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Paleoenvironmental significance of Benthic Foraminifera and Ostracoda from the late Quaternary of the Ceará Basin, Brazilian Equatorial Margin

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Abstract

Benthic foraminifera, ostracods and pteropods are reliable paleoenvironmental indicators in Quaternary deposits. However, in the Ceará Basin, on the Brazilian Equatorial Margin, these microfossils are poorly studied. This paper investigates environmental changes during the Pleistocene–Holocene transition in the Icaraí subbasin based on micropaleontological analysis of the core ANP 1011. Seventy-four taxa of benthic foraminifera, represented predominantly by *Globocassidulina*, *Uvigerina*, *Pyrgo* and *Melonis*, have been identified. The ostracod assemblages are composed mainly by the families Macrocyprididae, Cytheruridae, Trachyleberididae, Pontocyprididae and Krithidae, of which the genus *Krithe* was the most abundant. The composition of the ostracod assemblages identified in this study area differs somewhat from other regions of the Brazilian Margin. The assemblages of foraminifera and ostracod characterize a typical bathyal paleoenvironment. The occurrence of pteropods and dominance of epifaunal foraminifera taxa, mainly *Pyrgo* sp. and *Miliolinella* sp. in the lower portion of the core (Pleistocene), indicates higher phytodetritus input and oxygen concentration. A conspicuous environmental change was observed in the upper portion of the core, which corresponds to the Holocene, where the increase of infaunal foraminifera (e.g., *Uvigerina*, *Globocassidulina* and *Melonis*) suggests reduction in the organic matter input and, probably, increased bacterial density and depletion in dissolved oxygen in the sediment.

KEYWORDS: Pleistocene-Holocene; paleoceanography; bathyal; calcareous microfossils; paleoecology.

INTRODUCTION

Ecological studies using benthic foraminifera and ostracods are important for understanding present environments and interpreting past oceanic conditions (Morigi *et al.* 2001, Yasuhara *et al.* 2017, Bergue *et al.* 2021, De Almeida *et al.* 2022). Due to their adaptive potential, benthic foraminifera are spread in a variety of environments such as estuaries, lagoons and even extreme ecosystems such as abyssal plains and subduction zones (Murray 1991, 2001). Benthic foraminifera can be differentiated by microhabitats in epifaunal, which live in the upper 1 cm of sediment, and infaunal, which burrow into soft sediment below 1 cm of the sediment (Corliss and Chen 1988, Corliss 1991, Murray 1991, Jorissen *et al.* 1995). Significant changes in diversity and abundance of benthic foraminifera are recorded worldwide in response to hydrological changes linked to glacial-interglacial cycles (Schnitker 1980, Lukashira and Bashirova 2015) and their influence on productivity (Schmiedl and Mackensen 1997, Ohkushi *et al.* 1999).

The distribution of deep-sea benthic foraminifera in the sediment is controlled by several factors, mainly the organic flux to the ocean floor (its quantity, quality and periodicity) and bottom water oxygenation (Fontanier *et al.* 2002, 2003, Hayward *et al.* 2002, Gooday *et al.* 2010, Murray 2001, Jorissen *et al.* 2007). In the deepest part of ocean basins, where strongly oligotrophic conditions prevail, the corrosiveness of the bottom waters (highest in the Antarctic Bottom Water [AABW]) may control the distribution of cosmopolitan taxa (Mackensen *et al.* 1995, Schmiedl *et al.* 1997, Jorissen *et al.* 2007).

Ostracods are microcrustaceans with a bivalve chitin-calcitic carapace and an abundant fossil record in both nonmarine and marine depositional sequences (Rodriguez-Lazaro and Ruiz-Muñoz 2012). As they are sensitive to changes in environmental parameters (e.g., temperature, salinity and productivity), ostracods are considered reliable paleoecological indicators (Armstrong and Brasier 2005, Rodriguez-Lazaro and Ruiz-Muñoz 2012). Although taxonomic analysis provides essential data for the characterization of depositional environments, more

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Supplementary data

Supplementary data associated with this article can be found in the online version: Supplementary Appendix A and B and Supplementary Tables.

accurate ecological interpretation also demands to differentiate autochthonous from allochthonous carapaces (van Harten 1986, Whatley 1988, Zhou and Zhao 1999, Boomer *et al.* 2003).

Despite their paleoceanographic potential, studies on bathyal Quaternary calcareous microfossils in the Brazilian Equatorial Margin are still scarce. The main objective of this work was to study benthic foraminifera, ostracods and pteropods from a sediment core from the offshore portion of the Ceará Basin during the Pleistocene–Holocene transition to reconstruct the environmental changes at this site.

STUDY AREA

The study area is part of the Icaraí subbasin (Ceará Basin), which lies between the Acaraú and Mundaú subbasins (Fig. 1). It is separated from the Mundaú subbasin by the Forquilha fault and from the Acaraú subbasin by the northern extension of the Transbrasiliano lineament (Antunes *et al.* 2008).

Surface waters of the Equatorial Atlantic Ocean are presently influenced by the North Brazilian Current (NBC), the North Equatorial Sub-Current, the North Equatorial Counter-Current and the North Equatorial Current (Silveira *et al.* 2004). The NBC stems from the bifurcation of the southern branch of the South Equatorial Current when it reaches the Brazilian Continental Margin, between 10°S and 15°S (Schott *et al.* 2004, Talley 2011). According to Johns *et al.* (1998), the mobility of NBC coincides with changes in surface transport, associated with the wind shear in the tropical Atlantic and the seasonal migration of the ITCZ. The NBC is the largest surface flow component of the Atlantic meridional overturning circulation, through the northward surface water transport and the inter-hemispheric oceanic heat exchange (Zhang *et al.* 2011).

A total of five water masses exert influence in the study area, from the surface to the 2,125 m water depth where the core ANP 1011 was obtained: the Tropical Water (the surface water TW, 0–150 m), the South Atlantic Central Water (the pycnoclinic water SACW, 150–500 m), the Antarctic Intermediate Water (the intermediate water AAIW, 500–1,300 m), the Upper Circumpolar Water (the intermediate water UCPW, 500–1,300 m), and the North Atlantic Deep Water (the deep water NADW, 1,300–3,500 m) (Silveira *et al.* 2020). The TW presents the highest values of temperature and salinity of the water column (Emilsson 1961). The SACW, near its origin in the tropics, is characterized by the largest variation of temperature and salinity due to its position at the pycnocline level (Tomczak and Godfrey 1994). The AAIW is characterized by the high values of oxygen and low salinity (Reid *et al.* 1977, Reid 1994). The UCPW presents lower oxygen concentrations and salinity and high dissolved nutrients associated with intense local silicate (Stramma and England 1999, Mémery *et al.* 2000). The NADW is characterized by high values of oxygen and temperature, a secondary salinity maximum and low local levels of nutrients (Maamaatuaiahutapu *et al.* 1994). Moreover, this water mass is not corrosive to aragonite (Gerhardt *et al.* 2000).

