Journal of Foraminiferal Research, v. 38, no. 1, p. 23–38, January 2008

BENTHIC FORAMINIFERA ASSOCIATED WITH THE SOUTH BAHIA CORAL REEFS, BRAZIL

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ABSTRACT

The objective of this study was to assess foraminiferal faunas and their relationship to sediment texture and composition in the reef areas from the coastline to the 30-m isobath between the cities of Corumbau and Nova Viçosa in the extreme south of the State of Bahia. Cluster analysis of the species, identified from 38 samples of surface sediments, revealed a strong correlation with grain size. The principal relationships established between these species and the sediments were the following: (i) *Amphistegina lessonii* and *Peneroplis carinatus* were abundant in sandy carbonate sediments and (ii) *Ammonia beccarii*, *Elphidium poeyanum*, *Pyrgo subsphaerica*, *Quinqueloculina disparilis curta* and *Q. lamarckiana* were abundant in mixed sand and mud, whether carbonate or mixed carbonate and siliciclastic. The fluctuation in the richness index among samples indicated microenvironmental areas that were unfavorable for some foraminiferal species. Local hydrodynamic conditions result in environments with greater energy where finer sediments, together with many foraminiferal species, have been removed. In more protected areas, weaker hydrodynamic conditions permit the accumulation of fine sediments and organic matter, making the environment suitable for diverse forms of foraminifera. In general, faunal composition is typical of tropical carbonate platforms, where the reef structures provide a variety of microenvironments that account for the variations observed in the foraminiferal fauna.

INTRODUCTION

Coral reefs are considered among the richest marine ecosystems, providing economic resources as well as protection to coastal areas. Coral reefs are also sensitive indicators that monitor global change. Since the colonization of Brazil, man has abused the local coral reefs, principally through the influence of sediments and pollution (caused by increasing urban and industrial development in coastal regions and by the exploration for fossil fuels). Additionally, marine tourism, exploitation of reef organisms and fishing (Leão and Kikuchi, 1999) have directly impacted these ecosystems. Considering the importance of reef ecosystems, it is necessary to understand their responses to anthropogenic activities.

Environmental indicators are important tools that can provide insight into the phenomena that affect marine ecosystems. As changes occur in ecological conditions, habitats are altered, thereby affecting biodiversity. In this context, the use of foraminiferal assemblages as environmental quality indicators of reefs has been widespread (Machado and Souza, 1994; Sanches and others, 1995; Machado, 1995; Andrade and others, 1996; Cockey and others, 1996; Leipnitz and others, 1996; Rossi and others, 1996; Bicchi and others, 2002; Nascimento, 2003; Hallock and others, 2003; Langer and Lipps, 2003), thanks to the abundance, diversity and preservation potential, as well as ease of collection in the field, storage, and laboratory preparation of these organisms (Scott and others, 2001; Yanko and others, 1999).

An important characteristic that has broadened the use of foraminifera in environmental studies is the fact that the distribution of these organisms is influenced by diverse abiotic and biotic factors, including light, temperature, salinity, oxygen availability, alkalinity, depth, organic matter, substrate and water turbidity (Haynes, 1965; Murray, 1973, 1991; Boltovskoy and others, 1991). Alterations in any of these factors are reflected in foraminiferal assemblages (Murray, 1973, 1991; Debenay, 1988). This characteristic makes these organisms an important tool for identifying variations that have occurred in the environment and for understanding ocean circulation patterns (Passos, 2000).

Studies in Brazil (Machado and Souza, 1994; Leitnitz and others, 1996; Sanches and others, 1995; Machado, 1995; Rossi and others, 1996; Machado and others, 1999) in recent decades have related foraminiferal faunas in reef areas to various environmental parameters. In the inter-reef area of Guarajuba, State of Bahia (BA), Andrade and others (1996) reported the distribution of the larger foraminiferal fauna based on samples of sediment collected over approximately ten years. Moraes and Machado (2000) correlated the low percentage of abraded specimens to the protection offered by pools at the top of the Itacimirim (BA) reef based on an analysis of the state of preservation and coloration of some genera present in the reef. Moraes (2001) and Moraes and Machado (2003) interpreted the hydrodynamic and transportation patterns in reef areas of Praia do Forte (BA) and Itacimirim (BA) based on textural characteristics and sediment composition, as well as on the distribution, coloration and state of preservation of foraminiferal tests collected from the tops of these reef structures. The objective of our study is to report foraminiferal species that inhabit reef areas located at the extreme south of the State of Bahia, an area of growing urban development and tourism, and to relate their distribution to the texture and composition of sediments that border this coral reef area.

GEOLOGICAL-PHYSIOGRAPHICAL SCENARIO

The present study focuses on the reef areas between the cities of Corumbau and Nova Viçosa, in the extreme south of the State of Bahia, and includes structures and reef banks along the continental shelf from the coast to the 30-m

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isobath (Fig. 1). The region covers approximately 7,000 km^2, and the points sampled vary in distance from the coastline between ~1.5–100 km (Fig. 1).

Melo and others (1975) were the first to describe this section of the continental shelf in relation to its physiography, emphasizing its flat and shallow character. The platform is generally less than 60 m in depth and less than 30 m in depth around the reef structures. Water depths among the coastal reefs (internal arc) and the coastline do not surpass 15 m. In the Caravelas channel, which separates the coastal reefs from the coastline, the depth varies between 10–20 m. In the Abrolhos channel, which separates the coastal reefs from the islands of the Abrolhos Archipelago (external arc), the depth ranges around 20–30 m (Leão, 1982; Fig. 1).

In the areas studied, the platform is the widest in the entire State of Bahia, reaching a maximum of 246 km in the region where the reefs of Parcel dos Abrolhos are situated, near the Abrolhos Archipelago (Fig. 1). According to Leão and Brichta (1995), the inner section of the platform to a depth of 20 m shows a gentle topography resulting from infilling by Holocene sediments, whereas the surface of the middle and outer portions contain numerous shallow banks, uncountable biogenic structures, and volcanic structures that constitute the five islands of the Abrolhos Archipelago (Fig. 1). Reef buildups occur along the shallowest features of the area. This group of coral reefs is composed of coral platforms and isolated pinnacles that parallel the coast, as well as pinnacles that border the islands of the Abrolhos Archipelago. This section of the Brazilian continental shelf presents two distinct sedimentary facies: (i) a facies of siliciclastic sediments and (ii) a facies of predominately carbonate sediments of biogenic origin (Leão and Brichta, 1995).

The siliciclastic sediments are composed of quartzitic sand, with contents above 50%, and predominate along a relatively narrow strip parallel to the coastline, widening at the mouths of the great rivers (Mello and others, 1975). Siliciclastic concentrations fall rapidly offshore and represent less than 10% of the sediment on reefs that border the islands of the Abrolhos Archipelago (Leão and Kikuchi, 1995). The siliciclastic muds that accumulate in the depressions in the inter-reef zones are predominately kaolinite and illite. According to Leão and Kikuchi (1995), this siliciclastic sediment comes from two principal sources: (i) relic sediments that eroded from the Tertiary deposits of the Barreiras Group and accumulated on the shelf during the pre-Holocene regression and (ii) sediments that were deposited by rivers and subsequently transported along the coast during the Holocene.

The carbonate sediments consist of bio-detritus with calcium carbonate concentrations >50%. The highest concentrations of carbonate sediments occur adjacent to the reefs. For example, the calcium carbonate concentration reaches 100% (Leão, 1982) along the coral reefs of the external arc of Abrolhos. Carbonate sediments also cover a large part of the middle and outer shelf and part of the inner shelf extending very close to the coastline, where coastal coral reefs and algae are found (Leão and Brichta, 1995). Several studies attribute these carbonates to *in situ* production by the reef fauna and flora (Leão and Kikuchi, 1995; Leão and others, 2006). In the area of the Abrolhos Bank, sand and gravel consist of fragments of encrusting coralline algae (Leão and Brichta, 1995), predominantly produced by mechanical erosion (Leão and Kikuchi, 1995).

The climate in this part of the Bahia coast is humid tropical; average air temperatures vary between 24°C in winter and 27°C in summer. The temperature in the coldest month (July) reaches on average 22°C; the summers are long and hot with average temperatures above 24°C (Köppen in SEI, 1998). Precipitation varies between 1,500 and 3,000 mm/yr; the annual average in the coastal region adjacent to the Abrolhos area is 1,750 mm/yr. The rainiest months are March, April and May, when 37% (612 mm) of the annual precipitation falls (Nimer, 1989). The average monthly surface water temperature varies between 24.5°C in August and 27.5°C in March, with bottom water only 2°C lower in the deeper depths of the bank. Salinity varies between 36.5–36.7 psu (Leão and Machado, 1989).

