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Palaeoenvironment of the Miocene Pirabas Formation mixed carbonate–siliciclastic deposits, Northern Brazil: Insights from skeletal assemblages

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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

The Bragantina Platform is an onshore basin of the Brazilian equatorial margin, including the Pirabas Formation, the youngest bioclastic-dominated formation in the area (early–middle Miocene), testifying to the final demise of carbonate factories along this margin area and the transition to a siliciclastic-dominated sedimentation. Although the greatest part of the Pirabas Formation is overlain by the Barreiras Formation and the post-Barreiras deposits, the outcrops provide the opportunity to investigate these Neogene successions that are the onshore equivalent of the large offshore basins (*e.g.* Amapá Formation: Foz do Amazonas and Ilha de Santana Formation: Pará-Maranhão) of the margin. The latter are deemed to represent an important target for reservoir models. Aiming to thoroughly describe the Pirabas Formation deposits and provide a quantitative and simple approach to analysing the outcropping successions, this study examines seven different successions and a quarry using palaeontological and petrographical methods. Similar to the modern Brazilian equatorial margin, the siliciclastic fraction in the Pirabas Formation rocks decreases as the distance from the coast increases, whereas the bioclastic material is found in greater amounts offshore. However, while the carbonate production close to the Amazon River mouth currently occurs hundreds of kilometres offshore, the carbonate factories in coastal along the Pirabas platform are also located in coastal waters. This indicates that the terrigenous input over the carbonate rocks was still lower than that found at present. The combining analysis of the skeletal and foraminiferal assemblages enabled a separation of protected embayments (characterised by seagrass-related assemblages), exposed areas (characterised by bioclastic shoals) and mangrove forests (characterised by dark fine-grained sediments). This accurate approach serves as an unprecedented reference for the northeastern part of the South American equatorial margin and lays the foundation for future research.

1. Introduction

The Brazilian equatorial margin comprises five large offshore basins (from northwest to southeast, Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará and Potiguar) and several onshore basins (Ávila, 2018; Pellegrini and Ribeiro, 2018; Nogueira et al., 2021). The thick sedimentary cover of these basins records the long evolution of the Brazilian equatorial margin following the breakup of the African and American plates owing to the Atlantic Ocean opening (Szatmari et al., 1987; Brandão and Feijó, 1994a, b; Figueiredo et al., 2007; Soares et al., 2007; Trosdtorf et al., 2007; Pellegrini and Ribeiro, 2018; Cruz et al., 2019). The recent discovery of the world-class hydrocarbon plays along

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the margin (*e.g.* the Zaedyus field in the French Guiana-Suriname), and the conjugate African margin (*e.g.* Jubilee field; Brownfield and Charpentier, 2006; Zalán, 2015; Kelly and Doust, 2016; Ávila, 2018; Pellegrini and Ribeiro, 2018; Wong and Geuns, 2019; Zalán et al., 2019) have emphasized the need to improve our knowledge concerning the succession of these large offshore basins. Amongst these offshore basins, the Pará-Maranhão and Barreirinhas basins, representing a geological continuum (Trosdtorf et al., 2007), are the least explored (Pellegrini and Ribeiro, 2018). The onshore (and thus the easiest accessible) portions is represented by the Bragantina Platform (Nogueira et al., 2021). The Bragantina Platform comprises deposits whose age ranges from the Cretaceous to the late Neogene (*e.g.* Rossetti et al., 2013; Aguilera et al., 2014; Ávila, 2018; Nogueira et al., 2021). Most early Neogene successions of the Bragantina Platform are represented by the Pirabas Formation, which comprises carbonate to mixed siliciclastic–carbonate deposits formed in the shallow-water coastal settings (Petri, 1957; Ferreira, 1977; Góes et al., 1990; Rossetti et al., 2013; Aguilera et al., 2014; Antonioli et al., 2015; Nogueira and Nogueira, 2017; Aguilera et al., 2020a, b; Nogueira et al., 2021, Fig. 1). These deposits are equivalent to those of the Pirabas Formation of the Barreirinhas Basin and those of the upper part of the Ilha de Santana Formation of the Pará-Maranhão Basin. They could be correlated to the upper part of the Amapá Formation of the Foz do Amazonas Basin (Pamplona, 1969; Rossetti and Góes, 2004; Figueiredo et al., 2007; Soares et al., 2007; Trosdtorf et al., 2007; Rossetti et al., 2013; Cruz et al., 2019, Fig. 1). Consequently, correlating onshore and offshore sedimentary records would aid in reconstructing the stratigraphic, large-scale geometries and palaeoenvironmental evolution of the Brazilian equatorial margin, improving the understanding of the onshore Pirabas Formation. Moreover, the Pirabas Formation is the last bioclastic-dominated formation of this margin area. The deposits which overlie the Pirabas Formation mainly comprise the siliciclastic material, revealing the transition from a

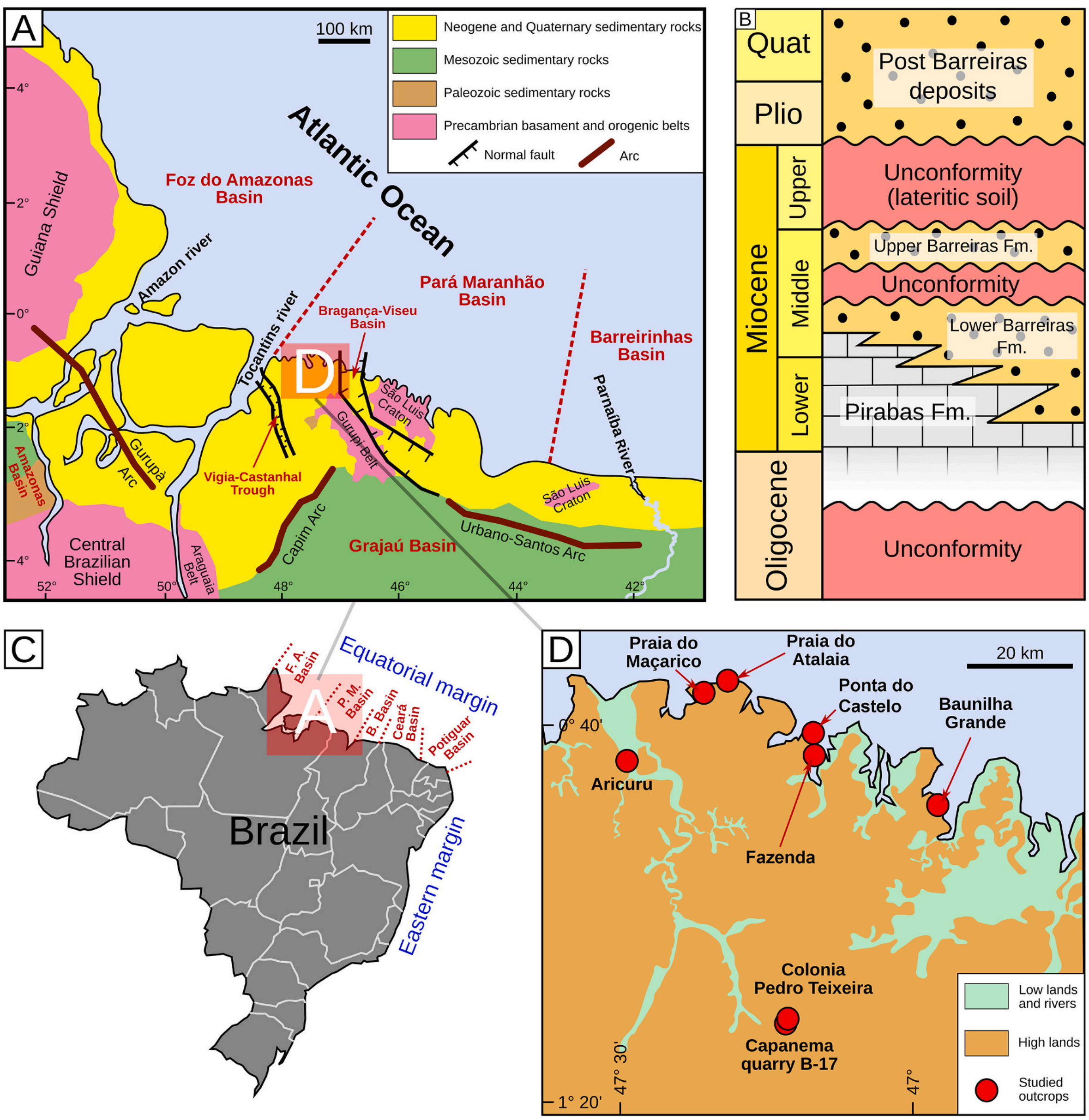

Fig. 1. Map displaying the fossiliferous outcrop and quarry localities of the Pirabas Formation along the equatorial Brazilian coast. A) Cenozoic architecture of the Eastern Amazonian coast (modified from Nogueira et al. (2021) and Soares et al. (2011); the square marked by a D illustrates the area of the Bragantina platform, that is, the study area, displayed in Panel D. B) Stratigraphy succession of Pirabas–Barreiras formations (modified from Rossetti, 2001 and Nogueira et al., 2021). C) Outline map of Brazil (square empty A shows the area of interest displayed in Panel A). D) Detailed map (modified from Vasquez et al., 2008) showing the studied localities.

carbonate platform environment, which persisted for millions of years, to a siliciclastic-dominated platform similar to that of the current margin (Nogueira et al., 2021, Fig. 1). The timing and dynamics of this remarkable change are stored within the offshore basins of the margin and Pirabas Formation, further revealing the need for a coherent framework for analysing the onshore and offshore sedimentary records.

According to Freimann et al. (2014) the correlation of the lithological and geophysical well logs, spontaneous potential, electrical resistivity and gamma-ray analyses indicates that the Pirabas Formation has a thickness of approximately 120 m in onshore areas. However, only the upper 5–15 m are exposed in small and discontinuous outcrops scattered along the coast (*e.g.* Aguilera et al., 2020a, b). The outcrop surfaces are often altered, hindering detailed studies on large-scale sedimentary structures. Longer sections have only been observed in quarries and short drill cores (*e.g.* Aguilera et al., 2014; Nogueira et al., 2021). Although recent assessments have significantly expanded our knowledge concerning the Pirabas Formation palaeontology (Antonioli et al., 2015; Nogueira and Ramos, 2016; Nogueira and Nogueira, 2017; Aguilera et al., 2020a, b; Lima et al., 2020a, b; Bencomo et al., 2021; De Araújo et al., 2021; Lima et al., 2021; Nogueira et al., 2021), the patchy nature of the outcropping successions curtails any attempts to establish large-scale correlations. Furthermore, as most described boreholes from successions stem from drillings performed for groundwater prospecting, they are largely based on cuttings, resulting in poorly constrained stratigraphic analyses and often confusing lithological descriptions. Therefore, a comprehensive quantitative approach considering all the limited available information is needed to further understand the Pirabas Formation and correlate and compare the various sections. This study integrates lithological descriptions with palaeontological analyses of the scattered outcrops deposits of the Pirabas Formation aiming to provide a comprehensive framework for integrating further researches and offset the limitations owing to the lack of extensive outcrops. The skeletal assemblages of the bioclastic carbonates be influenced by the temperature, water depth, light availability, seafloor characteristics, sedimentation rate and nutrient concentrations (*e.g.* Lees and Buller, 1972; Carannante et al., 1988; Hayton et al., 1995; James, 1997; Lokier et al., 2009; Coletti et al., 2017, 2019; Pomar et al., 2017; Michel et al., 2018). Their accurate analyses combined with the petrographic studies might help reconstruct a comprehensive palaeoenvironmental scenario to better correlate the onshore Pirabas Formation with the offshore basin successions, improving our knowledge with respect to the Brazilian margin sedimentary deposits for both scientific research and industrial purposes.

