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Foraminiferal assemblages in Ubatuba Bay, south-eastern Brazilian coast

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SUMMARY: Live benthic foraminifera assemblages were studied in 40 surface sediment samples collected in the Ubatuba Bay (northern coast of São Paulo State) in order to investigate the relationship between the geological, physicochemical parameters and the ecological data. The area has significant contributions of terrestrial inputs from four rivers that flow into the bay. Biological data were analyzed with multivariate techniques of cluster analysis and a Principal Component Analysis (PCA) was carried out for abiotic factors. The Suborder Rotaliina was dominant in the whole studied area. The result of the cluster analysis allowed us to recognize three groups of stations corresponding to three foraminifera assemblages and different environment conditions. The PCA revealed approximately the same three groups obtained with the cluster analysis. A slight increase in diversity in the outer bay was measured. The inner environment is dominated by *A. tepida,* evidencing local instabilities. Infaunal species are distributed in the middle region associated with mud and a high content of organic matter, while the most external region has similar percentages of epifaunal and infaunal, which indicates the higher energy condition in this portion of the bay. We also quantified the abnormal specimens that were mainly present in the inner bay, especially represented by *A. tepida* specimens.

Keywords: live benthic foraminifera, surface sediment, Ubatuba, Brazil.

RESUMEN: Asociaciones de foraminíferos en la bahía de Ubatuba, sureste de la costa brasileña. – Fueron estudiadas las asociaciones de foraminíferos bentónicos vivos en 40 muestras de sedimento superficial colectadas en la Bahía de Ubatuba (costa noreste de São Paulo) con la intención de investigar la relación entre los parámetros geológicos, físico-químicos y los datos ecológicos. El área posee una importante contribución de origen terrestre a través de cuatro ríos que desembocan en la bahía. Los datos biológicos fueron analizados con técnicas multivariadas de análisis de agrupamiento y un Análisis de Componentes Principales (ACP) fue aplicado a los datos abióticos. El Suborden Rotaliina fue dominante en el área de estudio. El resultado del análisis de agrupamiento permitió reconocer tres grupos de estaciones que corresponden a tres asociaciones de foraminíferos representando las diferentes condiciones del ambiente. El ACP reveló aproximadamente los mismos tres grupos obtenidos con el análisis de agrupamiento. Fue medido un leve incremento de la diversidad hacia el exterior de la bahía. El ambiente más interno es dominado por *A. tepida* evidenciando la inestabilidad local. La porción media de la ensenada estuvo dominada por especies infaunales asociadas a las altas concentraciones de fango y materia orgánica, mientras que la región más externa presenta porcentajes similares de epifauna e infauna, indicando las condiciones de mayor energía prevalecientes en este sector. También fueron cuantificados los especimenes anormales los cuales estuvieron principalmente presentes en la parte más interna de la bahía representados especialmente por la especie *A. tepida*.

Palabras clave: foraminíferos bentónicos vivos, bentos, sedimentos superficiales, Ubatuba, Brasil.

INTRODUCTION

The paleoecological interpretation of fossil foraminiferal assemblages depends on understanding the ecological processes that presently operate and their relationship with the local hydrodynamic, physiographic characteristics and sedimentation patterns. Through this knowledge earth scientists may gain insights into the dynamics of spatial variations of biotic and abiotic parameters in the environment. Working with old sediments, it is possible to use this perception to reconstitute the geohistorical evolution of a given sedimentary basin.

Despite of the increment in the last decade of foraminiferal works on the Brazilian coast (see Debenay *et al.* (2001) and references therein), there has been a lack of works relating foraminiferal fauna and coastal sedimentation. During the 1990s, a complete study program of the Ubatuba region (south-eastern coast of Brazil) was initiated with the purpose of obtaining an overall view of the sedimentary processes and energy gradient of its enclosed bays. Many advances in the comprehension of these processes were obtained by Mahiques (1992, 1995) and Mahiques *et al.* (1998). They researched the modern sedimentation pattern in the Ubatuba coastal region by identifying the main mechanisms of input and remobilization of sediments, as well as the existence of an energy gradient acting over the area. Later, Burone *et al.* (2003) researched the origin and the spatial distribution of organic matter in Ubatuba Bay.

Another important aspect to consider is that the north coast of São Paulo State (especially Ubatuba Bay) is strongly affected by increasing tourism and urbanization. Due to its physiography, the water circulation and dispersion of exotic elements are restricted when compared with open sea areas. For this reason studying the benthic foraminifera and its response is a very important tool for understanding the environmental conditions of the ecosystem, and also for monitoring, conserving and restoring it.

Starting from the knowledge provided by these authors this work points towards identifying the present foraminiferal assemblages and assessing the relationship between the geological, physicochemical parameters and the ecological data. Thus, it provides a wider data basis that can be used for new paleoecological works.

MATERIAL AND METHODS

Study area

Ubatuba Bay is situated on the northern coast of São Paulo State - Brazil (23°25'S-23°27'S and 45°01'W-45°03'W) forming an area of approximately 8 km^2, varying from 4 to 16 m in depth (Fig. 1). It faces eastward and is protected from the

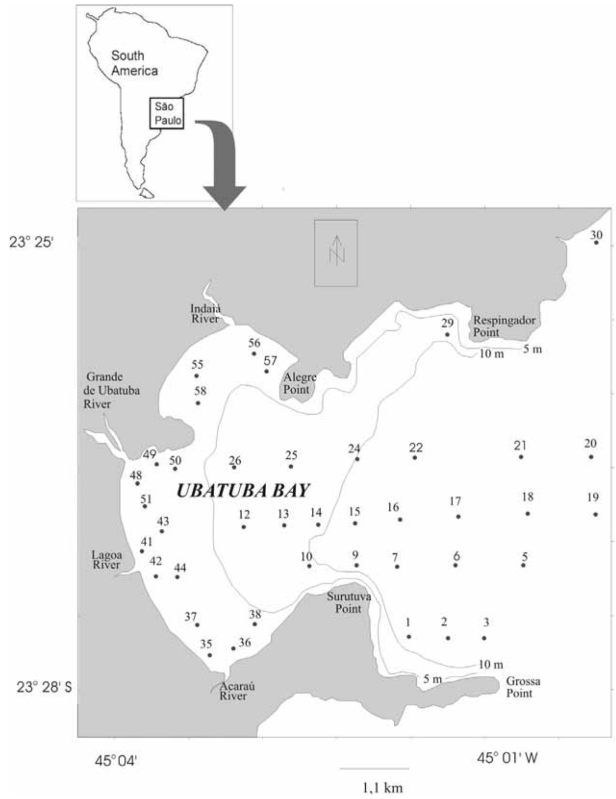

FIG. 1. – Map of the study area with the 40 sampling stations (black dots).

southerly and southwesterly waves arising from the open sea. It has an outlet between Ponta do Respingador and Ponta Grossa. In terms of depth, the bay may be divided into an inner and an outer part. The inner part extends from the coastline to 10 m deep, and is characterized by weak low hydrodynamic energy. The outer part lies between 10 and 16 m deep and is strongly influenced by currents and waves from the open sea.

The whole area is geologically characterized by the presence of granites and migmatites proceeding from the Serra do Mar mountain chain, which reaches the shore in this area of the coast (Mahiques *et al.*, 1998).

According to Mahiques (1995), Ubatuba Bay shows high heterogeneity in surface bottom sediments. Coarse grains are concentrated near the north and east rocky margins of Ponta Surutuva, whereas fine sediments are deposited in the northeast of Ponta Surutuva. The rest of the area is covered by coarse and medium silt. Water circulation is generally clockwise with inflow coming from the south. The terrestrial input of sediments is strongly dependent on the rainfall regime (Mahiques *et al.*, 1998), leading to a higher contribution during the summer season. Four rivers flow into the bay, namely Acaraú River, da Lagoa River, Grande de Ubatuba River and Indaiá River. As Ubatuba City is an important tourist town, its influence on the bay water quality is very high (CETESB, 1996, 2000; Abessa and Burone, 2003), especially during summer vacations (rainy periods) when large amounts of untreated sewage coming from the city are carried into the bay.

