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Biofaciological zonation of benthic foraminifera of the continental shelf of Campos Basin, SE Brazil



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ABSTRACT

Data on the microbiofaciological zonation of benthic foraminifera were obtained from 82 sub-samples from the subsurface sediments of the continental shelf of Campos Basin, in southeastern Brazil. The abundance and distribution of the 93 species identified during the study were related to depth and temperature of the water, as well as to sediment grain size. Four biofacies were established: biofacies I, represented by the sandier coastal sediments and dominated by *Pseudonion atlanticum* and miliolids; biofacies II, associated with carbonated substrates, and represented by *Amphistegina lessonii* and miliolids; biofacies III, represented by mini-cores A2, where *Bulimina marginata* is predominant in all the samples; and biofacies IV, associated with the muddy substrates of the outer continental shelf, dominated by *B. marginata*, *Discorbis orbicularis* and *Globocassidulina subglobosa*. In general, the miliolids were more abundant in sandy sediments (except A2), while the bolivinids and buliminids predominated in the sediments with a silt fraction, which were normally associated with higher levels of organic matter. The highest species diversity and equitability, and lowest dominance indices were recorded in the sandy sediments, whereas the silty sediments were characterized by a predominance of opportunists such as *Bolivina* spp. and *Bulimina* spp. Species that were abundant in one stratum of a mini-core tended to be abundant throughout the core, indicating stable conditions over long periods, which guaranteed the settlement of these species.

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1. Introduction

The present sedimentation in the continental margin off Southeast Atlantic is strongly dominated by the oceanic water mass dynamics and shelf circulation due to the lack of any considerable river input. The hydrodynamical processes determine primary productivity and sediment redistribution on the shelf, leading to the establishment of the differences in sedimentation rates and sedimentary faciology (Mahiques et al., 2010). Sedimentation rates in the Campos Basin shelf, off the coast of southeastern Brazil, have been well documented, with average values varying from 70 cm/ky,

to the north area, and from 120 cm/ky, to the southern area, and are strongly correlated with areas of higher primary productivity and/or of terrigenous input, as well as with the flow of the Brazil Current (Viana et al., 1998; Mahiques et al., 2004).

Understanding biofaciological zonation of benthic foraminifera in samples of mini-cores collected in the Campos Basin is important because it presents the opportunity to carry out a historical study of how the depositional environment and associated foraminiferal assemblages have changed through recent times. Previous studies of benthic foraminiferal distributions on the SE Brazilian shelf have shown terrigenous influence inshore, coarse carbonate sediments with abundant *Amphistegina* along the outer shelf where terrigenous influence is restricted by coastal or shelf geomorphology, and muddier sediments offshore where terrigenous influence provides source material and hydrodynamics allow their accumulation. Mahiques et al. (2005) reported that sediment deposition rates in

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this region are several mm/decade. The goal of our study was to examine 10 cm cores to establish a microfasciological zonation of the benthic foraminifera of the continental shelf of Campos Basin and test the hypothesis that sediment composition and foraminiferal assemblages have remained relatively stable over the past several hundred years.

2. Regional setting

The study area corresponds to the continental shelf of the Campos Basin at depths of between 25 m and 100 m, limited by the coordinates 21°09'09" and 23°08'07" S and 40°17'54" and 42°00'55" W (Fig. 1). The superficial sediments of the inner and middle continental shelf range from siliciclastic to bioclastic formations. The outer shelf is dominated by sandy sediments, primarily siliciclastic ones, followed by carbonates. The siliciclastic sands that predominate over most of the outer shelf form extensive fields of sand waves. The mud content of these substrates is normally less than 5% (Viana and Faugères, 1998; Viana et al., 1998; Mello e Sousa et al., 2006).

In addition to the many kilometers of banks of carbonates that form well-defined ridges in some places, the outer margin of the shelf is marked by an extensive system of deep gullies. The edge of the continental shelf is defined by an escarpment between the 120 m and 220 m isobaths, with a slope of up to 14° in places (Viana and Faugères, 1998; Gonthier et al., 2003; Machado et al., 2004).

The sedimentation process that predominates on the continental shelf off southeastern Brazil is dominated by the mass of oceanic waters and the circulation of currents on the continental shelf itself. These hydrodynamic processes determine primary production and the redistribution of the sediments on the shelf, and are thus responsible for the establishment of geographic variation in sediment accumulation rates and sedimentary facies distribution (Mahiques et al., 2002).

The continental shelf is characterized by the interaction among coastal or shelf waters (CW; $33 < S < 33.7$ and $4\text{ °C} < T < 21\text{ °C}$), Tropical Waters (TW) and the Waters of the Central South Atlantic (WCSA) that form the Brazilian Current (BC). Resurgence events induced by the local winds are observed in the area adjacent to Cabo Frio principally between September and April, in association with the coastal intrusion of the WCSA. The local physiography also contributes to the generation of a low pressure divergence zone between the coast and the Brazilian Current, which is diverted, allowing the upsurging of the masses of cold water from the bottom (Bentz et al., 2005).

This phenomenon is one of the principal mechanisms responsible for the intrusion of the WCSA onto the continental shelf. When this water reaches the surface near the coast, it causes a reduction in the temperature, which is normally associated with an increase in primary productivity, in particular of the phytoplankton. At Cabo Frio, the upwelling occurs within a narrow zone of less than 100 km from the coast (Moser and Ganesella-Galvão, 1997).

3. Material and methods

3.1. Data collection

Samples were collected for the analysis of sedimentary parameters, the physical–chemical characteristics of the water column, and the composition of the benthic foraminifera in April and May, 2008, by the Environmental Heterogeneity of the Campos Basin Project (HABITATS), which was coordinated by PETROBRAS-CENPES, in Rio de Janeiro. Sediment samples were collected using

a box core sampler, which retrieved the 0–2 cm strata. Granulometric analyses were based on the method of Folk and Ward (1957) for granules of over 2 mm, whereas the particles of less than 2 mm were analyzed by laser diffraction (Shimadzu model SALD-3101). The levels of calcium carbonate (CaCO₃) were determined by gravimetric analysis.

Temperature and salinity were measured using a CTD (Conductivity, Temperature, and Depth) sampler. The analyses of the benthic foraminiferal were based on the examination of nine mini-cores of up to 10 cm divided vertically at intervals of 1 cm, with a total of 82 samples being collected. The samples were preserved in 10% formaldehyde buffered with borax (sodium tetraborate).

