundance of opportunist groups with low species richness is characteristic of an unstable environment with fluctuations in oxygen levels (e. g., Leckie, 1987; Haig, 1979, 2020; Pezelj and Drobnjak, 2019), which is consistent with previous assessments of the Romualdo Formation, based on macroinvertebrates (Prado et al., 2015; 2018). During marine transgressions, low sedimentation rates and limited oxygen at the seafloor would favor only a few opportunist species, present in homogeneous, but abundant assemblages (Nagy, 2016).

The predominance of porcelaneous species, represented by the QuinSP assemblage, in the Santo Antônio and Cedro sections (Fig 8, Table 2), indicates conditions of normal to increased salinity, such as confined (hypersaline lagoons) or shallow marine environments (Boltovskoy and Wright, 1976; Araripe et al., 2021). Due to the restrictions of these shallow environments, which have high evaporation rates and increased salinity, they would have been colonized by opportunistic taxa well adapted to these conditions, leading to the predominance of porcelaneous groups (Debenay et al., 2001; Greiner, 1974; Araripe et al., 2022). Miliolids are considered to be able to tolerate dysoxic conditions, and even survive in anoxic environments (Moodley and Hess, 1992; Martínez-Colón et al., 2018). In this context, the foraminiferal assemblages of the Santo Antônio and Cedro sections, which are dominated by opportunistic miliolids, would have been capable of developing on the seafloor under stressful conditions. In these sections, peaks of calcareous benthic species richness, and the presence of morphogroups with rare planktonic forms, would have been interspersed with periods when foraminifera were absent. At Santo Antônio, the lack of foraminifera in these levels is compensated for by an abundance of ostracod specimens, primarily mixohaline genera (*Pattersoncypris*, *Damonella*), which are correlated with high salinity, including evaporitic environments (Poropat and Colin, 2012; Araripe et al., 2021; 2022). This variation indicates moments of marine incursions followed by periods of retreating sea level (Hu et al., 2015; Xi et al., 2016).

At the top of Santo Antônio section, however, the presence of both porcelaneous and hyaline foraminifera reflects an increase in both species richness and abundance, which represents a shift toward a more stable marine environment. These assemblages (QuinCon and QuinOG), which are characterized by epifaunal (*Quinqueloculina* sp. 1, *Spirosigmoillina* sp., *Sigmoilinita tenuis*, *Miliolinella* sp., *Conorboides minutisima*, and *Pattellina subcretacea*) and shallow infaunal forms (*Ellipsoidella* sp., *Pseudosaracenaria* sp., *Astacolus gratus*), are associated with rare and poorly-diversified planktonic foraminifera, which is consistent with the previous assessments of the same levels, based on nannofossils

(Araripe et al. 2022; Pedrosa et al. 2023). Species-rich assemblages tend to be associated with stable environments, whereas low species richness reflects stressful and poorly-oxygenated conditions (Murray, 2006). Similar distribution patterns were observed in the Sobradinho section, albeit with a more diverse planktonic fauna (Melo et al., 2020 and the present study). The presence of planktonic microfossils (foraminifera and nannofossils) in the Santo Antônio and Sobradinho sections also indicates environments influenced by open sea currents (Hart and Bailey, 1979; Leckie, 1989; Motamedalshariati et al., 2017). Globular morphotypes, such as *Hedbergella* and *Pseudoguembelitria*, are surface water-dwellers in epicontinental seas. These would thus be the first planktonic species to appear in the transgressive phase and the last to disappear during the regressive phase (Leckie, 1987; Huber and Leckie, 2011).

Agglutinated foraminifera occur in the lower portions of both the Cedro and Serra do Mãozinha sections, and correspond to a marine incursion at the base of the two sections. The genera *Bathysiphon*, *Rhabdammina*, and *Hyperammina* are considered to be deep-water organisms, forming a “flysh-type” assemblage in deep neritic to upper bathyal conditions in the Sergipe-Alagoas Basin (Koutsoukos et al., 1991; Koutsoukos and Bengtson,1993; 2000). Although foraminifera with agglutinated tests are considered to be deep-water forms, they have been recorded in shallow and marginal marine environments since the Carboniferous (Wightman et al. 1994; Tibert and Scott, 1999).
The uncoiled genus *Ammobaculites* is typical of estuarine channel environments in proximal zones where fluvial processes and the deposition of sandstone are prominent (Tibert et al., 2003). Agglutinated tests have a high preservation potential (Podobina, 1990; Tibert et al., 2003) and the rarity or absence of calcareous test from these levels may reflect the pressure of dissolution processes.

Sedimentary facies reflect changes in the depositional setting, which are linked to the ecological factors that influence the ecology of the microfauna (Caratelli and Archuby, 2023). In the present study, all the assemblages were composed of a large proportion (> 76%) of epifaunal and epi- to shallow infaunal taxa (*Quinqueloculina* and *Conorboides*) with active herbivorous and detritivorous niches, which are related to finely-grained facies. The *Bathyshiphon* assemblage is composed entirely of suspension-feeding epifaunal taxa (Koutsoukos and Hart, 1990), and occurs in coarse-grained sandstones, compatible with the transgressive sequence of the Romualdo Formation (Custódio et al. 2007), which indicates shallow water marine conditions at the base of the Cedro and Serra do Mãozinha sections.

Stable marine environments are characterized by taxa with both epifaunal and infaunal modes of life. A predominance of infaunal species is considered to reflect a restrictive environment (Jorissen et al., 1995; Van der Zwann et al., 1990). In the sections studied here, however, it is possible to observe a relationship between the occurrence of epifaunal species and periods of environmental instability, which may have been related to limitations in oxygenation and nutrient availability. Epifaunal taxa have an advantage in environments subject to limitations of nutrients or oxygen, whereas infaunal taxa tend to proliferate when nutrients and oxygen are more plentiful in the sediment. The observed patterns are thus consistent with a scenario of poorly-oxygenated waters and continental supply, developed during a transgressive phase. The generally low species richness of the assemblages and the predominance of a few opportunistic species (the QuinSP assemblage) suggest an environment with stressing conditions, in which organic matter was likely confined to the sediment-water interface with eu-mesotrophic conditions and reduced sedimentation rates (Caratelli and Archuby, 2023). This is also suggested by the low epifaunal-shallow infaunal ratio (12%) and the rare deeper infaunal taxa (e.g., *Pleurostomella*) found in the assemblages.

In addition, most of shallow-water infaunal forms are internal molds, suggesting the presence of more corrosive pore waters, which would have dissolved the original calcareous walls during their diagenesis. This corrosive process also appears to have affected some of the epifaunal porcelaneous forms (miliolids), given that most specimens are internal molds. In the samples dominated by epifaunal aragonitic foraminifera (e.g. *Conorboides*), by contrast, the shells are well preserved. Aragonitic tests are more susceptible to taphonomic degradation (Berger, 1978), which implies a more stable marine environment in the case of these samples (i.e., less corrosive agents).

Low oxygen levels have been recorded previously in the Romualdo Formation (Bom et al. 2021; Heimhofer et al. 2008). In a multiproxy analysis of the Sobradinho section, Bom et al. (2021) found evidence of deposition under the influence of low oxygenated and sulphide-rich bottom waters. These authors concluded that the black shales found throughout the section were deposited under dysoxic to anoxic bottom water conditions.

The small size of the tests of the benthic foraminifera analyzed in the present study also support the interpretation of dysoxic environments (Araripe et al., 2019). Some authors (Boltovskoy et al., 1991; Bradshaw, 1961) have correlated small test sizes in foraminifera with low oxygen conditions. These organisms would consume less oxygen during their metabolic activities, which is an important physiological pre-requisite for survival in low-oxygen environments, and likely a competitive advantage, resulting in a predominance of small-sized tests during anoxic/dysoxic periods (Koutsoukos and Hart 1990).

The outcrops of the Romualdo Formation vary considerably across the basin in their sedimentological and micropaleontological characteristics, with a sedimentary complex approximately 100 m thick in the eastern portion (in the Sobradinho and Serra do Mãozinha sections), decreasing to around 20 m in the central and western portion (the Santo Antônio and Cedro sections). Despite the thicker sediments found in the eastern portion of the basin, the benthic foraminifera of these sections were species-poor and had the highest proportion of unproductive samples, in comparison with the central sections. These differences may reflect shifts in paleoecological and paleoenvironmental conditions related to changes in sea level within the Araripe Basin. Within this extensive epicontinental sea, oxygen deficient conditions were likely severe and widespread, playing a fundamental role in the distribution patterns of the foraminifera in the Romualdo Formation.

Table 2 Occurrence of foraminiferal assemblages in Santo Antonio, Cedro, Sobradinho and Serra do Mãozinha sections with the characterization and paleoenvironmental interpretation of each assemblage

Sections	**Planktonic species**	**Assemblages**	**Dominant Shell type**	**Main Families**	**Living strategy**	**Paleoenvironmental Interpretation**
Santo Antônio	*Pseudoguembelitria* sp. *Hedbergella* spp. *Lliputianella*? sp.	*QuinSP..*	Porcelaneous	Hauerinidae Hemigordiospidae	Epifaunal/ shallow infaunal	Hypersaline to shallow marine with connection to open marine (Boltovskoy and Wright, 1976; (Hart and Bailey, 1979; Leckie, 1989; Motamedalshariati et al., 2017)
		QuinCo	Hyaline	Conorboididae	Epifaunal	
		QuinOG	Porcelaneous	Nodosariidae Vaginulinidae	Epifaunal/ shallow infaunal	
Cedro	--	*QuinSP..*	Porcelaneous	Hauerinidae	Epifaunal/ shallow infaunal	Estuarine/ Proximal shallow marine (Tibert et al., 2003).
		Bathysiphon	Agglutinnated	Ammodiscidae Rhabdamminidae	Epifaunal	
Sobradinho	*Pseudoguembelitria* sp. *Hedbergella* sp.	*QuinCo*	Hyaline	Conorboididae Nodosariidae Vaginulinidae	Epifaunal	Shallow marine with connection to open marine (Hart and Bailey, 1979; Leckie, 1989; Motamedalshariati et al., 2017)
Serra do Mãozinha	--	*Bathysiphon*	Agglutinnated	Ammodiscidae Rhabdamminidae	Epifaunal	Proximal shallow marine (Tibert et al., 2003).

Conclusions

Twenty-seven benthic and five planktonic foraminiferal taxa were identified in the present study. Porcelaneous benthic foraminifera predominated in the Santo Antonio and Cedro sections, but were rare in the Sobradinho section, while planktonic species occurred in only two sections (Santo Antonio and Sobradinho).

Four assemblages were defined: the *Quinqueloculina* assemblage (recorded in the Santo Antônio, Cedro, and Sobradinho sections), the *Quinqueloculina–Conorboides* assemblage (Santo Antônio and Sobradinho sections), the *Quinqueloculina–*other groups assemblage (Santo Antônio section), and the *Bathysiphon* assemblages (Cedro and Serra do Mãozinha sections). All these benthic assemblages are typical of marginal marine environments, with varying stratigraphical occurrences and local distribution in the four sections.

The assemblages recorded in the present study had low species richness, a predominance of opportunistic species, an abundance of epifaunal foraminifera, and relatively small body sizes. These characteristics may all reflect low oxygen levels in shallow-water or marginal marine environments. The distribution patterns of the foraminifera appear to have been influenced by decreasing sedimentation rates and oxygen availability, which were, in turn, a response to changes in sea level, reflecting the establishment of the different marginal marine environments in the Romualdo Formation of the Araripe Basin.

Declaration of interests

☒ 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.

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4.5 Artigo 3 - Considerações Paleobiogeográficas de foraminíferos do Aptiano - Albiano de mares epicontinentais do Nordeste do Brasil

A ser submetido à revista Palaeogeography, Palaeoclimatology, Palaeoecology

CONSIDERAÇÕES PALEOBIOGEOGRÁFICAS DE FORAMINÍFEROS DO APTIANO - ALBIANO DE MARES EPICONTINENTAIS DO NORDESTE DO BRASIL

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Resumo

O presente trabalho tem como objetivo correlacionar a fauna de foraminíferos da Formação Romualdo da Bacia do Araripe (NE, Brasil) com associações faunísticas de bacias de idade Aptiana – Albiana localizadas em outras regiões do Brasil e do mundo, para analisar modelos de distribuição biogeográficas de foraminíferos e colaborar para o entendimento das dinâmicas de mares epicontinentais. Dentre as bacias do Nordeste do Brasil, apenas a Sergipe-Alagoas, Araripe, Parnaíba e Potiguar possuem a ocorrência de foraminíferos nas camadas de idade Aptiano-Albiano. Com base em estudos prévios, já foram identificadas 154 espécies, sendo as famílias Vaginulinidae, Epistominidae, Rhabdamminidae e Hyperaminidae as mais comuns entre essas bacias, e representam uma fauna dominada por táxons bentônicos de carapaças hialinas e aglutinantes. De todas as bacias do nordeste do Brasil, a Sergipe-Alagoas possui maior riqueza de espécies de foraminíferos, isto está relacionado principalmente por tal bacia possuir a sucessão estratigráfica mais completa, sendo uma bacia amplamente estudada. Já para a Bacia do Araripe, cerca de 52 espécies foram identificadas representando 1/3 da fauna das bacias do Nordeste do Brasil (33,7%). Muitas das espécies encontradas na Bacia do Araripe são cosmopolitas, com alguns poucos gêneros de ocorrência endêmica para a região. Os foraminíferos planctônicos estão correlacionados com a regiões da Oeste da África e América do Norte com forte influência Tetiana (*Hedbergella*, *Globigerinelloides*). As associações bentônicas (*Lingulogavelinella*, *Pseudonodosaria*, *Agathammina*), indicam latitudes médias a baixas e uma bioprovincia Tetiana/Transicional.

Palavras-chave: Mares epicontinentais, Tétis, Bacia do Araripe, Nordeste do Brasil.

1 - Introdução

Durante o Período Cretáceo, a aceleração na expansão das placas tectônicas e das atividades *hot spots* do globo produziram regiões topograficamente elevadas no fundo marinho. Essas elevações interferiram no deslocamento episódico do nível global do mar, inundando com mares interiores/epicontinentais várias regiões ao redor do mundo (Kauffman, 1984; Haq et al. 2014).

Os mares interiores ou epicontinentais compreendem corpos de águas rasas, formados a partir dessas variações eustáticas, que possuem uma conexão por vezes, limitada com o mar aberto. Estes, possuem grandes variações de temperatura e salinidade da água, podendo ser mais salgadas, e em algumas situações com um caráter salobro ou até mesmo de água doce (especialmente próximo a suas bordas) (Davydov et al. 2012; Carvalho, 2022). Por se estenderam por áreas continentais amplas com profundidades de água menores de 100 m, os mares epicontinentais são caracterizados por uma circulação lenta em comparação a ambientes costeiros de mesma profundidade que enfrentam o mar aberto (Slingerland, 1986; Wells et al. 2007), tendo importante influência nas dinâmicas e associações de espécies marinhas.

O intervalo Aptiano – Albiano representa um período importante nas alterações climáticas e oceânicas. Com o aumento da área e do volume dos mares epicontinentais e marginais, houve um aumento na produção de carbono orgânico, que juntamente com condições climáticas de águas frias e pouco oxigenadas do fundo marinho podem ter ocasionado Eventos de Anoxia Oceânico reconhecidos em escala global (Schlanger e Jenkyns, 1976; Arthur e Premoli Silva, 1982; Jenkyns, 1995; Jenkyns e Wilson, 1999).

Embora os mecanismos responsáveis pelas EAOs tenham sido fortemente debatidos e ainda não sejam definitivamente compreendidos, não há dúvida de que eles contribuíram significativamente para as mudanças e evolução da comunidade marinha, especialmente nas assembléias de foraminíferos (Erbacher et al., 1998; 1999; Leckie et al., 2002; Dumitrescu e Brassell., 2005; Okano et al., 2008).

Os principais fatores que controlam a composição, diversidade e abundância das assembléias de foraminíferos são considerados salinidade, oxigênio e disponibilidade de recursos tróficos (Sjoerdsma and Van der Zwaan, 1992; Jorissen et al., 1995; Fontanier et al.,2002). Esses fatores foram condicionados a todas as variações ocorridas no Aptiano – Albiano que ocasionaram um ambiente marinho com bastante instabilidade. O presente trabalho tem como objetivo investigar as associações de foraminíferos descritas para o Aptiano – Albiano nas bacias do Nordeste do Brasil e bacias internacionais, além de discutir padrões de distribuição paleobiogeográficos.

2 - Material e métodos

Foi realizado o levantamento bibliográfico dos trabalhos de interesse para o desenvolvimento desta pesquisa, com ênfase nas bacias de idade Aptiano-Albiano no Nordeste do Brasil e em outras localidades internacionais.