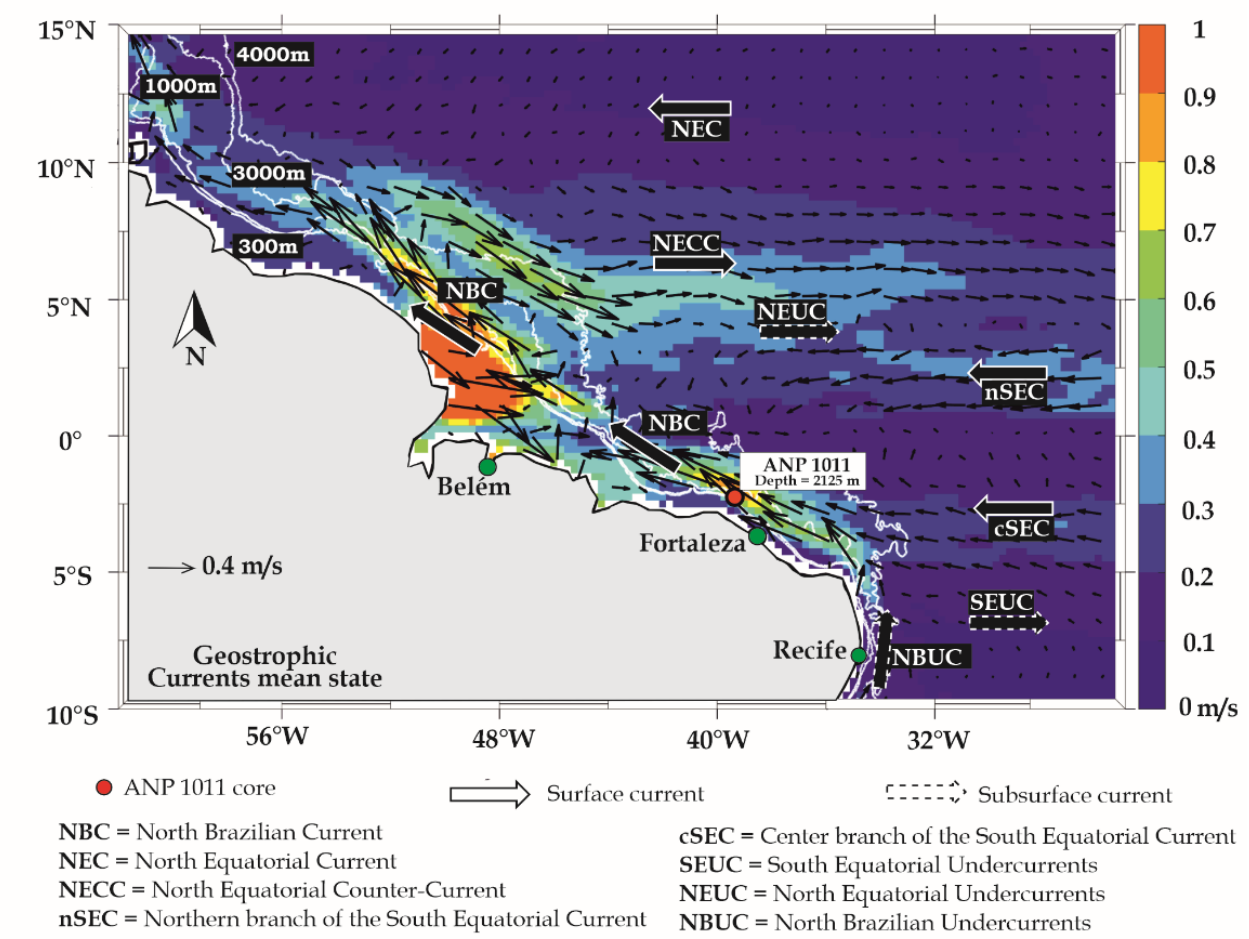

Figure 1. Location map of the core ANP 1011 in the Ceará Basin showing the surface circulation in the Brazilian Equatorial Margin, the physiography of the study area, and current arrows are superimposed on their speed (Noucoucouk *et al.* 2021).

MATERIALS AND METHODS

The studied samples were obtained from the piston-core ANP 1011 (39°23'22"W/2°13'03"S, 2,125 m water depth), which was given by the Agência Nacional do Petróleo, Gás Natural e BioCombustível (ANP) to the Laboratório de Geologia Marinha e Aplicada (LGMA) da Universidade Federal do Ceará (UFA). The studied interval measures 151.5 cm in length, wherein approximately 15 samples of 46 g in mass were prepared for carbonatic microfossil analysis. The chronostratigraphic positioning of the section, according to planktic foraminifera, corresponds to the Upper Pleistocene (Biozone Y) and Holocene (Biozone Z, subzones Z2 and Z1) (Noucoucouk *et al.* 2021).

Sample preparation followed the standard methodology for Quaternary calcareous microfossils adapted from Murray (2006), which consists of washing in tap water on a sieve of 0.062-mm mesh and oven-drying at 60°C. After drying, another sieving on a 0.150-mm mesh was carried out, and from this residue, all the benthic foraminifera, ostracods, and pteropods were collected under a stereomicroscope and stored in micropaleontological slides (see Suppl. Mat.). In line with the objectives of this study, we chose to use only 0.150 mm for all groups studied. According to Cappelli and Austin (2019), the benthic foraminiferal assemblages picked from the large size fraction (> 150 mm) still provide useful information on prevailing environmental conditions and remain useful for an overview of environmental change. Well-preserved specimens of each morphotype were photographed and examined in a scanning electron microscope (SEM) PHENOM XL at *Laboratório de Micropaleontologia Aplicada* (LMA) of *Universidade Federal de Pernambuco* (UFPE).

The identification of benthic foraminifera follows basically Loeblich and Tappan (1988, 1994), van Morkhoven *et al.* (1986), Boltovskoy *et al.* (1980), and the World Register of Marine Species (WoRMS), an online taxonomic database (https://www.marinespecies.org/foraminifera/) for suprageneric taxonomy. The suprageneric taxonomy of Ostracoda followed Liebau (2005). Previous studies on Quaternary Ostracoda also were consulted to identify taxa at the species level (e.g., Brandão 2004a, 2004b, 2010, Yasuhara *et al.* 2009b, 2015, Bergue *et al.* 2021, Maia *et al.* 2021, Yasuhara *et al.* 2021). Finally, the pteropods were identified according to Janssen (2012), and references therein. All figured specimens are held in the collections of the LMA under the curatorial numbers 00357–00428, 00513.

The paleoecological interpretation of benthic foraminifera was based on Boltovskoy and Wright (1976), van Morkhoven *et al.* (1986), Jones (1994), and Murray (1991, 2006), and microhabitats (epifaunal and infaunal) were based on test morphology (Corliss and Chen 1988, Murray 1991, Fontanier *et al.* 2003, Schweizer 2006). The relative abundance (RA) of benthic foraminifera and ostracods corresponds to the ratio between the number of individuals of a species (N) and the number of individuals of all species in the same sample (T): RA = (N × 100)/T. The RA values are expressed in percentage, and the data obtained were classified as rare (< 5%), common (5–19%), and abundant (> 20%). In addition, the RA for agglutinated, porcelaneous, and hyaline tests of benthic foraminifera was calculated for each sample. Because some samples presented low recovery of specimens, only samples with > 80 specimens were considered in the statistical analyses. The richness of ostracods corresponds to the absolute number of species.

The carbonate content in the samples was obtained through the digestion of approximately 0.5 g of sample in an Erlenmeyer flask with 10 mL of hydrochloric acid (HCl), stirred periodically over 24 h. Then, the supernatant was removed, and the decarbonated sample was washed with distilled water to remove HCl, residues. Later, the sample was oven-dried at 60°C and weighed again. The calcium carbonate content in the sample was calculated through the mass difference before and after decarbonation. To determine the content of organic matter and organic carbon, the method of Walkley (1947), as modified by Loring and Rantala (1992), was adopted.

