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Foraminifera, Thecamoebians and Palynomorphs as Hydrodynamic Indicators in Araguari Estuary, Amazonian Coast, Amapá State – Brazil

Foraminíferos, Tecamebas e Palinomorfos como Indicadores da Hidrodinâmica no Estuário do Araguari, Costa Amazônica, Estado do Amapá - Brasil

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Abstract

The Araguari estuarine dynamics is singular among traditional models of estuaries under tidal regime due to influence of macrotidal and tidal bore. In order to establish estuarine zones in Araguari according foraminifera, thecamoebians, paliynomorphs and physical-chemistry parameters, sixteen sample stations were established along the estuary. Turbidity and temperature were the environmental parameters which allowed determination of the estuarine gradient. Eighteen species of foraminifera, ten of thecamoebians and fourteen of particulate organic matter types were identified. Cluster analysis in R-mode showed three microorganism assemblages and four palynomorph ones. The CCA analyze shows turbidity and total organic matter with the most influence over foraminiferal and thecamoebians distribution at Araguari. Clustering analysis in Q-mode using all data formed four groups suggesting three estuarine zones in Araguari: Zone I composed of thecamoebian species and continental palynomorphs; Zone II - composed by mangrove foraminifera, thecamoebians and all palynomorph assemblages; and Zone III – composed by mangrove and estuarine foraminifera and all palynomorph assemblages.

Keywords: foraminifera; thecamoebian; palynomorphs

Resumo

O regime de macromaré e a pororoca controlam a dinâmica estuarina do Araguari, na qual é muito diferente dos modelos tradicionais dos estuários sob este regime de maré. Objetivando estabelecer zonas estuarinas no Araguari com base em assembléias de foraminíferos, tecamebas, palinomorfos e parâmetros físico-químicos, foram estabelecidas dezesseis estações amostrais ao longo do estuário. A turbidez e a temperatura foram os parâmetros ambientais que permitiram determinar gradiente estuarino. Dezoito espécies de foraminíferos, dez espécies de tecamebas e quatorze espécies de palinomorfos foram identificadas. A análise de agrupamento em modo-R mostrou a existência de assembléias de foraminíferos e quatro de palinomorfos. A análise em CCA demonstrou que a turbidez e a matéria orgânica como os parâmetros de maior influência na distribuição dos foraminíferos tecamebas no Araguari. A análise de agrupamento em Modo-Q usando todos os dados formou quarto grupos de estações que sugerem a existência de três zonas estuarinas: Zona I - composta por tecamebas e palinomorfos continentais; Zona II – compostas por foraminíferos de manguezal, acritacos e todas as assembléias de palinomorfos; e Zona III – composta por foraminíferos de manguezal e estuarinos e por todas as assembléias de palinomorfos.

Palavras-chave: foraminíferos; tecamebas; palinomorfos

1 Introduction

Foraminifera and thecamoebians are useful hydrodynamic bioindicators because their microfaunal composition evidence environmental characteristics like oxygen changes, depth, sedimentological features and other informations, like contamination by organic effluents or heavy metals in coastal areas (Schaefer, 1991; Alve, 1995).

Blending of marine and fresh water is detected by a change in assemblage composition and behavior, suggesting that some agents like tidal amplitudes and fluvial discharge can be qualitatively monitored through biotic features in estuaries (Bonetti & Eichler, 1997).

Valuable studies about foraminiferal assemblages in macrotidal estuaries have been carried out to generate tidal plain zonations applied to studies of sea level changes in Australia (Wang & Chapell, 2001), France (Debenay e*t al.,* 2003), and Argentina (Scott *et al.,* 1990). They were also a biotic tool to identify hydrodynamic parameters in England and China (Wang & Murray, 1983).

Wang & Murray (1983) have investigated several microtidal estuaries (Qiangtan, Yangtaze, Humbler and Severn) characterized by a foraminifera population composed by carried specimens + reworked material + autochthonous specimens. The carried specimens were too small and were associated to fine grains; the autochthonous ones were larger and showed young features. The reworked material was broken or damaged. In microtidal estuaries, the opposite ensues: the number of carried and reworked specimens is much smaller than in macrotidal estuaries.

Wang & Murray (1983) point out that in well-mixed (macrotidal) estuaries assemblages are much similar to those in mesotidal estuaries, but the number of exotic species is 50% larger than dead assemblages. Moreover, assemblage distribution in estuaries can be influenced by great transportation features that can inhibit the development of longitudinal zonation.

Scott *et al.* (1990) have performed a comparative study of foraminiferal zonation in the tidal plains of South America and at corresponding latitudes of the North Hemisphere. Among the six estuaries analyzed by these authors, three of them present macrotidal conditions: Rio Grande, Rio Chico and Bustamante Bay. The dominant foraminifera order in those estuaries was Textulariida. In Rio Grande Estuary the fauna was dispersed and the dominant species were *Trochammina macrescens* and *Polysaccammina ipohalina*. In addition to these species there were a great number of reworked Tertiary thecamoebian species that indicate great fluvial catchments and high hydrodynamics. In Chico River Estuary *Trochammina inflata* and *T. squamata* were dominant. In Bustamante Bay the upper area of the salt marshes was dominated by *T. macrescens, T. inflata* and *P. ipohalina* and by *Miliammina fusca* in the subtidal only. According to the authors, the fauna was very similar in both hemispheres and the vertical relationship among species in the North Hemisphere also holds for the South Hemisphere.

In South Alligator Estuary located in North Australia, Wang & Chappell (2001) evaluated the foraminifera assemblages potential to reconstruct paleotidal and salinity conditions in macrotidal tropical estuaries during the Holocene. Ninety-two species were identified, but only 12 of them presented live specimens. In the main channel a zonation was identified: a gradual decrease of porcelanous tests species (e.g. *Quinqueloculina ferrusaccii*) and an increase of hyaline species (e.g. *Ammonia beccarii*, *Shkoinella globosa* and *Reussella spinulosa*) and brackish water species (e.g. *Thurammina? limnetes*, *Trochammina inflata*, *Arenoparella asiatica*, *Lituola sal*sa, *Miliammina fusca*, *Stomoculina multiangula, Pseudonanionella variabilis* and *Trichohyalus tropicus*). Palaeoenvironmental interpretation was carried out using a palynological analysis to support the foraminiferal assemblages responses.

