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Marine Pollution Bulletin 52 (2006) 61–73
MARINE POLLUTION BULLETIN
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Foraminiferal responses to polluted sediments in the Montevideo coastal zone, Uruguay

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Abstract

A study of foraminiferal assemblages was carried out in 24 sediment samples collected from the Montevideo coastal zone (south-eastern coastal region of South America) to assess the response of the benthic foraminifera to the polluted sediments. The area is affected by different pollutants such as sewage, hydrocarbons and heavy metals derived from different sources. Biological data were analyzed with multivariate techniques of cluster analysis and a principal component analysis (PCA) was performed for abiotic factors. The results allowed the recognition of different species assemblages corresponding to different sub-environments, which reflected the prevalent ecological conditions. The Montevideo Bay, particularly, its inner part showed an extremely poor foraminiferal fauna—including a totally azoic station—and high percentages of abnormal tests, when compared with the adjacent Punta Carretas and Punta Yeguas zones. Mean faunal density showed a strong relationship with organic matter, oxygen and heavy metal concentrations, as well as redox potential and pH values of each sub-environment. Although the adjacent zones presented a moderate pollution degree, it was noticed that a positive effect on the foraminiferal density specially on *Ammonia tepida*, caused by the sewage pipe located in Punta Carretas, a pure organic contamination. Differences among foraminiferal assemblages seemed to be related to the combined action of the several kinds of pollutants and the natural abiotic variables, like the rapid salinity changes that occurred in this area.

Keywords: Benthic foraminifera; Heavy metals; Hydrocarbons; Sediment pollution; Estuary; Río de la Plata

1. Introduction

Several strategies can be adopted to characterize, evaluate and monitor environmental quality. In polluted areas, the determination of physical–chemical variables by analytic methods has been prioritized historically. Nevertheless, there are several organisms that can be used as environmental indicators and the success of evaluation plans or environmental monitoring depends mainly on the correct choice of the bioindicator that will be used. Among the benthic organisms used for assessing anthropogenic effects, benthic foraminifera are one of the preferred groups because they are very sensitive to environmental stress. Studies dealing with benthic foraminifera as bioindicators of pollution have been increasing over the last decades. In this way, the first studies investigating the relationship between foraminifers and pollution were carried out by Zalesny (1959) and Resig (1960) working in California Southern coastal region. Since that time, pollution studies using these organisms have been expanded to include bays, harbors, and costal margins worldwide (see Alve, 1991, 1995; Boltovskoy et al., 1991; Yanko et al., 1999; Angel et al., 2000; Debenay et al., 2001a, among others). These studies have shown that the distribution of

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doi:10.1016/j.marpolbul.2005.08.007

benthic foraminifers is affected by several anthropogenic contamination factors, like organic enrichment of the sediments, heavy metal loading and petroleum hydrocarbons. Foraminiferal response to these conditions can include shifts in abundance, in species composition and the presence of test abnormalities.

This study aims to document the benthic foraminiferal assemblages in the Uruguayan coast (an impacted area) and to relate these assemblages to the environmental conditions. As far as we know, this is the first study on the Uruguayan coast concerning foraminiferal distribution in a polluted area.

1.1. Study area

The Montevideo coastal zone is situated in the middle Río de la Plata basin (Ayup, 1986), on the east coast of South America between 34°50′–34°56′S and 56°05′–56°25′W (Fig. 1). It covers an area of about 38,000 km^2 and drains a 3,170,000 km^2 basin, the second largest in South America. The Río de la Plata is a coastal-plain tidal river, with a semi-enclosed shelf sea at the mouth. The mean annual river flow is 25,000 $m^3 s^{-1}$, with a maximum in June and a minimum in January (Nagy et al., 1997). Tides are semi-diurnal with amplitude of about 40 cm on the Uruguayan coast. Features such as salinity, depth of the halocline and vertical mixing vary with astronomic tidal oscillations on an hourly basis, while axial winds influence water height and salinity variations on a daily basis. The outer Río de la Plata and the adjacent continental shelf are covered with sand, while silt clay, clayed silt and silt are confined to the upper and middle Río de la Plata basin (López-Laborde, 1997).

The Montevideo Bay lies in the Montevideo coastal zone with an approximate area of 10 km^2 and a mean depth of 5 m. It is geologically characterized by Precambrian outcrops and, in some regions, by more recent materials derived from these belonging to the Geological Formation Libertad-North Zone (Cardellino and Ferrando, 1969). The modern sediments are mainly fine grained, as clay and silt (Ayup, 1986). Predominant winds are from NE and W-SW, and they are very important in determining water circulation at shallow depths (Moresco and Dol, 1996), which is mainly clockwise.

1.2. Pollution conditions

The study area is affected by different pollutants that are derived from different sources. Thus, Montevideo Bay harbors the ANCAP refinery (Uruguayan Petroleum Company), the Batlle stream water plant (UTE, electrician Uruguayan company) and the Port of Montevideo. As can be seen from Fig. 1 that three streams flow into the bay: the Miguelete Stream, Pantanoso Stream and the Seco Stream, the latter flows through a pipe. These streams carry wastes from many different industries and urban centers, as well as from a great number of sewage sources. The entrance to the port is by a 9.3 km width channel and the port's main structure is in the southern area (La Teja Dock) between the mouths of the Pantanoso and Miguelete streams, where oil tankers are loaded and unloaded. In the opposite side, eastwards of the Montevideo costal zone (Punta Carretas region), lies the most important sewage pipe of Uruguay. Authorities of Montevideo are planning the construction of another one, of similar characteristics, westwards in the Punta Yeguas zone, that will concentrate the sewage of the Pantanoso and Miguelete streams. At present these sewage are discharged into Montevideo Bay.