2. Geological setting and hydrocarbon systems

The basins of the Brazilian equatorial overlay a complex Precambrian basement (*e.g.* São Luís Craton) and were shaped by the extensional tectonics that created the Atlantic Ocean (Figueiredo et al., 2007; Soares et al., 2007; Trosdtorf et al., 2007; Soares et al., 2008, 2011; Nogueira et al., 2021). Three main supersequences can be recognised in most basins, which represent the large-scale stratigraphic organisation of the margin: 1) pre-rift; 2) syn-rift and 3) post-rift/passive margin (Figueiredo et al., 2007; Soares et al., 2007; Trosdtorf et al., 2007). The pre-rift sedimentary supersequence primarily comprises sandstones and marls deposited in the continental settings whose age ranges from the Paleozoic to the early Cretaceous. The syn-rift supersequence spans from the Berrasian–Aptian to the Albian and comprises sediments deposited in the continental and shallow-water marine environments. The passive margin (Albian–Recent) supersequence comprises various sedimentary deposits related to the marine environments ranging from the shallow carbonate platforms to deep-water basins. Different hydrocarbon systems are recognised within the margin, with various sources and reservoirs (Pellegrini and Ribeiro, 2018). The following are the main source rocks: 1) Devonian shales of the pre-rift supersequence (Pimenteiras Formation, Pará-Maranhão and Barreirinhas basins), which represent source rocks in the conjugated African margin (Soares et al., 2007; Trosdtorf et al., 2007); 2) lower Cretaceous lacustrine shales of the pre-rift supersequence (Pendência Formation, Potiguar Basin); 3) lacustrine and lagoonal Aptian shales of the syn-rift supersequence (Cassiporé and Codó formations, Foz do Amazonas, Pará-Maranhão and Barreirinhas basins; Mundaú and Paracuru formations, Ceará Basin and Pescada and Alagamar formations, Potiguar Basin); 4) Albian to Cenomanian calcilutites and marine shales of the initial post-rift supersequence (Limoeiro Formation, Foz do Amazonas Basin and Caju Group, Pará-Maranhão and Barreirinhas basins), which are source rocks in the conjugate African margin and 5) Cenomanian to Turonian marine shales of the post-rift supersequence (Travosas Formation, Pará-Maranhão and Barreirinhas basins), which are source rocks in the conjugated African margin. The main known reservoirs of the various systems are: 1) Berrasian to Albian fluvial–deltaic sandstones of the syn-rift supersequence (Cassiporé Formation, Foz do Amazonas Basin; Canárias Group, Pará-Maranhão Basin; Bom Gosto and Barro Duro formations, Barreirinhas Basin; Mundaú and Paracuru formations, Ceará Basin; Pendência, Pescada and Alagamar formations, Potiguar Basin); 2) Cretaceous to Paleogene shelf and turbiditic sandstones of the post-rift supersequence (Limoeiro Formation, Foz do Amazonas Basin; Travosas Formation, Pará-Maranhão and Barreirinhas basins; Ubarana Formation, Ceará Basin and Açu and Ubarana formations, Potiguar Basin). Among these sandstones, the turbiditic host world-class plays in both the South American (Zaedyus, French Guiana-Suriname) and conjugated African margins (Jubilee); 3) Paleogene shelfal calcarenites (Amapá Formation, Foz do Amazonas Basin and Ilha de Santana Formation, Pará-Maranhão Basin) and 4) Neogene shelf and turbidite sandstones of the late passive margin supersequence (Orange Formation, Foz do Amazonas Basin).

From the palaeoenvironmental perspective, the passive margin supersequence can be divided into two main stages: the pre-Amazon stage (Late Cretaceous–middle Miocene, *i.e.* prior to the establishment of the Amazon transcontinental river drainage) and the Amazon fan stage (late Miocene–nowadays, *i.e.* following the establishment of the modern Amazon drainage system; Vasquez et al., 2008; Figueiredo et al., 2009; Gorini et al., 2014; Nogueira and Nogueira, 2017; Cruz et al., 2019 and references therein). The Pirabas Formation in the Pará state (Fig. 1) is a young Cenozoic formation of this margin, although its age is poorly constrained owing to a inadequate preservation of microfossils. Molluscs and ostracods suggest that the Pirabas Formation might extend from the late Oligocene to the latest early Miocene (Ferreira and Cunha, 1957; Nogueira and Nogueira, 2017), while palynomorphs, foraminifera and nannofossils indicate that it extends from the early to the middle Miocene (Antonioli et al., 2015 and references therein; Aguilera et al., 2020a, b). Although the stratigraphic framework is still incomplete, its composition reveals that it should have deposited towards the end of the pre-Amazon stage. Thus, it should have recorded the initial stages of the progressive transition of the margin from a carbonate-dominated to a siliciclastic-dominated environment. Older formations, such as the Amapá Formation, mainly comprise the biogenic carbonates (mostly large benthic foraminifera) and only in the lower–middle Miocene interval display a relevant terrigenous fraction (*e.g.* De Mello e Sousa et al., 2003). Similar to the current Brazilian equatorial margin, the Pirabas Formation was characterised by a complex coastline displaying various shallow-water marine environments developed along a gently sloping platform (Petri, 1957; Góes et al., 1990; Antonioli et al., 2015; Nogueira and Nogueira, 2017; Aguilera et al., 2020a, b; Bencomo et al., 2021; Nogueira et al., 2021). This large number of shallow-water facies has been historically grouped into three major ecological facies (Petri, 1957; Ferreira, 1977), namely, the Castelo, related to the open shallow-water marine settings, Capanema (also termed the Canecos), associated with the lagoonal settings and Baunilha Grande, related to the magrove-dominated coastal settings (Petri, 1957; Ferreira, 1977; Antonioli et al., 2015; Nogueira and Nogueira, 2017). Since each of these facies includes a large variety of different lithological and palaeontological assemblages (only grouped by a general palaeoenvironmental interpretation), they were defined as ecofacies. They lack accurate and detailed descriptions. As these facies are interlayered rather than stacked, they display a complex pattern, with gradual, lateral and vertical facies transitions (Ferreira and Francisco, 1988; Antonioli et al., 2015).

From the palaeontological perspective, the Pirabas Formation exhibits a high diversity of the shallow-water marine fossils. These include foraminifera (Petri, 1957), ostracods (Nogueira et al., 2019), molluscs (Maury, 1925), bryozoans (Távora et al., 2014; Zágoršek et al., 2014; Ramalho et al., 2015, 2017; Muricy et al., 2016), echinoids (Santos, 1958, 1967; Mooi et al., 2018; Bencomo et al., 2021), crustaceans decapods (Beurlen, 1958; Brito, 1971, 1972; Martins-Neto, 2001; Távora et al., 2002; Távora and Dias, 2016; Aguilera et al., 2020b; Lima et al., 2020a, b; Lima et al., 2021), fishes (Aguilera et al., 2014, 2017), mammal sirenids (Toledo, 1989), ichnofossils (Soares et al., 2019; De Araújo et al., 2021) and fossil pollens, suggesting the presence of mangrove forests (Leite, 2004; Antonioli et al., 2015).

The Pirabas Formation is gradually overlain by the Barreiras Formation and post-Barreiras siliciclastic deposits. Moreover, their age is poorly constrained; the Barreiras Formation is deemed to have been deposited between the early Miocene and the late Miocene, whereas the post-Barreiras deposits should cover the late Neogene (Nogueira et al., 2021, Fig. 1).

3. Materials and methods

Field trips for sample collection were conducted at seven outcrops and a quarry located at i) Praia do Atalaia (ATA; 0°35′37″S, 47°18′54.4″ W), ii) Aricuru (ARI; 0°43′50.14″S, 47°29′ 20.01″W), iii) Praia do Maçarico (MAÇ; 0°36′44.61″S, 47°21′26.58″W), iv) Ponta do Castelo (PTA; 0°40′55.69″ S, 47°10′13.30″ W), v) Fazenda (FA; 0°42″43.79″ S, 47°9′58.65″W), vi) Baunilha Grande (BAU; 0°48′2.4″S, 43°57″3.2W), vii) Colônia Pedro Teixeira (COL; 1°10′38″S, 47°13′00″W) and viii) Capanema quarry B17 (B17; 1°10′S, 47°13' W; Fig. 1). Simplified stratigraphic logs of the various outcrops are illustrated in Figs. 2 and 3. The locality Colônia Pedro Teixeira was visited. However, the outcrop no longer exists, and samples were obtained from the Brazilian Geological Service collection. The Pirabas Formation is poorly exposed at the Baunilha Grande, impeding an adequate section description. Sampling activities were authorised by the Brazilian National Mining Agency, under the control of paleontological research direction. The samples for the petrography (Tables 1 and 2) analysis comprise 27 micro-plugs obtained with a portable drill from the lithified lithologies. The samples are stored in the Paleoecology and Global Changes Laboratory of Fluminense Federal University. The sub-samples destined for the palaeontological and petrographic analyses were consolidated using the epoxy resin followed by thin-section preparation (barring the black siliciclastic mudstone of Praia do Maçarico, Sample MAÇ-3, which was too soft to be prepared as a thin section). The petrographic characteristics and skeletal and foraminiferal assemblages were examined in all thin sections. The skeletal assemblages were quantified by the point-counting technique (Flügel, 2010), using a 300 μm grid and counting over 500 points in each section. The foraminiferal assemblages were investigated by counting all occurring specimens in each section. Both

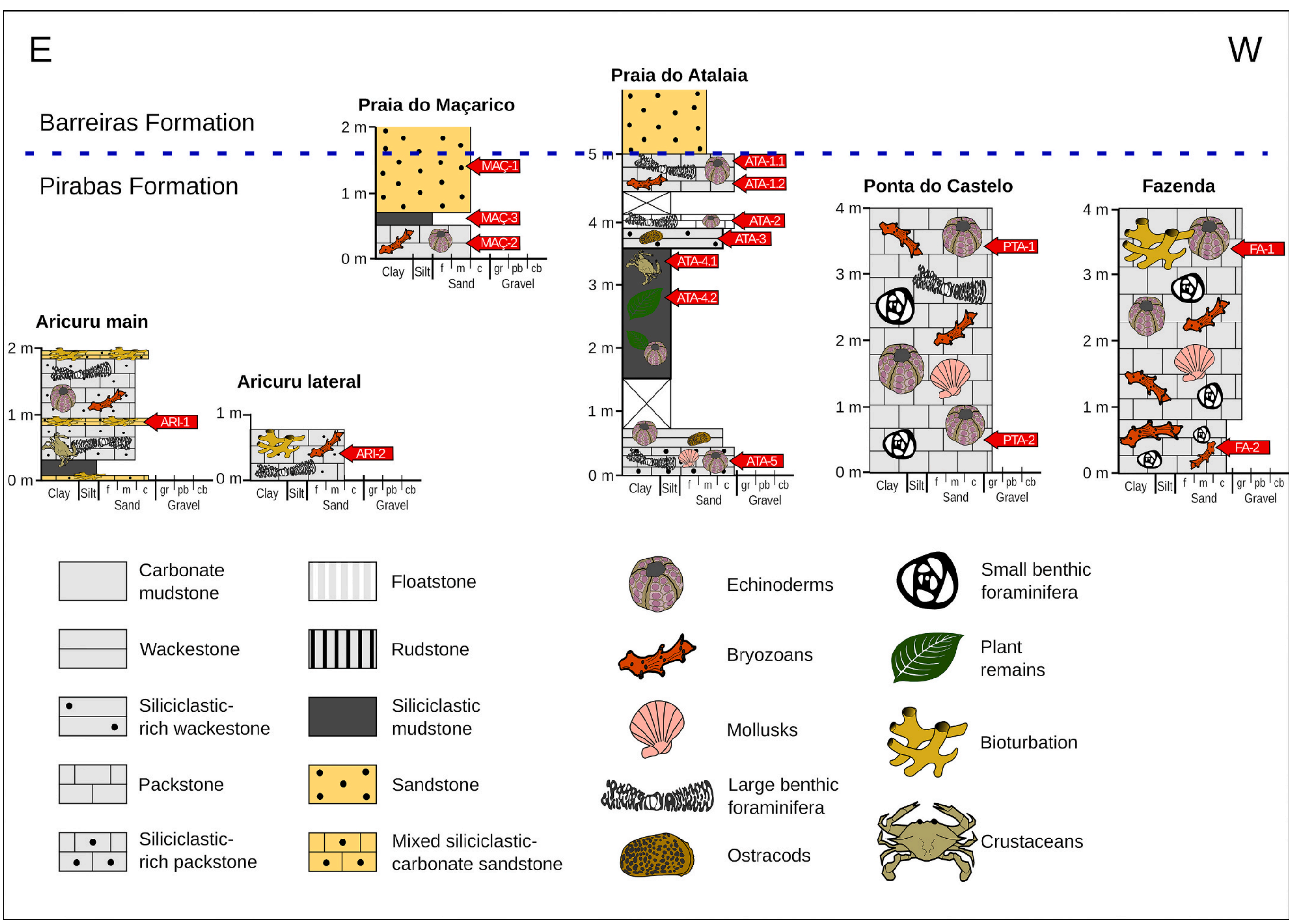

Fig. 2. Simplified stratigraphic logs of the investigated outcrops. The position of the boundary between Pirabas and Barreiras formations is merely indicative as the transition between the two formations is usually gradual.