RESULTS

The analysis of the core ANP 1011 allowed identification of abundant and diversified assemblages of foraminifera (Figs. 2 and 3) and, to a lesser degree, of ostracods (Fig. 4) and pteropods (Fig. 3). The list of the taxa of benthic foraminifera and Ostracoda with their complete names (authors and dates), identified and cited in the present study, can be consulted in Suppl. Mat. 1 and 2.

Foraminifera

A total of 2,233 benthic foraminifera were examined and identified 74 species, distributed in 42 genera (Suppl. Mat. 3), with the genera *Globocassidulina* and *Uvigerina* classified as abundant with RA above 20%. The taxa *Melonis barleeanum* (Williamson, 1858), *Pyrgo murrhina* (Schwager, 1866), *Pyrgo* sp., *Quinqueloculina* sp., *Uvigerina auberiana* (d'Orbigny, 1839), and *Uvigerina proboscidea* (Schwager, 1866) presented values of RA between 5 and 19%, which is considered common.

The genera *Miliolinella*, *Quinqueloculina*, *Cibicides*, and *Cibicidoides* showed the same RA values of 6.7% in the sample 110–107 cm (Pleistocene) (Fig. 5), while *Fisurina* and *Triloculina* reached peaks of 12.4 and 10.1%, respectively, in this same sample. The genus *Uvigerina* was frequent in all intervals, showing a high RA (17.3%) in the Pleistocene (90–87 cm) and an abundant RA in the Pleistocene-Holocene transition (82–79 cm) (Fig. 5).

The RA of epifaunal species is higher in 110–107 cm (56.2%) and 130–127 cm (53.7%), which correspond to the Biozone Y (Fig. 6). The RA of infaunal species revealed the highest abundance in the core top (Biozone Z), with values above 60% (Fig. 6). Hyaline tests are predominant in all samples, varying between 97.9% in the sample 70–67 cm and 61.8% in the sample 110–107 cm (Fig. 6).

Ostracods and pteropods

A total of 86 ostracod specimens (Suppl. Mat.), corresponding to 7 genera and 11 bathyal species, were recovered (Fig. 4). The sample 130–127 cm was the most abundant with 21 specimens, followed by the samples 70–67, 50–47, and 42–39 cm with 16, 12, and 12 specimens, respectively. Only the genus *Krithe* represented by *Krithe sinuosa* Ciampo, 1986 and *Krithe morkhoveni* van den Bold, 1960, was abundant (75.5% of the total specimens). Juvenile individuals of this genus were also recovered, but identification at the species level was not feasible. The genera *Argilloecia* (8.1%) and *Macromckenziea* (5.81%) were classified as common, and the genera *Bythoceratina*, *Cytheropteron*, *Ambocythere*, and *Rugocythereis* as rare (1.16–3.48%). One species (1.16%), represented only by a juvenile specimen, was left in open nomenclature (Gen. et sp. indet.). The distribution of the most representative taxa is presented in Fig. 5.

The highest abundance (53 specimens, corresponding to 61.62%) and richness (11 species) were verified in the Holocene, which registers *Argilloecia labri* Yasuhara and Okahashi, 2015, *Argilloecia* sp., *Cytheropteron* sp., *Ambocythere* cf. *A. circumporus* Bergue *et al.* 2017, *Ambocythere* sp., *Macropyxis bathyalensis* (Hullings 1967), *Bythoceratina scaberrima* (Brady 1866), and *Krithe morkhoveni*.

Pteropod assemblages are mainly composed of taxa belonging to the families Lamacinidae (*Heliconoides* sp.), Atlantidae