3.2. Laboratory analyses

3.2.1. Foraminifera

The samples of benthic foraminifera were stained with Rose Bengal (2 g per liter) for 24 h before being washed in a 0.062 mm mesh sieve, and dried at 60 °C. Sample volume was standardized to 1 g per sample. A minimum of 300 foraminiferal (total fauna) tests were picked per sample. In this study, the dead fauna was considered to be equivalent to the total fauna, given that the tests of living organisms were not stained.

A number of studies (Stigter et al., 1999; Murray and Bowser, 2000; Edelman-Furstenberg et al., 2001; Licari and Mackensen, 2005; Hayward et al., 2006; Horton and Murray, 2006) have shown that, for the investigation of distribution patterns, the live sample represents the instantaneous composition of the assemblage at a given moment in time, whereas the dead fauna provides a more reliable and representative sample of the composition of the fauna over the long term, which will be preserved in the sediments. Short-term variations in environmental conditions, which have a limited impact on the fauna, have little effect on the general characteristics of the assemblage. In this case, only the permanent conditions that affect the living organisms will be identified (Albani and Serandrei Barbero, 1982; Albani et al., 1998).

Given the possibility of post-mortem alterations in the characteristics of the specimens, extreme care was taken to identify potential evidence of alterations of the test (wear or fragmentation) or dissolution. No evidence of these processes was found in the specimens analyzed, however, indicating that they represented a predominantly *in situ* material.

3.2.2. Data analysis

The statistical analyses focused on the species that presented a density of at least 1% in at least two different substrates (Denne and Sen Gupta, 1991; Mackensen et al., 1995). Based on these criteria, the taxa analyzed together represent 98% of the total foraminiferal abundance.

The one way ANOVA test was used to identify significant differences in the mini-cores regarding the composition of the assemblages. Assessment of the associations among foraminiferal species was based on a Q-mode cluster analysis derived from a Bray–Curtis similarity matrix, in order to determine the distribution patterns among the different samples. This analysis weights rare and abundant species equally (Clarke and Warwick, 1994) and groups samples in pairs. In order to understand the relationship between the distribution of foraminiferal species and the refined environmental variables, the results of this cluster analysis were run in a Canonical Correspondence Analysis (CCA).

The data were log-transformed ($\ln(x + 1)$) for ordination in order to reduce the effects of the different scales and homogenize variances, reducing the relative importance of the dominant

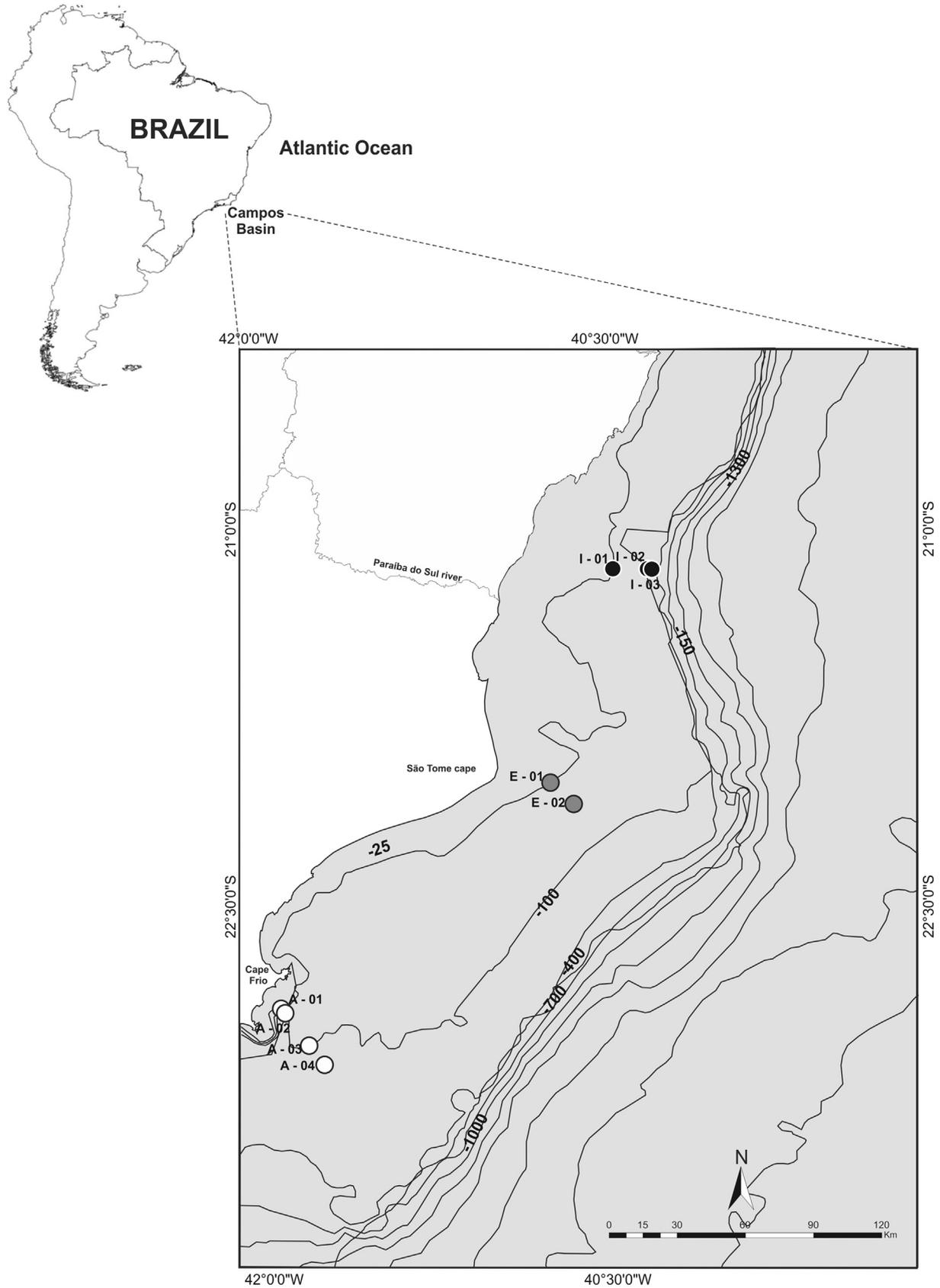


Fig. 1. Bathymetric map of the study area in the Campos Basin showing the locations of the mini-cores.

species in the analysis. The environmental variables that presented a high degree of interdependence – indicated by a variance inflation factor (IF) of over 20 – were excluded from the multicollinearity analysis.