Moyano et al. (1993) and Moresco and Dol (1996) studied the hydrocarbon and heavy metal concentrations in intertidal sediments along the coast of the Montevideo area. They found sediments at the mouth of the Pantanoso stream to be severely contaminated, particularly by chromium, a metal released with the untreated wastewaters of numerous tanneries located along its shore. More recently, Muniz et al. (2002) studied lead and chromium in

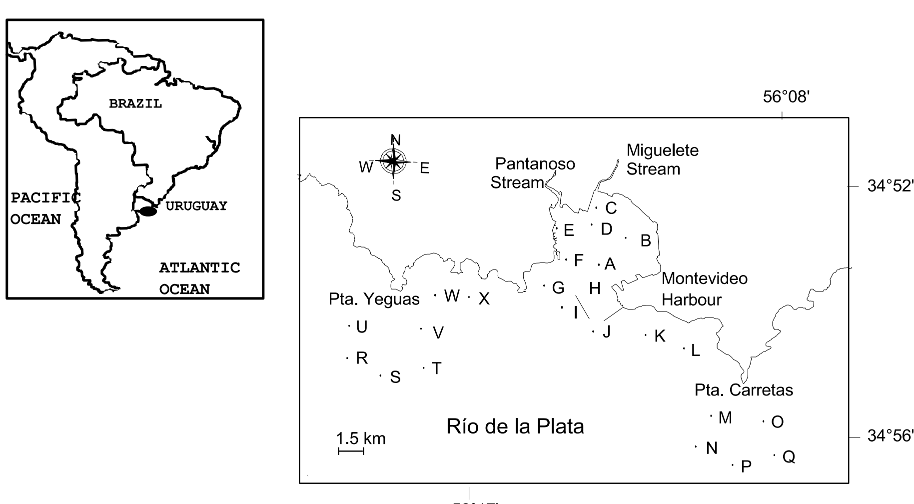

Fig. 1. Study area map with the 24 sampling stations (black dots).

Montevideo coastal zone sediments, and classified the inner region of the bay as highly polluted, and the adjacent coastal zone as moderately polluted. Danulat et al. (2002) defined the Montevideo Port as a hyper-eutrophic system that receives considerable nutrients and organic loads. Muniz et al. (2004) also detected an important enrichment of copper in sediments when compared with previous studies in the area.

2. Materials and methods

Samples were collected from 24 stations in January 1998 (Fig. 1). At each station seven sediment samples were taken with a corer (5 cm internal diameter) for the analysis of the following variables: granulometric parameters, photosynthetic pigment content of surface sediments, redox potential, organic matter content, Cr, Pb and petroleum hydrocarbon concentrations. The detailed methodology used for the analysis of each variable can be found in Muniz et al. (2002). Bottom water samples were obtained using Hydro-Bios bottles in order to measure temperature and to determine dissolved oxygen content by the Winkler titration method (Grasshoff, 1983). Salinity and pH were determined with an YSI multiparameter device, and depth was measured using a Hummingbird echo-sounder.

The seventh corer was used to study the foraminiferal fauna. The uppermost 3 cm layer of the sediment was taken at each station forming a volume of about 60 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 alcohol) for 48 h to differentiate between living and dead foraminifera (Walton, 1952). In the laboratory, the wet samples were carefully washed through 0.500 mm, 0.250 mm and 0.062 mm sieves to separate the size fractions. All living specimens in each sample were picked and identified following the generic classification of Loeblich and Tappan (1988).

2.1. Data analysis

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 Moristita-Horn and the Unweighted Pair Group Method Using Arithmetic Averages (UPGMA) according to Sneath and Sokal (1973). A data matrix was created using the absolute frequency of living foraminiferal species from the 24 stations. Data were transformed using the $\log(x+1)$ to increase the importance of smaller values leading to a more normalized distribution.

From the knowledge of density (defined as the total number of individuals in a sample of 60 cm^3 of sediment) it was possible to calculate some statistical parameters. The specific diversity (H', $\log_e$) was determined using the Shannon–Weaver index or information function (Shannon and Weaver, 1963). The evenness (J') was calculated according to Pielou index (1975) and the species richness (S) was defined as the total number of species in each station.

A principal component analysis (PCA) was carried out for the ordination of sample locations based on the abiotic

Table 1
Environmental variables studied in the Montevideo coastal zone

Stations	Depth (m)	Temperature (°C)	PSU	pH	Oxygen (mg l^{-1})	Sand (%)	Silt (%)	Clay (%)	Md (%)	OM (%)	Eh (mV)	Chl *a* (ugg^{-1})
A	2	24.6	3	6.0	2.5	16.9	73.3	9.8	4.5	6.6	96	6.2
B	2	24.6	3	7.1	2.4	7.8	66.2	26.0	5.9	11.3	34	11.6
C	1.5	24.6	4	7.1	1.8	25.5	60.6	13.9	4.7	8.3	44	3.5
D	6.5	22	15	7.2	3.3	6.6	65.0	28.4	5.8	12.0	12	8.8
E	1.5	24	3.5	7.2	3.2	18.4	73.8	8.1	4.7	12.8	9	0.8
F	3.5	22.9	9	7.3	4.6	17.3	77.5	5.2	4.7	3.5	194	0.5
G	4.5	23.9	12	7.4	6.6	10.0	86.1	3.9	4.8	7.2	156	0.3
H	6.5	22.4	14.5	7.3	3.6	6.3	75.1	18.6	6.1	9.4	88	0.5
I	7	22.4	14	7.4	4.6	7.3	92.1	0.7	5.2	6.2	199	0.2
J	11	21.8	16	7.4	4.3	3.2	75.1	21.7	6.1	9.5	74	0.3
K	6	21.4	21.1	7.9	4.7	4.4	88.9	6.7	5.3	6.8	102	0.1
L	6	21.5	21.1	7.7	4.7	9.9	77.2	12.9	5.4	6.9	212	0.5
M	9	21.7	22.1	7.9	4.8	3.5	85.3	11.2	5.3	4.8	144	0.5
N	9	21.9	22.4	8.0	5.7	8.6	76.6	14.8	4.9	4.5	140	0.5
O	10	21.8	22.8	7.8	5.6	2.1	88.8	9.1	5.4	6.1	176	0.8
P	9	22	23	8.0	5.4	7.0	84.3	8.7	5.3	4.6	138	0.4
Q	10	22	22.8	8.0	5.9	2.4	74.7	22.8	5.4	5.9	176	0.2
R	8	21.7	20.3	8.0	4.2	2.4	88.8	8.8	5.5	6.1	184	0.3
S	7.5	21.7	20.8	8.0	4.6	5.2	88.0	6.8	5.1	5.6	155	0.3
T	7	21.8	21.4	8.0	4.7	3.0	86.4	10.6	5.3	5.2	148	0.2
U	7.5	21.5	21.3	8.0	4.2	4.5	82.7	12.8	5.3	5.5	154	0.4
V	8	21.6	21.3	8.0	4.2	2.2	90.5	7.3	5.9	6.6	220	0.6
W	7.5	21.5	18.3	7.9	4.4	7.2	70.0	22.8	6.0	6.5	214	0.1
X	6.5	21.5	18.9	7.8	4.5	7.5	84.8	7.7	5.3	5.4	163	0.3

Md = mean diameter; OM = organic matter; Eh = redox potential; Chl *a* = chlorophyll *a* content.

