MedCrave
Step into the World of Research
Journal of Aquaculture & Marine Biology

Research Article
Open Access
CrossMark

Evidence of upwelling on the Brazilian continental shelf of Rio Grande do Norte

Abstract

This study evaluates Foraminiferal assemblages and their relation with grain size, calcium carbonate content, organic matter, and mineralogy of sediment samples collected at the sediment-water interface along a transect on the northern continental shelf of Rio Grande do Norte State, Brazil, adjacent to the city of Areia Branca. The sedimentary sequence of this shelf is represented by lithostratigraphic units of a marine regressive sequence dominated by four facies: Siliciclastic sand, Silicibioclastic Sand, carbonate mud, and Biosiliciclastic sand. The carbonate content ranged from 5.83% to 85% and the organic matter content from 1.16% to 27.05%. Mineralogical characters separated the predominant siliciclastic content (37% to 92%) from the bioclastic content (8% to 63%). We have identified 14 species out of 50 species of Foraminifera, associated to particular depths and sediment types as follows: (1)deeper-water sediments in the middle shelf contain *Bolivina striatula, Bulimina marginata, Triloculina trigonula, Pyrgo ringens, Textularia gramen* (2)the shallowest sediments in the inner shelf contain *Ammonia tepida, Buccella peruviana, Miliolinella subrotunda,* and *Quinqueloculina patagonica,* (3)the central parts of the transect, also in the inner shelf, provide habitats for *Quinqueloculina lamarckiana, Textularia earlandi, Buliminella elegantissima, Discorbis peruvianus,* and *Pyrgo nasuta.* The distribution of *Uvigerina striata* and *Buccella peruviana* is probably related to colder water temperatures and possibly the occurrence of an upwelling phenomenon for the deepest parts of the area rather than the sedimentological features discussed here.

Keywords: habitats, inner and middle shelf, benthic foraminifera, upwelling

Volume 12 Issue 3 - 2023

Mary L. da S. Nogueira,[1] Patricia P. B. Eichler,[1] Miguel Evelim Penha Borges,[2] André Rosch Rodrigues,[3] Helenice Vital[1]

[1]Programa de Pós-Graduação em Geodinâmica e Geofísica (PPGG), Laboratório de Geologia e Geofísica Marinha e Monitoramento Ambiental (GGEMMA), Centro de Ciências Exatas e da Terra (CCET) da Universidade Federal do Rio Grande do Norte (UFRN), Brazil

[2]Instituto Federal do Rio Grande do Norte, Brazil.

[3]Departamento de Oceanografia, Programa de Pós-graduação em Oceanografia Ambiental, Universidade Federal do Espírito Santo-UFES, Brazil.

Correspondence: Patricia P. B. Eichler, Departamento de Geologia, Universidade Federal do Ceará (UFC), Brazil, Email patriciaeichler@gmail.com

Received: September 25, 2023 | **Published:** October 9, 2023

Highlights

a) Species are associated with particular depths and sediment types.

b) Deeper-water sediments contain *Bolivina striatula, Bulimina marginata, Triloculina trigonula, Pyrgo ringens, Textularia gramen*

c) Shallower-water sediments contain *Ammonia tepida, Buccella peruviana, Miliolinella subrotunda,* and *Quinqueloculina patagonica,*

d) Inner shelf is habitat for *Quinqueloculina lamarckiana, Textularia earlandi, Buliminella elegantissima, Discorbis peruvianus,* and *Pyrgo nasuta.*

e) The distribution of *Buccella peruviana* is related to the upwelling of colder waters.