Many proxies are employed on paleoenvironmental interpretation purpose, although isolated works and no comparative results. Some authors thus propose that it would be useful to compare foraminifera with other proxies such as ostracods, dinofagellates, algae, palynomorphs and others (Debenay *et al.,* 2003).

The study of a depositional system based on the assemblage of particulate organic matter (POM) or palynomorphs, may indicate specific environmental conditions, such as hidrodynamic and sedimentological parameters (Tyson, 1995). The sedimentary organic matter behaves as other sedimentary particles. Determination of the assemblage and its relative abundance associated to sedimentological data allow distinguish organic matter source.

Although palynofacies is largely applied in petroleum geology studies, it is also useful in all sorts of research concerned to particulate transfers and POM catchments, in order to reconstruct depositional environments and their hidrodynamics (Sebag *et al.,* 2006). Other data provided by palynofacies proxy are: contrasting biological inputs in estuaries; distinguishing between aquatic and terrestrial POM origin, if it occurs (Tyson, 1995); variance on sedimentary organic matter, always linked to fluctuations in water level or terrestrial sedimentary fluxes (Sebag *et al*., 2006); and determining if the POM is allochthonous or not based on particles composition (Di Giovanni, 1994; Tyson, 1995).

Palynofacies is sensitive proxy to perceive environmental changes caused by either climatic or human influence. It could also play a major role in biogeochemical cycles and fluxes in terrestrial geosystems, including hydrological fluxes (Di Giovanni *et al*., 2002).

In Brazilian estuarine regions, studies on foraminiferal and thecamoebian assemblages were made in order to establish estuarine zones according to different levels of salinity influence (Closs, 1964; Dias-Britto *et al*., 1988; Barbosa, 1995; Eichler & Bonetti, 1995). However, foraminiferal assemblages are less used to reveal hydrodynamic patterns in estuarine environments. There are lack of studies on foraminifera and thecamoebians assemblages distribution on macrotidal coastal regions in Brazil like those in the Amazonian region (between 2º N and 2º S) since they are inhospitable.

In the present study, a combination of foraminiferal and thecamoebians assemblages, palynofacies, and abiotic parameters were performed at Araguari Estuary to identify a depositional zonation representing hydrodynamic and ecological patterns that could be applicable to paleoenvironmental analysis in the Amazonian region.

2 General Settings

Araguari Estuary is located next to the Amazon River's mouth and is the main estuarine system on Amapá State coast (Figure 1). This estuary has influence of Amazon River water by its mouth. During rainy season, fresh water inputs system by flooding of alluvial plain (Santos, 2006). Water in Araguari river has great influence of Amazonas fluvial system due to proximity, it results in no representative salinity level at river mouth.

Total annual rainfall at the Araguari River mouth is between 1500 and 3500 mm/year (Bezerra *et al*., 1990). Seventy percent of the rain falls between the months of December and May, in the rainy season.

The maximum discharge occurs in May and the minimal in December. Liquid discharge is 23 x 10^9 m^3/year and solid discharge is 7 x 10^5 ton/year (Allison *et al*., 1995).

Araguari Estuary is a macrotidal estuary with a 5 m tidal range at Ponta do Guará (DHN, 2000). The influence of the tide reaches the city of Ferreira Gomes, 120 km inland. The tidal bore (locally known as *pororoca*) occurs in the estuary up to 50 km from the mouth and plays an important role in erosional and depositional phenomena (Santos *et al*., 2005). The estuary has a predominantly fine-grained sedimentary regime represented by mud changing to fine sand seaward (Santos, 1994).

The estuary is located on the Pré-Araguari unit whose depositional history is linked to ancient river systems and to the sea level change in the Holocene (Costa, 1996). Its evolution is connected to the evolutionary history of the Amazon River mouth. Costa (1996) and Santos (2006) point out that the establishment of the estuarine channel of Araguari River took place 500 years ago with the formation of the least meander and recent mouth of this river. The estuary is bordered by lowlands with flooded *várzea* forest that changes to the mangrove seaward.

3 Material and Methods

3.1 Field work

Sixteen samples were collected at Araguari Estuary in the rainy season, between March and April 2005 (Figure 1). A van Veen grab was used to collect samples in the subtidal region during low tide. From the sediment under consideration were set aside 50 ml to foraminiferal and thecamoebian analysis, 100 g to grain size analysis, 50 g to total organic matter analysis and 10 ml to particulate organic matter analysis.

Physicochemical parameters of superficial water (temperature, salinity, pH, oxygen, turbidity, conductivity) were measured in the field with HORIBA equipment during low tide.

3.2 Grain Size

The grain size analysis was performed according to the methodology described in Suguio (1973), whereby wet samples pass through a 0.062 mm sieve to separate the mud sediment. The finest fractions were analyzed using the pipette method and the textural classification adopted was the one by Flemming (2000).

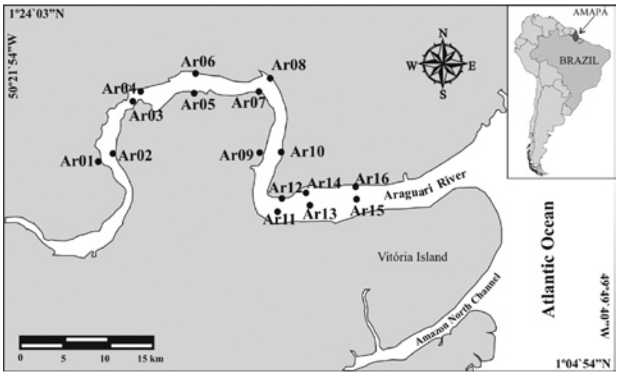

Figure 1 Location map of the samples in Araguari River Estuary**.**

3.3 Total Organic Matter (TOM)

In organic matter processing the loss of ignition method (LOI) was used, which is based on sequential heating of the samples in a muffle furnace. Fifty grams of dry sample were oven dried for 24 hours at a temperature above 60º C to determine TOM. Afterwards, the sediment was weighed and the carbonates were burned in a muffle furnace at 500°C. After 4 hours the sample was weighed again. TOM was determined by the difference between the initial and the final weight.