Table 2
Cr and Pb concentration in the Montevideo coastal zone, showing mean values and one standard deviation (SD)

Station	Cr (mg/kg)		Pb (mg/kg)	
	Mean	SD	Mean	SD
A	131.5	6.21	215.1	64.06
B	81.1	4.54	246.7	81.65
C	91.5	5.12	369.6	54.23
D	657.1	76.3	352.2	51.68
E	368.1	39.53	64.9	5.85
F	43.7	2.44	44.7	23.69
G	30.9	1.72	39.1	2.84
H	83.7	4.69	65.4	5.90
I	42.1	2.35	38.5	2.80
J	56.2	3.13	41.7	2.17
K	38.9	2.16	56.4	5.10
L	42.5	2.37	57.9	5.23
M	40.1	2.22	58.5	5.28
N	40.3	2.23	58.9	5.31
O	39.3	2.18	57.9	5.21
P	36.7	2.03	55.1	4.95
Q	39.3	2.19	55.2	4.95
R	38.8	2.16	54.5	4.88
S	36.9	2.04	55.4	4.96
T	37.4	2.07	55.1	4.93
U	38.3	2.11	56.2	5.03
V	38.9	2.15	56.7	5.12
W	42.1	2.34	54.8	4.90
X	38.1	2.12	54.9	4.91

factors. The matrix was constructed using 14 variables presented in Tables 1 and 2. To perform uni and multivariate analyses, we used the software Multivariate Statistical Package (MVPS) from Kovach (1999).

3. Results

A total of 18 species and 18,341 individuals of benthic foraminifera were recorded at the 24 sampling stations of the Montevideo coastal zone (Table 3) belonging to the suborders Rotaliina (13 species) and Textulariina (five species).

3.1. Cluster analysis

The result of the Q Mode cluster analysis allowed the recognition of two major groups of stations: Group I, hereby called Inner Bay zone; and Group II, that can be divided into two sub-groups: Groups IIa and b denominated Punta Carretas zone and Punta Yeguas zone, respectively (see Fig. 2). Similar results were obtained by the R Mode that evidences the different ecological conditions in the three sub-environments (Fig. 3). The assemblages were named according to the dominant species in each one.

The Inner Bay zone bunched the inner bay stations (A, B, C, E and F) and it is characterized by a low number of species with few individuals in each station. Although station D is located in this portion of the bay, it does not belong to the cluster because it was an azoic zone. It is possible to distinguish a small group in the R Mode that bunched two species (*Psammosphera* sp. and *Buliminella elegantissima*), which only appear in the Inner Bay zone. This sub-environment seems to be under stressed environmental conditions due to the different pollutants that come from different sources and strongly affect this zone. It is characterized by the highest concentration of organic matter and heavy metals (Cr and Pb) and the lowest values of Eh in the sediments. Also, the lowest values of pH and salinity in the water column were registered in this zone.

Group IIa (Punta Carretas zone) bunched the stations located in the Punta Carretas region in addition to stations I and J (see Figs. 1 and 2). It is constituted by a total of nine stations characterized by *Ammonia tepida* assemblage. This assemblage consisted of nine hyaline species and *A. tepida* represented 99.1% of the total assemblage.

On the other hand, Group IIb (Punta Yeguas zone) included the stations placed in the same name region plus stations G and H. The foraminiferal assemblage corresponding with this sub-environment is *Miliammina fusca* (73.3%) constituted by six species (two hyaline and four agglutinated). This zone showed values of pH and Cr slightly lower than Punta Carretas zone.

3.2. Foraminiferal density, diversity and evenness

In order to have a better insight into the general behavior for the response of foraminiferal fauna to the abiotic factors, we calculated the mean density ($\bar{D}$) from each one of the sub-environments (groups) described above. The $\bar{D}$ is defined by $\bar{D} = \frac{\sum_i D_i}{N}$, where D_i is the density for the station i ($i = \mathrm{A}, \mathrm{B}, \mathrm{C}, \ldots$) and N is the number of stations of each group.

The Inner Bay zone presents the lowest mean density ($\bar{D} = 15$; Fig. 4) recorded in the whole area, with values that ranged between 11 and 22 ind samp^{-1}. In addition, station D was a totally azoic place. This sub-environment showed intermediate values of diversity (between 0.760 and 1.337) and high evenness, with values approaching 1. Despite this, the local richness is the lowest registered in the whole area (between 3 and 5 species; Table 3).

In the other extreme, Punta Carretas (Fig. 4) zone showed the highest mean density ($\bar{D} = 1220$) with values ranged between 121 and 6565 ind samp^{-1}. In general, the diversity was low, ranged between 0.134 and 0.918, and evenness from 0.061 to 0.570. The richness showed the highest values with a maximum of 14 species at station O (Table 3). *A. tepida* appeared as the dominant species in this environment with densities up to 6390 ind samp^{-1} at station O.