As the E2 and I1 mini-cores, and the 8 cm extract of the I2 core presented less than the required minimum of 300 foraminiferal specimens, they were excluded from the CCA. The Paleontological Statistics program (PAST), version 2.3, was used to calculate diversity and equitability indices, and cluster analyses, while the ordination analyses were run in CANOCO, version 4.5.

4. Results

4.1. Environmental characteristics of the sampling stations

The granulometric analyses revealed sediments composed primarily of sandy fraction. Sand predominated in the mini-cores from the inner (A1, E1, and I1) and middle shelf (A2 and E2), while finer fractions – silt and clay – prevailed on the outer shelf (A3 and A4), with silt generally being more common than clay. Gravel and other granules were scarce, never constituting more than 29.7% of the substrate (Fig. 2 and Table 1).

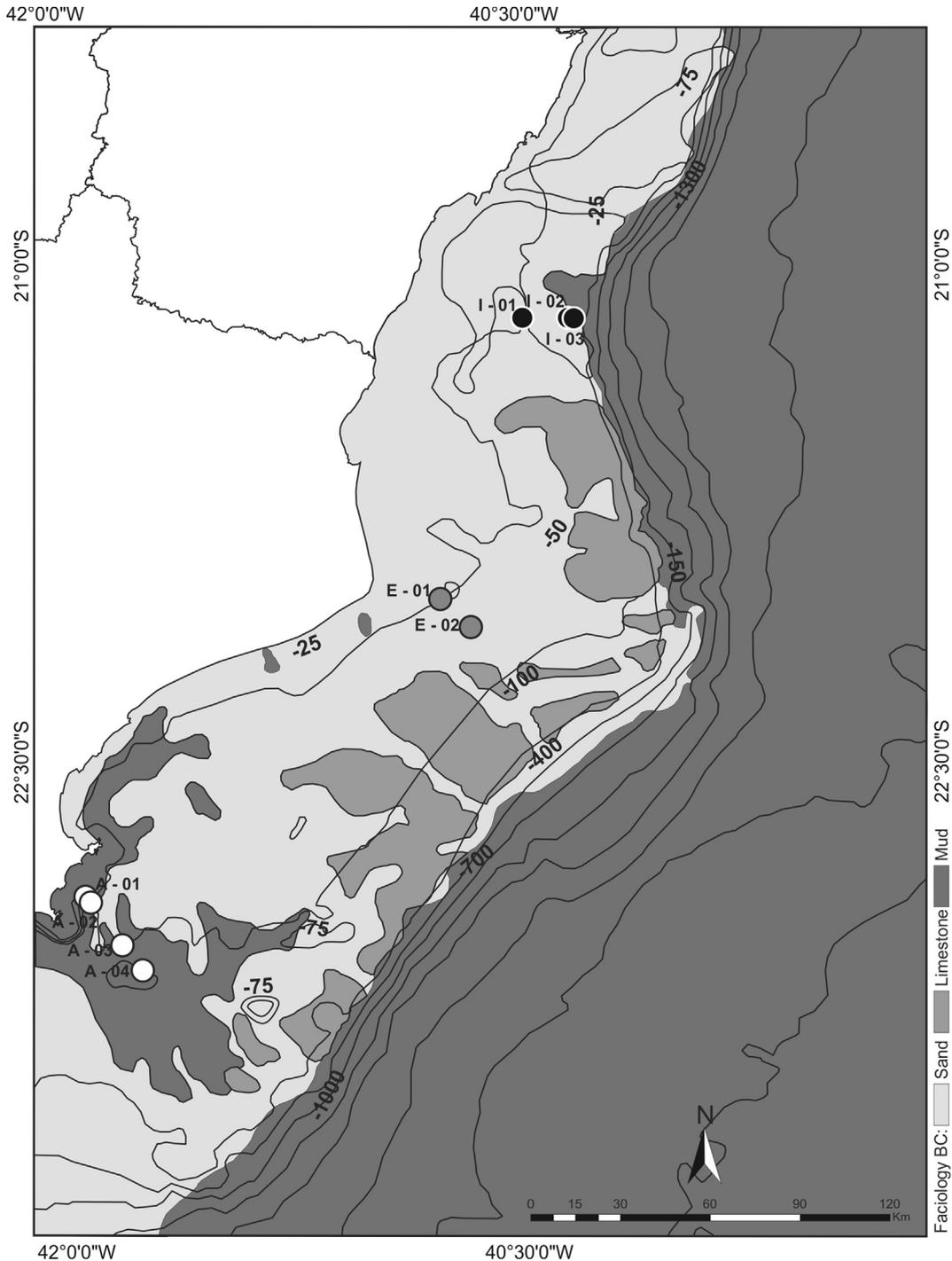


Fig. 2. Facies map of the Campos Basin, showing the analyzed transects in the present study.

Table 1
Geographic coordinates, water depth, surface temperatures (ST), bottom temperatures, surface salinity (SS), bottom salinity of the nine mini-cores collected for the present study.

Station	Subsamples total	Latitude (S)	Longitude (W)	Water depth (m)	ST (°C)	BT (°C)	SS	BS	% Carbonate	Wentworth nomenclature
A1	10	22° 55' 03"	42° 00' 55"	29	23.8	21.6	35.2	35.8	38.7	Medium sand
A2	10	22° 55' 48"	41° 53' 47"	47.5	23.7	19.5	35.1	35.9	5.8	Very fine sand
A3	10	23° 03' 31"	41° 47' 46"	80	23.5	19.8	35.2	35.9	16.8	Medium silt
A4	10	23° 08' 07"	41° 43' 56"	103	23.5	18.0	35.1	35.9	21.8	Fine silt
E1	9	22° 01' 44"	40° 44' 59"	28.4	24.2	23.4	34.8	35.8	21.2	Very fine sand
E2	9	22° 06' 52"	40° 39' 07"	52.7	24.6	19.8	34.4	36.3	5.4	Medium sand
I1	6	21° 10' 57"	40° 28' 33"	26.6	24.8	23.7	36.8	36.8	2.5	Coarse sand
I2	8	21° 22' 57"	40° 19' 48"	53	24.7	21.3	36.7	36.6	66.0	Fine sand
I3	10	21° 09' 09"	40° 17' 54"	71.7	25.1	20.9	36.6	36.5	55.8	Very coarse sand

Surface temperatures varied from 23.4 °C to 25 °C, and bottom temperatures from 18 °C to 23.7 °C (Table 1). Salinity at the surface ranged from 34.4 to 36.8, and from 35.7 to 36.7 at the bottom (Table 1).