3.4 Foraminifera and Thecamoebians

An aliquot of 50 ml of sediment was washed through a 0,5 and a 0,063 mm sieve. After drying, the microfauna was separated by flotation in carbon tetrachloride. Counts were carried out under a stereomicroscope for the 0,063 mm residues. Systematic revision for classification of phyla was based on Margulis *et al*. (1999), for class and order on Sen Gupta (1999), for genera on Loeblich & Tappan (1988) and for species on several authors (Scott & Medioli, 1980; Boltovskoy *et al.* 1980; Debenay *et al.* 2002 and 2004)

3.5 Particulate Organic Matter

Sample preparation for particulate organic matter analysis was conducted according to non-oxidative palynological procedures proposed by Tyson (1995) and Mendonça Filho *et al*. (2002). All mineral components were removed by hydrochloric and hydrofluoric acids before heavy-liquid separation. The remaining organic matter was used to mount the slides. The slides were analyzed by transmitted light microscopy and 300 palynomorphs were counted from each sample to determine their composition and abundance. The following types of particulate organic matter were identified: amorphous organic matter, opaque and translucent phytoclasts, cuticles, membranes, fungal hyphae, fungal spores, spores, pollen grains, freshwater algae, palynoforaminifera and dinoflagellates. Their relative abundance indicates the sources and depositional parameters of sediments which reach the estuary.

3.6 Cluster Analysis

Cluster analysis was employed based on percentage and composition of particulate organic matter and foraminifera/techamoebian components, in order to establish groupings and to recognize the relationship between them. To identify divisions of samples based on palynomorph approach, Q-mode (cluster of samples) and R-mode (cluster of component groups) cluster analyses were performed using the STATISTICA software. These cluster analyses forms shows groupings based on the characteristics of the individual components. The results are displayed in dendrograms which combined assess reasons for clustering.

3.7 Canonical Correspondence Analysis

Canonical Correspondence Analysis (CCA) was used to show which environmental data measure influence of the foraminiferal and thecamoebian community structure. Through a graph, CCA shows how environmental variables influence species distribution. Species frequency was standardized to the power of 0.5 to perform CCA analysis in PCord 0.4 Software. Relative Euclidean Distance was used to calculate the variation coefficient.

4 Results

4.1 Abiotic Parameters

The physicochemical parameters of bottom water varied along the estuary. Salinity remained zero at all stations. Dissolved oxygen values varied as much longitudinally as between margins. The highest values were obtained on the right margin (7 mg/l at station AR07). Turbidity increased gradually at the river mouth. At the stations next to the mouth, turbidity values were 990 NTU. These values might be even larger, since HORIBA equipment does not record values over 900 NTU**.** The average temperature in the estuary was 28.7°C, showing a tendency towards lower temperatures next to the mouth. The pH did not show great variation between stations, but conductivity did, especially between margins (Table 1).

Stations	T	pH	Tubidity	O2	Sand	Silt	Mud	Classification	TOM
	(°C)		(NTU)	(mg/l)	(%)			(Flemming, 2000)	(%)
AR 01	28.9	5.3	14	5.5	0	88	12	slighty clayey silt	2.3
AR 02	29	5.42	37	4.77	0	84	16	slighty clayey silt	2.1
AR 03	30.4	5.86	180	6.78	0	79	21	clayey silt	2.5
AR 04	29.9	5.65	180	0.46	0	60	40	slighty clayey silt	3.4
AR 05	30.2	6.82	300	8.1	0	75	25	clayey silt	2.5
AR 06	32	6.34	360	2.9	0	20	80	slightly silt clay	2.3
AR 07	28.9	7.13	250	7.02	0	77	23	slightly clayey silt	2.3
AR 08	29	5.36	300	1.35	4	84	12	slightly clayey silt	3.4
AR 09	27.9	5.47	590	6.12	26	69	5	extremely clayey sandy mud	3.1
AR 10	28.1	5.89	410	2.41	0	80	20	slightly clayey silt	2.8
AR 11	27.3	6.36	990	4.16	0	94	6	clayey silt	1.5
AR 12	28.2	6.59	990	5.07	0	86	14	slightly clayey silt	1.8
AR 13	27	6.61	990	5.71	1	88	11	very siltyslightly sand mud	1.6
AR 14	26.8	6.09	10	2.64	0	65	35	silt	2.9
AR 15	27.9	6.11	990	4.07	1	97	2	silt	1.2
AR 16	27.8	5.29	990	4.45	2	87	11	slightly clayey silt	1.6

Table 1 Abiotic parameters from Araguari River Estuary.

The dominant grain size in this estuarine system was silt, low concentrations at stations AR08, AR09 and AR16. The textural classification obtained in the Araguari Estuary varied from extremely clayey sandy mud to slightly clayey silt (Table 1).

Total organic matter (TOM) was highest in the mid-portion of the estuary (2.3 - 3.4%) and lowest next to mouth (1.2 – 2.9%).

4.2 Foraminifera and Thecamoebians

Were identified eighteen foraminifera and ten thecamoebian taxa (Table 2). At stations AR01, AR03, AR05, AR07, AR10, AR11, and AR15 foraminifera and thecamoebian tests were absent.

Five species of calcareous foraminifera were identified only at station AR16: *Ammonia tepida, Bolivina translucens*, *Bolivina striatula, Globobigerinoides* spp. and *Milionella subrotunda*. Stations AR05 and AR07 showed a large number of broken foraminifera tests, while at stations AR11, AR15 and AR16 tests were well preserved.