Dentre as bacias do Nordeste do Brasil, a Sergipe-Alagoas (Margem continental), a Potiguar e do Ceará (Margem equatorial) e Araripe, Parnaíba, São Luiz, Grajaú e Tucano (Intracratônicas) contém o registro da evolução tectônica do Atlântico Sul, com desenvolvimento de mares epicontinentais. Destas, apenas a Sergipe-Alagoas, Araripe, Parnaíba e Potiguar registraram a ocorrência de foraminíferos nas camadas de idade Aptiano-Albiano até o presente momento (Petri, 1962; Schaller, 1969; Bengston e Berthou, 1988; Koutsokos, 1989; Do Carmo et al. 2018; Melo et al. 2020; Araripe et al. 2021, 2022; Bom et al. 2021; Barros et al. 2022).

Em relação as bacias internacionais, foram estudadas neste trabalho: Bacias da Austrália (Queensland, Eromanga e Carnarvron), Sudoeste da África (Kwanza e Walvis Ridge), EUA (Blake Nose) e Marrocos (Agadir-Essouira). No geral, as localidades foram categorizadas em três grandes regiões, Atlântico Sul (Equatorial e Central), Atlântico Norte e Oceano Indico (Grandstain et al. 1978; Haig e Barnbaum, 1978; Haig, 1982, 2005; Scheibnerová et al. 1981; Butt et al. 1982, 1984; Haig e Laynch, 1993;

Holbourn e Moullade, 1998; Witam, 1998; Bourgeoini et al. 2002; Kochhann et al. 2013, 2014; Bamba et al. 2011) (Tabela 1).

Tabela 1 - Regiões analisadas no presente estudo.

Regiões	**Países**	**Bacias**
Atlântico sul	Brasil	Araripe
		Sergipe/Alagoas
		Parnaíba
		Potiguar
	Angola	Kwanza
		Walvis Ridge
Atlântico Norte	EUA	Blake Nose
	Marrocos	Ágadir-Essouira
Oceano Índico	Australia	Carnavron
		Eromanga
		Queensland

Foi realizada a análise de *Cluster* (Everitt et al., 2011), gerada através do *software* PRIMER 7 (Clarke & Gorley, 2015), utilizando dados binários (presença-ausência) dos gêneros de foraminíferos descritos para cada bacia sedimentar, a matriz de similaridade dos gêneros foi construída baseada no índice de Jaccard e utilizada para análise dos dados.

3 - Resultados

2.1 - Atlântico Sul (Equatorial e Central)

A fauna de foraminíferos da Bacia Sergipe-Alagoas se estende por todo o Cretáceo (Petri, 1963; Koutsoukos 1989; Koutsoukos et al. 1991). No Aptiano superior ocorre a primeira sedimentação marinha, apresentando favuselídeos e nodosaríideos com outros elementos de microfauna marinha, sugerindo condições de águas hipersalinas, quentes e rasas em plataforma carbonática. Porém a volta de condições parálicas (indicadas por níveis com microgastrópodes e microbivalves sem a ocorrência de foraminíferos e equinóides) indicam a natureza cíclica local do nível do mar durante esse episódio. A microfauna bentônica é caracterizada por espécies aglutinantes (ex: *Ammobaculites*, *Haplophragmium*), representando um ambiente lagunar e por uma microfauna planctônica composta por hedbergelídeos e globigerinelídeos que se torna mais abundante em ambientes mais profundos (nerítico a batial) (Koutsoukos et al. 1991a e b).

Nas bacias Parnaíba e Potiguar, apenas 5 táxons foram identificados (Do Carmo et al. 2018, Barros et al. 2022) representando 3% da fauna total encontrada. Na Bacia Potiguar, na Formação Alagamar e nas Camadas Pontas de Tubarão, as ocorrências registradas pertencem ao grupo dos foraminíferos aglutinantes (*Gaudryinella*) e de carapaça orgânica. Apesar de serem registrados com outros microfósseis não-marinhos (ostracodes, conchostráceos e palinomorfos) a ocorrência desses foraminíferos de carapaça orgânica estaria indicando uma influência marinha para a camada (Do Carmo et al. 2018).

Para a Bacia do Parnaíba, na Formação Codó (Aptiano superior) a influência marinha já foi discutida por alguns autores (Bastos et al. 2014, Sousa et al. 2020, Barros et al. 2022) indicando um ambiente lacustre/lagunar com água salobra permanente. A distribuição dos microfósseis encontrados por Barros et al. (2022) demonstrou diferentes episódios da influência marinha, em alguns momentos, ocasionada por uma conexão intermitente com o mar aberto, principalmente onde ocorrem os gastrópodes marinhos e foraminíferos. As espécies bentônicas encontradas pertencem aos gêneros *Pseudogaudrynella*, *Gaudryina*, *Astacolus* e *Epistomina,* tendo o registro de fauna planctônica, porém sem identificação.

Já para a Bacia do Araripe, cerca de 52 espécies foram identificadas (Melo et al. 2020; Bom et al. 2021, Araripe et al. 2022) representando 1/3 da fauna das bacias do Nordeste do Brasil (33,7%). A fauna é representada por uma associação bentônica dominada por miliolídeos e alguns gêneros aglutinantes (Araripe et al. 2021; 2022; Bom et al. 2021), que caracteriza um ambiente hipersalino a marinho raso e uma fauna planctônica, caracterizada por espécimes muito pequenos, representados pelas famílias Hedbergellidae e Globigerinelloididae que indicaria um ambiente marinho com conexão com mar aberto (Melo et al. 2020).

A bacia Cote d'Ivore, Gana, possui o registro de 49 espécies identificadas (Holbourn e Moullade, 1998; Bamba et al. 2017). A fauna é constituída predominantemente por foraminíferos bentônicos dos gêneros *Marginulinopsis, Laevidentalina, Gavelinella.* Em relação aos foraminíferos planctônicos, são destaques a fauna de *Hedbergella* e *Globigerinelloides* os quais possuem tamanhos diminutos e baixa riqueza, provavelmente relacionado ao Evento anoxia global (Breheret, 1995). A presença dos foraminíferos indica a influência do ambiente marinho na bacia durante o aptiano-albiano.

As bacias de Kwanza e Walvis possui o registro de 90 espécies (63 e 27 respectivamente (Scheibnerová et al. 198; Caron, 1978; Kochhann et al. 2013, 2014). A fauna bentônica possui baixa abundância e riqueza, caracterizada pela associação de foraminíferos aglutinantes, já as espécies planctônicas, são dominadas por hedbergelídeos. A associação é típica de plataforma continentais abertas, ricas em carbonatos.

2.2 - Atlântico Norte

Na Bacia Blake Nose são registrados 17 táxons (Grandstain et al. 1981; Huber et al. 2011). É composta por táxons bentônicos e planctônicos bem preservados. Os foraminíferos planctônicos globosos são abundantes com a representação dos gêneros *Hedbergella*, *Pseudoguembelitria* e *Globigerinelloides*. Os gêneros *Osangularia*, *Astacolus* e *Berthelina* são comuns.

A Bacia Agadir-Assouira possui o registro de 34 táxons, as camadas do Aptiano – Albiano são ricas em microfósseis carbonáticos (Witam, 1998; Bourgeoini et al. 2002; But et al. 1982;1984). Globigerinídeos, Rotaliporoides e Lagenidas são abundantes. A associação encontrada infere ambientes de mar aberto e plataformas externas.

2.3 - Oceano Índico

As bacias Eromanga, Canarvron e a região de Queensland na Austrália, possui uma associação de foraminíferos abundante. Foram registrados 307 táxons (58, 74 e 175 respectivamente) nos trabalhos analisados (Haig and Barnbaum, 1978; Haig, 1982; Haig and Lynch, 1993; Haig, 2005).

Haig (1979) e Handerson (2000) descrevem três associações (Ammobaculites, Marssonella, Recurvoides) encontradas no Cretáceo Inferior da Austrália com distribuição global. Segundo Haig (1979) a associação Ammobaculites é encontrada em areias e lamas, caracterizada por baixa riqueza, com abundância de foraminíferos aglutinantes silicosos e uma assembleia distinta de foraminíferos hialinos aparentemente adaptados a águas frias, baixos níveis de oxigênio e condições ligeiramente salobras. É representada principalmente nas bacias epicontinentais do Cretáceo médio. Os gêneros *Sacammina, Reophax*, *Miliammina*, *Haplophragmoides* são mais comuns. A associação Marssonella são encontrados em sedimentos ricos em carbonatos depositados em mar aberto. É caracterizada pela assembleia diversa de rotalídeos associados com aglutinantes calcários. Gaudryina, Pseudosigmoilina e nodosariídeos são comuns. A associação Recusvoides é caracterizada por espécies aglutinantes silicosas, e a ausencia de formas calcárias. Os foraminíferos planctônicos podem ocorrem, porém com baixa representatividade.Recurvoides, Plectorecurvoides, Thalmannammina são comuns. Essa associação é característica de ambientes de águas profundas.

2. 4 Análise de agrupamento

Entre as bacias brasileiras, foram registradas 154 espécies de foraminíferos (125 bentônicas e 29 planctônicas), sendo a Bacia Sergipe/Alagoas a que registra o maior número de espécies (104). De acordo com a análise de similaridade entre os gêneros das bacias brasileiras, *Astacolus, Conorboides* e *Hyperammina* são mais comuns, e correlaciona a Bacia Sergipe/Alagoas com a Bacia do Araripe (Figura 1; Tabela 1). As bacias Potiguar e Parnaíba se diferenciam das demais, provavelmente pelo baixo registro de espécies. As famílias Vaginulinidae, Epistominidae, Rhabdamminidae e Hyperaminidae são as mais comuns entre essas bacias, e representam uma fauna dominada por táxons bentônicos de carapaças hialinas e aglutinantes. Os foraminíferos planctônicos são representados principalmente pelas famílias Hedbergellidae e Globigerinelloididae.

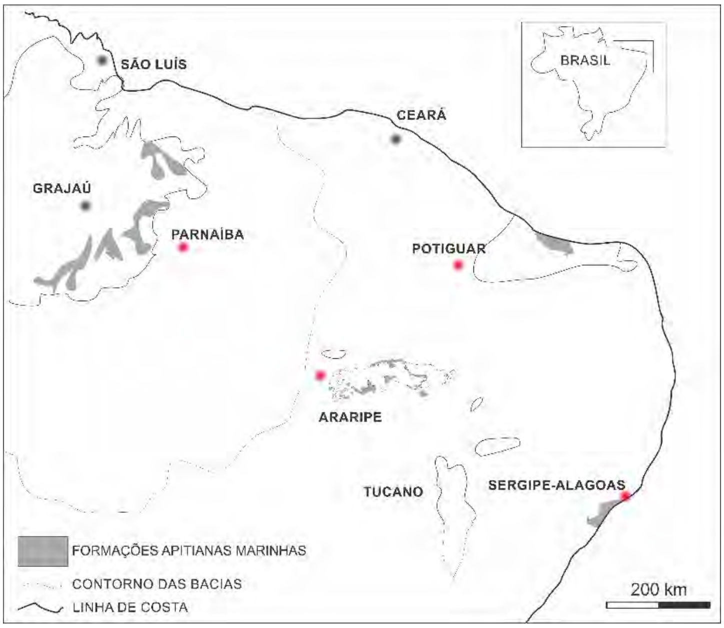
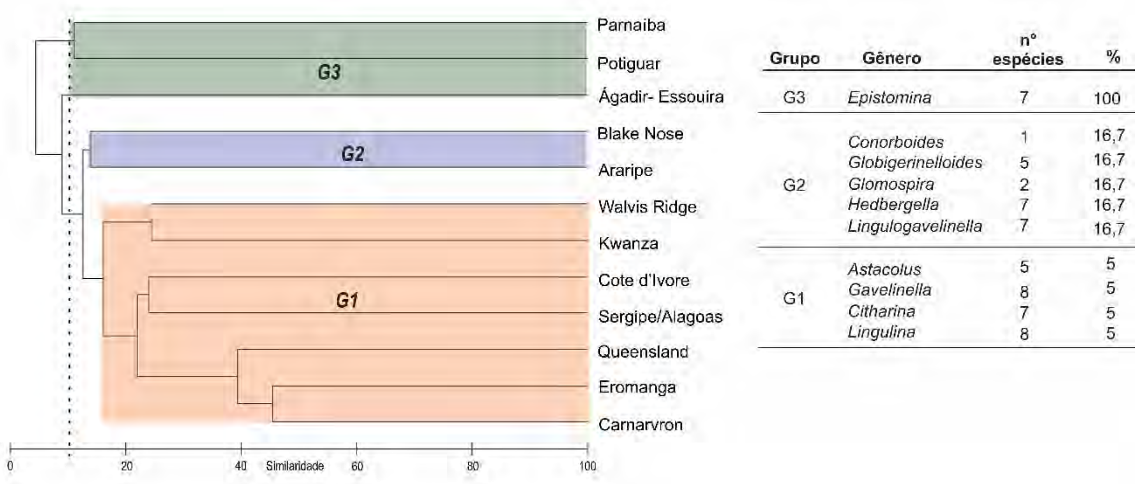


Figura 1 – Mapa de localização das bacias do Nordeste do Brasil com registro de mares epicontinentais. Em vermelho as bacias com ocorrência de foraminíferos.

Tabela 1. Dados dos gêneros com maior ocorrência nas bacias do Nordeste do Brasil. Araripe, Sergipe/Alagoas, Potiguar, Parnaíba.

Gênero	Araripe	Sergipe/ Alagoas	Potiguar	Parnaíba
Ammobaculites	*x*	*x*		*x*
Glomospira	*x*	*x*		
Bathysiphon	*x*	*x*		
Hyperammina	*x*	*x*		
Rhabdammina	*x*	*x*		
Gaudrynopsis	*x*	*x*		
Astacolus	*x*	*x*		*x*
Epistomina		*x*		*x*
Lingulogavelinella	*x*	*x*		
Conorboides	*x*	*x*		
Pseudonodosaria	*x*	*x*		
Spirillina	*x*	*x*		
Globigerinelloides	*x*	*x*		
Hedbergella	*x*	*x*		
Gaudriynella			*x*	

De acordo com os resultados obtidos, já foram registrados 59 gêneros de foraminíferos do aptiano/albiano em mares epicontinetais do nordeste do Brasil e em outras localidades do mundo, resultando em 461 espécies estudadas. A região do Oceano Índico (Austrália) contém o maior número de espécies quando comparada com as outras regiões. Apesar da ocorrência de gêneros cosmopolitas (Lenticulina, Gavelinella), cada região possui suas associações com a dominância de táxons distintos (Figura 2).



Grupo	Gênero	n° espécies	%
G3	*Epistomina*	7	100
G2	*Conorboides*	1	16,7
	Globigerinelloides	5	16,7
	Glomospira	2	16,7
	Hedbergella	7	16,7
	Lingulogavelinella	7	16,7
G1	*Astacolus*	5	5
	Gavelinella	8	5
	Citharina	7	5
	Lingulina	8	5

Figura 2 – Análise de agrupamento dos gêneros de foraminíferos das regiões do globo analisadas. G1: Bacias da Austrália, Sudoeste da Africa e Bacia Sergipe- Alagoas; G2: Bacia do Araripe e Blake Nose (América do Norte); G3: Bacias Parnaíba, Potiguar e Agadir (Marrocos). Agrupamento baseado na ausência/presença de foraminíferos. Tabela com os gêneros de maior similaridade e número de espécies de cada agrupamento.

3. Discussão

Durante muito tempo as associações de foraminíferos do Cretáceo inferior das bacias brasileiras foram relacionadas a modelos de distribuição internacionais, provenientes de outras bacias de mesma idade (Haig, 1979). Essas variações específicas nos padrões de ocorrências dos foraminíferos é reflexo da evolução paleoambiental e paleoecológica desse grupo, nas bacias do nordeste brasileiro.

A abertura do Atlântico desencadeou respostas tectônicas que refletiram no surgimento de mares epicontinentais, resultando na formação de distintos microambientes com o desenvolvimento da fauna de foraminíferos, principalmente os bentônicos. Essa diversidade de nichos ecológicos serviu para distinguir a fauna de foraminíferos das bacias aptianas/albianas do Nordeste em relação a outras bacias do mundo e até mesmo entre elas.

A Bacia Sergipe-Alagoas, junto com a Bacia do Araripe, é uma das mais estudadas e com maior riqueza de espécies em mares epicontinentais do Nordeste (Petri, 1962; Schaller, 1969; Begston e Berthou, 1988; Kousoukos, 1989; 1992; 2001; Koutsoukos e Benstson, 2007; Koutsoukos et al. 1991a; Melo et al. 2020; Bom et al. 2021; Araripe et al. 2021; 2022; Luft-Souza et al. 2022).