Punta Yeguas zone presented intermediate values of mean density ($\bar{D} = 600$; Fig. 4) varying from 268 to 1352 ind samp^{-1}, as well as intermediate richness and evenness, ranged between 4 and 8 species and from 0.428 to 0.734, respectively. Despite *A. tepida* was the dominated species, as in Punta Carretas Zone, with the R Mode cluster was possible to detect a different assemblage corresponding to

Table 3
Density of foraminífera species present in the Ubatuba Bay in each station

Foraminifera/stations	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Ammobaculites exiguus							25			2			1		21			6	17	9	4	2	1	
Ammonia parkinsoniana							152	51			66	42	11	15	48	2	1	11	42	65		31		56
Ammonia rolshauseni																								5
Ammonia tepida	3	8	12		12	2	241	159	112	117	308	137	911	1120	6390	1230	1000	157	665	600	379	242	329	530
Ammotium salsum							38	12			2		3	1	3		1				1		8	
Bolivina pulchella															6									
Brizalina striatula													17	8	1	4	16		12		9			5
Bulimina marginata															3		1							
Buliminella elegantissima	7	1	5		8															5				
Cibicides variabilis												1	1	1	6	1	5							
Discorbis williamnsoni														2	4	3				7				5
Elphidium excavatum					5	2	16	7	8	5	10	3	9	25	12	1	3	1	11	30	1		3	2
Milammina fusca						8	287	116			2		2	6	34	5	24	93	600	222	191	174	202	415
Pararotalia cananeiaensis								7	1	3	5	1	11		21	1	1							8
Pseudononion atlanticum								8					4	2	15	8	12		5					
Psammosphera sp.	3	2	5		7																			
Rosalina sp.														1	1									
Trochammina sp.						1	5													1				
Total	13	11	22	0	32	13	764	360	121	127	393	184	970	1181	6565	1255	1064	268	1352	939	585	449	543	1026

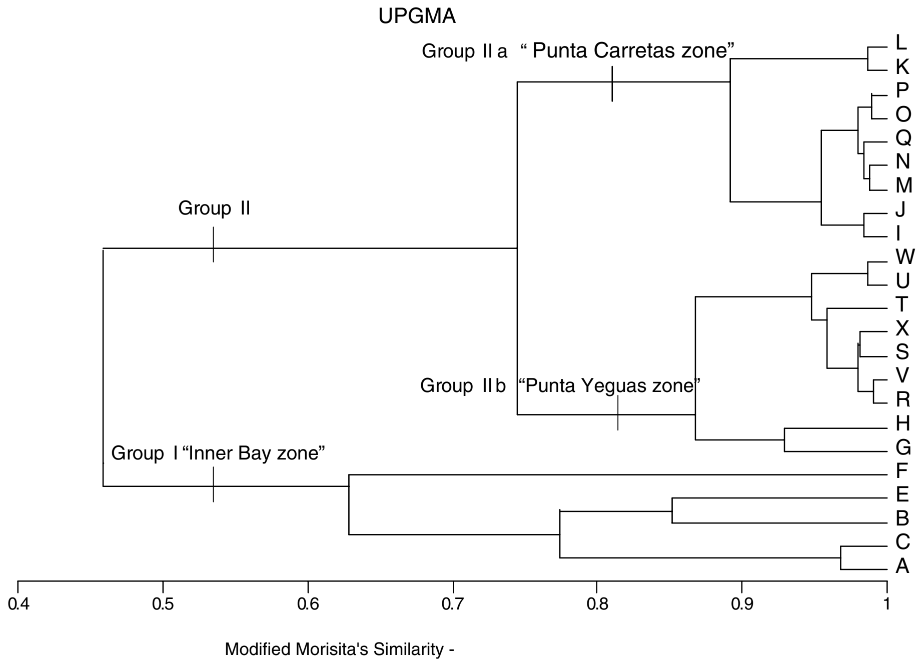

Fig. 2. Dendrogram classifications showing the station groups.

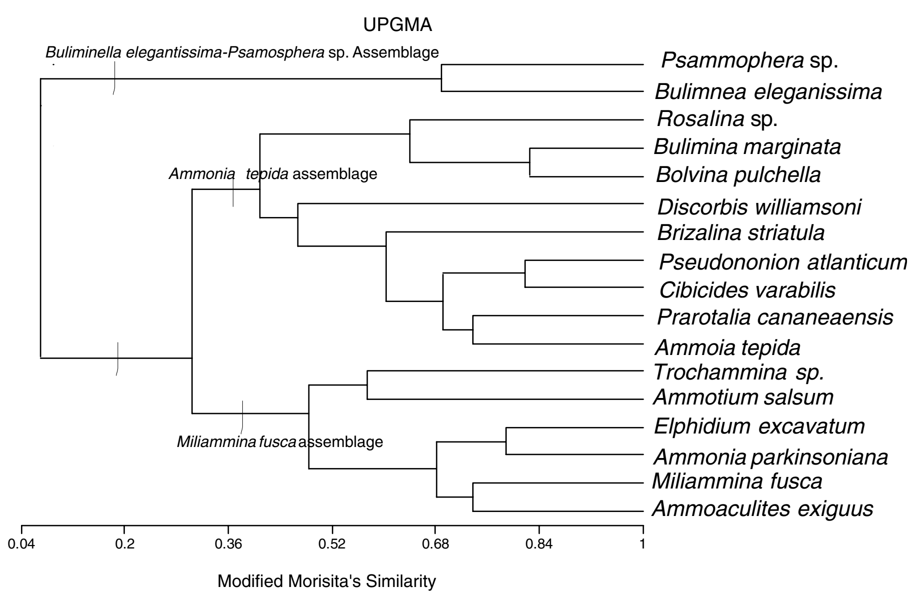

Fig. 3. Dendrogram classifications showing the species assemblages.

this sub-environment. This is the *M. fusca* assemblage and it differs from *A. tepida* assemblage not only quantitatively, but also in its species composition.

The mean density values of each sub-environment were plotted against Cr, Pb, organic matter content, dissolved oxygen concentrations, Eh and pH (Fig. 5). As a general feature, it is possible to relate the impoverish zone of Montevideo Bay to all the chosen abiotic variables: high OM and heavy metal concentrations and the low redox, pH and dissolved oxygen concentrations. As a consequence of the homogeneous dependence of abiotic parameters with the mean density, we cannot distinguish which one is the determinant factor for the faunal impoverishment. In fact, the extremely low density possible results from the integrated action of all this factors.