A great number of thecamoebians species occurred in the inner part of the estuary (AR01, AR03, AR05), except *Centropyxis constricta* which was the dominant species at AR10 and *Plagiopyxis* spp. which represented 3% of the population at AR16. The foraminifera, in the opposite way of thecamoebians, were dominant at the stations next to the mouth and the most frequent species were *Arenoparrella mexicana, Haplophragmoides wilberti, Jadamminina polystoma* and *Trochamminita salsa.*

4.3 Particulate Organic Matter

Fourteen types of particulate organic matter were identified (Table 3): amorphous organic matter (AOM), equidimensional opaque phytoclast (O-eq), lath opaque phytoclast (O-La), wood traiched (with and without pits, Wp and Ww), cuticles (Cu), membranes (Mb), fungal hyphae (Fh), pollen grains (Pg), spores (Sp), fungal spores (Fs), freshwater algae (Fwa), foraminiferal linings (Pf) and dinoflagellate cysts (Dc).

The most abundant group was the phytoclasts which includes cuticles, membranes and fungal hyphae. The AOM group was also greatly representative. The palynomorphs group which includes pollen grains, spores, palinoforaminifera and dinocysts was not as abundant as the others, especially the marine ones (foraminiferal and dinocysts), whose presence was punctual (Table 3).

Four genera and one species of typically Devonian achritarchs were identified (Eisenack & Cramer, 1979) but not counted, because they constitute reworked material. These are: *Ammonidium sp, Exochoderma sp., Micrhystridium*

	Species/Stations	AR 01	AR 03	AR 05	AR 07	AR 10	AR 11	AR 15	AR 16
	Total of tests in 50 ml	145	8	9	35	27	20	19	63
	Number of species	6	2	5	4	4	7	6	15
FORAMINIFERA	*Ammonia tepida*	-	-	-	-	-	-	-	1
	Arenoparrella mexicana	-	-	-	25	-	20	16	16
	Bolivina striatula	-	-	-	-	-	-	-	1
	Bolivina traslucens	-	-	-	-	-	-	-	3
	Haplophragmoides manilaensis	-	-	-	-	-	15	-	-
	Haplophragmoides wilberti	-	-	-	-	8	20	21	28
	Globobigerinoides spp.	-	-	-	-	-	-	-	1
	Jadammina polystoma	-	-	12	-	-	10	42	8
	Miliamina fusca	-	-	-	-	4	-	-	-
	Miliolinella subrotunda	-	-	-	-	-	-	-	4
	Polysaccammina ipohalina	-	-	-	-	-	-	-	4
	Saccammina sphaerica	-	-	-	-	-	-	-	1
	Siphotrochammina lobata	-	-	-	25	-	-	6	-
	Textularia paranaguaensis	-	-	-	-	-	-	-	1
	Trochammina inflata	-	-	-	-	-	5	-	1
	Trochammina squamata	-	-	-	25	-	-	-	-
	Trochamminata irregularis	-	-	-	-	-	-	-	4
	Trochamminita salsa	-	-	-	25	-	25	10	21
TECHAMOEBIANS	*Centropyxis constricta*	5	-	-	-	85	-	-	-
	Cucurbitella corona	1	-	-	-	3	-	-	-
	Difflugia caprelota	7	-	-	-	-	-	-	-
	Difflugia globulus	82	13	-	-	-	-	-	-
	Difflugia protaeiformis	-	-	33	-		-	-	-
	Difflugia urceolata	-	-	-	-	-	5	-	-
	Difflugia viscidula	-	-	33	-	-	-	5	-
	Diflugia oblonga	2	87	11	-	-	-	-	-
	Lagenodifflugia vas	-	-	11	-	-	-	-	-
	Plagiopyxis sp.	3	-	-	-	-	-	-	3

Table 2 Frequency (%) of foraminifera and thecamoebians species from Araguari River Estuary.

Species/ Stations	AR01	AR02	AR03	AR04	AR05	AR06	AR07	AR08	AR09	AR10	AR11	AR12	AR13	AR14	AR15	AR16
AOM	24,9	23	9,8	32,9	19,2	11,9	18,3	24,3	26,9	15	17,2	5,8	31,3	25,9	35,4	38,9
O-La	6,6	2,9	4,7	4,6	11,7	5,5	11,3	5,1	2,4	5,6	7,7	2,9	3,8	0,5	3,8	4,6
O-eq	20,2	9,1	17,2	10,5	17,8	20,6	14,6	10,7	15,4	15,9	12,9	11,5	9,1	5,7	6,1	2,8
Wp	5,6	2,4	7,9	1,8	7	1,8	2,8	1,9	3,4	5,1	6,7	3,4	2,4	1,4	-	0,9
Ww	7	11,5	11,2	9,1	14,6	8,3	10,8	14,5	13	13,6	18,2	23,1	20,2	16,5	26,4	17,1
Cu	11,7	26,3	12,6	12,8	13,6	18,3	17,8	20,1	25,5	15,9	16,3	14,4	5,8	14,6	17,9	12,5
Mb	-	1,9	1,4	3,7	-	-	-	0,9	1,9	5,6	2,9	1	1,9	5,2	2,8	5,6
Fh	7	4,8	9,3	1,4	1,9	1,8	1,4	0,9	2,4	3,3	3,8	3,4	10,6	9	2,4	4,6
Sp	8,5	3,8	6	9,1	2,8	11,5	6,6	7,5	3,4	4,2	3,8	8,7	6,3	6,6	3,3	5,6
Pg	7,5	9,1	13,5	12,3	9,9	13,3	11,7	12,1	4,3	12,1	6,2	18,3	5,8	6,6	1,9	3,2
Fs	0,9	1,9	2,3		0,5	0,9	-	-	1	-	1	1	-	4,7	-	4,2
Fwa	-	3,3	3,7	1,4	0,9	6	4,7	1,9	0,5	3,7	3,3	6,7	2,9	2,4	-	-
Dc	-	-	-	-	-	-	-	-	-	-	-	-	-	0,5	-	-
Pf	-	-	0,5	0,5	-	-	-	-	-	-	-	-	-	0,5	-	-

Table 3 Palynomorph types from Araguari River Estuary. (AOM - amorphous organic matter; O-eq - equidimensional opaque phytoclast; O-La - lath opaque phytoclast; Wp - wood traiched; Ww - wood traiched without pits; Cu - cuticles, Mb - membranes, Fh - fungal hyphae, Pg - pollen grains; Sp – spores; Fs - fungal spores; Fwa - freshwater algae, Pf - foraminiferal linings; Dc - dinoflagellate cysts).

sp. and *Umbellaspheridium sp*., and *Stellinium micropolygale* (Figure 2). The achritarchs were concentrated at AR06 and AR08 stations.