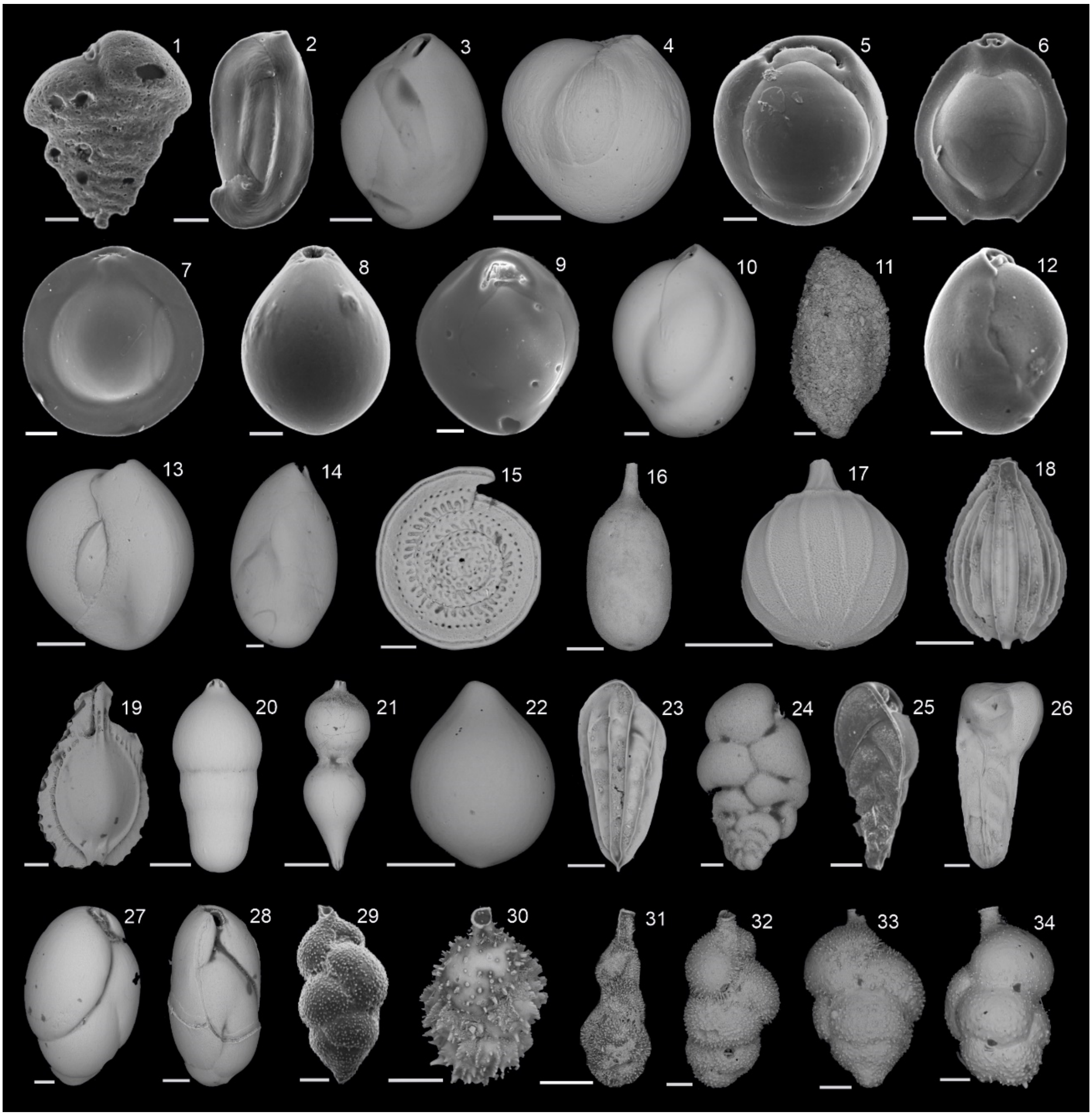

Figure 2. Benthic foraminifers > 0.150 mm from the core ANP 1011: 1. *Siphotextularia flintii*; LMA-00357; 2. *Massilina* sp.; LMA-00358; 3. *Miliolinella* sp.; LMA-00359; 4. *Miliolinella subrotunda*; LMA-00360; 5. *Pyrgo quadrata*; LMA-00361; 6. *Pyrgo murrhina*; LMA-00362; 7. *Pyrgo* aff. *P. depressa*; LMA-00363; 8. *Pyrgo lucernula*?; LMA-00364; 9. *Pyrgo* sp.; LMA-00365; 10. *Quinqueloculina* sp.; LMA-00366; 11. *Sigmoilopsis schumbergeri*; LMA-00367; 12. *Triloculina sommeri*; LMA-00368; 13. *Triloculina* sp.; LMA-00369; 14. *Triloculinella* sp.; LMA-00370; 15. *Spirillina decorata*; LMA-00371; 16. *Lagena hispidula*; LMA-00372; 17. *Lagena* sp.; LMA-00373; 18. *Lagena arquata*; LMA-00374; 19. *Lagenosolenia* sp.; LMA-00375; 20. *Nodosaria* sp.; LMA-00376; 21. *Amphicoryna* sp.; LMA-00377; 22. *Fissurina circularis*; LMA-00378; 23. *Bolivina interjuncta*; LMA-00379; 24. *Bolivina britanica*; LMA-00380; 25. *Bolivinita quadrilatera*; LMA-00381; 26. *Bolivinita* sp.; LMA-00382; 27. *Globobulimina affinis*; LMA-00383; 28. *Globobulimina* sp.; LMA-00384; 29. *Uvigerina auberiana*; LMA-00385; 30. *Uvigerina peregrina*; LMA-00386; 31. *Uvigerina proboscidea*; LMA-00387; 32. *Uvigerina* cf. *U. hispida*; LMA-00388; 33–34. *Uvigerina* spp.; LMA-00389. Scale bar =100 μm.

(*Atlanta* sp.), and Cavoliniidae (*Creseis*? sp.) (Fig. 3). Abundance peaks were recorded in the samples 28–25 cm (1,017 specimens), 110–107 cm (727 specimens), 102–99 cm (145 specimens), and 62–59 cm (106 specimens).

Carbonate and organic matter content

The carbonate content analysis revealed values between 78.61 and 27.06% (Suppl. Mat.; Fig. 6). The highest values were observed in the middle (90–59 cm), decreasing toward the core top (6–0 cm). Concerning the organic matter content, the analyses revealed values between 0.9 and 2.3%, with an average of 1.4%, with the highest values at 70–67 and 42–39 cm (Fig. 6). Similar variation was observed in organic carbon levels, which ranged from 0.5 to 1.4%, with an average of 0.8%. The highest values also occur in the samples 70–67 and 42–39 cm (Fig. 6).

DISCUSSION

Foraminifera

The foraminifera assemblages of the core ANP 1011 characterize a typical bathyal paleoenvironment, as indicated by