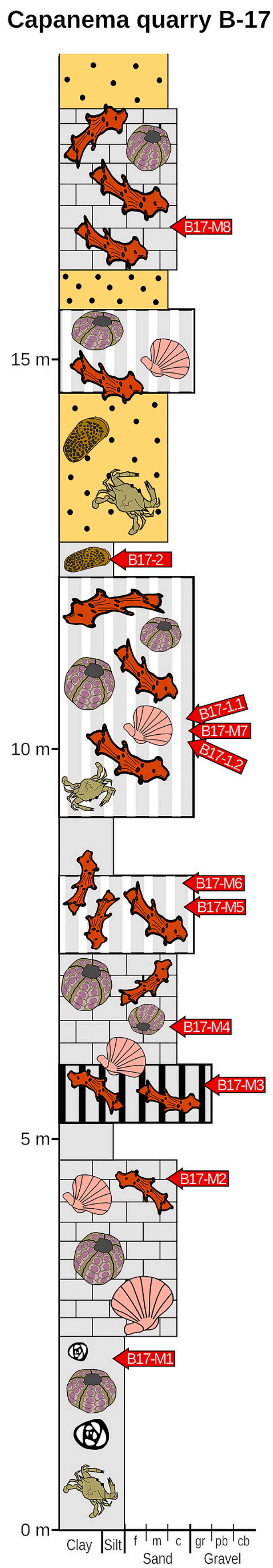

Fig. 3. Simplified stratigraphic logs of the investigated Capanema quarry B17 log is based on Costa (2011).

point-skeletal assemblage counting and foraminiferal assemblage area counting were performed in the samples, demonstrating abundant and sufficiently well-preserved skeletal assemblages.

4. Results

As the outcropping successions are located close to the sea level, rock surfaces are usually altered, hindering analyses on an outcrop scale (Fig. 4). Three main lithologies are observed, as exemplified by the Praia do Atalaia outcrop (Fig. 2). These include the bioclastic and frequently grain-supported rocks (Fig. 4A, B, H–K), mudstones (Fig. 4B and C), locally dark-coloured and rich in plant remains and siliciclastic sandstones, often located in the upper part of the section and probably associated with the overlying Barreiras Formation. Macro-fossils can be found in common in the bioclastic rocks and mainly comprise echinoderms (Fig. 4D), molluscs (mainly preserved as internal moulds; Fig. 4E, I and K) and vertebrate remains. Furthermore, locally dense networks (*e. g.* Aricuru outcrop) of large-sized burrows, mainly attributed to *Thalassinoides* ichnogenus (Fig. 4F and G) occur.

Based on the lithological characteristics, two main groups of samples were recognised, namely, the mudstones (ATA-3, ATA-4.1, ATA-4.2, MAÇ-1, MAÇ-3, B17–2 and B17-M2) and coarse-grained sedimentary rocks (the remaining samples; Tables 1 and 2). Excluding Samples B17–2 and B17-M2, which are the carbonate mudstones, samples belonging to the former group comprise large amounts of siliciclastic grains (Fig. 5). Barring ARI-1 and BAU-1, samples comprising the second group consist mainly of the bioclastic material (Tables 1 and 2; Fig. 6). ARI-1 is a fine-grained sandstone that presents a small biogenic fraction (echinoderm fragments, ostracods and benthic foraminifera; Tables 1 and 2; Fig. 6A and B). BAU-1 is a micrite-rich siliciclastic–carbonate sandstone displaying a skeletal assemblage consisting entirely of crustacean fragments, associated with common angular fine-grained siliciclastic particles (Tables 1 and 2; Fig. 6C and D).

The bioclastic coarse-grained rocks belonging to the second group are characterised by various biogenic fragments. Overall, the skeletal assemblage contains echinoderms, bryozoans (mostly erect-flexible cellariform colonies; *sensu* Nelson et al., 1988; Smith, 1995), large benthic foraminifera (mainly soritids) and molluscs (Tables 1 and 2; Fig. 7A–D). Soritids prevail mainly in the Praia do Atalaia and Aricuru outcrops (*i.e.* in the eastern part of the study area; Figs. 1, 7A and 7E), whereas echinoderms and bryozoans are more common at Ponta do Castelo, Fazenda, Colônia Pedro Teixeira and Capanema quarry B17 (*i.e.* in the western part of the study area; Tables 1 and 2; Fig. 7B, C and D). Mollusc moulds and mouldic porosity possibly associated with the molluscs dissolution are common in most samples, especially in ATA-5 and samples from Capanema quarry B17 (Figs. 4E and 7B), indicating that molluscs were probably more abundant prior to diagenesis. Small benthic foraminifera are usually abundant (Tables 1 and 2). Red calcareous algae are found in great amounts (Fig. 7F), mainly occurring in coastal areas (Praia do Atalaia, Praia do Maçarico, Ponta do Castelo and Fazenda) and almost absent from the inland outcrops (Aricuru, Colônia Pedro Teixeira and Capanema quarry B17) (Tables 1 and 2; Fig. 1). Barnacles are relatively common in the skeletal assemblage of Capanema quarry B17 (Table 2). Green calcareous algae (mainly *Halimeda*) and ostracods are usually not abundant (Tables 1 and 2; Fig. 8). No sample characterised by common planktonic foraminifera was observed.

The foraminiferal assemblages from Praia do Atalaia and Aricuru are dominated by soritids (probably belonging to the *Sorites*) and associated with common small rotaliids, small miliolids (mainly *Pyrgo* and *Triloculina*) and textulariids, with rare *Amphistegina* and *Planorbulina* specimens (Tables 1 and 2; Fig. 9). The Ponta do Castelo and Fazenda assemblages (Tables 1 and 2) are dominated by small miliolids, thick-walled *Amphistegina* specimens (Fig. 9E), textulariids and small rotaliids. Furthermore, soritids are common (mainly *Sorites* fragments and rarer, poorly preserved, large miliolids potentially belonging to the

Table 1
Lithological characteristics, skeletal and foraminiferal assemblages of the examined samples from the outcrops based on point- and area-counting analysis, respectively.

	Praia do Atalaia						Aricuru		Praia do Maçarico		Ponta do Castelo		Fazenda		Baunilha	Colônia Pedro Teixeira
	ATA-1.1	ATA-2	ATA-3	ATA-4.1	ATA-4.2	ATA-5	ARI-1	ARI-2	MAÇ-1	MAÇ-2	PTA-1	PTA-2*	FA-1	FA-2*	BAU-1	COL-1
Lithology	Packstone	Packstone	Siliciclastic-rich-wackestone	Black Mudstone	Iron rich nodule	Siliciclastic-rich packstone	Mixed siliciclastic carbonate sandstone	Siliciclastic-rich packstone	Mud-supported sandstone	Wackestone to packstone	Packstone to grainstone	Packstone to grainstone	Coarse-grained packstone	Packstone	Mixed siliciclastic carbonate sandstone	Packstone to rudstone
Terrigenous grains	Fine to coarse sand sized, angular to rounded	Fine to coarse -sand sized, angular to rounded	Fine-sand sized, angular	//	Sand-sized, angular	Fine to coarse sand sized, angular to rounded	Fine-sand sized, angular	Fine-sand sized, angular	//	Coarse-sand sized, angular	Sand sized, subangular to subrounded	Sand sized, subangular	Sand sized, subangular to subrounded	Fine-sand sized, angular	Fine-sand sized angular grains	Coarse-sand sized angular grains
Main bioclastic components	BRY & LBF	LBF	//	//	BRY & ECH	ECH	ECH & OS & SBF	LBF	//	BRY & ECH & MOL & RCA	ECH	ECH	BRY & ECH	BRY	Crustacean fragments	BRY
Secondary bioclastic components	ECH	ECH & MOL & RCA	//	//	SBF	BRY & LBF & MOL	//	BRY & SBF	//	//	BRY & SBF	LBF & SBF	MOL & LBF & SBF	ECH & LBF & SBF	//	ECH & MOL
Foraminiferal assemblage	Soritids, small rotaliids	Soritids	//	//	//	Soritids, textulariids	//	Soritids, small miliolids	//	//	Small miliolids, textulariids, soritids, small rotaliids	Textulariids, soritids, *Amphistegina*	Small miliolids, small rotaliids, soritids, textulariids, *Amphistegina*	*Amphistegina*, small rotaliids, small miliolids, soritids, textulariids	//	//
Alteration of bioclasts	Moderate	Moderate	Strong	//	Strong	Moderate	Moderate	Moderate	Complete	Strong	Low to moderate	Low to moderate	Low to moderate	Low to moderate	Strong	Low
Point Counting																
Echinoderms (ECH)	15%	10%	//	//	//	40.5%	//	8.5%	//	//	37%	35%	32%	23%	//	30%
Bryozoans (BRY)	27%	3.5%	//	//	//	12.5%	//	12%	//	//	16%	9%	27.5%	43%	//	43%
Molluscs (MOL)	9%	10%	//	//	//	13%	//	1%	//	//	10%	11%	14.5%	1%	//	24%
Sorites (LBF)	31.5%	46%	//	//	//	23%	//	63%	//	//	7.5%	14.5%	5%	6%	//	1%
Amphistegina (LBF)	0%	0%	//	//	//	0%	//	0%	//	//	1.5%	1.5%	0.5%	6.5%	//	0%
Other large benthic foraminifera (LBF)	1.5%	0%	//	//	//	0%	//	0%	//	//	0%	7.5%	0%	0%	//	0%
Small benthic foraminifera (SBF)	8%	7.5%	//	//	//	2.5%	//	9%	//	//	16%	13%	12%	18%	//	2.5%
Red calcareous algae (RCA)	0%	23%	//	//	//	7.5%	//	0%	//		7%	5.5%	3.5%	1%	//	0%
Green calcareous algae (GCA)	6%	0%	//	//	//	0%	//	2.5%	//	//	3.5%	0%	2%	0.5%	//	0%
Barnacles (BAR)	0%	0%	//	//	//	0%	//	0%	//	//	0%	0%	2%	0%	//	0%
Ostracods (OS)	2%	0%	//	//	//	1%	//	4%	//	//	1.5%	0%	1%	1%	//	0%
Serpulids (SER)	0%	0%	//	//	//	0%	//	0%	//	//	0%	3%	0%	0%	//	0%

Table 2
Lithological characteristics, skeletal and foraminiferal assemblages of the examined samples of Capanema Quarry B17 based on point- and area-counting analysis, respectively.