A associação encontrada na Bacia Sergipe Alagoas possui grande riqueza de espécies bentônicas e planctônicas, provavelmente relacionada a maior incidência de águas de mar aberto nesta bacia. Os foraminíferos aglutinantes são encontrados em ambientes de mares profundos e os gêneros planctônicos *Favusella*, *Hedbergella* e *Gavelinella* são comuns na bacia. Quando comparada com a bacia Sergipe Alagoas, a Bacia do Araripe possui uma baixa riqueza, onde os foraminíferos bentônicos de carapaças calcárias são mais abundantes que os aglutinantes, e estes, diferentes da Sergipe-Alagoas, são encontrados em ambientes mais rasos. Os gêneros *Quinqueloculina*, *Conorboides* e *Spirillina* são comuns.

A fim de identificar uma associação faunística que representa as bacias Aptianas Albianas do nordeste do Brasil, foi possível perceber que apesar das particularidades de cada bacia, de uma forma geral, a fauna de foraminíferos é característica de mares rasos, de águas salobras com conexão com o mar aberto. Possui características semelhantes às associações *Ammobaculites* e *Marssonella* descrita por Haig, (1979), porém essa associação se diferencia por possuir baixa riqueza, onde os foraminíferos de carapaças calcárias são mais abundantes que os aglutinantes. Além disso, foi possível perceber:

- Nos ambientes transicionais ou hipersalinos os miliolídeos são dominantes, principalmente na bacia do Araripe.
- Na plataforma interna a fauna de foraminíferos bentônicos se apresenta com maior riqueza, com dominância de Conorboididae e Vaginulinidae.
- Na plataforma interna/média de conexão com o mar aberto a ocorrência de foraminíferos bentônicos estão associados a fauna planctônica com dominância de *Hedbergella* e *Globigerinelloides*.

O fator que influencia diretamente na distribuição dos grupos é a disponibilidade de carbonato de cálcio (Haig, 1979), representada pela ocorrência isolada dos foraminíferos aglutinantes na ausência de formas calcárias. A solubilidade do carbonato de cálcio (e sua disponibilidade para precipitação orgânica) é controlada pela temperatura, salinidade e profundidade da água (Greiner, 1974; Murray, 1973; 2006). Em mares quentes, hipersalinos e rasos, é menos solúvel e mais facilmente disponível para a calcificação orgânica (Haig, 1979).

Outro fator importante é a disponibilidade de oxigênio associado a eventos anóxicos ocorrida no Aptiano – Albiano. As condições anóxicas teriam afetado a associação de foraminíferos fazendo com que em alguns locais ocorra a dominância de uma fauna oportunista e pouco desenvolvida representada pelos moldes de miliolídios. A distribuição dos foraminíferos planctônicos está relacionada ao fato dos gêneros *Hedbegella* e *Globigerinelloides* serem mais habituados a águas superficiais. As formas globosas e de tamanho diminuto são as primeiras formas planctônicas a compor uma associação de ambiente transgressivo (Eicher and Worstell, 1970; Eicher, 1967).

De acordo com a análise de agrupamento, as bacias brasileiras possuem afinidades distintas com bacias de outras regiões do globo. A Bacia Sergipe/Alagoas apresenta maior similaridade com as bacias da Austrália e do sudoeste da África, sendo *Astacolus*, *Gavelinella* e *Citharina* os gêneros comuns. As assembleias de foraminíferos recuperadas nos depósitos marinhos do Aptiano superior na bacia Sergipe-Alagoas possuem características de afinidade Tetiana/Transicional (Koutsoukos et al., 1991a e b). A microfauna de maneira geral, sugere que a área norte do Atlântico Sul teve alguma troca de água, pelo menos superficial, com as províncias tetianas de baixa latitude, sendo relacionadas com o oeste da África. A ocorrência de uma fauna vindo de região ao norte (Boreal) e/ou sul (Austral) de alta latitude também ocorre, demonstrada pela ocorrência das assembléias de Vaginulinídeos e Nodosariidíeos semelhantes as assembléias no Oceano Índico.

A bioprovíncia transicional é mais evidente em baixas latitudes durante o Cretáceo superior. É reconhecida em mares epicontinentais no sul e norte de Tétis, onde assembléias intermadiárias, com afinidades biogeográficas misturadas, são registradas (Kousoukos, 1989).

A Bacia do Araripe, possui maior similaridade com as bacias do Atlântico Norte (Blake Nose), sendo os gêneros *Conorboides* e *Spirillina* os mais comuns nas duas regiões. A associação é característica de regiões tropicais/subtropicais (Melo et al. 2020) e ocorrência de *Globigerinelloides* e *Hedbergella* demostra uma similaridade com as assembleias da América do Norte e Oeste da África, caracterizando também bioprovíncias Tetianas.

Alguns autores já correlacionaram a microfauna com afinidade tetiana (Arai e Coimbra, 1990; Melo et al. 2020; Araripe et al. 2021;2022). De acordo com Arai (2014), a águas do mar de tétis chegaram nas bacias de margem continentais brasileiras através do mar existente na região atual do nordeste do Brasil, passando pelas bacias São Luís, Parnaíba, Araripe, Tucano até chegar na Sergipe-Alagoas. Fazendo com que a influência do Atlântico Norte fosse mais efetiva para a Bacia do Araripe.

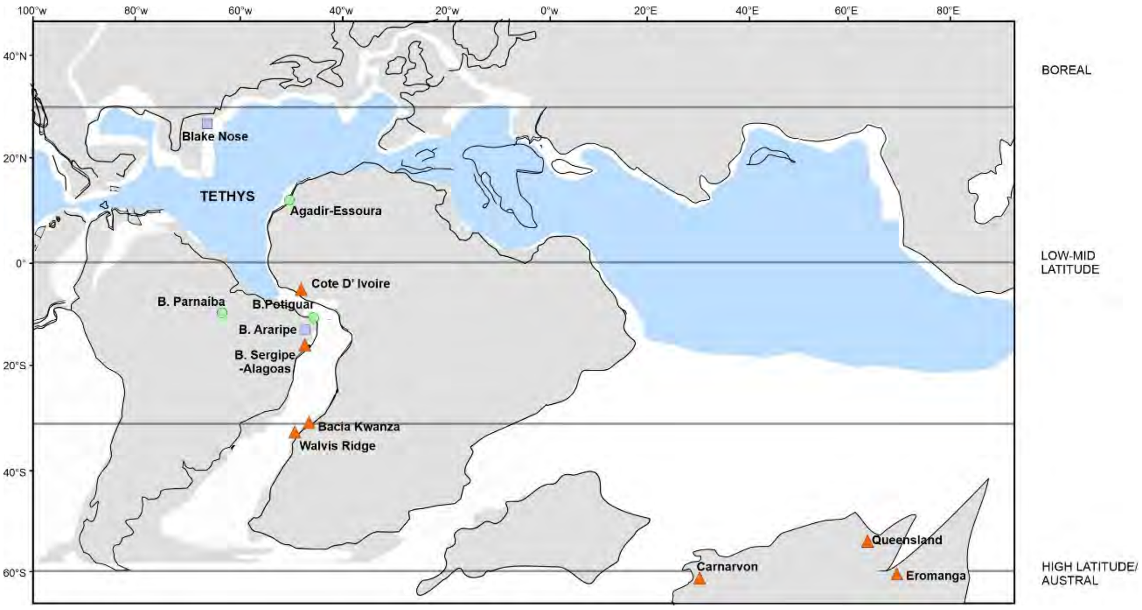


Figura 3 - Reconstrução paleobiogeográfica com as associações de foraminíferos do Aptiano – Albiano (Modificado de http://www.odsn.de).

4. Conclusão

O Aptiano – Albiano é um intervalo importante para a compreensão das variações paleoceanográficas e paleoclimáticas. A assembleia de foraminíferos do Aptiano – Albiano encontrada na Bacia do Araripe é típica de mares epicontinentais, de águas salobras com conexão com o mar aberto. Sua distribuição é condicionada principalmente pela disponibilidade de carbonato de cálcio e oxigênio no ambiente. Entre as bacias do Nordeste do Brasil, as bacias do Araripe e Sergipe Alagoas possuem maior similaridade, com mais de 15 gêneros em comum. A bacia Sergipe/Alagoas além da afinidade com as bacias do oeste da África, possui uma afinidade com bacias do oceano indico, demonstrando também uma afinidade Austral de baixas latitudes. Para a Bacia do Araripe a associação de foraminíferos demostra uma similaridade com as assembleias da América do Norte e Norte da África, caracterizando bioprovíncias Tetianas/transicionais.

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5 CONSIDERAÇÕES FINAIS

Na presente tese foram demostrados os resultados obtidos sobre a paleocologia e bioestratigrafia e paleobiogeografia de microfósseis carbonáticos da Formação Romualdo, Bacia do Araripe.

A seção Santo Antônio, localizada em Santo Antônio, se mostrou a seção mais promissora para o estudo dos micrófósseis carbonáticos. Recuperando a maior riqueza de foraminíferos, ostracodes e nanofósseis calcários. Podendo ser observado duas incursões marinhas que ocorreram em momentos distintos na Formação Romualdo. A primeira no Aptiano superior representada pelo aumento de diversidade da fauna marinha, e uma segunda incursão no Albiano, representada pela ocorrência dos nanofósseis calcários.

Para os ostracodes, foram identificados 21 táxons. Entre eles, 6 gêneros já descritos para a bacia *Pattersoncypris, Damonella, Alicenula, Ilyocypris, Cypridea* e *Theriosynoecum* e 6 gêneros com nova ocorrência *Dicrorygma, Microceratina*, *Mantellina*, *Mongolianella, Paracypris, Perissocytheridea*. Algumas destas espécies tipicamente marinhas.

Para os nanofósseis foram identificados 10 táxon *Biscutum constans*, *Biscutum* sp., *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp., *Retecapsa surirella*, *Thoracosphaera* sp., *Zeughrabdotus noeliae*, *Watznaueria barnesiae*, and *Watznaueria* sp. Com destaque para a ocorrência da espécie *Hayesites albiensis.*

Nas quatro seções estudadas (Santo Antônio, Cedro, Sobradinho e Serra do Mãozinha), foram identificados 33 táxons de foraminíferos bentônicos e 6 táxons foraminíferos planctônicos que se distribuíram de maneira distinta em cada seção. De maneira geral, as espécies representam um ambiente de mar epicontinental refletindo a formação de diferentes subambientes que foram sendo desenvolvidos de forma gradativa durante o estabelecimento do ambiente marinho na Bacia do Araripe.

Com base nos dados levantados, a Bacia do Araripe possui uma associação de foraminíferos com maior similaridade com as assembleias da América do Norte e Norte da África, caracterizando afinidades biogeográficas misturadas sendo reconhecidas bioprovíncias Tetianas/transicionais.

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Upper Aptian–lower Albian of the southern-central Araripe Basin, Brazil: Microbiostratigraphic and paleoecological inferences

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A B S T R A C T

The aim of this study was to produce an integrative analysis of macroinvertebrates (decapods, gastropods, and bivalves) and microfossils collected in the Romualdo Formation, south-central Araripe Basin. Additionally, we provide the first report of calcareous nannofossils, a diverse and unique association of the marine ostracods *Dicrorygma* cf. *minuta*, *Perissocytheridea* spp., *Dicrorygma* (*Orthorygma*?) *dimorpha*, and *Paracypris* sp. and benthic and planktonic foraminifera. The Santo Antonio section contains assemblages of Tethyan origin that indicate an unstable paleoenvironment formed by hypersaline lagoons with two marine ingressions. Planktonic foraminifera assemblages comprised of *Hedbergella aptiana* and *Pseudoguembelitria* sp., suggest that the first marine ingression occurred in the Aptian (possibly late Aptian – planktonic foraminifera biozone *Paraticinella rohri*), while the second occurred during the early Albian (biozone CC8), as indicated by calcareous nannofossils (*Hayesites albiensis*). The fossil assemblages that characterize the Romualdo Formation, provide new biostratigraphic information and point towards the probable Aptian–Albian boundary in the Santo Antônio section.

1. Introduction

Changes in tectonic reconfigurations of the eastern margin and equatorial margin contributed to the genesis of small interior basins in North-eastern Brazil (Assine, 1994, 2007; Matos, 1992). Among these basins, the Araripe Basin stands out for its extension and is known internationally for the presence of Early Cretaceous non-marine and marine fossils in the Romualdo Formation (Maisey, 1991).

For decades, the Romualdo Formation has been the focus of many taxonomic, biostratigraphic, paleoenvironmental and paleogeographic studies, which have aimed to understand the composition of its fossil communities and the Early Cretaceous seaways (Arai et al., 1994; Arai, 2014, 2016; Araripe et al., 2021; Assine et al., 2014, 2016; Beurlen, 1963, 1966; Mabesoone et al., 1999; Prado et al., 2015; Valença et al., 2003). The age of the Romualdo Formation has been assigned to the Aptian–Albian (e.g., Arai et al., 1997; Arai and Assine, 2020; Coimbra et al., 2002; Custódio et al., 2017; Melo et al., 2020; Neumann et al., 2002).

The paleontological research presented here for the Romualdo Formation, corresponded to a detailing of the work started in Araripe et al. (2021). In this study, an integrated analysis of the paleoenvironmental conditions occurred in the Romualdo formation was performed

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revealing, new data on macroinvertebrate fauna and carbonate microfossil assemblages, including benthic and planktonic foraminifera, the first occurrence of calcareous nannofossils and a uniquely diverse suite of marine ostracods. These analyses provide valuable paleoecological, paleogeographic and biostratigraphic insights into the Early Cretaceous paleoenvironmental reconstruction of this region.

2. Geological setting

The Araripe Basin is located between the Brazilian states of Pernambuco, Piauí, and Ceará (Fig. 1). The sedimentary record of the Araripe Basin includes pre-rift, rift, and post-rift I and II sequences that precede and succeed the Gondwana fragmentation (Assine, 2007; Ponte and Ponte Filho, 1996). The Romualdo Formation age is Aptian to Albian, based on palynological and Ostracoda data (Arai et al., 1997; Aureliano et al., 2014; Coimbra et al., 2002; Custódio et al., 2017; Neumann et al., 2002; Pereira et al., 2015), although some authors consider the age of the Romualdo Formation as Aptian (Arai and Assine, 2020; Melo et al., 2020), and others as Albian (e.g. Beurlen, 1964; Coimbra et al., 2002, 2021; Heimhofer et al., 2008; Heimhofer and Hochuli, 2010; Lima, 1978).

In terms of lithology, the Romualdo Formation is composed of nearshore/shallow marine conglomerates and sandstones, marine-influenced dark shales, and bioclastic limestone tempestites that indicate marine ingressions (Custódio et al., 2017). The marine macrofauna fossils include fishes (Maisey, 1991; Silva and Valença, 1968), mollusks (Beurlen, 1963; Pereira et al., 2016; Rodrigues et al., 2020), decapod crustaceans (Maisey and Carvalho, 1995; Prado et al., 2018a, b; Saraiva et al., 2018), and echinoderms (Beurlen, 1966; Manso and Hessel, 2012). Whereas microfossils are represented by ostracods (Antonietto et al., 2012; Arai and Coimbra, 1990; Berthou et al., 1990; Colin and Depèche, 1997; Krömmelbein and Weber, 1971; Silva Teles Jr. and Viana, 1990; Tomé and Lima Filho, 2010; Tomé et al., 2014) and foraminifera (Araripe et al., 2021; Melo et al., 2020), as well as palynomorphs, (dinocysts and palynoforaminifera) (Arai and Coimbra, 1990; Berthou et al., 1994; Do Carmo et al., 2008; Pons et al., 1990, 1996).

One of the most complete outcrops of the Romualdo Formation is found at the Sobradinho section, which is approximately 100-m-thick and is located in the municipality of Jardim, Ceará (Fig. 1.3) (Arai and Assine, 2020; Bom et al., 2021; Custódio et al., 2017; Fürsich et al., 2019). Custódio et al. (2017) defined five lithofacies (FA-1 to FA-5) in Romualdo formation, that reflect a transgressive and regressive cycle in the basin. Furthermore, Melo et al. (2020) described marine microfossil assemblages correlated to the *Microhedbergella miniglobularis* Zone, which is a global upper Aptian biozone.