4.4 Cluster Analysis

The Q-mode group that shows similarity among stations formed 4 groups (Figure 3): A (stations AR11, AR13, AR15 and AR16), B (AR02, AR04, AR05, AR06, AR07, AR08, AR09, AR12 and AR14), C (AR10) and D (AR01 and AR03).

The R-mode analysis for palynomorphs formed four assemblages (Figure 3): I – spores, pollen grains and freshwater algae; II – Equidimensional opaque phytoclasts, lath opaque phytoclasts and wood traiched without pits; III – Palynoforaminifera, dinocysts, fungal hyphae, fungal spores; and IV – AOM, cuticles, membranes and wood traiched with pits. The dendrogram's major break was between groups II and III, showing the difference between the most abundant components and the less abundant ones.

The R-mode analysis for foraminifera and thecamoebians formed three microorganism assemblages (Figure 3): I – *Plagiopyxis* spp., *Diffugia capreolata, Cucurbitella corona, Centropyxis constricta* and *Miliammina fusca*; II – *Lagenodifflugia vas*, *Difflugia protaeiformes, Difflugia oblonga, Trochammina squamata, Trochammina inflata, Siphotrochammina lobata* and *Jadammina polystoma*; III - *Haplophragmoides wilberti, Haplophragmoides manilaensis, Trochamminita salsa, Arenoparrella mexicana, Trochamminita iregularis, Textularia paranaguaensis, Saccammina sphaerica, Miliolinella subrotunda, Polysaccamina ipohalina, Globobigerinoides* spp., *Bolivina striatula, Bolivina translucens*, and *Ammonia tepida.*

The integration between the three clusters suggested that Group A has high abundance of Assemblage IV of palynomorphs and Assemblage III of microorganisms; Group B showed a high abundance of Assemblage II of palynomorphs and Assemblage III of microorganisms**;** Group C showed high abundance of Assemblage I of palynomorphs and no foraminifera. Group D showed the same characteristics as Group C (Figure 3).

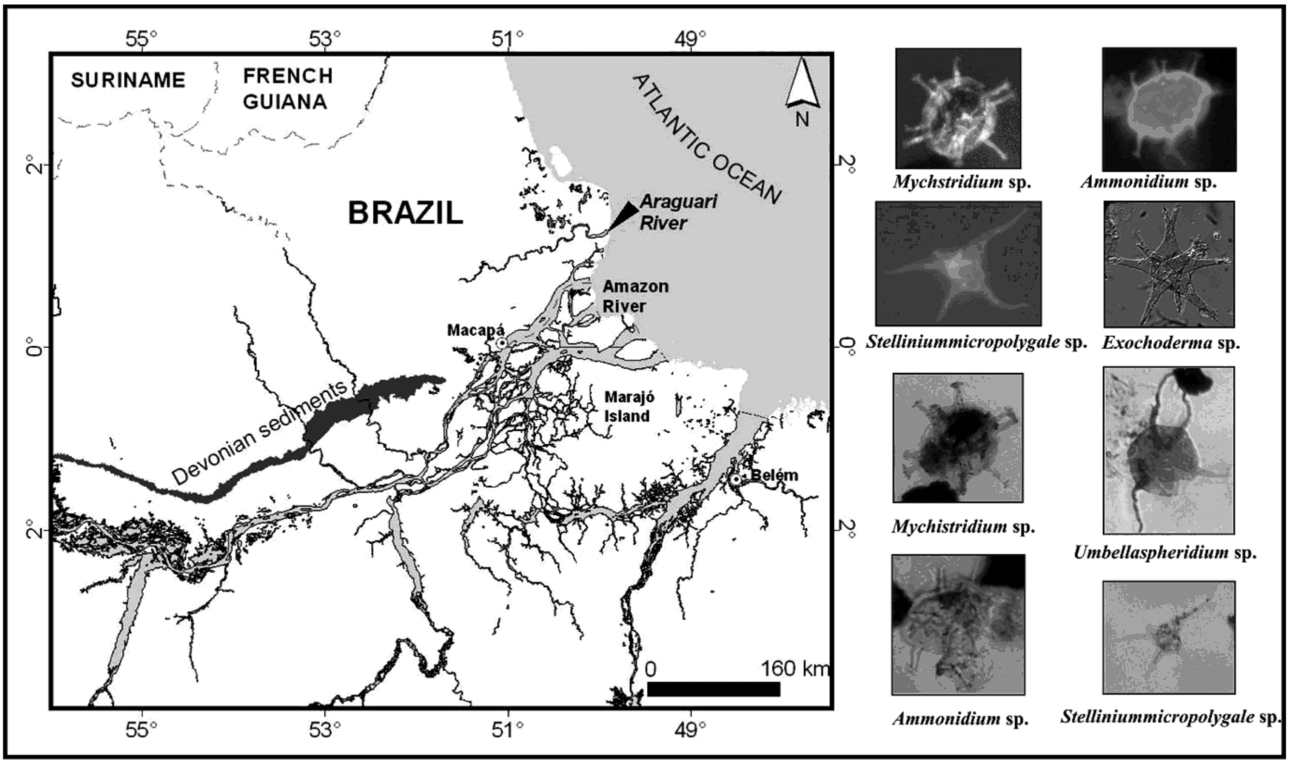

Figure 2 Devonian rocks from the Amazon Basin and the achritarch identified in Araguari Estuary sediments.