Locality	Capanema quarry B17										
	B17-M1	B17-M2	B17-M3	B17-M4	B17-M5	B17-M6	B17-M7	B17–1.1	B17–1.2	B17-2	B17-M8
Depth from the base of the quarry (m)	2.1	4.5	5.8	6.3	8	8.2	10.2	10.2	10.2	12.5	16.8
Lithology	Mudstone	Packstone	Rudstone	Packstone	Floatstone	Packstone	Floatstone	Packstone to floatstone	Packstone to floatstone	Mudstone	Packstone
Terrigenous grains	Very-fine sand sized, angular	Sand to coarse-sand sized, angular	Coarse-sand sized, angular	Coarse to very-coarse sand sized, angular	Coarse-sand sized, angular	Coarse-sand sized, angular	Coarse-sand sized, angular	Sand sized, angular	Coarse-sand sized, angular	Sand sized, angular	Sand to fine sand sized, angular
Main bioclastic components (section observation)	ECH & SBF	MOL	BRY & MOL	BRY & ECH	BRY	BRY & ECH	BRY & ECH	ECH	ECH & BRY & MOL	SBF & OS	BRY & ECH
Secondary bioclastic components (section observation)	PLK	ECH & SBF	ECH & BAR	BAR & MOL	ECH & MOL	MOL & SBF	MOL & SBF	BRY & MOL	BAR	//	MOL & SBF
Foraminiferal assemblage (area counting)	Small benthic rotaliids, planktonic foraminifera	Small benthic rotaliids, soritids, planktonic foraminifera, textulariids	//	Small benthic rotaliids, textulariids, soritids	Small benthic rotaliids, planktonic foraminifera	Small benthic rotaliids, *Planorbulina*	Small benthic rotaliids, textulariids	Small benthic rotaliids	Small benthic rotaliids	//	Small benthic rotaliids, planktonic foraminifera
Alteration of bioclasts	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Point Counting											
Echinoderms (ECH)	//	15.5%	9%	54.5%	15.5%	22%	27.5%	53%	29%	//	26.5%
Bryozoans (BRY)	//	24.5%	57.5%	28%	67.5%	65%	56.5%	19%	25%	//	55.5%
Molluscs (MOL)	//	41%	15.5%	6.5%	15.5%	11.5%	8.0%	23.5%	23%	//	8.5%
Sorites (LBF)	//	1%	0%	5.5%	0%	0%	0.0%	0%	5.5%	//	0.0%
Amphistegina (LBF)	//	0%	0%	0%	0%	0%	0.0%	0%	0%	//	0.0%
Other large benthic foraminifera (LBF)	//	0%	3%	0%	0%	0%	0.0%	0%	0%	//	0.0%
Small benthic foraminifera (SBF)	//	12%	0%	0.5%	1%	1%	5%	2%	0%	//	6.0%
Red calcareous algae (RCA)	//	0%	0%	0%	0%	0%	0.0%	0.5%	0%	//	0.0%
Green calcareous algae (GCA)	//	0%	0%	0%	0%	0%	0.0%	0%	0%	//	0.0%
Barnacles (BAR)	//	0%	13%	3%	0%	0%	2.5%	2%	14.5%	//	0.0%
Ostracods (OS)	//	6%	2%	2%	0.5%	0.5%	0.5%	0%	1.5%	//	3.5%
Serpulids (SER)	//	0%	0%	0%	0%	0%	0.0%	0%	0%	//	0.0%

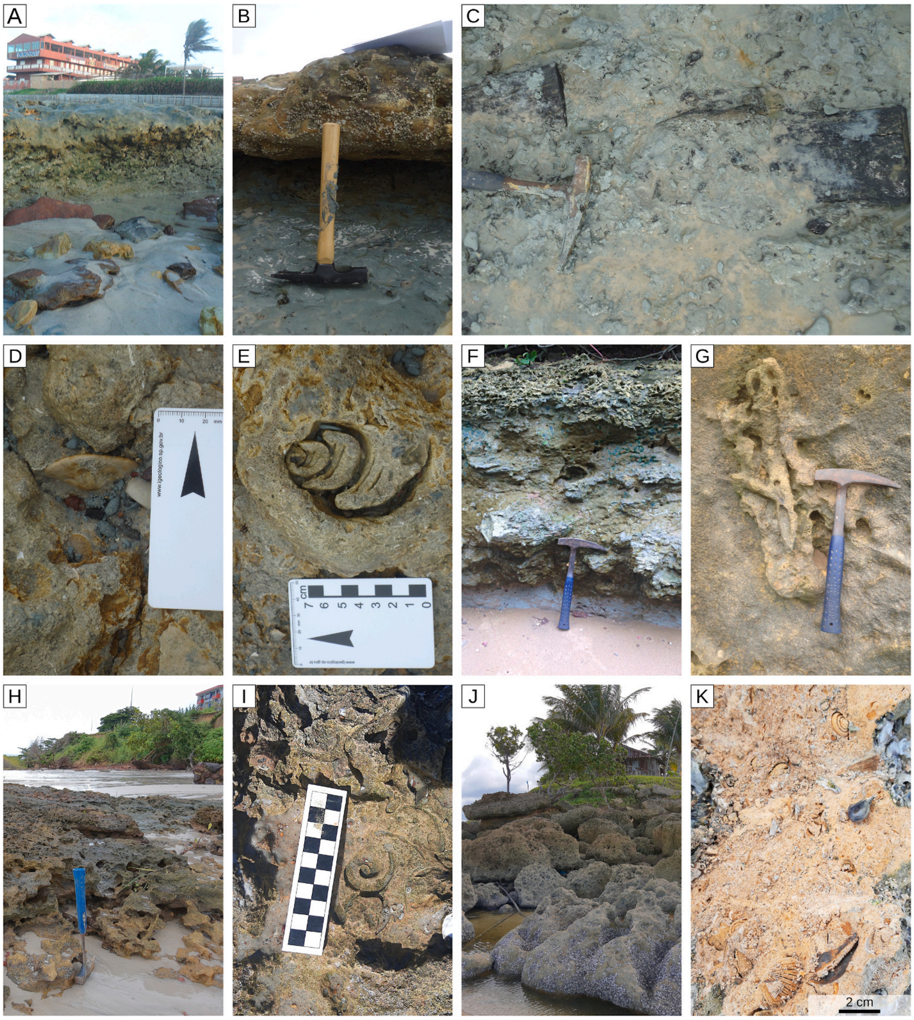

Fig. 4. Pirabas Formation outcrops. A) Praia do Atalaia, an overview of a part of the outcrop exposed on the beach. B) Praia do Atalaia, mudstones overlain by the bioclastic rocks. C) Praia do Atalaia, mudstone with plant remains. D) Praia do Atalaia, irregular echinoderm. E) Praia do Atalaia, internal model of gastropod. F) Aricuru outcrop. G) Aricuru, *Thalassinoides*. H) Lower part of the Praia do Maçarico section. I) Ponta do Castelo, internal mould of gastropod. J) Fazenda outcrop. K) A fresh surface of the coarse-grained bioclastic rock from the Fazenda outcrop.

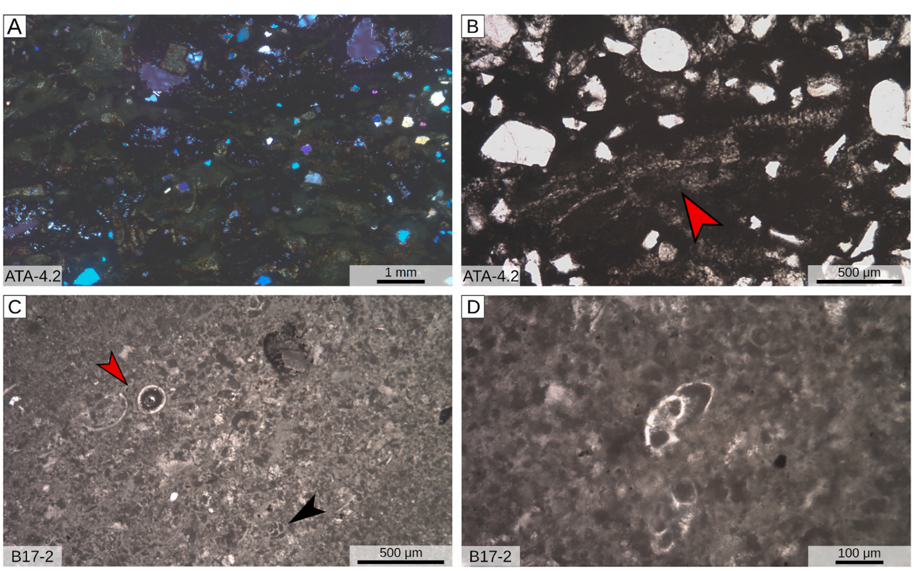

Fig. 5. Mud-supported samples. A) Sample ATA-4.2, a mud-supported, iron-rich nodule collected from the black mudstones from the Praia do Atalaia outcrop. B) Quartz grain embedded into the iron-rich muddy-matrix; red arrowhead = poorly preserved colony of erected flexible bryozoans. C) Sample B17-2, a carbonate mudstone with scattered bioclastic fragments, including ostracods = red arrowhead and small benthic foraminifera = black arrowhead. D) Detail of a small benthic rotaliid.

Archaiasinae sub-family; Fig. 7F); rare *Planorbulina* specimens were also observed at Ponta do Castelo (Tables 1 and 2; Fig. 9). Benthic foraminifera are less common in the samples derived from Colônia Pedro Teixeira and Capanema quarry B17, whereas the assemblage mostly comprises small rotaliids and extremely rare soritids (Tables 1 and 2).

Overall, although large benthic foraminifera were common in most samples, typical early Miocene markers (*e.g. Lepidocyclina* and *Miogypsina*) were not clearly observed, suggesting that the investigated samples

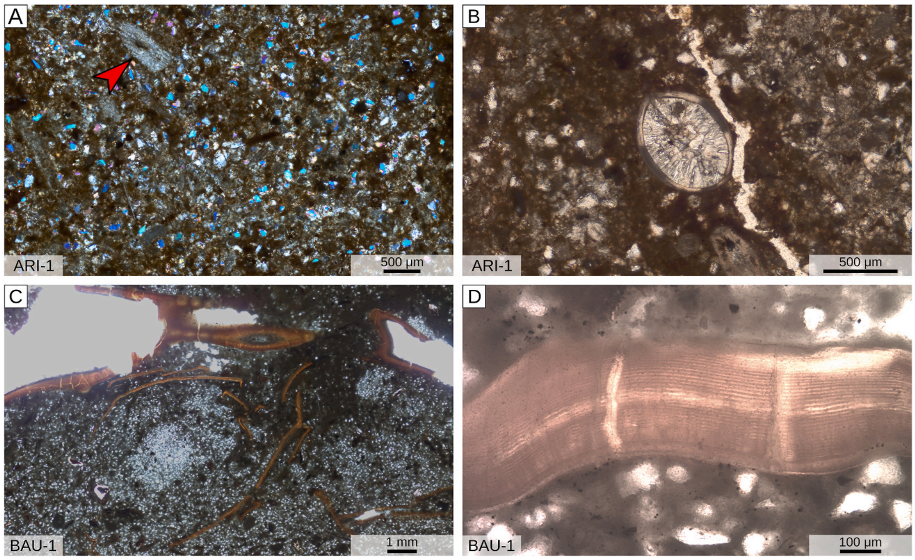

Fig. 6. Mainly siliciclastic, grain-supported, samples. A) Sample ARI-1, mixed siliciclastic–carbonate sandstone displaying echinoderm fragments = red arrowhead. B) Detail of an ostracod. C) Sample BAU-1, mixed siliciclastic–carbonate sandstone containing crustacean fragments. D) Detail of a crustacean shell microstructure.

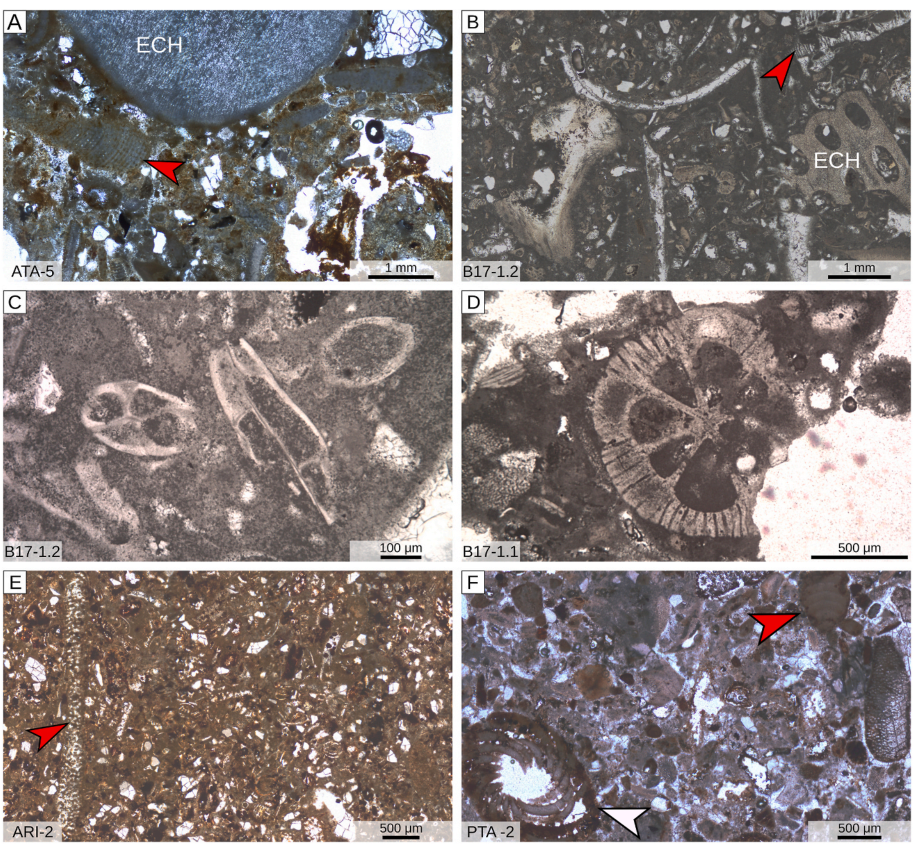

Fig. 7. Skeletal assemblage of grain-supported bioclastic samples; major components. A) Sample ATA-5, ECH = large echinoderm spine; red arrowheads = soritid fragments. B) Sample B17–1.2, molluscs (both preserved and recrystallised), bryozoans = white arrowhead and echinoderms. C) Sample B17–1.2, small erect-flexible cellariiform bryozoan colonies. D) Sample B17–1.1, slightly larger and thicker erect-flexible colony of cellariiform bryozoan. E) Sample ARI-2, siliciclastic-rich packstone containing a large soritid specimen = red arrowhead. F) Sample PTA-2, grain-supported bioclastic sample from Ponta do Castelo displaying large miliolids = white arrowhead and articulated red coralline algae = red arrowhead.

had a post early Miocene age based on both regional and global large benthic foraminiferal distributions (Abreu et al., 1993; Abreu et al., 1986 in Pessoa, 1999; BouDagher-Fadel and Price, 2010, 2013).

