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Paleontological study of the Oligocene/Miocene boundary in the Ilha de Santana and Pirabas formations, Pará-Maranhão Basin on the Northwest equatorial platform of Brazil

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A R T I C L E I N F O

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A B S T R A C T

Sedimentary carbonate outcrops of the Pirabas Formation at the Bragantina platform in North Brazil represent the exposed portion of the entire carbonate succession in the marine equatorial platform from the subsurface Ilha de Santana Formation (Cretaceous/Maastrichtian-Miocene/Messinian) in the Pará-Maranhão Basin. The transgressive deposits, flooding, and advance of the carbonate platform were investigated through the study of outcrops of the Pirabas Formation (type locality in the Ilha de Fortaleza, Pará state) and the analogous carbonate from the uppermost section of the Ilha de Santana Formation from the well 1-MAS-16-MA (510–660 m below sea floor). The stratigraphic analyses were based on petrography, microCT, microfossil assemblages (foraminifera, ostracods, and bryozoans) and index species (*Amphistegina*, *Archaias*, *Pyrgo*, *Quinqueloculina*, *Pirabasoporella*, *Nellia*, *Skylonia*, and *Alpheus*), and biofacies approach. The Ilha de Santana Formation (Burdigalian/Langhian at 510–660 mbsf section of 1-MAS-16-MA) and the Pirabas Formation (Burdigalian at the Ilha de Fortaleza outcrops) suggest that shallow-water sedimentary facies are similar to those deposited in the marginal basins and mark the start of siliciclastic supplies to the inner platform and the decline of coralline algae carbonate factories.

1. Introduction

The Cenozoic is distinguished by remarkable climate and paleoceanographic global changes that have been recorded during the Oligocene and Miocene epochs, including the Late Oligocene Warming, the Miocene Climate Optimum, and the Middle Miocene Climate Transition (Lear et al., 2015; Frigola et al., 2018; Steinthorsdottir et al., 2021 and references therein). These changes have resulted from alternating cold and warm periods, coupled with fluctuations in sea levels (Kominz et al., 2008; Müller et al., 2008; Miller, 2009; Miller et al., 2020), which have had notable impacts on marine ecosystems.

Given the fragmented and discontinuous nature of the geological record pertaining to continental shelves, our comprehension of how shallow marine water environments responded to the climatic oscillations during this Oligocene to Miocene interval remains globally limited (Alvarado et al., 2023; Kumar et al., 2023).

However, the currently equatorial Brazilian shelf exhibits a distinctive composition of mixed carbonate-siliciclastic deposits (Testa and

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Bosence, 1999; Mahiques et al., 2019). These deposits predominantly contain bioclastic elements, primarily composed of shallow-water heterozoan (*sensu* James, 1997 ; Michel et al., 2018). It is also worth noting that the Oligocene–Miocene transition, a significant environmental event (Rossetti et al., 2013), does not coincide with the expected major faunal turnover (Alvarado et al., 2023).

The primarily faunal turnover within the Ilha de Santana Formation in the Pará-Maranhão Basin, Brazil, occurs during the late early Miocene to the early middle Miocene (Burdigalian: 20.44–15.98 Ma to Langhian: 15.98–13.82 Ma) (geochronological time scale of Gradstein et al., 2020). This pattern in the Brazilian North shelf (Alvarado et al., 2023) is also observed in the South shelf at Campos Basin (BouDagher-Fadel et al., 2010).

The middle Miocene (Langhian: 15.98–13.82 Ma to Serravallian: 13.82–11.63 Ma) witnessed significant global climate fluctuations, beginning with a warming climate during the Middle Miocene Climatic Optimum (MMCO), compared to the late Oligocene – early Miocene transition, and following by a notable expansion of the Antarctic ice sheet during the Middle Miocene Glaciation (MMG) (Frigola et al., 2018; Methner et al., 2020).

Finally, the late Miocene on the equatorial Brazilian coast was characterized by the establishment of the Amazonas River Delta, the progradation of the Barreiras Formation, and the collapse of carbonate producers (Figueiredo et al., 2007; Rossetti et al., 2013; Cruz et al., 2019; Nogueira et al., 2021; Aguilera et al., 2022).

Following Soares et al. (2007), presentation of the PETROBRAS chronostratigraphic chart and descriptions of the Pará-Maranhão Basin on the equatorial platform of Brazil, there has been a noticeable dearth of research papers aimed at confirming and updating our understanding of the paleostratigraphy and geochronology concerning with the carbonate-siliciclastic deposits within this basin. This scarcity emphasizes the need for comprehensive contributions to validate and enhance the existing knowledge of this basin, particularly focusing on the upper portion of the Miocene Ilha de Santana Formation section.

The Miocene carbonate-siliciclastic deposits of the Pirabas Formation are well-documented in marine coastal outcrops and quarries at the Pará state (Aguilera et al., 2022 and reference therein). However, the correlation of carbonate sedimentary successions between the subsurface Ilha de Santana Formation in the Pará-Maranhão Basin and the exposed coastal plain outcrops of the Pirabas Formation at the Pará requires careful interpretation. This correlation is essential for shedding light on the significant paleoenvironmental Miocene changes and biota collapses, especially the decline of carbonate producers, including coralline algae and heterozoan invertebrate assemblages.

A comprehensive integrated analysis is necessary to elucidate the transitional sedimentary sequence between the subsurface Burdigalian–Langhian section of the Ilha de Santana Formation (510–660 m below sea floor) (mbsf from here onward) and the coastal outcrops of the Burdigalian sections of the Pirabas Formation. This analysis should encompass multiple aspects, including lithology, petrography, paleontology assemblages (foraminifera, ostracods, and bryozoans), and paleoenvironmental interpretations.

2. Geological setting

The Ilha de Santana Formation (Abreu et al., 1986; Brandão and Feijó, 1994; Soares et al., 2007; Zalán, 2015; Pellegrini and Ribeiro, 2018) is a significant geological unit situated within the Humberto de Campos Group in the Pará-Maranhão Basin, part of the marine Equatorial Platform of Brazil. This formation comprises an extensive carbonate sequence from the Cretaceous (Maastrichtian) and encompasses a substantial portion of the Cenozoic (Oligocene and Miocene), consisting of a diverse succession of calcarenites, calcirudites, calcilutites, marls, shales, and mudstones.

In the uppermost section of well 1-MAS-16-MA (between 510 and 660 mbsf) as investigated by Alvarado et al. (2023), evidence suggests an age spanning from Burdigalian–Langhian. This interval represents the initial biofacies (BF-1) of the Ilha de Santana Formation, dominated by fragments of calcareous algae and large benthic foraminifera. Amphisteginids are the predominant large benthic foraminifera, with minor occurrences of soritids and small benthic foraminifera (both hyaline and porcelaneous). However, encrusting benthic foraminifera, mollusks, bryozoans, corals, and echinoderms are relatively scarce (Alvarado et al., 2023).

The Pirabas Formation (Maury, 1925) is well-recognized through coastal plain outcrops in municipalities such as Maracanã, Salinópolis, and São João de Pirabas, as well as quarries in Capanema and Primavera, all located in the Pará state, along the northeastern Atlantic coastal of Brazil. This unit represents a mixture of carbonatic–siliciclastic deposits formed in shallow waters (Rossetti et al., 2013; Aguilera et al., 2022), spanning from the late early Miocene to the late middle Miocene. However, recent studies examining the Ponta do Castelo and Fazenda outcrops, based on palynomorphs, suggest an age of late early Miocene (Burdigalian) (Gomes et al., 2023). The Pirabas Formation is notable by its coralline algae beds associated with a rich diversity of marine micro- and macrofossil fauna, mostly composed by foraminifera, ostracods, sponges, mollusks, echinoids, ophiuroids, asteroids, crinoids, bryozoans, decapod crustaceans, fish, sirenid mammals, and ichnofossil, extensively documented in numerous studies (e.g. Aguilera and Páes, 2012; Aguilera et al., 2017; Ramalho et al., 2019; Lima et al., 2020a, b; Bencomo et al., 2021; De Araújo et al., 2021; Kerber and Moraes–Santos, 2021; Lima et al., 2021; Aguilera et al., 2023). Aguilera et al. (2022) distinguish four main facies within the Pirabas Formation: i) facies α1, shallow-water offshore platform characterized by echinoderm-bryozoan packstone to rudstone (with ≤10% of siliciclastic content in the rock); ii) facies α2, shallow-water inner platform, comprising siliciclastic-rich wackestone to packstone (with siliciclastic content ranging between 10% and 30%); iii) facies β, shallow coastal plain dominated by siliciclastic fine-grained sandstone to mudstone (with ≥50% siliciclastic content); and, iv) facies *Y*, restricted tidal coastal plain of marginal mangroves dominated by sand-sized angular grains, iron-rich nodules, and pyritized fossils.

These paleoenvironments range from the marginal mangrove zone to the surf zone and shallow-water sandy bottoms (Aguilera et al., 2020a, 2020b). They also include the inner to middle platform areas influenced by high-energy tropical storms at the Ponta do Castelo and Fazenda outcrops studied here (Aguilera et al., 2023).

Notably, the Pirabas Formation is also recorded in subsurface sections of the Barreirinhas Basin, within the Humberto de Campos Group, overlapping the Ilha de Santana Formation (Pamplona, 1969; Trosdtorf Jr. et al., 2007) in the Brazilian equatorial carbonate platform (see Cruz et al., 2019 and reference therein). However, there are currently no specific research papers available that provide detailed insights into micropaleontology, carbonate frameworks, geochemistry, or comprehensive biostratigraphy for the subsurface section of the Pirabas Formation in the Barreirinhas Basin. The original study of Trosdtorf Jr. et al. (2007) comment the age of the sequence within the super drifted, with divisions including E80-N10 (transgressive deposit at the equatorial margin), N20–N30 (flooding and advancement of carbonate platform), and N40–N50 (rapid advancement of carbonate platform).

The transitional microfossil assemblage at the uppermost section closely reassembles a sedimentary sequence that extends the marginal coastal plain bordering the Pará-Maranhão Basin in the expressive shallow water carbonate–siliciclastic deposit of Miocene Pirabas Formation and the uppermost section (between 510 and 660 mbsf) from the Ilha de Santana Formation,

Both, Ilha de Santana Formation (Burdigalian – Langhian at 510–660 mbsf section of 1-MAS-16-MA) and the Pirabas Formation (Burdigalian at the Ilha de Fortaleza outcrop) suggest that shallow-water sedimentary facies and microfossil assemblages are similar to those deposited in the marginal basins and mark the start of siliciclastic supplies to the inner platform and the reduction of coralline algae carbonate factories.

