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Calcareous nannofossils, biostratigraphy, and paleobiogeography of the Aptian/Albian Romualdo Formation in the Araripe Basin, North-Eastern Brazil

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Abstract

The objectives of this study were the biostratigraphic and paleobiogeographic interpretations of the calcareous nannofossil records of the Romualdo Formation (Aptian-Albian) in the south-central portion of the Araripe Basin. The methods used to process the samples were decanting, smear slide, centrifugation, and ultra-thin section confection. The taxonomic and biostratigraphic interpretations were carried out through qualitative and quantitative investigations. A total of 11 genera and 17 species of calcareous nannofossils, namely, *Biscutum constans*, *Biscutum* sp., *Braarudosphaera africana*, *Braarudosphaera* sp., *Calculites* sp., *Discorhabdus ignotus*, *Hayesites albiensis*, *Hayesites* sp., *Nannoconus bucheri*, *Nannoconus* sp., *Retecapsa surirella*, *Rhagodiscus* sp., *Thoracosphaera* sp., *Watznaueria barnesiae*, *Watznaueria* sp., *Zeughrabdotus erectus*, and *Zeughrabdotus noeliae* were identified. The integrated analysis of three outcrops suggests two distinct marine phases: the first in the Aptian, recognized in two outcrops, and during the Albian age. The genera *Hayesites* and *Nannoconus* suggest a strong Tethyan affinity. Differently, other calcareous nannofossils such as *Watznaueria*, *Thoracosphaera*, and *Braarudosphaera* recorded here are considered more resistant, cosmopolitan, and/or opportunistic species. *Biscutum* and *Zeughrabdotus* are sensitive calcareous nannofossils because they are more susceptible to dissolution and cannot be surely used to define this paleobiogeography and biostratigraphic range.

KEYWORDS: nanoplankton; lower cretaceous; paleoenvironment; marine ingressions; facies analysis.

INTRODUCTION

The Araripe Basin and the Romualdo Formation have been the focus of many taxonomic, biostratigraphic, paleoenvironmental, and paleogeographic studies that have aimed to understand the composition of the fossil communities and marine incursions in the interior of northeastern Brazil during the Early Cretaceous (Arai *et al.* 1994, Arai 2014, 2016; Araripe *et al.* 2021, Araripe *et al.* 2022, Assine *et al.* 2014, Assine *et al.* 2016, Barreto *et al.* 2022, Beurlen 1963, 1966, Mabesoone *et al.* 1999, Prado *et al.* 2015, Valença *et al.* 2003).

The age of the Romualdo Formation has been attributed to the Aptian-Albian (Arai *et al.* 1997, Arai and Assine 2020, Araripe *et al.* 2022, Coimbra *et al.* 2002, Custódio *et al.* 2017, Melo *et al.* 2020, Neumann *et al.* 2002). In this formation, there is evidence of connections to the surrounding basins and the Tethys Sea, and although the influence of marine waters is clear, there are divergences regarding the seaway route (Arai 2014, Assine 1994, Beurlen 1963, 1966, 1971, Braun 1966, Fürsich *et al.* 2019, Kroth *et al.* 2021, Mabesoone and Tinoco 1973, Pereira *et al.* 2015, Pereira *et al.* 2016, Pereira *et al.* 2018, Prado *et al.* 2018).

Many microfossil groups from the Romualdo Formation have been well studied, as well as those from other nearby units (Antonietto *et al.* 2012, Arai 2014, 2016, Araripe *et al.* 2021, Coimbra *et al.* 2002, Melo *et al.* 2020, Rios-Netto *et al.* 2012). However, the first record of calcareous nannofossils from this formation and from the Araripe Basin was reported by Araripe *et al.* (2022). Our study details and records new species of this fossil group recovered in the PE-01-SA section (Araripe *et al.* 2022) and in two more distinct outcrops (PE-02-CD and PE-03-ZG), all located in the south-central

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region of the basin in the municipality of Exu, Pernambuco (Fig. 1). The occurrence and detailed analysis of calcareous nannofossils provide valuable taxonomic, biostratigraphic, and paleogeographic information that sheds new light on the paleoenvironments of the Lower Cretaceous Romualdo Formation. The recent discovery of calcareous nannofossils in the Romualdo Formation has stimulated new discussions and studies with an emphasis on microfossils and shows that this formation lacks index fossils for high-resolution biostratigraphic dating.

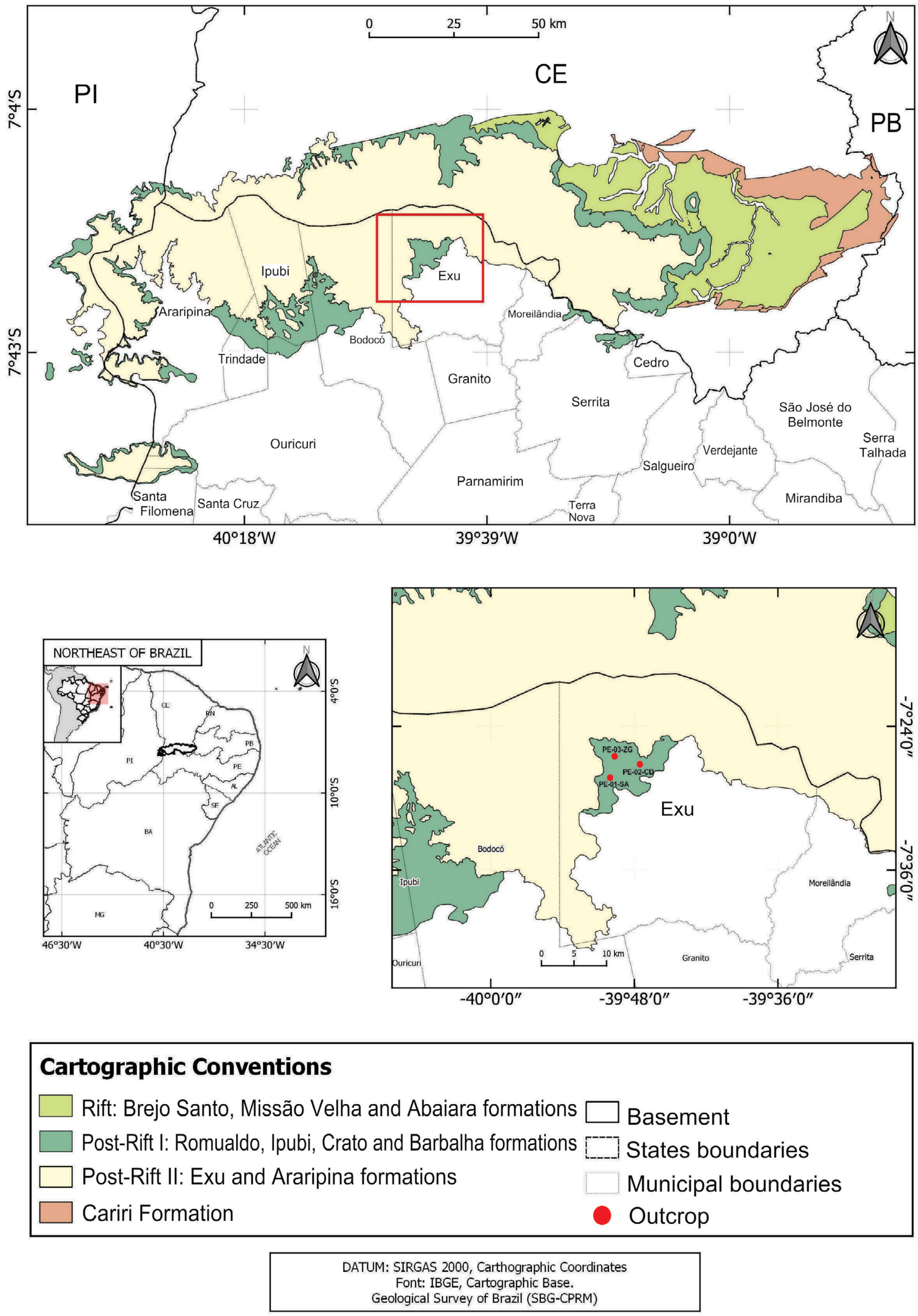


Figure 1. Map of the Araripe Basin, highlighting the location of the studied outcrops PE-01-SA, PE-02-CD, and PE-03-ZG in the Romualdo Formation.

GEOLOGICAL SETTINGS

The evolution of the interior basins in northeastern Brazil is directly related to the fragmentation process of the Gondwana Supercontinent during the Mesozoic, which culminated in the installation of the South Atlantic Ocean (Matos 1992). Records of the sequences that precede and follow this rupture phase have been observed in the Araripe Basin, located between the states of Pernambuco, Piauí, and Ceará (Fig. 1). The Romualdo Formation is the uppermost unit of the Santana Group, recognized in the Post-Rift I phase (Assine 2007) of the stratigraphic basin sequence (Fig. 1).