5. Discussion

5.1. *Integrated palaeontological and sedimentological interpretation*

Two main groups (α, β) and three main facies (α_1, α_2 and β) can be recognised. Group α includes biogenic-rich samples derived from Praia do Atalaia, Praia do Maçarico, Ponta do Castelo, Fazenda, Colônia Pedro Teixeira outcrops and Capanema quarry B17 and those with a more mixed siliciclastic–carbonate composition (ATA-3, ATA-5 and BAU-1). Two facies can be recognised in this group.

First is Facies α_1, echinoderm–bryozoan packstone to rudstone rich in molluscs and soritids (Table 3). Along the modern coast of northern Brazil, bioclastic sediments are only found offshore; close to the coast, the platform is dominated by terrigenous sediments (Vital et al., 2008;

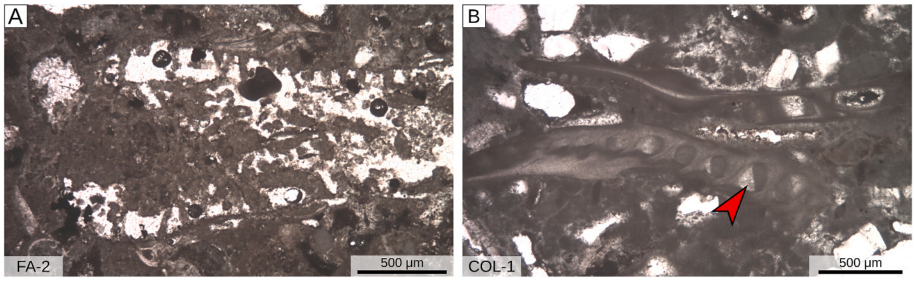

Fig. 8. Skeletal assemblage of grain-supported bioclastic samples; minor components. A) Sample FA-2, *Halimeda*. B) Sample COL-1, barnacles.

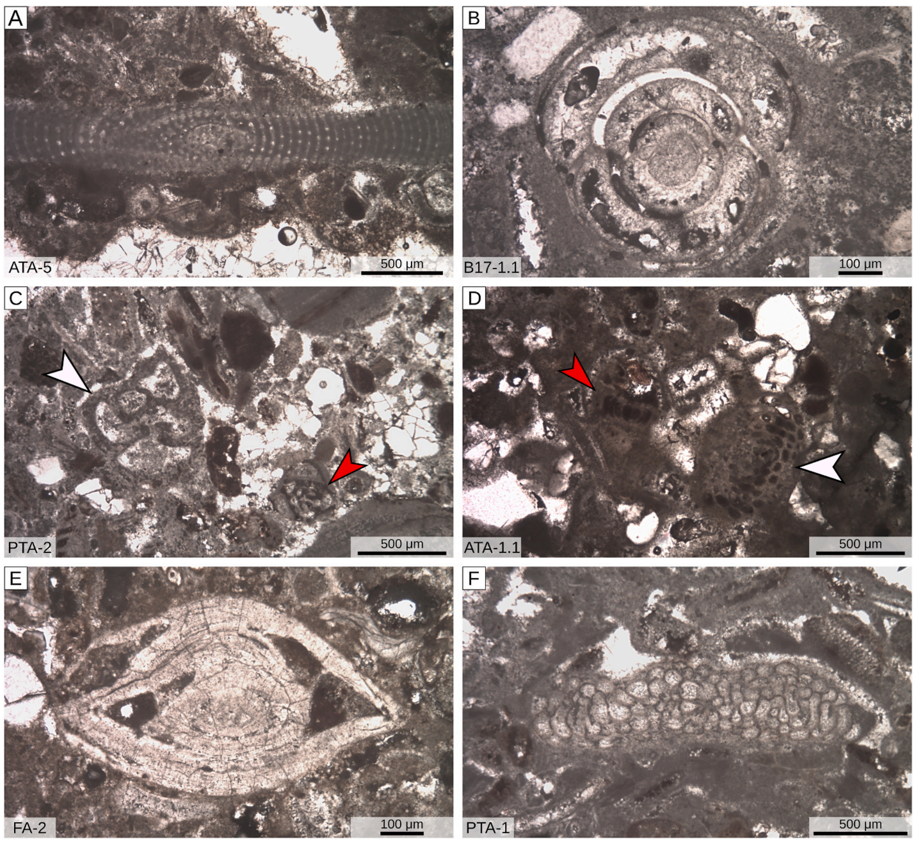

Fig. 9. Foraminiferal assemblage of grain-supported bioclastic samples. A) Sample ATA-5, soritid, possibly *Sorites*. B) Sample B17–1.1, *Pyrgo*. C) Sample PTA-2, a textulariid = white arrowhead and a small miliolid = red arrowhead. D) Sample ATA-1.1, *Planorbulina*. E) Sample FA-2, thick-walled *Amphistegina* specimen. F) Sample PTA-1, *Planorbulina*.

Nascimento et al., 2010; De Mahiques et al., 2019). Near the Amazon River mouth, bioclastic sediments are found offshore at distances exceeding 200 km and at water depths exceeding 1000 m (De Mahiques et al., 2019). Several hundreds of kilometres eastwards (*e.g.* offshore of the state of Ceará), they occur much closer to the coast (60 km or less) and in shallower waters (between 20 and 70 m; Vital et al., 2008; Nascimento et al., 2010; De Mahiques et al., 2019). The skeletal assemblage of Facies α_1 clearly points towards a very shallow-water setting. *Planorbulina* and *Sorites* are epiphytes (Langer, 1993; Murray, 2006; Mateu-Vicens et al., 2014). Thus, they commonly occur within the water-depth range of seagrasses (generally, less than 20 m; Duarte, 1991). Erect-flexible cellariiform bryozoan colonies (Fig. 7C and D) generally occur in shallow waters (mainly in depths less than 50 m; Smith, 1995). Furthermore, the shallow-water settings are supported by the crustacean assemblages observed at Capanema quarry B17 by Aguilera et al. (2014). Moreover, the relatively common barnacles characterising the skeletal assemblage of Capanema quarry B17 (Table 2) support a shallow-water setting as these sessile crustaceans are generally abundant in very shallow waters (Coletti et al., 2018). Overall, Facies α1 probably represents the distal parts of the inner sectors of a moderate-energy carbonate platform.

Facies α2, siliciclastic-rich wackestone to packstone (Table 3) is represented by the mixed siliciclastic–carbonate samples derived from the Praia do Atalaia and Aricuru outcrops (α2). The proximal inner platform along the tropical continental margins is usually dominated by terrigenous sediments (*e.g.* Bilings and Ragland, 1968; Vital et al., 2008; De Mahiques et al., 2019). Consequently, the environment represented by this facies was probably located landwards from the one represented by Facies α1 and was probably associated with the shallower-water conditions. A very shallow marine setting matches of the observed skeletal and foraminiferal assemblages (Table 1) and crustacean and ichnofossil assemblages from the Praia do Atalaia and Aricuru outcrops (Soares et al., 2019; Aguilera et al., 2020b; Lima et al., 2020b; De Araújo et al., 2021). Thus, Facies α2 probably represents the intermediate

Table 3
Summary of the characteristics of the recognised facies.

Code	α_1	α_2	β
Extended name	Echinoderm-bryozoan packstone to rudstone	siliciclastic-rich wackestone to packstone	siliciclastic fine-grained sandstone to mudstone
Lithological classification	Packstones to rudstones	Wackestones to packstones	Sandstones to mudstones
Siliciclastic terrigenous fraction	Minor (10% of the whole rock or less)	Relevant (between 10% and 30%)	Majority (more than 50%)
Common bioclastic components	Echinoderms, bryozoans	Echinoderms, bryozoans, large benthic foraminifera (soritids), crustacean remains	
Relevant bioclastic components	Mollusks, large benthic foraminifera (soritids, amphisteginids), small benthic foraminifera	Mollusks, coralline red algae	
Minor bioclastic components	Coralline red algae, barnacles,		Echinoderms, plant remains
Rare bioclastic components	Halimeda, ostracods, crustacean remains, vertebrate remains	Ostracods, small benthic foraminifera, vertebrate remains	Crustacean remains, bryozoans, small benthic foraminifera
Paleoenvironmental interpretation	Distal inner carbonate platform	Intermediate inner carbonate platform	Proximal inner carbonate platform, close to entry-points of terrigenous material

portion of the inner platform.

Further palaeoenvironmental information about Facies α1 and α2, in particular information regarding the proximal inner platform distance can be provided by the skeletal and foraminiferal assemblages. Samples derived from Aricuru and Praia do Atalaia are characterised by a high concentration of soritids (Table 1), suggesting the presence of a macrophyte meadow. This finding combined with the abundance of micrite and relevant siliciclastic fraction, mainly comprising fine-sand-sized grains (Table 1), provides evidence that these outcrops were probably originally located relatively close to the coast, possibly in an embayment protected from strong waves, a setting favourable for the development of extensive macrophyte meadows. Conversely, samples derived from Fazenda and Ponta do Castelo are characterised by a lower terrigenous fraction, coarser-grained bioclastic particles, less amounts of micrite and a higher number of thick-walled *Amphistegina* specimens (Table 1; Fig. 9E; see Hallock et al., 1986 and Mateu-Vicens et al., 2009 for the environmental significance of test thickness in *Amphistegina*). This evidence is suggestive of higher hydrodynamic energy and thus of a more distal inner platform compared to Aricuru and Praia do Atalaia. Capanema quarry B17 and Colônia Pedro Teixeira are characterised by a higher number of bryozoans and barnacles and less large benthic foraminifera and coralline algae than Praia do Atalaia, Aricuru, Fazenda and Ponta do Castelo (Table 1 and 2). This suggests the presence of coastal settings with turbid waters and reduced light availability at the seafloor, leading to unfavourable conditions for plants, algae and symbiont-bearing organisms but favourable for heterotrophs, such as bryozoans and barnacles (Hallock and Schlager, 1986; Brasier, 1995a, b).