3. Material and methods

The Ilha de Santana Formation samples from the uppermost section, extracted from the Humberto de Campos Group, Brazil (Fig. 1), encompass eleven cutting samples taken from the well 1-MAS-16-MA, between 510 and 660 mbsf within the Pará-Maranhão Basin, situated on the equatorial platform of Brazil, 200 km away from the coastline (0° 14′9.3″ N, 44° 48′21.3" W). The core was loaned by the Brazilian

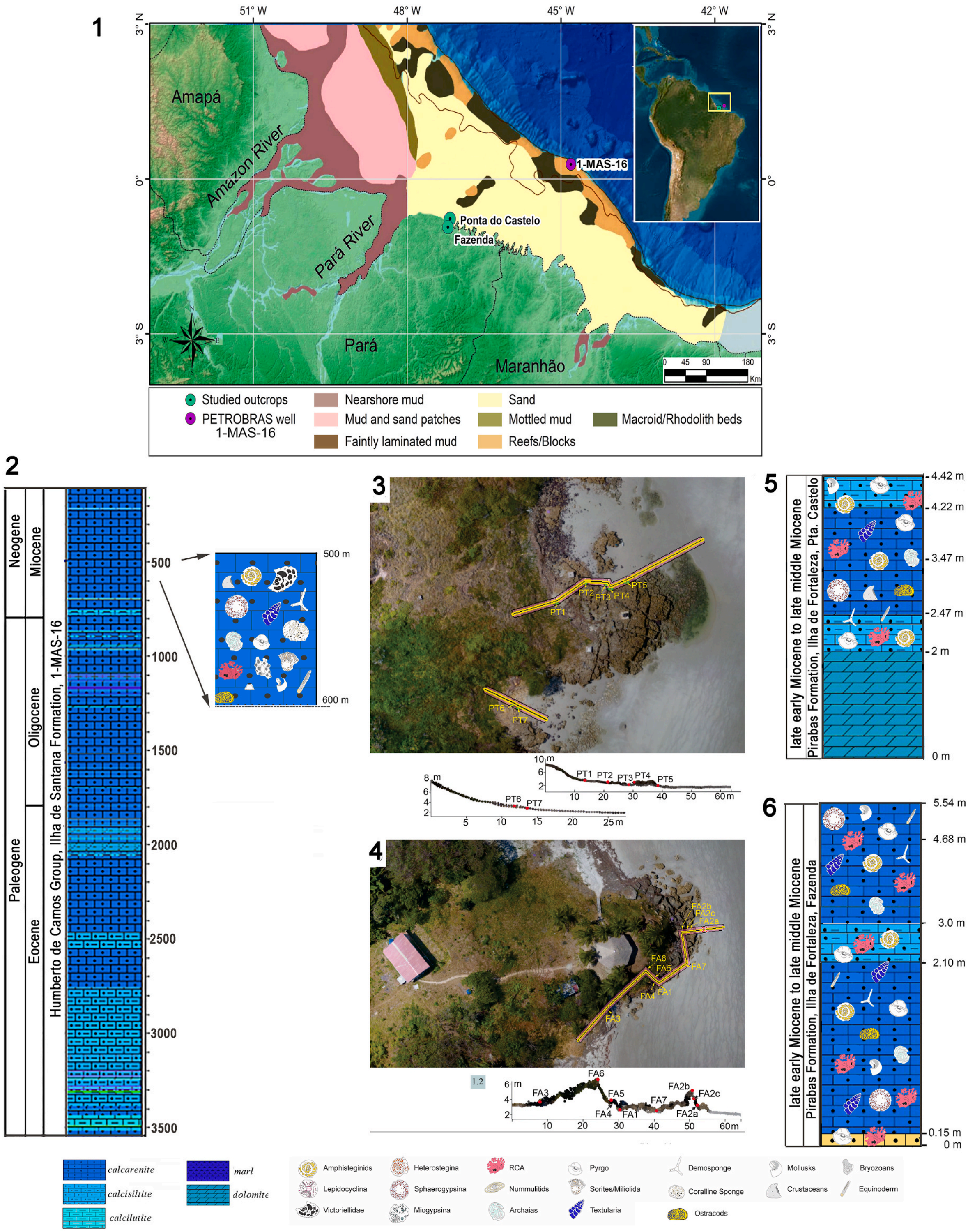

Fig. 1. 1, Map of the northwestern Brazilian platform (modified from Banha et al., 2022; Vale et al., 2022; Alvarado et al., 2023) showing the Pará-Maranhão Basin, the reference location of the Pirabas Formation outcrop at Ilha de Fortaleza in the coastal plain, and the subsurface referential point of the Ilha de Santana Formation from the wells 1-MAS-16-MA (0°14′9.30″ N; 44°48′21.25″ W) in the equatorial platform. 2, the schematic section of 1-MAS-16-MA from the Ilha de Santana Formation and the schematic study section 510 to 660 m depth). 3, detailed samples profiles 1 and 2 of planimetric images showing the outcrops samples from the Ponta do Castelo transect (PT1–PT7). 4, detailed samples profile of planimetric images showing the outcrops samples from the Fazenda sample transect (FAZ1–FAZ7). 5, the schematic section from the Ponta do Castelo outcrop. 6, the schematic section from the Fazenda outcrop.

National Petroleum Agency (ANP, Protocol SAA 46.19), along with the associated well drilling data (Protocol 48610.211469/2019–39) for subsequent analysis.

To prepare the cutting samples, measuring 3 cm^3 each, taken from depths of 510, 522, 534, 540, 552, 558, 570, 588, 624, 642 and 660 mbsf, they underwent a series of treatments. These treatments included exposure to acetic acid for 3 min, followed by washing, sieving, and drying. After this initial processing, the specimens were meticulously picked while being observed under a stereomicroscope.

Additionally, samples from the Pirabas Formation, extracted from the type locality at Ilha de Fortaleza (Ponta do Castelo: 0°40′55.69″ S, 47°10′13.30″ W, and Fazenda: 0°42″43.79″ S, 47°9′58.65″W), São João de Pirabas municipality, Pará, Brazil, dating back to the Miocene (Burdigalian) (Fig. 1), consisted of 13 samples, each weighing approximately 1 kg. These samples were disaggregated in warm water at 70 °C, and then further processed in the laboratory, sieved, using mesh sizes of 500 μm, 250 μm, 125 μm, and 63 μm. The samples had a spacing according to the lithology changes and almost two samples by layer. Then, the specimens were picked using a stereomicroscope. Selected specimens were subsequently prepared for scanning electron microscope (SEM) imaging employing a TESCAN Mira3 FEG electron microscope. The samples were affixed to aluminum supports with a 12 mm diameter using double-sided carbon adhesive tape, followed by metallization with a thin layer of Au over a 90-s period, creating an average film thickness

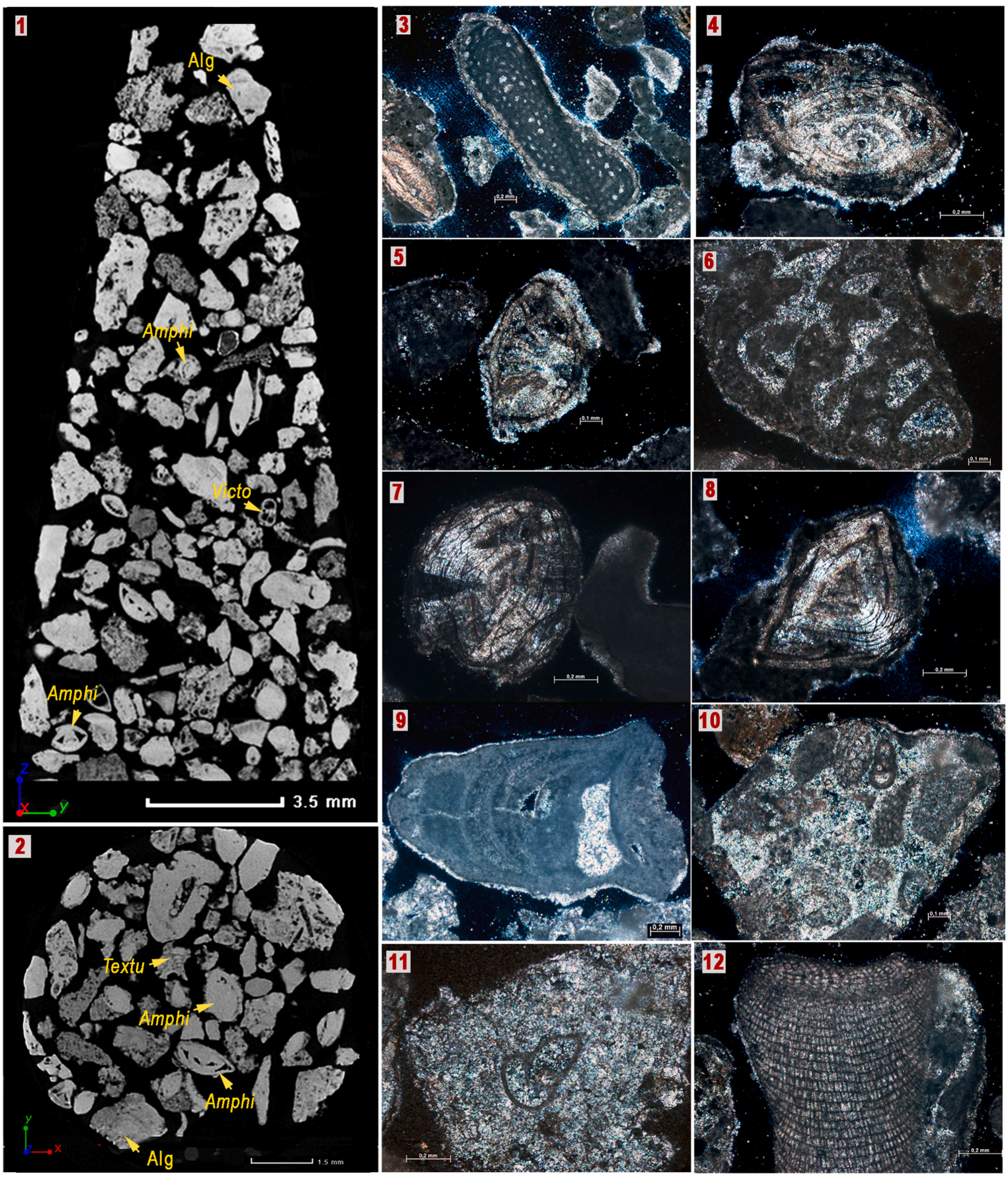

Fig. 2. 1–2, Digital microCT sections; 3–12 photomicrograph of petrography thin section from the same cutting samples from the Ilha de Santana Formation (well 1–MAS-16-MA; section depth 570 m). 3, coralline algae; 4–5, *Amphistegina*; 6, *Textularia*; 7–8, *Amphistegina*; 9, coralline algae; 10, small benthic foraminifera and algae; 11, small benthic foraminifera; 12, coralline algae. Abbreviations: Alg = algae; *Amphi* = *Amphistegina*; Bryo = bryozoans; *Textu* = *Textularia*; *Victo* = *Victoriella*.

of 12 nm. Images were captured using secondary electron detection, utilizing a voltage acceleration ranging from 5 to 1 kV and a working distance of approximately 15 mm.