Trade winds influence this section of the Brazilian coast from two principal directions: northeast and east during spring and summer (October to March) and southeast during the fall and winter (April to September; Nimer, 1989). Strong south winds can occur during the episodic arrival of cold fronts between May and August.

Although systematic measurements of the wave regime for this region are not available, Bittencourt and others (2000) constructed general wave refraction patterns for the coast of the State of Bahia, reporting that prevailing wave directions coincide with the wind regime: (i) wave-fronts from the northeast and east occur during spring and summer, and (ii) wave-fronts from the southeast and southwest coincide with fall and winter. The waves that come from the northeast and east promote a coastal drift from north to south, whereas the southeast and southwest waves promote a coastal drift from south to north (Bittencourt and others, 2000). However, it is important to point to out that the coral reefs strongly influence sediment dispersal patterns in the study area. These reefs reduce and modify wave action in the coastal areas behind them, producing deviations in the direction of the wave fronts and creating wave shadow zones (Martin and others, 1999 in Leão and others, 2006).

The principal ocean current in this region of the continental shelf is the Brazil Current, which is derived from the southern branch of the Equatorial Current. Warm, saline, nutrient-poor waters that flow south characterize the Brazil Current; the current's influence extends from the surface to depths of approximately 400 m (Muller and others, 1998). Locally, this current is influenced by tidal currents, the amplitude of which are approximately 2.5 m in the channels between the reefs and have velocities of up to 1.54 m/sec (Leão and Machado, 1989). Thus, water circulation and hydrodynamic conditions in this section of the Brazilian coast are complex due to the interactions between surface waves, internal waves, waves generated by the local winds, tidal currents and interactions between ocean currents and eddies that break away from them (Dominguez, 2000).

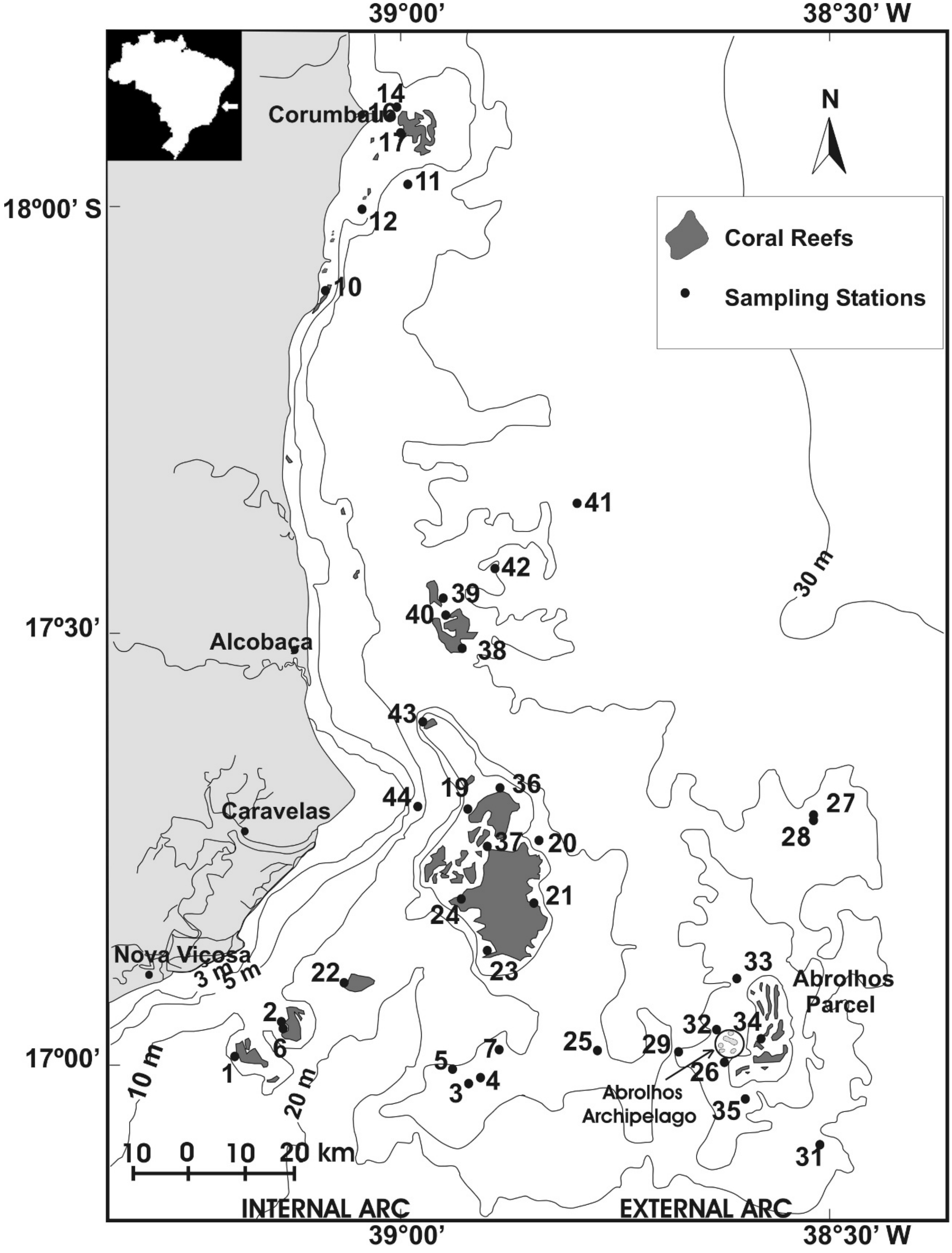

FIGURE 1. Location map of sampling stations in the inter-reef areas studied. The inset in the upper left shows the location relative to the Brazil coastline (modified from Leão and others, 2006).

MATERIALS AND METHODS

The samples for this study were furnished by Professor Zelinda M. A. N. Leão of the Federal University of Bahia and collected during an expedition organized by the Conservation International of Brazil as part of the Abrolhos Bank evaluation program. In November and December 2000, 68 samples of bottom surficial sediments were collected from the vicinity of reefs that extend from the coastline to the 30-m isobath between the cities of Corumbau and Nova Viçosa. Each sample was collected from the top 5 cm of sediment. At the time of sample collection, depths were determined for all stations. From those 68 samples, only 38 were selected for this study (Fig. 1) because at many of the reefs, two or three samples were collected in very close proximity to the others.

Divers using scuba equipment collected samples from as close as possible to the base of the reefs at depths ranging from 1.8–27 m (Table 1). The locations were determined using GPS. At each station, an average of 400 grams of sediment was collected for textural analysis, carbonate content analysis and determination of biogenic components, including foraminifera. Bottom-water temperature was not measured at all the stations, but at those where it was measured, it varied from 23.0–27.8°C.

In the Geosciences Coastal Studies Institute Laboratory of the Federal University of Bahia, samples were wet sieved over screens with 0.062 mm openings to remove salts and the mud fraction. After washing, subsampling was carried out so that approximately two-thirds of the total weight of the sample was used for textural analysis, study of sediment composition and carbonate content (Leão and others, 2006). The data obtained from the textural analysis were grouped as gravel (>2 mm), sand (2–0.062 mm) and mud (<0.062 mm). The remaining third of each sample was provided for foraminiferal analysis.

The first 300 foraminifera (benthic and planktonic) found in each sample were isolated using a stereoscopic microscope and stored on Franke slides. For the determination of foraminiferal diversity, due to the large quantity of material, the samples were quartered when necessary. The foraminifera removed from each sample were identified to species, when possible, based principally on the studies of Andrade (1997), Barker (1960), Bock (1971), Boltovskoy and others (1980), Closs and Barberena (1960), Leipnitz (1991), Leipnitz and others (1992), Levy and others (1995), Machado (1991) Rossi (1999) and Tinoco (1955, 1958). Based on the number of individuals per species and following the methodology proposed by Dajoz (1983), Tinoco (1989), Clarke and Warwick (1994) and Valentin (2000), the following indices were calculated: (i) relative frequency (F), the ratio between the number of individuals of a species (n) and the total number of individuals of the sample (T), where $F = n \times 100/T$, and (ii) frequency of occurrence (FO), the ratio between the number of samples in which the species occurred (p) and the total number of samples analyzed (P), where $FO = p \times 100/P$. The FO values are classified, in accordance with Dajoz (1983), into three groups: consistent (occurrence >50%), accessory (49–25%) and incidental (<24%). The indices of Shannon diversity (1948), Margalef richness (1958) and Pielou equitability (1984) were also calculated. To emphasize assemblages of foraminiferal species that occur in the study area, an analysis of similarity was made. R- and Q-mode cluster analyses were applied using the Bray-Curtis Index and the unweighted pair-group method of amalgamation (UPGMA) applied to the species considered consistently present in the area under study (Table 2).