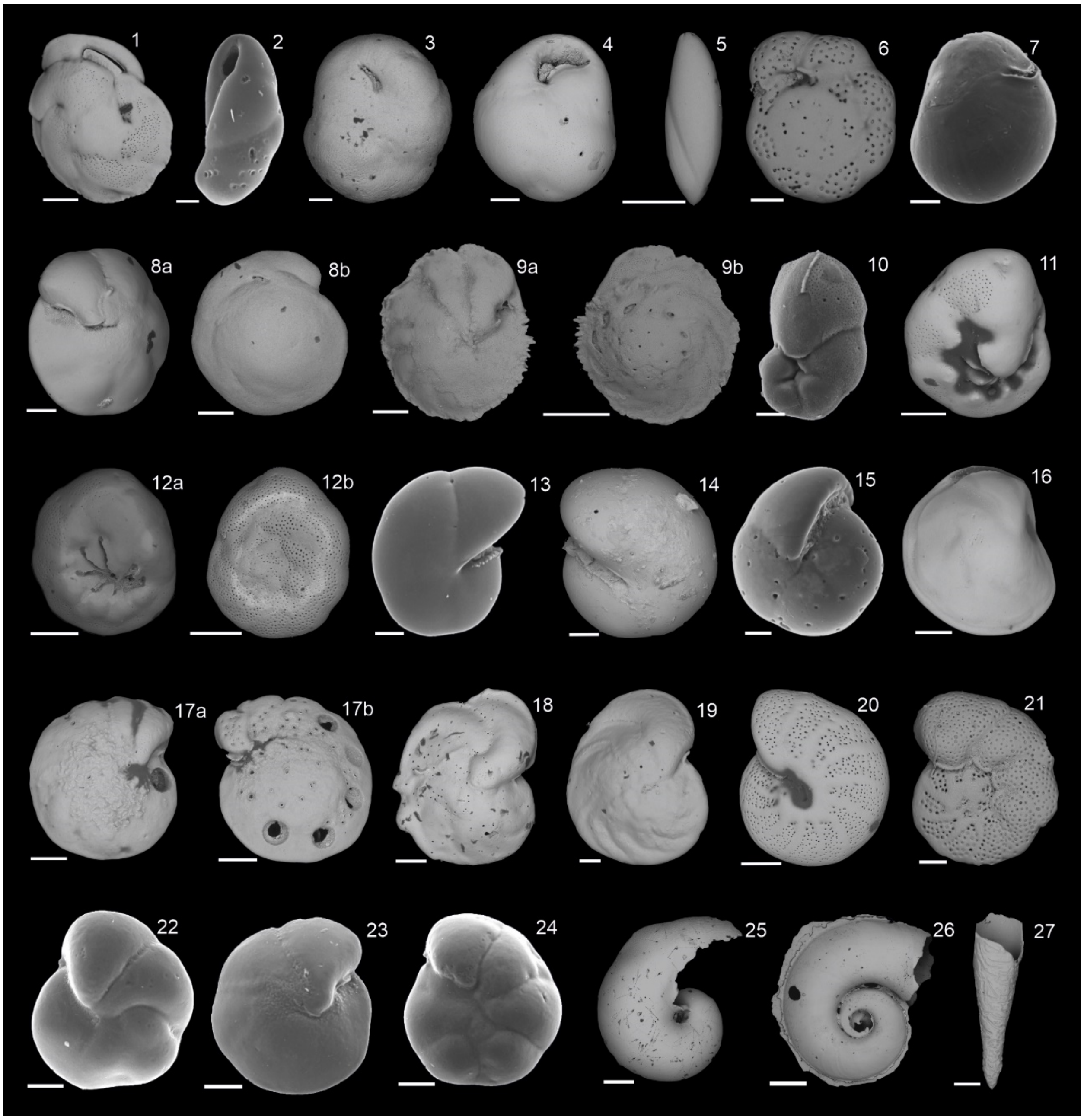

Figure 3. Benthic foraminifera and pteropods >0.150 mm from the core ANP 1011: 1. *Cassidulina* sp.; LMA-00390; 2. *Cassidulinoides* sp.; LMA-00391; 3. *Globocassidulina subglobosa*; LMA-00392; 4. *Globocassidulina* sp.; LMA-00393; 5. *Fursekoina* sp.; LMA-00394; 6. *Anomalinoides* sp.; LMA-00395; 7. *Chilostomella globata*; LMA-00396; 8a-b. *Oridorsalis umbonatus*; LMA-00397; 9a-b. *Osangularia culter*; LMA-00398; 10. *Cancris nuttalli*; LMA-00399; 11. *Valvulineria glabra*; LMA-00400; 12a-b. *Rosalina bradyi*; LMA-00401; 13. *Melonis barleeanum*; LMA-00402; 14. *Melonis pompilioides*; LMA-00403; 15. *Pullenia bulloides*; LMA-00404; 16. *Cibicides* sp.; LMA-00405; 17a-b. *Cibicides kullenbergi*; LMA-00406; 18. *Cibicidoides lobatulus*; LMA-00407; 19. *Cibicidoides wuellerstorfi*; LMA-00408; 20. *Cibicidoides incrassatus*; LMA-00409; 21. *Cibicidoides cicatricosus*; LMA-00410; 22. *Cibicidoides* aff. *C. bradyi*; LMA-00411; 23. *Cibicidoides* aff. *C. mundulus*; LMA-00412; 24. *Cibicidoides* sp.; LMA-00413; 25. Lamacinidae (*Heliconoides* sp.); LMA-00414; 26. Atlantidae (*Atlanta* sp.); LMA-00415; 27. Cavoliniidae (*Creseis*? sp.); LMA-00416. Scale bar = 100 μm.

Cibicidoides wuellerstorfi (Schwager, 1866), *Melonis pompilioides* (Fichtel and Moll, 1798), *Globocassidulina subglobosa*, and *Pyrgo murrhina* (Douglas and Heitman 1979, Murray 1991, Rathburn and Corliss 1994).

Murgese and De Deckker (2005) argued that the calcareous infaunal rate indicates high carbon influx and low dissolved oxygen, whereas the porcelaneous rate indicates high dissolved oxygen. Most miliolids are sensitive to oxygen depletion (Bernhard and Sen Gupta 1999); however, in deep environments, the vertical distribution of foraminifera is controlled mainly by food availability in oligotrophic settings (e.g., abyssal plains) (Jorissen *et al.* 1995). Miliolids are associated with oxygen-rich North Atlantic Deep Water (Peterson and Lohmann 1982).

The linkage of foraminifera's assemblage composition with environmental parameters, such as occurrence, microhabitats, organic carbon flux, and dissolved oxygen (Table 1), allowed the characterization of two environmental settings (Fig. 6).

Environmental setting I

This environmental setting corresponds to Biozone Y (Fig. 6) and is characterized by the dominance of the epifaunal taxa *Cibicidoides, Miliolinella, Triloculina, Pyrgo,* and *Quinqueloculina*. The higher abundance of epifaunal species in the sample 110–107 cm suggests an increase in phytodetritus input and oxygenation (Caralp 1984, 1988, Lutze and Coulbourn 1984, Gupta and Thomas 2003). *Cibicidoides wuellerstorfi* and *Pyrgo murrhina* were relatively abundant in the core ANP 1011 during the Pleistocene, which suggests a cold and highly oxygenated scenario (Gupta and Satapathy 2000, Gupta and Thomas 2003). *Cibicidoides wuellerstorfi* characterizes cold environments with active currents, low-to-intermediate

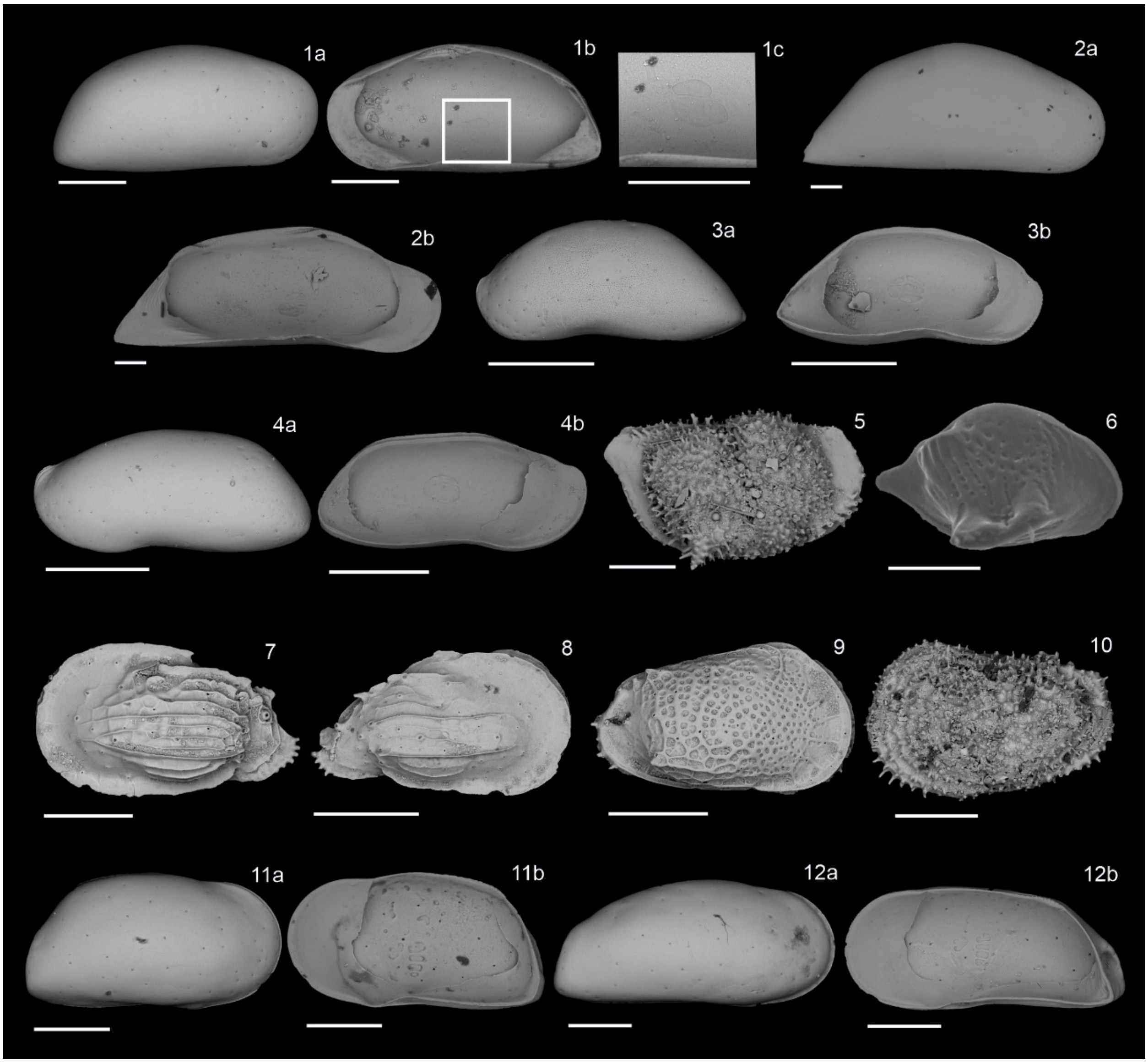

Figure 4. Bathyal ostracods > 0.150 mm from the core ANP 1011: 1. *Macromckenziea* sp.; LMA-00417; 1a. RV, lateral view; 1b. RV, internal view; 1c. adductor scars detail; 2. *Macropyxis bathyalensis*; 2a. LMA-00418, RV, lateral view; 2b. LMA-00513, LV, internal view; 2b. RV, internal view; 3. *Argilloecia labri*; LMA-00419; 3a. LV, lateral view; 3b. LV, internal view; 4. *Argilloecia* sp.; LMA-00420; 4a. LV, lateral view; 4b. LV, internal view; 5. *Bythoceratina scaberrima*; RV, lateral view; LMA-00421. 6. *Cytheropteron* sp.; RV, lateral view; LMA-00422; 7. *Ambocythere* cf. *A. circumporus*; LV, lateral view; LMA-00423; 8. *Ambocythere* sp. 1; RV, lateral view; LMA-00424; 9. Gen. et sp. indet.; RV, lateral view; LMA-00425; 10. *Rugocythereis* sp.; LV, lateral view; LMA-00426; 11. *Krithe sinuosa*; LMA-00427; 11a. RV, lateral view; 11b. RV, internal view; 12. *Krithe morkhoveni*; LMA-00428; 12a. RV, lateral view; 12b. RV, internal view. LV: left valve; RV: right valve. Scale bar = 200 µm.