For both the Ilha de Santana and Pirabas formations samples, selected fossil underwent microCT scanning to generate 3D volumetry digital images. These images were then subject to detailed examination of their outer and inner morphologies using a V | Tome |x M (GE Measurement & Control Solutions, Wunstorf, Germany). The Phoenix Data software was used for 3D reconstructions, incorporating slice alignment, beam hardening correction, ring artifact reduction, and application of a mathematical edge-enhancement filter to enhance specimen contrast. The 3D visualizations were accomplished using VG Studio Max v 3.0 software, with additional image editing carried out in Adobe Photoshop.

In conjunction with these analyses, 12 thin petrographic sections were prepared from the cutting samples obtained from the Ilha de Santana Formation subsurface section (510–660 mbsf), while 19 thin petrographic sections were generated from the Pirabas Formation outcrops at Ilha de Fortaleza for qualitative and quantitative analysis. These samples were fixed on 76 × 26 mm glass slides and polished to a thickness of 30 μm. Photomicrographs were obtained using a petrographic microscope AXIO Lab A1 (Zeiss), equipped with an integrated Axiocam Erc 5s digital system.

4. Results

4.1. Ilha de Santana Formation (section 510 to 660 mbsf)

The lithology and petrographic characteristics of this section primarily consist of calcarenite, mostly composed of bioclastic materials. The primary bioclastic components comprise encrusting and articulate coralline algae, with a notable abundance of large benthic foraminifera species such as soritids, nummulitids, planorbulids, amphisteginids, and

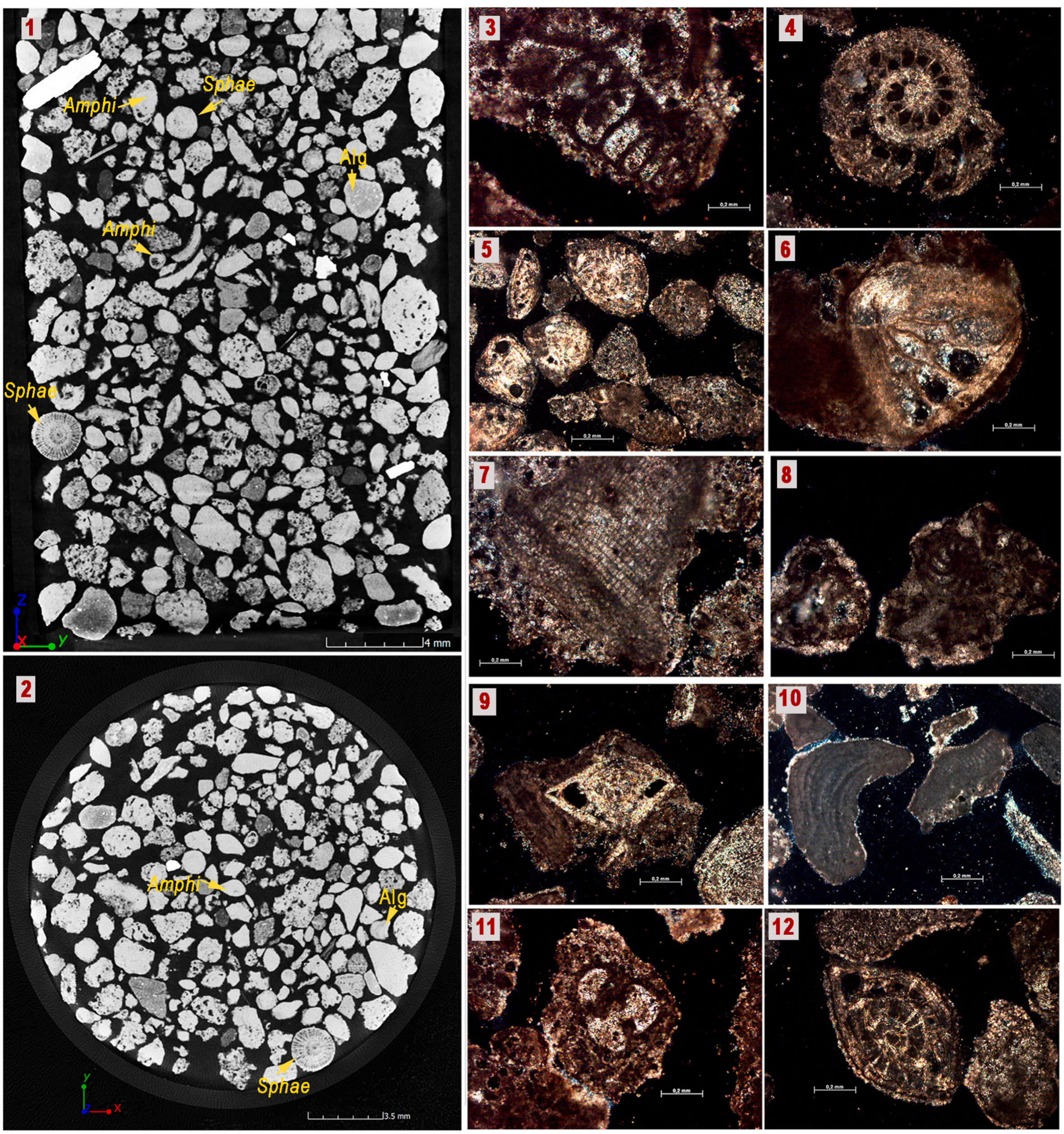

Fig. 3. 1–2, Digital microCT sections; 3–12, photomicrograph of petrography thin section from the same cutting samples from the Ilha de Santana Formation (well 1–MAS-16-MA; section depth 522 m). 3, *Textularia*; 4–6, *Amphistegina*; 7, coralline algae; 8, *Archaias*; 10, coralline algae; 11, agglutinate foraminifera; 12, *Amphistegina*. Abbreviations: Alg = algae; *Amphi* = *Amphistegina*; *Sphae* = *Sphaerogypsina*.

small textularids (Figs. 2 and 3). Other bioclastic components include bryozoans and echinoids. Ostracods, sponges, mollusks, cirriped, and decapod crustaceans are present. However, the occurrence of fish remains is relatively rare.

The fossil assemblage found within the Ilha de Santana Formation is mostly represented by: coralline algae (Corallinales and Corallinaceae); Porifera (Demospongiae); Foraminifera (Acervulinidae, Amphisteginidae, Nummulitidae, Planorbulinidae, Soritidae, and Textularidae); ostracods (Bairdiidae, Hemicytheridae, and Thaerocytheridae); bryozoans (Jaculinidae and Steginoporellidae); crinoids (Comatulidae); ophiuroids

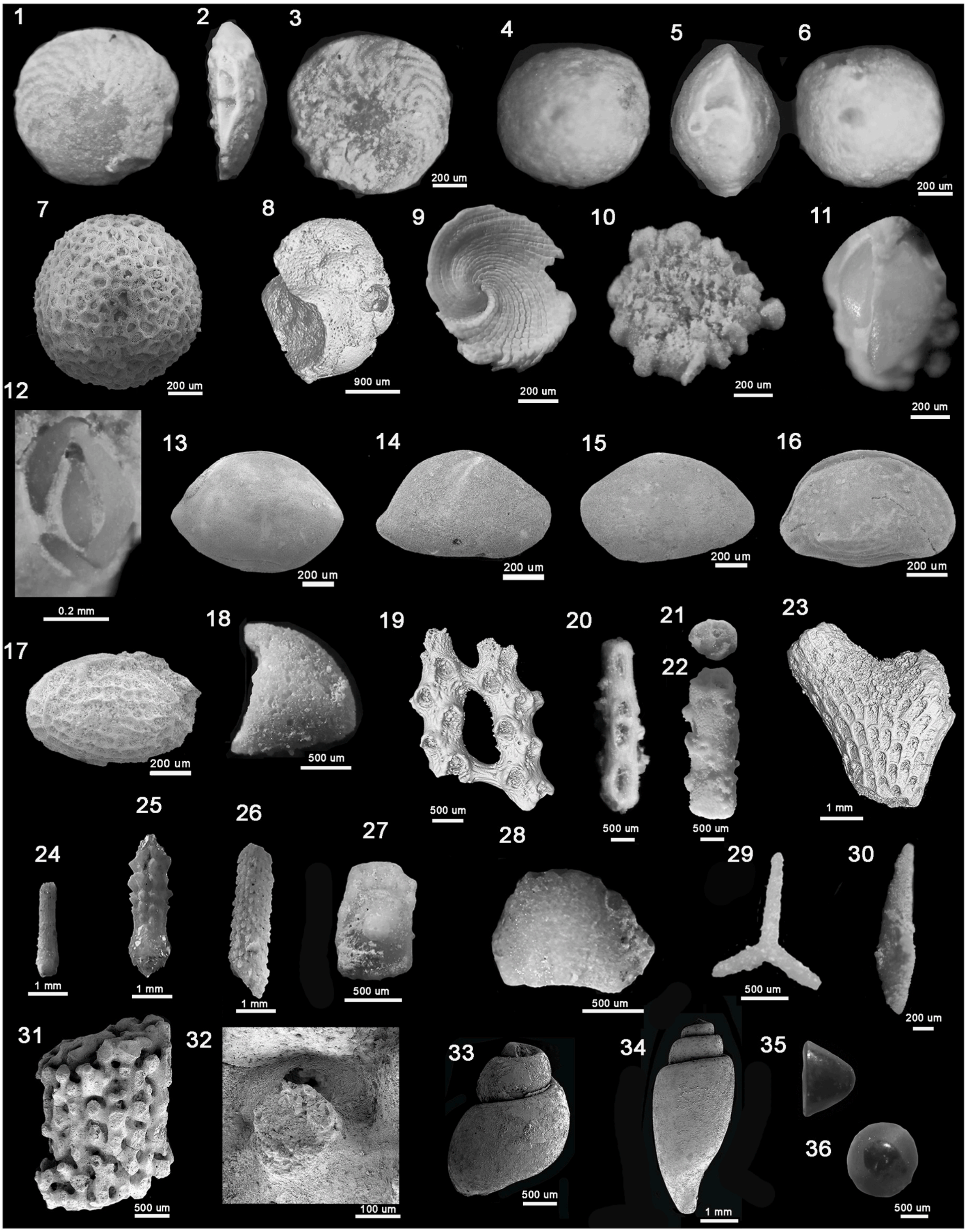

Fig. 4. Fossil diversity from the Ilha de Santana Formation (Pará-Maranhão Basin, well 1-MAS-16-MA, section 510 to 660 m). 1–3, *Amphistegina lessonii*; 4–6, *Amphistegina* sp.; 7, *Sphaerogypsina* sp.; 8, *Victoriella* sp.; 9, *Archaias angulatus*; 10, *Planorbulinella* sp.; 11, *Pyrgo* sp.; 12, *Quinqueloculina* sp.; 1–12, foraminifera; 13–17, ostracods; 18, *Alpheus* sp.; 19, *Pirabasoporella atalaiaensis*; 20, *Nellia tenella*.; 21–22, *Margaretta* sp.; 23, *Metrarabdotos* sp., 24–27, echinoids spines and ambulacral plate; 28; Gorgonocephalidae ophiuroids; 29–30, Demospongiae spicules; 31–32, indeterminate coral; 33, Naticidae (cf. *Amauropsis*); 34, Margenillidae (cf. *Marginella*); 35–36, Teleostean teeth.