The species considered consistent were digitally imaged at the Biostratigraphy and Paleoecology Laboratory of CENPES–PETROBRAS in Rio de Janeiro. During the process, the specimens were coated with gold using a metallizer EDWARDS SCANCOAR SIX and imaged by secondary electrons in a ZEISS DSM-940[A] scanning electron microscope, operated at 20 KV, with a working distance of 32 mm.

TABLE 1. Station numbers and percentages of gravel, sand and mud.

Stations	Gravel (%)	Sand (%)	Mud (%)
#1	12.73	76.36	10.91
#2	0.05	82.44	17.51
#3	4.79	48.22	46.99
#4	1.12	21.10	77.78
#5	0.74	16.05	83.21
#6	0.19	47.38	52.43
#7	5.88	31.88	62.24
#10	15.11	61.36	23.53
#11	13.28	78.25	8.47
#12	0.06	75.88	24.06
#14	7.00	48.95	44.05
#16	27.34	45.60	27.06
#17	0.18	4.62	95.20
#19	27.88	71.77	0.35
#20	2.15	56.06	41.79
#21	7.05	58.12	34.83
#22	3.59	95.83	0.58
#23	0.11	21.86	78.03
#24	6.89	90.44	2.67
#25	36.49	60.92	2.59
#26	47.78	49.28	2.94
#27	66.69	31.64	1.67
#28	17.62	72.97	9.41
#29	49.31	50.29	0.40
#31	13.88	80.26	5.86
#32	3.89	95.76	0.35
#33	1.06	71.38	27.56
#34	9.63	14.89	75.48
#35	0.22	26.41	73.37
#36	5.98	35.46	58.56
#37	8.42	69.41	22.17
#38	1.25	11.42	87.33
#39	1.92	45.89	52.19
#40	0.04	8.95	91.01
#41	38.69	40.62	20.69
#42	5.72	74.06	20.22
#43	2.30	41.41	56.29
#44	0.00	36.60	63.40

RESULTS

ENVIRONMENTAL AND SEDIMENTOLOGICAL VARIABLES

The samples were predominantly composed of sands and muds (Fig. 2). The sand fraction was represented at all stations, with >50% sand-sized sediments present in nearly half of the samples (Table 1). The mud fraction was also

TABLE 2. For consistent species (frequency of occurrence greater than 50%): sample number, frequency of occurrence, absolute abundance and relative abundance.

Species	Sample number	Frequency of occurrence	Absolute abundance	Relative abundance
Ammonia beccarii	23	60.53	475	5.23
Amphistegina gibbosa	23	60.53	136	1.50
Amphistegina lessonii	31	81.58	414	4.56
Archaias angulatus	27	71.05	1565	17.25
Discorbis floridana	24	63.16	69	0.76
Discorbis mira	26	68.42	100	1.10
Elphidium discoidale	28	73.68	287	3.16
Elphidium poeyanum	29	76.32	560	6.17
Elphidium sagrum	23	60.53	75	0.83
Eponides repandus	23	60.53	172	1.90
Heterostegina depressa	21	55.26	81	0.89
Peneroplis bradyi	16	50.00	93	1.02
Peneroplis carinatus	25	65.79	320	3.53
Peneroplis proteus	21	55.26	105	1.16
Pyrgo bulloides	31	81.58	270	2.98
Pyrgo elongata	31	81.58	192	2.12
Pyrgo subsphaerica	34	89.47	375	4.13
Quinqueloculina angulata	27	71.05	281	3.10
Quinqueloculina bicornis	28	73.68	93	1.02
Quinqueloculina bicostata	23	60.53	167	1.84
Quinqueloculina candeiana	29	76.32	253	2.79
Quinqueloculina disparilis curta	35	92.11	606	6.68
Quinqueloculina lamarckiana	37	97.37	914	10.07
Quinqueloculina parkeri	24	63.16	188	2.07
Quinqueloculina polygona	36	94.74	373	4.11
Sorites marginalis	28	73.68	321	3.54
Spiroloculina antillarum	24	63.16	83	0.91
Spiroloculina caduca	20	52.63	84	0.93
Spiroloculina estebani	22	57.89	53	0.58
Textularia agglutinans	22	57.89	70	0.77
Triloculina bicarinata	24	63.16	66	0.73
Triloculina trigonula	26	68.42	184	2.03

present at all stations, 14 of which were >50% mud (Table 1). The gravel fraction was present in percentages >30% in only five samples (Table 1).

Bioclastic sediments were present in amounts below 80% in only seven samples (Table 3). Among the bioclastic constituents were shells and skeletal debris of coralline red algae, mollusks, *Halimeda*, foraminifera, bryozoa, echinoderms, ostracods, coral and tube worms, as well as fragments and spicules of sponges and crustaceans. Among these components, only the particles of coralline algae, mollusks, *Halimeda*, foraminifera and bryozoa occurred in amounts greater than 5% in the samples. Quartz grains were the principal siliciclastic constituent: their concentrations were above 50% and were associated with smaller percentages of rock fragments and, more rarely, mica platelets and heavy minerals.

SPECIES COMPOSITION AND DISTRIBUTION OF FORAMINIFERA

In the 38 samples examined, 150 species were identified, representing 40 genera (38 benthic and 2 planktonic) distributed among the orders Miliolina, Rotaliina, Textulariina, Globigerinina and Lagenina. In the 38 samples, 11,400 specimens were identified, among which 11,345 were identified at the species level (Appendix 1). Of 150 species identified (Appendix 2), 32 species were classified as consistent (21% of the species), 27 as accessory (18% of species) and 91 as incidental (61% of species). Among the consistent species (Table 2), none occurred in all samples, although *Quinqueloculina lamarckiana* was found in 37 (97%) samples (Table 2).

Although the number of foraminifera analyzed was the same for all samples (300 specimens), the number of species identified per sample (Fig. 3A) varied between 18 (sample #24) and 62 (sample #38). The Margalef richness index, R (Margalef, 1958), obtained for each station was highest in sample #38 (R=10.7), followed by samples #16, 22, 23 and 20. These samples, in addition to having the most species among all samples, are characterized by small-sized foraminifera, notably the genera *Quinqueloculina* (especially *Q. lamarckiana*), *Ammonia* (*A. beccarii*) and *Pyrgo* (especially *P. elongata* and *P. subsphaerica*, among others). Station #24 presented the lowest richness index (R=2.98), followed by stations #19, #25, #33 and #6 (Fig. 3B). These stations were characterized by macroforaminifera (especially *Archaias angulatus*) as the most abundant species. Based on the Pielou equitability (J') calculation (Pielou, 1984), station #24 had the lowest index (J'=0.31), and 84% of the samples had an equitability >0.70 (Fig. 3B).

Diversity is an indication of both species richness and equitability. The Shannon-Wiener (H') index (Shannon, 1948) shows that the station with the greatest diversity is #38 (H'=3.58 bits/ind) with 62 species, followed by stations #23 (H'=3.40 bits/ind), #20 (H'=3.31 bits/ind), #1 (H'=3.28 bits/ind) and #17 (H'=3.24 bits/ind); whereas the least diverse were #24 (H'=0.91 bits/ind) and #19 (H'=1.63 bits/ind), with the number of species equal to 18 and 20, respectively (Fig. 3B).