The Santo Antônio outcrop is located in Carrancudo Creek in the municipality of Exu (7°30′06″S, ~~S~~/39°32′36″W), Pernambuco State, at a distance of 50 km from the Sobradinho section (Fig. 1.3). It has a predominantly shale lithology, which is sometimes accompanied by the presence of calcareous concretions containing fossil fish (*Vinctifer comptoni*, *Calamopleurus* sp., *Tharrias araripis*, *Branerion* sp. and *Rhacolepsis buccalis*) interspersed by siltstones and thin sandstones with invertebrates, as well as bioclastic sandstones (Fig. 2). Compared to the Sobradinho section (Fig. 1.3), the Santo Antônio section is closer to the top of the Romualdo Formation.

3. Materials and methods

The samples were collected of approximately 20 cm. Its selected based on lithological variation composition throughout the section. A total of 22 samples were analyzed from the Santo Antônio section,

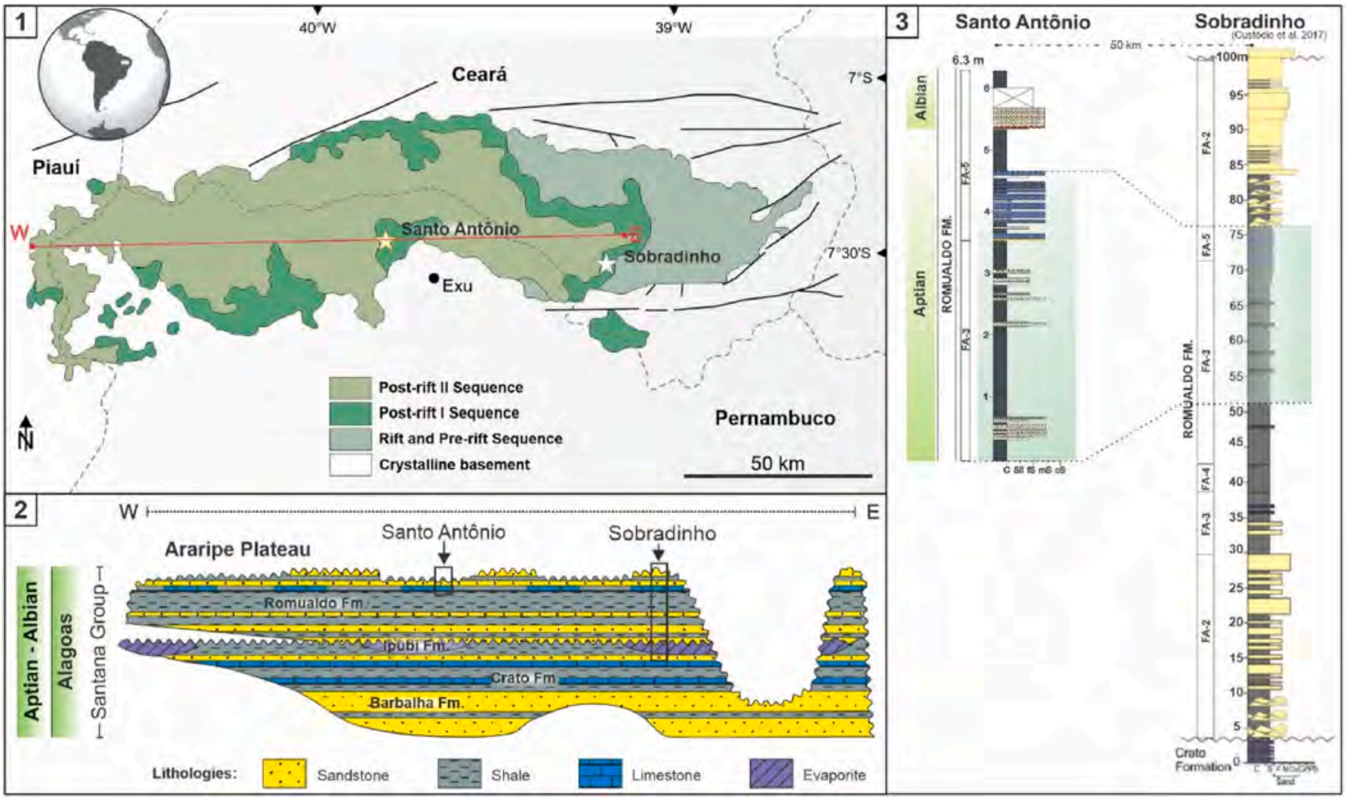

Fig. 1. (1) Map of the Araripe Basin showing the position of the studied section and the localities of Santo Antônio (Exu, PE) and Sobradinho (Jardim, CE) (stars). (2) Santo Antonio section in the lithostratigraphic column of the post-rift I sequence marked by the rectangle and its chronostratigraphy (modified Assine, 2007; Barreto et al., 2022). Lithologies: sandstone, shale, limestone, evaporite; (3) Correlations with the facies association (FA-3 and FA-5) of the Sobradinho outcrop (Custódio et al., 2017) are emphasized (green).

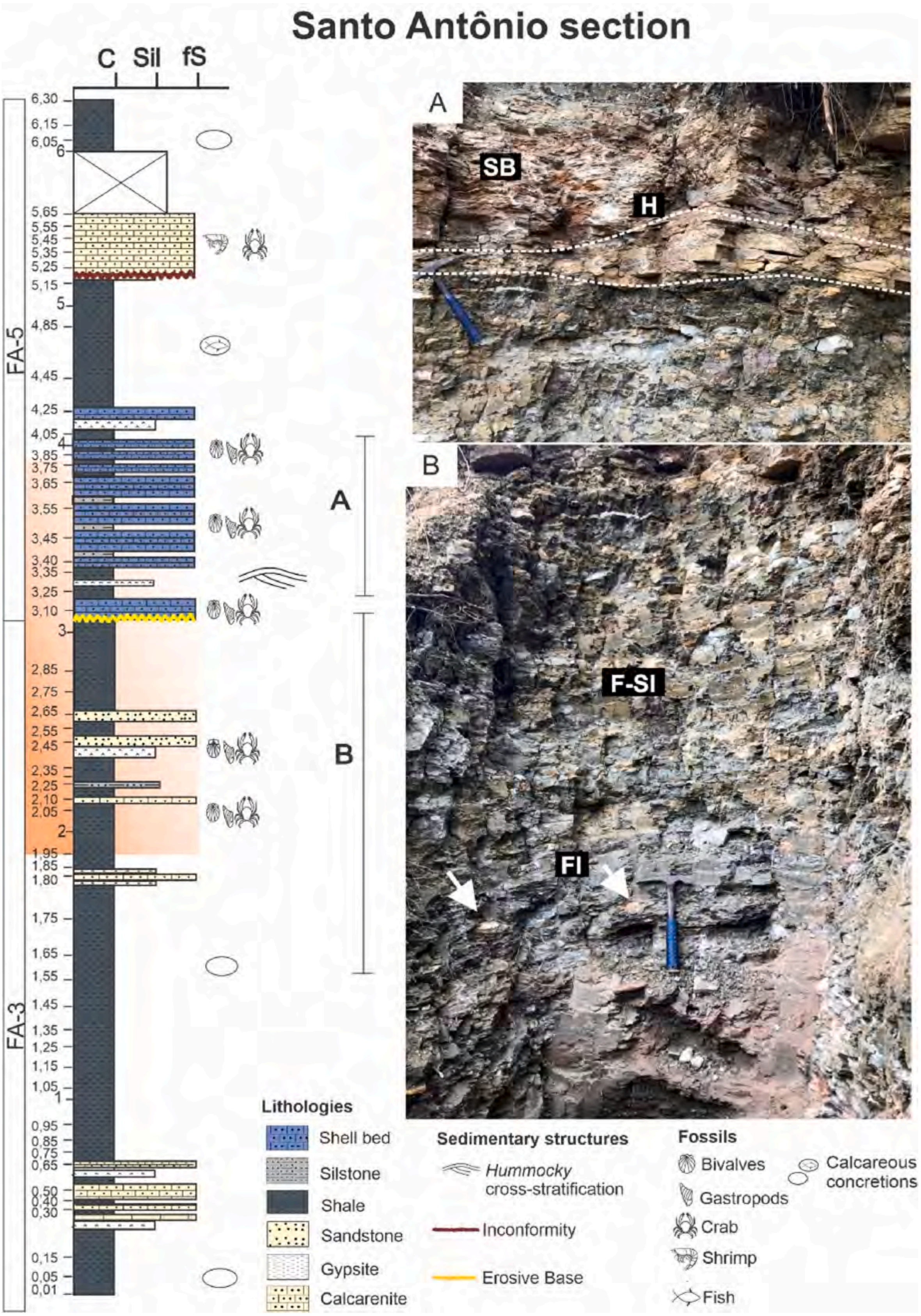

Fig. 2. Lithostratigraphy of the Santo Antônio outcrop with the collected samples (meters). The interval studied by Araripe et al. (2021) is marked by the orange rectangle. The white arrows in B indicates the position of calcareous concretions. Abbreviations: Fl: shale, F: siltstone, Sl: calciferous sandstone, SB: shell bed.H: hummocky cross-stratification; FA-3: inner shelf; FA-5: storm-dominated marine. C: clay Sil: silt fS: fine sand.

distributed across 6.3 m of outcrop (Fig. 2). All samples and slides from this study were placed in the collection of the Laboratório de Paleontologia, in the Departamento de Geologia of Centro de Tecnologia e Geociências, at the Universidade Federal de Pernambuco (PALEOLAB-DGEO-CTG-UFPE).

Abundance, diversity and taphonomic data were only obtained for macroinvertebrate specimens that were larger than 2 mm in width (Kidwell and Holland, 1991). To calculate abundance values, we considered articulated bivalves and half the number of disarticulated valves, whole gastropod shells and their fragments with more than 70% of the shell preserved, articulated crab carapaces, and whole shrimp. Approximately 150 specimens were counted per layer, with this number varying according to bioclast availability (Kidwell et al., 2001). To support the paleoecological and paleoenvironmental reconstruction of macroinvertebrate assemblages, the degree of specimen transport and reworking was characterized according to sorting, packaging, articulation, abrasion, bioerosion, incrustation, and fragmentation in each layer.

Foraminifera and Ostracoda analyses were prepared by disaggregation in 28% hydrogen peroxide solution. The samples were then washed with 250, 125, and 63 μm sieves and dried at 60 °C. After sieving, the foraminifera were analyzed under a stereomicroscope (SteREO Discovery V8, ZEISS, Germany). At least 300 foraminifera and ostracod specimens were selected from each sample for taxonomic identification. Foraminifera were identified according to Loeblich and Tappan (1988) and Ellis and Messina (1940–2006) and the suprageneric systematics for ostracods followed the method adopted by Liebau (2005). Following identification, the ostracod and foraminifera specimens were photographed using a scanning electron microscope JEOL-JSM-640 at the Laboratório de Dispositivos e Nanoestruturas at the Universidade Federal de Pernambuco.

For the study of calcareous nannofossils, the samples were prepared using four methodologies: decantation (Antunes, 1997), smear slides (Bown, 1998), short centrifugation made at 15 s/1000 rpm (Bown and Young, 1998), and thin sections (Erba et al., 2010), totaling 76 prepared slides. After processing, the fossil content of each slide was investigated and described using a ZEISS Axion Vision Imager A.2 (objective 100×) polarized light microscope with an attached AxioCam MRc camera; the photomicrographs were produced using ZEN 3.4 Blue edition (ZEISS, Germany). Slides made via these four methods were qualitatively analyzed with respect to the presence of calcareous nannofossils. However, quantitative analyses could only be performed on the decantated slide (Antunes, 1997).

The same intervals sampled for ostracods/foraminifera, calcareous nannofossils, and invertebrates, were selected for the palynological analysis and prepared. The materials were treated according to the standard palynological protocol described by Uesugui (1979). Four palynological slides were made for each sampled level, totaling 176 slides. The slides were examined using a Zeiss PrimoStar and Axion Vision Imager A.2 polarized light microscope (100x) with an attached camera (AxioCam MRc); Axion Vision Release v. 4.8 was used for photomicrographs (ZEISS, Germany). After analyzing 176 slides, it was determined that all the samples lacked palynomorphs.

The salinity variation in the Romualdo Formation has always been the subject of discussion by several authors (Araripe et al., 2021; Bom et al., 2021). In this study, the organisms showed a good response to salinity variation therefore they are used as tools for paleoenvironmental interpretations. We used the paleoecological preferences of organisms, regarding environmental salinity levels, as the parameters for the cluster analysis. Marine organisms were assigned the number 1, and those adapted to different salinities were assigned the number 2. Ward's method was based on a cut-off at a Euclidian distance of 14. Ward's method started with two clusters (number 1 and number 2), each containing a single group of organisms (marine and adapted to different salinities). These two clusters are combined to make one cluster containing both groups. At each step, the process makes a new cluster that minimizes variance (Szmrecsanyi, 2012). Species diversity, relative abundances and taphonomic features were also analyzed in order to interpret paleoenvironmental changes across the Santo Antônio section. Statistical analyses were conducted using PAST v. 4.04 (Hammer et al., 2001).

The bioestratigraphy data follow Huber and Leckie (2011) and Bartenstein and Bolli (1986) for foraminifera, Schaller (1969) for ostracod and Roth (1978) and Sissingh (1977) for calcareous nannofossils.

4. Results

4.1. Sedimentary facies

The Santo Antônio section (6.5 m) presents from its base to 3.10 m, the predominance of medium-gray shales and argillites with non-fossiliferous carbonate concretions interbedded with yellowish calcarenites and calciferous sandstone both with foraminifera and ostracod. These interbedded layers are characterized by decametric to centimeters thickness. Some of these layers (2.1 and 2.45 m) presents invertebrates fossils (bivalves, gastropods, shrimps, and crabs). These layers present cross-stratification and cross-bedded and rippled in sandstones. Centimeters layers of gypsum are observed. According the facies association codes applied by Custódio et al. (2017) to the Romualdo Formation, this interval could be related to the inner shelf facies association (FA-3).

In the interval 3.10–4.25 m is characterized by an erosive base at 3.10 m. Yellowish calcarenites with hummocky cross stratification interbedded with centimeter layers of gray argillite. Calcarenites composed of larger concentration of mollusks, gastropod and crustacean fossils (shell bed) also presents foraminifera and ostracoda. An erosive base at 3.1 m is observed.

In the interval 4.25–6.30 m (top) is characterized by medium gray shales with carbonate concretions with fishes and yellowish calcarenite with ostracoda, foraminifera, calcareous nannofossils, rare crustaceans. An inconformity at 5.25 m is observed. Gray shales with non-fossiliferous carbonate concretions are present. The interval 5.65 m–6m wasn't colleted. According the facies association codes applied by Custódio et al. (2017) to the Romualdo Formation, both intervals could be related to the storm-dominated marine facies association (FA-5).

4.2. Fauna and flora characterization

The macroinvertebrate fossils identify along the sampled section corresponds mainly to bivalves and gastropods, followed by decapods. Nine taxa are identified, bivalves of the families Corbulidae (*Corbula* sp.), Mytilidae (*Brachidontes araripensis*) and Lucinidae, which aren't identified at the species level. The identified gastropods are of the families Trochidae (*Calliostoma* sp.), Acteonidae (*Acteon* sp.), Cerithiidae (*Cerithium* sp.), Naticidae (*Natica*? sp., *Tylostoma ranchariensis*) and Cassiopidae. Crustaceans are represented by the brachyuran crabs of the families Orithopsidae (*Exucarcinus gonzagai*) and Eogeryonidae? (*Romualdocarcinus salesi*), and the dendrobranchiata shrimp of the family Sergestidae (*Paleomattea deliciosa*) (Fig. 3). All of the above organisms are marine, with the exception of the eurihalines lucinids, *B. araripensis* and *Corbula* sp.

Microfossils of the Santo Antônio section present a more diverse association of foraminifera and ostracods than previously reported for the Araripe Basin (Antonietto et al., 2012; Arai and Coimbra, 1990; Araripe et al., 2021; Berthou et al., 1990; Colin and Depèche, 1997; Krömmelbein and Weber, 1971; Melo et al., 2020; Silva Teles Jr. and Viana, 1990; Tomé and Lima Filho, 2010; Tomé et al., 2014).