(Gorgonocephalidae); decapod crustaceans (Alpheidae); and teleostean fishes (Fig. 4, Table 1).

The paleoenvironment of this section is characterized by dense bioclast beds mostly composed of coralline algae, associated with epifauna that inhabits shallow water, characterized by oligotrophic conditions, normal salinity levels, and warm water temperatures. This environment is situated in the inner marine platform, relatively distant from coastal influences far from the terrigenous sediment input from the coast.

Both macro and microfossil assemblages from this section interval provide evidence suggesting an age range from the late early Miocene (Burdigalian) to early middle Miocene (Langhian). This evidence is supported by the presence of bryozoans comprising *Pirabasoporella atalaiensis, Nellia* cf. *tenella.,* and *Skylonia* sp*.,* decapods (*Alpheus* sp.), the abundance of *Amphistegina lessonii*, and the common occurrence of species such as *Archaias angulatus*, *Pyrgo* sp., *Quinqueloculina* sp., and *Sphaerogypsina* sp. On the other hand, the absence of *Lepidocyclina* and *Miogypsina* distinguished this uppermost section from deeper sections. This estimated age aligns with the Biozone IS-1, Biofacies 1 characterized by the assemblage of *Amphistegina*–*Sphaerogypsina*, and the U/Pb analyses suggesting Burdigalian–Langhian age discussed in Alvarado et al. (2023).

4.2. Pirabas Formation from the Ilha de Fortaleza type locality

At Ponta do Castelo outcrop, the lithology and petrography are primarily characterized by packstone, mudstone and wackstone. Terrigenous grains, predominantly sand-sized and possessing subangular to subrounded shapes, are prevalent. The primary bioclastic components consist of echinoid spines likely from cidarids, as well as fragments of jaculinids and quadricellariids bryozoans. The foraminifera assemblage comprises small miliolids, textulariids, soritids, small rotaliids, and large amphisteginids (Fig. 5, Tables 2 and 3).

Conversely, at the Fazenda outcrop, the lithology is characterized by coarse-grained packstone, with terrigenous grains being sand-sized and subangular to subrounded. The primary bioclastic components include bryozoans and echinoids, followed by mollusk fragments. The foraminifera assemblage consists of small miliolids, rotaliids, soritids, textulariids, and large amphisteginids (Fig. 6, Tables 2 and 3).

The fossil assemblage within the Pirabas Formation predominantly includes macrofossils such as: i) mollusks (bivalves and gastropods) typically inhabiting shallow waters, sandy coastlines with seagrasses, mangroves, sandy beaches, and consolidated bottoms; ii) echinoderms (echinoids, crinoids, and ophiuroids) inhabiting shallow waters over sandy bottoms; iii) bryozoans (encrusting, erect, and free), mostly found on shells, tests, and consolidate bottoms; iv) corals (ahermatypic), primarily in shallow-water environments with soft bottoms; v) crustaceans (cirripeds and decapods) typically found in shallow-waters, sandy coastlines, seagrasses, and mangroves; vii) fishes (sharks, rays, and bonefish) exhibiting demersal and pelagic habits (Table 1; see Aguilera et al., 2023 and references therein for detailed paleoenvironment). The microfossil comprises i) encrusting and articulate coralline algae; ii) sponges; iii) foraminifers; iv) ostracods; and v) bryozoans (Figs. 7 and 8; Table 1; Aguilera et al., 2023 and references therein).

Based on the macro- and microfossil assemblages, diversity, lithology, and geochemistry, both the Ponta do Castelo and Fazenda outcrops suggest a paleoenvironment characterized by clean tropical shallow waters within the inner platform, with minimal terrigenous input. The stratigraphy and faunal assemblages from the Ponta do Castelo and Fazenda outcrops point an age of late early Miocene (Burdigalian).

Table 1
Microfossil diversity and counts of specimens from the Ilha de Santana Formation (well 1-MAS-16-MA), Pará-Maranhão Basin, Brazil.

ILHA DE SANTANA FORMATION (Well 1-MAS-16-MA)											
FORAMINIFERA	**510 m**	**522 m**	**534 m**	**540 m**	**552 m**	**558 m**	**570 m**	**588 m**	**624 m**	**642 m**	**660 m**
Amphistegina lessonii		285	220	367	2070	865	500	475	875	969	165
Miogypsina sp.			2		1						145
Nummulites sp.							5		2		
Lepidocyclina sp.											43
Sphaerogypsina sp.		60	9	10	15	17	8	3	6	6	1
Planorbulinella sp.			3	4	8		2	14	4	2	
Victoriella sp.		3	2	3	1		1	2	1	14	2
Archaias angulatus		1				18		1			6
Pyrgo sp.							3	1		2	
Quinqueloculina sp.						1			1		
OSTRACODA											
Bairdoppilata sp.	1	8						5	2	3	3
Paranesidea sp.							1				
Neonesidea sp.								2			
Aurila sp.								2			
Quadracythere sp.							1				
BRYOZOA											
Mamilloporidea		13				2					
Metrarabdotos sp.		5		1		2					
cf. Microporidae		1									
Pirabasoporella atalaiensis					12	21	1	3	2	1	
Nellia tenella		3	8	2	10	1			2	1	
Bryozoa ind.				2						5	4
PORIFERA											
Demosponges megasclere									4	3	5
ECHINODERMATA											
Echinoids ind.		59	6	20	2	14	8		7	28	2
MOLLUSCA											
Naticidae and Margenillidae (molds)										3	3
TELEOSTEI											
Teleostean (teeth)		1		1				1			
CRUSTACEA DECAPODA											
Alpheus sp.		1									
dactyl ind.		2			2	2			3	2	

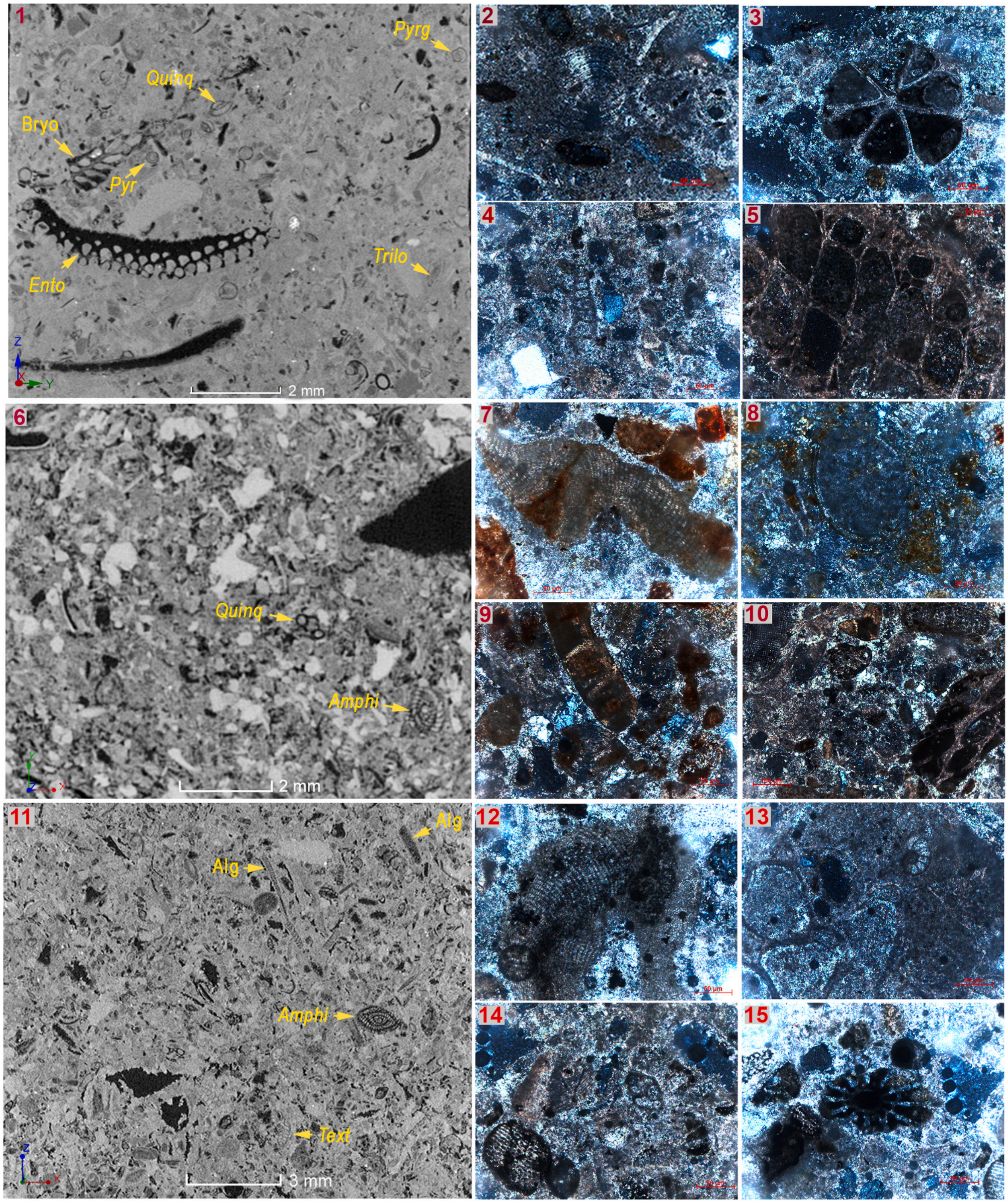

Fig. 5. Digital microCT sections (left column) and photomicrograph of petrography thin section (right doble column) of same lithified rock plugs samples from Ilha de Fortaleza, Ponta do Castelo outcrop. 1, plug PTA1; 2, *Amphistegina*; 3, bryozoan; 4, *Textularia*; 5, bryozoan. 2, plug PTA2; 7, coralline algae; 8, ostracod; 9, algae and *Amphistegina*; 10, bryozoan; 11. Plug PTA6; 12, coralline algae; 13, bryozoan and small benthic foraminifera; 14, *Amphistegina*, small benthic foraminifera, echinoid, and algae; 15, echinoid spine. Abbreviations: Alg = algae; *Amphi* = *Amphistegina*; Bryo = bryozoans; *Pyr* = *Pyrgo*; *Quinq* = *Quinqueloculina*; *Text* = *Textularia*; *Trilo* = *Triloculina*.