organic flux, and high oxygenation (Gupta and Thomas 2003, Sousa *et al.* 2006) (Tab. 1). Furthermore, *Pyrgo murrhina* lives in low organic carbon environments (Lutze and Coulbourn 1984) and prefers cold and well-ventilated waters (Caralp 1984, Gupta and Srinivasan 1996, Gupta and Thomas 2003, Murgese and De Deckker 2005).

Species of *Quinqueloculina* are highly mobile in fine-grained sediments in both shallow (Severin *et al.* 1982) and deep

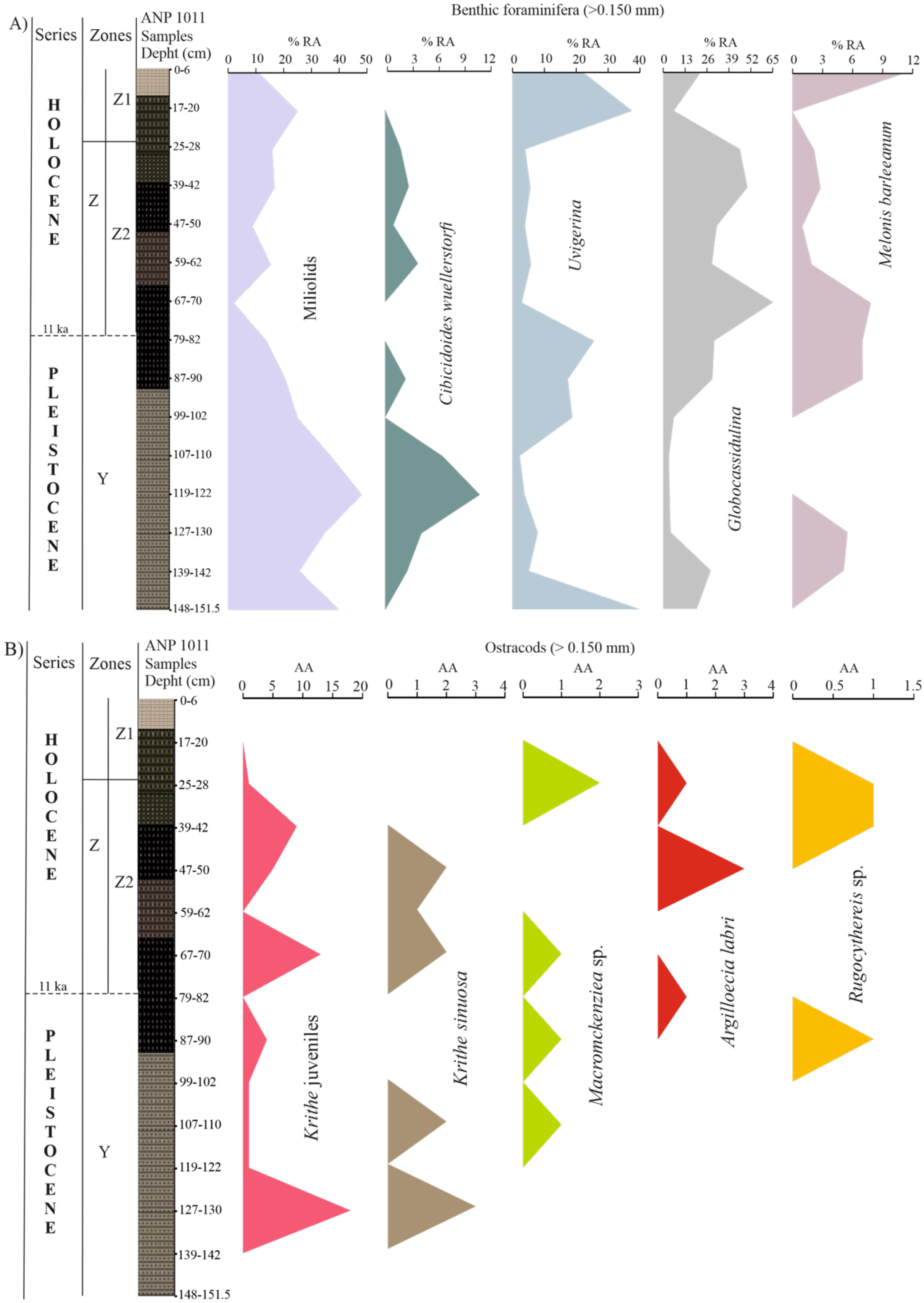

Figure 5. Graphic representation of (A) the relative abundance (RA) of main genera and species of benthic foraminifera and (B) of the absolute abundance (AA) ostracods identified in core ANP 1011.

waters (Gross 2000). These movements probably respond to the oxygen depletion in deeper layers combined with the presence of labile food at the water-sediment interface (Gooday *et al.* 2010). Some species migrate upward and downward in response to changes in the thickness of the oxygenated layer associated with the decomposition of organic matter (Ohga and Kitazato 1997, Kitazato *et al.* 2000).

According to Gooday (2002), the accumulation of phytodetritus on the seabed usually occurs in areas with highly seasonal primary production. Our data demonstrate that epifaunal species are related to higher phytodetritus input and oxygen concentration during the Pleistocene (glacial period). Similar results were obtained by De Almeida *et al.* (2015) in the Santos Basin and Rodrigues *et al.* (2018) in the Pelotas Basin, where the phytodetritus influx was higher during the glacial stages than in the interglacial MIS 5. The decrease in infaunal species, calcium carbonate content, and organic carbon in the sample 110–107 cm results probably from the decrease in the availability of organic matter. In the present study, the high RA of porcelaneous foraminifera during the Pleistocene (Biozone Y, sample 122–119 cm) may be related to oxygenation (Murgese and De Deckker 2005).

Environmental setting II

This interval corresponds to Biozone Z (Fig. 6) and is characterized by environmental instability with a tendency to increase (predominance of uvigerinids) or decrease (predominance of cassidulinids) oxygenation. Oxygen concentration and nutrient are highly influential on infaunal assemblages' composition (De Rijk *et al.* 1999, Jorissen *et al.* 2007). The increase in infaunal taxa (*Uvigerina* and *Melonis*) in the core ANP 1011 in the Pleistocene-Holocene transition indicates higher concentrations of organic carbon and nutrient and lower oxygenation (Miao and Thunell 1993, Gooday 1994, Mackensen *et al.* 1995, Fontanier *et al.* 2002, Martins *et al.* 2006, Murray 2006, Eichler *et al.* 2008, Nagai *et al.* 2009).