This study recovers a total of 6694 foraminiferal specimens and 8370 ostracods. Both benthic and planktonic foraminiferal taxa are identified; the 19 benthic foraminifera taxa includs *Glomospira* sp. *Quinqueloculina* sp.1, *Quinqueloculina* sp. 2, *Miliolinella* sp., *Agathammina pusilla*, *Spirosigmoilina rajke*, *Sigmoilinita tenuis*, *Spirosigmoilina* sp., *Spirillina minima*, *Spirillina* sp., *Pseudosaracenaria*? sp., *Palmula saggittaria*,

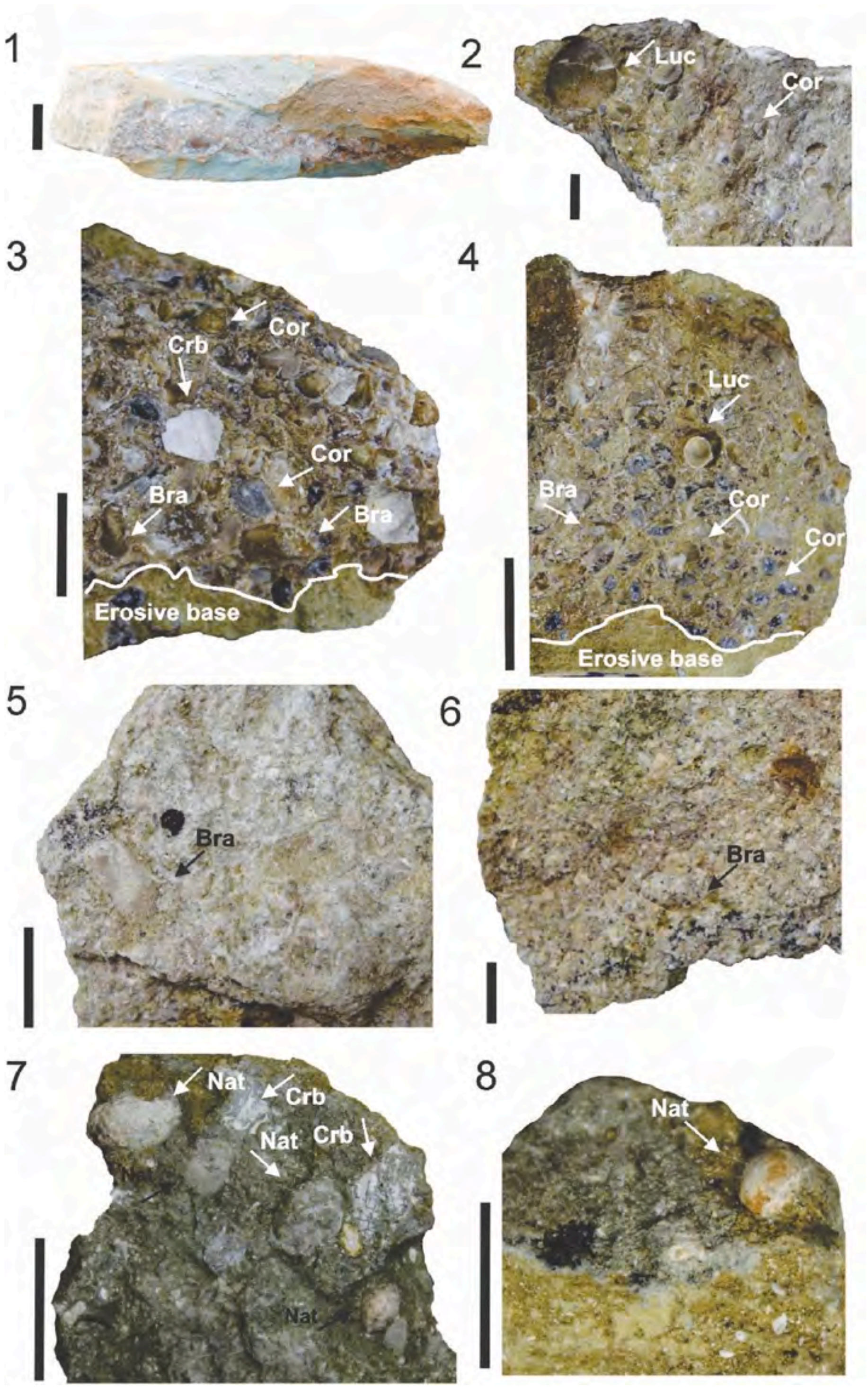

Fig. 3. Macroinvertebrate assemblages from the Romualdo Formation at Santo Antônio section: (1–4) Assemblage A, interval from 2.65 to 3.65 m (DGEO-CTG-UFPE-8876-8878); Erosive base at 3.1 m; (5–8) Assemblage C, (5–6) interval from 3.75 to 4.5 m (DGEO-CTG-UFPE-8873), (7–8) interval from 2.25 to 2.65 m (DGEO-CTG-UFPE-8870). Note in (1) the hummocky cross-stratification. Arrows indicate the taxa present. Abbreviations: Nat, Naticidae; Crb, crabs; Cor., Corbulidae; Luc, Lucinidae; Bra, *Brachidontes araripensis*. Section view: 1, 3–4; Plan view: 2, 5–8. Scale bar: 3 mm.

Astacolus gratus, *Astacolus howchini*, *Ellipsoidella*? sp., *Nodosarella* sp., *Pseudonodosaria* sp., *Pleurostomella* sp. and *Conorboides minutissima*. Six planktonic foraminiferal taxa also are identified: globose or pseudoglobose forms are attributed to *Pseudoguembelitria* sp., low trochospiral coiled forms are assigned to *Hedbergella* aff. *daminiae, Hedbergella aptiana* and *Hedbergella* sp., and hedbergelliforms with elongated final chambers are identified as *Liliputianella?* sp. (Fig. 4).

Fourteen ostracod taxa are identified, including five mixohaline species, namely, *Pattersoncypris salitrensis*, *Pattersoncypris angulata*, *Damonella grandiensis*, *Mantelliana* sp., *Alicenula leguminella*, and *Theriosynoecum quadrinodosum*, and seven typically marine taxa — *Dicrorygma* cf. *minuta*, *Microceratina* sp., *Dicrorygma* (*Orthorygma*?) *dimorpha*, *Paracypris* sp. Three more species are found that belong to the genus *Perissocytherideа* Stephenson (1938) (Fig. 5).

The occurrence of calcareous nannofossils is notable for four samples: 6.30, 5.55, 5.35, and 5.25 m. The species observed are *Biscutum constans*, *Biscutum* sp., *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp., *Retecapsa surirella*, *Thoracosphaera* sp., *Zeughrabdotus noeliae*, *Watznaueria barnesiae*, and *Watznaueria* sp. (Fig. 6).

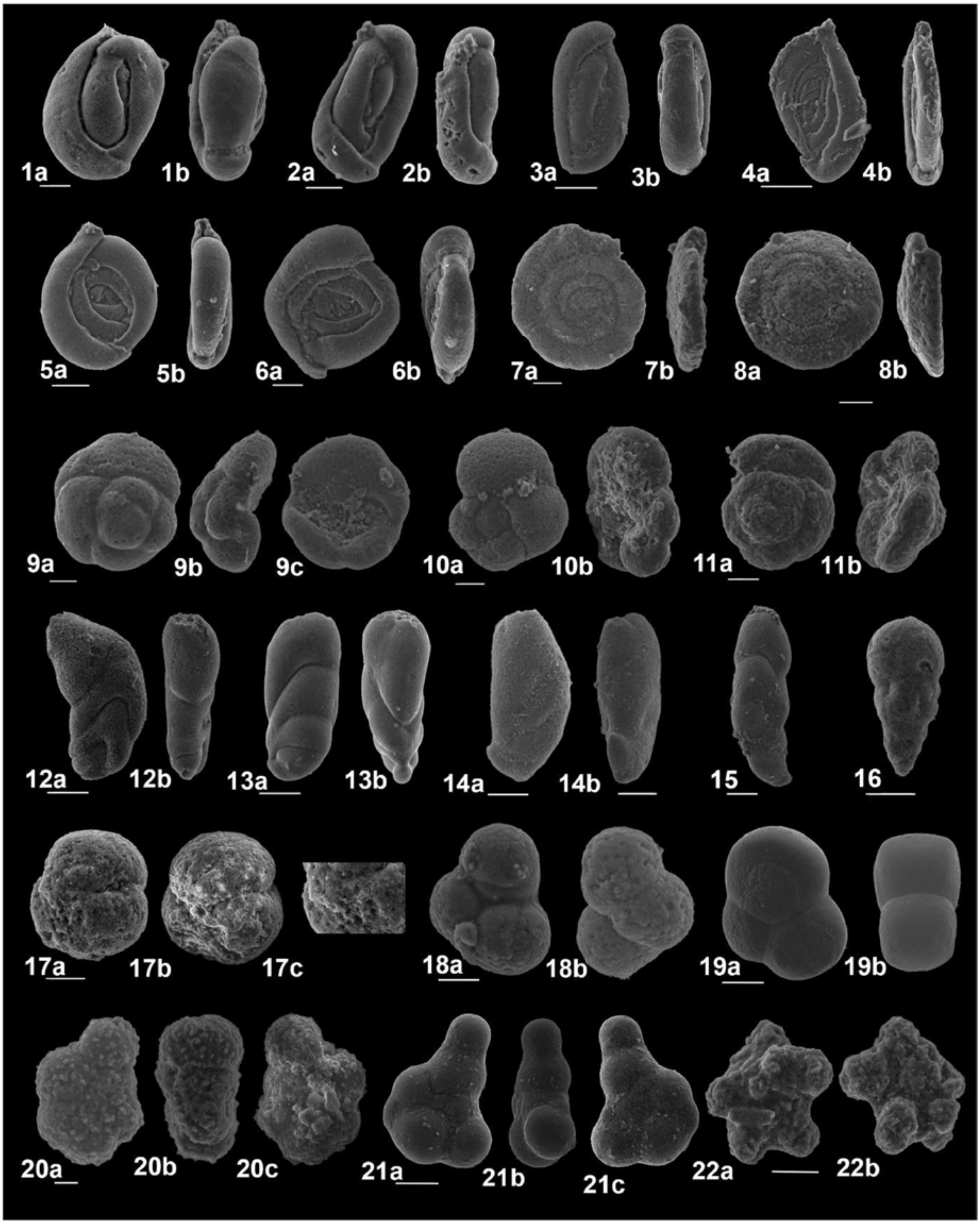

Fig. 4. **1 (a–b)** *Quinqueloculina* sp.1 at 3.1 m (N°. DGEO-CTG-UFPE – 1480); **2 (a–b)** *Quinqueloculina* sp. 2 at 3.55 m (N°. DGEO-CTG-UFPE – 1481); **3 (a–b)** *Miliolinella* sp. at 5.5 m (N°. DGEO-CTG-UFPE – 1482); **4 (a–b)** *Sigmoilinita tenuis* at 5.35 m (N°. DGEO-CTG-UFPE – 1483); **5 (a–b)** *Spirosigmoilina* sp.1 at 5.45 m (N°. DGEO-CTG-UFPE – 1484); **6 (a–b)** *Spirosigmoilina rajke* at 5.45 m (N°. DGEO-CTG-UFPE – 1485); **7 (a–b)** *Spirillina minima* at 5.55 m (N°. DGEO-CTG-UFPE – 1478); **8 (a–b)** *Spirillina* sp. at 5.65 m (N°. DGEO-CTG-UFPE – 1479); **9 (a–c)** *Conorboides minutissima* at 5.45 m (N°. DGEO-CTG-UFPE – 1497); **10 (a–b)** *Conorboides minutissima* at 5.45 m (N°. DGEO-CTG-UFPE – 1496); **11 (a–b)** *Conorboides minutissima* at 4.05 m (N°. DGEO-CTG-UFPE – 1495); **12 (a–b)** *Palmula saggittaria* at 0.3 m (N°. DGEO-CTG-UFPE – 1490); **13 (a–b)** *Astacolus gratus* at 3.55 m (N°. DGEO-CTG-UFPE – 1491); **14 (a–b)** *Astacolus howchini* at 5.65 m (N°. DGEO-CTG-UFPE – 1489); **(15)** *Pseudosaracenaria*? sp at 3.55 m Figura 6 (N°. DG-CTG-UFPE – 1488); **(16)** *Pseudonodosaria* sp. at 3.55 m (N°. DGEO-CTG-UFPE – 1487); **17 (a–c)** *Pseudoguembelitria* sp. at 4.05 m (N°. DGEO-CTG-UFPE – 1501); **18 (a–b)** *Hedbergella* sp. at 3.45 m (N°. DGEO-CTG-UFPE – 1500); **19 (a–b)** Gen indet. at 2.1 m (N°. DGEO-CTG-UFPE – 1503); **20 (a–c)** *Hedbergella aptiana* at 5.45 m (N°. DGEO-CTG-UFPE – 1498); **21 (a–c)** *Hedbergella* aff. *daminiae* at 1.8 m (N°. DGEO-CTG-UFPE – 1499); and **22 (a–b)** *Liliputianella?* sp. at 4.05 m (N°. DGEO-CTG-UFPE – 1502). The bar equals 50 μm.

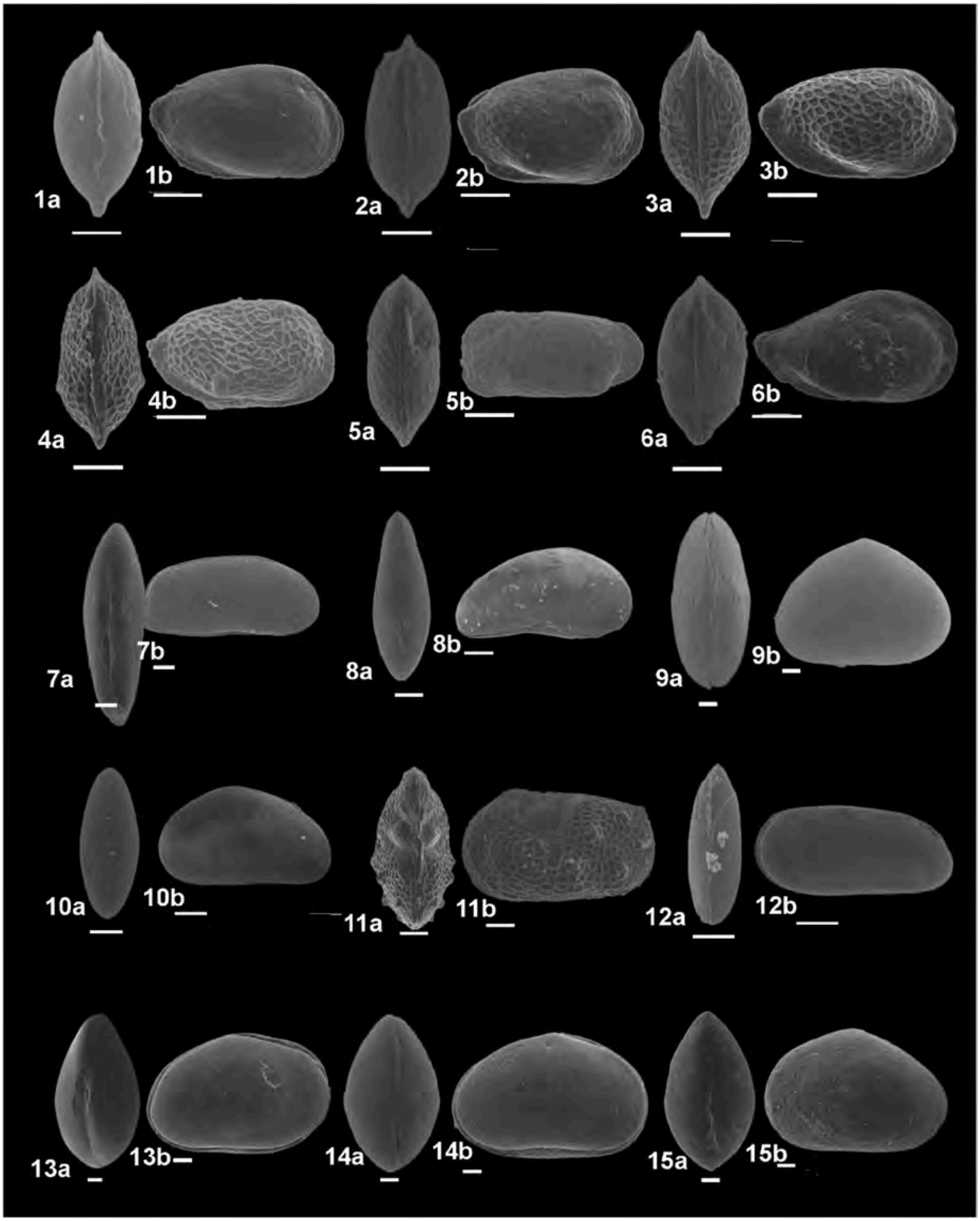

Fig. 5. **1(a,b)** *Dicrorygma* cf. *minuta* at 3.1 m (N°. DGEO-CTG-UFPE-1522); **2(a,b)** *Perissocytheridea* sp. 2 at 0,3 m (N° DGEO-CTG-UFPE-1520); **3(a,b)** *Perissocytheridea* sp. 3 at 4.05 m (N° DGEO-CTG-UFPE-1521); **4(a,b)** *Perissocytheridea* sp. 1 at 3.1 m (N° DGEO-CTG-UFPE-1519); **5(a,b)** *Microceratina* sp. at 3.1 m (N° DGEO-CTG-UFPE-1525); **6(a,b)** *Dicrorygma* (*Orthorygma*?) *dimorpha* at 5.65 m (N° DGEO-CTG-UFPE-1524); **7(a,b)** *Mongolianella* sp. at 3.1 m (N° DGEO-CTG-UFPE-1511); **8(a,b)** *Paracypris* sp. at 2.65 m (N° DGEO-CTG-UFPE-1517); **9(a,b)** *Mantellina* sp. at 5.45 m (N° DGEO-CTG-UFPE-1516); **10(a,b)** *Damonella grandiensis* at 0.3 m (N° DGEO-CTG-UFPE-1513); **11(a,b)** *Theriosynoecum quadrinodosum* at 3.1 m (N° DGEO-CTG-UFPE-1528); **12(a,b)** *Alicenula leguminella* at 0.3 m (N° DGEO-CTG-UFPE-1527); **13(a,b)** *Pattersoncypris salitrensis* at 2.65 m (N° DGEO-CTG-UFPE-1505); **14(a,b)** *Pattersoncypris angulata* at 2.65 m (N° DGEO-CTG-UFPE-1507); **15(a,b)** *Pattersoncypris micropapillosa* at 3.1 m (N° DGEO-CTG-UFPE-1510). The scale bar equals 100 μm.