Data collection

A total of 40 sediment samples were collected during the austral summer of 1998 (February) using a Kajak-Brinkhurst corer sampler (with 10 cm diameter, it penetrates the sediment by gravity) on board the Research Vessel "Veliger II".

To study the living benthic foraminiferal fauna, the uppermost 3 cm of the core were taken off at each station forming a volume of about 230 cm^3 per sample. Immediately after sampling, the material was stained with buffered rose Bengal dye (1 g of rose Bengal in 1000 ml of distilled water) for 48 hours to differentiate between living and dead foraminifera (Walton, 1952). In the laboratory, the wet samples were carefully washed through 0.5 mm, 0.250 mm and 0.062 mm sieves to segregate the size fractions. After drying at 60°C the remaining portion in the smallest sieve was submitted to floatation with carbon trichlorethylen. The floated material was transferred to filter paper and air-dried. All the living specimens in each sample were picked and identified following the generic classification of Loeblich and Tappan (1988). Species were classified by their mode of life (infaune or epifaune) and their feeding strategy (herbivore or detritivore) according to Murray (1991).

Separate samples were taken for organic carbon, nitrogen, sulphur, organic matter and grain size analysis. Organic carbon, total nitrogen and sulphur were determined using 500 mg of freeze-dried and weighted sediment. It was decarbonated with 1 M solution of hydrochloric acid, washed 3 times with deionized water, freeze-dried again and then analyzed in a LECO CNS 2000 analyzer. The granulometric composition was analyzed using low-angle laser light scattering (LALLS), type Malvern 2000, and the size intervals were classified using the Wentworth scale (Wentworth, 1922 *in* Suguio, 1973).

The temperature of bottom water was measured by means of reversing thermometers. The salinity was determined in the laboratory by a salinometer and a PSU scale was employed. pH was measured on board using a Digimed pH-meter model DM-2.

Data analysis

Although in the laboratory we quantified all the foraminiferal individuals (live and dead), we only considered the living fauna for all data analyses. Biological data were analyzed with multivariate techniques of cluster analysis. The classification of stations ("Q Mode") and classification of species ("R Mode") were made using the quantitative similarity coefficient of Morisita-Horn and the Unweighted Pair Group Method Using Arithmetic Averages (UPGMA) (Sneath and Sokal, 1973). A data matrix was created using the absolute frequency of living foraminiferal species from the 40 stations. Species occurring with a frequency of ≤1% of the total assemblage at any station were eliminated from the matrix. Since these species have very low abundance, they contribute poorly to the results and merely cause "noise" in the multivariate analysis (Milligan and Cooper, 1987). The specific matrix was transformed using the log(x +1) transformation to increase the importance of smaller values and obtain a more normalized distribution.

The specific diversity of the recognized assemblages was determined by using the Shannon-Wienner index or information function (H') (Shanon and Weaver, 1963), and the α Fisher index (Murray, 1973). These two measures are complementary. The α index eliminates the effects of sample size while the information function gives an indication of the heterogeneity within an assemblage (Murray, 1991). The evenness (J') was calculated with the Pielou index (1975) and the species richness (S) is simply the total number of species in each station.

In order to improve our understanding about each sub-environment departing from the calculated diversity of each station we introduced the concept of mean diversity $\bar{H}'$, defined by

$$\overline{H'} = \frac{\sum_k H_k' S_k}{\sum_k S_k} \quad ,$$

where the sum over k extends for the number of stations. Each sub-environment has a mean diversity value $\bar{H}'$. Notice that our concept of mean diversity includes a pondering weighted by the richness of

TABLE 1. – Geographic positions, water depth, temperature, salinity and pH of the 40 samples.

Stations	latit. (S)	long. (W)	depth (m)	T (°C)	Sal PSU	pH
1	23° 27'13"	45° 01' 53"	12	26.43	35.19	8.16
2	23° 27'10"	45° 01' 35"	13	27.00	35.19	8.15
3	23° 27' 8"	45° 01'11"	15	26.21	35.24	8.01
5	23° 27' 2"	45° 00' 20"	16	28.43	35.21	8.14
6	23° 27' 30	45° 00' 40"	15	28.18	35.26	8.15
7	23° 26' 33"	45° 01' 00"	15	29.42	35.13	8.14
9	23° 26' 36"	45° 02' 16"	10	28.86	34.73	8.27
10	23° 26' 46"	45° 02' 36"	10	28.96	34.69	8.22
12	23° 26' 50"	45° 02' 52"	8	30.40	34.92	8.19
13	23° 26' 34"	45° 03' 26"	6	29.16	34.81	8.25
14	23° 26' 28"	45° 03' 00"	8	28.00	35.02	8.26
15	23° 26' 20"	45° 02' 40"	9	28.51	34.63	8.27
16	23° 26' 18"	45° 02' 12"	11	29.70	35.10	8.15
17	23° 26' 13"	45° 01' 44"	11	29.18	35.01	8.10
18	23° 26' 9"	45° 01' 16"	13	28.69	35.17	8.12
19	23° 26' 50"	45° 00' 6"	16	26.54	35.28	8.15
20	23° 25' 57"	45° 00' 6"	14	26.42	35.19	7.99
21	23° 25' 34"	45° 01' 16"	13	26.70	35.18	8.14
22	23° 25' 28"	45° 00' 40"	12	28.43	35.17	8.13
24	23° 25' 42"	45° 01' 55"	10	28.86	24.67	8.20
25	23° 25' 48"	45° 02' 20"	9	29.13	34.68	8.22
26	23° 25' 54"	45° 02' 56"	7	30.50	34.84	8.14
29	23° 25' 9"	45° 02' 00"	8	28.91	35.11	8.15
30	23° 25' 40"	45° 01' 6"	14	26.65	35.15	8.12
35	23° 24' 46"	45° 03' 6"	10	27.00	29.78	7.94
36	23° 27' 13"	45° 03' 30"	1.35	30.40	34.92	8.22
37	23° 27' 11"	45° 03' 14"	2	28.00	34.48	8.13
38	23° 27' 6"	45° 03' 37"	1.18	29.33	34.85	8.24
41	23° 27' 1"	45° 03' 12"	3	29.00	28.01	8.42
42	23° 27' 32"	45° 03' 17"	1.15	29.00	24.60	8.20
43	23° 26'44	45° 03' 52"	1.3	29.00	29.91	8.25
44	23° 26' 36"	45° 03' 56"	1.78	29.00	28.62	8.30
48	23° 26' 44"	45° 03' 52"	1.72	28.00	24.55	8.13
49	23° 26' 45"	45° 03' 48"	1.65	28.00	25.42	8.00
50	23° 26' 46"	45° 03' 36"	2	29.00	29.40	8.06
51	23° 26' 48"	45° 04' 1"	0.1	29.00	26.76	8.10
55	23° 26' 13"	45° 03' 56"	0.3	29.80	31.39	8.17
56	23° 26' 6"	45° 04' 2"	3	29.80	30.88	8.15
57	23° 25' 56"	45° 03' 56"	2	29.19	32.00	8.10
58	23° 26' 00"	45° 03' 48"	2.5	29.70	32.41	7.96

each station. In this way, we suppose that the $\bar{H}$' number is the best one synthesizing the ecological features of a middle scale environment.