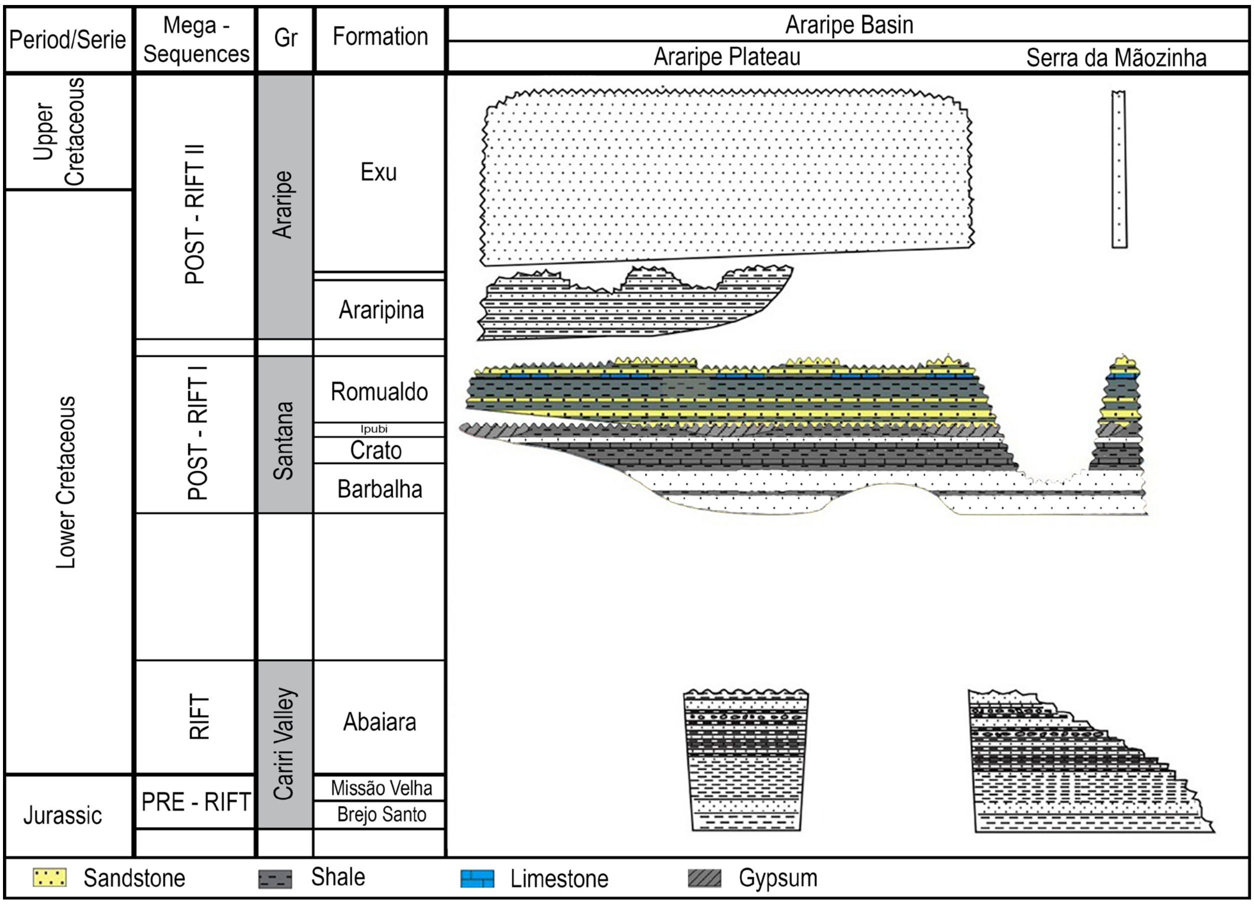
For a long time, the deposition of the Santana Group was related to lacustrine and fluvial paleoenvironments, with the exception of the Romualdo Formation, where marine incursions are marked by the occurrence of typical marine fossils (Arai *et al.* 1994, Arai, 2014, 2016, Araripe *et al.* 2022, Assine 1992, 1994, Assine *et al.* 2016). This suggests a shallow marine storm-dominated environment (Custódio *et al.* 2017). However, new paleoenvironmental interpretations have been proposed for the Araripe Basin. Arai (2014) recorded microforaminifers in the Crato Formation. Also, Goldberg *et al.* (2019) found marine palynomorphs and microforaminifers, and Fauth *et al.* (2022) observed microfossils and ichnofossils, both studies interpreted as related to marine ingressions in the Crato and Barbalha formations, respectively. Sedimentological interpretations suggest that the deposition of conglomerates and sandstones occurred in coastal environments, while the dark shales are interpreted because of marine ingressions (Custódio *et al.* 2017).

The Romualdo Formation is characterized by marls and calcareous fossiliferous carbonate concretions, interspersed with shales, and often bearing gastropods, bivalves, and shrimps. Gastropod shell beds are very common at some points in the basin. The top of the Romualdo Formation is marked by bioclast concentrations, fine to coarse sandstone with trough crossbedding, ripples, and conglomerates (Chagas 2006, Custódio *et al.* 2017, Rodrigues *et al.* 2020, 2022) (Fig. 2). This formation overlies the evaporitic sequence of the Ipubi Formation and is unconformably overlain by alluvial sequences of the Araripina and Exu formations (Assine 2007, Assine *et al.* 2014, Martill 2007).

During the deposition of the Romualdo Formation, estimated to have occurred from Late Aptian to Early Albian, undisputed marine strata were deposited in the interior basins in northeastern Brazil, mainly indicated by its fossiliferous content (Arai and Assine 2020, Araripe *et al.* 2022, Barreto *et al.* 2022).

MATERIALS AND METHODS

Sample processing and analysis of calcareous nannofossils were performed in the Laboratório de Paleontologia (PaleoLab) at the Geology Department of the Universidade Federal de Pernambuco (UFPE). A total of 22 samples were



Source: Assine (2007).

Figure 2. Lithostratigraphic chart of the Araripe Basin.

collected from the PE-01-SA section, 30 from PE-02-CD, and 25 from PE-03-ZG.

Five distinct methodologies were used to prepare each sample. These included decanting (Antunes 1997), decanting (mod.) (Antunes 1997), smear (Smear Slide, Bown 1998), centrifugation, performed at 1,000 r.p.m. for 15 s (short centrifuging, Brown and Young 1997), and ultra-thin section preparation (Bottini 2010). After processing, the fossil content of each slide was investigated using a polarized ZEISS Axion Vision Imager A.2 light microscope (100× objective) with an AxioCam MRc attached; the photomicrographs were produced using ZEN 3.4 Blue edition. Scanning electronic microscope (SEM) images were taken at the Programa de Pós-Graduação em Ciências dos Materiais (PGMTR - UFPE) using Tescan Mira3. A total of 110 slides were prepared for the PE-01-SA section, 150 for PE-02-CD, and 125 for PE-03-ZG. All the analyzed slides were deposited in the Scientific Collection of Microfossils of the Geology Department, Technology and Geosciences Center at the Universidade Federal de Pernambuco (DGEO-CTG-UFPE). Due to the absence of calcareous nannofossil records in the Romualdo Formation before Araripe *et al.* (2022), sample preparation was performed in a more detailed manner, using five distinct methodologies with the aim of identifying and excluding any possible loss and/or non-identification of species in the studied material.

For qualitative calcareous nannofossil analysis, we observed the slides prepared using the five described methods, and taxa identification was based on the taxonomy from Perch-Nielsen (1985), Bown *et al.* (1988), Burnett (1998), and Nannotax3 (Young *et al.* 2017). The quantitative analysis was only performed on the decanted (mod.) slides (Antunes 1997). For this quantification, the following criteria were adopted: abundance, classified as common (C) if one or more specimens were observed in each field of view of each slide; few (F) if, on average, a specimen could not be observed in 10 fields of each slide; and rare (R) if a specimen could be seen less than 10 times in all the slides. Preservation (P) was a subjective category that considered the state of the calcareous nannofossils registered in each sample. In general, preservation was classified as Poor (P) – broken specimens, without primary morphological characteristics; Moderate (M) – whole and broken specimens with alterations in primary morphological characteristics; and Good (G) – all specimens whole, with primary morphological characteristics and easy identification. Total species richness (TSR) was related to the total number of taxa registered in each sample (minimum value = 1; maximum value = 14). TSR should not be confused with diversity. The former only aims to estimate the total number of registered species, while the latter also considers the percentage that each taxon occupies in a sample.

In this study, we applied the most widely used biostratigraphic frameworks. Several calcareous nannofossil biozones have been previously proposed for the Cretaceous, such as Sissingh's (1977; CC zones) biozones. These biozones are based on cosmopolitan data including European and North African sections. In addition, the Roth's (1978; NC zones) biozone was established in the low-latitude region of the northwestern Atlantic Ocean (Burnett 1998).

Furthermore, faciological analyses were made from the three studied outcrops and correlated with the sedimentary facies described by Custódio *et al.* (2017) due to lithological similarities and macrofossils.

RESULTS

Faciological association and correlation

The PE-01-SA section (7°30′06″S, 39°32′36″W) records the upper part of the Romualdo Formation and is situated approximately 10 km from the other outcrops. The PE-01-SA section is characterized by the presence of shales with calcareous concretions containing fossil fish *Vinctifer comptoni* (Agassiz 1841), *Calamopleurus* sp., *Tharrias araripis* (Jordan and Branner 1908), *Branerion* sp., and *Rhacolepsis buccalis* (Agassiz 1841) interspersed with siltstones and fine sandstones with invertebrates, as well as bioclastic limestones (Araripe *et al.* 2022, Duque and Barreto 2017, Rodrigues *et al.* 2020, 2022). The sedimentary facies of this section are interpreted as tidal-dominated coastal (FA-2) and inner shelf (FA-3) facies (Fig. 3).