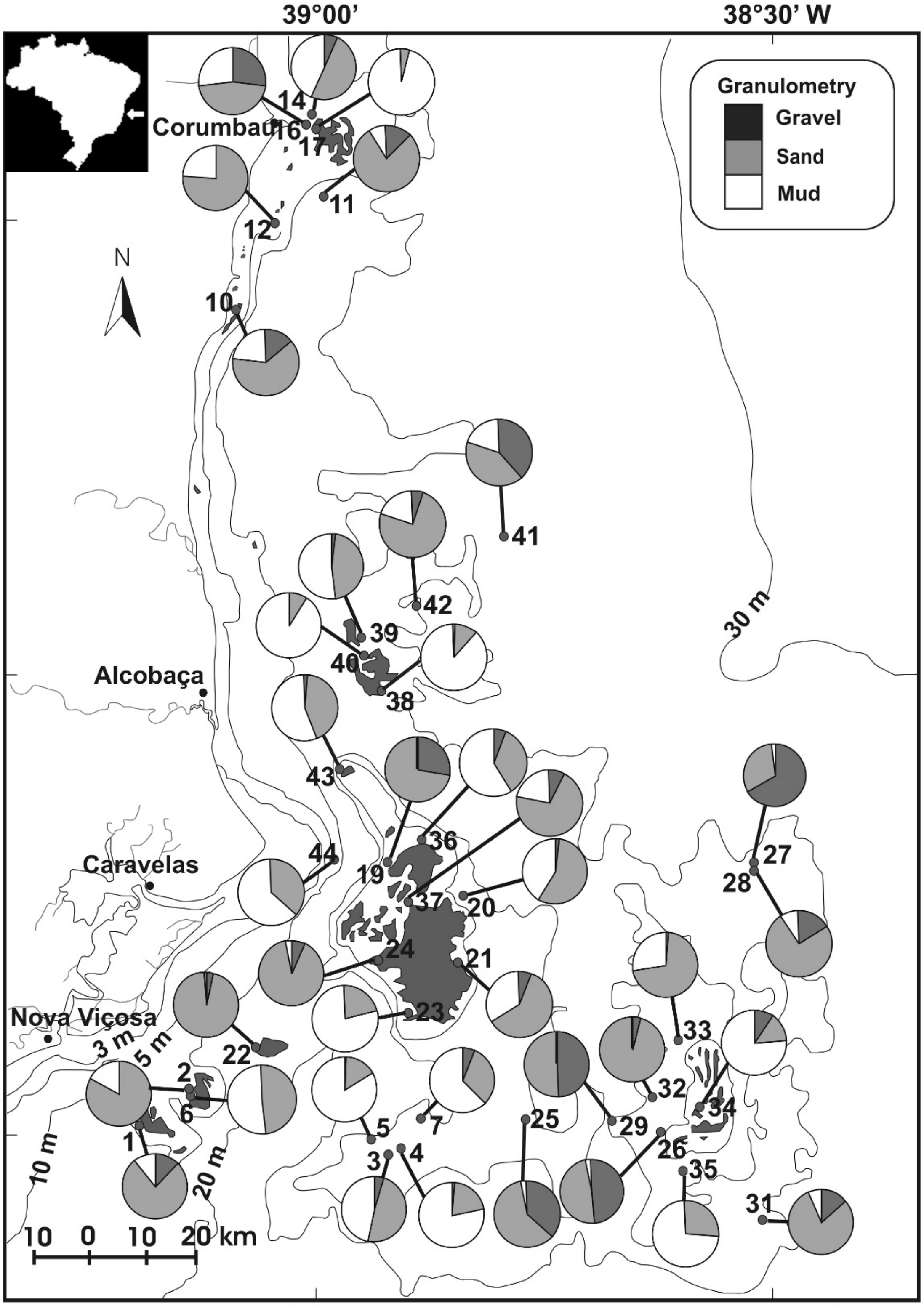

FIGURE 2. Sediment textures: gravel (>2 mm), sand (2–0.062 mm) and mud (<0.062 mm).

NUMERICAL CLASSIFICATION ANALYSIS

Sedimentological Associations

Based on the percentage data for gravel, sand and mud in each sample, a dendrogram, which shows the association of the samples through the Bray-Curtis dissimilarity coefficient, was constructed (Fig. 4). This dendrogram reveals two major groups (Group I and Group II) at a distance of 0.38. Groups I and II each are divided into two sub-groups at a distance of ~0.33; Group I is subdivided into

TABLE 3. Station numbers, depths of collection and percentages of bioclastic and siliciclastic components.

Stations	Depth (m)	Bioclastic (%)	Siliciclastic (%)
#1	9.0	33.49	66.51
#2	4.0	92.80	7.20
#3	21.0	93.78	6.22
#4	16.1	98.10	1.90
#5	26.0	93.14	6.86
#6	7.0	57.01	42.99
#7	20.0	90.54	9.46
#10	1.8	73.17	26.83
#11	13.0	98.77	1.23
#12	4.0	89.64	10.36
#14	6.0	100.00	0.00
#16	5.0	80.19	19.81
#17	4.5	100.00	0.00
#19	15.0	97.56	2.44
#20	20.5	74.90	25.10
#21	17.0	91.91	8.09
#22	4.0	90.99	9.01
#23	16.0	93.89	6.11
#24	5.0	98.18	1.82
#25	18.0	98.67	1.33
#26	18.0	96.08	3.92
#27	22.0	97.17	2.83
#28	22.5	94.79	5.21
#29	21.3	95.75	4.25
#31	18.3	100.00	0.00
#32	7.7	47.64	52.36
#33	16.6	97.73	2.27
#34	24.6	100.00	0.00
#35	27.0	99.04	0.96
#36	13.7	88.19	11.81
#37	13.2	99.12	0.88
#38	18.0	99.06	0.94
#39	15.6	98.36	1.64
#40	18.4	94.51	5.49
#41	25.8	97.61	2.39
#42	24.2	76.89	23.11
#43	5.6	85.27	14.73
#44	9.3	11.89	88.11

subgroups A and B at a distance of ~3.0, and Group II is subdivided into subgroups C and D also at a distance of ~3.0. Group I (Fig. 4) consists of samples of muddy sediments (mud >30%). All of the samples in subgroup A have mud percentages >70%. Subgroup B is composed of samples with a mud content between 30% and 70%. Group II consists of samples with a mud content below 30%. Subgroup C is formed by samples with the coarsest textures—specifically, with gravels >20% and sand <60%. Sub-group D consists of samples with gravel-size sediments <20% and sand >60%.

Fauna Associations

The dendrogram in figure 5 groups together the species considered consistent (occurrence frequency >50%) in the study area. Most striking is the clear separation of the species *Archaias angulatus* from the other groupings. Using 0.7 as the cut-off level of the Bray-Curtis dissimilarity index, three microfaunal assemblages can be distinguished: Assemblages I, II and III.

Assemblage I consists of 12 species: *Quinqueloculina bicostata*, *Textularia agglutinans*, *Triloculina bicarinata*, *Q. bicomis*, *Peneroplis proteus*, *P. bradyi*, *Elphidium sagrum*, *Discorbis mira*, *Spiroloculina caduca*, *Spiroloculina antillarum*, *Spiroloculina stebani* and *Discorbis floridana* (Fig. 5). These species do not appear to show any preference for the textural characteristics of the sediment and, in general, are found in abundance in samples of textural Groups I and II of figure 4.

Assemblage II consists of seven species: *Eponides* sp., *Quinqueloculina parkeri*, *Q. candeiana*, *Peneroplis carinatus*, *Amphistegina lessonii*, *Heterostegina depressa* and *A. gibbosa* (Fig. 5). This assemblage is made up of species that are most abundant in samples of textural Group II of figure 4, representing a mud content below 30%.

Assemblage III consists of 12 species: *Sorites marginalis*, *Pyrgo subsphaerica*, *P. bulloides*, *Quinqueloculina lamarckiana*, *Q. disparilis curta*, *Triloculina trigonula*, *Q. polygona*, *Q. angulata*, *P. elongata*, *Elphidium discoidale*, *E. poeyanum* and *Ammonia beccarii*. These species are found in greater abundance in samples from textural Group I of figure 4, specifically, those samples with a mud content higher than 30%.

DISCUSSION

In accordance with the results obtained by the textural and compositional analyses of the sediments, it is possible to see the great influence of reefs upon the characteristics and distribution of bottom sediments. Leão (1999) refers to the role of reef organisms in the production of carbonate sediment in the Abrolhos region. Biological production, in addition to the transport and reworking of siliciclastic sediments, are processes responsible for gradation of sedimentary facies from those dominated by siliciclastic constituents in the coastal zone to those dominated by carbonate reef sediments outward from the coast. According to Leão, there are three distinct types of sediments in this section of the Brazilian platform: (i) quartz sands along the coast; (ii) biogenic material in the reef areas, and (iii) mixed sediments in the intermediate area between the coastal reef and external arcs.

The sedimentological data used in the present study, which are based on analyses reported by Leão and others (2006), do not provide evidence for high concentrations of siliciclastic material even in the reefs closest to the coastline, with the exception of sample #44. This distribution can be explained by two factors. The first is the existence of an insignificant supply of soil material to the coastal arc of reefs during the dry period, according to Leipe and others (1999), who note the restriction of soil sediments to the Caravelas channel, which is situated between the coast and the coastal reefs. These authors note two types of mechanisms that block the transport of siliciclastic material outward from the coast: (i) the along-shore current to the south from the Caravelas channel resulting from the sum of the Brazil Current and low-tide currents, and (ii) the existence of the coastal arc reefs themselves, which impede the passage of coastal sediments offshore. The second factor is that the samples in the present study were collected close to the base of the reef structures, where the principal source of the sedimentary material originates from the skeletal breakdown of reef organisms (Leão and others, 2006).