A Principal Component Analysis (PCA) was carried out to order sample location for the abiotic factors. A first matrix (previously normalized and centred) was constructed using all the variables measured. However, in order to avoid redundancy and perform a more realistic ordination, the variables with a low percentage contribution were eliminated. In this way, a second matrix was obtained using a total of 13 variables, namely total organic carbon (TOC), total nitrogen (N), sulphur (S), C/N ratio, C/S ratio, silt, clay, fine sand (FS), very fine sand (VFS), salinity, temperature, pH and depth. To perform the calculations of uni- and multivariated techniques we used the software Multivariate Statistical Package (MVSP) (Kovach, 1999).

RESULTS

Environmental data

Salinity data are shown in Table 1, with values ranging from 24.55 to 35.26. A slightly positive gradient towards the mouth of the bay was detected showing the river water influence. The bottom temperature (Table 1) varied slightly around 28°C and the pH values (Table 1) were superior to 8 at most of the stations.

Bottom sediments varied from gravel to clay (Table 2). At the middle regions (stations 12, 13 14, 15, 16, 23, 24, 25 and 29) as well as at the inner ones (38, 44, 51 and 58), mud was the dominant sediment fraction with values higher than 40%. Stations 1, 2, 3, 7, 9 and 10 (south region) showed the highest grain size heterogeneity. The highest values of organic carbon as well as nitrogen and sulphur were

TABLE 2. – Organic variables and percentages of surface sediment fractions in the 40 samples. TOC = total organic carbon; N = total nitrogen and S = sulphur VCS = very coarse sand; CS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sand.

Stations	TOC (%)	N (%)	S (%)	C/N ratio	C/S ratio	Gravel (%)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Silt (%)	Clay (%)
1	0.38	0.05	0.05	7.60	7.60	0.00	12.24	18.06	13.39	18.23	23.48	14.51	0.00
2	0.28	0.03	0.03	9.33	8.60	0.00	9.24	10.05	9.12	16.51	29.82	12.39	0.00
3	2.58	0.27	0.30	9.55	8.60	0.00	0.04	0.19	7.98	11.68	29.82	41.53	4.45
5	1.04	0.12	0.12	8.60	8.60	0.00	0.00	0.00	3.10	13.90	40.30	38.00	4.70
6	1.70	0.20	0,17	8.50	10.0	0.00	0.00	0.00	3.50	14.87	38.90	38.07	4.66
7	0.96	0.10	0.16	9.60	6.00	1.70	16.21	20.11	20.63	14.36	17.90	9.09	0.00
9	0.72	0.08	0.07	9.00	10.28	0.00	1.00	0.60	5.40	19.18	36.12	32.03	5.66
10	1.33	0.15	0.15	8.86	8.86	0.00	0.00	11.30	6.00	1.30	6.01	57.18	8.80
12	0.67	0.06	0.15	11.16	4.46	0.00	0.00	0.00	7.22	11.96	30.28	46.35	4.19
13	2.16	0.24	0.31	9.00	6.96	0.00	0.00	0.00	2.93	10.89	38.32	46.12	3.41
14	2.14	0.25	0.31	8.56	6.90	0.00	0.00	0.00	2.68	5.51	21.94	63.55	6.32
15	1.74	0.17	0.20	10.23	8.70	0.00	0.00	0.00	0.06	2.79	17.52	70.00	9.,53
16	1.66	0.18	0.19	9.22	8.73	0.00	0.00	0.00	1.99	8.42	26.50	54.71	8.38
17	2.81	0.31	0.27	9.06	10.40	0.00	0.00	0.00	2.89	22.99	57.13	14.99	2.00
18	2.41	0.26	0.19	9.26	12.68	0.00	0.00	0.00	3.64	14.73	38.93	38.04	4.66
19	1.64	0.22	0.15	7.45	10.93	0.00	0.00	0.00	4.20	23.25	40.02	29.68	2.85
20	1.77	0.21	0.17	8.40	10.41	0.00	0.00	0.00	6.74	20.71	41.08	27.63	3.82
21	2.15	0.26	0.22	8.26	9.77	0.00	0.00	0.00	4.59	13.74	37.41	39.66	4.29
22	1.03	0.12	0.10	8.58	10.30	0.00	0.00	0.00	4.72	23.00	47.10	13.79	3.20
24	0.23	0.02	0.04	11.50	5.75	0.00	0.00	0.00	1.01	9.80	29.28	51.63	6.62
25	1.11	0.11	0.28	10.09	3.96	0.00	0.00	0.00	1.03	4.69	26.15	61.84	6.29
26	0.43	0.04	0.05	10.75	8.60	0.00	0.00	0.00	2.75	12.71	48.10	33.92	2.48
29	2.05	0.21	0.48	9.76	4.27	0.00	0.00	0.00	0.00	1.06	15.83	69.84	10.97
30	1.29	0.14	0.11	9.21	11.72	0.00	0.00	0.00	4.27	7.87	25.80	54.87	7.19
35	0.21	0.04	0.04	5.25	5.25	0.00	0.00	0.00	13.00	20.05	37.90	29.94	3.00
36	0.36	0.04	0.07	9.00	5.14	0.00	0.00	0.00	13.55	19.50	37.87	29.91	2.63
37	0.22	0.03	0.04	7.33	5.50	0.00	0.21	0.25	10.12	28.61	53.17	7.64	0.00
38	0.24	0.04	0.04	6.00	6.00	0.00	0.00	0.00	8.67	7.95	31.16	42.35	4.82
41	0.28	0.03	0.03	9.33	9.33	0.00	0.00	0.00	2.45	13.15	51.23	31.10	2.07
42	0.32	0.04	0.05	8.00	6.40	0.00	0.00	0.00	8.21	14.02	43.02	34.38	0.37
43	0.16	0.02	0.03	8.00	5.33	0.00	0.00	0.00	0.87	10.56	61.56	24.93	2.13
44	0.64	0.07	0.09	9.14	7.11	0.00	0.00	0.00	10.59	13.49	31.30	41.48	3.14
48	0.40	0.04	0.06	10.00	6.66	0.00	0.00	0.20	4.20	12.06	41.10	38.49	2.17
49	0.47	0.04	0.07	11.75	6.71	0.00	0.00	0.10	5.40	13.84	45.56	32.18	2.92
50	0.43	0.04	0.06	10.75	7.16	0.00	0.00	0.00	5.56	13.46	47.01	31.60	2.37
51	0.25	0.03	0.03	8.33	8.33	0.00	0.00	0.16	4.24	11.05	43.12	38.39	2.97
55	0.12	0.02	0.02	6.00	6.00	0.00	0.00	0.00	0.00	20.97	73.78	5.25	0.00
56	0.21	0.02	0.03	8.70	7.00	0.00	0.00	0.00	16.70	26.39	44.12	11.32	1.47
57	0.12	0.02	0.02	6.00	6.00	0.00	0.00	0.00	1.20	23.78	70.00	4.05	0.00
58	1.40	0.24	0.15	5.83	9.30	0.00	0.00	0.00	0.57	9.31	36.80	52.59	0.73

recorded at the stations with high silt values, which corresponded to the middle portion of the bay (Table 2). Carbon-nitrogen ratios (C/N) in the study area ranged between 5.2 and 11.5 and carbon-sulphur ratios (C/S) varied from 3.96 to 12.68.

Fauna

In the whole area a total of 43 species of living benthic foraminifers was found (Table 3), belonging to the suborders Rotaliina (31 species), Textulariina (9 species) and Miliolina (3 species).

Cluster analysis

The result of the Q Mode cluster analysis allowed three groups of stations to be recognised. The same clustering was also obtained by the R Mode that shows three species assemblages. It clearly evidenced the existence of different ecological conditions for different regions in the bay (Figs. 2, 3 and 4). The assemblages were named according to the dominant species in each one.

Group I includes sixteen stations located in the inner part of the bay (near the rivers) and is characterized by the *Ammonia tepida* assemblage. It consists of hyaline species (57.3%), agglutinant species (28.5%) and porcelanoid species (14.2%). *A. tepida* represented 83.2% of the total assemblage and showed the highest proportion of individuals with morphological abnormalities (Table 4 and Fig. 5). This sub-environment appears to be under unstable environmental conditions due to the inflow of the local rivers and is characterized by sediments with a significant contribution of very fine sand.