4.2. Foraminifera

4.2.1. Composition and abundance of the foraminifera

A total of 93 foraminifera taxa were identified, representing 43 genera (Table 5). The calcareous hyalines were the predominant group (65 species), followed by the porcelanous (21 species) and agglutinated forms (seven species). The most common hyalines were *Bulimina marginata*, *Globocassidulina subglobosa*, *Pseudonion atlanticum*, and *Amphistegina lessoni*. The hyalines were the most abundant foraminifera in the area adjacent to Cabo Frio (mini-cores A2, A3, and A4). The porcelanous forms were found throughout the shelf, although they were more abundant in the north and along the coastal stations, where they constituted between 26% (A1, at 1 cm) and 63% (I3, at 9 cm) of the fauna.

The agglutinated species represented less than 10% of total abundance. Abundance was 8% in the mini-cores from the shallow-water points, with *Textularia agglutinans* the most abundant species at A1 and *Textularia candeina* at E1. In the northern sector, the abundance of agglutinated species varied from 3% to 8%, being *Textularia pseudotrochus* the most abundant. No agglutinated species were found at stations A2–4, which are located in the deepest sector of transect A, close to Cabo Frio.

Overall, the most abundant species were *B. marginata* (18%), *G. subglobosa* (11%), and *P. atlanticum* (10%). *P. atlanticum* was the most widely-distributed species, being recorded in 62% of the sub-cores. Another 12 species (representing 55% of the specimens) were observed in between 40% and 60% of the samples, while 27 species (4% of the abundance) were found in no more than 10% of the samples.

The abundance of miliolids was associated with a reduction in the presence of *Bolivina* spp. and *Bulimina* spp. In mini-core A1 and transects E and I, miliolid abundance ranged from 32% to 43%, whereas that of *Bolivina* and *Bulimina* reached no more than 8%. The greatest abundance of *Bolivina* and *Bulimina* – between 14% and 75% – was recorded in mini-cores A2, A3, and A4, in which miliolids did not exceed 8%.

4.2.2. Species richness, diversity and equitability

No more than 22 individuals were recovered in mini-cores E2, I1, and in the 8 cm sample at I2. Species richness in these probes varied from 1 to 12 (Table 2). In the case of the standardized samples (minimum of 300 individuals), the number of species varied from 11, at a depth of 7 cm in mini-core A2, to 58 species at 7 cm in core I3 (in which the highest species richness indices were recorded). As a total of 93 taxa were identified in the present study, between 46% and 63% of the total species richness were observed in the different extracts of this core (Table 2).

Table 2

Ecological parameters recorded for the different foraminiferal assemblages sampled in the present study. S⁻ mean total richness; H⁻ mean diversity; J⁻ mean equitability; D⁻ mean dominance.

	S ⁻	H ⁻	J ⁻	D ⁻
A1	32	2.8	0.8	0.1
A2	17	1.1	0.4	0.6
A3	28	2.2	0.7	0.2
A4	28	2.0	0.6	0.3
E1	26	1.8	0.6	0.3
E2	5	1.5	1.0	0.3
I1	2	0.6	0.7	0.6
I2	37	2.6	0.7	0.1
I3	49	3.3	0.9	0.1

Mini-core I3 was also the most diverse (H⁻), followed by I2 and A1. The indices recorded for I3 were all above 3, whereas those for A1 and I2 were between 2.3 and 3. For A3, the indices were approximately 2.2. The mini-cores A2 and A4 returned the lowest indices of species diversity and equitability. Dominance in the A2 core was mostly above 0.5, except for the 9 cm (0.42) and 10 cm (0.48) extracts (Table 2).

4.2.3. Communities of benthic foraminifera

Regarding the composition of foraminifera in the analyzed mini-cores, there were no significant differences between the strata, indicating that represent relatively uniform facies over the depth sampled (Table 3). Foraminiferal taxa with similar distributions were grouped hierarchically in four biofacies (Fig. 3).

Table 3

Details of the one way ANOVA. df degrees of freedom; F F-test; p p-value.

	Sum of squares	df	Mean square	F	p (same)
A1					
Between groups	0.480	9	0.053	0	1
Within groups	111118	940	118.210		
Total	111118	949			
A2					
Between groups	0.17076	8	0.021	3.96E-05	1
Within groups	455648	846	538.591		
Total	455648	854			
A3					
Between groups	1.453	9	0.161	9.26E-04	1
Within groups	163798	940	174.253		
Total	163799	949			
A4					
Between groups	1.625	9	0.181	0.001	1
Within groups	259039	940	275.573		
Total	259041	949			
E1					
Between groups	0.168	8	0.021	7.58E-05	1
Within groups	235024	846	277.806		
Total	235024	854			
I2					
Between groups	0.262	6	0.044	0	1
Within groups	99995.2	658	151.968		

Table 3 (continued)

	Sum of squares	df	Mean square	F	p (same)
Total	99995.4	664			
Between groups	5.621	9	0.625	0.013	1
Within groups	44642	940	47.491		
Total	44647.6	949			

4.2.3.1. *Biofacies I – sandy coastal sediments.* This association is characterized by the mini-cores A1 and E1, located on the inner continental shelf, and classified as very fine (E1) and medium-grained sands (A1). *P. atlanticum*, *Quinqueloculina* spp., *Cibicides concentricus*, and *Miliolinella* spp. were abundant in these biofacies.