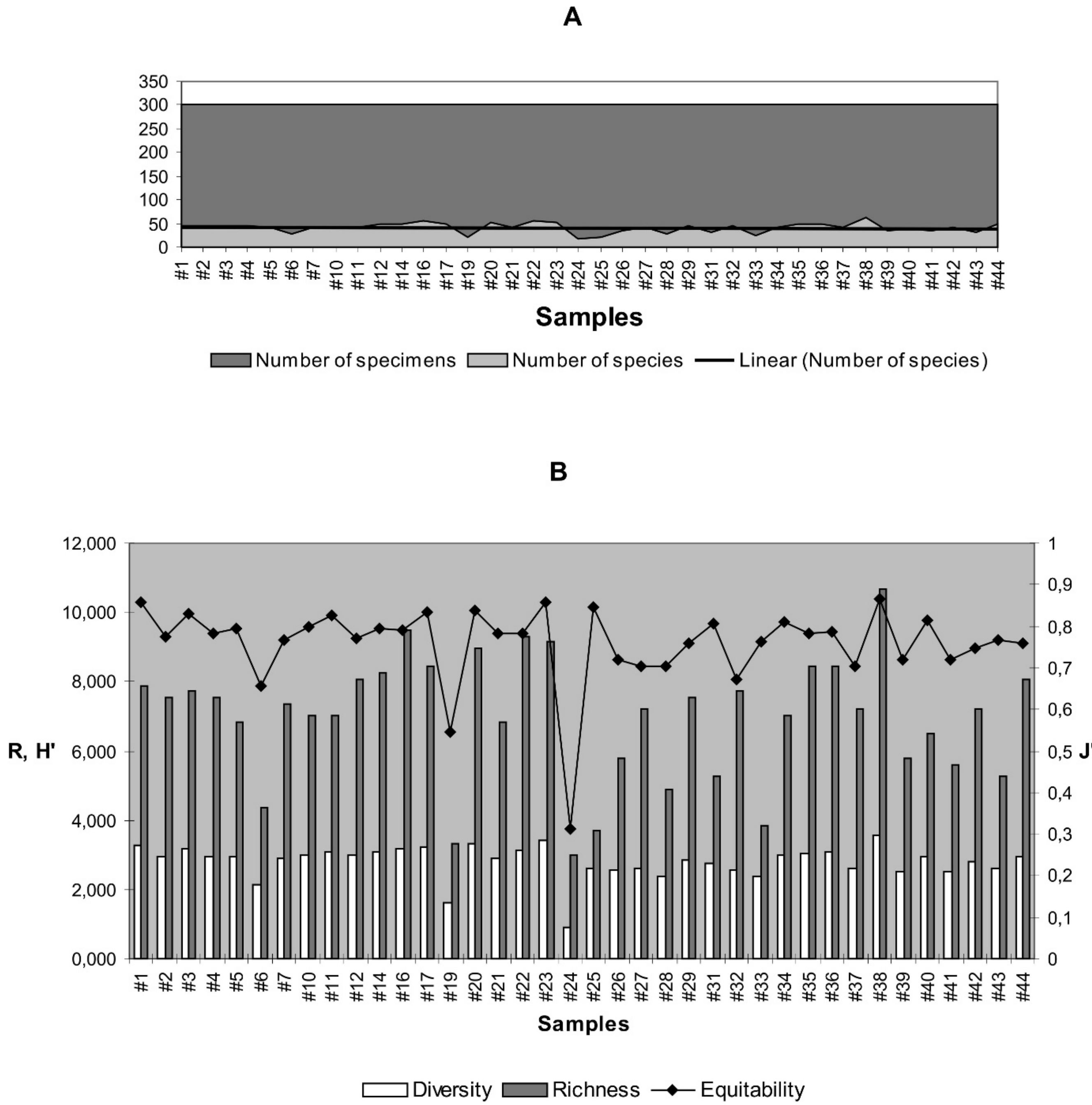

FIGURE 3. **A** Number of specimens and species at each sampling station. **B** diversity (H'), richness (R) and equitability (J') at each station.

The siliciclastic sediments are predominantly quartz grains associated with lower percentages of rock fragments and, more rarely, mica platelets and heavy minerals. Their sources are from sediments reworked from the Barreiras Group, which covers a great part of the continental zone and surfaces along the coast, as well as from river sediments that reach the reefs carried by currents of the coastal system (Leão and Ginsburg, 1997), primarily during the winter period when the volume of river flow is high and south and southeast waves are intense.

The bioclastic sediments are predominately skeletal in nature, made of both detrital material from the mechanical breakdown of reef structures and from biological erosion. Bioclastic sediments are largely grains produced *in situ* resulting from the fragmentation and/or deposition of the skeletons of organisms, which compose the biota associated with the reefs. Regarding textures of bioclasts, the gravel fraction predominates in areas more removed from the coast and consists mostly of rhodoliths. Sand-size bioclasts predominate throughout the study area, with no characteristic distribution pattern. Processes of mechanical action, resulting from wave action, can explain the dominance of the sand fraction. The protected reef zones, where wave action is practically absent, are exceptions. Similarly, the

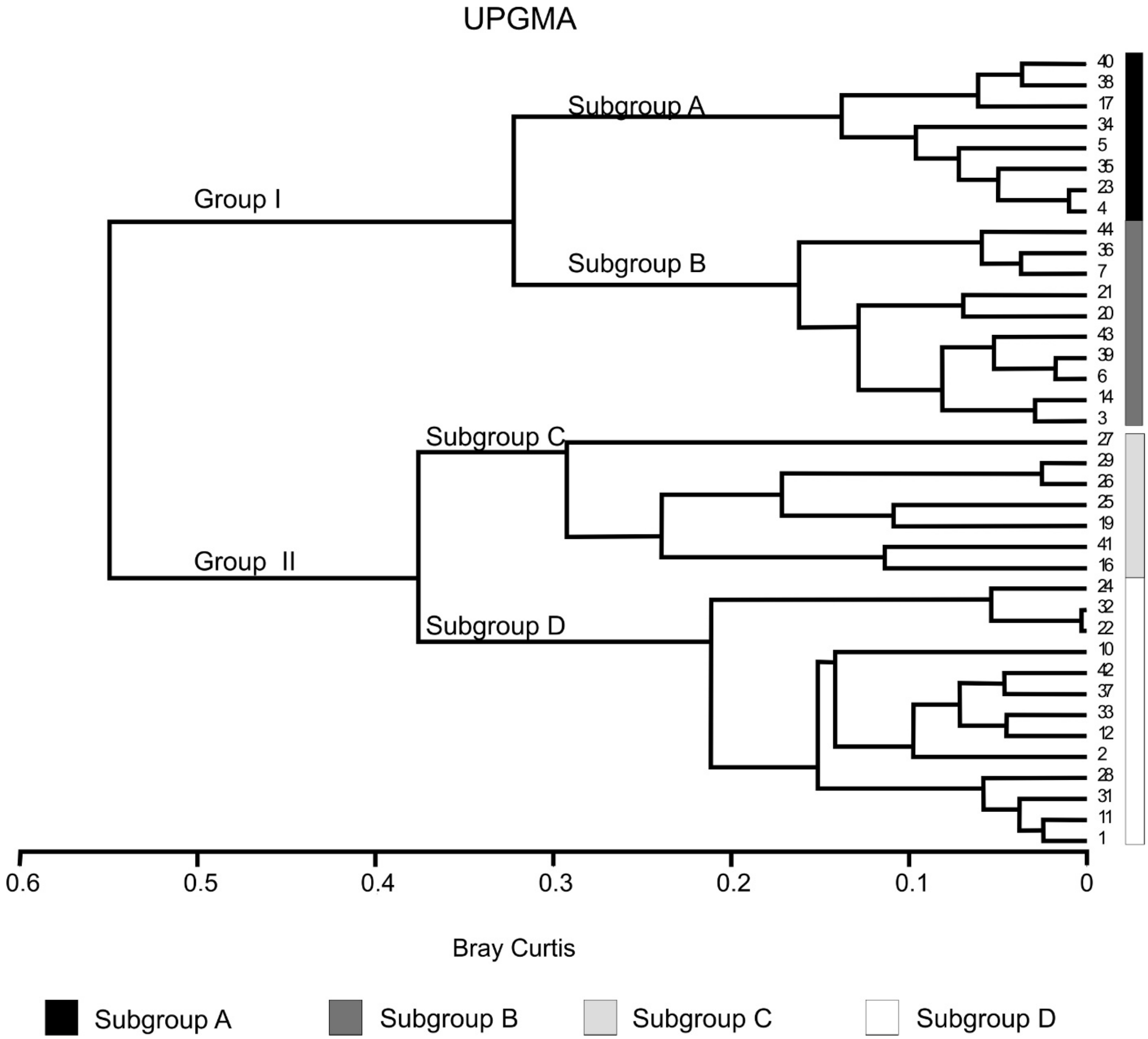

FIGURE 4. Dendrogram station groupings based on sedimentological data (percentages of gravel, sand and mud): **Group I** = mud >30% (Subgroup A = mud >70%, Subgroup B = mud 30–70%), **Group II** = mud <30% (Subgroup C = gravel >20%, and sand <60%; Subgroup D = gravel <20% and sand >60%).

mud fraction does not show any distinct distribution patterns. The occurrence of rather high percentages of mud of predominately biogenic origin can be explained by the sampling, which occurred very near the reef structures, a zone that presents innumerable inter-reef channels that serve as traps for muddy sediment.