TABLE 3. – Absolute abundance of foraminifera species present in Ubatuba Bay at each station.

Foraminifera / Stations	1	2	13	14	15	16	17	18	19	20	21	22
Ammobaculitis exiguus Cushmann and Bronnimann, 1948	2	0	0	0	0	0	0	0	0	0	0	0
Ammonia tepida (Cushman), 1926	16	5	28	40	2	3	4	7	4	1	0	11
Ammotium psedocassis (Cushmann and Bronnimann), 1948	1	3	0	0	0	0	0	0	0	0	0	0
Ammotium salsum (Cushmann and Bronnimann), 1948	0	0	0	0	0	0	0	0	0	0	0	0
Angulogerina angulosa Williamson, 1858	0	0	0	0	0	0	0	1	0	0	0	0
Bolivina compacta Sidebottom, 1905	10	6	11	6	15	12	7	5	3	12	9	9
Bolivina doniezi Cushman and Wickenden, 1929	12	22	13	9	19	3	12	6	8	8	7	2
Bolivina pulchella d'Orbigny, 1840	0	0	5	9	17	13	10	1	0	0	0	0
Bolivina sp.	1	1	10	6	8	3	5	0	1	0	0	1
Brizalina striatula Cushman, 1922	111	85	20	17	8	22	15	6	11	17	12	1
Bulimina marginata d'Orbigny, 1826	4	4	0	0	0	0	0	0	0	0	0	2
Buliminella elegantissima (d'Orbigny), 1839	100	91	163	136	201	179	153	74	29	33	23	17
Cancris sagra d'Orbigny, 1839	29	38	0	0	0	0	0	1	1	0	0	0
Cibicides floridanus Galloway and Wissler, 1927	10	27	0	0	0	0	0	0	0	1	0	1
Discorbis williamsoni (Chapman and Parr), 1932	8	15	0	0	0	0	0	0	2	2	0	2
Elphidium excavatum (Terquem) 1876	31	26	0	0	0	0	0	0	3	0	0	0
Fissurina quadricostulata (Reuss, 1870)	0	0	0	0	0	0	0	0	0	0	0	1
Fursenkoina pontoni (Cushman, 1932)	0	0	2	5	0	0	0	0	0	8	4	8
Gaudryina exilis Cushman and Bronnimann, 1948	7	0	0	0	0	0	0	0	0	0	0	0
Guttulina sp.$_1$	9	23	0	0	0	0	0	0	0	0	0	0
Guttulina sp.$_2$	2	3	0	0	0	0	0	0	0	0	0	0
Hanzawaia boueana (d'Orbigny), 1846	35	49	0	0	0	0	0	4	1	2	0	1
Haynesina germanica (Ehrenberg, 1840)	0	0	0	0	0	0	0	0	0	0	0	0
Hopkinsina pacifica Howe and Wallace, 1932	1	3	1	1	3	15	0	14	29	12	7	26
Lagena caudata d'Orbigny, 1826	1	2	0	0	0	0	0	0	2	1	0	0
Lagena striata (d'Orbigny), 1839	7	10	0	0	0	0	0	2	1	1	0	0
Lenticulina sp.	0	0	0	0	0	0	0	0	0	0	0	0
Miliammina fusca (Brady), 1870	0	0	0	0	0	0	0	0	0	0	0	0
Nonionella pulchella Hada, 1931	11	20	0	0	0	1	5	11	58	104	0	104
Pararotalia cananeiaensis Debenay *et al*., 2000	0	0	0	0	0	0	0	5	4	8	0	15
Poroeponides lateralis (Terquem), 1878	10	28	0	0	0	0	0	0	0	0	0	0
Pseusoclavulina sp.	2	0	0	0	0	0	0	0	0	0	0	0
Pseudononion atlanticum (Cushman), 1926	64	58	0	0	0	12	22	176	200	378	11	388
Pseudononion grateloupi (d'Orbigny)	3	2	0	0	0	0	0	15	7	9	0	7
Quinqueloculina milletti (Wiesner), 1912	3	1	0	0	0	0	0	0	0	0	0	0
Quinqueloculina patagonica d'Orbigny, 1839	4	7	0	0	0	0	0	2	0	0	0	0
Reophax scottii Chaster, 1892	0	0	0	0	0	0	0	0	0	0	0	0
Textularia earlandi Parker, 1952	0	0	0	0	0	0	0	0	0	0	0	0
Tiphotrocha comprimata (Cushman and Bronnimann), 1948	1	0	0	0	0	0	0	0	0	0	0	0
Triloculina cultrata (Brady) 1881	29	36	0	0	0	0	0	0	0	0	0	0
Uvigerina bifurcata d'Orbigny, 1839	15	14	12	7	2	7	1	18	5	12	25	12
Uvigerina peregrina Cushman, 1923	0	0	0	0	0	0	0	0	0	0	0	6
Virgulina riggii Boltovskoy, 1954	26	3	0	0	0	2	1	8	4	0	3	1
Total	565	582	265	236	275	272	235	356	373	609	101	615

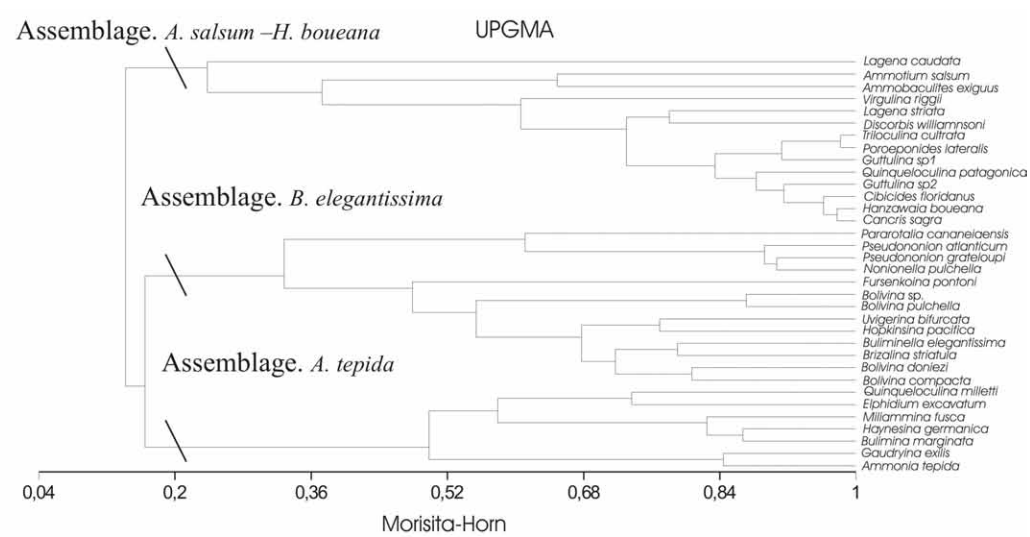

FIG. 2. – Dendrogram classifications showing the assemblages of the species. R-mode.