Introduction

Foraminifera are excellent indicators of sea level change on continental margins and are useful in paleoenvironmental reconstructions.[1–4] While the distribution of each species is unique, groups of species (assemblages or communities) can be recognized as inhabiting particular areas such as mangroves, estuaries, bays, inner/outer shelves and deep basins. These natural habitats have particular geomorphologic and hydrographic characteristics, and may be further differentiated by variables such as depth, salinity, temperature, organic content, textural parameters, and oxygen supply.[5]

Poorly oxygenated bottom waters of other continental shelves and slopes often related to upwelling are known to support Foraminiferal habitats in which species of *Bolivina* and *Bulimina* are relatively abundant.[6] We speculate that similar assemblages of benthic foraminifera in our inner and middle shelf are strongly affected by upwelling. For example, species of *Buliminacea, Fursenkoina*, and *Nonionella*, abundant in organic-rich, low-oxygen sediments in modern seas, increased in proportional abundance after world warming began. In addition, the offset in $\delta^{13}C$ values between epifaunal to shallow infaunal taxa and a deeper infaunal species is greater in sediments with higher abundances of these taxa, further supporting increased organic carbon flux. An increase in laminated sediments coincident with these faunal and geochemical changes suggests dysoxic conditions accompanied by an increase in organic carbon. Taken together, this multiproxy record suggests that high-organic, low-oxygen, environments developed in shallow waters during Early Miocene warming, perhaps driven by similar upwelling mechanisms thought to drive hypoxia on the modern Oregon coast.[7,8]

In spite of the great economic (petroleum, salt, marine production, fisheries), social (major cities) and historical (since the time of discovery) importance of tropical shelves in northeastern Brazil, we still do not have comparable data for bio-indicators of environmental changes such as sea level rise, water temperature rise, global warming, drill cutting disposal, contamination and pollution. The present investigation is an attempt to partly fill this gap; demonstrating that Foraminiferal biodiversity patterns show traceable responses to temporal environmental changes in this highly complex environment.

This multi-proxy study aims to evaluate Foraminiferal assemblages and their relation with grain size, carbonate content, organic matter and mineralogy on a transect on the northern continental shelf of Rio Grande do Norte State, adjacent to the city of Areia Branca (see Figure 1).

Regional setting

This continental shelf represents a modern, highly dynamic mixed carbonate-siliciclastic system characterized by reduced width (40 km) and shelf-break at a depth of around 60 m.[9–11]

The study area is within the Potiguar Basin geological domain, which is within the Meso-Cenozoic basins of the Brazilian equatorial margin. The sedimentary packages that make up the platform in this sector are represented by the lithostratigraphic units of a marine regressive sequence (Early Campanian-Holocene) represented by the Ubarana Formation (marine shales), Guamaré Formation (carbonates) and Tibau Formation (sandstones and conglomerates), revealing a coastal-shelf-slope-basin environment.[12]

According to Dominguez et al.,[13] winds predominantly from the northeast (Figure 1) reach the northern coast of Rio Grande do Norte, within the belt of trade winds controlled by the movements of the Intertropical Convergence Zone. The mean velocity of the winds, measured directly from the shoreface is 5m/s in April and 9m/s between August and October; it may reach up to 18 m/s during the month of August.[14]

According to Caldas,[15] the Brazilian continental shelf adjacent to the Rio Grande do Norte state is dominated by the North Brazil Current (NBC). The NBC corresponds to the class of the southern equatorial current with a significant longshore current in an E-W direction. Within this context, our study area is part of a semidiurnal meso-tidal regime.[16,17]

Considering the geomorphology and sedimentation, Vital et al.,[18] and Gomes and Vital[19] divided the continental shelf into three domains: 1. Inner shelf, dominantly siliciclastic sediments (up to 15m water depth), 2. Middle shelf, dominantly siliciclastic-carbonates (15 to 25m water depth), and 3. Outer shelf, dominantly carbonate sediments (25 to 40m water depth)

As shown in Figure 1, bed forms ranging from centimeters to kilometers are present on this shelf. The continental shelf is 35.5 km to 37 km wide toward 40 m isobaths. In front of Apodi Valley, it widens to 47 km. The outer shelf and the shelf edge start at 40 m water depth. In according to Lima and Vital,[9] Gomes et al.,[20] and Vital et al.,[21] five main features were recognized: (a) very large longitudinal dunes; (b) incised valleys; (c) reefs; (d) regions with a flat base, and (e) very large transversal dunes. Additional features were also identified: (f) two head canyons (C1 and C2) (Figure 1).