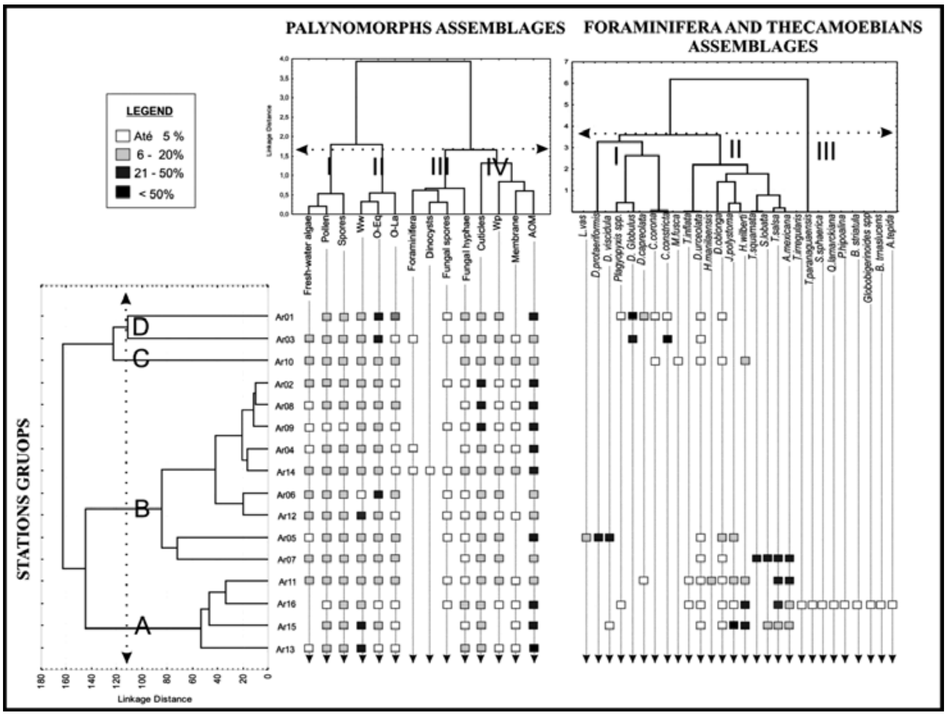

Figure 3 Cluster analysis dendrogram in Q-mode and R-mode.

4.5 Canonical Correspondence Analysis

CCA analysis used environmental patterns with temperature, pH, oxygen, turbidity and total organic matter (TOM). The variation coefficient was 46% in axis one and 25% in axis two. These parameters have been described in literature with responsible to foraminifera and thecamoebian distribution in the sediment. Two groups were defined on the axis influenced by TOM and turbidity (Figure 4). The station AR05 was the only sample which was not influenced by axis one, since it stood alone on the graph. Dissolved oxygen was responsible for station position in relation to axis two.

All thecamoebian species and *Miliammina fusca* presented positive response to the environmental parameters shown on axis one. On the other hand, the thecamoebians *Difflugia protaeirformis*, *Lagenodifflugia vas, Difflugia oblonga, Difflugia globolus,* and the foraminifera *Trochammina squamata, Jadammina polystoma* and *Siphotrochammina lobata* were related to high values of dissolved oxygen (Figure 4).

The species CCA showed three groups, which in axis 1 responded to total organic matter (TOM) and in axis 2 responded to turbidity. Group B showed the *M. fusca* and thecamoebians species relationship to high values of TOM and negative relationship to turbidity. Axis 2 showed a large foraminifera species group linked to low oxygen and high turbidity (Figure 4).

5. Discussion

5.1 Abiotic Parameters

The null value of salinity at Araguari stations was the result of high rain concentration in wet season. The season from December to April concentrates 70% of the year's pluviometric values (Bezerra *et al*., 1990). The sampling carried out in ebb tide may have contributed to the null salinity. However, even in low precipitation periods, salinity on the Amapá State coast does not reach 12% because of the great discharge (about 300,000 m^3/s) of fresh water from the Amazon River (Limeburner *et al*., 1992).

Dissolved oxygen, conductivity and pH values were considered normal for estuarine environments. The heterogeneity showed between stations was the result of the variation of margin characteristics, such as vegetation and proximity of small drains. The changes in the water closer to the sea and the great depth explain the low temperatures next to the mouth.

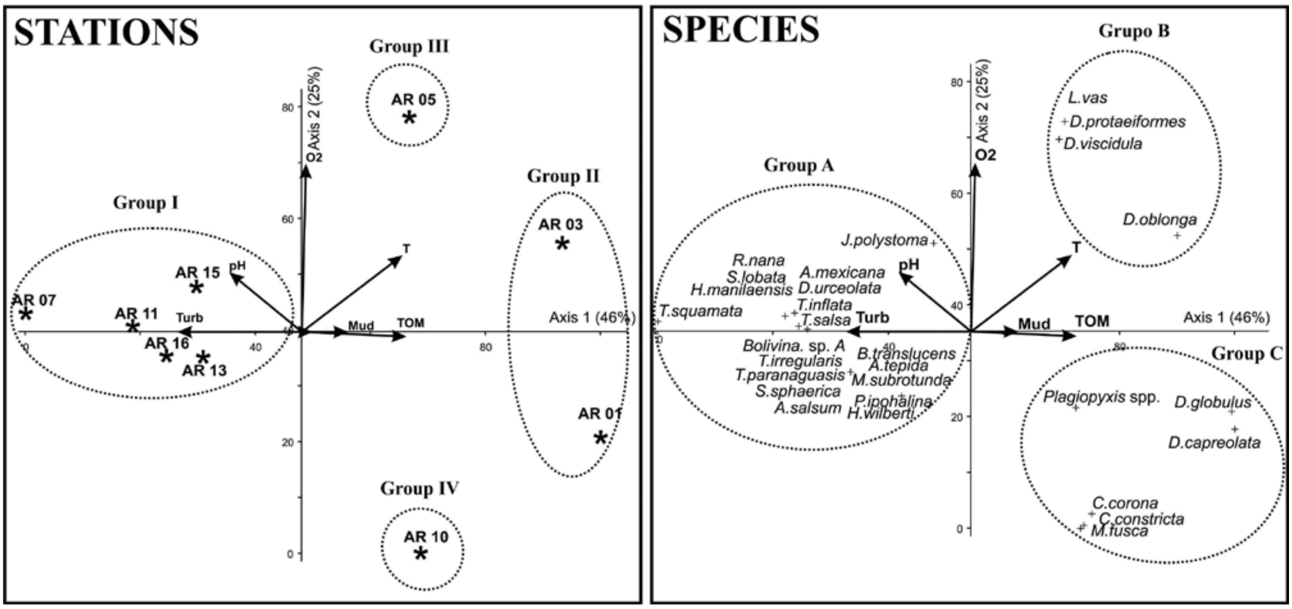

Figure 4 Canonical correspondence analysis from station samples and species from Araguari Estuary.