5. Discussion

The carefully approached studies of faunal assemblages for accurate interpretations need to take the context of lithology, the age, and the micro- and macrofossil inter-relationship. The comparative analysis between cuttings from the Ilha de Santana Formation 1-MAS-16-MA and to the Pirabas Formation outcrop samples at Ilha de Fortaleza, need to take in account the intrinsic uncertainty related to the stratigraphic placement of cuttings samples to perform highly accurate analyses of biota context, using the interval (biozone type *sensu* Andrade Oliveira et al., 2017). First, in the cutting samples the medium to large fossil specimen sizes is pulverized during the mechanical drill processes and transport by the drilling fluid; second, cast and empty molds (print) of specimens (e.g., mollusks, echinoids, and corals) from the pulverized rock cannot be recorded; and third, the sample rock volume is reduced. Cuttings samples for stratigraphy research are highly efficient for

Table 2
Microfossil diversity and counts of specimens from the Pirabas Formation (Ponta do Castelo and Fazenda outcrops in the type locality of Ilha de Fortaleza, Pará state, Brazil).

PIRABAS FORMATION (ILHA DE FORTALEZA)													
FORAMINIFERA	**Ponta do Castelo**							**Fazenda**					
	PTA1	**PTA2.1**	**PTA2.2**	**PTA3.1**	**PTA3.2**	**PTA4**	**PTA6**	**FAZ2**	**FAZ3.1**	**FAZ3.2**	**FAZ3.3**	**FAZ5**	**FAZ6**
Ammonia beccarii	1			71	1			83				2	
Amphistegina lessonii	2			327	16	6		8	10		17	16	10
Archaias angulatus	5	5	1		15	1						4	7
Bolivina sp.				3				1					
Cibicides sp.				34								4	6
Cibicides pirabensis				46		19							
Cibicidoides wuellerstorfi				2							1		
Discorbis sp.				18		11							
Discorbis paraensis						11		18					
Elphidium poeyanum				12				3					
Elphidium sagrai	1			4									
Lagena cf. *perlucida*	6			1				8			5		
Nonioella pirabensis					1								
Oolina sp.				1									
Pyrgo depressa	58	28	38	44	7	14	2	46	18	22	3		7
Pyrgo cf. *inornata*		1											
Pyrgo subsphaerica	31	15	20	14	3	13	1	17	9	4	4		
Pyrgo sp.	17		4			3		4	2				
Quinqueloculina lamarckiana	6	13	17		2	5		7	6	5			
Quinqueloculina fusiformis	1	3	9	4				17					
Triloculina oblonga	4		3	1		3		1					
Uvigerina peregrina								2					
Globigerina bulloides	2			1									
Globigerina sp.	2			3				1					
Globigerinella sp.	1												
Globigerinoides subquadratus	5												
Globoturborotalita sp.	1												
OSTRACODA													
Aurila amygdala	1		6	4					1			2	
Aurila cf. *cicatricosa*	1												
Aurila sp.					1								
Bairdoppilata pintoi					1								
Bairdoppilata oblongata					1								
Cativella sp.		66	14		1	28	1						
Cytheridea sp.		1	6	5	1			1	1				2
Cytherella cf. *notossinuosa*				3	2			1	4			5	2
Cytherelloidea mediocythara	2										1		
Cytheretta cf. *punctata*				1				1	1			3	
Cushmanidea sp.		4	4										
Quadracythere sp. 1			4	5	3				3	1			
Quadracythere sp. 2			4	1									
Gangamocytheridea sp.				3									
Neonesidea amygdaloides		4	8	10		19	5	1	5			2	7
Neonesidea sp.		1	7	4	1	5		10	4			4	6
Paracytheridea sp.					2								
Paracypris sp.		2						2	5			2	
Propontocypris sp.		2	2			7		4		1			1
Pellucistoma magniventra									5				
Puriana rugipunctata				1									
Semicytherura sp.	1	1			1			2					
Xestoleberis dactylotypa		13		13	4	22		5					
BRYOZOA													
Bugula sp.	134			77		9			9			1	1
Catenicella sp.	14					3				3	4		
Pirabasoporella atalaiensis	22			22									
Cyclostomatida	2												
Pasythea sp.	12			2		18				2			
Nellia tenella	411	3		426	17	29			71	4	2		
Skylonia sp.				31					4				
?*Reteporidea* sp.				2									
Crisia sp.	3			2	2				1			2	
Metrarabdotos sp.	5												
PORIFERA													
Demospongiae (megascleras)	3		3	568		9	21		37	4	4	3	13
ECHINODERMATA													
Equinoids ind.	2			69	1	10			7	2	1		5
Prionocidaris sp.				1									
MOLLUSCA													
Mollusk ind.	13		38	158		12		1					6
PISCES													
Fish ind.	1	6	2	4	4	1		1	2			2	9

Table 3
Lithological characteristics, skeletal and foraminiferal assemblages of the examined samples from the Ilha de Fortaleza outcrops based on point- and area-counting analysis, respectively.

ID sample	Matrix	Cement	Grains	Matrix description	Cement description	Grain description	Bioclasts description	Classification
FAZ6 (510 cm)	60%	10%	30%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.	Homogeneous carbonate cement	Quartz grain between 100 and 1297 μm (fine to coarse sand) predominantly grains with 187 μm (fine sand), calcite grains with 140 μm (fine sand), and bioclast range between 305 and 2900 μm (medium sand to gravel).	Algae (62,5%), Benthic Foraminifera (7,03%), Planktonic Foraminifera (5,46%), Bryozoans (15,62%), Echinoids (8,6%), and Ostracods (0,78%).	Wackstone
FAZ5 (426 cm)	70%	0%	30%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.		Poorly selected, rounded calcite grains, ranging from 70 to 810 μm (fine sand to coarse sand), predominating grains with around 200 μm (medium sand), and the presence of bioclasts.	Algae (28.57%), Benthic Foraminifera (14.28%), Planktonic Foraminifera (4.76%), Bryozoasn (23.8%), and Echinoids (28.57%).	Wackstone
FAZ3 (255 cm)	85%	0%	15%	Homogeneous carbonate matrix, dark, and micritic		Calcite grains ranging from 50 to 700 μm (silt to coarse sand), with a predominance of 125 μm grains (fine sand), and the presence of bioclasts.	Algae (45%), Benthic Foraminifera (21.57%), Planktonic Foraminifera (7.84%), Bryozoans (13.72%), Echinoids (7.84%), and Ostracods (3.92%).	Wackstone
FAZ2 (150 cm)	80%	0%	20%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.		Quartz grains poorly selected, angular, ranging from 43 to 202 μm (silt to medium sand) with a predominance of 100 μm grains (fine sand), calcite grains around 400 μm (medium sand), and bioclasts.	Algae (35.29%), Benthic Foraminifera (13.72%), Planktonic Foraminifera (15.68%), Bryozoans (25.5%), Echinoids (5.88%), and Ostracods 3.92%).	Wackstone
FAZ7 (25 cm)	60%	10%	30%	Homogeneous, dark micritic clayey matrix, crystallized between the grains	Microcrystalline carbonate cement recrystallized between the grains and the bioclast cavity	Calcite grains ranging from 60 to 1600 μm (fine sand to coarse sand) with a predominance of grains of about 125 μm (fine sand); Quartz grains about 160 μm (coarse sand), presence of opaque minerals, and bioclasts ranging from 831 μm to 5474 μm (coarse sand to gravel).	Algae (59.4%), Benthic Foraminifera (7.24%), Bryozoans (11.59%), Echinoids (17.39%), Ostracods (1.44%), Molluscs (1.44%), and Barnacles (1.44%).	Mudstone
FAZ1 (10 cm)	20%	20%	60%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.	Microcrystalline carbonate cement recrystallized between the grains and the bioclast cavity	Quartz grains poorly selected, angular, around 233 μm (fine sand), calcite grains, with a characteristic cleavage angle, around 170 μm (fine sand), smaller amounts of opaque minerals around 290 μm (medium sand), and bioclasts around 40, 7 μm (silt).	Algae (66%), Benthic Foraminifera (5%), Planktonic Foraminifera (1.76%), Bryozoans (14.4%), Echinoids (10.58%), Ostracods (0.88%), Molluscs (0.8%), and Fish Scale (0.29%).	Packstone
PTA1 (440 cm)	85%	0%	15%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.		Calcite grains measuring between 30 and 550 μm (silt to medium sand), with grains of about 395 μm (medium sand) predominating, and the presence of bioclasts.	Algae (57.04%), Benthic Foraminifera (12.67%), Planktonic Foraminifera (3.52%), Bryozoans (13.38%), Echinoids (12.67%), and Ostracods (0.7%).	Mudstone
PTA6 (420 cm)	75%	0%	25%	Homogeneous carbonate matrix, dark, and micritic		Calcite grains poorly selected, angular, ranging from 75 to 600 μm (fine sand to coarse sand), mostly of grains with 250 μm (medium sand), and presence of bioclasts.	Algae (58%), Benthic Foraminifera (8.6%), Planktonic Foraminifera (2.4%), Bryozoans (6.17%), and Echinoids (7.4%).	Wackstone
PTA2 (397 cm)	60%	0%	40%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.		Calcite grains poorly selected, angular, ranging from 64 to 1000 μm (fine sand to coarse sand), with 100 μm grains predominating (fine sand), and the presence of bioclasts.	Algae (51.37%), Benthic Foraminifera (8.2%), Planktonic Foraminifera (3.6%), Bryozoans (17.43%), Echinoids (16.51%), and Ostracods (2.75%).	Packstone
PTA7 (372 cm)	60%	0%	40%	Homogeneous carbonate matrix, dark, and micritic		Calcite grains, poorly selected, angular and well fragmented, ranging from 50 to 1400 μm (silt to coarse sand), with 325	Algae (53%), Benthic Foraminifera (9.6%), Planktonic Foraminifera	Packstone

(continued on next page)

Table 3 (*continued*)

ID sample	Matrix	Cement	Grains	Matrix description	Cement description	Grain description	Bioclasts description	Classification
						μm grains predominating (medium sand), and the presence of bioclasts.	(2.4%), Bryozoans (9.6%), and Echinoids (25.3%).	
PTA4 (244 cm)	55%	0%	45%	Homogeneous carbonate matrix, dark, and micritic		Calcite grains rounded, ranging from 50 to 2300 μm (silt to gravel), with 200 μm grains predominating (medium sand), and the presence of bioclasts.	Algae (56.43%), Benthic Foraminifera (14.3%), Planktonic Foraminifera (0.99%), Bryozoans (12.8%), Echinoids (13.8%), and Ostracods (0.99%).	Wackstone/ Packstone
PTA3 (224 cm)	75%	0%	25%	Homogeneous carbonate matrix, dark, micritic, and conglomeratic-like appearance.		Poorly selected, angular calcite grains, varying from 86 to 800 μm (fine sand to coarse sand), with 215 μm grains predominating (medium sand), and the presence of bioclasts.	Algae (66.66%), Benthic Foraminifera (7.69%), Planktonic Foraminifera (3.8%), Bryozoans (7.69%), and Echinoids (14.1%).	Packstone

microfossils, such as foraminifera, ostracods, and associated bioclast especially in long stratigraphy sections (see Da Silva, 2007; Andrade Oliveira et al., 2017; Alvarado et al., 2023). On the other hand, micro- and macropaleontology research at the outcrops were useful for a large horizontal scale, and useful for collections of large and articulate specimens, e.g., echinoderms (Bencomo et al., 2021), crustacean decapods (Lima et al., 2020a), fish (Aguilera et al., 2013), marine mammals (Kerber and Moraes–Santos, 2021); and even ichnofabrics (De Araújo et al., 2021); however, the stratigraphic section from the Pirabas Formation outcrops usually is restricted to a few meters.