3.3. Ordination

As can be seen in Fig. 6, the PCA analysis bunched the stations according to their environmental conditions, in approximately the same two primary groups obtained with the cluster analysis. Group I is formed by the stations

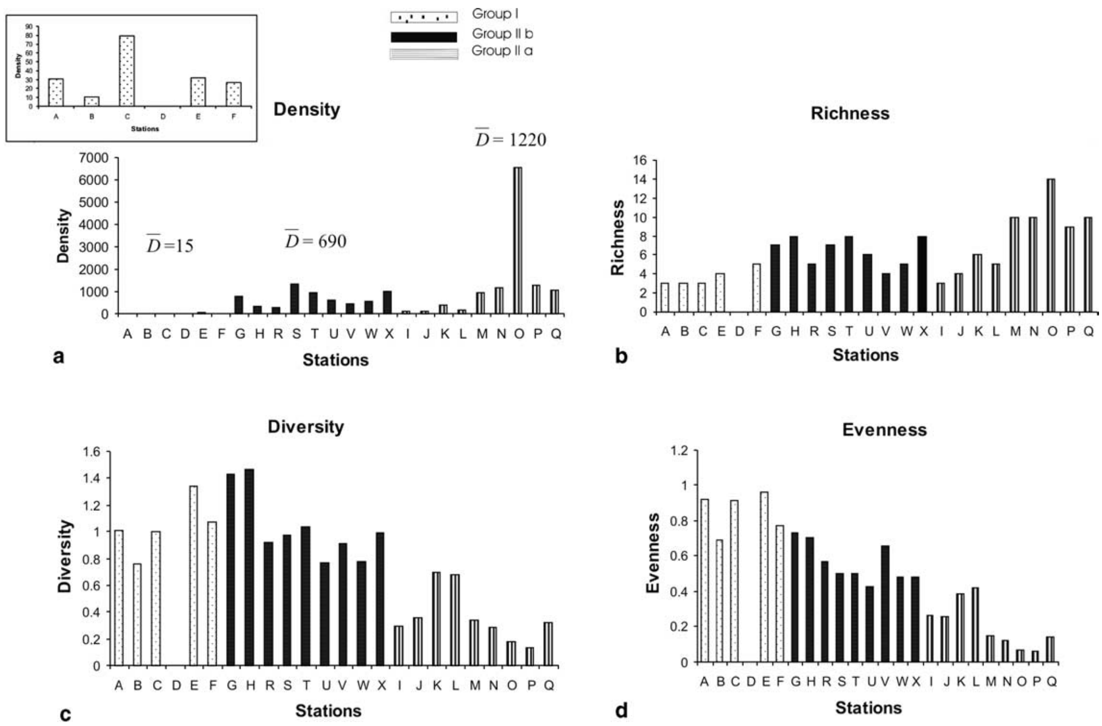

Fig. 4. Populational parameters used to relate the foraminiferal assemblages to the environment conditions. $\bar{D}$ = mean density.

located in the Inner Bay (A, B, C, D and E) and it is positively correlated with Axis I. On the other side, Group II which is formed by the remaining stations F to X is negatively correlated with Axis I. The first and the second component together explained 75.6% of the total data variance, being 54.8% explained only by the first component. Axis I was positively correlated with Cr and Pb concentrations, temperature, sand, organic matter and Chl *a*, and was negatively correlated with Eh and silt. Axis II was positively correlated with depth, salinity, pH, clay and mean diameter.

3.4. Morphological abnormalities

Out of the 18 species found in the study area, only three species exhibited morphological abnormalities (*A. tepida*, *B. elegantissima* and *Elphidium ecxavatum*). Basically, all the hyaline specimens observed in the Inner Bay zone showed at least one type of abnormality. In the Inner Bay zone, more than 58% of the hyaline specimens showed morphological deformities. When we consider the total population in each station, this number reaches 72.7% (Table 4). Morphological abnormalities in this zone were manifested as protuberances of one chamber (Fig. 7F), aberrant chamber shape and size (Fig. 7B and I), additional chamber (Fig. 7J and K), overdeveloped chambers (Fig. 7C), double apertures (Fig. 7M) and siamese twins (Fig. 7E). Some specimens accumulate more than one type of deformation and we named this type as complex deformities (Fig. 7D).

In the outermost regions (Punta Carreta and Punta Yeguas zones), the percentages of deformed specimens were much lower (between 0.03% and 0.08%). In these zones, the morphological deformities were manifested basically by aberrant chamber size (Fig. 7B).

4. Discussion

As have been shown by Muniz et al. (2002), the Montevideo coastal zone has at least two different regions clearly related to their environmental characteristics and degree of anthropogenic impact. In the present work, it was possible to understand how the different features of these regions are reflected in the benthic foraminiferal assemblages.

4.1. The inner bay zone

This sub-environment occupies the inner shallow region of Montevideo Bay and do not have a defined foraminiferal assemblage. *Psammosphera* sp. and *B. elegantissima* were grouped together in the R Mode cluster, as a consequence of its limited distribution. Other species like *A. tepida* and *Elphidium excavatum* were also observed with low density in this inner region. In addition, high percentages of abnormal tests were observed, most of them were classified as complex. In general, population parameter's values recorded in this zone can be connected with the high degree of local contamination. Montevideo Bay receives wastes from many different industries, urban centers and from a great number of sewage pipes through three streams that flow into it. Consequently, this region has higher organic load and lower oxygen content in bottom sediments as well as grossly polluted by Cr (657.1 mg/kg), Pb (369.6 mg/kg)