24	25	26	29	30	35	36	37	38	41	42	43	44	48	49	50	51	55	56	57	58
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	7	2	3	705	863	701	608	67	98	114	228	59	42	36	48	997	1122	1101	1351
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	18	3	1	12	2	16	0	14	0	0	0	8	0	1	0	2	1	1	3	5
15	7	8	1	5	2	0	0	131	0	1	2	0	2	1	2	2	0	0	1	1
10	6	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	9	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	41	35	75	9	0	4	115	0	2	10	6	23	3	7	4	2	3	14	17	19
0	0	0	0	0	35	110	90	73	0	0	0	0	0	0	0	0	0	0	0	0
188	156	127	85	7	182	74	263	404	77	72	345	374	49	38	107	39	52	89	198	240
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	2	57	79	195	228	0	1	5	5	1	0	0	2	12	7	6	10
0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	0	0	0	0	0	0
6	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	23	57	22	17	0	0	0	9	0	0	0	0	4	7	1	3
21	20	20	0	22	0	0	3	9	0	0	0	2	0	0	4	4	3	0	0	21
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	15	18	6	1	1	2	1	2	1	1	1	1	7	4	3	2
0	0	0	0	129	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	3	5	1	2	2	2	1	1	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	0	0	390	0	0	40	148	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	31	26	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	27	17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	2	23	0	0	0	0	0	0	0	0	0	0	0	0
398	287	240	165	602	1024	1227	1475	1696	149	186	474	652	115	90	155	100	1079	1244	1330	1652

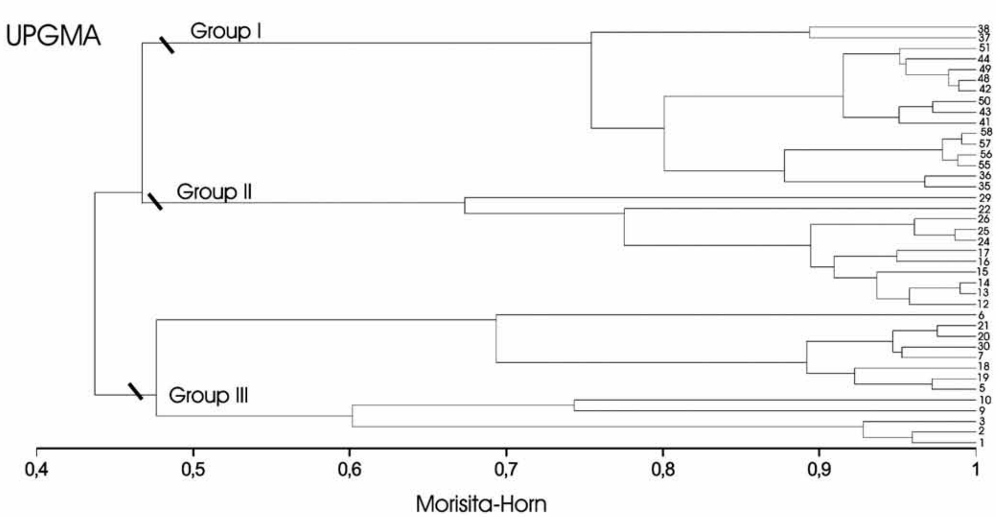

FIG. 3. – Dendrogram classifications showing the groups of stations. Q-mode.

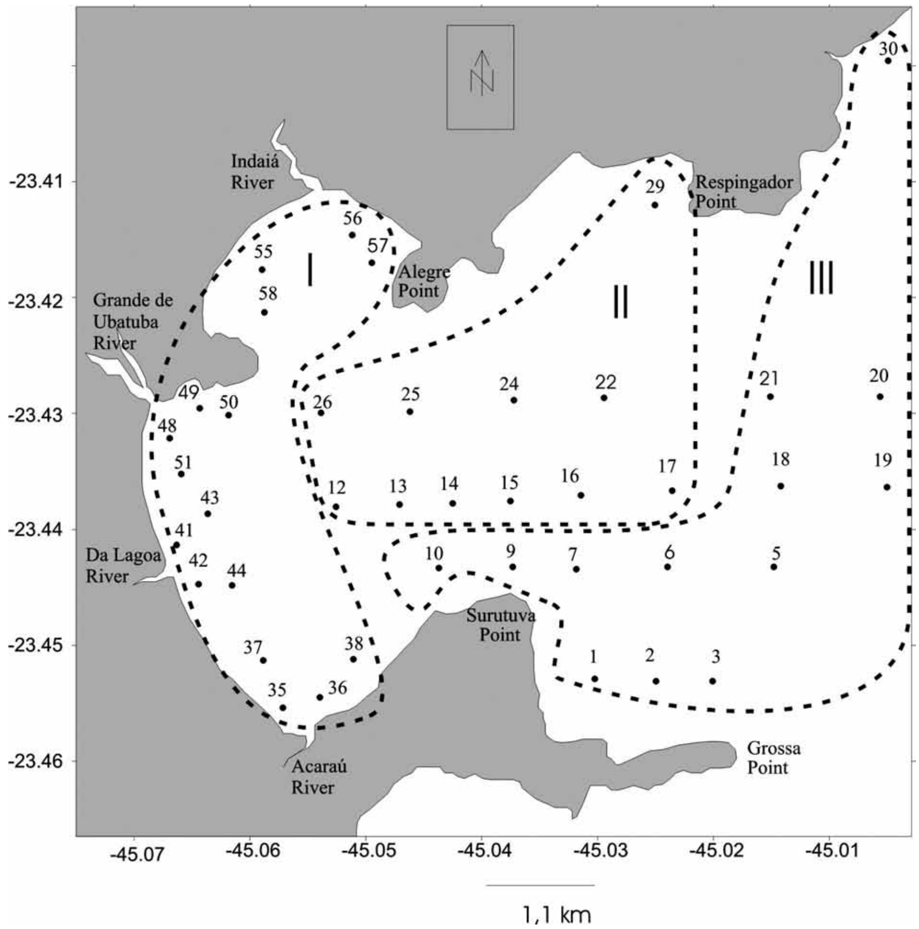

FIG. 4. – Map of the study area showing the three groups of stations resulting from the "Mode Q" classifications.

Group II is formed by eleven stations located in the middle region of the bay. The foraminiferal assemblage is dominated by the hyaline species *Buliminella elegantissima* (46.2%), but also has a significant contribution of *Pseudononion atlanticum* (25.0%). This assemblage is formed by the agglomeration of thirteen hyaline species (Fig. 2). In the grain size analysis, mud was the dominant fraction with values higher than 40%.

Finally, thirteen samples grouped together to form group III, which includes the stations bordering the rocky margins of Ponta Surutuva (1, 2, 3, 9 and 10) and the outermost bay stations. The foraminiferal assemblage corresponding to this sub-environment is the *Ammotium salsum* - *Hanzawaia boueana* assemblage (19.2% and 15.5% respectively). As most species belonging to this assemblage have rather similar abundances we decided to name it by the two most abundant species. It is constituted by hyaline (71.4%), agglutinant (14.2%) and porcelanoid species (14.2%). This assemblage is characterized by the significant presence of epifaunal foraminifera while the other two groups are formed basically by infaunal species. Apart from the stations near Ponta Surutuva, most stations of this group are composed of very fine sand. In terms of coarse sediment, it was observed that a high number of tests stayed back on the 0.250 mm and 0.500 mm sieves, while for the other groups most of the individuals were retained in the 0.062 mm.

A wider discussion of each assemblage taking into account all the variables will be presented in the next section, after presenting the other biological results.