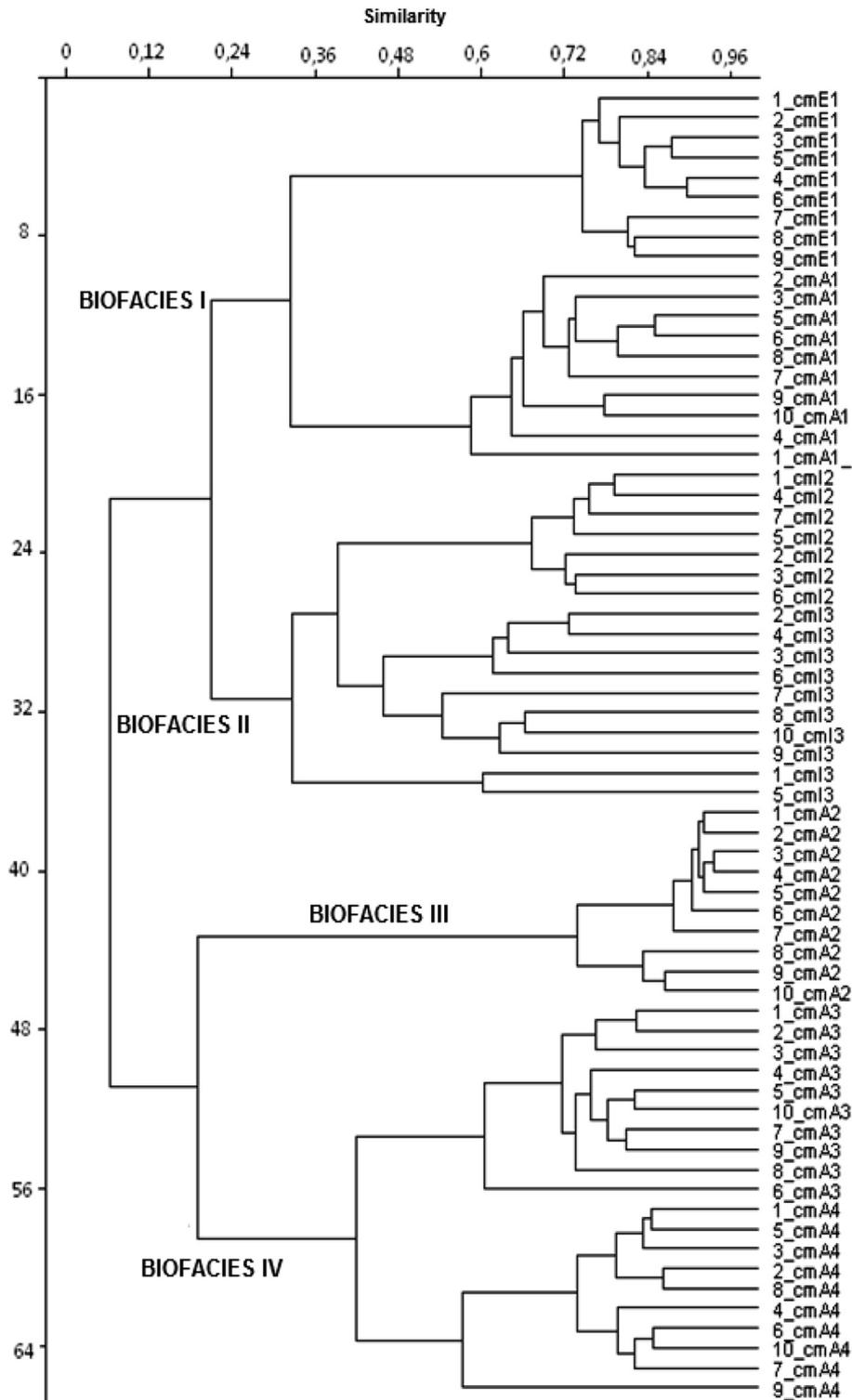


Fig. 3. Diagram of similarity between mini-cores.

4.2.3.2. *Biofacies II – carbonate sediments.* This association includes 17 subsamples from mini-cores I2 and I3, located between the inner and outer continental shelf, with the highest proportions of carbonates, 66% and 55.83%, respectively. *Amphistegina lessonii*, *Discorbis floridensis*, *Eponides advena*, *Planorbulina mediterraneensis*, *Planulina exorna*, *Planulina wuellerstorfi*, *Pyrgo bulloides*, *Reussella atlantica*, *Textularia majori*, and *T. pseudotrochus* were recorded exclusively in this group, which was thus characterized by the highest diversity indices. The most abundant species were *A. lessonii*, *Miliolinella* spp., *Quinqueloculina* spp., and *P. exorna*.

4.2.3.3. *Biofacies III – transition between the inner and outer continental shelf.* Association represented by mini-core A2 located in the sector south of Cabo Frio at a depth of 48 m, with sediments of predominantly very fine sand. Low diversity and equitability related to the predominance of *B. marginata*, which accounted for 75% of the foraminiferal abundance. In addition, miliolids were relatively rare, accounting for only 8% of abundance, on average. The properties of the sediment, granule size, depth, and the reduced species richness distinguished this biofacies from all the others.

4.2.3.4. *Biofacies IV – muddy sediments of the outer continental shelf.* This biofacies is represented by the mini-cores A3 and A4, located on the outer continental shelf, in the deepest waters of the study area, where the silt fraction predominates. Mini-core A3 was defined as medium silt, and A4 as fine silt. The most abundant species were *Discorbis orbicularis*, *B. marginata*, and *G. subglobosa*. The abundance of *G. subglobosa* increased with depth, reflecting a clear vertical stratification. *G. subglobosa* was most abundant in this biofacies, and *D. orbicularis* and *B. marginata* were also relatively abundant. By contrast, the lowest abundance of miliolids was recorded in this biofacies, with mean values ranging from 2.3% to 4.0%.

4.2.4. *Influence of environmental factors on the communities of benthic foraminifera*

The canonical correspondence analysis (CCA) indicated that four of the environmental variables analyzed were the primary factors

determining the distribution of benthic foraminifera: bottom temperatures (BT), the percentage of sand and silt in the substrate, and depth. Axis I explains 46.7% of the variation, with a positive relationship with silt concentrations. Axis II corresponds to 29.2% of the variation, and is related to the parameters sand content and bottom temperatures (Fig. 4; Tables 4 and 5).

Table 4

Details of the environmental variables used for the Canonical Correspondence Analysis (CCA).