5.1. Ilha de Santana Formation faunal assemblages from the uppermost section 510 to 660 mbsf

The diversity of fossil fauna content from cutting samples, as explained previously, results in a sample bias, unfavorable to macrofossil records (Biozona IS-1, Biofacies 1 of Alvarado et al., 2023). However, microfossils and specially foraminifera, ostracods, and associate bioclasts are widely used to identify biozone and paleoenvironments.

The benthic foraminifera assemblages dominated by *Amphistegina lessonii*, following by *Sphaerogipsina*, *Planorbullinella*, and *Archaias angulatus*, contrast with the scarce occurrence of *Victoriella*, *Textularia*, *Pyrgo*, and *Quinqueloculina*, and mainly by the absence of lepidocyclinids and miogypsinids (Table 1). These fossil assemblages suggest a paleoenvironmental transition and the beginning of the post Miocene species turnover, toward the upper carbonate sequence exposed in the coastal margin (Alvarado et al., 2023). Previously the species *Amphistegina lessonii* was recorded in the shallow marine carbonate deposit of Miocene interval of the Marajó Formation, Marajó Basin, Cururú well, CR-1-PA. It exhibited notably high abundance (≥80%) in the interval 245 to 259 mbsf of the section (Petri, 1954). This species was widely recorded from most of the Pirabas Formation outcrops and quarries (Petri, 1957; Aguilera et al., 2020a, 2020b, 2022).

The ostracod assemblages from the Ilha de Santana Formation are those belonging to Bairdiidae (*Bairdoppilata* and *Neonesidea*) and the species of *Bairdoppilata* (e.g., *B. antillea* and *B. oblonga*) have been previously recorded from Dominican Republic at the Late Miocene Cercado Formation (Tortonian age, NN11a), Late Miocene Gurabo Formation (Messinian age, NN11b, to Early Pliocene), early late Pliocene to middle Pliocene Mao Formation (Zanclean age, NN14-NN15) (see Saunders et al., 1986 for detailed geology of Dominican Republic). Both species (*B. antillea* and *B. oblonga*) was recorded from the Pirabas Formation at the Ilha de Fortaleza outcrops (Nogueira et al., 2019) and agree with the shallow water distribution and late early Miocene discussed here. *Paranesidea elegantissima* and *Neonesidea* sp., recorded from the Pirabas Formation in the Capanema quarry B-17 and in the Primavera core FPR 160 (Nogueira et al., 2019), require revision, particularly regarding their age and the correlation with the outer neritic to upper bathyal depths of the Cojimar Formation in Cuba (Domínguez-Samalea et al., 2021). By the other hand, the record of these species cited by Nogueira et al. (2019) from Panama cannot be validated because the Panama Formation does not exist and it is clearly a mistake. Hemicytheridae, represented by *Aurila* sp., were identified within Ilha de Santana Formation, and previous records of *Aurila laevicula* and cf. *A. cicatricosa* cited by Nogueira et al. (2019) demonstrate a close relationship with late Miocene to Pleistocene *Aurila laevicula* found in the Springvale and Waccamaw formations of the central western Atlantic USA, as reported by Swain (1968).

The record of the arborescent bryozoan *Pirabasoporella atalaiaensis* and *Nellia* cf. *tenella* from the Ilha de Santana Formation (late early Miocene to early middle Miocene in the uppermost section 510 to 660 mbsf) has a relationship with the species *P. atalaiaensis* and *N. tellena* from the Miocene Pirabas Formation described by Zágoršeket et al. (2014) and Ramalho et al. (2019).

Mollusk specimens are rarely preserved in the cuttings samples; however, molds of very small gastropods (cf. *Amouropsis* and cf. *Marginella*) were recorded together with small fragments of bivalves.

The crustacean decapod claws of Alpheidae (*Alpheus* sp.) from the Ilha de Santana Formation was previously recorded from the outcrops of the Pirabas Formation (Lima et al., 2020b). Other taxa such as mollusks, echinoderms, sponges, and fish are rare and remain in open nomenclature.

Abundant large bottom beds, predominantly composed of red calcareous algae (mainly crustose but also including articulated taxa), exert a dominant influence within the paleoecological context of the photic zone.

5.2. Pirabas Formation faunal assemblages from the Ilha de Fortaleza outcrops

Most of benthic foraminifera (Fig. 7, Table 1) comprise shallow water rotaliid of *Amphistegina*, *Elphidium*, *Cibicides*, and *Discorbis*, which inhabit coralline algae and coral reefs (Mateu-Vicens et al., 2009; Prazeres et al., 2017). Nearshore and lagoon foraminifera are represented by miliolids and comprise *Pyrgo*, *Quinqueloculina*, and *Archaias*, which mostly inhabit inner platform (Murray, 2006; Sariaslan and Langer, 2021; Wilson and Carvajal-Chitty, 2021). Shallow water to open ocean species, including the lagenids, comprise *Lagena* and *Oolina*, and neritic to pelagic planktonic included *Globigerina*, *Globigerinella*, *Globigerinoides*, and *Globoturborotalita* (Araújo and de Araújo, 2010).

The ostracods (Fig. 7, Table 1) comprise Cytherellidae, Bairdiidae, Pontocyprididae, Bythocytheridae, Xestoleberididae, Cushmanideidae, Cytheruridae, Cytheridae, Cytherettidae, Hemicytheridae, and

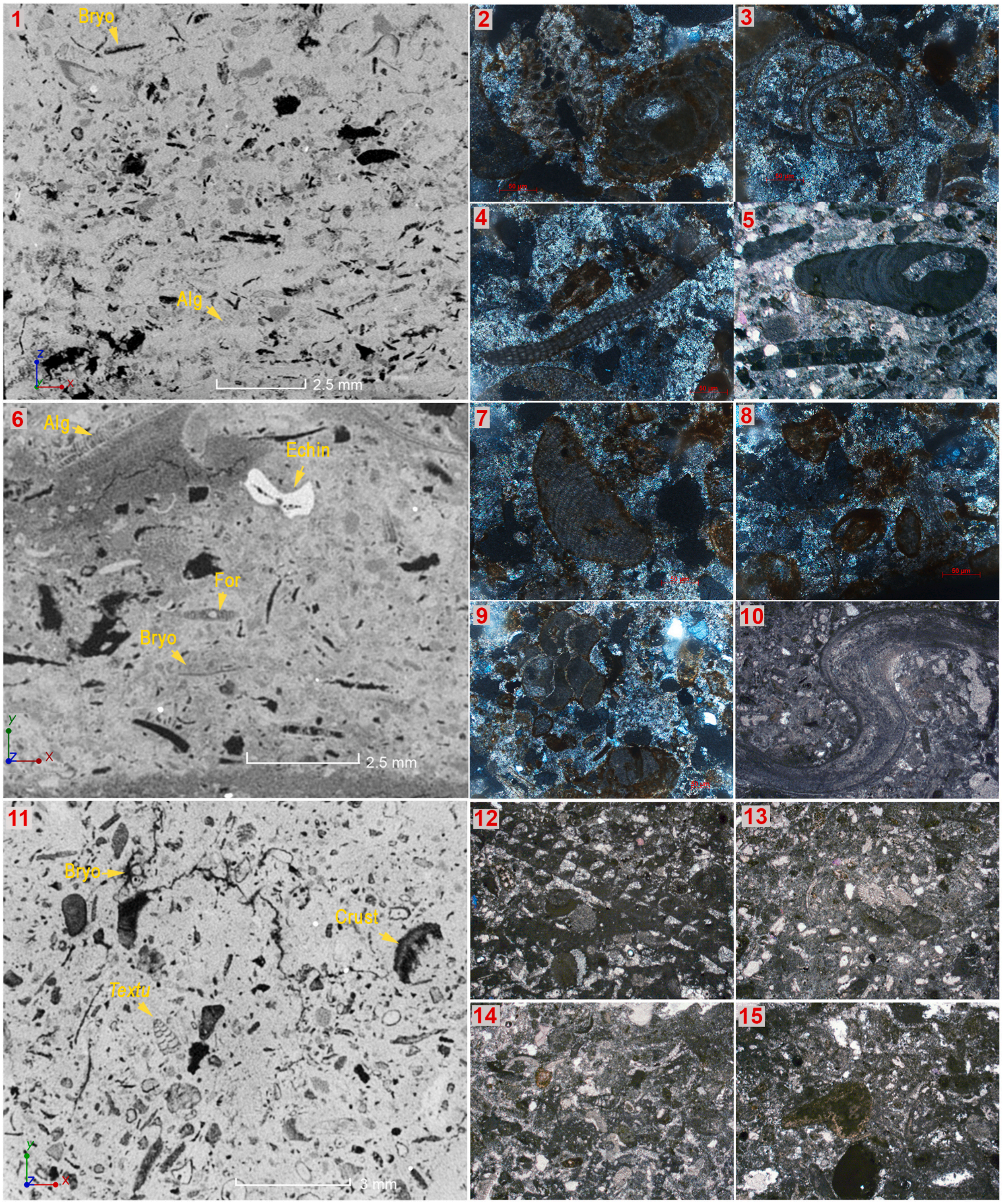

Fig. 6. Digital microCT sections (left column) and photomicrograph of petrography thin section (right doble column) of same plugs from Ilha de Fortaleza, Fazenda outcrop. 1, plug FAZ1; 2, bryozoan; 3, small benthic foraminifera; 4, 5, coralline algae and bryozoan; 6, plug FAZ3; Bryo; 7, coralline algae; 8, small benthic foraminifera; 9, bryozoan; 10, ichnofossil; 11, Plug FAZ6; 12, bryozoan; 13, spine of echinoid; 14, *Textularia*; 15, small benthic foraminifera and crustacean decapod. Abbreviations: Alg = algae; Bryo = bryozoans; Crust = crustacean; Echin = echinoderms; For = foraminifera; *Text* = *Textularia.*

Trachyleberididae that inhabit the inner and mid-outer shelfs.