Material and methods

Seven sediment samples were collected along a transect (Figure 1) with a Van Veen grab and sub-sampled for analyses of Foraminifera, grain size, carbonate content, organic matter, and mineralogy. We usually collect the first cm (where we have a visual on the layer where bacterial activity is taking place) to estimate the population dynamics so we do not need to have equipment that preserves the structure.

The uppermost layer of the sediment (about 1 cm) was removed and stored in a mixture of 1 liter of alcohol and 1 gram of Bengal rose stain. After staining, a fixed volume of 50 cm^3 of sediment was washed through a 0.063-mm sieve and dried in an oven at 70°C. This fraction was floated using trichloroethylene. The residues were examined for Foraminiferal tests. The procedure can be seen in Eichler et al.[22]

Each sample for grain size analysis was washed with distilled water. Sand samples were then dried for 24h at (maximum) 65°C, and clay samples were lyophilized. Subsequently, samples were manually homogenized and classified according to grain size, by using a Ro-Tap sieve shaker or a laser particle-size analyzer (CILAS 1180L). Statistical parameters[23] were calculated, and sediments were classified.[18,24]

To quantify the carbonate content, approximately 12 g of sediment was collected from each sample and transferred to a plastic tube. Subsamples were treated with a solution of 10% hydrochloric acid to dissolve their carbonate fraction. After dissolution, subsamples were washed repeatedly in freshwater to remove residues, dried, and weighed. Carbonate composition (%) was calculated by the difference between the pre-and post-treatment subsample weight.

Total organic matter was calculated by the difference between initial and subsequent weights after burning in a muffle furnace. The samples were heated for approximately 5 hours at a temperature of 600°C so that all organic material was eliminated.

Absolute and relative abundances of living Foraminifera species were recorded for each sediment sample. Relative abundance data were computed for foraminiferal species that contribute 10% or more to the assemblage in more than one sample, and subjected to Q-mode cluster analysis. The Bray-Curtis distance coefficient was used to measure differences between fourth-root transformed samples, and the group-average method was used to amalgamate samples into a hierarchical dendrogram.

Data from relative frequency were contoured on ARCGIS software and used to observe micro-faunal patterns. Species identification was done using an optical microscope and taxonomic determination of species was based on the Catalogue of Foraminifera;[25,26] scanning electron micrographs were taken to aid with occasional problematic identifications and for illustrative purposes. Similarity matrices were constructed to help differentiate sub-environments using PRIMER, a University of Plymouth software.[27]

The mineralogical description of each sedimentary facies was done in the samples using optical microscopy at a magnification of 50x, noting mineralogy, color, structure and texture. Data on abiotic patterns were then integrated in GIS (Geographic information system) software and in electronic worksheets.

Results

Table 1 illustrates the sedimentological features of collected samples. Sand dominates in the bottom sediment followed by mud and gravel. The percentage of grain size fraction indicates that medium, coarse, and very fine sand predominate. Silt is limited in station P55, which is localized inside the channel. The percentage of mud is higher in station P32. The degree of sorting in sediments alternated from moderately sorted (P12, P20, P25, P35) with values below 1, to poorly sorted (P5, P32, and P55) with values above 1. Carbonate content ranged between 5.83% to 85%. Samples P32, P35, and P55 had the highest concentration of carbonate (Table 1).

St, Stations; IS, Inner shelf; DC, Deep Chanell; SC, Shallow Chanell; The grain size fraction is percentage %, V.C.S, Very Coarse Sand; C.S, Coarse Sand; M.S, Medium Sand; V.F.S, Very Fine Sand; S.C, Sorting Coefficient

The TOM content ranged between 1.16% to 27.05% with an average of 13.23%. Organic matter concentration was the highest at station P32 (27.05%), followed by station P55 (7.15%), with the other stations showing concentrations of <7% (Table 1). The percentage of silt and very fine sand was higher at stations P32 (59.8%; 23.2%), P55 (9.7%; 10.0%), and P05 (9.6%; 59.6%).