4.3. Biostratigraphy

4.3.1. Calcareous nannofossil

Regarding calcareous nannofossils, fragments of *Thoracosphaera* sp. are identified in the 5.25 m and 5.35 m samples, and *Biscutum constans* and fragments of *Thoracosphaera* sp. are identified in the 6.30 m sample. However, 5.55 m is the most diverse and fossiliferous sample, containing *B. constans*, *Biscutum* sp., *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp, *Retecapsa surirella*, *Thoracosphaera* sp, *Zeughrabdotus noeliae*, *Watznaueria barnesiae* and *Watznaueria* sp. It is possible to identify the occurrence

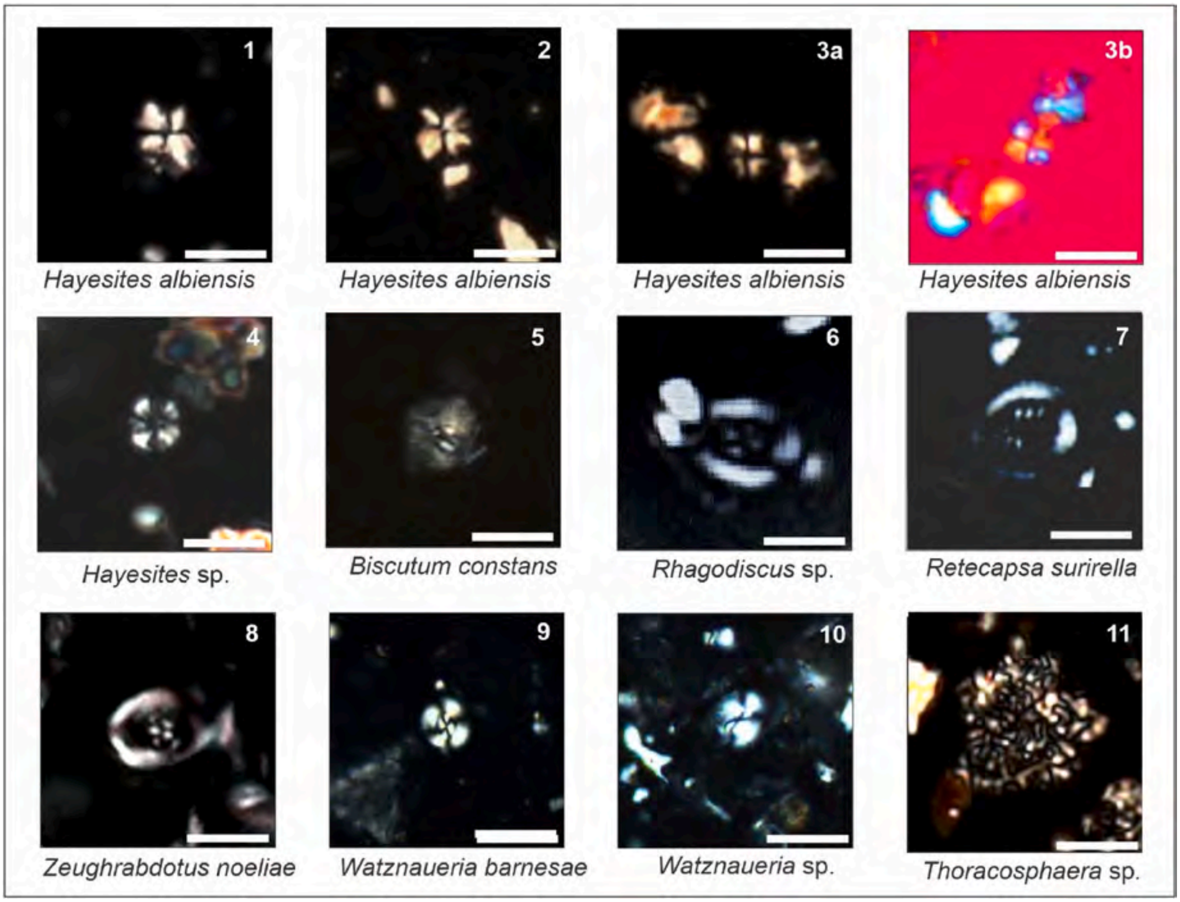

Fig. 6. **(1**–**3)** *Hayesites albiensis* at 5.55 m; **(4)** *Hayesites* sp. at 5.55 m; **(5)** *Biscutum constans* at 5.55 m; **(6)** *Rhagodiscus* sp. at 5.55 m; **(7)** *Retecapsa surirella* at 5.55 m; **(8)** *Zeughrabdotus noeliae* at 5.55 m; **(9)** *Watznaueria barnesiae* at 5.55 m; **(10)** *Watznaueria* sp. at 5.55 m; **(11)** *Thoracosphaera* sp. at 5.55 m; (N°. DGEO-CTG-UFPE – 1529). The scale bar equals 5 μm.

of *Hayesites albiensis*, which is morphologically characterized by six to eight segments. Thus, it is possible to assign the 5.55 m sample to the Albian age (equivalent to biozone CC8) (Fig. 7).

4.3.2. Planktonic foraminifera

Aptian foraminifera species are identified (*Hedbergella* sp., *Hedbergella* aff. *daminiae, Hedbergella aptiana, Pseudoguembelitria* sp. and *Liliputianella* sp.) at the intervals 2.25–5.45 m. The genus *Pseudoguembetria* has stratigraphy range restrict to upper Aptian (Huber and Leckie, 2011). Its first occurrence in the section marks the base of the *Paraticinella rohri* biozone and the occurrence of *H. aptiana* associated with *Pseudoguembelitria* sp., at 5.45 m, marks the upper Aptian *P. rohri* biozone (Kennedy et al., 2014) (Fig. 7).

4.3.3. Ostracoda

Damonella grandiensis is recorded throughout the section (0.3–6.3 m), characterizing the *Damonella grandiensis* biozone (Nascimento et al., 2017), related to the Aptian–Albian (Alagoas Local Stage). Notably, the presence of marine species such as *Dicrorygma* cf. *minuta*, *Paracypris* sp., *Microceratina* sp., *Dicrorygma (Orthorygma) dimorpha*, and species assigned to *Perissocytheridea* (*Perissocytheridea* sp 1. *Perissocytheridea* sp. 2, *Perissocytheridea* sp.3) provide a new record of marine ostracods for the *Damonella grandiensis* biozone. This biozone is characterized by the appearance of *D. grandiensis*, which is synonymous with Ostracode 207 (*in* Brito et al., 1984), and is an index fossil for the late Aptian–early Albian (Alagoas local stage) (Brito et al., 1984) (Fig. 7).

4.4 Fossil Assemblages The Cluster analysis reveals three assemblages (denoted as A, B, and C) at the Santo Antônio section (Fig. 8). Assemblage A occurs from 3.1 to 3.65 m, assemblage B from 5.25 to 5.65 m, and assemblage C is distributed throughout the section at four intervals: (1) 0–0.3 m, (2) 2.25–2.65 m, (3) 3.75–4.5 m, and (4) 6.3 m. The intervals from 1.8 to 2.1 m and 4.85–5.15 m lack macro- and microfossils. Variations in the diversity and abundance of macroinvertebrate and calcareous microfossils are clearly observed, indicating gradual changes in community composition at certain levels of the section.

4.3.4. Assemblage A

Assemblage A (3.1–3.65 m) occurs in tabular layers of calcareous sandstone/siltstone with hummocky cross-stratification, representing the interval with the greatest faunal richness, including invertebrates, foraminifera and ostracods. This assemblage has the greatest diversity of marine invertebrate taxa, including the crab species *Exucarcinus gonzagai* and *Romualdocarcinus salesi* and the gastropods *Natica*? sp., *Calliostoma* sp., Cassiopidae, *Acteon* sp. and *Cerithium* sp. The latter two species are observed to have remarkably reduced sizes. On the other hand, the abundance of mixohaline species is remarkably higher, characterized by the bivalves *Brachidontes araripensis*, *Corbula* sp. and lucinids. Bivalves represent more than half of the bioclasts, and are mostly intact, articulated, and have closed valves. Gastropods are less represented in the samples but are still more frequent than crabs. Though fragmented bioclasts are present, they had lower abundances and are larger in size. Unbroken specimens are well-preserved with little abrasion. The assemblage is poorly sorted and bioclast-supported, forming shell beds. Shell beds shows a more complex internal organization, with randomly distributed bioclasts, often nested, in addition to exhibiting an erosive base (Fig. 3 1–4).

Ostracods and foraminifera are abundant in assemblage A (mean

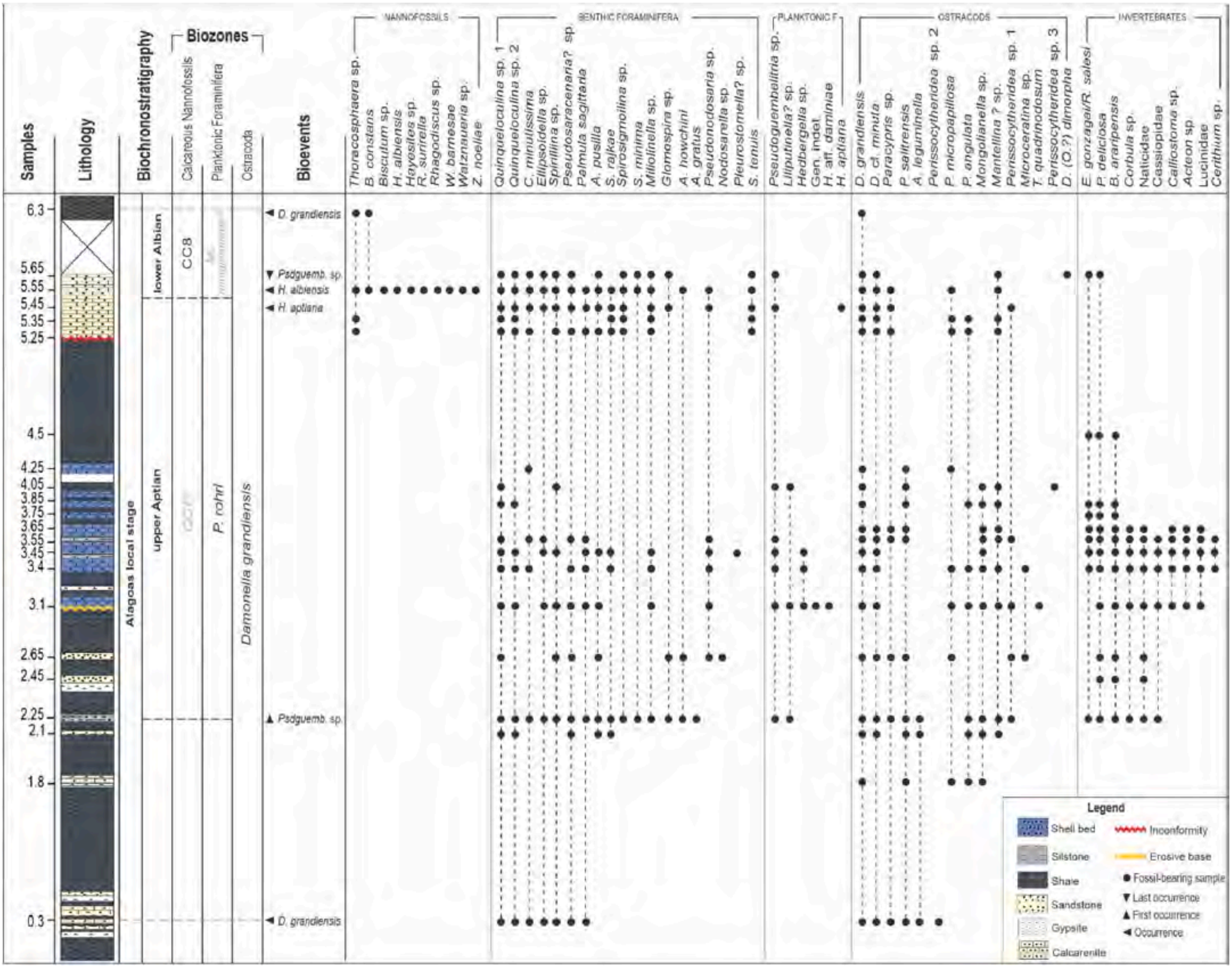

Fig. 7. Biochronostratigraphy based on calcareous nannofossils and planktonic foraminifera of the upper Aptian–Albian interval from the Santo Antônio section, Romualdo Formation, Araripe Basin and Stratigraphic distribution of macroinvertebrates, ostracods, foraminifera, and calcareous nannofossils along the Santo Antonio section.

average: 350 specimens from each group per sample). The diversity of benthic foraminifera is 8–10 taxa per sample. In this assemblage, foraminifera with porcelaneous tests predominated, while there are few calcareous hyaline specimens. Among the porcelaneous foraminifera, the genus *Quinqueloculina* is dominant, although other species with calcareous hyaline tests also occurr, including *Spirillina* sp., *Pseudosaracenaria*? Sp., *Pseudonodosaria* sp., and *Conorboides minutissima*, which are the most representative. This assemblage also includs the greatest abundance of planktonic species recorded in the entire section, such as *Pseudoguembelitria* sp., *Hedbergella* sp., *Hedbergella* aff. *daminiae*, and *Liliputianella*? sp. With respect to ostracods, the assemblage has similar abundance values for mixohaline and marine species, where *Damonella grandiensis* and *Dicrorygma* cf. *diminuta* are the dominant species. In terms of diversity, there is a predominance of mixohaline species, but at low abundance.

4.3.5. Assemblage B

Assemblage B (5.25m–5.65 m) occurs in calcareous sandstones and is marked by an local inconformity surface. It contains microfossils (foraminifera, ostracods, and calcareous nannofossils) and there is a near-complete absence of macroinvertebrates, with the exception of two marine decapod species: *Paleomattea deliciosa* and *Exucarcinus gonzagai*. The average abundance of foraminifera for this interval is 650 specimens per sample, with a higher diversity of benthic foraminifera (~15 taxa per sample). A great abundance and diversification of hyaline foraminifera is recorded in this benthic assemblage, including *Conorboides minutissima*, *Spirillina* sp.*i* and *Spirillina minima*. Porcelaneous forams are distributed among *Quinqueloculina* spp., *Spirosigmoilina rajke* and *Sigmoilinita tenuis.*

In assemblage B, very low abundances of planktonic foraminifera are recorded, including *Pseudoguembelitria* sp. and *Hedbergella aptiana*. The abundance of ostracods in this assemblage is 700 specimens, with a diversity of seven taxa per sample. Similar to assemblage A, this assemblage is mainly composed of the species *Dicrorygma.* cf. *minuta* and *Damonella grandiensis*, however there is a greater diversity of marine species. In addition to the dominance of *Dicrorygma* cf. *minuta*, there are other typically marine ostracods such as *Dicrorygma (Orthorygma?) dimorpha*, *Paracypris* sp. and *Perissocytherideа* spp.

The greatest diversity and abundance of calcareous nannofossils is recognized and recovered from this assemblage, especially at 5.55 m, with the occurrence of the species *Biscutum constans*, *Biscutum* sp., *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp., *Retecapsa surirella*, *Thoracosphaera* sp., *Zeughrabdotus noeliae*, *Watznaueria barnesiae*, and *Watznaueria* sp.