The comparative analysis between the sedimentological characteristics described above and the foraminiferal fauna present in the study area shows that the relationships of these organisms with the sediment are well established. However, upon analysis of the spatial distribution of the fauna studied, it is noted that the heterogeneity of the fauna is much greater than the variability observed in the sediments, which varied mostly between sand and mixed quantities of carbonate sand and mud. Therefore, it is believed that although the granulometric characteristics and composition of the substrata exert a certain influence in the distribution of the populations, as already cited by some authors (Boltovskoy and Wright, 1976; Kitazato, 1988; Murray, 1991), there are other environmental variables that help explain the distribution observed for the fauna (i.e., hydrodynamic conditions, temperature, etc.).

None-the-less, the existing relationship between certain species abundant in the area and the texture and composition of the sediment are evident. As shown by the numerical classification analysis of the species, there is a strong correlation exemplified by the species *Amphistegina lessonii* and *Peneroplis carinatus*, which are more abundant in sandy carbonate sediments, whereas the species *Ammonia beccarii*, *Elphidium poeyanum*, *Pyrgo subsphaerica*, *Quin-*

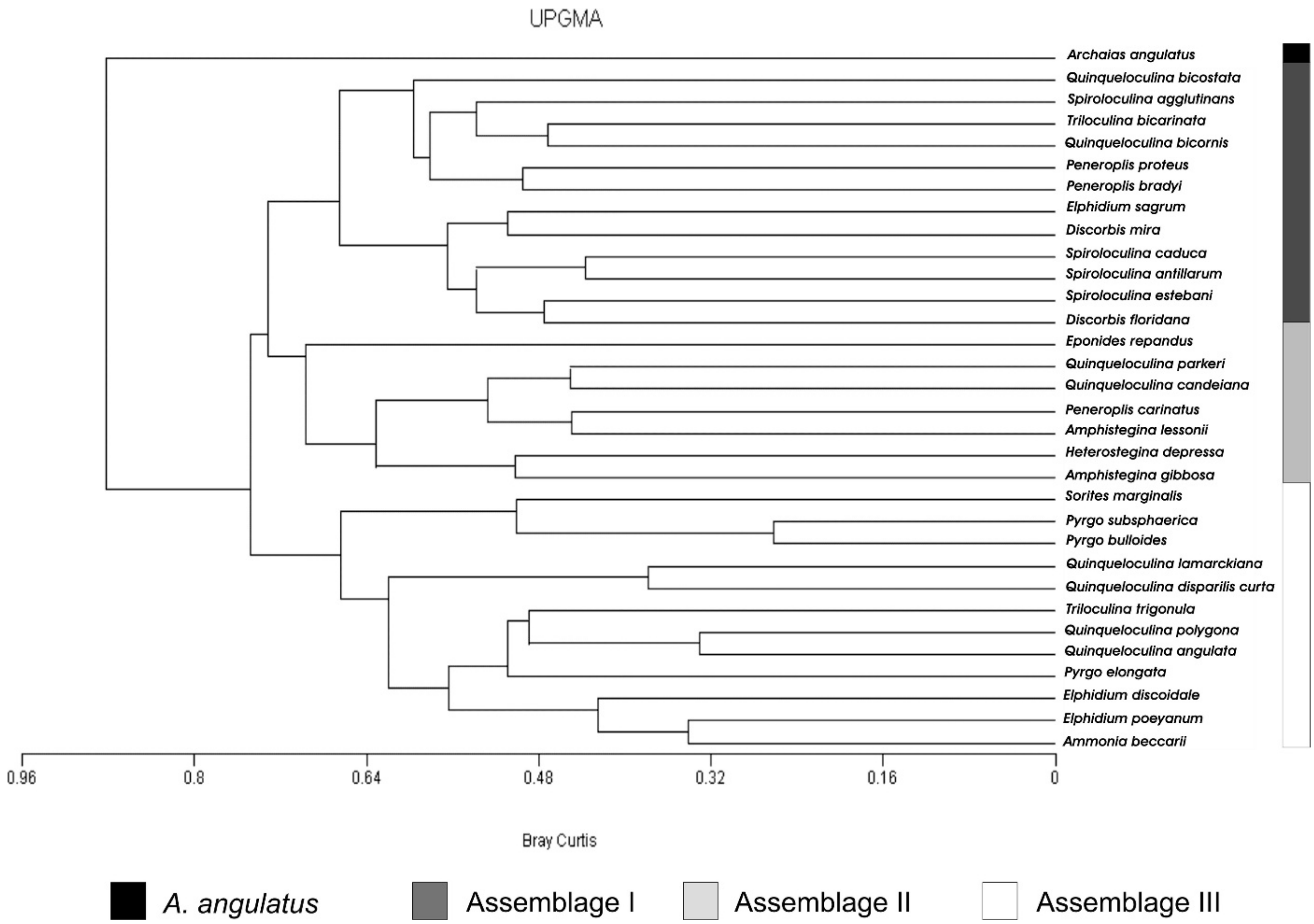

FIGURE 5. Dendrogram illustrating the species assemblages identified in the area studied.

queloculina disparilis curta and *Q. lamarckiana* are more abundant in sediments with mixed percentages of sand and mud composed of carbonate to mixed carbonate and siliciclastic material. Among other species, substrate preference is evident. For example, *Eponides repandus*, *Quinqueloculina parkeri*, *Q. candeiana*, *Heterostegina depressa* and *Amphistegina gibbosa* are found in higher abundance in samples with low mud content. However, these species were also found in lower abundance in samples in which the mud content exceeded 30%. The same was observed among the species *Archaias angulatus*, *Pyrgo bulloides*, *P. elongata*, *Triloculina trigonula*, *Quinqueloculina polygona*, *Q. angulata* and *Elphidium discoidale*, all of which were found in higher percentages in samples with mud contents above 30% but were also present in samples with low mud content. Thus, other factors besides sediment texture influence the distribution of these species.

Leão (1982) analyzed the distribution of the principal groups of foraminifera along a transect perpendicular to the coast, from the beach zone to the external reefs in the Abrolhos region. A comparison of Leão's results with ours reveals the similarities and differences in the distribution of the species related to the distribution of the sediments. In both studies, the species *Ammonia beccarii* and *Elphidium poeyanum* were found preferentially in areas proximal to the coast. Leão also found these species in greater abundance in the areas rich in siliciclastic sediments, whereas, in the present study, the same species were abundant in carbonate areas.

According to Murray (1991), some calcareous taxa, such as the genera *Ammonia*, *Elphidium* and *Nonion*, are tolerant to conditions of reduced salinity. Although we have no data on salinity for the stations sampled, it is possible that there is a reduction in salinity in the area influenced by the river estuary, which could explain the presence of *Ammonia beccarii* in these areas.

As in Leão (1982), this study shows that *Amphistegina* occurs predominately in the carbonate sediments of the external reefs, whereas *Archaias angulatus* occurs in both mixed (siliciclastic and carbonate) and carbonate sediments. Leão (1982) reported that *A. angulatus* showed a preference for external reef areas, whereas we found this species in both the coastal and external reefs. According to Cottey and Hallock (1988), *Archaias angulatus* lives most abundantly in shallow-water environments of relatively low energy. In general, numerous studies have shown that tests of this species occur commonly in back-reef, reef-flat and fore-reef sediments.