Facies β, siliciclastic fine-grained sandstone to mudstone (Table 3), includes mainly fine-grained, locally pyrite-rich and siliciclastic samples of Group β (and Sample ATA-4.2) and occurs in the Aricuru, Praia do Atalaia and Praia do Maçarico outcrops. Currently, the siliciclastic-dominated northern equatorial margin of Brazil displays a strip of fine-grained sediments very close to the coast, in water depths less than 20 m (Vital et al., 2008; De Mahiques et al., 2019). Furthermore, the mudstone samples (ATA-4.1, MAÇ-1 and MAÇ-3) included in this group display a dark colour. This dark colour suggests a restricted environment under low hydrodynamic conditions that foster organic matter preservation and the precipitation of authigenic iron minerals (Otero et al., 2009; Moreira et al., 2017; Gu et al., 2020). Mangrove forests are important carbon sinks as their dense root network restricts water circulation, favouring organic matter preservation, leading to reduced oxygen concentrations in sediments and influencing the behaviour of redox-sensitive elements (Ferreira et al., 2007; Otero et al., 2009; Marchand et al., 2012). As mangrove forests are currently common in the intertidal zone of the study area (*e.g.* Menezes et al., 2008), the inner-platform settings of the upper Pirabas Formation were also characterised by a dense mangrove cover. Moreover, this assumption is supported by the extensive palynological research on the Pirabas Formation demonstrating the presence of mangrove pollens (*e.g.* Antonioli et al., 2015; Aguilera et al., 2020a). Sample ATA-4.2 is an authigenic nodule of pyrite. Framboidal, amorph and acicular pyrites have been observed in the siliciclastic mudstone layers of the Praia do Atalaia successions (Da Mata, 2021). The genesis of this nodule is most likely related to the prevailing redox conditions in the mangrove forests. Overall, Facies β probably represents the proximal and siliciclastic-dominated portion of the inner platform. These sectors are most likely characterised by a complex mosaic of tidal flats (fine sandstones) and mangrove forests (siliciclastic mudstones).

The limited exposed area of the observed outcrops and the poor preservation of the material (Figs. 2–4) significantly hindered the observation of sedimentary structures related to either currents or mass-transport events. However, the scarcity of skeletal grains related to the middle or outer platform carbonate factories (*e.g.* encrusting coralline algae) or pelagic settings (*e.g.* planktonic foraminifera) indicates that the bioclasts produced in the inner platform were not subsequently transported into the deeper settings. The abundance of micrite, poorly sorted sediments and local presence of burrows networks suggesting that probably the lateral transport of skeletal grains was relatively limited. Therefore, it is reasonable to assume that the analysed samples of the Pirabas Formation formed in the inner-platform shallow-water settings.

The Miocene Pirabas Formation was probably similar to the eastern stretches of the modern northern Brazilian margin, where bioclastic sediments already occur in shallow waters. Since the investigated outcrops are located close to the Amazon River mouth, the terrigenous fluxes were probably lower during the deposition of the Pirabas Formation compared with current conditions. The lack of hermatypic corals and abundance of bryozoans suggest that the Pirabas Formation carbonate factory was already influenced by terrestrial runoff. Terrestrial runoff is a major source of nutrients (both phosphates and nitrates) to marine coastal ecosystems (*e.g.* Föllmi, 1996). At tropical latitudes, nutrient abundance can prevent the formation of coral reefs, favouring carbonate factories dominated by heterotrophs (like bryozoans) that can take advantage of the plankton abundance and lack of competition from symbiont-bearing corals (Hallock and Schlager, 1986; Brasier, 1995a, 1995b; Halfar et al., 2004; Reijmer et al., 2012; Reymond et al., 2016; Coletti et al., 2017, 2019). Based on the general palaeoenvironment interpretation, the analysis indicates that an increasing number of carbonate biogenic factories are found at longer distances from the coastline. Furthermore, this trend can be observed in modern sediments from the northern Brazil margin (Nascimento et al., 2010). The siliciclastic Facies β is mainly located in the eastern part of the study area, whereas Facies α_1 dominates the western part. This indicates that during the deposition of the upper Pirabas Formation, the Cratonic Amazon River (*i.e.* the Amazon River prior to the establishment of the transcontinental drainage) was already the main entry point for the siliciclastic material in the study area.

5.2. Evolution of the mixed siliciclastic–carbonate margin

Based on the analysed dataset that includes most lithologies from outcrops and quarries at the Pirabas Formation, most observed variabilities seems to be related to the distance from the proximal inner platform, that is, the main source of terrigenous material. However, both the position of the coastline and terrigenous fluxes can change over time. Decrease in the sea level causes the progradation of siliciclastic-dominated sedimentary environments over bioclast-dominated environments, whereas increase in the sea level promotes the opposite. Certainly, the sea-level decrease that ensued the middle Miocene climatic optimum high-stand (Miller et al., 2020) has been advocated as the main driver of the progradation of the siliciclastic Barreiras Formation over the bioclastic Pirabas Formation and collapse of near-shore carbonate production along the Brazilian equatorial margin (*e.g.* Nogueira et al., 2021). The increase in the terrigenous sediment supply following the middle–late Miocene initiation of the transcontinental drainage of the Amazon River (Figueiredo et al., 2009, 2010) contributed to moving carbonate production progressively offshore. Finally, the coastal rainfall variations (Schneider et al., 2014) might have led to terrigenous flux changes along the margin. Regardless of the main cause of the increase in the terrigenous supply, the samples from the outcropping portion of the Pirabas Formation clearly reveal the presence of a terrigenous-influenced platform similar to that of the modern northeastern Brazilian equatorial margin. Furthermore, the geographical distribution of the siliciclastic-dominated lithologies indicates that during the deposition of the uppermost Pirabas Formation (*i.e.* the outcropping portion), the Cratonic Amazon River was already a relevant entry point of the siliciclastic material along the margin. The stratigraphic columns of the investigated outcrops as well as the general stratigraphy of the study area (Figs. 1–3) clearly indicate that following the end of the early Miocene (at least following the local extinction of miogypsinids and lepidocyclinids, which are absent from the upper Pirabas Formation), the siliciclastic supply progressively increased. During the deposition of the upper Pirabas Formation, the influx of the Cratonic Amazon River and other coastal rivers was probably not high enough to completely prevent near-shore carbonate production as it is currently but was already strong enough to prevent photozoan carbonate factories from colonising the margin. When comparing the skeletal assemblage from the lower Amapá Formation, largely dominated by symbiont-bearing large benthic foraminifera and calcareous algae (De Mello e Sousa et al., 2003) to the skeletal assemblage of the upper Pirabas Formation, which is dominated by heterotrophs (*i.e.* echinoderms and bryozoans), it becomes clear that the latter developed under an increase of coastal plain drainages and nutrient supply compared with the former. The analyses of the large underground portion of the Pirabas Formation would allow to follow the near-effect of the sediment influx on the margin over time (i.e. the physical smothering of carbonate producers) separating the far-effect (i.e. the increases in nutrient supplies that can prevent photozoan-dominated production), thereby constraining the stages of this evolution.

This type of analysis on outcrops and quarries sections and offshore cores could keep track of this process and may help in correlating the various cores providing information on the large-scale geometry of the basin and its deposits. This context improves our knowledge with respect to those with hydrocarbon potential, such as those at the intermediate inner platform that are characterised by the coarse-grained bioclastic production and are favourable to burrowing crustaceans (De Araújo et al., 2021).

6. Conclusions

The Pirabas Formation is the youngest bioclastic-dominated sedimentary formation of the Brazilian equatorial margin. It records the Neogene evolution of the platform from the carbonate-dominated pre-Amazon stage to the siliciclastic-dominated Amazon fan stage and represents an important target for the oil industry and groundwater exploration. This study provides a detailed description of the main facies and skeletal assemblage of the outcropping portion of the Pirabas Formation, providing unprecedented insight for the analysis of core-based data. Similar to the modern Brazilian equatorial margin, the findings indicate that the ratio between the terrigenous and bioclastic fractions is a clear and straightforward proxy for the distance from the proximal inner platform, which is useful in recognising restricted coastal environments characterised by organic matter preservation and authigenic mineral precipitation (*e.g.* mangrove swamps). Furthermore, the skeletal and foraminiferal assemblages greatly help in discriminating between different inner-platform settings.

Extending this approach to the subsurface portion of the Pirabas Formation could help improve the stratigraphic framework of the Cenozoic succession. The correlation of the offshore and onshore records of the Pirabas Formation with the reservoir-bearing Amapá and Ilha de Santana formations and tracking the evolution of the Brazilian equatorial margin from a carbonate-dominated environment to a siliciclastic-dominated environment. Extending this approach to the subsurface portion of the Pirabas Formation could help improve the stratigraphic framework of the Cenozoic succession.

Author contributions

OA, GC and VTK conceived and designed the experiments. OA and APL performed the field trip and sample collections. OA and GC performed the experiments. OA, MVAM, APL, VTK and GC analysed the data, the information context and revised the manuscript. OA and GC wrote the paper.

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

The data that has been used is confidential.

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References

Abreu, W.S., Regali, M.P.S., Shimabukuro, S., 1986. O Terciário da plataforma continental do Maranhão e Pará, Brasil: bioestratigrafia e evolução paleoambiental. In: Anais do XXXIV Congresso Brasileiro de Geologia, vol. 1, pp. 145–159. Goiânia.

Abreu, W.S., Viviers, M.C., Antunes, R.L., 1993. Bioestratigrafia e paleoecologia das seções carbonáticas terciárias das bacias Potiguar, Ceará e Pará/Maranhão, com base em macroforaminíferos, Parte 1 (Oligoceno Superior – Recente). PETROBRAS/ Cenpes/Divex/Sebipe, Rio de Janeiro, p. 45 p. (Relatório Interno).

Aguilera, O., Schwarzhans, W., Moraes-Santos, H., Nepomuceno, A., 2014. Before the flood: Miocene otoliths from eastern Amazon Pirabas Formation reveal a Caribbean type fish fauna. J. S. Am. Earth Sci. 56, 422–446. https://doi.org/10.1016/j.jsames.2014.09.021.

Aguilera, O., Zoneibe, L., Carrillo-Briceño, J.D., Kocsis, L.K., Vennemann, T.W., Toledo, P.M., Nogueira, A., Amorim, K.B., Moraes-Santos, H., Polck, M.R., Ruivo, M. D.L., Linhares, A.P., Monteiro-Neto, C., 2017. Neogene sharks and rays from the Brazilian blue Amazon. PLoS One 12. https://doi.org/10.1371/journal.pone.0182740 e0182740 – 34.

Aguilera, O., Oliveira de Araújo, O.M., Hendy, A., Nogueira, A.A.E., Nogueira, A.C.R., Maurity, C.W., Kutterd, V.T., Martins, M.V.A., Coletti, G., Borba, B., Silva-Caminha, S.A.F., Jaramillo, C., Bencomo, K., Lopes, R.T., 2020a. Palaeontological framework from Pirabas Formation (North Brazil) used as potential model for equatorial carbonate platform. Mar. Micropaleontol. 154, 1–23. https://doi.org/10.1016/j.marmicro.2019.101813.

Aguilera, O., Bencomo, K., de Araújo, O.M.O., Dias, B.B., Coletti, G., Lima, D., Silane, A. F., Polk, M., Alves-Martin, M.V., Jaramillo, C., Kutter, V.T., Lopes, R.T., 2020b. Miocene heterozoan carbonate systems from the western Atlantic equatorial margin in South America: the Pirabas Formation. Sediment. Geol. 407, 1–28. https://doi.org/10.1016/j.sedgeo.2020.105739.

Antonioli, L., de Araújo Távora, V., Dino, R., 2015. Palynology of carcinolites and limestones from the Baunilha Grande ecofacies of the Pirabas Formation (Miocene of Pará state, northeastern Brazil). J. S. Am. Earth Sci. 62, 134–147. https://doi.org/10.1016/j.jsames.2015.05.005.

Ávila, R.M., 2018. Brazilian Equatorial Margin Prospectivity. Open Acreage Brazil, Oil and Gas Concessions. Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, Rio de Janeiro. August 27th, 2018.

Bencomo, K., Mihaljević, M., De Araújo, O.M.O., Lopes, R.T., Lima, D., Aguilera, O., 2021. Dominance of Miocene echinoderms in the equatorial Neogene marine platform of Brazil and their insights into the paleoenvironment. J. S. Am. Earth Sci. 112 (1) https://doi.org/10.1016/j.jsames.2021.103595.

Beurlen, K., 1958. Contribuição a paleontologia do estado do Pará. Bol. Mus. Para. Emilio Goeldi 5, 1–49.

Bilings, G.K., Ragland, P.C., 1968. Geochemistry and mineralogy of the recent reef and lagoonal sediments south of Belize (British Honduras). Chem. Geol. 3 (2), 135–153.

Brownfield, M.E., Charpentier, R.R., 2006. Geology and Total Petroleum Systems of the Gulf of Guinea Province of West Africa, 2207-C. U.S. Geological Survey Bulletin, p. 32. https://doi.org/10.3133/b2207C.

BouDagher-Fadel, M.K., Price, G.D., 2010. Evolution and paleogeographic distribution of the lepidocyclinids. J. Foraminifer. Res. 40 (1), 79–108.