The gradual increase in turbidity at the Araguari river mouth was expected, both because of the influence of the Amazon River's sedimentary plume and the tidal bore process in the region (Santos, 2006). During the tidal bore passage, concentration of suspended material can reach 8.108 kg/m^3, when it is usually 0.274 kg/m^3 before the event (Santos *et al*., 2005). Distribution of the turbidity plume can be seen in satellite images (Figure 5).

The little concentration of sand inside Araguari Estuary is related to the absence of source areas of this grain size. The great percentages of mud close to the river mouth is originated by the Amazon River sedimentary plume plus the macrotidal regime (Santos, 1994). The tidal bore could also cause low values of total organic matter at the river mouth.

5.2 Foraminiferal and Thecamoebians Distribution

The richness of thecamoebian species is a typical characteristic of aquatic Amazonian ecosystems (Walker & Lages, 1980). The genus *Centropyxis* was dominant at all stations and it is considered opportunistic (Patterson *et al.,* 1985). It is associated to low organic matter values and to high salinity values (Bonetti, 1995). This genus is commonly found in the lower estuary with in Araguari Estuary (Oliveira, 1999).

The genus *Difflugia* was associated to the inner estuary with high organic matter levels. This pattern has been shown mainly by *D. oblonga* in other estuaries (Kliza & Schröder-Adams, 1999).

The Araguari Estuary differs much from other macrotidal estuaries in species distribution pattern, as well as in species number. In macrotidal estuaries usually occur great number of species in the middle portion, a moderate number at the mouth and a low number in the inner portion (Reddy & Rao, 1984). At Araguari a great number of species occurred next to the mouth.

The estuary presented a small number of foraminifera species. This indicates that in the rainy season Araguari Estuary presents low fertility, and the species identified are typical of mangroves.

Salinity is considered an ecological parameter that greatly influences foraminifera and thecamoebian distribution (Reddy & Rao, 1984). Salinity was null throughout the samples. It is possible existence of interstitial salinity and/or those microorganisms were able to survive in this sediment because the high organic matter and great nutrient concentration could have constituted favorable conditions.

The presence of oligohaline species indicates that the Amazon River discharge and the rainfall volume reduce salinity on the Amapá State Coast, rendering the survival of typical marine species in Araguari Estuary impossible.

The identified calcareous species (*A. tepida*, *Bolivina translucens*, *Bolivina striatula, Miliolinella subrotunda* and *Gobigerinoides* spp.) were mostly small and well preserved. All specimens were found at station AR16 next to the mouth. These facts suggest the suspension transport of tests. Santos (1994) identified other biogenic material with sponge spicules and briozoa transported into Araguari Estuary. Estuarine foraminifera genera (*Ammonia, Brizalina, Quiqueloculina, Pseudononion*) were found in the region by Vilela & Koutsoukos (1995) only in the continental shelf at depths over 30 meters.

The microorganism distribution along the estuary, where the thecamoebians species were decreasing and foraminifera species increasing seaward, demonstrated that a transition aof freshwater to brackish water gradient occursat the mouth.

R-mode cluster analysis grouped the organisms by river influence. Group A was composed only of thecamoebians species and *Miliammina fusca* representing the inner portion of the estuary. Laut (2003) reported that *M. fusca* is the agglutinated foraminifera most resistant to low salinity, but it shows low tolerance to suspended organic matter. Group B, composed by *Trochammina* species and thecamoebians, suggest great mixing of water masses. Group C was represented by species which discloses marine charactheristcs.

CCA analysis showed two distinct regions in the estuary, one where high values of organic matter and low turbidity occurred (AR01, AR03, AR10), and another where these values were the opposite (AR07, AR11, AR15 and AR16).

5.3 Palynomorph Distribution

The palynofacies parameters represent dispersion of their component trends biased by environmental conditions like depositional processes, hydrodynamics, fluvial influx, etc. The components may suggest some environmental information, e.g. phytoclasts may suggest fluvial influence while dynocists and palynoforaminifera indicate a marine influence (Meyer *et al.*, 2005). In Araguari Estuary the phytoclast group, including all sorts of phytoclasts, cuticles, membranes and fungal hyphae have dominated samples on an abundance basis. The amorphous organic matter (AOM) is also greatly representative as is, on a lesser scale, the palynomorph group, including pollen grains, spores and zoomorphs. The high percentage of phytoclasts may suggest low transport of organic matter particles, oxide conditions and fluvial environment (Tyson, 1993).

The phytoclasts group influence was so representative that it has controlled all groups formed. In addition, the AOM group is composed of degraded plant material (it shows no fluorescence under blue light or ultraviolet excitation, like algae AOM). We thus infer that the presence of allochthonous material of continental origin is intense, reaching 80% of the material considered (PHYTO and AOM groups). This component's abundance might be justified by the sample stations being on the tidal plain of the Araguari River, where this sedimentation preferentially occurs.

The Amazon River influence on Araguari estuarine hydrodynamics can be perceived in many ways, such as in the overall estuary salinity which is not typical of main estuarine classifications. To gauge the magnitude of this influence, must consider that the Amazon River mouth sedimentary basin reaches the continental shelf, continental slope and oceanic basin down to the 3,000 m isobath (Silva *et al.*, 1999). Its sedimentary discharge is 1.1-1.3 x 10^9 ton/year (Costa & Silveira, 1998) and some oceanic water physicochemical parameters (salinity and suspended material concentration) are controlled by it. Considering how close Araguari Estuary is to the Amazon River mouth and that it is a tide-dominated estuary, the conditions described above have great influence over the estuary, reflecting on the palynofacies results.

The phytoclast abundance shows how is small the marine influence on Araguari Estuary. It is evidenced by punctual occurrence of marine palynomorphs, in other hand there is an extreme abundance of those continental components.