Foraminiferal density, diversity, richness and evenness

In Figures 6a to 6d we have represented the density, *H'*, S and *J'* for the three sub-environments recognized in this study. Group I has the highest density registered in the whole area with values up to 1707 individuals/sample near the Indaiá River. However, the lowest density was also registered in this group with 91 individuals/sample near the

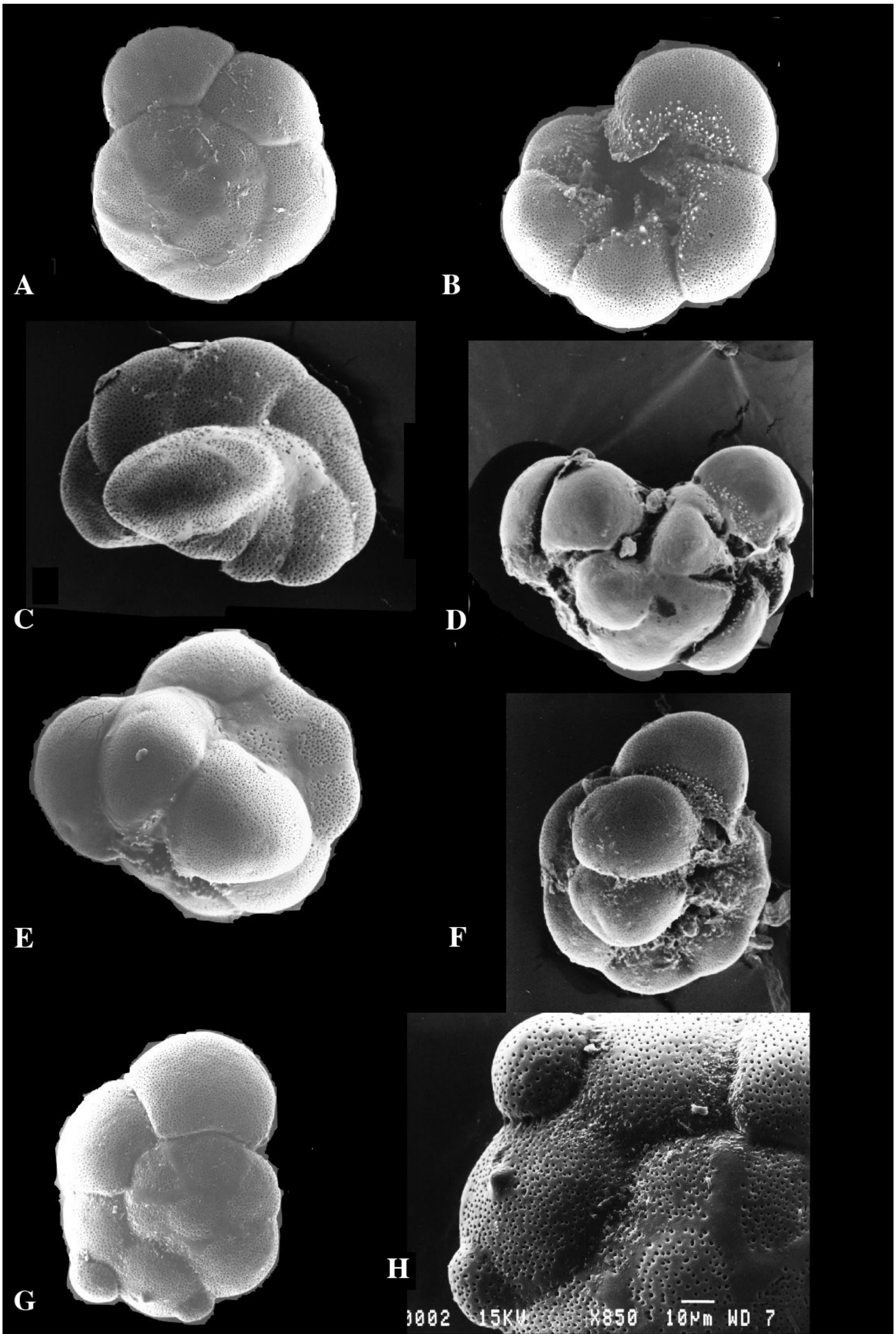

FIG. 5. – *Ammonia tepida*; A, spiral side view of normal specimens × 370; B, umbilical side view of normal specimen × 450; C, aberrant chambers shape, size and distorted chamber arrangement × 350; D, siamese twins × 350; E, siamese twins × 380; F, umbilical side showing development of additional chambers × 450; G, spiral side showing development of additional chambers and pustules × 370; H, detail of G showing the abnormalities × 850.

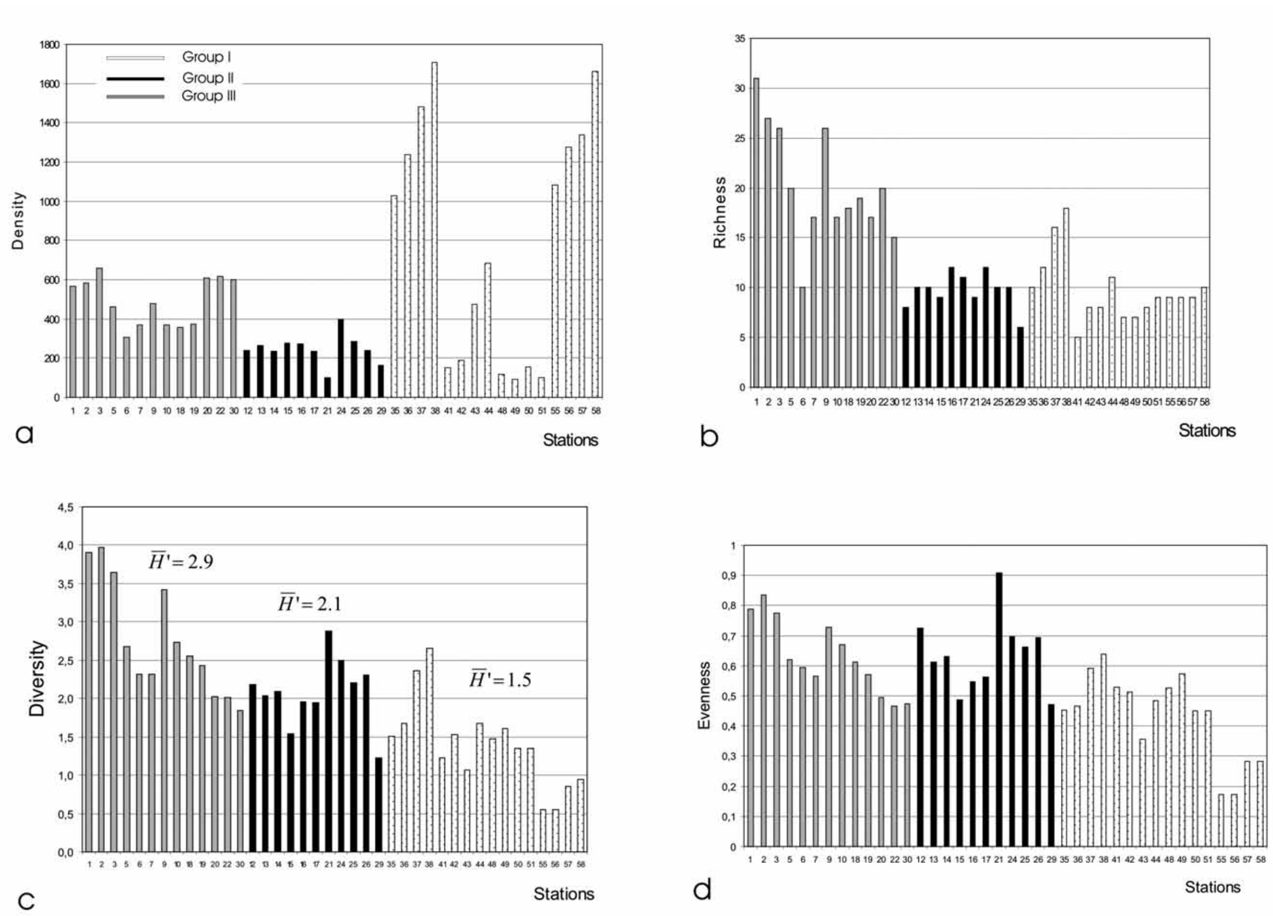

FIG. 6. – Populational parameters used to relate the foraminiferal assemblages to the environmental conditions; $\bar{H}$'mean diversity; a: density; b: richness; c: diversity (Shannon-Wiener index); d: evenness.

Ubatuba River. In this sense, this group exhibits a high contrast in density that will be analyzed in the next section. As a general fact, *H*' showed low values ($\bar{H}$'= 1.5) especially in those stations where *A. tepida* appeared with high densities as the dominate species. The α Fisher ranged between α = 1 and α = 3, which also represents the lowest values in the bay. Species richness ranged between 5 and 18.