Based on the frequency of occurrence (FO) analysis of the 150 species encountered, 32 are considered as consistent, 27 as accessories and 91 as incidental. Among the consistent species, *Quinqueloculina lamarckiana*, *Q. polygona*, *Q. disparilis curta* and *Pyrgo subsphaerica* deserve emphasis

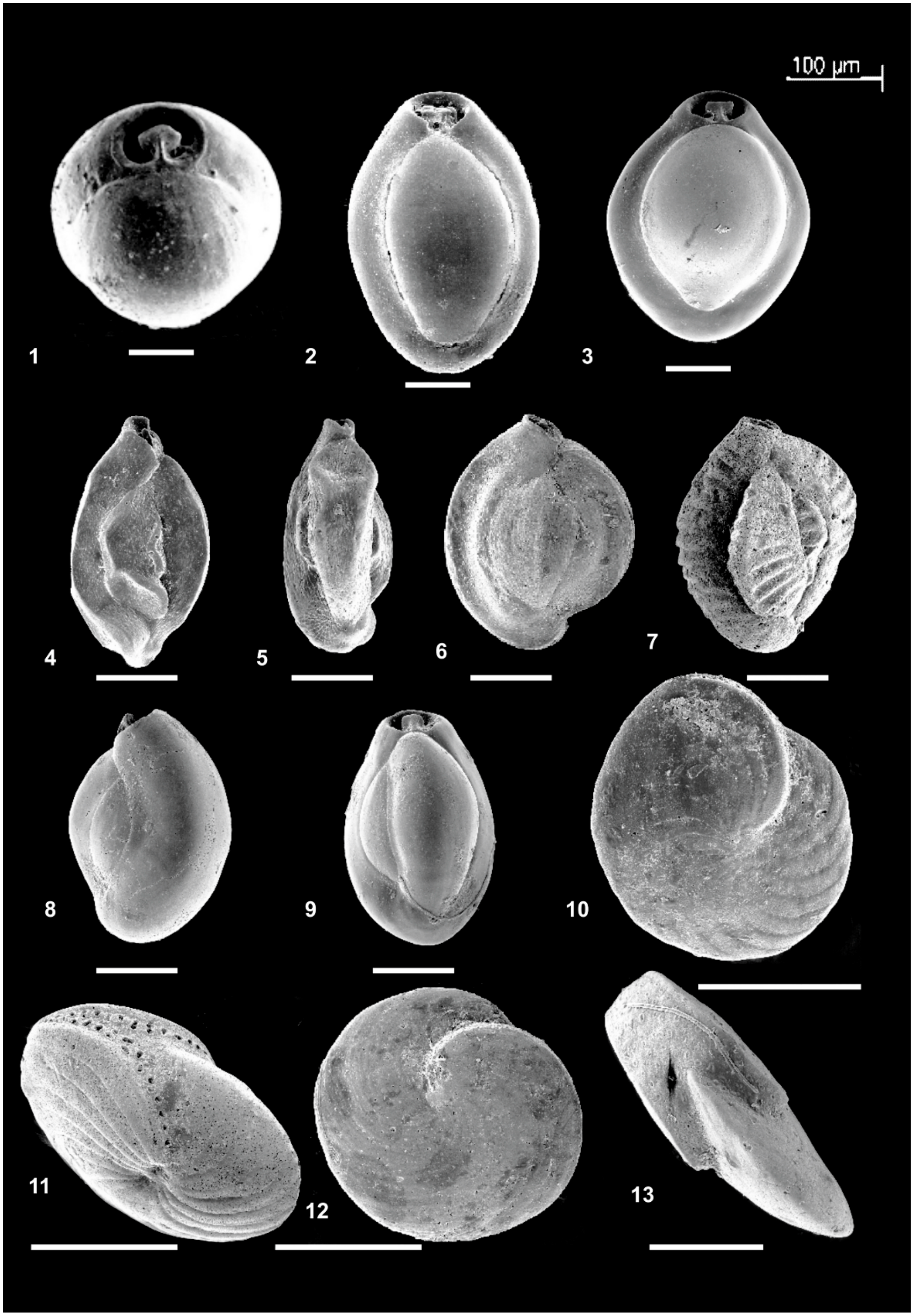

PLATE 1

1 *Pyrgo bulloides* (d'Orbigny). **2** *Pyrgo elongata* (d'Orbigny). **3** *Pyrgo subsphaerica* (d'Orbigny). **4**, **5** *Quinqueloculina angulata* (Williamson). **6** *Quinqueloculina disparilis curta* (Cushman). **7** *Quinqueloculina parkeri* (Brady). **8**, **9** *Triloculina trigonula* (Lamarck). **10**, **11** *Peneroplis carinatus* d'Orbigny. **12**, **13** *Archaias angulatus* (Fichtel and Moll).

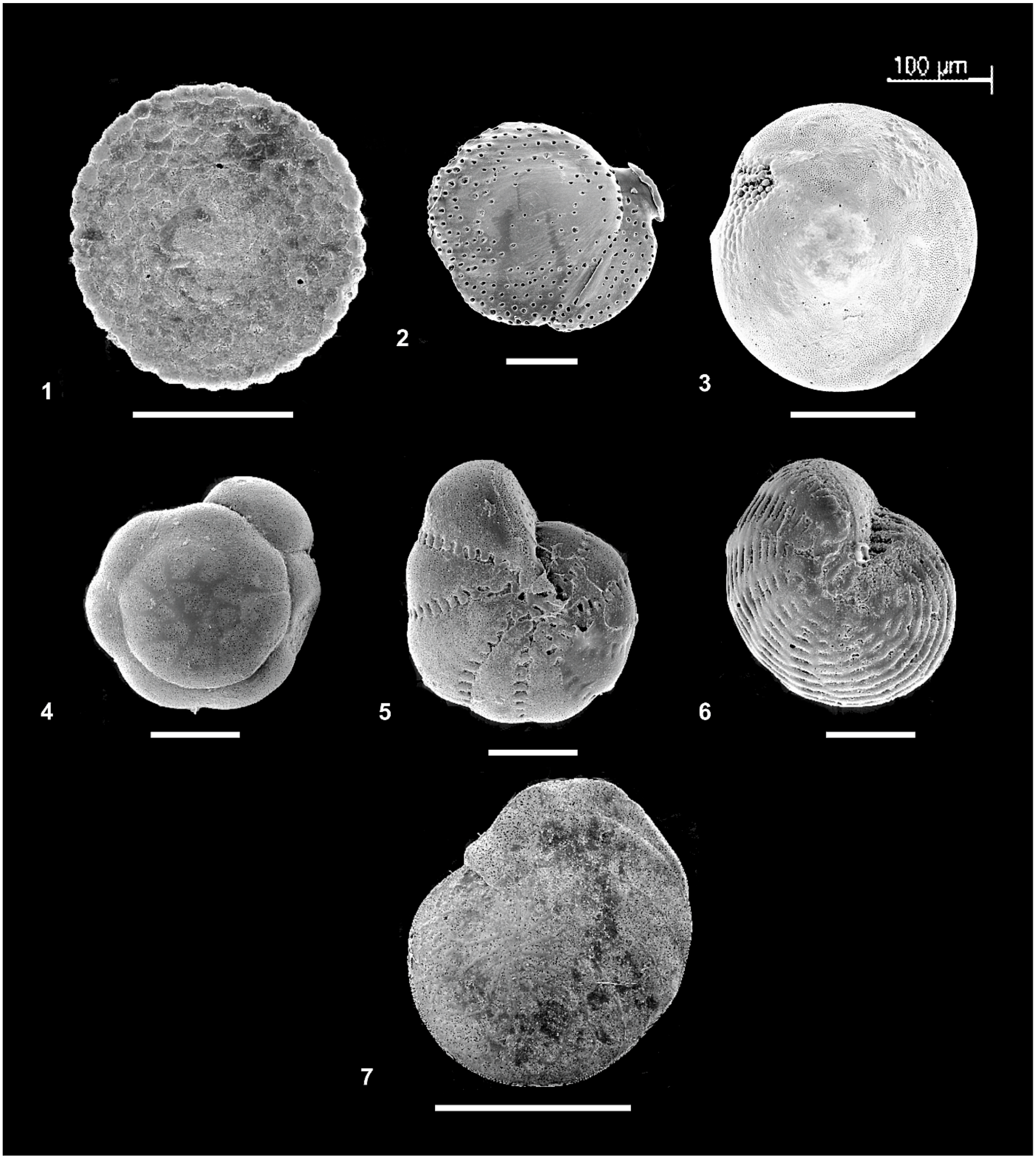

PLATE 2
1 *Sorites marginalis* (Lamarck). **2** *Siphonina pulchra* (Cushman). **3** *Amphistegina lessonii* (d'Orbigny). **4** *Ammonia beccarii* (Linnaeus). **5** *Elphidium poeyanum* (d'Orbigny). **6** *Elphidium sagrum* (d'Orbigny). **7** *Heterostegina depressa* (d'Orbigny).

for being present in 37, 36, 35 and 34 samples, respectively, out of the 38 samples analyzed. Considering the agitated state of the waters in reef environments, the high frequency of occurrence of these species could be attributed to the morphological characteristic of their tests. According to Thomas and Schafer (1982), species with more robust tests are more resistant to breakage and tend to have broader distributions than more fragile forms. The fragile condition of the tests of many species could, consequently, explain the great number of incidental species found in the present study.