The siliciclastic content ranged between 37% and 92%, and the bioclastic content was between 8% and 63% (Table 1). Station P55 showed high bioclastic content (63%) and rock fragments (25%).

The samples are grouped into four main sedimentary facies. According to classification based on Vital et al.,[18] AS 1b: Siliciclastic sand (P5, P20, and P25 stations); AS 2b: Silicibioclastic Sand (P12 and P35 stations); LB 2: Carbonate mud (P32 station); AB 1b: Biosiliciclastic sand (P55 station), see Figure 2.

Figure 3 shows samples of each sedimentary facies. The composition is comprised of quartz, biotite, rock fragments, and heavy minerals. The quartz is generally sub-rounded to round with sphericity ranging from medium to high. It can be easily recognized by its granular habit and vitreous luster. At station P12, individual fragments of quartz show moderate to weak selection. The smaller particles were more rounded, with sphericity ranging from medium to high, while the coarser particles tended to be more angular, with sphericity ranging from medium to low. At station P20, clean grains showed a degree of sorting ranging from moderate to high. The biotite exhibits a lamellar pattern, micaceous brightness, and color ranging from black to brown. Rock fragments and heavy minerals were present in significantly lower numbers. The rock fragments were composed of quartz, feldspar, and biotite. Heavy minerals were tourmaline and garnet.

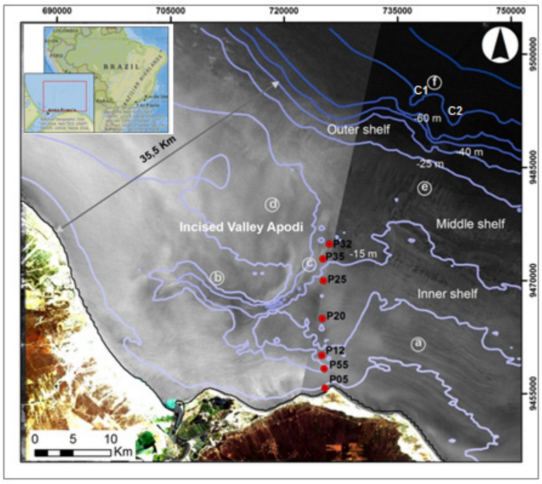

Figure 1 Location map of the study area, the northern continental shelf in Rio Grande do Norte State, Brazil, and bedforms typical of this area. (a) very large longitudinal dunes, (b) incised valleys, (c) reefs, (d) regions with a flat base, (e) very large transversal dunes, (f) head canyons (C1 and C2). Red circles refer to the sediment sample transect used in this study.

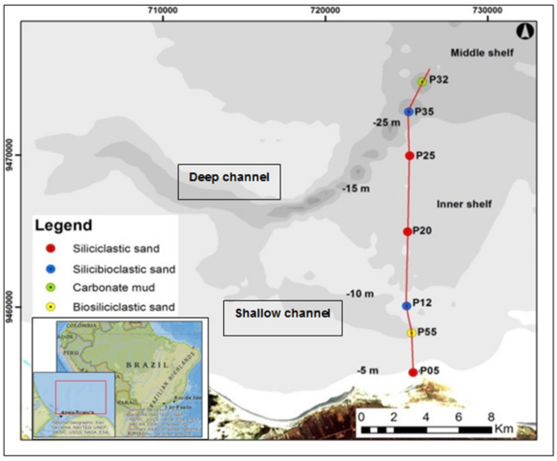

Figure 2 The distribution of sedimentary facies along the transect on the northern continental shelf of Rio Grande do Norte State.