The PE-03-ZG section (39°34′18″W, 7°31′16″S) is characterized by shales interspersed with fine sandstone containing invertebrates and microfossils and interpreted as an inner shelf facies (FA-3). The presence of bioclastic limestones at the upper part of the section is equivalent to storm-dominated marine facies (FA-5). The PE-02-CD section (39°35′32″W, 7°29′35″S) presents fine sandstone interspersed with siltstone and shale, with invertebrate fossils and microfossils related to tidal flat (FA-2) and platform (FA-3) facies. The top of the section also shows the bioclastic limestones (shell beds) of the storm-dominated marine facies (FA-5) (Fig. 3).

In the PE-01-SA section, the more favorable levels for the recovery of calcareous nannofossils occur in the inner shelf facies (FA-3) at the upper part of the section, in particular in the limestone levels, which present a greater abundance and richness of this group. The shale and siltstone levels are less fossiliferous. For section PE-02-CD, calcareous nannofossils were recovered from the limestone and shell bed (FA-5), but the levels composed of shale and siltstone present a higher richness and abundance. In the PE-03-ZG section, samples of calcareous nannofossils are only recorded at the top of the section, in limestone and shell beds from the storm-dominated facies (FA-5). The three more fossiliferous levels of this outcrop present an increase in abundance and diversity at the top of the section (Table 1).

In this study, the lithostratigraphy and facies correlation suggest that the marine ingressions evidenced in the sections PE-02-CD and PE-03-ZG are contemporary (FA-5), whereas the marine ingression recorded in the PE-01-SA section is more recent (FA-3).

Calcareous nannofossils

The first record of calcareous nannofossils from the Romualdo Formation was described for the PE-01-SA outcrop

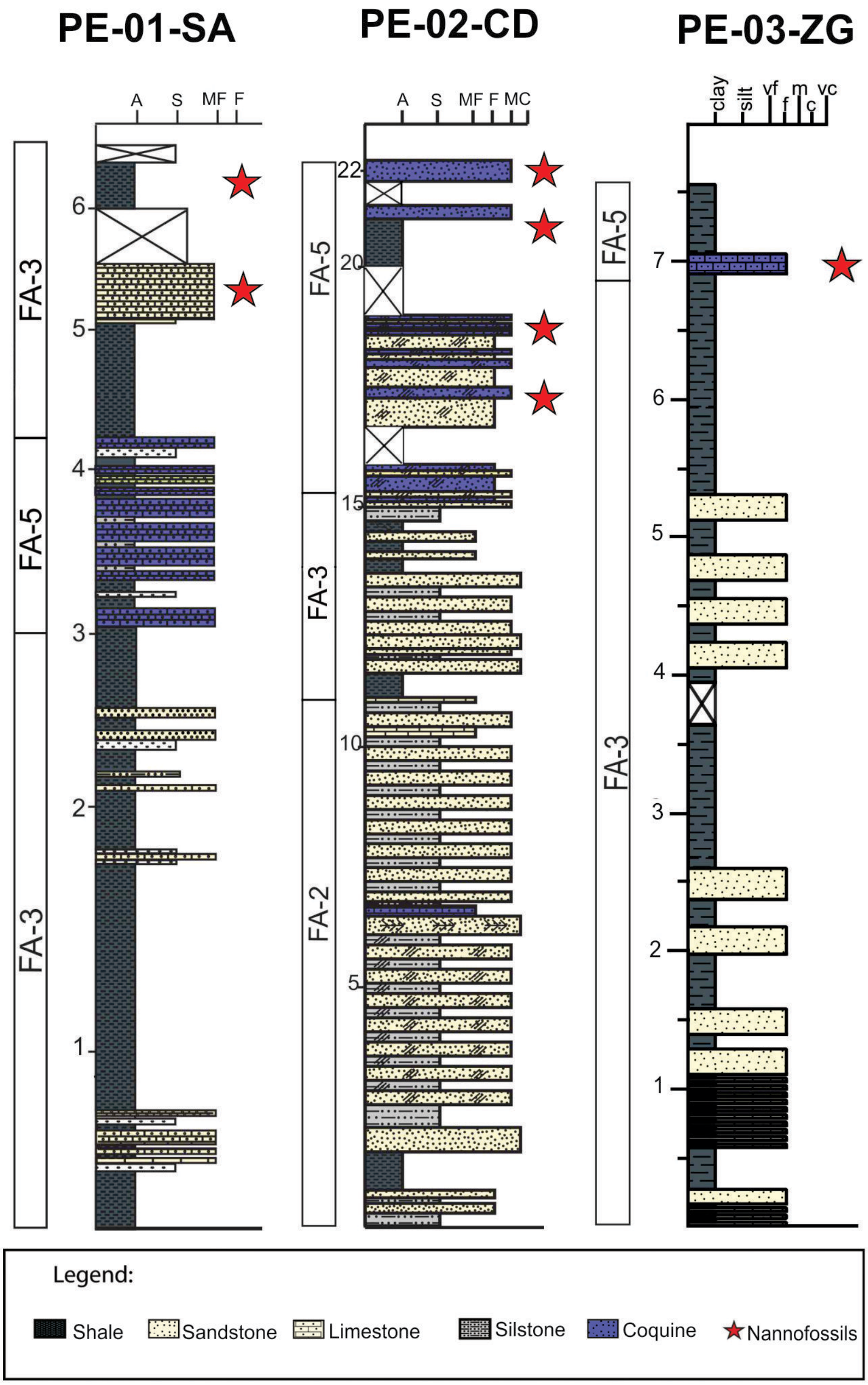


Figure 3. Lithostratigraphic and faciological correlation of the studied profiles. Tide-dominated coastal (FA-2); Inner shelf (FA-3); Inner to outer shelf faces (FA-4); and Storm-dominated (FA-5). Red stars correspond to the calcareous nannofossils occurrences. The profiles are in meters.

Table 1. Facies, lithology, and calcareous nannofossils correlation presented in the PE-01-SA, PE-02-CD, and PE-03-ZG.

Facies	Description	Calcareous nannofossils
FA-2 = Tidal-dominated coastal	Shales with calcareous concretions containing fish fossils interspersed with siltstones and fine sandstones with invertebrates	–
FA-3 = Inner shelf	Shales interspersed with fine sandstone containing invertebrates and microfossils	*B. constans, Biscutum* sp., *B.* ex. gr. *B. africana, Braarudosphaera* sp., *Calculites* sp., *D. ignotus, H. albiensis, Hayesites* sp., *R. surirella, Rhagodiscus* sp., *Thoracosphaera* sp., *W. barnesiae, Watznaueria* sp., *Z. erectus,* and *Z. noeliae*
FA-5 = Storm-dominated marine	Bioclastic limestones (shell beds)	*B. constans, Biscutum* sp., *Hayesites* sp., *N. bucheri, Nannoconus* sp., *Thoracosphaera* sp. and *W. barnesiae*

by Araripe *et al.* (2022). However, in this study, new species are described from the outcrop PE-01-SA (*Braarudosphaera* ex. gr. *B. africana*, *Braarudosphaera* sp., *Calculites* sp., *Discorhabdus ignotus*, and *Zeughrabdotus erectus*), and additional calcareous nannofossils are also recovered from two new outcrops nearby the Exu area. The associations are not as rich as those recorded for PE-01-SA. However, there is a well-preserved association with less diverse and more abundant species richness. Among the slide analyses and descriptions, better results were obtained using only three methodologies (smear, decanting, and modified decanting).

In the PE-01-SA outcrop, the occurrence of calcareous nannofossils is recorded at four levels: 6.30, 5.55, 5.35, and 5.25 m. The observed species are *Biscutum constans*, *Biscutum* sp., *Braarudosphaera* ex. gr. *B. africana*, *Braarudosphaera* sp., *Calculites* sp., *Discorhabdus ignotus*, *Hayesites albiensis*, *Hayesites* sp., *Retecapsa surirella*, *Rhagodiscus* sp., *Thoracosphaera* sp., *Watznaueria barnesiae*, *Watznaueria* sp., *Zeughrabdotus erectus*, and *Zeughrabdotus noeliae* (Fig. 4). In PE-02-CD, the occurrence of calcareous nannofossils is recorded at five levels: 22, 19, 18, 17.9, and 17.5 m. The identified species are *Biscutum constans*, *Biscutum* sp., *Hayesites* sp., *Nannoconus* sp., and *Thoracosphaera* sp. In the PE-03-ZG section, *Nannoconus bucheri*, *Nannoconus* sp., *Thoracosphaera* sp., *Watznaueria barnesiae*, and *Watznaueria* sp. are present at the top of the section.

The assemblage is moderately preserved and has low richness (1–14) and few to rare abundance. PE-01-SA and PE-03-ZG are most promising in terms of diversity and abundance. The PE-02-CD section was the poorest regarding the qualitative and quantitative analyses (Fig. 5).