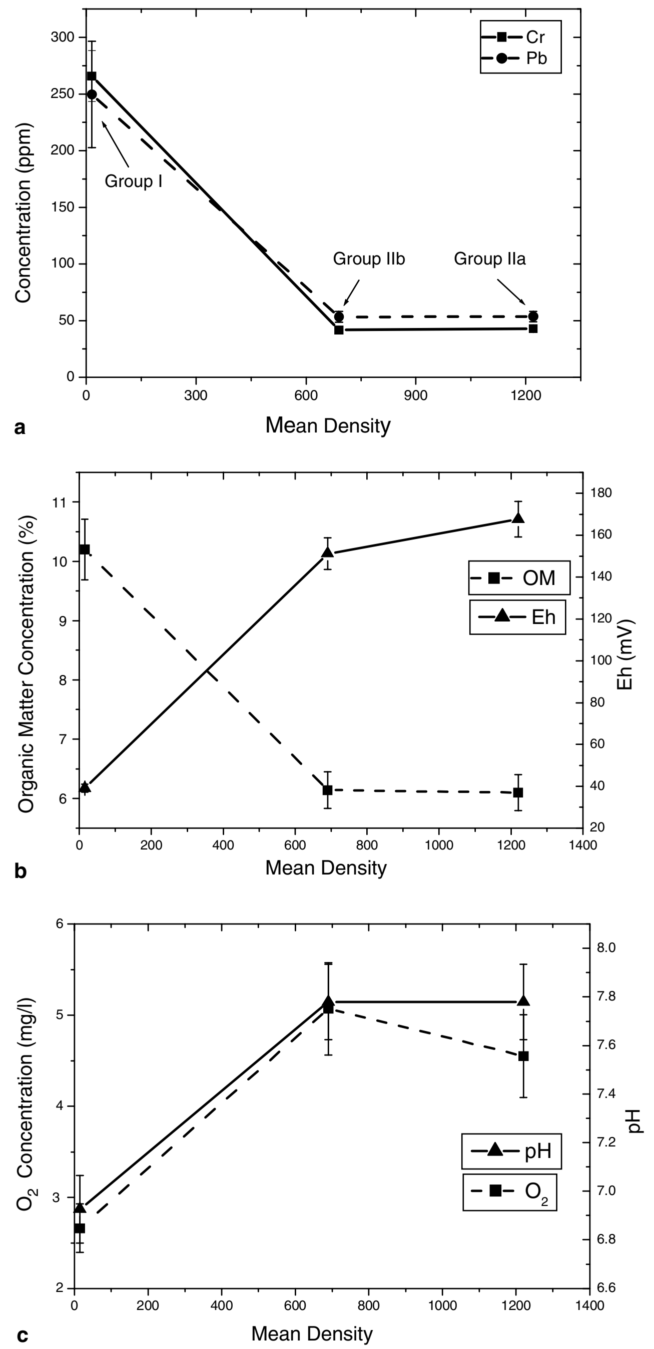

Fig. 5. Mean values of some abiotic parameters as a function of mean density for the three sub-environments of the whole area. The groups are marked only in (a).

and hydrocarbons (PAHs = 10.61 μg/g, aliphatic hydrocarbons = 0.61 μg/g and phytane = 0.89 μg/g) as seen by Muniz et al. (2002). It also presented the most impoverished foraminiferal population and lowest redox potential than any other zone. All the living species found in this inner region have been reported to show great tolerance to contaminants and low oxygen content. *B. elegantissima* has shown particular resistance to oxygen depletion (Bonetti, 2000), while *A. tepida* occurs close to outfalls discharging heavy metals, sewage, and other chemical and thermal effluents (Alve, 1995; Cearreta et al., 2000; Burone and Pires-Vanin, accepted for publication). These species, together with *E. excavatum* showed activity after 24 h of anoxia, and are also recognized as facultative anaerobes (Moodley and Hess, 1992), characteristics that probably allowed them to develop under more perturbed conditions. Moreover, this area registered very low densities and richness showing the extreme case of an azoic zone (station D). Perhaps, the frequent dredging activities in station D are also responsible for its azoic character.

The separation of the two zones, is quite evident from PCA (Fig. 6), where Group I clustered those stations located in the inner portion of the Montevideo Bay. Furthermore, station D that is included in this group (in which none individual was observed) is located close to the ANCAP petroleum refinery and it presented the highest PAHs and Cr concentrations.

Another warning signal of the local stressed conditions is the partial post-mortem dissolution of calcareous test. This is probably a consequence of acid sediment conditions due to the large amounts of organic material that enters into Montevideo Bay through the streams inputs. Redox potential (Eh) is an indicator of the presence of oxygen and organic matter in the sediment (Pezeshki and Delaune, 1993), the low redox values registered in the surface sediments of the study area should be the consequence of the high oxygen demand induced by the decomposition of the large amount of organic matter.

Hydrographic characteristics of the Montevideo Coastal zone are extremely unstable. They are basically determined by dynamic interactions between freshwater and marine components. The low salinity values registered in the Inner Bay zone were not expected, since, previously recorded values were usually around 15 as those observed in the adjacent Punta Carretas and Punta Yeguas zone (Gómez-Erache et al., 2001). These low values can be the consequence of the high pluvial period registered few days before the sampling survey. It is known, that the typical species living in estuaries are adapted to great salinity variability. Venturini et al. (2004) showed that despite the salinity gradient from the inner part of Montevideo Bay to the outermost part, an organic and chemical pollution gradient was also observed, which seemed to be a relevant determining factor in explaining the macrobenthic community structure in this area. Therefore, the impoverishment in foraminiferal fauna registered in this portion should not be only the result of the low salinity values.

Species diversity can be viewed as a measure of environmental stress on benthic foraminiferal communities, being that low species diversity is usually a characteristic of polluted environments (Bretsky and Lorenz, 1970; Schafer et al., 1991; Yanko et al., 1998). However, in the present study, we point out the relative high diversity values observed in the Inner Bay zone when compared to those obtained in the other two zones (Punta Carretas and Punta Yeguas). According to Warwick and Clarke (1993), species composition varies considerably from place to place

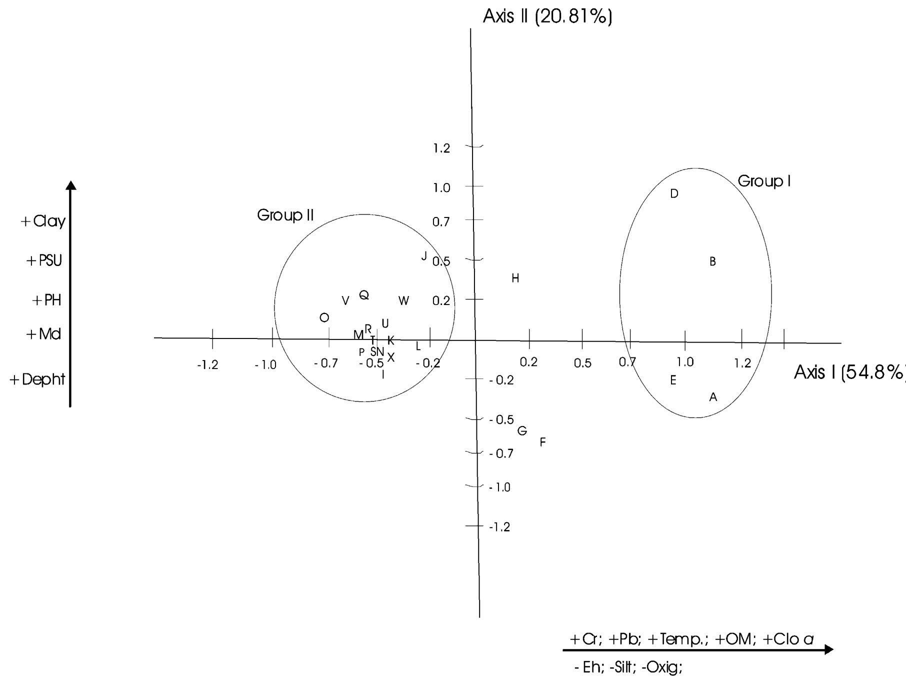

Fig. 6. PCA ordination diagram of sampling based on the selected variables measured. The two main groups formed are shown (Groups I and II).