In general, the middle region (group II) had low density values ranging between 101 and 398 individuals/sample. This sub-environment showed intermediate values of diversity ($\bar{H}$'= 2.1) and α that varied between 3 and 5 as well as an intermediate number of species between 6 and 12 (Figs. 6c and 7).

Finally, in group III the density had intermediate values varying from 308 to 658 individuals/sample. This group had the highest *H*' and α index (*H'*= 3.97 and α ranged between 5 and 7), which can be summarized by the highest mean diversity ($\bar{H}$'= 2.9), which represents an increase of almost 100% with respect to group I. The richness also was at its maximum in this group.

The evenness of distribution of the species showed more homogeneous values for groups II and III, when compared with the values from group I, which had lower values.

Ordination

The PCA analysis allowed us to distinguish two principal components that explain 60.1% of the total data variance (Axis 1: 45.7% and Axis 2: 14.4%). Axis 1 was positively correlated with total organic carbon, nitrogen and sulphur content, depth, salinity, silt and clay content; it was negatively correlated with fine sand and very fine sand. Axis 2 was positively correlated with pH, C/S and C/N ratios and negatively correlated with nitrogen, sulphur, salinity and depth.

As can be seen in Figure 8 it was possible to group the stations into approximately the same three groups obtained with the cluster analysis, according to their environmental conditions. Group I is almost the opposite of group II. The first one is negatively

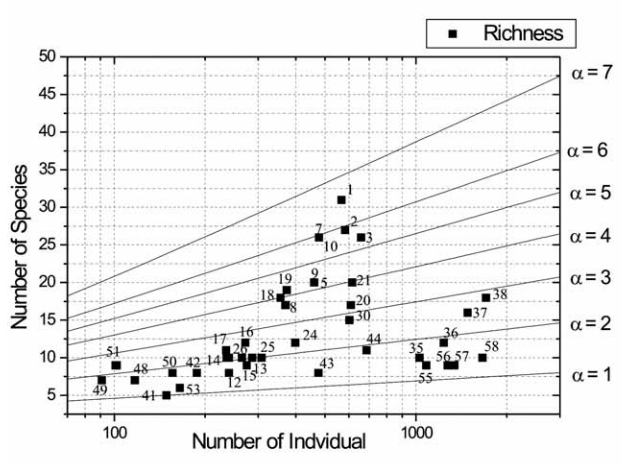

FIG. 7. – Plot of the Fisher Index α calculated for the population of foraminifera.

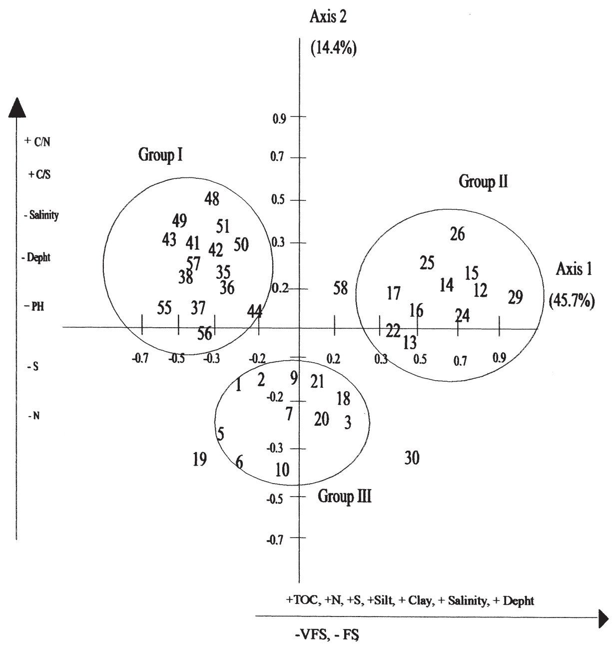

FIG. 8. – PCA ordination diagram of sampling based on the selected variables measured. The three main groups formed are shown (Group I, II and III).

correlated with Axis 1 due to low TOC, S, N and mud concentrations, low salinity and depth, and high fine sand and very fine sand. On the other hand, group II is positively linked with Axis 1, because of the presence of high concentrations of pelitic (fine) sediment and TOC. In the PCA diagram group III is in an intermediate position between groups I and II. This is the consequence of its heterogeneous sediment, and its high depth and salinity.

Morphological abnormalities

Out of the 43 species found in the present study, only 6 species exhibited morphological abnormalities. Abnormal specimens were mainly present in the inner bay, especially represented by *A. tepida* specimens. The maximum number of deformed specimens was recorded at stations 55, 56, 57 and 58 which are near the Indaiá River (Table 4 and Fig. 5). We identified several morphological deformities such as aberrant chamber shape and size (Fig. 5C), siamese twins (Fig. 5D), additional chamber (Fig. 5E), abnormal growth (Fig. F), among other minor type abnormalities. Furthermore, some specimens accumulated more than one deformation pustule, protuberance or additional chamber (Figs. 5G, H).

DISCUSSION

According to Mahiques (1995, 1998) and Burone *et al.* (2003) the spatial distribution of surface sediments and their geochemistry reveals the existence of different sediment facies that are strongly related to local hydrological conditions. These environmental characteristics are reflected in the foraminiferal assemblages.

Stations group I

The inner sub-environment occupies the shallower part of the bay and the foraminiferal assem-

TABLE 4. – Number of abnormal tests (NAT) by species by station.

Species / Stations	13	143	22	26	35	36	37	38	42	44	48	50	51	55	56	57	58
Ammonia tepida	2	3	2			11		5	13	9	4	5	1	25	50	36	41
Buliminella elegantissima	2		1	2	1		2		8	6		2			1		
Brizalina striatula			1		1	1			1						3		
Elphidium excavatum						4		2		2				5		2	3
Pararotalia cananeiaensis											1	1					
Pseudononion atlanticum						2											1
% Total NAT	1.5	1.3	0.6	0.8	0.2	1.5	0.1	0.4	11.8	2.6	4.3	5.2	1.0	2.8	4.3	2.8	2.7

blage corresponds to group I. It is represented basically by mixohaline calcareous, agglutinated species and one species typical of very low salinity water (*Miliammina fusca*). Among these, the generalist species *A. tepida* was the dominant one. This area is subjected to freshwater input from the coastal rivers and from domestic sewage. This distribution of *A. tepida* is consistent with other authors that have pointed out its ability to tolerate lower salinities (Walton and Sloan, 1990). Furthermore, Debenay *et al*. (2001) state that the growth of this species may be favoured by a temporary decrease in water salinity and input of nutrients that clearly happens in this region of the bay. It is known that the nutrients are usually implied in an increase of primary producers (microalgae), which results in an important feeding source for herbivore foraminiferal fauna, such as *A. tepida*.

Very fine sand, such as in the sediment dominant fraction, and the highest C/N ratios also indicate the terrestrial contribution in this sub-environment that is represented by group I of the PCA that groups together the shallowest stations. The PCA also reveals the effect of the contribution from rivers through its low salinity and high sand percentage.

This area registered high densities, as a consequence of *A. tepida* occurrence. In association, this area showed low diversity values, which is also connected with the dominance of *A. tepida*. Both the low α Fisher index and the low evenness values that appear in this region corroborate the non-homogeneous species distribution and the environment instability that also reflect the low diversity. All these features can be seen as a result of a high adaptability of *A. tepida* to survive in an unstable environment. The living population results from the organism's capability to survive and reproduce in certain environments. In this way, it is possible to consider the regions that are near the Acaraú and Indaiá rivers as the most productive areas due to their high standing crop.