Most of the species encountered in this study are common in the tropical Atlantic Ocean (e.g., Buzas and Culver, 1982, and references therein; Larsen, 1982; Martin and Liddell, 1988). Similarly, most have previously been reported in various studies carried out in Brazilian coastal environments and in oceanic islands of the South Atlantic Ocean, by Narchi (1965), Ribas (1966), Tinoco (1966), Leão (1982), Machado and Souza (1994), Leipnitz and others (1996), Andrade and others (1996), Machado (1995), Sanches and others (1995), Machado and others (1999), Machado (2000) and Moraes (2001), among others. However, the specific diversity found in this study can be considered high (150 species and 39 genera), if compared to that observed by other authors for Bahia reef environments. For example, Brady and others (1888) described 124 species of foraminifera from the Abrolhos Archipelago; Sanches and others (1995) identified 91 species for the same area; and Moraes (2001) found 78 species for the reefs of Praia do Forte and Itacimirim, the north coast of the State of Bahia. In a previous study of the reef area of Praia do Forte, Machado and others (1999) noted the presence of 27 genera of Foraminifera. However, the greater diversity observed in this study could be related to the manner of sampling, including an extensive area with different conditions, and to the greater number of samples collected. The indices of diversity found in this study varied greatly among stations, as the number of species ranged between 18 and 62 (Shannon-Wiener diversity indices of 0.90 and 3.57, respectively). This variability could be due to the patchy distribution of living foraminifers combined with the hydrodynamic sorting of the tests, as indicated by the association of the more diverse assemblages with sediments with substantial mud fractions.

Sample #38 (Fig. 2), with the largest number of species, occurred in the most mud-rich sample (87% mud), which was 99% carbonate. This composition was clearly favorable for miliolids, which constituted 73% of the foraminifers in the sample. High diversity indices were found in similar sediments, indicating a relationship between the muddy sediments and the diversity observed in this area. Ferreira (1977) postulated a relationship between the texture and both abundance and diversity of associated foraminifera, emphasizing the existence of a depleted fauna in coarse-grained samples, which retain much less organic matter. Furthermore, since we were examining the thanatocoenosis (total assemblage of foraminiferal tests, both living and dead at the time of collection), simple hydraulic sorting undoubtedly removed smaller tests and thereby reduced both abundance and diversity.

The values based on the Margalef (R) Richness Index calculation also showed variable species richness for the area. The highest value for this index was found in sample #38, whereas the lowest value corresponds to sample #24. These results were expected, since richness is a function of the number of species and specific diversity. The existence of low richness values for some samples supports the idea of the existence of unfavorable microenvironments in the area. The significant abundance of macroforaminifera in the areas of low foraminiferal richness (index below 4.00) supports the assumption that hydrodynamic sorting occurs at some stations.

CONCLUSIONS

Foraminifera in the inter-reef areas of the extreme south of the State of Bahia (between Corumbau and Nova Viçosa) include *Archaias angulatus* and *Quinqueloculina lamarckiana* as the most abundant species, when present, and *Quinqueloculina lamarckiana*, *Q. polygona*, *Q. disparilis curta* and *Pyrgo subsphaerica*, as the most common species.

Through the integration of data on the foraminiferal fauna, sediment texture and composition, and sample depth, we conclude that environmental variables other than those analyzed influence fauna distribution. Water dynamics and organic matter content are of possible importance.

The specific diversity is considered high, but variable among the samples. Finer sediments ($<$2 mm) exhibit higher-diversity foraminiferal assemblages, while the coarser sediments ($>$2 mm) contain lower diversities and are dominated by macroforaminifera. Diversity and depth are directly related; higher diversities were found in samples collected from depths greater than 13 m. Hydrodynamic sorting, which removes organic matter and smaller tests, is likely a major contributing factor in species diversity and richness.

ACKNOWLEDGMENTS

The authors are deeply indebted to Dr. Pamela Hallock for her insightful suggestions, which greatly improved the manuscript. The authors received Research Scholarship grants from CNPq (National Council for Scientific and Technological Development).

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Received 15 February 2006
Accepted 18 September 2007

APPENDIX 1

Absolute frequency (AF) and relative frequency (RF) of foraminiferal species in the samples. The table can be found on-line at the JFR Article Data Repository at http://www.cushmanfoundation.org/jfr/index.html, item number JFR DR200801.

APPENDIX 2

Faunal reference list: Alphabetical listing of original references to the taxa identified to the species level in this study.

Ammonia beccarii (Linnaeus): *Nautilus beccarii* Linnaeus, 1758, p. 710.

Amphistegina gibbosa d'Orbigny: *Amphistegina gibbosa* d'Orbigny, 1839, p. 120, pl. 8, figs. 1–3.

Amphistegina lessonii d'Orbigny: *Amphistegina lessonii* d'Orbigny, 1826, p. 304, pl. 17, figs. 1–4.

Archaias angulatus (Fichtel and Moll): *Nautilus angulatus* Fichtel and Moll, 1803, p. 113, pl. 22, fig. a–c.

Discorbis floridanus Cushman: *Discorbis floridana* Cushman, 1922, p. 39, pl. 5, figs. 11–12.

Discorbis mira Cushman: *Discorbis mira* Cushman, 1922, p. 39, pl. 6, figs. 10–11.

Elphidium discoidale (d'Orbigny): *Polystomella discoidalis* d'Orbigny, 1839, p. 56, pl. 6, figs. 23–24.

Elphidium poeyanum (d'Orbigny): *Polystomella poeyana* d'Orbigny, 1839, p. 55, pl. 6, figs. 25–26.

Elphidium sagrum (d'Orbigny): *Polystomella sagra* d'Orbigny, 1839, p. 55, pl. 6, figs. 19, 20.

Eponides repandus (Fichtel and Moll): *Nautilus repandus* Fichtel and Moll, 1798, p. 35, pl. 3, figs. a–d.

Heterostegina depressa d'Orbigny: *Heterostegina depressa* d'Orbigny, 1826, p. 305, pl. 17, figs. 5–7.

Peneroplis bradyi Cushman: *Peneroplis bradyi* Cushman, 1930, p. 40, pl. 14, figs. 8–10.

Peneroplis carinatus d'Orbigny: *Peneroplis carinatus* d'Orbigny, 1839, p. 33, pl. 3, figs. 7, 8.

Peneroplis proteus d'Orbigny: *Peneroplis proteus* d'Orbigny, 1839, p. 60, pl. 7, figs. 7–11.

Pyrgo bulloides (d'Orbigny): *Biloculina bulloides* d'Orbigny, 1826, p. 297, pl. 16, figs. 1–4.

Pyrgo elongata (d'Orbigny): *Biloculina elongata* d'Orbigny, 1826, p. 298, figured in Parker, Jones and Brady, 1871, pl. 8, fig. 6.

Pyrgo subsphaerica (d'Orbigny): *Biloculina subsphaerica* d'Orbigny, 1839, p. 162, pl. 8, figs. 25–27.

Quinqueloculina angulata (Williamson): *Miliolina bicornis* var. *angulata* Williamson, 1858, p. 88, pl. 7, fig. 196.

Quinqueloculina bicornis (Walker and Jacob): *Serpula bicornis* Walker and Jacob, 1798, p. 633, pl. 14, fig. 2.

Quinqueloculina bicostata d'Orbigny: *Quinqueloculina bicostata* d'Orbigny, 1839, p. 195, pl. 12, figs. 8–10.

Quinqueloculina candeiana d'Orbigny: *Quinqueloculina candeiana* d'Orbigny, 1839, p. 199, pl. 12, figs. 24–26.

Quinqueloculina disparilis d'Orbigny var. *curta* Cushman: *Quinqueloculina disparilis* d'Orbigny var *curta* Cushman, 1917, p. 49, pl. 14, figs. 2a–c.

Quinqueloculina lamarckiana d'Orbigny: *Quinqueloculina lamarckiana* d'Orbigny, 1839, p. 189, pl. 11, figs. 14–15.

Quinqueloculina parkeri (Brady): *Miliolina parkeri* Brady, 1881, p. 46, figured in Brady, 1884, pl. 7, fig. 14.

Quinqueloculina polygona d'Orbigny:1839 *Quinqueloculina polygona* d'Orbigny, 1839, p. 198, pl. 12, figs. 21–23.

Sorites marginalis (Lamarck): *Orbulites marginalis* Lamarck, 1816, p. 196, no. 1.

Spiroloculina antillarum d'Orbigny: *Spiroloculina antillarum* d'Orbigny, 1839, p. 166, pl. 9, figs. 3–4.

Spiroloculina caduca Cushman: *Spiroloculina caduca* Cushman, 1922, p. 61, pl. 11, figs. 3–4.

Spiroloculina estebani Tinoco: *Spiroloculina estebani* Tinoco, 1958, p. 17, pl. 3, figs. a–d.

Textularia agglutinans d'Orbigny: *Textularia agglutinans* d'Orbigny, 1839, p. 136, pl. 1, figs. 17, 18, 32, 34.

Triloculina bicarinata d'Orbigny: *Triloculina bicarinata* d'Orbigny, 1839, p. 158, pl. 10, figs. 18–20.

Triloculina trigonula (Lamarck): *Miliolites trigonula* Lamarck, 1804, p. 351, pl. 17, fig. 4.