Higher abundances of *Uvigerina peregrina* Cushman 1923, *Uvigerina auberiana*, *Uvigerina* sp., *Melonis barleeanum*, and *Globocassidulina subglobosa* in the core top (Biozone Z) point to increased availability of organic carbon during warm intervals (Gupta and Thomas 2003). According to Lohmann (1978) and Streeter and Shackleton (1979), the presence of *Uvigerina* is usually congruent with low oxygenation between 2,000 and 4,000 m throughout the Atlantic. Higher *Uvigerina* percentages have also been observed in areas of high surface productivity and organic carbon-rich sediments (Woodruff and Douglas 1981, Boersma 1986, Lutze 1986, Boyle 1990, Maia *et al.* 2022). The species *Uvigerina peregrina* is typical of low-oxygen waters and/or organic-rich sediments in modern oceans (Peterson 1984, Mackensen *et al.* 1995). The common presence of *Uvigerina proboscidea*, at the top of the Pleistocene (Suppl. Mat.) in the core ANP 1011, demonstrates higher surface productivity and perhaps higher biogenic sediment accumulation (Kroon *et al.* 1991, Gupta and Srinivasan 1992). *Uvigerina proboscidea* is abundant in regions of high productivity in the Atlantic (Thomas *et al.* 1995), Indian (Gupta and Thomas 1999, Almogi-Labin *et al.* 2008), and Pacific (Woodruff 1985), particularly when the productivity is high throughout the year and food supply presents low or absent seasonality (Ohkushi *et al.* 1999). In addition, *Uvigerina proboscidea* characterizes areas of high carbon flux and low dissolved oxygen concentration (Murgese and De Deckker 2005).

High abundances of *Melonis barleeanum* in both the North (Thomas *et al.* 1995) and South Atlantic (Schmiedl and Mackensen 1997) characterize high productivity with sustained flow of organic matter. On the contrary, in the Indian Ocean, *Melonis barleeanum* indicates moderate organic flow with intermediate to high seasonality (Murgese and De Deckker 2005).

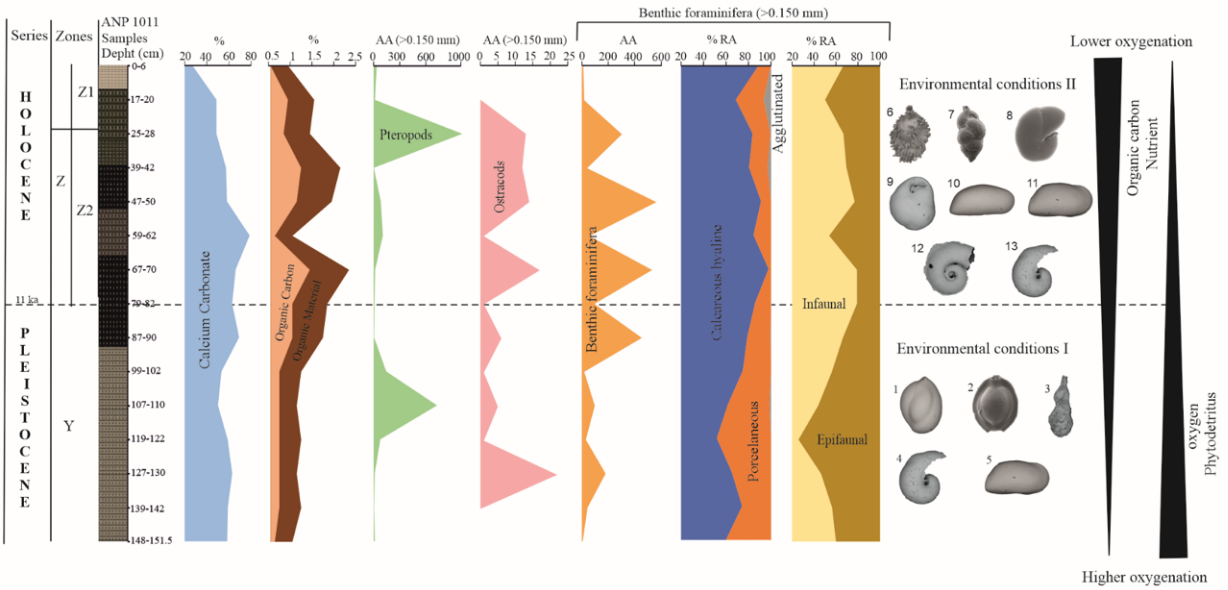

Figure 6. Integration and interpretation of data in the ANP 1011 core: calcium carbonate, organic material and organic carbon, absolute abundance (AA) of ostracods, pteropods and benthic foraminifera, relative abundance (RA) of agglutinated, porcelaneous and hyaline tests of benthic foraminifera, and relative abundance of infaunal and epifaunal foraminifera of the ANP 1011 core: (1) *Quinqueloculina* sp.; (2) *Pyrgo murrhina*; (3) *Uvigerina proboscidea*; (4, 13) Lamacinidae (*Heliconoides* sp.); (5, 11) *Krithe sinuosa*; (6) *Uvigerina peregrina*; (7) *Uvigerina auberiana*; (8) *Melonis barleeanum*, (9) *Globocassidulina* sp.; (10) *Macromckenziea* sp.; (12) Atlantidae (*Atlanta* sp.).

Table 1. Paleoecological inferences and microhabitat preferences of benthic foraminifera found in the core ANP 1011.

Taxa	Microhabitats	Paleobathymetry	Paleoecology inferences	References
Cibicides Walker and Jacod (1798)	Shallow infaunal	Neritic to abyssal	Well oxygenated environments with stable physicochemical conditions	Fontanier *et al.* (2003) Schweizer (2006) Kaiho (1994) Kouwenhoven (2000)
Cibicidoides wuellerstorfii (Schwager 1866)	Epifaunal	Bathyal	Occur in environments with stronger undercurrents and greater oxygenation of sediments	Corliss and Chen (1988) Holbourn and Henderson (2002) Sousa *et al.* (2006)
Globocassidulina Voloshinova (1960)	Infaunal	Shelf to bathyal	Associated with strong bottom currents and high oxygen bottom water conditions	Murray (1991) Mackensen *et al.* (1995) Smart (2008) Kaiho (1994)
Globocassidulina subglobosa Brady (1881)	Infaunal to intermediate infaunal	Bathyal to abyssal	Well-oxygenated deep waters and good carbonate preservation	Fontanier *et al.* (2002) Burone *et al.* (2011) Singh and Gupta (2004) Katz and Miller (1993) Jones (1994)
Melonis barleeanum Williamson (1858)	Infaunal	Neritic to bathyal	Intermediate organic flux, intermediate-to-high seasonality, and refractory organic matter	Murray (1991) Pflum and Frerichs (1976) Gupta and Thomas (2003)
Melonis pompilioides (Fichtel and Moll 1798)	Infaunal	Neritic to upper-middle bathyal	High-moderate organic flux and intermediate seasonality	Douglas and Heitman (1979) Van Morkhoven *et al.* (1986) Gupta and Thomas (2003)
Pullenia bulloides (d'Orbigny 1846)	Infaunal	Lower bathyal to Abyssal	Low oxygen concentration and high flow of organic matter	Murray (1991) Miller *et al.* (1987) Katz and Miller (1993) Gooday (1994)
Pyrgo lucernula? (Schwager 1866)	Epifaunal	Middle bathyal to abyssal	Low organic carbon and of well-ventilated cold waters	Van Morkhoven *et al.* (1986) Gupta and Satapathy (2000) Gupta and Thomas (2003)
Pyrgo murrhina (Schwager 1866)	Epifaunal	Bathyal to abyssal	Cool, strongly pulsed organic flux, high oxygenation, and high seasonality	Murray (1991) Jones (1994) Gupta and Thomas (2003)
Uvigerina d'Orbigny (1826)	Infaunal	Neritic to abyssal	Carbon rich and oxygen poor conditions	Murray (1991) Schweizer (2006) Kaiho (1994) Kawagata *et al.* (2006)
Uvigerina peregrina Cushman (1923)	Shawoll infaunal	Neritic to abyssal	Related to sediments with a rich supply of organic matter and high concentrations of bacteria, as well as low oxygen conditions on the sea floor	Morigi *et al.* (2001) Fontanier *et al.* (2002) Mackensen *et al.* (1995) Murray (2006)
Uvigerina proboscidea Schwager (1866)	Shawoll infaunal	Neritic to abyssal	High surface productivity with sustained flux of organic matter, carbon flux, and low dissolved oxygen concentrations	Morigi *et al.* (2001) Loubere (1991, 1994) Gupta and Mélice (2003) Murgese and De Deckker (2005)