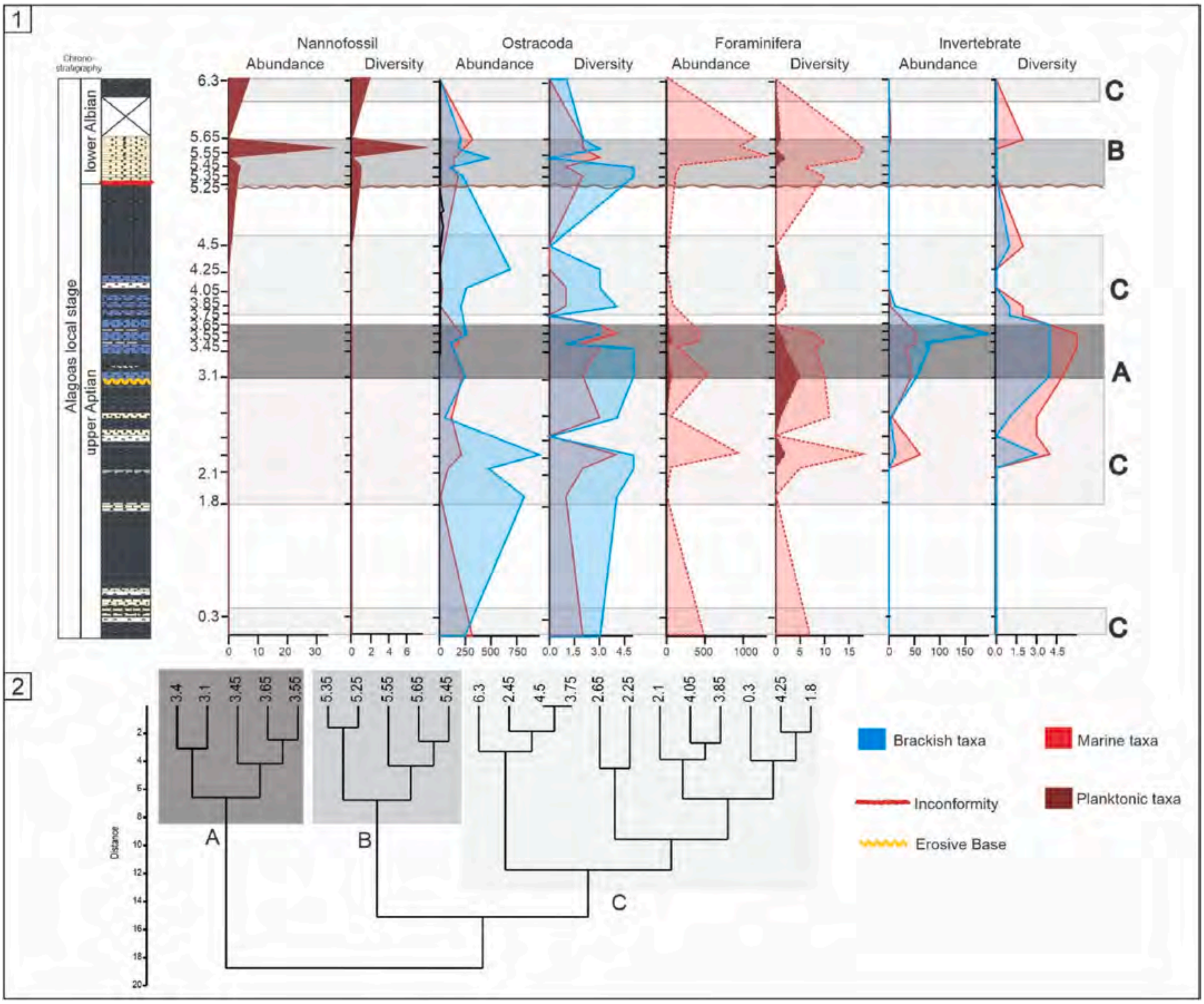

Fig. 8. (1) Stratigraphic distribution of assemblages based on the abundance and diversity of invertebrates, foraminifera, ostracods, and calcareous nannofossil taxa along the Santo Antônio section (A: Marine incursion I, B: Marine incursion II and C: Hypersaline lagoon); (2) Clustering based on marine and mixohaline species.

4.3.6. Assemblage C

Assemblage C is distributed across four intervals, occurs in shales interspersed with fine sandstone/siltstone and is characterized by a low diversity of invertebrates and microfossils. Marine invertebrates are only represented by the crabs *Exucarcinus gonzagai* and *Romualdocarcinus salesi*, as well as cassiopid and naticid gastropods (*Tylostoma ranchariensis* and *Natica*? sp.), where the latter is also smaller in size. The eurihaline fauna is characterized by bivalve corbulids and *Brachidontes araripensis*. The invertebrates are found preserved at distinct intervals: 2.25–2.65 m, where marine taxa are abundant; and 3.75–4.5 m, with a greater number of eurihaline specimens (Fig. 8 5–8). Bivalvia are more abundant, followed by crabs and gastropods, respectively. The majority of fragmented bioclasts (unidentified) are found in silty/sandy sediments. The best preservation is seen in shale. The bivalves are found predominantly disarticulated. Between 3.75 and 4.5 m, fragmented shells form amalgamated and thickened layers, with intact *Brachidontes araripensis* valves on top. The gastropods are well-preserved, intact, and slightly abraded with all whorls present, however a few specimens present apertures, making generic designation difficult. The crabs are disarticulated. The assemblage is weakly packed and poorly sorted, with fossils concordant to the bedding plane without a preferential orientation.

As for foraminifera, porcelaneous species dominate all intervals of Assemblage C. The lowermost interval (0–0.3 m) is composed of the porcelaneous genus *Quinqueloculina*, and the hyaline genus *Conorboides*. At 2.1 and 2.25 m, *Quinqueloculina* and *Miliollinela* sp. are abundant, as well as the hyaline species, *Spirillina* sp. and *Spirillina minima*. The interval from 4.05 to 4.5 m shows low fossil abundances with the dominance of *Quinqueloculina*.

With respect to ostracods, assemblage C has a greater abundance and diversity of mixohaline species, but with variations in the composition of the fauna at the three recorded intervals. The interval 0–0.3 m is composed of the species *Damonella grandiensis* and the marine species *Dicrorygma* cf. *minuta*. At 1.8–2.25 m and 3.85–4.5 m mixohaline species are dominant with *Damonella grandiensis*, followed by *Pattersoncypris salitrensis*, and *Pattersoncypris angulata*. In addition, there are rare occurrences of the calcareous nannofossil species *Biscutum constans* and the calcareous dinoflagellate *Thoracosphaera* sp. At the top of the section, the sample at 6.3 m also lacks foraminifera.

5. Discussion

Correlating the interpretations of the Santo Antonio section with those of the sections of the eastern border of the Araripe Basin (Serra do Mãozinha and Sobradinho) studied by several authors (Custódio et al., 2017; Fürsich et al., 2019; Goldberg et al., 2019; Kroth et al., 2021; Melo et al., 2020), this section is inserted in the FA-3 and FA-5 facies in the highstand systems tract (Fig. 1.3). Probably due to the location of the section (south-central of the basin), the detailed scale of work and the paleoecological application of macro- and microfossils used in the Santo Antonio section it is possible to identify sea level oscillations within the transgressive-regressive cycle at the Aptian-Albian interval. Correlating with the Sobradinho Section (Custódio et al., 2017), which represents a continuous section of Romualdo Formation (100 m), from Crato to Exu formations, the sucession of inner shelf to storm dominated facies association (FA-3 to FA-5) occurs in the middle to upper portion of the Romualdo Formation, and therefore, the Santo Antonio Section could represent a new biostratigratigraphic-determinated of the upper Aptian-early Albian boundary in south-central Araripe Basin. This cycle occurs on a global/regional scale as observed by Haq, 2014).

5.1. Age assignment

The base of the CC8 biozone is defined by the first occurrence of *Prediscosphaera columnata*, while the top is marked by the first occurrence of *Eiffelithus turriseiffelli* and indicates the base of the Albian (Sissingh, 1977). The first occurrence of *Hayesites albiensis* defines the beginning of biozone NC8b (Bralower and Mutterlose, 1995; Roth, 1978), which corresponds to the base of the CC8 biozone (Sissingh, 1977). Therefore, the appearance of *H. albiensis* after *P. columnata* is also recognized as an Albian marker.

Kennedy et al. (2017) described a *Hayesites albiensis/irregularis* association in biozone CC7 in a Pre-Guittard section, Arnayon, Drôme, France, as they had difficulty in distinguishing these two species in the studied sections. However, in the Sergipe-Alagoas basin, specimens of *Hayesites albiensis* with intergrowth were recognized by Silva Jr. et al. (2020) in biozone CC8. In this study, the occurrence of *Hayesites albiensis* in sample 5.55 m, points to the Albian age (CC8 Zone).

The stratigraphic distribution of *Pseudoguembelitria* aff. *blakenosensis* (from the *Hd. infracretaceous* Zone through the *Pa. rohri* Zone) suggests upper Aptian for the lower part of the section. However, the last occurrence of *P.* aff. *blakenosensis* with the record of calcareous nannofossils at the top of the section suggests biozone CC8, which is approximately correlated with the *Microhedbergella miniglobularis* Zone (Huber and Leckie, 2011; Kennedy et al., 2014).

The Aptian planktonic foraminifera, with the record of *H. aptiana,* suggests that the *Paraticinella rohri* Zone, its inffered to the CC7 Zone of calcareous nannofossil (Sissingh, 1977). The biostratigraphic data can be correlated with those obtained by Melo et al. (2020) in an interval of the Romualdo Formation, in the Sobradinho section. However, Boudagher-Fadel et al. (1997) suggests expanding the range of *H. aptiana* (*Blefuscuiana aptiana*) to the Albian, considering that its last occurrence is observed in Albian Biozone 2.

Barreto et al. (2022) in Santo Antônio section analyzed fish teeth (at 5 m sample) and the result of the U/Pb dating was 110 ± 7.4 Ma which comprises the Aptian-Albian limit. The occurrence of *H. aptiana* predates the occurrence of the calcareous nannofossil *H. albiensis* both above 5 m. Therefore, the uppermost part of the Romualdo Formation in the Santo Antônio section records the transition of upper Aptian to Albian and the lower Albian (Fig. 7).

The integrated biostratigraphy of microfossil data for the Romualdo Formation at the Santo Antônio section characterized the upper Aptian to lower Albian. The data from this study, confirm the Aptian for the Romualdo Formation, previously mentioned by Arai and Coimbra (1990), Mabesoone and Tinoco (1973), Regalli (2001), Rios-Netto and Regalli (2007) and Silva and Valença (1968). Likewise, the Albian, mentioned by Beurlen (1964), Coimbra et al. (2002), Lima (1978), Heimhofer and Hochuli (2010) and Valença et al. (2003) recorded here for the first time through the occurrence of calcareous nannofossils.

5.2. Paleoenvironmental interpretations

According to the results of cluster analysis, the environments in the Santo Antônio section ranged from lagoon to marine, with the presence of different groups of marine macrofossils and microfossils, some of which are adapted to wide variations in salinity, which diversify throughout the section. The different assemblages suggest periods of variation in environmental stability, which are likely related to episodes of sea level rise and fall during the late Aptian to the early Albian in the Araripe Basin. Thus, it is possible to infer that paleoenvironmental changes could have influenced the stratigraphic distribution of the faunal assemblages (Fig. 8).

5.2.1. Marine incursion I (late Aptian)

The identified invertebrate taphonomic features between 3.1 and 3.65 m (random distribution of fossils, nesting of bioclasts, and mixture of well-preserved and fragmented fossil materials) suggest that storm waves are primarily responsible for the final sedimentation of these assemblage (Fürsich and Oschmann, 1993), as previously suggested for other shell beds in the Romualdo Formation (e.g., Custódio et al., 2017; Prado et al., 2015; 2016; Rodrigues et al., 2020; Sales, 2005). So, this interval of the Santo Antonio section it is correlated with the FA-5 facies "Marine storm-dominated facies" by Custódio et al. (2017).

The preservation of articulated infaunal bivalves (*Corbula* sp.) is also compatible with deposition from storm waves that would have rapidly reworked and deposited living bivalves. The presence of hummocky cross-stratification in these layers and an erosive base at 3.1 m already recorded throughout the basin (Sales, 2005; Prado et al., 2015) supports the idea of bioclast reworking by storms and suggests deposition in offshore transitional zones, between fair-weather and storm wave bases, where they are the most common (Nichols, 2009).

Fürsich et al. (2019) identified a second transgressive-regressive cycle represented only by a transgressive unit characterized by storm shell beds whose presence of abundant marine elements indicates more stable salinity and oxygen conditions. This information is corroborated by Kroth et al. (2021), suggesting that its deposition was mainly related to the remobilization of an epeiric sea substrate by storm events and that the sea influx and its following retreat are reflected in the increase and subsequent reduction of the abundance of shell beds throughout the basin. This phase is represented in Santo Antonio by high diversity of marine organisms (assemblage A) representing in the deposit the first marine incursion (late aptian) deposited under stromy conditions. The abundance of euryhalines in this range also suggests salinity fluctuations in the environment.

Marine invertebrate taxa are predominant, however there are signs of fluctuations in salinity evidenced by the reduced body size of some of these organisms (e.g *Acteon* sp. and *Cerithium* sp.) (Fürsich et al., 2001; Pereira et al., 2017) and an increase of *Brachidontes araripensis* and *Corbula* sp. body sizes, which, due to their euryhaline and gregarious habits, adapt easily to different salinity environments.

In Assemblage A, there was a dominance of porcelaneous foraminifera compared to hyaline calcareous foraminifera, as previously observed by Araripe et al. (2021). The dominance of porcelaneous species (mainly milliolids) suggests proximal conditions at the levels at which they occur (Debenay et al., 2001).

The abundance of benthic foraminifera in relation to planktonic foraminifera was greater along the entire Santo Antônio section. Following the ratio that is mainly used as a proxy for paleobathymetry (Van der Zwaan et al., 1990), our results indicated a shallow marine environment (Culver, 1988). Another possible justification for this result could be credited to the dissolution of calcium carbonate, since previous studies have shown that the Romualdo Formation is rich in organic carbon content (Arai and Assine, 2020; Custódio et al., 2017). The abundance of organic matter is an important factor as the corrosivity of sediment pore water depends on its breakdown (Murray, 2006). This influence the pH of the paleoenvironment and would mainly affect the preservation of planktonic foraminifera which are more affected by dissolution than benthic (Boltovskoy and Totah, 1992; Nguyen et al., 2009). Unfortunately, it was not possible to evaluate this information based on the analyses carried out in this study.

The ostracod fauna was highly diverse. The dominant species were *Dicrorygma.* cf. *minuta*, typically marine (Babinot et al., 2007) and *Damonella grandiensis*, which can tolerate variations in salinity (Tomé et al., 2014). Calcareous nannofossils are rare in the upper Aptian section, and their absence in Assemblage A could be related to a proximal marine environment.

5.2.2. Marine incursion II (early Albian)

This interval of the Santo Antonio section is correlated with facies FA5 - " storm-dominated marine ", described by Custódio et al. (2017) and having been interpreted as shallow marine environment. At 5.25 m a local incorformity is marked by a regressive-transgressive cycle. This interval is characterized by increased diversity of marine fauna in response to sea level rise.In Santo Antonio, the interval 5.25 and 5.65 m (Assembly B) represents the second marine ingression and is mainly represented by microfossils since the rare occurrence of marine decapods alone would not allow more detailed paleoecological interpretations. This event was not represented in Fürsich et al. (2019) or any other work, being here recorded for the first time in the basin.

Assemblage B records the second marine incursion, and represents the first occurrence of calcareous nannofossils, as well as an increase benthic foraminifera and ostracod diversity and a decrease in the abundance and diversity of planktonic foraminifera.

At the top of the section (5.65 m), the presence of rare decapods *Paleomattea deliciosa* suggests a distal marine paleoenvironment, since most sergestids occur in the deep sea (Tavares and Martin, 2010). The benthic foraminiferal fauna is characterized by calcareous hyaline and porcelaneous taxa that vary in abundance depending on the levels of the section sampled. We observed a good representation of porcelaneous taxa however, hyaline species were dominant, suggesting a more stable, unconfined paleoenvironment with greater marine influence (Frontalini et al., 2011). Benthic foraminifera were more diverse and abundant than planktonic foraminifera, which were represented by a single genus (*Pseudoguembelitria* sp). In addition to the presence of planktonic and benthic foraminifera, the occurrence of some ostracod species typical of marine environments (*Dicrorygma* cf. *minuta*, *Paracypris* sp., *Microceratina* sp., *Parataxodonta* sp., *Perissocytheridea* spp.), corroborated the idea of a more stable marine environment. The greatest diversity and abundance of calcareous nannofossils was also observed in this interval, which could represent a distal marine environment. These taxa include: *Biscutum constans*, *Biscutum* sp., *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp., *Retecapsa surirella*, *Thoracosphaera* sp., *Zeughrabdotus noeliae*, *Watznaueria barnesiae*, and *Watznaueria* sp. In general, the specimens described were smaller in size compared to those recognized in Brazilian marginal basins, possibly due to variations in salinity and nutrient supply (Antunes, 1997).