Environmental variables	Correlations		% Variance's explanation	p	F
	Axis I	Axis 2			
Bottom temperatures (BT)	-0.7758	0.3210	0.51	0.002	13.54
Deep	0.6541	-0.7166	0.35	0.002	10.66
Silt	0.6972	-0.3712	0.25	0.002	8.88
Sand	-0.3547	0.7240	0.35	0.002	11.82
% Cumulative variance					
Data species	22.5	14.2			
Data species-relationship environmental	46.7	29.2			
∑ eigenvalues =	2.911				
∑ eigenvalues =	1.405				

Table 5

Taxonomic references for the species of benthic foraminifera identified in the present study, and the respective acronyms used in the CCA.

<i>Amphistegina lessonii</i> d'Orbigny, 1826	Aml
<i>Ammonia beccarii</i> (Linnaeus, 1767)	Amb
<i>Amphicorina scalaris</i> (Batsch, 1791)	Ans
<i>Angulogerina angulosa</i> (Williamson, 1858)	Ana
<i>Bolivina doniezi</i> Cushman and Wickeden, 1929	Bod
<i>Bolivina elongata</i> Hantken 1845	Boe
<i>Bolivina göesi</i> Cushman, 1922	Bog
<i>Bolivina minima</i> Cushman, 1922	Bom
<i>Bolivina morenoi</i>	Bomo
<i>Bolivina ordinaria</i> Phleger and Parker, 1951	Boo
<i>Bolivina striatula</i> Cushman, 1922	Bos
<i>Bolivina subaenariensis</i> Cushman, 1937	Bosu
<i>Bolivina subspinescens</i> Cushman, 1922	Bosbs
<i>Buccella peruviana</i> (d'Orbigny) 1839	Bup
<i>Bulimina aculeata</i> d'Orbigny, 1826	Bua
<i>Bulimina echinata</i> d'Orbigny, 1826	Boe
<i>Bulimina gibba</i> Fornasini, 1900	Bog
<i>Bulimina marginata</i> d'Orbigny, 1826	Bum
<i>Bulimina patagonica</i> d'Orbigny, 1839	Bup
<i>Bulimina</i> spp.	Bul
<i>Buliminella imbricata</i> (Reuss, 1851)	Bui
<i>Buliminella laevis</i> (Beissel, 1891)	Bula
<i>Buliminella</i> spp.	Buli
<i>Cancris oblonga</i> (Williamson, 1858)	Cas
<i>Cancris sagra</i> (d'Orbigny, 1839)	Cao
<i>Cassidulina curvata</i> Phleger & Parker 1951	Cac
<i>Cassidulina laevigata</i> d'Orbigny, 1826	Cal
<i>Cassidulina norcrossi</i> Phleger and Parker, 1951	Can
<i>Cassidulina</i> spp.	Cas
<i>Cassidulinoides parkerianus</i> (Brady, 1884)	Cip
<i>Cibicides concentricus</i> (Cushman 1918)	Cic
<i>Cibicides corpuentus</i> Phleger and Parker 1951	Cico
<i>Cibicides</i> spp.	Cibi
<i>Discorbis candeiana</i> (d'Orbigny, 1839)	Dic
<i>Discorbis floridensis</i> Cushman, 1931	Difl
<i>Discorbis globosa</i> (Sidebottom 1926)	Dig
<i>Discorbis orbicularis</i> (Terquem 1878)	Dio
<i>Discorbis</i> spp.	Disc
<i>Elphidium excavatum</i> (Terquem, 1875)	Ele
<i>Elphidium frigidum</i> Cushman, 1933	Elf
<i>Elphidium gunteri</i> Cole, 1931	Elg
<i>Elphidium semistriatum</i> (Cushman, 1899)	Els
<i>Elphidium</i> spp.	Elp
<i>Eponides advena</i> (Cushman, 1923)	Epa
<i>Eponides ellisorae</i> Garret, 1939	Epe
<i>Eponides exiguus</i> Brady, 1930	Epex
<i>Eponides repandum</i> (Fichtel and Moll 1803)	Epr
<i>Eponides</i> spp.	Epo

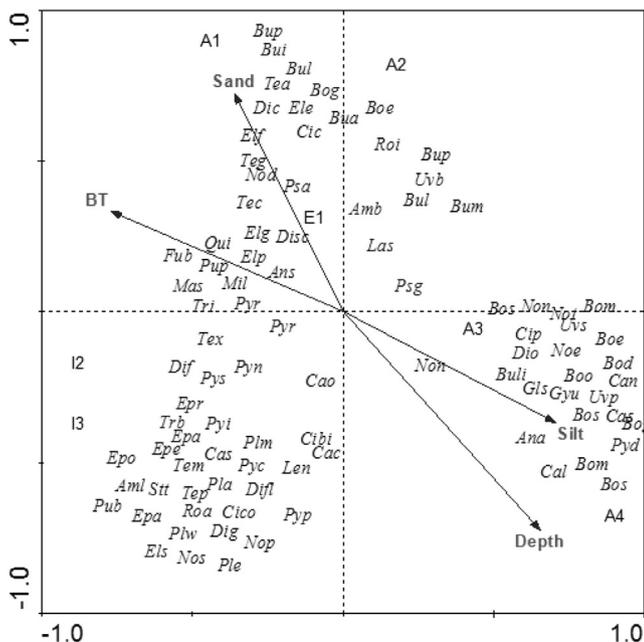


Fig. 4. Ordination diagram (CCA) for the benthic foraminiferal species based on environmental variables.

Table 5 (continued)