Table 4
NAT: number of abnormal tests, NH: number of hyaline specimens, NT: total number of individuals

Sample	NAT/NH × 100	NAT/NT × 100
A	80	61.54
B	88.88	72.72
C	58.82	45.45
E	64	50
F	75	23.07
G	0.24	0.13
H	1.7	1.11
I	0.82	0.82
J	0.8	0.78
O	0.03	0.03
P	0.08	0.08

depending on local environmental conditions, and it is possible that an unperturbed community in an area and a perturbed one in another have the same diversity. So, in this case, we might consider another population parameters such as density, assemblage composition or the presence of abnormal tests as more suitable indicators of the prevalent ecological conditions.

4.2. Punta Yeguas and Punta Carretas zones

The fauna recorded in these zones is similar to that registered by Boltovskoy (1965) from a similar region in the Argentinean coastal zone.

Although the PCA analysis bunched together Punta Yeguas and Punta Carretas zones as a consequence of their similar environmental conditions, it was possible to distinguish both through the foraminiferal assemblages and their population parameters (Figs. 2, 3 and 6). A higher number of agglutinated species was recorded in the stations of Punta Yeguas, while calcareous species dominated in Punta Carretas zone. This pattern can be related to the great marine influence on the latter region as indicated by the presence of *Pararotalia cananeiaensis*. This is a small marine species easy to be transported by currents and used as an indicator of marine influence (Debenay et al., 2001a). Moreover, the presence *P. cananeiaensis* in this area can be the response to the entrance of more saline water, considering that the mean upstream limit of the saline intrusion is located just at the transverse section of Punta Yeguas (Nagy et al., 2002).

According to Muniz et al. (2002), in contrast with Montevideo Bay, Punta Carretas and Punta Yeguas are not grossly polluted by Cr, Pb and petroleum hydrocarbons. However, the most important sewage pipe of Uruguay flows in the region of Punta Carretas. Species richness and density are quite higher in Punta Carretas than in Punta Yeguas, being that the opportunistic species *A. tepida* is the dominant one, especially in Punta Carretas zone. This species has high adaptability to environmental variability and, according to Debenay et al. (2001b), its growth may be favored by a temporary decrease in water salinity and nutrients input, which are common features in this zone, due to the spatial oscillation of the salinity front. In addition, within Punta Carretas zone, station O—the one located closest to the sewage pipe—presented a maximum density peak (most of them belonging to *A. tepida* with 6565 individuals). The enrichment caused by the sewage pipe in Punta Carretas zone could be supporting the relatively high number of species and determining the fundamental difference between Punta Carretas and Punta