The increase of the infaunal taxa *Globocassidulina* in the early Holocene indicates well-oxygenated deep waters with strongly pulsed food supply and good carbonate preservation in oligotrophic environments (Ohkushi *et al.* 1999, Singh and Gupta 2004). The succession of low and high incidences of *Globocassidulina subglobosa* indicates variations in the intensity of organic matter input, probably in response to climatic and oceanographic changes (Rodrigues *et al.* 2018). Peterson and Lohmann (1982) related this taxon to the poorly oxygenated circumpolar deep water, while Corliss (1979) found it associated with the AABW in the southwestern Indian Ocean. This taxon is often abundant in regions with low organic matter input and strong bottom currents (Schmiedl *et al.* 1997, Nees and Struck 1999). According to Noucoucouk *et al.* (2020, 2021), conditions of increased organic matter influx predominated in the study area, during the Holocene, causing environmental variations and affecting the distribution of the biota.

Ostracods

The ostracod assemblages registered are composed mostly of macrocypridids, krithids, trachyleberidids, pontocypridids, and cytherurids. The presence of *Krithe*, *Argilloecia*, *Macromckenziea*, *Macropyxis*, *Ambocythere*, *Bythoceratina*, and *Rugocythereis* (Suppl. Mat.) characterizes a typical bathyal environment, as observed in previous studies (e.g., Dingle *et al.* 1990, Bergue *et al.* 2006, 2016, 2021, Brandão 2010, Yasuhara *et al.* 2013, 2021, Maia *et al.* 2021, 2022).

This is the first study on deep-sea ostracods from the Brazilian Equatorial Margin, but the paucity of material prevents detailed comparison with other studies in the Brazilian Margin. The macrocypridid *Macromckenzia* is widely distributed in bathyal regions along the Atlantic Ocean (Brandão 2010), but it is represented here by a species different from all others registered in the South Atlantic (Maddocks 1990, Brandão 2004a, 2004b, 2010). On the contrary, *Macropyxis bathyalensis* is a typical North Atlantic species, and it is registered for the first time in the Brazilian Equatorial Margin. *Krithe morkhoveni* and *K. sinuosa* have wide distribution in the Atlantic Ocean and Mediterranean (van den Bold 1960, Coles *et al.* 1994, Rodriguez-Lazaro and Cronin 1999). The highest species richness occurs in the sample 28–25 cm, where nine species are registered. In the samples 142–139 and 130–127 cm, *Krithe* was more frequently associated with the epifaunal foraminifera *Pyrgo* sp. In the samples 70–67 and 42–39 cm, the association occurred with the infaunal taxon *Globocasidulina* sp. The same zoogeographic pattern is presented by *Bythoceratina scaberrima*.

Two species of *Ambocythere*, a genus diverse in the Atlantic Ocean deep waters (Yasuhara *et al.* 2015), have been registered in this study. One of them has a strong similarity to *Ambocythere circumporus*, however, with stronger longitudinal ribs and a caudal process that is more acuminate and less spinose. Another species of the genus herein recorded, *Ambocythere* sp., differs in having a conspicuous perforate spine near the posterior cardinal angle and subdued ornamentation. The nearest study on deep-sea ostracods was carried out at ODP site 925, Ceará Rise (Yasuhara *et al.* 2009a, 2021); however, the taxonomic similarity between the two sites is represented only by *Argilloecia labri*, possibly due to the low abundance of the material herein studied.

Pteropods

Several studies have shown the sensitivity of late Quaternary pteropods to temperature, oxygen concentration, and salinity, proving their importance for paleoclimatic reconstructions (Herman 1971, Singh *et al.* 2005, Wall-Palmer *et al.* 2014, Giamali *et al.* 2020, 2021). Peaks of abundances of pteropods are positively correlated with aragonite saturation state, O_2 concentration, pH, salinity, and temperature and negatively correlated with nutrient concentration (Howes *et al.* 2015, Johnson *et al.* 2020, Giamali *et al.* 2021). Two genera of pteropods were identified in the present study: *Heliconoides* d'Orbigny, 1835 and *Atlanta* Lesueur, 1817; a third was tentatively identified as *Creseis* Rang, 1828. Two peaks of abundance are observed in the core ANP 1011 (base and top, Fig. 6), both associated with epifaunal foraminifera, reinforcing the hypothesis of a higher oxygenated paleoenvironment with a lower concentration of nutrients. The variations observed in the distribution of pteropods may be caused by displacement of water masses, with good preservation indicating NADW influence and poor preservation (due to corrosion) related to climatically induced variations of intermediate water masses (Gerhardt *et al.* 2000).

CONCLUSION

The integrated analysis of calcareous microfossils (i.e., foraminifera, ostracods, and pteropods) demonstrated to be a valuable approach for paleoceanographic studies in late Quaternary deposits in the Ceará Basin. Benthic foraminifera recovered in the > 0.150 mm fraction is abundant and diverse, although we are aware that our analysis would possibly benefit from an additional > 0.062 mm fraction. The model based on the ecological characteristics of the benthic foraminifers allowed the characterization of two ecological settings during the Pleistocene-Holocene transition. The environmental setting I corresponds to the glacial period (late Pleistocene), and it is characterized by the abundance of epifaunal species, high productivity, phytodetritus input, increased oxygen concentration, but lower organic carbon. The environmental setting II corresponds to the interglacial period (Holocene) and is characterized by environmental instability, with periods of lower oxygenation (predominance of uvigerinids) and higher oxygenation (predominance of cassidulinids). During this environmental setting, there is also a higher organic carbon, nutrient, and food supply. Studies focused on the fraction of >0.062 mm, however, are necessary for a more detailed paleoenvironmental scenario. The taxonomic composition of ostracod assemblages herein studied differs in some degree compared to other regions of the Brazilian Margin. The low richness of the ostracod fauna reflects probably the low abundance; however, the higher richness during the Holocene in relation to the Pleistocene is in accordance with previous studies in the Atlantic Ocean.

More studies focused on the taxonomy of ostracods are necessary to assess the actual diversity and relationship with adjacent oceanic areas.

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