5.2.3. Hypersaline lagoon (late Aaptian)

Due to the lithological, sedimentological, and macrofossil characteristics, this interval of the Santo Antonio section is correlated with facies FA3- "Marine facies of the inner shelf", described by Custódio et al. (2017) and has been interpreted in this study as a shallow marine environment. However, in the paleoecological analysis of the macro- and microfossils it is observed that the environments are more diverse than described by Custódio et al. (2017). In this study, FA3 facies is characterized by marine incursion II and a lagoon environment.

Fürsich et al. (2019) identified a depositional sequence composed of two transgressive-regressive cycles, the first (more basal) is represented by transgressive, early regressive and late regressive units, in general with low species diversity, small fauna and predominance of euryhaline organisms, suggesting a stressful environment with oxygen and salinity oscillating. In Santo Antonio from 0.3 to 2.65 m (assembly C), only the late regressive unit of this first cycle is represented, with small marine fossils predominating and low diversity of euryhalines, indicating a lagoonal environment that is also stressful.

Assemblage C exhibits low taxonomic diversity and a high abundance of opportunistic macroinvertebrates and microfauna. These organisms are more adapted to unstable environments, such as hypersaline lagoons characterized by a restricted connection to the sea, shallow depths, and high rates of evaporation. The abundance of *Brachidontes araripensis* indicates possible environmental stress, caused by factors such as variations in salinity, temperature, and anoxic to dysoxic conditions at the sediment–water interface (Terra Nova et al., 2007). This species is a colonizer in small intertidal lagoons, and can become dominant, with thousands of individuals per square meter (Guerreiro and Reiner, 2000). The marine gastropods *Tylostoma ranchariensis* and *Natica?* sp. are very small, which may represent an adaptation to the restricted environment.

The fragmented bioclasts in this assemblage occurred in silty/sandy sediments interspersed with shale. This suggests that while calm conditions predominated, higher energy events were likely responsible for the sediment input into the environment, bringing with them highly fragmented and well-sorted bioclasts. These events would abruptly bury recently dead organisms present at the sediment-water interface. The substrate formed by the dense accumulation of shells would have also favored colonization by *Brachidontes araripensis* at the intervals at which they are found intact (3.75–4.5 m) due to their epifaunal nature (e.g. fixed by byssus; Terra Nova et al., 2007).

Assemblage C indicates a low-stability environment, represented by a few groups of organisms. In restricted environments, porcelaneous foraminifera (milliolids) are dominant. These environments become hostile to other groups of foraminifera and favorable to the development and dominance of porcelaneous foraminifera (Debenay et al., 2001). This can be observed during periods of decreased sea levels (regressive events) where lagoon sub-environments of saturated water are formed, due to evaporation (Greiner, 1974). These environments become hostile to other groups of foraminifera and favorable to the development and dominance of porcelaneous foraminifera (Debenay et al., 2001). This can be observed during periods of decreased sea levels (regressive events) where lagoon sub-environments of saturated water are formed, due to evaporation (Greiner, 1974). In these hypersaline environments there is a decrease in faunal diversity and an increased abundance of opportunistic species (Schmiedl et al., 2000).

Mixohaline ostracods, such as *Damonella grandiensis* and species belonging to the genus *Pattersoncypris*, were also notable within the assemblage. According to Poropat and Colin (2012), *Pattesoncypris* is strongly correlated with areas of high salinity, including evaporitic environments. The dominance of this genus in the samples may also represent environments with high salinity and contributes to the characterization of a hypersaline lagoon (Antonietto et al., 2012). With respect to calcareous nannofossils, only *Biscutum constans* and *Thoracosphaera* sp. were present in Assemblage C (at 6.3 m, the top of the section). These species are also considered as opportunistic in the Cretaceous period (Erba et al., 1992; Tremolada et al., 2006).

In the intervals (0.3m-1.8 m and 4.85–5.15 m), near assemblage C, there is an absence of macro- and microfossils that may be related to adverse environmental conditions (e.g. anoxia, high salinity) or caused by diagenetic and post-diagenetic alterations. Therefore, throughout the studied section, it is possible to observe periods of marine stability (assemblages A and B), followed by periods of low stability (Assemblage C) which suggests transgressive and regressive pulses along the Santo Antônio section shallow-water marine section (Fig. 9).

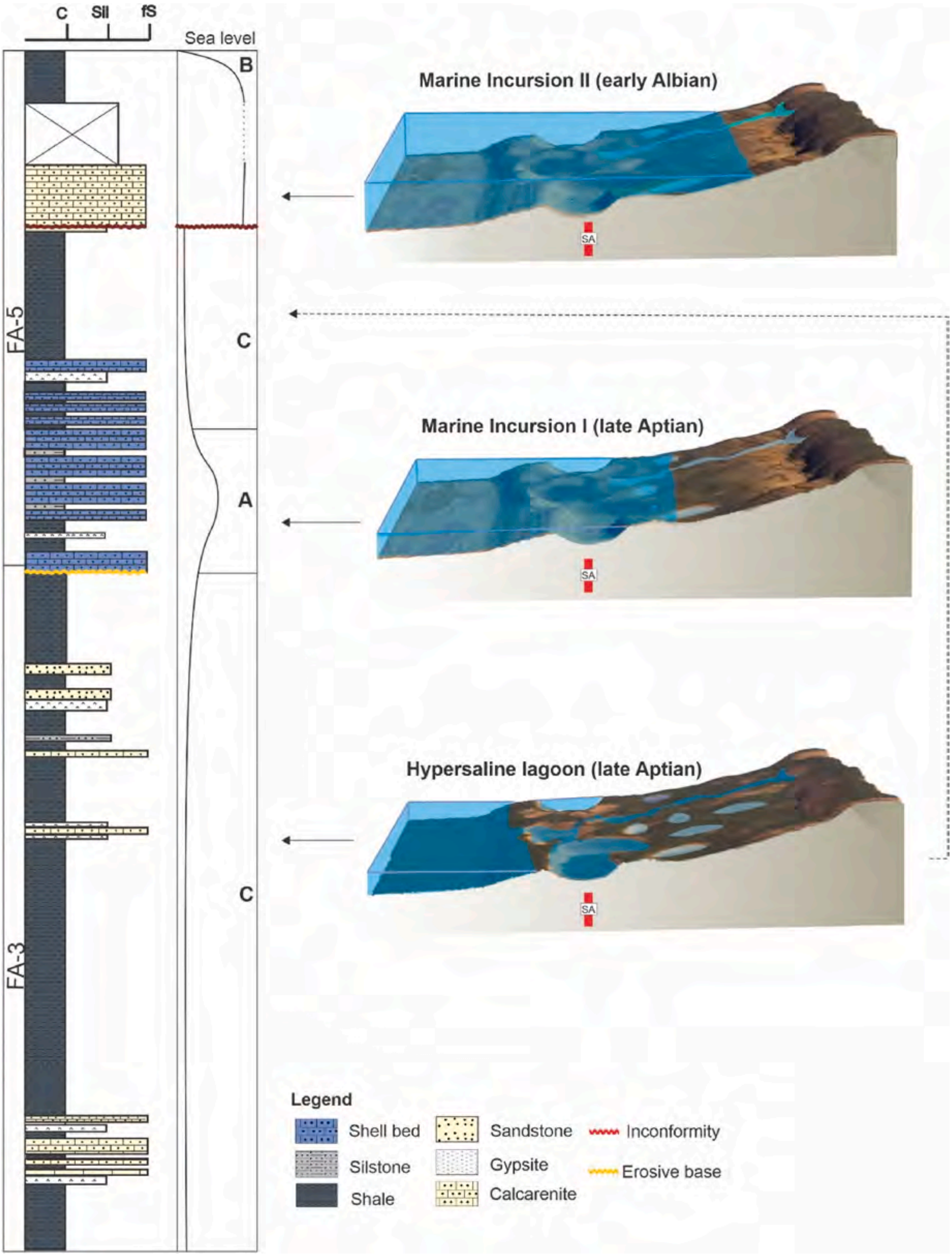

Fig. 9. Paleoenvironmental reconstructions of Santo Antônio section according to assemblages A, B, and C (A: Marine incursion I, B: Marine incursion II and C: Hypersaline lagoon). The illustrated vegetation is not based on palynological data but is illustrative only.

5.3. Paleobiogeography

Among the mollusks, the distribution of Cassiopidae, originally from southern Europe, Asia, and North Africa, increased due to the opening of new routes caused by sea level rise. These taxa arose and became extinct in the Cretaceous and were widely distributed throughout the Tethys Ocean (Beurlen, 1964; Cossmann, 1909; Maury, 1936; Mennessier, 1984; Pereira et al., 2016; Stephenson, 1952). The genus *Tylostoma,* in turn, occurred from the Upper Jurassic to the Upper Cretaceous. In North America, this genus has been recorded in the Aptian, middle Albian, and Cenomanian (Maury, 1936). Due to its geographic distribution, it is also considered a typical Tethyan taxon (Sohl, 1987). In

Brazil, both cassiopids and *Tylostoma* are found in the Aptian–Albian of the Sergipe and Araripe basins, as well as in the Turonian of the Potiguar Basin (Beurlen, 1964; Cassab, 2003; Fürsich et al., 2019; Maury, 1924, 1936; Pereira et al., 2015, 2016, 2018). As for decapods, only crabs of the family Orithopsidae could be used for paleogeographic reconstructions due to their well-preserved paleontological record in the Cretaceous. The earliest occurrences of this group are in the Aptian–Albian of Colombia, England, USA and Brazil (Prado et al., 2018b; Schweitzer et al., 2016). In Brazil, the only genus present in the Romualdo Formation is *Exucarcinus*. Given its similarity to the Colombian genera (*Aetocarcinus*, *Colombicarcinus*, and *Planocarcinus)*, it is speculated that its occurrence in Brazil is also associated with the Tethys (Prado et al., 2018).

Most of the benthic foraminiferal taxa found in this study are cosmopolitan (e.g., *Quinqueloculina*, *Spirillina*, *Astacolus*, *Conorboides*) (Bengtson and Koutsoukos, 1992, Bengtson et al., 2007, Koutsoukos and Bengtson, 2007a, b). Koutsoukos (1989), described a similar association in the Sergipe–Alagoas Basin. According to this author, the fauna in question would have originated in the Tethys Ocean and migrated from a permanent marine connection with the Central Atlantic during the late Aptian.

The occurrence of the benthic porcelaneous genus *Agathaminna* also suggests the influence of the Tethys Ocean (paleo- and neo-Tethyan). This genus has been recorded since the Paleozoic in several regions (e.g., Miklukho-Maklay and Ukharskaya, 1975; Nestell and Nestell, 2006; Pronina and Gubenko, 1990; Wolanska, 1959), including the Mesozoic deposits on the South America equatorial margin (Trinidad) in strata assigned to the upper Aptian *Paraticinella rohri* biozone (Ando et al., 2013; Bartenstein and Bolli, 1986) and more recently in the Araripe Basin, with the species *Agathammina pusilla* in the Aptian strata of the Romualdo Formation (Araripe et al., 2021). *Hedbergella aptiana* is a cosmopolitan planktonic species recorded worldwide in Aptian strata, and has been frequently recorded in upper Aptian sections of Brazilian marginal basins (Koutsoukos, 1989; Melo et al., 2020; Viviers et al., 2018).

In relation to ostracods, species of the genus *Pattersoncypris* are widely distributed in most Brazilian equatorial marginal and interior basins, occurring mainly in the Paraíba, Grajaú, Sergipe–Alagoas, and Araripe basins (e.g. Do Carmo et al., 2008; 2013, 2018). Assemblages composed of *Pattersoncypris salitrensis*, *P. micropapilosa*, and *P. angulata* are of great importance in Lower Cretaceous biostratigraphic studies (e.g. Bate, 1999; Do Carmo et al., 2008; Nascimento et al., 2017; Poropat and Colin, 2012; Tomé et al., 2014). Whereas *Dicrorygma* cf. *minuta* has a paleobiogeographic affinity with the northern margin of the Tethys Ocean (Babinot et al., 2007). The genus *Perissocytheridea* shows a wide biogeographic distribution throughout the Cretaceous in marginal Brazilian and North African basins. The genus *Perissocytheridea*, has been recorded in the middle Cenomanian of the Essaouira Basin, Morocco (Andreu, 2002) and other occurrences of this genus in the Cenomanian–Coniacian have been described by Vivière (1985) in North Africa and the Middle East. Trabelsi et al. (2015) recorded species of *Perissocytheridea*, associated with *Damonella*, *Alicenula*, *Harbinia (Pattersoncypris)* and *Cypridea*, in the lower Aptian strata of Tunisia. In some Brazilian marginal basins several authors have described species of *Perissocytheridea* in the Upper Cretaceous of the Potiguar Basin (Piovesan et al., 2014a, 2014b, 2015, 2020; Viviers et al., 2000), in the Aptian?–Albian and Santonian–Campanian of the Santos Basin (Berge et al., 2011; Piovesan et al., 2013) and in the upper Albian of the Sergipe Basin (Vazquez Garcia et al., 2021). The occurrence of *Perissocytheridea* in the upper Aptian intervals of the Araripe Basin, represents the older record of this genus in Brazilian basins.

The calcareous nannofossil taxa recorded in this study display strong Tethyan affinities (e.g., *Hayesites* sp.) (Mutterlose, 1992). *Hayesites albiensis* appears to be restricted mainly to southern England, which may be a possible reflection of the Tethyan provincialism exhibited in this species (Jeremiah, 2001). Pedrosa et al. (2019) and Silva Jr. et al. (2020) also observed a Tethyan affinity in the Sergipe–Alagoas Basin based on the occurrence of *H. albiensis*. On the other hand, other nannoplankton species, such as *Watznaueria barnesiae* and *Thoracosphaera* sp., are recognized as cosmopolitan. *W. barnesiae*, in particular, is an opportunistic taxon and its abundance may be related to peaks in productivity within restricted environments (Eshet et al., 1992; Lees, 2002; Lees et al., 2006).

6. Conclusions

The locality of the Santo Antônio section, in the Araripe Basin (northeastern Brazil) presents a diverse assemblage of microfossils and invertebrates of Tethyan origin, which suggests marine incursions into hypersaline lagoons, in a clear scenario of environmental instability. This study allows for the identification of the first occurrence of calcareous nannofossils (*Biscutum constans*, *Biscutum* sp., *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp., *Retecapsa surirella*, *Thoracosphaera* sp., *Zeughrabdotus noeliae*, *Watznaueria barnesiae*, and *Watznaueria* sp.) and marine ostracods (*Dicrorygma* cf. *minuta*, *Perissocytheridea* spp, *Dicrorygma* (*Orthorygma*?) *dimorpha* and *Paracypris* sp.) in this basin. The presence of the planktonic foraminifera *Hedbergella aptiana* and *Pseudoguembelitria* sp., infers a possible late Aptian age (*P. rohri* biozone) for most of the Santo Antônio section, with the exception of the top, where the presence of the calcareous nannofossil *Hayesites albiensis*, suggests an early Albian age (Zone CC8). Therefore, at the Santo Antônio section, the Romualdo Formation represents a lagoonal to marine sedimentary environment that encompasses the late Aptian–early Albian transition and provides new biostratigraphic and paleoenvironmental insights into this time interval.

CRediT authorship contribution statement

Rilda C. Araripe: Data curation, Investigation, Writing – original draft, Writing – review & editing. **Flávia A. Pedrosa Lemos:** Investigation, Formal analysis, Data curation. **Ludmila A.C. do Prado:** Investigation, Formal analysis, Data curation. **Maria Emilia T.R. Tomé:** Supervision. **David H.D. Oliveira:** Supervision, Resources, Conceptualization. **Priscilla A. Pereira:** Formal analysis, Data curation, Conceptualization. **Luiz Ricardo S.L. Nascimento:** Formal analysis, Data curation. **Yumi Asakura:** Methodology. **Christiano Ng:** Project administration, Conceptualization. **Marta Claudia Viviers:** Supervision. **Alcina F. Barreto:** Project administration, Conceptualization.

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.

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Appendix A. Supplementary data

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