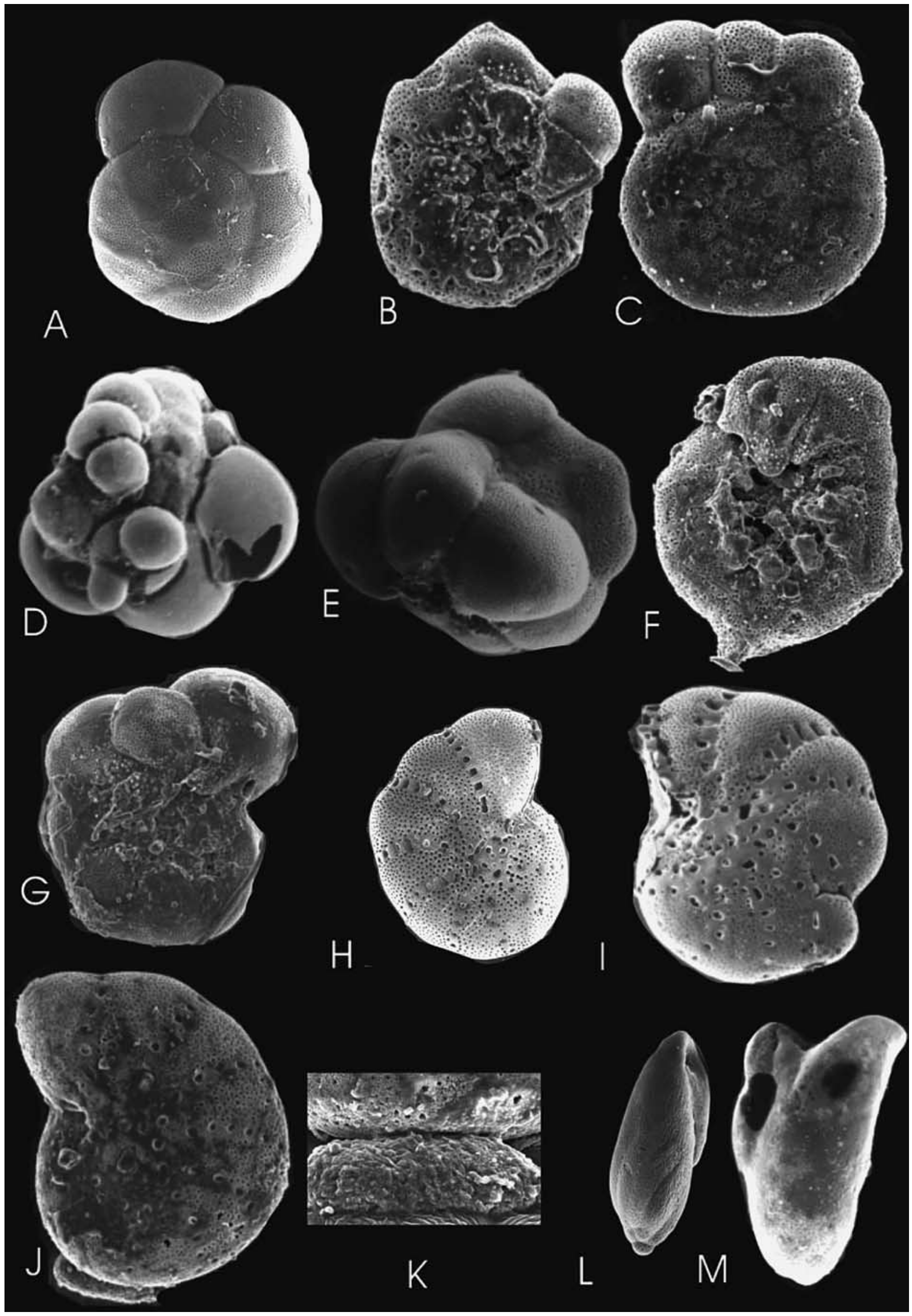

Fig. 7. A—Normal specimen × 230 (*Ammonia tepida*), B—Aberrant chambers shape and size × 300 (*A. tepida*), C—Overdeveloped chambers × 270 (*A. tepida*), D—Complex abnormality × 250 (*A. tepida*), E—Siamese twins × 380 (*A. tepida*), F—Reduced size of some chambers and presence of pustule × 370 (*A. tepida*), G—Aberrant chamber arrangement × 170 (*A. tepida*), H—Normal specimen × 220 (*Elphidium excavatum*), I—Aberrant chamber shape (the last chamber is broken) × 160 (*E. excavatum*), J—Additional chambers × 220 (*E. excavatum*), K—Detail of figure J × 1200 (*E. excavatum*), L—Normal specimen × 500 (*Buliminella elegantissima*), and M—Double aperture × 330 (*B. elegantissima*).

Yeguas assemblages composition, named *A. tepida* and *M. fusca*, respectively.

4.3. Abnormalities

Ecological data reported in the literature as causes of abnormal test formation are from natural and anthropogenic origin. Morphological abnormalities are a general feature occurring among all benthic foraminifera. This phenomenon occurs in both cold and warm water, independent of latitudes, taxonomic affinity, feeding strategy, or test morphology (Yanko et al., 1998). Abnormal test shapes have been reported from areas subjected to high variability of environmental parameters such as salinity (e.g., Arnal, 1955; Tufescu, 1968; Closs and Madeira, 1968) and temporary acidification of the environment (Le Cadre et al., 2003). Some abnormalities may also be the result of chemical damage (summarized in Boltovskoy and Wright, 1976). However, deformed test appears to increase dramatically in areas subjected to different types of pollutants, e.g. oil slicks (Vénèc-Peyré, 1981), sewage discharge (Watkins, 1961), agrochemicals (Bhalla and Nigam, 1986), high organic matter content (Caralp, 1989; Burone, 2002; Burone and Pires-Vanin, accepted for publication) and heavy metal contamination (Sharifi et al., 1991; Alve, 1991; Yanko et al., 1994, 1998; Samir and El-Din, 2001; Vilela et al., 2004). 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 effects and would be very difficult to isolate any single specific cause.

In the present work, we observed that besides the marked negative population response to the presence of a significant concentration of pollutants in the Inner Bay zone, the presence of abnormal test emphasizes the adverse effects of these pollutants over the foraminiferal fauna. The organic matter content in the sediment of the Montevideo Bay was high compared to estuaries of nearby regions (Benvenuti, 1997; Ieno and Bastida, 1998; Muniz and Venturini, 2001). Therefore, the more perturbed environmental conditions observed mainly in the Inner Bay zone, such as the probable occurrence of acidic sediments and oxygen depletion, which can result from the high organic content, may be responsible for the abnormalities in foraminiferal test.

In addition to this, Samir and El-Din (2001) working in a polluted area with benthic foraminiferal assemblages from El-Mex Bay (Egypt) observed a strong correlation between test deformation and heavy metals concentration. Considering that in our work, we registered in the sediment higher values of Cr (368 mg/kg) and Pb (369.6 mg/kg) than those registered in El-Mex Bay Cr (152.6 mg/kg) and Pb (157.7 mg/kg), we can suggest that heavy metals were also related to the abnormalities that we observed in foraminiferal tests.

5. Conclusion

In this work, we have studied the effect of pollution on foraminiferal fauna in an estuarine region of the Río de la Plata. Through the foraminiferal assemblages presented in the study area, it was possible to distinguish three different sub-environments. On one hand, Montevideo Bay, the inner bay particularly, which showed an extremely poor foraminiferal fauna—including a totally azoic station—evidencing the high degree of local contamination. On the other hand, Punta Carretas and Punta Yeguas that even though they presented a moderate pollution degree, it was noticed a positive effect on density of foraminiferal fauna, especially on *A. tepida*, caused by the inputs of the sewage pipe, a more pure organic contamination.

Species diversity not only appeared to be a good indicator of the health environment, but also the mean density could be used to evidence local productivity and environmental conditions. We detected a strong relationship between organic matter, oxygen and heavy metal concentrations, as well as redox potential and pH values with the mean density of each sub-environment. The diverse pollution sources and the complex mixture of different contaminants in the sediments make difficult to identify the effect of a single stressor on benthic foraminifera, even more, in high variable environments such as estuaries. Then, we can conclude that such an extreme harmful condition in Montevideo Bay is a consequence of the combined action of all polluted factors present in the bay. We also have to remark the stressing effect of natural abiotic variables, like the rapid salinity changes.

Finally, we can state that the high percentages of abnormal tests in Montevideo Bay seem to be related with the high contamination level. Nevertheless, a detailed analysis about the relationship between the abnormalities and heavy metal concentrations is being performed with X-ray techniques, and will be published elsewhere.

Acknowledgements

We are grateful to Fondo Clemente Estable to provide a pos-doctoral fellowship (No. 8268) to LB. The Uruguayan Army is acknowledged for the use of its facilities during the field work. Comisión Sectorial de Investigación Científica (CSIC) of Uruguay and the Government of Montevideo City (IMM) provided financial support for this study. LB expresses her gratitude to Carlos Martinez that kindly allowed the use of the laboratory of the Sección Oceanología of the Facultad de Ciencias, Uruguay.

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