Most of the bryozoan are arborescent (Fig. 8, Table 1). *Bugula* species are known to settles on the solitary ascidian (Walters, 1992), seagrasses (Keough and Chernoff, 1987), and over consolidated bottom up to 45 m deep (Vieira et al., 2012). *Catenicella* inhabits shallow waters, up to 12 m deep, and settle on the calcareous substrate such as coral colonies (Flórez et al., 2021), filamentous and foliose calcareous algae (Vieira et al., 2012), or, over another sessile organisms (Ramalho et al., 2014), adhering coral reef (Flórez et al., 2021), and over filamentous, foliose, or calcareous algae (Vieira et al., 2012). *Nellia* and *Skylonia* settle to indurated sediments and seaweeds, requiring moderate to high-energy shallow water environments for their survival (Mohan and Ramesh, 2019). *Nellia* has been found in shallow to deeper water (Di Martino et al., 2017) and Cyclostomatida are characteristic of open bays and inner environments (Ramalho et al., 2019). *Margaretta*, *Nellia*, *Catenicella*, *Bugula*, and Cyclostomatida was have been found in Caribbean fossil cemented to a coral reef, inhabiting the cryptic spaces, contributing significantly to the accretion of the reef framework (Flórez et al.,

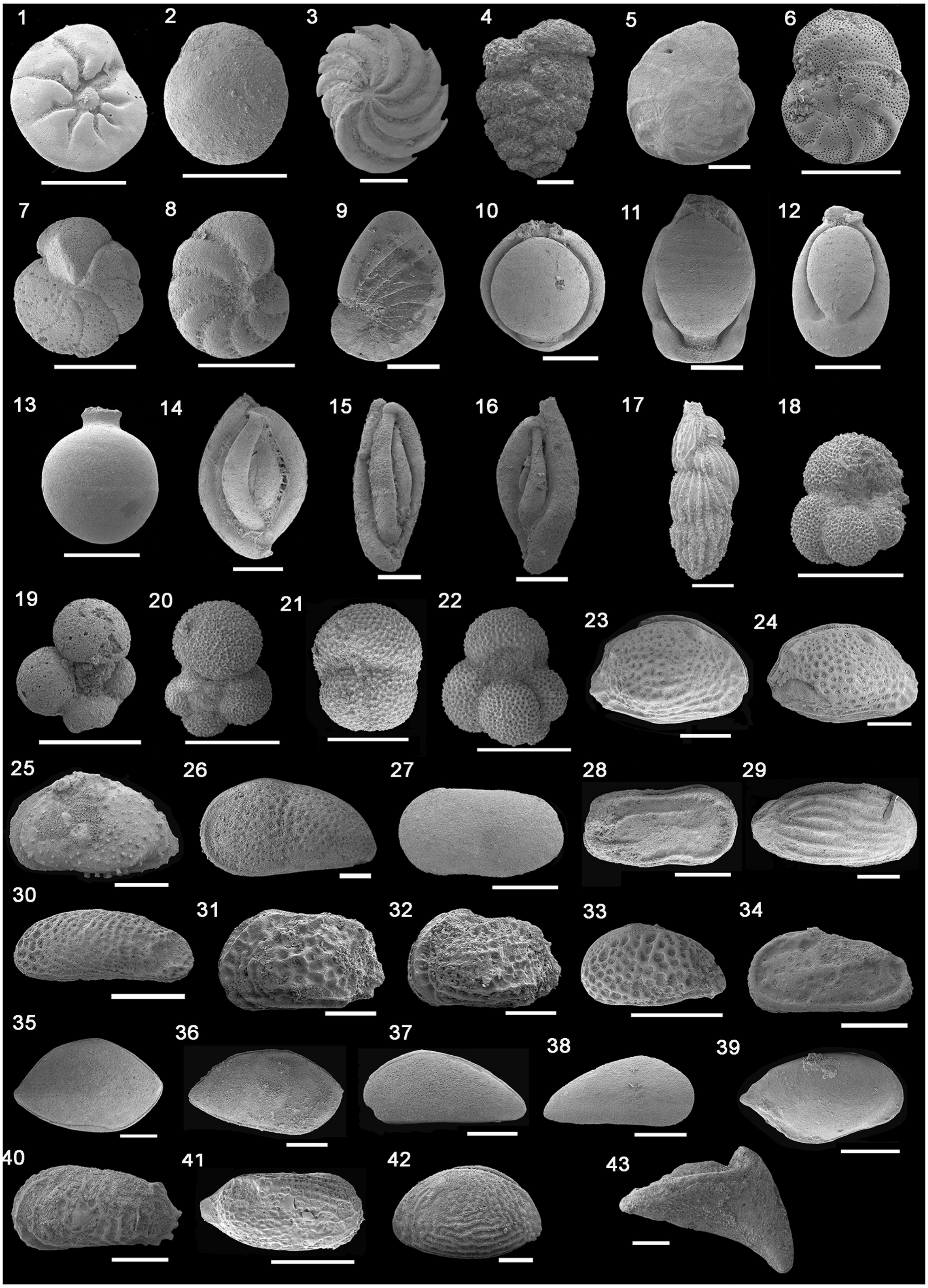

Fig. 7. SEM images of foraminifera, ostracods, and decapod crustaceans species diversity from the Ilha de Fortaleza (Ponta do Castelo and Fazenda outcrops), São João de Pirabas, Pará state, Brazil. 1, *Ammonia beccarii*; 2, *Amphistegina lessonii*; 3, *Archaias angulatus*; 4, *Bolivina* sp.; 5, *Cibicides* sp.; 6, *Cibicidoides wuellerstorfi*; 7, ?*Discorbis* sp.; 8, *Elphidium poeyanum*; 9, *Nonioella pirabensis*; 10, *Pyrgo depressa*; 11, *Pyrgo* cf. *inornata*; 12, *Pyrgo subsphaerica*; 13, *Pyrgo* sp.; 14, *Quinqueloculina lamarckiana*; 15, *Quinqueloculina fusiformes*; 16, *Triloculina oblonga*; 17, *Uvigerina peregrina*; 18, *Globigerina bulloides*; 19, *Globigerina* sp.; 20, *Globigerinella* sp.; 21, *Globigerinoides subquadratus*; 22, *Globoturborotalita* sp.; 23, *Aurila amygdala*; 24, *Aurila* cf. *cicatricosa*; 25, ?*Cativella* sp.; 26, ?*Cytheridea* sp.; 27, *Cytherella* cf. *notossinuosa*; 28, *Cytherelloidea mediocythara*; 29, *Cytheretta* cf. *punctata*; 30, *Cushmanidea* sp.; 31, *Quadracythere* sp. 1; 32, *Quadracythere* sp. 2; 33, *Gangamocytheridea* sp.; 34, *Neocaudites* sp.; 35, *Neonesidea amygdaloides*; 36, *Neonesidea* sp.; 37, *Paracypris* sp.; 38, *Propontocypris* sp.; 39, *Pellucistoma* ?*magniventra*; 40, *Puriana rugipunctata*; 41, *Semicytherura* sp.; 42, *Xestoleberis* ?*dactylotypa*; 43, *Alpheus* sp. Scale bar: 200 μm.

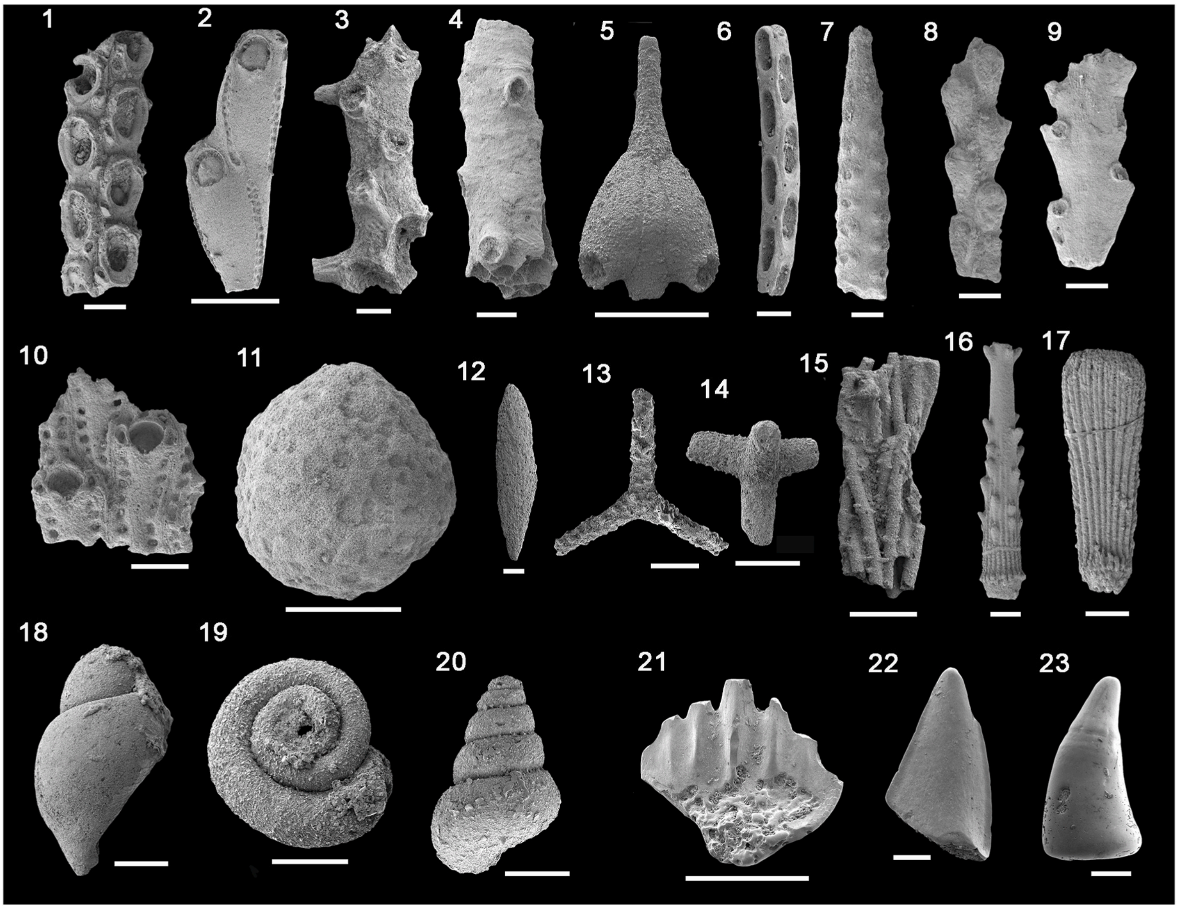

Fig. 8. Micropaleontology diversity from the Pirabas Formation (Ilha de Fortaleza, Ponta do Castelo and Fortaleza outcrops). 1, *Bugula* sp.; 2, *Catenicella* sp.; 3, *Pirabasoporella atalaiensis*; 4, Cyclostomatida; 5, *Pasythea* sp.; 6, *Nellia tenella*; 7, *Skylonia* sp.; 8, *Crisia* sp.; 9, *Metrarabdotos* sp.; 10, ind.; 11, *Buguloidea*; 12–15, sponges spicules; 16–17, echinoid spines; 18–20, gastropods; 21, shark dermal denticle; 22, shark teeth; 23, teleostean teeth.

2021, 2022). The presence of Jaculinidae (*Pirabasoporella*) within the Pirabas Formation suggests its preference for shallow waters and its ability to withstands high water current speeds (Zágoršeket et al., 2014). The occurrence of *Pasythea* in both the Pirabas Formation in Brazil and from the Chipolas Formation in Florida (Di Martino et al., 2017) suggests a shallow water paleoenvironment. *Crisia* inhabits consolidate bottoms up to depths of 45 m (Vieira et al., 2012).