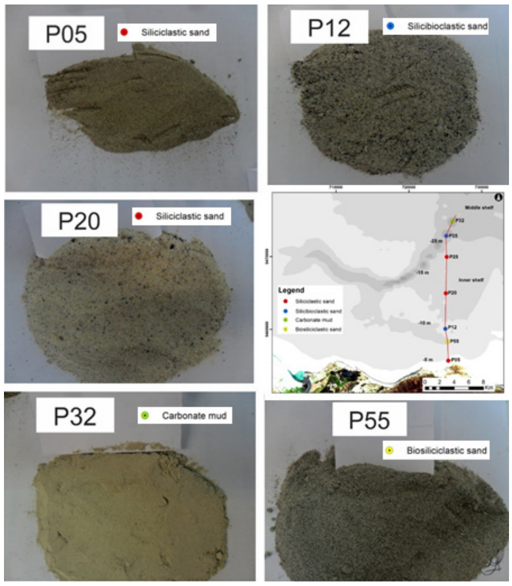

Figure 3 Sediment facies along the transect on the northern continental shelf of Rio Grande do Norte State.

Table 1 Sedimentological features of sediment samples

St.	Location	Depth(m)	G.	V. C.S	C. S	M. S	F.S	V. F.S	Sand	Silt	Clay	Mud	S. C	Carbonate	TOM
P05	IS*	3.03	0.00	0.00	14.24	5.68	8.4	59.64	87.96	9.61	2.43	12.04	1207.00	15.83	2.15
P12	IS*	9.95	0.00	0.00	30.69	49.76	15.13	2.7	98.29	0.9	0.81	1.71	0.724	30.00	3.13
P20	IS*	11.59	1.81	39.89	34.94	20.46	2.13	0.65	98.08	0.00	0.11	0.11	0.886	8.33	1.16
P25	IS*	14.81	0.00	0.00	39.09	50.85	7.56	1.66	99.16	0.22	0.62	0.84	0.656	5.83	1.31
P32	DC*	28.05	0.00	0.00	0.00	0.00	0.07	23.21	23.28	59.75	16.97	76.72	1658.00	85.00	27.05
P35	DC*	22.05	0.00	0.00	26.05	46.14	19.84	5.08	97.12	2.2	0.68	2.88	0.877	41.67	5.11
P55	SC*	10.09	0.00	0.00	21.31	31.52	23.9	10.03	86.77	9.7	3.53	13.23	1566.00	63.33	7.15

Table 2 Species found in the studied samples and their occurrence in stations (Occ Sts)

	Species	Occ Sts		Species	Occ Sts
CALCAREOUS	*Ammonia rolshauseni*	3	CALCAREOUS	*Miliolinella suborbicularis*	3
	Ammonia tepida	6		*Miliolinella subrotunda*	7
	Amphistegina sp.	2		*Neoeponides procerus*	1
	Angulogerina angulosa	2		*Nodobaculariella convexiuscula*	1
	Bolivina difformis	3		*Peneroplis pertusus*	1
	Bolivina striatula	6		*Poroeponides lateralis*	1
	Buccella peruviana	5		*Pseudononium atlanticum*	6
	Bulimina marginata	3		*Pyrgo nasuta*	3
	Bulimina patagonica	2		*Pyrgo ringens*	7
	Bulimina pupoides	1		*Pyrgo subsphaerica*	4
	Buliminella elegantissima	5		*Quinqueloculina funafutiensis*	2
	Cassidulina subglobosa	4		*Quinqueloculina intricata*	7
	Cibicides dispars	3		*Quinqueloculina lamarckiana*	7
	Cibicides fletcheri	4		*Quinqueloculina milletti*	4
	Cibicides mckannai	4		*Quinqueloculina patagonica*	7
	Cornuspira involvens	1		*Reussella* sp.	6
	Cymbaloporetta sp.	1		*Rosalina globularis*	1
	Discorbis peruvianus	5		*Rosalina* sp.	1
	Discorbis valvulatus	5		*Sagrinella* sp.	1
	Discorbis williamsoni	2		*Spiroloculina planata*	2
	Elphidium articulatum	3		*Spiroloculina sp.*	3
	Elphidium discoidale	6		*Triloculina trygonula*	4
	Elphidium galvestonense	4		*Uvigerina striata*	2
	Fissurina laevigata	3		*Wiesnerella* sp.	3
	Fissurina lucida	5	AGGLUTINATED	*Arenoparrella mexicana*	1
	Gutulina sp.	1		*Textularia earlandi*	3
	Hanzawaia boueana	3		*Textularia gramen*	7
	Hopkinsina pacifica	1		*Trochammina inflata*	2
	Lagena tortilis	1		*Trochammina ochracea*	1
	Lenticulina sp.	1		*Trochammina plana discorbis*	2
	Miliolinella labiosa	1			