Biostratigraphy

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

Kennedy *et al.* (2017) described a *Hayesites albiensis*/*irregularis* association in the CC7 biozone, in the Vocontian Basin (France), since they had difficulty in distinguishing these two species in the studied sections. However, Bruno *et al.* (2020) recorded both species individually in the Kwanza Basin (Angola), and Silva Jr. *et al.* (2020) recorded *Hayesites albiensis* specimens in the CC8 biozone in the Sergipe-Alagoas Basin. The occurrence of *Hayesites albiensis* in the 5.55 m sample from the PE-01-SA section suggests the beginning of the Albian (CC8/NC8b biozone) (Araripe *et al.* 2022).

In the PE-01-SA section, the most fossiliferous sample was obtained at a level of 5.55 m. Fragments of *Thoracosphaera* sp. were identified in the samples from 5.25 to 5.35 m; *Biscutum constans* and fragments of *Thoracosphaera* sp. were identified in the sample from 6.30 m. The level of 5.55 m hosts *Biscutum constans*, *Biscutum* sp., *Braarudosphaera* ex. gr. *B. africana*, *Braarudosphaera* sp., *Calculites* sp., *Discorhabdus ignotus*, *Hayesites albiensis*, *Hayesites* sp., *Rhagodiscus* sp., *Retecapsa surirella*, *Thoracosphaera* sp., *Zeughrabdotus erectus*, *Zeughrabdotus noeliae*, *Watznaueria barnesiae*, and *Watznaueria* sp. Therefore, it was possible to attribute the sample at 5.55 m to the Albian age (equivalent to the CC8/NC8b biozone) (Araripe *et al.* 2022) (Fig. 5).

In the PE-02-CD section, the described association was composed of *Biscutum constans*, *Biscutum* sp., *Hayesites* sp., *Nannoconus* sp., and *Thoracosphaera* sp., which can be observed at the highest levels of the section, at depths of 17.5, 17.9, 18, 19, and 22 m (Fig. 5). Specimens of the genus *Nannoconus* were observed both from a lateral and basal view, preventing a secure identification at species level. The presence of the genus *Hayesites* within this association suggests an Aptian to Albian age, where the FO and last occurrence (LO) of this genus occur.

In the PE-03-ZG, the species *Nannoconus bucheri*, *Nannoconus* sp., *Thoracosphaera* sp., *Watznaueria barnesiae*, and *Watznaueria* sp. were recorded at the top of the section. Due to the absence of short temporal amplitude biostratigraphic markers, the presence of *Nannoconus bucheri* within the nannofossiliferous assemblage described suggests an Aptian age for the top of the outcrop (CC7 biozone, Fig. 5).

Paleoenvironmental and paleobiogeographic interpretations

Previously, Araripe *et al.* (2022) studied the PE-01-SA section and used biostratigraphic markers (FO *Hayesites albiensis* and LO of the foraminifera *Hedbergella aptiana*) to indicate the Aptian/Albian boundary in the section and concluded that this outcrop may represent the upper portion of the Romualdo Formation. Barreto *et al.* (2022) studied the same section, and the absolute dating of U/Pb in fish teeth (110.5±7.4 Ma) showed the Albian age, which may be extended to the Upper Aptian.

Considering the lithostratigraphy and facies correlation, it can be defined that the marine ingressions occurred in the sections PE-02-CD and PE-03-ZG are contemporary, whereas the marine ingression recorded in the PE-01-SA section is more recent.

Calcareous nannofossil species are typically widespread across a range of marine photic zone environments, but in some cases, more specific paleoecologies can be determined. These ecological preferences are usually determined using paleobiogeographic distribution analysis and by comparison with other paleontological and geochemical environmental proxies. The increase in diversity and abundance of calcareous nannofossils suggests a distal marine environment (Wise 1983, 1988, Bown 1998, Street and Bown 2000, Kanungo 2005, McAnena *et al.* 2013).

Calcareous nannofossil assemblages of Mesozoic age have been widely used to reconstruct paleoenvironmental and paleoclimatic conditions. The diverse assemblages of the low latitudes are dominated by *Watznaueria* spp., *Rhagodiscus* spp., *Nannoconus* spp., *Micrantholithus* spp., and *Conusphaera* spp., followed by r-strategists like *B. constans* and *Zeugrhabdotus* spp. These warm water thermophile taxa (*Rhagodiscus* spp., *Zeugrhabdotus* spp., and *Hayesites* spp.) indicate relatively warm

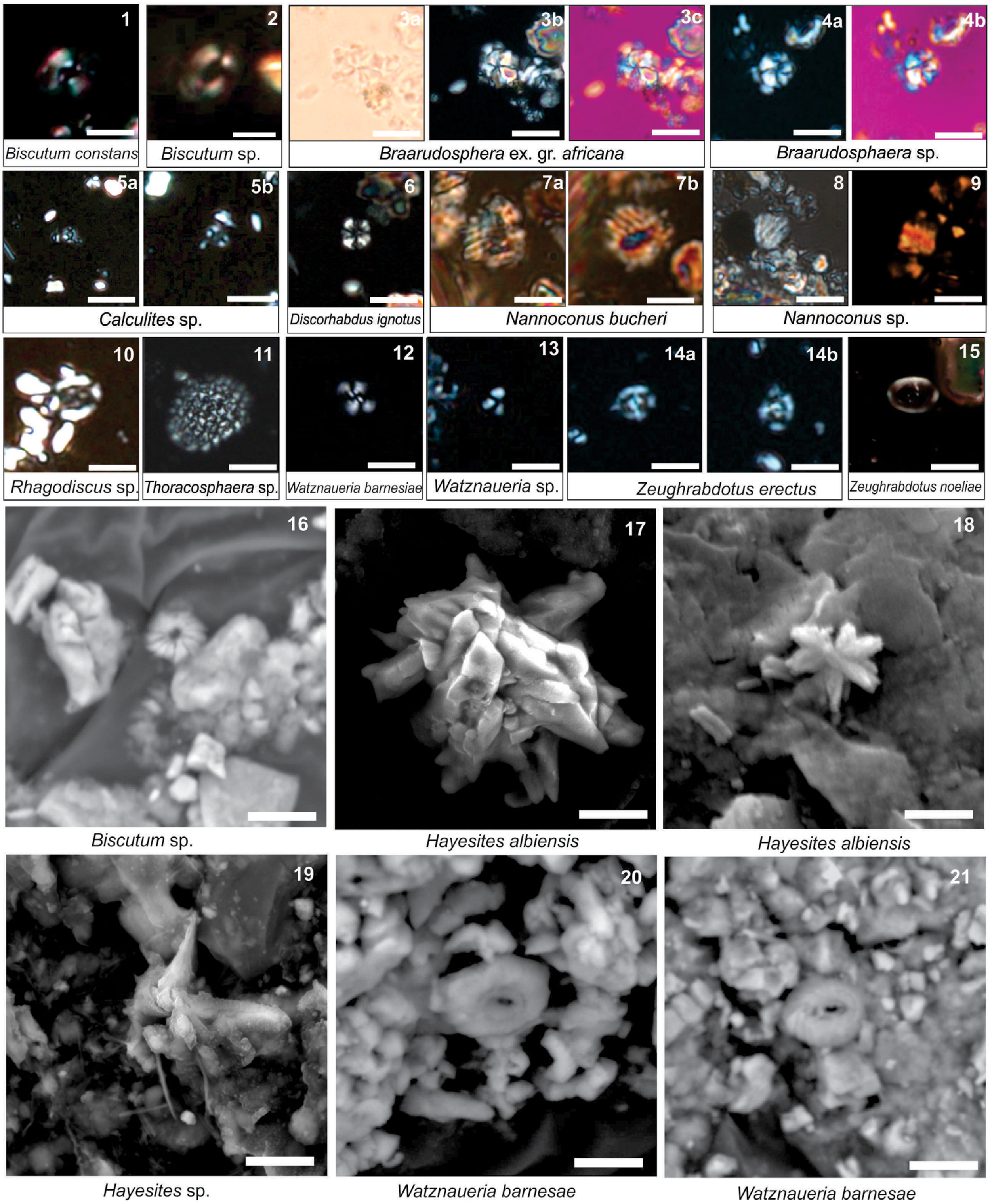


Figure 4. Calcareous nannofossils from the sections PE-01-SA, PE-02-CD, and PE-03-ZG. Petrographic microscope: 01–15 (scale: 5 μm). Images in cross-polarized light: 1, 2, 3b, 3c, 4a-b, 5a-b, 6, 7a-b, 8, 9, 10, 11, 12, 13, 14a-b, 15; cross-polarized light with addition of gypsum plate (1 λ): 3c, 4b; plane polarized light: 3a. *Braarudosphaera* ex. gr. *B. africana* (3a, 3b, 3c), *Braarudosphaera* sp. (4a, 4b), *Calculites* sp. (5a, 5b), *Discorhabdus ignotus* (6), *Zeughrabdotus erectus* (14a, 14b) are recorded for the first time in PE-01-SA (Araripe basin). SEM: 16–21 (scale: 3 μm).

surface water temperatures at the tropics and subtropics, often rich in nutrients (Erba 1987, Mutterlose 1989, 1991, Erba *et al.* 1992, Mutterlose and Kessels 2000, Street and Bown 2000, Herrle *et al.* 2003, Mutterlose *et al.* 2005, Thierstein 1976, Street and Bown 2000).