The mollusk assemblages comprise mainly of medium to large shells, displaying high diversity. Many of these shells are preserved as solid or empty molds within the rock matrix of the outcrops. Consequently, when the lithified rock is disaggregated, only small micro mollusk molds or fragments are retained (Fig. 8, Table 1). This pattern is similarly observed in petrographic thin records. The exposed mollusk assemblages within the outcrop rocks comprised shallow-water species that inhabiting various environments: seagrasses (Cerithiidae, Cassidae, and Strombidae), mangroves (Ranellidae, Melongenidae, Arcidae, and Veneridae), rocky habits (Turridae, Fissurellidae, Calyptraeidae, and Conidae), and sandy bottoms (Naticidae, Volutidae, Marginellidae, and Olividae). Additionally, some species inhabit deeper waters (Xenophoridae, Ficidae, Architectonicidae, Cassidae, and Turritellidae) (see Maury, 1925; Aguilera et al., 2023 for further details).

Tests and/or isolated spines of the echinoids *Abertella pirabensis*, *Anisopetalus oliveirai*, *Clypeaster lamegoi*, *Echinolampas paraensis*, *Phyllacanthus priscus*, and *Rhyncholampas oliveirai* species, as well as, crinoid ossicles of *Sievertsella* cf. *polonica* species, were frequent recorded in shallow water facies from the outcrops of Ilha de Fortaleza (see Bencomo et al., 2021; Aguilera et al., 2023 for further details). However, the echinoderm contents in disaggregated rocks and petrography thin consist mostly in indeterminate ossicles and spines, except *Prionocidaris* (Figs. 5 and 8, Table 1).

At the Ilha de Fortaleza outcrops, coral representation comprises ahermatypic solitary shallow-water species of *Flabellum* sp. and *Discotrochus* sp., frequently dispersed within the rock matrix. Flabellidae are solitary coral found in warm tropical shallow waters worldwide, extending to colder, deeper water, even including occurrences in Antarctica (Cairns, 2017). However, the record of fossils *Flabellum* and *Discotrochus* in the Pirabas Formation was correctly attributed to shallow tropical waters (Aguilera et al., 2020a, 2020b). Nevertheless, these Flabellidae were not recovered from disaggregated rocks and were not observed in the petrographic thin sections. Nonetheless, they are commonly found on the surfaces of the outcrop rocks.

This fossil species diversity and the paleoenvironment context mark the main tropical faunal turnover recorded from the late early to early middle Miocene at the equatorial Brazilian coast, and then during the late Miocene the collapse of the carbonate producers and the global species extinction/diversification (Steinthorsdottir et al., 2021).

The decapod crustacean fossil fauna within the Pirabas Formation predominantly comprises species adapted to shallow-water environments, exhibiting a clear segregation into three distinct ecological groups.

i) subtidal species: These species inhabit non-consolidated bottoms, encompassing muddy, sandy, and shelly bottoms. The first group is particularly noteworthy and includes a diverse array of genera and families, such as Aethridae, Calappidae, Leucosiidae, Parthenopidae, Panopeidae, and Portunidae (Beurlen, 1958; Brito, 1971; Lima et al., 2023). Many of these species live on with soft bottoms, either dwelling beneath rocks, coral rubbles or buried within sediment (Melo, 1996). The Portunidae, including swimming crabs, are frequently documented in locations such as the Capanema quarry B17 (Aguilera et al., 2014) and the Colônia Pedro Teixeira outcrop (Beurlen, 1958). It encompasses several species, such as *Callinectes paraensis* Beurlen, 1958, *C. pirabensis* Brito, 1971, *C. ferreirai* Brito (1971), and *Euphylax septendentatus* Beurlen, 1958. This group also finds representation in the Ilha de Fortaleza outcrops (Beurlen, 1958; Távora et al., 2010).

ii) semi-terrestrial species: This group is primarily represented by a single Grapsoidea species, *Uca maracoani* (Latreille, 1802). Extant counterparts of this superfamily are commonly associated with mangrove ecosystems. This finding aligns with the paleoenvironment interpretation for the Baunilha Grande outcrop (β group *sensu* Aguilera et al., 2022), the sole location where this species has been recorded (Brito, 1972; Távora et al., 2010; Lima et al., 2020a).

iii) burrow constructor species: The third ecological group comprises the burrow constructor, mostly attributed to the Alpheidae, which includes snapping shrimps. These species inhabit shallow water, typically on soft bottoms, and can be found either under rock, coral rubble, in self-dug burrows, or associated with burrows of unidentified hosts in subtidal mudflats (Lima et al., 2020b). Several claw fragments belonging to this group have been documented at the Atalaia and Aricuru outcrops (Lima et al., 2020b), and have also been recovered for the Ilha de Fortaleza outcrops (Fig. 4).

This ecological diversity of decapod crustaceans within the Pirabas Formation provides valuable insights into the paleoenvironment of the region during the formation's depositional period. These findings

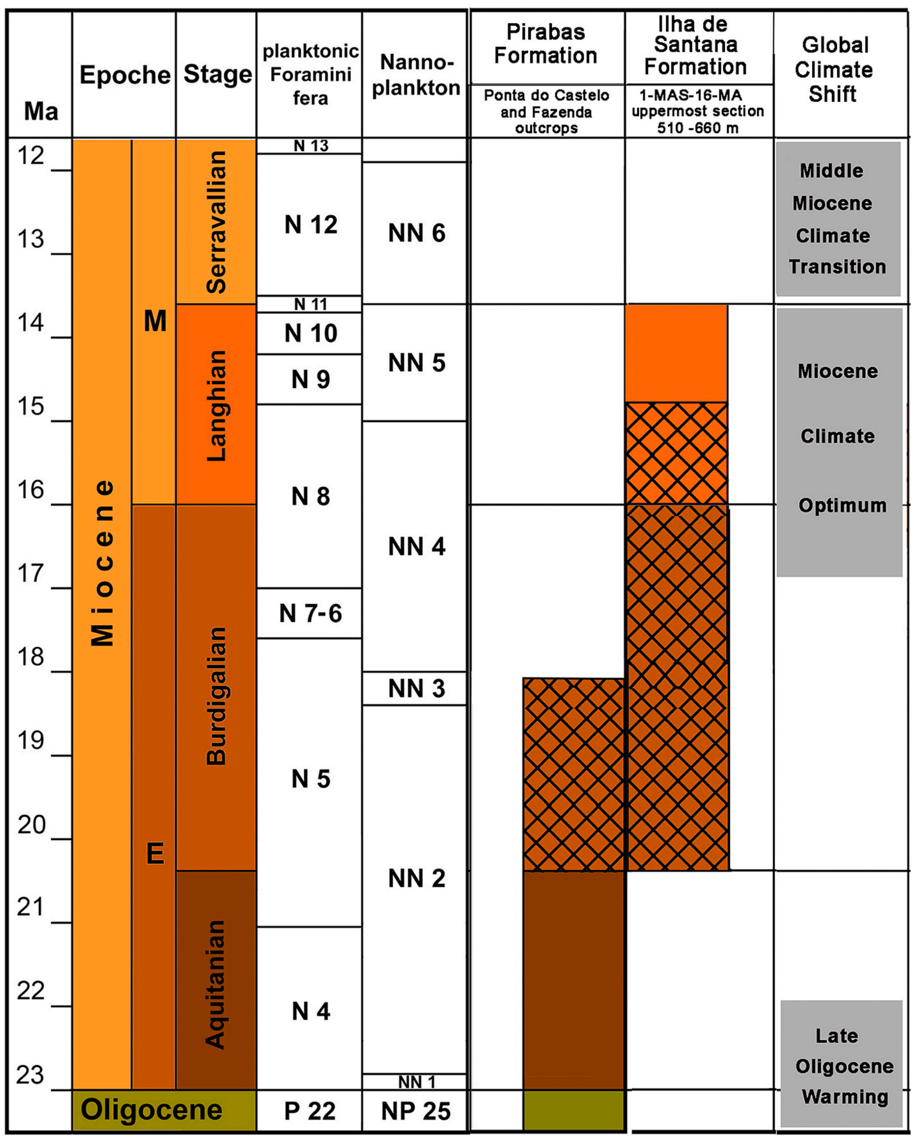

Fig. 9. Stratigraphic correlation chart depicting stratigraphic positions of the studied samples (crossed lines) from the Pirabas Formation outcrops (Ponta do Castelo and Fazenda) and from the Ilha de Santana Formation (uppermost section of core 1-MAS-16-MA at 510–660 m), and the most relevant events of global climate shift. The geochronological time scale follows Gradstein et al. (2020). The global climate shift follows Steinthorsdottir et al. (2021).The key fossils to assess age in the core (Ilha de Santana Formation) are *Amphistegina*, *Sphaerogypsina*, *Planorbulinella*, *Victoriella*, *Pirabasoporella atalaiensis* and *Nellia tenella* (Table 1), and the U/Pb data (Alvarado et al., 2023). The key fossils to assess age in the outcrops (Pirabas Formation) are *Amonia beccarii*, *Amphistegina lessonii*, *Archaias anqulatus*, *Cibicides pirabensis*, *Pyrgo depressa*, *Pyrgo subspaerica*, *Quinquelobulina lamarckiana*, *Quinqueloculina fusimormis*, *Pirabasoporella atalaiensis*, *Nellia tenella* (Table 2), *Operculodinium centrocarpum*, *Spiniferites ramosus*, *Zonocostites ramonae*, and *Lanagiopollis crassa* (Gomes et al., 2023).

underscore the significance of shallow-water habitats, including soft-bottom ecosystems, mangroves, and associated ecological niches, within the Ilha de Fortaleza outcrop.

6. Conclusions

Microfossils found in samples from section 510 to 660 m within the Ilha de Fortaleza Formation (Biozone IS-1, Biofacies 1) are characterized mainly by the records of the foraminifera *Amphistegina lessonii*, *Archaias* cf. *angulatus*, *Sphaerogipsina* sp., *Pyrgo* sp., and *Quinqueloculina* sp., the ostracods *Bairdoppilata* sp., *?Paranesidea* sp., *Neonesidea* sp., and *Aurila* sp., the bryozoans *Pirabasoporella atalaiensis*, *Nellia tenella*, and *Skylonia* sp., and the crustacean decapod *Alpheus* sp. These assemblages closely resemble microfossils found in the Pirabas Formation, indicating deposition in shallow waters within the photic zone and suggesting a coeval age.

While no continuous stratigraphic section exists, the coastal outcrops and quarries from the Pirabas Formation in the Pará, as well as the uppermost section 1-MAS-16-MA indicate overlapping ages, mostly considered coetaneous at the Burdigalian (Fig. 9).

Further exploration through deeper logs reaching the basement in the on-shore coastal plain of Pará is crucial to understanding the subsurface sections of Oligocene and Miocene sequences in the Pará-Maranhão Basin.

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CRediT authorship contribution statement

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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