BouDagher-Fadel, M.K., Price, G.D., 2013. The phylogenetic and palaeogeographic evolution of the miogypsinid larger benthic foraminifera. J. Geol. Soc. 170 (1), 185–208.

Brandão, J.A.S.L., Feijó, F.J., 1994a. Bacia da Foz do Amazonas. Bol. Geociencias Petrobras 8 (1), 91–99.

Brandão, J.A.S.L., Feijó, F.J., 1994b. Bacia da Pará-Maranhão. Bol. Geociencias Petrobras 8 (1), 101–102.

Brasier, M.D., 1995a. Fossil indicators of nutrient levels 1: eutrophication and climate change. In: Bosence, D.W.J., Allison, P.A. (Eds.), Marine Paleoenvironmental Analysis from Fossils, vol. 83. Geological Society Special Publication, Geological Society, London, pp. 113–132.

Brasier, M.D., 1995b. Fossil indicators of nutrient levels 2: evolution and extinction in relation to oligotrophy. In: Bosence, D.W.J., Allison, P.A. (Eds.), Marine Paleoenvironmental Analysis from Fossils, vol. 83. Geological Society Special Publication, Geological Society, London, pp. 133–150.

Brito, I.M., 1971. Contribuição ao conhecimento dos Crustáceos decápodos da Formação Pirabas. I – Brachyura Brachyrhyncha. An Acad. Bras Ciências 43, 489–498.

Brito, I.M., 1972. Contribuição ao conhecimento dos Crustáceos decápodes da Formação Pirabas. II - Brachyura Ocypodidae. An Acad. Bras Ciências 44 (1), 95–98.

Carannante, G., Esteban, M., Milliman, J.D., Simone, L., 1988. Carbonate lithofacies as paleolatitude indicators: problems and limitations. Sediment. Geol. 60 (1–4), 333–346.

Coletti, G., El Kateb, A., Basso, D., Cavallo, A., Spezzaferri, S., 2017. Nutrient influence on fossil carbonate factories: evidence from SEDEX extractions on Burdigalian limestones (Miocene, NW Italy and S France). Palaeogeogr. Palaeoclimatol. Palaeoecol. 475, 80–92.

Coletti, G., Bosio, G., Collareta, A., Buckeridge, J., Consani, S., El Kateb, A., 2018. Palaeoenvironmental analysis of the Miocene barnacle facies: case studies from Europe and South America. Geol. Carpathica 69, 573–592.

Coletti, G., Basso, D., Betzler, C., Robertson, A.H.F., Bosio, G., El Kateb, A., Foubert, A., Meilijson, A., Spezzaferri, S., 2019. Environmental evolution and geological significance of the Miocene carbonates of the eratosthenes seamount (ODP leg 160). Palaeogeogr. Palaeoclimatol. Palaeoecol. 530, 217–235.

Costa, S.A.R.F., 2011. Ictiólitos da Formação Pirabas, Mioceno do Pará, Brasil, e suas implicações paleoecológicas. Tese de Doutorado. Instituto de Geociências, Programa de Pós-graduação em Geologia e Geoquímica. Universidade Federal do Pará, Brazil.

Cruz, A.M., Reis, A.T., Suc, J.P., Silva, C.G., Praeg, D., Granjeon, D., Rabineau, M., Popescu, S.M., Gorini, C., 2019. Neogene evolution and demise of the Amapá carbonate platform, Amazon continental margin, Brazil. Journal of Marine and Petroleum Geology 105, 185–203.

Da Mata, G.A.T., 2021. Flora e fauna do Neógeno das áreas de manguezais de lagoas costeiras da plataforma equatorial do Brasil: Processo de piritização. MSc These, Universidade Federal do Pará, Instituto de Geociências, Brasil.

De Araújo, O.M.O., Aguilera, O., Coletti, G., Valencia, F.L., Buatois, L.A., Lopes, R., 2021. X-ray micro-computed tomography of burrow-related porosity and permeability in shallow-marine equatorial carbonates: a case study from the Miocene Pirabas Formation, Brazil. Journal of Marine and Petroleum Geology 127. https://doi.org/10.1016/j.merpetgeo.2021.10496.

De Mahiques, M.M., Siegle, E., Francini-Filho, R.B., Thompson, F.L., de Rezende, C.E., Gomes, J.D., Asp, N.E., 2019. Insights on the evolution of the living great Amazon reef system, equatorial west atlantic. Sci. Rep. 9 (1), 1–8.

De Mello e Sousa, S.H., Fairchild, T.R., Tibana, P., 2003. Cenozoic biostratigraphy of larger foraminifera from the Foz do Amazonas Basin, Brazil. Micropaleontology 49 (3), 253–266.

Duarte, C.M., 1991. Seagrass depth limits. Aquat. Bot. 40 (4), 363–377.

Ferreira, C.S., Cunha, O.R., 1957. Contribuição à Paleontologia do estado do Pará. Notas sobre a Formação Pirabas, com descrição de novos invertebrados fósseis. Bol. Mus. Para. Emilio Goeldi Nova Ser. Geol. 2, 1–60.

Ferreira, C.S., 1977. Fácies da Formação Pirabas (Mioceno Inferior): novos conceitos e ampliações (Projeto específico ABC FINEP). An Acad. Bras Ciências 49 (2), 353.

Ferreira, C.S., Francisco, B.H.R., 1988. As relações da Formação Pirabas (Oligoceno-Mioceno) com as formações continentais terciárias no NE do Pará. Anais do Congresso Brasileiro de Geologia 35 (2), 761–764.

Ferreira, T.O., Otero, X.L., Vidal-Torrado, P., Macías, F., 2007. Effects of bioturbation by root and crab activity on iron and sulfur biogeochemistry in mangrove substrate. Geoderma 142 (1–2), 36–46.

Figueiredo, J., Zalán, P.V., Soares, E.F., 2007. Bacia da Foz do Amazonas. Boletim de Geociências. PETROBRAS 15 (2), 299–309.

Figueiredo, J.J.J.P., Hoorn, C., Van der Ven, P., Soares, E., 2009. Late Miocene onset of the Amazon River and the Amazon deep-sea fan: evidence from the Foz do Amazonas Basin. Geology 37 (7), 619–622.

Figueiredo, J.J.J.P., Hoorn, C., Van der Ven, P., Soares, E., 2010. Late Miocene onset of the Amazon River and the Amazon deep-sea fan: evidence from the Foz do Amazonas Basin: reply. Geology 38 (7) e213–e213.

Flügel, E., 2010. Microfacies of Carbonate Rocks: Analysis Interpretation and Application. Springer, New York, p. 967.

Föllmi, K.B., 1996. The phosphorous cycle, phosphogenesis and phosphate-rich deposits. Earth Sciences Review 40, 55–124.

Freimann, B.C., Alves, J.G.V., Silva, M.W.C., 2014. Hydrological study through geophysical well logs – city of Salinópolis, PA. Águas Subterrâneas 28, 14–30.

Góes, A.M., Rossetti, D.F., Nogueira, A.C.R., Toledo, P.M., 1990. Modelo deposicional preliminar da Formação Pirabas no nordeste do estado do Pará. Boletim do Museu Paraense Emílio Goeldi, série Ciências da Terra 2, 3–15.

Gorini, C., Haq, B.U., dos Reis, A.T., Silva, C.G., Cruz, A., Soares, E., Grangeon, D., 2014. Late Neogene sequence stratigraphic evolution of the Foz do Amazonas Basin, Brazil. Terra. Nova 26 (3), 179–185.

Gu, L., Shah, C., Mao, J., Raassen, T., de Plaa, J., Pinto, C., Akamatsu, H., Werner, N., Simionescu, A., Mernier, F., Sawada, M., Mohanty, P., Amaro, P., Gu, M.F., Porter, F. S., López-Urrutia, J.R.C., Kaastra, J.S., 2020. X-ray spectra of the Fe-L complex II. Atomic data constraints from the EBIT experiment and X-ray grating observations of Capella. Astron. Astrophys. 627 (A93), 1–28.

Hallock, P., Forward, L.B., Hansen, H.J., 1986. Influence of environment on the test shape of *Amphistegina*. J. Foraminifer. Res. 16 (3), 224–231.

Hallock, P., Schlager, W., 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1, 389–398.

Halfar, J., Godinez-Orta, L., Mutti, M., Valdez-Holguìn, J.E., Borges, J.M., 2004. Nutrient and temperature controls on modern carbonate production: an example from the Gulf of California. Mexico. Geology 32, 213–216.

Hayton, S., Nelson, C.S., Hood, S.D., 1995. A skeletal assemblage classification system for non-tropical carbonate deposits based on New Zealand Cenozoic limestones. Sediment. Geol. 100 (1–4), 123–141. https://doi.org/10.1016/0037-0738(95)00071-2.

James, N.P., 1997. The cool-water carbonate depositional realm. In: James, N.P., Clarke, J.A.D. (Eds.), Cool-water Carbonates, vol. 56. SEPM Special Publication, pp. 1–20.

Kelly, J., Doust, H., 2016. Exploration for late cretaceous turbidites in the equatorial African and northeast South American margins. Neth. J. Geosci. 95 (4), 393–403 https://doi.org/110.1017/njg.2016.36.

Langer, M.R., 1993. Epiphytic foraminifera. Mar. Micropaleontol. 20 (3–4), 235–265.

Lees, A., Buller, A.T., 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Mar. Geol. 13 (5), M67–M73.

Leite, F.P.R., 2004. Palinologia. Org. In: Rossetti, D. de F., Góes, A.M. (Eds.), O Neógeno da Amazônia Oriental. Belém. Museu Paraense Emílio Goeldi, pp. 55–90.

Lima, D., Tavares, M., Lopes, R.T., de Araújo, O.M.O., Aguilera, O., 2020a. *Uca maracoani* (Crustacea, Decapoda, Ocypodidae) from a Miocene paleomangrove in Brazil: a case of evolutionary stasis among tropical American fiddler crabs. J. S. Am. Earth Sci. 99, 1–11. https://doi.org/10.1016/jsames.2020.102517.

Lima, D., Anker, A., Hyžný, M., Kroh, A., Aguilera, O., 2020b. First evidence of fossil snapping shrimps (Alpheidae) in the Neotropical region, with a checklist of the fossil caridean shrimps from the Cenozoic. J. S. Am. Earth Sci. 103, 1–11. https://doi.org/10.1016/j.jsames.2020.102795.

Lima, D., Tavares, M., Aguilera, O., 2021. The Inachoididae spider crabs (Crustacean, Brachyura) from the Neogene of the tropical Americas. J. Paleontol. 1–21. https://doi.org/10.1017/jpa.2021.91.