Braarudosphaera spp. are opportunistic algae adapted to survive in different conditions; *Watznaueria barnesiae* and *Thoracosphaera* sp. were recognized as cosmopolitan taxa, resistant to dissolution, covering a large range of temperatures, and common at both low and high altitudes throughout much of the Mesozoic (Fischer and Arthur 1977, Hardas and Mutterlose 2007, Herrle 2003, Kelly *et al.* 2003, Lees 2002, Mutterlose 1992, 1996, Premoli Silva *et al.* 1989, Roth and Krumbach 1986, Svábenická 1999, Thierstein and Berger 1978,

Calcareous Nannofossils -PE-01-SA

Depth (m)	Lithology	Chronostratigraphy	Sissingh (1977)	Roth (1978)	Preservation	Richness	Bioevents	*Biscutum constans*	*Biscutum* sp.	*Braahudosphaera africana*	*Calculites* sp.	*Discorhabdus ignotus*	*Hayesites albiensis*	*Hayesites* sp.	*Rhagodiscus* sp.	*Retecapsa surirella*	*Thoracosphaera* sp.	*Zeughrabdotus erectus*	*Zeughrabdotus noeliae*	*Watznaueria barnesae*	*Watznaueria* sp.
6.3		Albian	CC8	NC8b	P-M	2		R									R				
5.7					P	0															
5.6					M	14	*H. albiensis*	R	R	R	R	R	R	R	R	R	F	R	R	R	R
5.5		Aptian		NC8a	P	0															
5.4			CC7	NC7	P-M	1											R				
5.3					P-M	1											R				
4.3					P	0															

Legend: Coquine, Limestone, Shale, Silstone

Calcareous Nannofossils - PE-02-CD

Depth (m)	Lithology	Chronostratigraphy	Sissingh (1977)	Roth (1978)	Preservation	Richness	*Biscutum constans*	*Biscutum* sp.	*Hayesites* sp.	*Nannoconus* sp.	*Thoracosphaera* sp.
22		Aptian - Albian	CC7-CC8	NC6-NC9	M	1					R
21					M	0					
19					M	5	R	R	R	R	R
18					M	2		R			R
17.9					P-M	2		R			R
17.5					P-M	1					R

Legend: Coquine, Limestone, Sandstone, Shale, Silstone

Calcareous nannofossils - PE-03-ZG

Depth (m)	Lithology	Chronostratigraphy	Sissingh (1977)	Roth (1978)	Preservation	Richness	*Nannoconus bucheri*	*Nannoconus* sp.	*Thoracosphaera* sp.	*Watznaueria barnesae*	*Watznaueria* sp.
7.2		Aptian	CC7	NC6 - NC7	M-G	5	R	R	R	R	R
7.1					M	5	R	R	F	R	R
7					M	4		R	R	R	R
6					P						
5.6					P						
5.2					P						
5.1					P						

Legend: Coquine, Shale

Figure 5. Species distribution, preservation, richness, and abundance from section PE-01-SA, PE-02-CD, and PE-03-ZG. Abundance: Few (F) and Rare (R). Preservation: Poor (P), Moderate (M), and Good (G). Biostratigraphic table of calcareous nannofossils from section PE-01-SA, PE-02-CD, and PE-03-ZG.

Williams and Bralower 1995). Whereas *Tranolithus* spp. and *Retecapsa* spp. are likely indicators of shallow water environments, associated with the set of transgressive events (Pianka 1970, Tantawy 2008).

Biscutum constans, *Zeugrhabdotus* spp., *Discorhabdus ignotus*, and *Nannoconus* spp. are considered proxies of high fertility conditions, while *Watznaueria barnesiae*, a generalist taxon, is an indicator of low fertility (Roth and Bowdler 1981, Roth and Krumbach 1986, Premoli Silva *et al.* 1989, Thomsen 1989, Watkins 1989, Erba *et al.* 1992, Erba 1994, Herrle *et al.* 2003, Mutterlose and Kessels 2000, Street and Bown 2000, Mutterlose *et al.* 2005, Bottini *et al.* 2015, Bottini and Erba 2018).

Marine ingression: Aptian

The marine ingression is evidenced in PE-02-CD and PE-03-ZG and is correlated with the FA-5 facies (storm-dominated marine), and it has been interpreted as a shallow marine environment characterized by warm surface water temperatures (*Hayesites* sp., *Nannoconus bucheri, Nannoconus* sp., and *Watznaueria barnesiae*) and a fertility index ranging from high (*Biscutum constans, Biscutum* sp.) to low (*Watznaueria barnesiae*).

Marine ingression: Albian

This marine ingression is evidenced in the PE-01-SA outcrop, and it is correlated with the FA-3 facies (inner-shelf). It has been interpreted as a shallow marine environment characterized by warm surface water temperatures (*Hayesites albiensis, Rhagodiscus* sp., *Watznaueria barnesiae*, *Zeughrabdotus erectus*, and *Zeughrabdotus noeliae*) and a fertility index ranging from high (*Discorhabdus ignotus*, *Biscutum constans*, and *Zeugrhabdotus erectus*) to low (*Watznaueria barnesiae*).

The Albian marine ingression is marked by a higher diversity and abundance of calcareous nannofossils, suggesting a more distal marine environment than the Aptian marine ingression.

Paleobiogeography

Paleogeographic studies showed different paths regarding marine ingressions of the Aptian-Albian age in the northeastern Brazilian basins, mainly in the Araripe Basin (Arai 2014, Assine 1994, Custódio *et al.* 2017, Koutsoukos 1989).

The record of calcareous nannofossil taxa in this study shows a strong Tethyan affinity (genera *Hayesites*, *Nannoconus*, and *Rhagodiscus*) (Mutterlose 1992) (Fig. 6). The associations dominated by *Watznaueria* spp., *Rhagodiscus* spp., and *Nannoconus* spp. indicate average and low latitudes (Erba 1987, Erba *et al.* 1992, Herrle *et al.* 2003, Mutterlose 1987, 1991, 1992, 1996, Roth and Krumbach 1986, Street and Bown 2000). *Hayesites albiensis* seems to be mainly restricted to northern Africa (Bralower 1992) and southern England, which may be a possible reflection of the Tethyan provincialism demonstrated by 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* and *Nannoconus* spp. Araripe *et al.* (2022) endorsed the Tethyan influence with the occurrence of *Hayesites* spp. and *Nannoconus* spp.

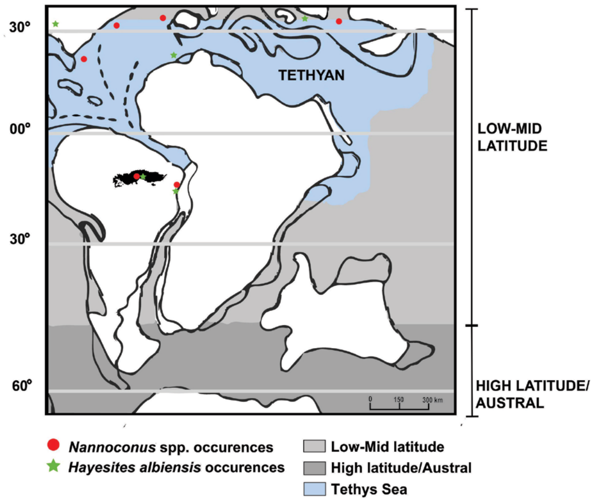


Figure 6. Paleogeographic reconstruction for Lower Cretaceous, highlights (blue) the Tethys Sea and its influence on the Araripe Basin. Modified from the map shown in Street and Bown map (2000).

In this study, the presence of calcareous nannofossils in the outcrops PE-01-SA, PE-02-CD, and PE-03-ZG suggests the record of marine incursions in the Araripe Basin, and the presence of *Hayesites*, *Nannoconus*, and *Rhagodiscus* indicates a strong influence of Tethyan origin in the Central-West portion of the Araripe Basin (Fig. 6).

CONCLUSION

The calcareous nannofossil association is characterized by 11 distinct genera and 17 species. This taxon's richness varies from 45 to 3 individuals; preservation is moderate; and abundance varies from rare to few. The calcareous nannofossils were recognized in the inner shelf facies, limestone, and shell bed levels.

- Five new occurrences (*Braarudosphaera* ex. gr. *B. africana*, *Braarudosphaera* sp., *Calculites* sp., *Discorhabdus ignotus*, and *Zeughrabdotus erectus*) were recognized for the first time in the PE-01-SA outcrop;
- The species *Biscutum constans*, *Biscutum* sp., *Hayesites* sp., *Nannoconus* sp., and *Thoracosphaera* sp. In the PE-03-ZG section, *Nannoconus bucheri*, *Nannoconus* sp., *Thoracosphaera* sp., *Watznaueria barnesiae*, and *Watznaueria* sp. were recognized in the PE-02-CD;
- The species *Biscutum constans*, *Biscutum* sp., *Hayesites* sp., *Nannoconus* sp., and *Thoracosphaera* sp. were recognized in the PE-03-ZG;
- The occurrence of calcareous nannofossils in the Romualdo Formation corroborates the possible marine ingressions proposed up until now. The correlation between the three analyzed sections suggests an Aptian marine ingression (PE-02-CD and PE-03-ZG) and another more recent marine ingression from the Albian age (PE-01-SA);
- The recorded assemblage in the PE-01-SA section indicates an Albian age at the top of the section (*H. albiensis*). Whereas PE-02-CD (based on lithostratigraphy and facies analysis) and PE-03-ZG were correlated to an Aptian age;

- The Romualdo Formation is characterized by marine ingressions in the Aptian and Albian, as highlighted in this study by the calcareous nannofossils and sedimentary facies;
- The recorded assemblage in the studied outcrops has a strong Tethyan affinity, with the genera *Hayesites* and *Nannoconus* standing out. But the calcareous nannofossil assemblage also includes more resistant, cosmopolitan, and/or opportunistic species (*Watznaueria*, *Thoracosphaera*, and *Braarudosphaera*).