<i>Fursenkoina bramletei</i> (Galloway and Moore, 1929)	Fub
<i>Globocassidulina subglobosa</i> (Brady, 1884)	Gls
<i>Gyroïdina umbonata</i> (Silvestre, 1898)	Gyu
<i>Lenticulina sulcata</i>	Las
<i>Lenticulina</i> spp.	Len
<i>Massilina secans</i> (d'Orbigny, 1826)	Mas
<i>Miliolinella</i> spp.	Mil
<i>Nodocubariella</i> spp.	Nod
<i>Nonion pompiloides</i> Fichtel & Moll, 1798	Nop
<i>Nonion</i> spp.	Non
<i>Nonionella extensa</i> Brotzen, 1936	NOE
<i>Nonionella turgida</i> (Williamson, 1858)	Not
<i>Nonionella</i> spp.	Non
<i>Planorbulina mediterraneensis</i> d'Orbigny, 1826	Plm
<i>Planulina ariminensis</i> d'Orbigny, 1826	Plm
<i>Planulina exorna</i> Phleger and Parker 1951	Ple
<i>Planulina wuellerstorfi</i> (Schwager, 1866)	Plw
<i>Pseudononion atlanticum</i> (Cushman, 1947)	Psa
<i>Pseudononion grateloupi</i> (d'Orbigny, 1826)	Psg
<i>Pyrgo bulloides</i> (d'Orbigny, 1826)	Pyb
<i>Pyrgo clypeata</i> d'Orbigny, 1846	Pyc
<i>Pyrgo depressa</i> (d'Orbigny, 1826)	Pyd
<i>Pyrgo inornata</i> (d'Orbigny, 1846)	Pyi
<i>Pyrgo nasuta</i> Cushman, 1935	Pyn
<i>Pyrgo patagonica</i> (d'Orbigny, 1939)	Pypa
<i>Pyrgo peruviana</i> d'Orbigny, 1839	Pyp
<i>Pyrgo ringens</i> (Lamarck, 1804)	Pyr
<i>Pyrgo subsphaerica</i> (d'Orbigny, 1839)	Pys
<i>Pyrgo</i> spp.	Pyr
<i>Quinqueloculina</i> spp.	Qui
<i>Rosalina atlantica</i>	Roa
<i>Rosalina isabelleana</i> d'Orbigny, 1839	Roi
<i>Stomartobina torrei</i> (Cushman and Bermúdez, 1948)	Sit
<i>Textularia agglutinans</i> d'Orbigny, 1839	Tea
<i>Textularia candeiana</i> d'Orbigny, 1839	Teca
<i>Textularia conica</i> d'Orbigny, 1839	Tec
<i>Textularia gramem</i> d'Orbigny, 1846	Teg
<i>Textularia mayori</i> Cushman, 1922	Tem
<i>Textularia pseudotrochus</i> Cushman, 1929	Tep
<i>Textularia</i> spp.	Tex
<i>Triloculina baldai</i> Bermúdez and Seiglie, 1963	Trb
<i>Triloculina</i> spp.	Tri
<i>Uvigerina bifurcata</i> d'Orbigny, 1839	Uvb
<i>Uvigerina peregrina</i> Cushman, 1923	Uvp
<i>Uvigerina striata</i> d'Orbigny, 1839	Uvs

Silt was related positively with the deeper water mini-cores, A3 and A4. Bottom temperatures separate groups III and IV from all the other associations. These two groups have much lower temperatures when compared to all the other mini-cores. The species that form axis I are responsible for 22.5% of the total variation. The genera *Bolivina*, *Bulimina*, *Globocassidulina*, and *Cassidulina* are positively related to the variables that correspond to this axis.

Axis II was formed by the variables sand and water depth. The stations at which sand predominated were clearly separated from all the others, with a particularly strong relationship being observed in the case of mini-cores A1, A2, and E1, which were 65%–100% sandy. The representative species of axis II correspond to 14.2% of the variability observed in this study. *Miliolinella* spp. and *Quinqueloculina* spp. were associated with the sandy fraction, as was *Textularia* spp.

5. Discussion

The mini-cores obtained from the continental shelf of the Campos Basin presented similar values of temperature and salinity, which indicates that the different sectors are influenced by the same oceanic currents (superficial waters of the continental shelf and the Brazilian Current). The influence of two other bodies of

water – Tropical Waters (TW) and Waters of the Central South Atlantic (WCSA) – is also apparent. The physical–chemical properties of the water column indicate the possible influence of the WCSA off the Cape of São Tomé (mini-core E2), which move southwards off Cabo Frio (mini-cores A2, A3, and A4). The bottom temperatures in these sectors were below 20 °C. However, the WCSA do not reach the surface, which would characterize an upwelling process.

Carbonates are typically deposited in clear, shallow waters, and under hydrodynamic conditions controlled by the action of waves and tides. In deeper waters, however (I2 and I3), deposition patterns are associated with marine currents. The BC at surface levels is what maintains the carbonate production and preservation (Mahiques et al., 2005; Giustina, 2006). The concentration of suspended particulate matter will also play a role in the carbonate deposition. The symbiotic species *A. lessonii*, which grows only in extremely clear waters and on carbonate algal sand (Oliveira-Silva et al., 2005; Bruno et al., 2009), was found only in the samples from transect I, which is protected by the carbonate bank, where the influence of the plume of fine sediments carried by the River Paraíba do Sul is greatly reduced (Murillo, 2008). Oliveira-Silva et al. (2005) obtained similar results from the Campos Basin in the vicinity of transect I.

The data on the calcium carbonate component and other sedimentological variables analyzed in the present study were obtained from the first few centimeters of the sediment–water interface, although they were considered to be representative of the whole sediment layer down to 10 cm, given the high sedimentation rates observed typically in the region (Mahiques et al., 2004, 2005; Nagai et al., 2009). This also assumes that the subsurface samples are representative of long-term historical records. For example, Mahiques et al. (2005) dated box cores collected off Cabo Frio and recorded ages of 100 years between depths of 6–8 cm, and sedimentation rates of 0.26 mm/y. Souto et al. (2011) registered 0.23 mm/yr from 10 cm to the top at 117 m. In addition, a high degree of correlation in the sedimentation indices was recorded off Cabo Frio (transect A) and in the sectors in which lithogenic sediments of the Campos Basin are deposited, i.e., transect E (Mahiques et al., 2004, 2005; Nagai et al., 2009). This procedure was also adopted by Bubenshchikova et al. (2008) for the analysis of the foraminifera at depths of up to 8 cm in the sediments of the waters off Okhotsk in the western Pacific Ocean.

These data also reinforce what was found with respect to the foraminiferal composition in the studied mini-cores, where there are no significant differences between facies indicating relatively uniform facies over the depth sampled. The highest rates of sedimentation are found near Cabo Frio, due to the local influence of coastal upwelling responsible for the increased primary productivity, and further north of the study area (Mahiques et al., 2004, 2005; Nagai et al., 2009; Souto et al., 2011).

Together with the ordination of the data, the clusters found in the present study indicate that the biofacies were formed on the basis of four principal parameters – bathymetry, temperature, sediment type, and species composition. Bathymetry plays an important role in the distribution of the benthic foraminifera due to the variation in topography, sunlight penetration, water energy, temperature, and hydrostatic pressure. The sediment type determines the availability of nutrients and oxygen at the surface and within the different layers of the substrate. Population density depends on a range of ecological factors that determine the geographic distribution of each species.