Lokier, S.W., Wilson, M.E.J., Burton, L.M., 2009. Marine biota response to clastic sediment influx: a quantitative approach. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 25–42.
Marchand, C., Fernandez, J.M., Moreton, B., Landi, L., Lallier-Vergès, E., Baltzer, F., 2012. The partitioning of transitional metals (Fe, Mn, Ni, Cr) in mangrove sediments downstream of a ferralitized ultramafic watershed (New Caledonia). Chem. Geol. 300, 70–80.
Martins-Neto, R.G., 2001. Review of some Crustacea (Isopoda and Decapoda) from Brazilian deposits (Paleozoic, Mesozoic and Cenozoic) with descriptions of new taxa. Acta Geol. Leopoldensia 24 (52/53), 237–254.
Mateu-Vicens, G., Hallock, P., Brandano, M., Demchuk, T., Gary, A., 2009. Test Shape Variability of *Amphistegina* d'Orbigny 1826 as a Paleobathymetric Proxy: Application to Two Miocene Examples. Geologic Problems Solving with Microfossils, vol. 93. SEPM Special Publication, pp. 67–82.
Mateu-Vicens, G., Khokhlova, A., Sebastián-Pastor, T., 2014. Epiphytic foraminiferal indices as bioindicators in Mediterranean seagrass meadows. J. Foraminifer. Res. 44 (3), 325–339.
Maury, C.J., 1925. Fósseis terciários do Brasil com descrição de novas formas Cretáceas. Serviço Geológico do Brasil, Monografia 4, 1–665.
Menezes, M.P.M.D., Berger, U., Mehlig, U., 2008. Mangrove vegetation in Amazonia: a review of studies from the coast of Pará and Maranhão States, north Brazil. Acta Amazonica 38 (3), 403–420.
Michel, J., Borgomano, J., Reijmer, J.J., 2018. Heterozoan carbonates: when, where and why? A synthesis on parameters controlling carbonate production and occurrences. Earth Sci. Rev. 182, 50–67.
Miller, K.G., Browning, J.V., Schmelz, W.J., Kopp, R.E., Mountain, G.S., Wright, J.D., 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. Sci. Adv. 6 (20) eaaz1346.
Mooi, R., Martínez, S.A., Del Río, C.J., Ramos, M.I.F., 2018. Late Oligocene-Miocene non-lunulate sand dollars of South America: revision of abertellid taxa and descriptions of two new families, two new genera, and a new species. Zootaxa 4369 (3), 301–326. https://doi.org/10.11646/zootaxa.4369.3.1.
Moreira, M., Díaz, R., Santos, H., Mendoza, U., Böttcher, M.E., Capilla, R., Albuquerque, A.L., Machado, W., 2017. Sedimentary trace element sinks in a tropical upwelling system. J. Soils Sediments. https://doi.org/10.1007/s11368-017-1803-4.
Muricy, G., Domingos, C., Távora, V.A., Ramalho, L.V., Pisera, A., Taylor, P., 2016. Hexactinellid sponges reported from shallow waters in the Oligo-Miocene Pirabas Formation (N Brazil) are in fact cheilostome bryozoans. J. S. Am. Earth Sci. 72, 387–397. https://doi.org/10.1016/j.jsames.2016.10.003.
Murray, J.W., 2006. Ecology and Applications of Benthic Foraminifera. Cambridge University Press.
Nascimento, F.S.D., Freire, G.S.S., Miola, B., 2010. Geochemistry of marine sediments of the Brazilian northeastern continental shelf. Braz. J. Oceanogr. 58 (spe2), 1–11.
Nelson, C.S., Hyden, F.M., Keane, S.L., Leask, W.L., Gordon, D.P., 1988. Application of bryozoan zoarial growth-form studies in facies analysis of non-tropical carbonate deposits in New Zealand. Sediment. Geol. 60 (1–4), 301–322.
Nogueira, A.A.E., Ramos, M.I.F., 2016. The genus *Perissocytheridea* stephenson, 1938 (Crustacea: Ostracoda) and evidence of brackish water facies along the Oligo-Miocene, Pirabas Formation, eastern amazonia, Brazil. J. S. Am. Earth Sci. 65, 101–121. https://doi.org/10.1016/j.jsames.2015.11.007.
Nogueira, A.A.E., Nogueira, A.C.R., 2017. Ostracods biostratigraphy of the Oligocene-Miocene carbonate platform in the Northeastern Amazonia coast and its correlation with the Caribbean region. J. S. Am. Earth Sci. 80, 389–403.
Nogueira, A.A.E., Ramos, M.I.F., Hunt, G., 2019. Taxonomy of ostracods from the Pirabas Formation (upper Oligocene to lower Miocene), eastern amazonia (Pará state, Brazil). Zootaxa 4573, 1–111. https://doi.org/10.11646/zootaxa.4573.1.1.
Nogueira, A.C.R., Amorim, K.B., Góes, A.M., Truckenbrodt, W., Petri, S., Nogueira, A.A. E., Bandeira, J., Soares, J.L., Baía, L.B., Imbiriba, M.J., Bezerra, I.S., Ribas, C.C., Cracraft, J., 2021. Upper Oligocene–Miocene deposits of eastern amazonia: implications for the collapse of Neogene carbonate platforms along the coast of northern Brazil. Palaeogeogr. Palaeoclimatol. Palaeoecol., 110178
Otero, X.L., Ferreira, T.O., Huerta-Díaz, M.A., Partiti, C.S.D.M., Souza Jr., V., Vidal-Torrado, P., Macías, F., 2009. Geochemistry of iron and manganese in soils and sediments of a mangrove system, Island of Pai Matos (Cananeia–SP, Brazil). Geoderma 148 (3–4), 318–335.
Pamplona, H.R.P., 1969. Litoestratigrafia da Bacia Cretácea de Barreirinhas. Rio de Janeiro. Bol. Tec. Petrobras 12 (3), 261–290. Rio de Janeiro julho/setembro 1969.
Pellegrini, B.S., Ribeiro, H.J.P.S., 2018. Exploratory plays of Pará-Maranhão and Barreirinhas basins in deep and ultra-deep waters, Brazilian Equatorial Margin. Braz. J. Genet. 48 (3), 485–502. https://doi.org/10.1590/2317-4889201820180146.
Pessoa N, O. da C., 1999. Análise estratigráfica integrada da plataforma mista (Siliciclástica-Carbonática) do Neógeno da Bacia Potiguar, Nordeste do Brasil. Dissertação de Mestrado, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Brasil.
Petri, S., 1957. Foraminíferos miocênicos da Formação Pirabas. Boletim da Faculdade de Filosofia Ciências e Letras, Universidade de São Paulo. Geologia (16), 1–80.
Pomar, L., Baceta, J.I., Hallock, P., Mateu-Vicens, G., Basso, D., 2017. Reef building and carbonate production modes in the west-central Tethys during the Cenozoic. Mar. Petrol. Geol. 83, 261–304.
Ramalho, L.V., Távora, V.A., Tilbrook, K.J., Zágorsek, K., 2015. New species of *Hippopleurifera* (Bryozoa, Cheilostomata) from the Miocene Pirabas Formation, Pará state, Brazil. Zootaxa 3999 (1), 125–134. https://doi.org/10.11646/zootaxa.3999.1.8.
Ramalho, L.V., Távora, V.A., Zagorsek, K., 2017. New records of the bryozoan *Metrarabdotos* from the Pirabas Formation (lower Miocene), Pará state. Brazil Palaeontologia Electronica 1–11. https://doi.org/10.26879/704, 20.2.32A.
Reijmer, J.J.G., Bauch, T., Schäfer, P., 2012. Carbonate facies patterns in surface sediments of upwelling and non-upwelling shelf environments (Panama, East Pacific). Sedimentology 59, 32–56.
Reymond, C.E., Zihrul, K.S., Halfar, J., Riegl, B., Humphreys, A., Hildegard, W., 2016. Heterozoan carbonates from the equatorial rocky reefs of the Galapagos Archipelago. Sedimentology 63, 940–958.
Rossetti, D.F., 2001. Late Cenozoic sedimentary evolution in northeastern Pará, Brazil, within the context of sea level changes. J. S. Am. Earth Sci. 14 (1), 77–89. https://doi.org/10.1016/S0895-9811(01)00008-6.
Rossetti, D.F., Góes, A.M., 2004. Geologia. In: Rossetti, D.F., Góes, A.M. (Eds.), O Neógeno da Amazônia Oriental. Museu Paraense Emílio Goeldi (Friedrich Katzer Collection), Belém, PA, pp. 13–52.
Rossetti, D.F., Bezerra, F.H.R., Dominguez, J.M.L., 2013. Late Oligocene–Miocene transgressions along the equatorial and eastern margins of Brazil. Earth Science Review 123, 87–112. https://doi.org/10.1016/j.earscirev.2013.04.005.
Santos, M.E.C., 1958. Equinóides miocênicos da Formação Pirabas. Boletim DNPM 179, 1–24.
Santos, M.E.C.M., 1967. Equinóides miocênicos da Formação Pirabas. Atas do 1º Simpósio sobre a Biota Amazônica 1, 407–410.
Schneider, T., Bischoff, T., Haug, G.H., 2014. Migrations and dynamics of the intertropical convergence zone. Nature 513 (7516), 45–53.
Smith, A.M., 1995. Palaeoenvironmental interpretation using bryozoans: a review. Geological Society, London, Special Publications 83 (1), 231–243.
Soares, E.F., Zalán, P.V., Figueiredo, J.-J.P., Trosdtorf Jr., I., 2007. Bacia do pará-Maranhão. Boletim de Geociências. PETROBRAS 15 (2), 321–329.
Soares, J.L., Santos, H.P., Brito, A.S., Nogueira, A.A.E., Nogueira, A.C.R., Amorim, K.B., 2019. The crustaceans burrow *Sinusichus* from the Oligocene–Miocene carbonate deposits of eastern Amazonia. Ichnos 27, 97–106. https://doi.org/10.1080/10420940.2019.1697256.
Soares Jr., A.V., Costa, J.B.S., Hasui, Y., 2008. Evolução da margem Atlântica Equatorial do Brasil: Três fases distensivas. Geociencias 27 (4), 427–437.
Soares Jr., A.V., Hasui, Y., Costa, J.B.S., Machado, F.B., 2011. Evolução do rifteamento e paleogeografia da margem Atlântica Equatorial do Brasil: Triássico ao Holoceno. Geociências-UNESP 30, 669–692.
Szatmari, P., Françolin, J.B.L., Zanotto, O., Wolff, S., 1987. Evolução tectônica da margem equatorial brasileira. Rev. Bras. Geociencias 17, 180–188.
Távora, V.A., Dias, J.J., 2016. New records of decapods in Pirabas Formation (Miocene), Pará state, Brazil. Annals of Aquaculture and Research 3 (2), 1019.
Távora, V.A., Mesquita, N., De Souza, S.R., Cacela, A.S.M., Teixeira, S.G., 2002. Sistemática e tafonomia dos crustáceos decápodes da ecofácies Capanema da Formação Pirabas (Mioceno Inferior) estado do Pará. Rev. Bras. Geociencias 32 (2), 223–230.
Távora, V.A., Souza, B.L.P., Nogueira Neto, I.L.A., 2014. Micropaleontologia da litofácies recifal da Formação Pirabas (Mioceno inferior), estado do Pará, Brasil. Anuário do Instituto de Geociências. UFRJ 37 (2), 100–110. https://doi.org/10.11137/2014_2_100_110.
Toledo, P.M., 1989. Sobre novos achados de sirênios (*Sirenotherium pirabense* Paula Couto, 1967) na Formação Pirabas (Pará, Brasil). Boletim do Museu Paraense Emílio Goeldi. Série Ciências da Terra 1 (1), 1–10.
Trosdtorf Jr., I., Zalán, P.V., Figueiredo, J.-J.P., Soares, E.F., 2007. Bacia de Barreirinhas. Boletim de Geociências. PETROBRAS 15 (2), 331–339.
Vasquez, M.L., Sousa, C.S., Carvalho, J.M.A., 2008. Mapa geológico e de recursos minerais do estado do Pará, escala 1:1.000.000. Programa Geologia do Brasil (PGB), integração, actualização e difusão de dados de geología do Brasil, Mapas geológicos estaduais. CPRM-Serviço Geológico do Brasil. Superintendência Regional de Belém.
Vital, H., Stattegger, K., Amaro, V.E., Schwarzer, K., Frazão, E.P., Tabosa, W.F., Silveira, I.M., 2008. A modern high-energy Siliciclastic-Carbonate Platform: continental shelf adjacent to northern Rio Grande do Norte State, northeastern Brazil. In: Hampson, G.J., Steel, R.J., Burgess, P.M., Dalrymple, R.W. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy, Journal of Sedimentary Research, vol. 90, pp. 175–188. https://doi.org/10.2110/pec.08.90.0177.
Wong, T., Geuns, L., 2019. The discovery of a major hydrocarbon occurrence in the Guiana Basin, offshore Suriname: a blessing or a curse? Academic Journal of Suriname 10, 1–6.
Zalán, P.V., 2015. Re-interpretation of an Ultra-deep Seismic Section in the Pará-Maranhão Basin - Implications for the Petroleum Potential of the Ultra-deep Waters. Offshore Technical Conference Brazil held in Rio de Janeiro, Brazil, 27-29 October 2015. OTC-26134-MS.
Zalán, P.V., Hodgson, N., Saunders, M., 2019. Foz Do Amazonas and Pará-Maranhão Basins Ready to Replicate Guyana Success. AAPG Annual Convention and Exhibition, San Antonio, Texas, 2019 Search and Discovery Article 30624.
Zágoršek, K., Ramalho, L.V., Berning, B., Távora, V.A., 2014. A new genus of the family Jaculinidae (Cheilostomata, Bryozoa) from the Miocene of the tropical western Atlantic. Zootaxa 3838 (1), 98–112. https://doi.org/10.11646/zootaxa.3838.1.5.