List of species

Biscutum constans (Górka, 1957) Black *in* Black and Barnes, 1959

Biscutum sp.

Braarudosphaera africana Stradner, 1961

Braarudosphaera sp.

Calculites sp.

Discorhabdus ignotus (Górka, 1957) Perch-Nielsen, 1968

Hayesites albiensis (Manivit 1971)

Hayesites sp.

Nannoconus bucheri Brönnimann, 1955

Nannoconus sp.

Retecapsa surirella (Deflandre & Fert, 1954) Grün *in* Grün and Allemann, 1975

Rhagodiscus sp.

Thoracosphaera sp.

Watznaueria barnesiae (Black *in* Black & Barnes, 1959) Perch-Nielsen, 1968

Watznaueria sp.

Zeughrabdotus erectus (Deflandre *in* Deflandre & Fert, 1954) Reinhardt, 1965

Zeughrabdotus noeliae Rood *et al.* 1971

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REFERENCES

Agassiz L. 1841. On the fossil fishes found by Mr. Gardnerin the province of Ceará, in the north of Brazil. *The Edinburgh New Philosophical Journal*, **30**:81-84.

Antonietto L.S., Gobbo S.R., Do Carmo D.A., Assine M., Silva J.E.L. 2012. Taxonomy, ontogeny, and paleoecology of two species of Harbinia TSAO, 1959 (Crustacea, ostracoda) from the Santana formation, lower Cretaceous, northeastern Brazil. *Journal of Paleontology*, **86**(4):659-668. https://doi.org/10.1666/11-012R.1

Antunes R.L. 1997. *Introdução ao estudo dos nanofósseis calcários.* Rio de Janeiro: Instituto de Geociências e UFRJ, 115 p.

Arai M. 2014. Aptian/Albian (early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective. *Brazilian Journal of Geology*, **44**(2):339-350. https://doi.org/10.5327/Z2317-4889201400020012

Arai M. 2016. Reply to the comments of Assine et al. (Comments on paper by M. Arai "Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective"). *Brazilian Journal of Genetics*, **46**:9-13.

Arai M., Assine M.L. 2020. Chronostratigraphic constraints and paleoenvironmental interpretation of the Romualdo formation (Santana group, Araripe basin, northeastern Brazil) based on palynology. *Cretaceous Research*, **116**:104610. https://doi.org/10.1016/j.cretres.2020.104610

Arai M., Coimbra J.C., Silva-Telles Júnior A.C. 1997. Síntese bioestratigráfica da Bacia do Araripe (Nordeste do Brasil). In: *Simpósio sobre a Bacia do Araripe e Bacias interiores do Nordeste*, v. 2. Crato.

Arai M., Lana C.C., Pedrão E. 1994. Ecozona Subtilisphaera spp.: registro eocretáceo de um importante episódio ecológico do Oceano Atlântico primitivo. *Acta Geologica Leopoldensia*, **39**(2):521-538.

Araripe R.C., Lemos F.A.P., do Prado L.A., Tomé M.E.T., Oliveira D.H., Pereira P.A., Nascimento L.R.S.L., Asakura Y., Ng C., Viviers M.C., Barreto A.F. 2022. Upper Aptian–lower Albian of the southern-central Araripe Basin, Brazil: Microbiostratigraphic and paleoecological inferences. *Journal of South American Earth Sciences*, **116**:103814. https://doi.org/10.1016/j.jsames.2022.103814

Araripe R.C., Oliveira D.H., Tomé M.E., Mello R.M., Barreto A.M.F. 2021. Foraminifera and Ostracoda from the Lower Cretaceous (Aptian–Lower Albian) Romualdo Formation, Araripe Basin, Northeast Brazil: Paleoenvironmental Inferences. *Cretaceous Research*, **122**:104766. https://doi.org/10.1016/j.cretres.2021.104766

Assine M.L. 1992. Análise estratigráfica da bacia do Araripe, Nordeste do Brasil. *Brazilian Journal of Geology*, **22**(3):289-300.

Assine M.L. 1994. Paleocorrentes e paleogeografia na Bacia do Araripe, Nordeste do Brasil. *Brazilian Journal of Geology*, **24**(4):223-232.

Assine M.L. 2007. Bacia do Araripe. *Boletim de Geociências da Petrobras*, **15**:371-389.

Assine M.L., Perinotto J.A.J., Custódio M.A., Neumann V.H., Varejão F.G., Mescolotti P.C. 2014. Sequências deposicionais do Andar Alagoas da Bacia do Araripe, Nordeste do Brasil. *Boletim de Geociências da Petrobras*, **22**:3-28.

Assine M.L., Quaglio F., Warren L.V., Simões M.G. 2016. Comments on paper by M. Arai "Aptian/Albian (early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective". *Brazilian Journal of Genetics*, **46**:3-7.

Barreto A.M.F., Bertotti A.L., Sylvester P.J., Prado L.A.C., Araripe R.C., Oliveira D.H., Tomé M.E.T.R., Lemos F.A.P., Nascimento L.R.L., Pereira P.A., Albayrak A.I. 2022. U/Pb geochronology of fossil fish dentine from Romualdo Formation, Araripe Basin, northeast of Brazil. *Journal of South American Earth Sciences*, **116**:103774. https://doi.org/10.1016/j.jsames.2022.103774

Beurlen K. 1963. Geologia e estratigrafia da Chapada do Araripe. Congresso Nacional de Geologia, Recife. *Anais da Academia Brasileira de Ciências*, **17**:47.

Beurlen K. 1966. Novos equinoides no Cretáceo do nordeste do Brasil. *Anais da Academia Brasileira de Ciências*, **38**:455-464.

Beurlen V.K. 1971. As condições ecológicas e faciológicas da Formação Santana na Chapada do Araripe (Nordeste do Brasil). *Anais da Academia Brasileira de Ciências*, **43**:411-415.

Bottini C. 2010. pCO2 effects on the production of pelagic biogenic carbonate and ocean chemistry: a case history from the Cretaceous. Dottorato di Ricerca in Scienze della Terra Ciclo XXIII.

Bottini C., Erba E. 2018. Mid-Cretaceous paleoenvironmental changes in the western Tethys. *Climate of the Past*, **14**(8):1147-1163. https://doi.org/10.5194/cp-14-1147-2018

Bottini C., Erba E., Tiraboschi D., Jenkyns H.C., Schouten S., Sinninghe Damsté J.S. 2015. Climate variability and ocean fertility during the Aptian Stage. *Climate of the Past*, **11**:383-402. https://doi.org/10.5194/cp-11-383-2015

Bown P.R. 1998. *Calcareous Nanofossil Biostratigraphy*. Cambridge.

Bown P.R., Cooper K.E., Lord A.R. 1988. A calcareous nannofossils biozonation scheme for the early to mid-Mesozoic. *Newsletter on Stratigraphy*, **20**(2):91-114. https://doi.org/10.1127/nos/20/1988/91

Bown P.R., Young J.R. 1997. Proposals for a revised classification system for calcareous nannoplankton. *Journal of Nannoplankton Research*, **19**(1):15-47.

Bralower T.J. 1992. Aptian-Albian Calcareous Nannonfossil Biostratigraphy of ODP Site 763 and the Correlation Between High- and Low Latitude Zonations. In: Proceedings of the Ocean Drilling Program, *Scientific Results*, 245-252.

Bralower T.J., Mutterlose J. 1995. Calcareous nannofossil biostratigraphy of site U865, Allison Guyot, central Pacific Ocean: a tropical Paleogene reference section. In: Proceedings of the Ocean Drilling Program, *Scientific Results*, **143**:31-74.

Braun O.P.G. 1966. *Estratigrafia dos sedimentos da parte inferior da região nordeste do Brasil (bacias do Tucano-Jatobá, Mirandiba e Araripe)*. Divisão de Geologia e Mineralogia/DNPM. v. 236.

Bruno M.D.R., Fauth G., Watkins D.K., Savian J.F. 2020. Albian-Cenomanian calcareous nannofossils from DSDP Site 364 (Kwanza Basin, Angola): Biostratigraphic and paleoceanographic implications for the South Atlantic. *Cretaceous Research*, **109**:104377. https://doi.org/10.1016/j.cretres.2020.104377

Burnett J.A. 1998. Upper Cretaceous. In: Bown P.R. (Ed.), *Calcareous Nannofossil Biostratigraphy*. London: Chapman & Hall, pp. 132-199. British Micropalaeontological Society Publication Series.

Chagas D.B. 2006. *Litoestratigrafia da Bacia do Araripe: reavaliação e propostas para revisão*. Dissertação de Mestrado, Departamento de Geologia Aplicada, Universidade Estadual Paulista, Rio Claro, 112 p.