The availability of nutrients and the concentration of oxygen in the bottom sediments and the interstitial spaces between granules are the principal factors controlling the ecology of benthic foraminifera, in terms of both the abundance of different species and

their association with others (Gooday, 1994; Geslin et al., 2004; Mendes et al., 2004). The benthic foraminifera from shelf settings respond rapidly to the slightest modifications of the environment. Given this, the biofacies should also be interpreted in the light of the ecological events indicated by the foraminiferal species identified in a given assemblage.

The relationship between benthic foraminifera and the sediments they inhabit is extremely complex. The levels of oxygen dissolved in the sediment and the accumulation of organic matter from the surface depend on the size of the granules, which also influences the porosity and permeability of the sediment (Austin and Evans, 2000; Armstrong and Brasier, 2005).

In sandy sediments, oxygen is not normally a limiting factor for the proliferation of benthic foraminifera, given that the interstitial spaces between the grains of sand guarantee the free circulation of oxygen, even at depths well below the sediment–water interface (van der Zwaan et al., 1999). This appears to be typical of mini-cores A1, E1, I2, and I3, in which this type of sediment was found.

In addition, the miliolids are indicators of environments with good levels of oxygenation, given that their abundance is reduced in areas in which oxygen is scarce, and these organisms are thus used as indicators of oxic environments in the reconstruction of paleoenvironments (Jannink et al., 1998; Jorissen, 1999; den Dulk et al., 2000; Morigi et al., 2001; Hyams-Kaphzan et al., 2009). In mini-cores A1, E1, I2, and I3, the mean abundance of miliolids was 35%, 30%, 43%, and 32%, respectively, while the records of the genera *Bolivina* and *Bulimina* ranged from 0.3 to 8.0%. This would be expected, given that these genera are known to be associated with the eutrophic zone and reduced bottom oxygen levels (Corliss, 1985; Sen Gupta and Machain-Castillo, 1993; van der Zwaan et al., 1999; Schmielid et al., 2000; Disaró et al., 2006; Szarek et al., 2006; Nagai et al., 2009; Soma De, 2010). In the present case, biofacies I and II have high indices of diversity and equitability, in particular at station I3, where the lowest diversity index (3.14) was recorded at a depth of 1 cm.

While mini-core A2 represents a sandy environment, the abundance of miliolids was only 8%. This station was dominated by *B. marginata* (abundance of between 63% and 80%) and characterized by reduced diversity, of 0.66791–1.314. Areas dominated by a single species, as observed at this station, are typical of conditions of environmental stress induced by natural and/or anthropogenic factors.

The dominant species observed in the samples from the outer continental shelf (cores A3 and A4), *B. marginata* and *G. subglobosa*, were associated with *Angulogerina angulosa*, *Bolivina doniezi*, *Bolivina göesi*, *Bolivina elongata*, *Bolivina minima*, *Bolivina ordinaria*, *Bolivina striatula*, *Bolivina subspinescens*, *Bolivina subaenariensis*, *Bulimina aculeata*, *Bulimina echinata*, *Bulimina gibba*, *Cassidulina curvata*, *Cassidulina laevigata*, *Cassidulina norcrossi*, *Uvigerina peregrina*, and *Uvigerina striata*, which are typical of areas with high nutrient concentrations (Corliss, 1985; Corliss and Chen, 1988; Fariduddin and Loubere, 1997; Schmielid et al., 1997; Morigi et al., 2001; Altenbach et al., 2003; Martins et al., 2006; Mello e Sousa et al., 2006; Eichler et al., 2008; Nagai et al., 2009; Soma De, 2010).

In addition to the reduction of species richness and the increase in dominance, biofacies III and IV are characterized by an increase in the abundance of infaunal organisms, predominantly bolivinids and buliminids. The composition of these biofacies, which are located in muddy sediments, indicates not only an increase in the availability of nutrients, but also environments with low-oxygen levels (Martins et al., 2006; Nagai et al., 2009).

Many species that tolerate low-oxygen concentrations are typical of muddy environments (van der Zwaan et al., 1999). These species are usually considered to be opportunists due to their ability to proliferate in habitats with a deficiency of oxygen. In

addition, the mean abundance of miliolids in the subsurface spaces did not exceed 5%, whereas the abundance of *Bolivina* and *Bulimina* was between 14% and 41%.

Burone et al. (2011) also found a greater abundance of infaunal species in the vicinity of Cabo Frio, at a depth of 44 m, and attributed this finding to the mesotrophic conditions induced by the upwelling phenomenon observed in this sector. In this area, the concentrations of organic carbon in the sediment varied from 1.18% at a depth of 10 cm to 1.62% at 2 cm.

One other finding that reinforces this conclusion was the detection of the input of WCSA in the area of mini-cores A2, A3, and A4, which is related to the enrichment of nutrients, as discussed above. Analyzing the superficial sediments (0–2 cm) from transect A, Oliveira et al. (2011) concluded that there is an increased input of organic matter, in particular in cores A3 and A4. This phenomenon was attributed to two factors – (i) the localized predominance of silt/clay in certain areas of the continental shelf, and (ii) increased productivity on a local scale related to the Cabo Frio upwelling, in which case, the organic matter would have an autochthonous origin.

6. Conclusions

The classification and distribution of the benthic foraminiferal species observed in the present study permits the allocation of the fauna to four distinct groups – biofacies I (association with coastal sandy sediments – mini-cores A1 and E1 – dominated by *P. atlanticum* and miliolids), biofacies II (associated with carbonate sediments, represented by *A. lessonii* and miliolids), biofacies III (represented by mini-core A2, with a predominance of *B. marginata* in all the strata), and biofacies IV, which was associated with the muddy substrates of the outer continental shelf (A3 and A4) dominated by *B. marginata*, *D. orbicularis*, and *G. subglobosa*.

The miliolids were most abundant in the sandy sediments (except A2), while the bolivinids and buliminids predominated in the silty sediments, normally associated with increased levels of organic matter. In general, the highest diversity and equitability, and the lowest indices of dominance were recorded in the mini-cores with a sandy fraction. Species that were abundant in one stratum of a mini-core tended to be abundant throughout the core, indicating stable conditions over long periods, which guaranteed the settlement of these species.

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