We would like to point out the large difference between the densities registered in the stations located close to the Acaraú and Indaiá rivers (very high densities) and those near the da Lagoa and Ubatuba rivers (very low densities), apart from this difference there were no apparent variations in the sediment composition, salinity or temperature. This density increment is a biological effect that agrees with previous studies of domestic waste influence and organic enrichment on benthic foraminiferal populations (Watkins, 1961; Seiglie, 1971; Bates and Spencer, 1979; Alve, 1991, 1995; Yanko *et al*., 1994; Samir and El-Din, 2001, Burone *et*. *al*., 2006). On the other hand, it is possible to infer that the negative population response near the da Lagoa and Ubatuba rivers can be correlated to the rivers' water quality. Abessa and Burone (2003) worked with sediment toxicity tests in the four tributary rivers of the Ubatuba Bay, and concluded that the Grande de Ubatuba and da Lagoa rivers had high toxicity due to large amounts of sulphur, carbon and nitrogen contents in sediments, added to ammonia and organic phosphorus dissolved in interstitial water. Thus, this type of sewage probably includes toxins that inhibit the foraminiferal population growing. Moreover, according to CETESB (1996) these rivers receive untreated domestic sewage coming from Ubatuba City. For instance, during 1998 the rivers presented faecal coliform concentrations 10^3 times the maximum permissible by law, which is indicative of raw sewage (CETESB, 2000).

Group III Stations

To facilitate the understanding of the whole bay, we first discuss the behaviour of the outer most portion of the bay at the southern rocky margins represented by the group III stations and the *Ammotium salsum - Hanzawaia boueana* assemblage (see Figs. 2, 3 and 4).

This is a high-energy area where deposition of fine sediments is not possible due to strong currents that are associated with the heterogeneity of sediment grain size. As a result, high percentages of coarse, medium and fine sand were recorded, especially in those stations near Ponta Surutuva, the region of the oceanic inflow currents. The PCA also bunches these stations as a consequence of their sediment heterogeneity and high salinity, which testifies a marine contribution.

In a general way, substrate type and environment physical energy (i.e. waves and currents) play an important role in determining assemblage compositions (Murray, 1991). The foraminifera assemblage was represented by 50% of epifaune species divided into epifaunal-attached and epifaunal-clinging forms. The presence of epifaunal species with robust and large sized tests (> 0.5 mm) is indicative of the high energy acting in the place and the well oxygenated conditions (Sturrock and Murray, 1981). Mahiques (1995) registered high carbonate values

(> 30% CaO_3) occurring close to the rocky coast that is directly exposed to wave action. This fact could explain the foraminifera's big test size observed in this region.

The high values of diversity and the α Fisher index also indicate an environment with a conspicuous marine influence. Although the foraminifera density was not extremely high, the species distribution was quite homogeneous, which was shown by somewhat large values of evenness. In other words, if the species number increases, the individuals will tend to be more homogenously distributed among the existent species, and none of them will have a marked dominance. Therefore, the grain heterogeneity existent in this region provides a potential niche for many species with different modes of life such as epifaunal-clinging, epifaunal-attached, epifaunal-free and infaunal-free and different feeding strategies (suspensivore, herbivore and detritivore) reflecting high species diversity. Furthermore, in coarse sediments other factors, such as bacterial biofilms that act as a food source, could be taken into account. This feeding strategy has been suggested (Bernhand and Bowser, 1992; Langer and Gehring, 1993; Diz *et al.*, 2004) and demonstrated in laboratory cultures (Kitazato, 1994).

Group II Stations

The middle bay region is associated with group II, which is represented by the *Buliminella elegantissima* assemblage. This assemblage is composed basically by infaunal deposit-feeders species, which are generally associated with high levels of organic matter, low oxygen concentrations in interstitial pore water and low energy (Murray, 1991; Bonetti, 2000).

From the ecological point of view, the group II station can be seen as an intermediate environment, because its diversity values and α index lie between the values obtained in groups I and III. Although the absolute densities were, in general, small they are homogenously distributed between stations as well as species, which is reflected by the relatively high evenness in most stations. According to Mahiques (1995) and Burone *et al.* (2003), this region is subjected to calm depositional conditions, where mud is the predominant sediment fraction. This high mud concentration exhibits a direct relationship with organic carbon, total nitrogen and oxygen in the sediment. This fact is quite evident from PCA (Fig. 8), where group II brings together stations where mud is the predominant sediment fraction with high contents of TOC, N and S. The C/N ratios observed in the sediments of this region (values around 10) reflect a mixed origin of the organic matter coming into the area as a consequence of both continental and marine organic matter contribution (Mahiques, 1995; Burone *et al.*, 2003).

Morphological abnormalities

Ecological factors reported in the literature as causes of abnormal test formation may be of natural or anthropogenic origin. Deformed tests appear to increase dramatically in areas subjected to different types of pollutants, e.g. oil slicks (Vénec-Peyré, 1981), sewage discharge (Watkins, 1961), agrochemicals (Bhalla and Nigam, 1986), high organic matter content (Caralp, 1989), and heavy metal contamination (Sharifi *et al.*, 1991; Alve, 1991; Yanko *et al.*, 1994, 1998; Samir and El-Din, 2001; Vilela *et al.*, 2004, Burone *et al.*, 2006). Abnormal test shapes have also been reported in areas subjected to strong variations of environmental parameters such as salinity (e.g., Arnal, 1955; Tufescu, 1968; Closs and Madeira, 1968). Some abnormalities may also be a result of mechanical damage (summarized in Boltovskoy and Wright, 1976). A comprehensive review of deformities and their probable causes is given by Boltovskoy *et al.* (1991) and Alve (1995). According to them, abnormalities may be a result of multiple affects and it would be very difficult to isolate any single specific cause.

In the present work the abnormalities are mainly attributed to ecological factors, because the stations that contain the highest number of deformed tests are close to the non-toxic rivers. Nevertheless, the organic input from the rivers as a consequence of the untreated domestic sewage from Ubatuba City may be contributing to the apparition of abnormal forms.

CONCLUSIONS

From the foregoing discussion we can see a clear distinction between three different sub-environments for the whole bay. This division could be in relation to geological, physicochemical and biological parameters. Strong correlations between the foraminiferal fauna distribution and the abiotic factors were identified, as shown by the results of assemblage clustering, ecological magnitudes and principal component analysis. In the following, we emphasize some important conclusions.

- The inner environment is dominated by *A. tepida,* which is an opportunist species, evidencing local instabilities from both natural and anthropogenic factors. The regions close to the Indaiá and Acaraú rivers were shown to be the most productive in the whole area, as a direct consequence of the nutrient enrichment from the unpolluted rivers. The toxicity of fluvial waters had a significant negative effect on the foraminiferal population, reflected by its extremely low densities.

- The middle region of the bay appears to be a depositional area for fine sediments (basically mud) and organic matter caused by its low hydrodynamic energy. This environment is occupied by the *Buliminella elegantissima* assemblage that is basically formed by infaunal deposit-feeder species.

- The most external region has high energy and heterogeneous sediment and it is populated by large sized test foraminifera that are equally distributed in epifaunal and infaunal species. This corroborates the high energy and the inflow of the marine current into the bay.

- The foraminiferal mean diversity shows a gradual increase outwards in the bay. It clearly evidences the rivers' influence in the inner part and the marine conditions for the external area, which are connected by an intermediate zone. The mean diversity definition results in a practical and synthetic quantitative way to reveal the area's ecological conditions.

- In general, Ubatuba Bay had a lower α index when compared with other similar neighbouring bays (Sanches, 1992). This might be considered to be a consequence of the strong river influence as well as the closeness of the town.

- Abnormalities in the foraminifera tests were detected, especially in the inner region basically represented by *A. tepida*. As these abnormalities were seen in a naturally stressed environment, it is not possible to relate them to the existent contamination. Detailed studies should be carried out that analyze these anomalies and their possible causes.

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