Coimbra J.C., Arai M., Carreno A.L. 2002. Biostratigraphy of lower Cretaceous microfossils from the Araripe Basin, northeastern Brazil. *Geobiosciences*, **35**(6):687-698. https://doi.org/10.1016/S0016-6995(02)00082-7

Custódio M.A., Quaglio F., Warren L.V., Simões M.G., Fürsich F.T., Perinotto J. J.A., Assine M.A. 2017. The transgressive-regressive cycle of the Romualdo formation (Araripe basin): sedimentary archive of the early Cretaceous marine ingression in the interior of northeast Brazil. *Sedimentary Geology*, **359**:1-15. https://doi.org/10.1016/j.sedgeo.2017.07.010

Duque R.R.C., Barreto A.M.F. 2017. Novos sítios fossilíferos da Formação Romualdo (Cretáceo Inferior, Bacia do Araripe), Exu, Pernambuco, Nordeste do Brasil. *Anuário do Instituto de Geociências*, **41**(1):5-14. https://doi.org/10.11137/2018_1_05_14

Erba E. 1987. Mid-Cretaceous cyclic pelagic facies from the Umbrian-Marchean Basin: what do calcareous nannofossils suggest? *International Nannoplankton Association Newsletters*, **9**(4):52-53.

Erba E. 1994. Nannofossils and superplumes: the early Aptian nannoconid crisis. *Paleoceanography*, **9**(3):483-501. https://doi.org/10.1029/94PA00258

Erba E., Castradori M., Cobianchi M. 1992. Upper Triassic and Jurrassic calcareous nannofossil ranges. In: Proto-Decima F., Monechi S., Rio D. (eds.), *Proceedings of the International Nannoplankton Associadou Conference*, Firenze, 1989. Padova, pp. 27-40.

Fauth G., Kern H.P., Villegas-Martín J.P., Mota M.A.L., Santos Filho M.A.B., Catharina A.S., Leandro L. M., Luft-Souza F., Strohschoen Jr. O., Nauter-Alves A., Tungo E.J.F., Mauro Daniel Rodrigues Bruno M.D.R., Ceolin D., Baecker-Fauth S., Bom M.H.H., Lima F.H.O., Assine M.L. 2022. Primeval Aptian marine incursions in the interior of Northeastern Brazil following the Gondwana breakup. *Research Square*. https://doi.org/10.21203/rs.3.rs-1674479/v1

Fischer A.G., Arthur M.A. 1977. Secular variations in the pelagic realm. *Society of Economic Paleontologists and Mineralogists Special Publication*, **25**:19-50.

Fürsich F.T., Custódio M.A., Matos S.A., Hethke M., Quaglio F., Warren L.V., Assine M.L., Simões M.G. 2019. Analysis of a Cretaceous (late Aptian) high stress ecosystem: The Romualdo Formation of the Araripe Basin, northeastern Brazil. *Cretaceous Research*, **95**:268-296. https://doi.org/10.1016/j.cretes.2018.11.021

Goldberg K., Premaor E., Bardola T., Souza P.A. 2019. Aptian marine ingression in the Araripe Basin: implications for paleogeographic reconstruction and evaporite accumulation. *Marine and Petroleum Geology*, **107**:214-221. https://doi.org/10.1016/j.marpetgeo.2019.05.011

Hardas P., Mutterlose J. 2007. Calcareous nannofossil assemblages of Oceanic Anoxic Event 2 in the equatorial Atlantic: evidence of a eutrophication event. *Marine Micropaleontology*, **66**(1):52-69. https://doi.org/10.1016/j.marmicro.2007.07.007

Herrle J.O. 2003. Reconstructing nutricline dynamics of mid-Cretaceous oceans: Evidence from calcareous nannofossils from the Niveau Paquier black shale (SE France). *Marine Micropaleontology*, **47**(3-4):307-321. https://doi.org/10.1016/S0377-8398(02)00133-0

Herrle J.O., Pross J., Friedrich O., Kößler P., Hemleben C. 2003. Forcing mechanisms for mid-Cretaceous black shale formation: evidence from the upper Aptian and lower Albian of the Vocontian Basin (SE France). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **190**:399-426. https://doi.org/10.1016/S0031-0182(02)00616-8

Jeremiah J. 2001. A lower Cretaceous nannofossil zonation for the north sea basin. *Journal of Micropalaeontology*, **20**(1):45-80. https://doi.org/10.1144/jm.20.1.45

Jordan D.S., Branner J.C. 1908. The Cretaceous fishes of Ceará, Brazil. *Smithsonian Miscellaneous Collection*, **5**(1):1-29.

Kanungo S. 2005. *Biostratigraphy and palaeoceanography of mid-Cretaceous calcareous nannofossils: studies from the Cauvery Basin, SE India; the Gault Clay Formation, SE England; ODP Leg 171B, western North Atlantic and ODP Leg 198, northwest Pacific Ocean*. Unpublished PhD thesis, University College London, 260 p.

Kelly D.D., Norris R.D., Zachos J.C. 2003. Deciphering the paleoceanographic signifcance of Early Oligocene Braarudosphaera chalks in the South Atlantic. *Marine Micropaleontology*, **49**(1-2):49-63. https://doi.org/10.1016/S0377-8398(03)00027-6

Kennedy J.W., Gale A.S., Huber B.T., Petrizzo M.R., Bown P., Jenkyns H.C. 2017. The Global Boundary Stratotype Section and Point (GSSP) for the base of the Albian Stage, of the Cretaceous, the Col de Palluel section, Arnayon, Drôme, France. *Episodes*, **40**(3):177-188.

Koutsoukos E.A.M. 1989. *Mid- to Late Cretaceous Microbiostratigraphy, Palaeo-Ecology and Palaeogeography of the Sergipe Basin, Northeastern Brazil. Council for National Academic Awards/Polytechnic South West, Plymouth*. Unpublished Ph.D Thesis. 2 v.

Kroth M., Borghi L., Bobco F.E.R., Araújo B.C., Silveira L.F., Duarte G., Ferreira L.O., Guerra-Sommer M., Mendonça J.O. 2021. Aptian shell beds from the Romualdo formation (Araripe basin): implications for paleoenvironment and paleogeographical reconstruction of the northeast of Brazil. *Sedimentary Geology*, **426**:106025. https://doi.org/10.1016/j.sedgeo.2021.106025

Lees J.A. 2002. Calcareous nannofossil biogeography illustrates paleoclimate change in the Late Cretaceous Indian Ocean. *Cretaceous Research*, **23**(5)537-634. https://doi.org/10.1006/cres.2003.1021

Mabesoone J.M., Tinoco I.M. 1973. Palaeoecology of aptian Santana formation (northeastern Brazil). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **14**(2):97-118. https://doi.org/10.1016/0031-0182(73)90006-0

Mabesoone J.M., Viana M.S.S., Lima-Filho M.F. 1999. Late Mesozoic history of sedimentary basins in NE Brazilian Borborema Province before the final separation of south America and Africa. 3: Paleogeogeoghraphy. In: Simpósio sobre o Cretáceo do Brasil, 5, 1999. *Boletim de Resumo*, Serra Negra, pp. 621-626.

Manivit H. (1971). *Nannofossiles calcaires du Crétacé francais (Aptien-Maestrichtien). Essai de Biozonation appuyée sur les stratotypes.* PhD thesis, Université de Paris, Paris.

Martill D.M. 2007. The age of the Cretaceous Santana Formation fossil Konservat Lagerstätte of north-east Brazil: a historical review and an appraisal of the biochronostratigraphic utility of its palaeobiota. *Cretaceous Research*, **28**(6):895-920. https://doi.org/10.1016/j.cretres.2007.01.002

Matos R.M.D. 1992. The northeast Brazilian rift system. *Tectonics*, **11**(4):766-791. https://doi.org/10.1029/91TC03092

McAnena A., Flögel S., Hofmann P., Herrle J.O., Griesand A., Pross J., Talbot H.M., Rethemeyer J., Wallmann K., Wagner T. 2013. Atlantic cooling associated with a marine biotic crisis during the mid-Cretaceous period. *Nature Geoscience*, **6**:558-651. https://doi.org/10.1038/ngeo1850

Melo R.M., Guzman J.G., Lima D.S.A., Piovesan E.K., Neumann V.H.M.L., Sousa A.J. 2020. New marine data and age accuracy of the Romualdo formation, Araripe basin, Brazil. *Scientific Reports*, **10**:15779. https://doi.org/10.1038/s41598-020-72789-8

Mutterlose J. 1987. Calcareous nannofossils and belemnites as warmwater indicators from the NW-German Middle Aptian. *Geologisches Jahrbuch*, **96**:293-313.

Mutterlose J. 1989. Temperature-controlled migration of calcareous nannofloras in the north-west European Aptian. In: Crux J.A., Van Heck S.C. (eds.). *Nannofossils and their applications*. Chichester: INA Conference, pp. 122-142.

Mutterlose J. 1991. Das Verteilungs- und Migrationsmuster des kalkigen Nannoplanktons in der borealen Unter-Kreide (Valangin-Apt) NW-Deutschlands. *Palaeontographica*, **221**(1-4):27-152.