In Q-mode analysis only one group formed by nearly marine material (Group III, of the most distal stations) had also as the most abundant organic components of this group AOM and phytoclasts, confirming the low marine influence.

Some achritarchs were found. They were not counted together with the other palynomorphs because they seemed to be reworked material. All of the specimens found date from the Devonian period, although sedimentary material from this period is absent from the Amapá coastal plain (Figure 02). In Amapá State, the Guianense complex (Pre-Cambrian), the Barreiras formation (Pliocene) and the coastal plain (Pleistocene/Holocene) are known. The Devonian formations are located far inland on the Amazon Basin.

These achritarchs were dispersed over eight samples, ranging from the mouth of the river up to stations located 45 km inland. Coincidentally, this is nearly the tidal bore area of influence in the estuary (Figure 5).

In this way, achritarchs indicate that the material of the Araguari floodplain was formed by Devonian sediments of the Amazon Basin, or at least, that sediments from inner Amazon Basin reach estuary inland by tide.

5.4. Estuarine Zonation

Analysis of biotic and abiotic parameters suggested a possible compartment of Araguari Estuary (Figure 5):

- Zone I (Stations AR01, AR02, AR03, AR04) – composed of thecamoebians species and Assemblages I, II and IV of palynomorphs. Characterized by high organic matter concentration and low turbidity. It is the zone with major influence of Araguari fresh water.

- Zone II (Stations AR05, AR06, AR07, AR08, AR09, AR10) – fauna composed by mangrove foraminifera and thecamoebians and all palynomorph assemblages. It is the only region where assemblage III appears, composed of marine palynomorphs (palynoforaminifera and dinocysts) and Devonian achritarchs, was represented. In this zone the tidal bore reaches its maximum point in the estuary. This phenomenon drives water mixing and may also cause the remobilization of adjacent sediment. This zone's limit can be established at 50 km from the estuary mouth.

- Zone III (Stations AR11, AR12, AR13, AR14, AR15, AR16) – represents the influence area of salt water, where salt-species richness is higher. Transported material from the continental shelf by suspension was also present. Turbidity and pH were high and the temperature was lower than in other zones. This zone is also more influenced by Amazon River fresh water.

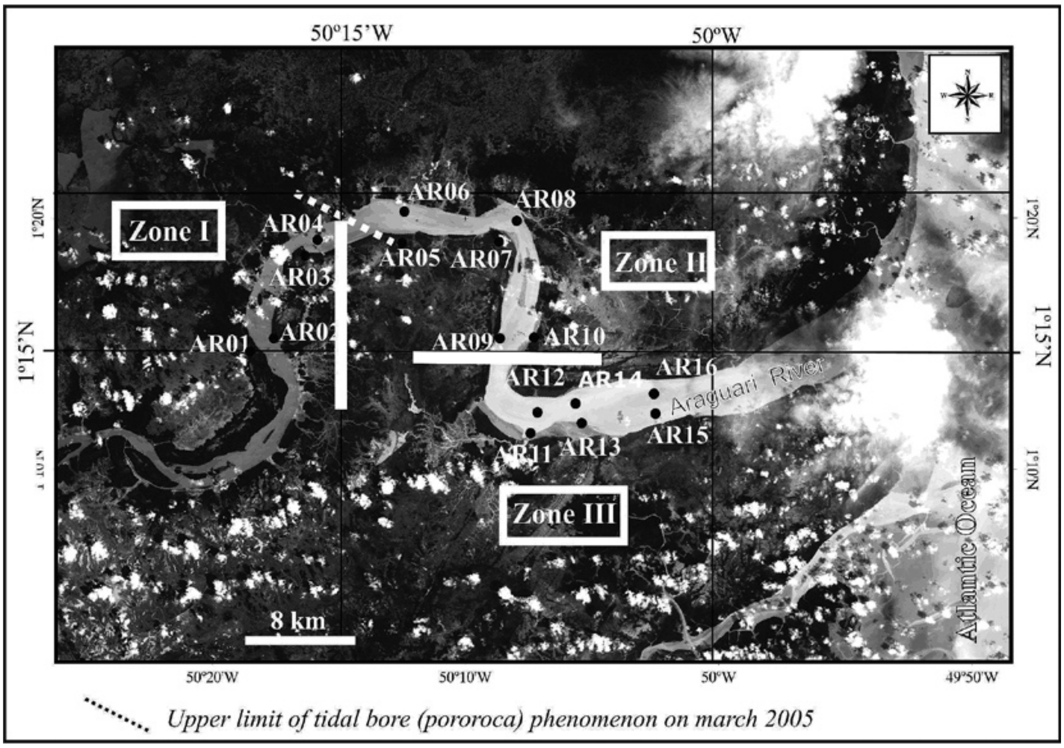

Figure 5
Compartments of Araguari estuary based on physical-chemistry patterns and foraminifera, thecamoebians and palynomorphs assemblages.

6 Conclusion

The results obtained indicate great influence of the Amazonian fluvial system over Araguari Estuary, which was even greater than the marine influence. Integrated proxies analysis has proven useful to understand macrotidal estuary dynamics.

Distribution of foraminifera, thecamoebians and palynomorphs species, improved water physico-chemical parameters and sedimentological analysis, made it possible to distinguish three estuarine zones which reflected marine influence and the Amazon River discharge, as well as the influence of the tidal bore within the estuary. The low marine influence could be seen at the mouth of the estuary by the presence of small calcareous foraminifera species, possibly transported in suspension, and by the presence of dinoflagellates and palynoforaminifera. The zone of tidal bore energy dissipation was evidenced by the mixture of the marine and shelf foraminifera, thecamoebians and palynomorphs. This zone can also be determined by satellite imagery at approximately 50 km from the estuary mouth towards the upper estuary. The fluvial influence region can be well delimited by the dominance of thecamoebians tests and continental palynomorphs.

A multiproxy approach was an important tool in the environmental and hydrodynamic analysis of Araguari River. However, an analysis during the dry season might complement and refine knowledge of the estuary's hydrodynamic patterns. The results may aid environmental monitoring studies, as well as serve in the recognition of sedimentary facies in paleoenvironmental studies, not only in the Araguari River region, but also on the coastal area of Amapá State.

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