Mutterlose J. 1992. Biostratigraphy and palaeobiogeography of Early Cretaceous calcareous nannofossils. *Cretaceous Research*, **13**(2):167-189. https://doi.org/10.1016/0195-6671(92)90034-N

Mutterlose J. 1996. Calcareous nannofossit palaeoceanography of the Early Cretaceous of NW Europe. *Mitteilungen aus dem Geologischen Staatsinstitut in Hamburg*, **77**:291-313.

Mutterlose J., Bornemann A.B., Herrle J.O. 2005. Mesozoic calcareous nannofossils: state of the art. *Palaontologische Zeitschrift*, **79**:113-133. https://doi.org/10.1007/BF03021757

Mutterlose J., Kessels K. 2000. Early Cretaceous calcareous nannofossils from high latitudes: implications for palaeobiogeography and palaeoclimate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **160**(3-4):347-372. https://doi.org/10.1016/S0031-0182(00)00082-1

Neumann V.H., Cabrera L., Mabessone J.M., Valença L.M.M., Silva A.L. 2002. Ambiente sedimentar e fácies da sequência lacustre Aptiana-Albiana da Bacia do Araripe, NE do Brasil. In: 6º Simpósio sobre o Cretáceo do Brasil, São Pedro. Boletim do 6º Simpósio sobre o Cretáceo do Brasil, pp. 37-41.

Pedrosa F.A., Araújo I.G., Antunes R.L., Lima M.F. 2019. Biostratigraphic Study Based on Calcareous Nannofossils from the Cretaceous of the Sergipe Basin, Northeast of Brazil. *Anuário do Instituto de Geociências*, **42**(3):207-222. https://doi.org/10.11137/2019_3_207_222

Perch-Nielsen K. 1985. *Mesozoic Calcareous Nannofossils:* Plankton Stratigraphy. New York: Cambridge University Press.

Pereira P.A., Cassab R.C.T., Almeida J.A.C., Barreto A.M.F. 2015. Moluscos da Formação Romualdo, Aptiano-Albiano, Bacia do Araripe, nordeste do Brasil. *Boletim do Museu Paraense Emílio Goeldi. Ciências Naturais*, **10**(2):231-246. https://doi.org/10.46357/bcnaturais.v10i2.482

Pereira P.A., Cassab R.C.T., Barreto A.M.F. 2016. Cassiopidae gastropods, influence of Tethys Sea of the Romualdo Formation (Aptian-Albian), Araripe Basin, Brazil. *Journal of South American Earth Sciences*, **70**:211-223. https://doi.org/10.1016/j.jsames.2016.05.005

Pereira P.A., Cassab R.C.T., Barreto A.M.F. 2018. The Families Veneridae, Trochidae, Akeridae and Acteonidae (Mollusca), in the Romualdo Formation: Paleoecological and Paleobiogeographic Aspects in the Lower Cretaceous of the Araripe Basin, NE of Brazil. *Anuário do Instituto de Geociências*, **41**(3):137-152. https://doi.org/10.11137/2018_3_137_152

Pianka E.R. 1970. On r- and K-Selection. *American Naturalist*, **104**(940):592-597.

Prado L.A.C, Fambrini G.L., Barreto A.M.F. 2018. Tafonomy of macroinvertebrates and Albian marine ingression as recorded by the Romualdo Formation (Cretaceous, Araripe Basin, Brazil). *Brazilian Journal of Geology*, **48**(3):519-531. https://doi.org/10.1590/2317-4889201820180048

Prado L.A.C., Pereira P.A., Sales A.M.F., Barreto A.M.F. 2015. Taphonomic and paleoenvironmental considerations for the concentrations of macroinvertebrate fossils in the Romualdo member, Santana formation, late aptian-early albian, Araripe basin, Araripina, NE, Brazil. *Journal of South American Earth Sciences*, **62**:218-228. https://doi.org/10.1016/j.jsames.2015.06.005

Premoli Silva I., Erba E., Tornaghi M.E. 1989. Palaeoenvironmental signals and changes in surface fertility in mid Cretaceous Corg-rich pelagic facies of the Fucoid Marls (Central Italy). *Grobios, Memoire Special*, **11**:225-236.

Rios-Netto A.D.M., Regali M.D.S.P., Carvalho I.D.S., Freitas F.I. 2012. Palinoestratigrafia do intervalo Alagoas da Bacia do Araripe, Nordeste do Brasil. *Revista Brasileira de Geociências*, **42**(2):331-342.

Rodrigues M.G., Matos S.A., Varejão F.G., Fürsich F.T., Warren L.V., Assine M.L., Simões M.G. 2020. Short-lived "Bakevelliid-sea" in the aptian Romualdo formation, Araripe basin, northeastern Brazil. *Cretaceous Research*, **115**:104555. https://doi.org/10.1016/j.cretres.2020.104555

Rodrigues M.G., Varejão F.G., Matos S.A., Fürsich F.T., Warren L.V., Assine M.L., Simões M.G. 2022. High-resolution taphonomy and sequencestratigraphy of internally complex, bakevelliid-dominated coquinas from the Aptian Romualdo Formation, Araripe Basin, NE Brazil. *Marine and Petroleum Geology*, **143**:105814. https://doi.org/10.1016/j.marpetgeo.2022.105814

Roth P.H. 1978. Cretaceous nannoplankton biostratigraphy and oceanography of the northwestern Atlantic Ocean. *Initial Reports of the Deep Sea Drilling Project*, **44**:731-760.

Roth P.H., Bowdler J.L. 1981. Middle Cretaceous calcareous nannoplankton biostratigraphy and oceanography of the Atlantic Ocean. *SEPM Special Publications*, **32**:517-546.

Roth P.H., Krumbach K.R. 1986. Middle Cretaceous calcareous nannofossil biogeography and preservation in the Atlantic and Indian Oceans: implications for palaeoceanography. *Marine Micropaleontology*, **10**(1-3):235-266. https://doi.org/10.1016/0377-8398(86)90031-9

Silva Jr. R., Rios-Netto A.M., Silva S.C., Valle B., Borghi L., Abbots-Queiroz F. 2020. Middle Cretaceous calcareous nannofossils from the cored well UFRJ-2-LRJ-01-SE, Sergipe-Alagoas Basin, Brazil: new biostratigraphy and paleobiogeographic inferences. *Cretaceous Research*, **106**:104245. https://doi.org/10.1016/j.cretres.2019.104245

Sissingh W. 1977. Biostratigraphy of Cretaceous calcareous nannoplankton. *Geologie en Mijnbouw*, **65**(1):37-65.

Street C., Bown P.R. 2000. Palaeobiogeography of Early Cretaceous (Berriasian-Barremian) calcareous nannoplankton. *Marine Micropalaeontology*, **39**(1-4):265-291. https://doi.org/10.1016/S0377-8398(00)00024-4

Svábenická L. 1999. Braarudosphaera-rich sediments in the Turonian of the Bohemian Cretaceous Basin, Czech Republic. *Cretaceous Research*, **20**(6):773-782. https://doi.org/10.1006/cres.1999.0182

Tantawy A.A. 2008. Calcareous nannofossil biostratigraphy and paleoecology of the Cenomanian e Turonian transition in the Tarfaya Basin, southern Morocco. *Cretaceous Research*, **29**(5-6):995-1007. https://doi.org/10.1016/j.cretres.2008.05.021

Thierstein H.R. 1976. Mesozoic calcareous nannoplankton biostratigraphy of marine sediments. *Marine Micropaleontology*, **1**:325-362. https://doi.org/10.1016/0377-8398(76)90015-3

Thierstein H., Berger W. 1978. Injection events in ocean history. *Nature*, **276**:461-466. https://doi.org/10.1038/276461a0

Thomsen E. 1989. Seasonal variability in the production of Lower Cretaceous calcareous nannoplankton. *Geology*, **17**(8):715-717. https://doi.org/10.1130/0091-7613(1989)017%3C0715:SVITPO%3E2.3.CO;2

Valença L.M.M., Neumann V.H., Mabesoone J.M. 2003. An overview on Callovian–Cenomanian intracratonic basins of Northeast Brazil: onshore stratigraphic record of the opening of the Southern Atlantic. *Geologica Acta*, **1**(3):261-275. https://doi.org/10.1344/105.000001614

Watkins D.K. 1989. Nannoplankton productivity fluctuations and rhythmically bedded pelagic carbonates of the Greenhorn Limestone (Upper Cretaceous). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **74**(1-2):75-86. https://doi.org/10.1016/0031-0182(89)90020-5

Williams J.R., Bralower T.J. 1995. Nannofossil assemblages, fine fraction stable isotopes, and the paleoceanography of the Valanginian–Barremian (early Cretaceous) North-Sea Basin. *Paleoceanography*, **10**(4):815-839. https://doi.org/10.1029/95PA00977

Wise S.W. 1983. Mesozoic and Cenozoic calcareous nannofossils recovered by DSDP Leg 71 in the Falkland Plateau region, Southwest Atlantic Ocean. *Initial Reports of the Deep-Sea Drilling Project*, **71**:481-550.

Wise S.W. 1988. Mesozoic-Cenozoic history of calcareous nannofossils in the region of the Southern Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **67**(1-2):157-179. https://doi.org/10.1016/0031-0182(88)90127-7

Young J.R., Bown P.R., Lees J.A. 2017. Nannotax3 website. International Nannoplankton Association. Available at: http://www.mikrotax.org/Nannotax3. Accessed on: January 19, 2022.