Citation: Nogueira MLS, Eichler PPB, Borges MEP, et al. Evidence of upwelling on the Brazilian continental shelf of Rio Grande do Norte. *J Aquac Mar Biol.* 2023;12(3):242–250. DOI: 10.15406/jamb.2023.12.00380

The bioclastic fraction consisted of echinoderms, mollusks, worm tubes, coralline algae, benthic foraminifera, and ostracods. Most of the grains were broken at stations P5 and P55 revealing a high hydrodynamic setting.

A total of 55 calcareous and 6 agglutinated foraminiferal species were found (Table 2). The miliolids of the genus *Quinqueloculina*, *Miliolinella,* and *Pyrgo* occurred in every sample and *Textularia gramen* was the only agglutinated that occurred in most of the samples.

Quantitative data on Foraminiferal assemblages are presented in Table 3, and Table 4 shows the relative frequency and absolute values of the total specimens in each sample, and their relation with geological data. Contour maps of the relative frequency of the more abundant species are presented in Figure 5.

Table 3 Relative frequency and absolute valor of the main Foraminiferal species and dominants (bold) in a stretch on the northern continental shelf of Rio Grande do Norte. (-) represents percentages below 0.25

Stations	**P05**	**P12**	**P20**	**P25**	**P32**	**P35**	**P55**
TOTAL SPECIMENS	8220	12300	1980	196	14200	16500	7290
Richness	46	39	25	39	24	20	19
Calcareous species	43	34	23	37	22	18	18
Agglutinated species	3	5	2	2	2	2	1
Ammonia rolshauseni	0.97	2.93		0.51			
Ammonia tepida	15.57	4.88	4.04	6.63	8.10	2.55	14.81
Bolivina striatula	1.46	0.49	2.02	4.08	7.04		1.85
Buccella peruviana	4.14	0.49			1.06	1.45	2.47
Bulimina marginata	0.73			0.51	1.76		
Buliminella elegantissima	0.26		1.02	1.58	0.35		1.23
Cibicides fletcheri	-			1.53		1.82	0.62
Cibicides mckannai		-			0.35	1.45	0.62
Discorbis peruvianus	3.89	0.98	8.08	8.67	8.45		
Discorbis valvulatus	-	0.73	2.02			3.27	2.47
Elphidium discoidale	1.22	-	1.01	0.51		0.73	4.32
Elphidium galvestonense	-	0.49		0.51	2.46		
Fissurina lucida	0.73			0.51	4.93	0.36	1.23
Miliolinella subrotunda	14.60	2.68	4.04	3.06	0.70	4.00	2.47
Pseudononium atlanticum	-		1.01	4.59	2.46	2.55	1.23
Pyrgo nasuta		1.49	2.04	2.63			
Pyrgo ringens	-	9.27	8.08	4.59	2.82	11.64	2.47
Pyrgo subsphaerica	-	2.20	3.03	3.57			
Quinqueloculina intricata	3.41	4.15	3.03	1.53	4.58	4.00	1.85
Quinqueloculina lamarckiana	19.95	39.51	26.26	23.47	3.87	14.55	13.58
Quinqueloculina milletti	0.49	0.73			7.04	1.45	
Quinqueloculina patagonica	10.95	11.95	12.12	4.08	18.66	19.27	41.98
Quinqueloculina sp.	2.19	1.22	5.05	3.06	3.52	0.36	
Reussella sp.	-	0.49		0.51	3.52	3.27	3.09
Spiroloculina sp.	-	1.22				1.09	
Textularia earlandi		1.73	1.02	2.63			
Textularia gramen	-	4.39	6.06	10.71	3.87	14.55	1.23
Triloculina trigonula	4.62				10.21	11.27	1.85
Uvigerina striata			1.02		1.05		
Other species (no. species)	12.90 (24)	10.73 (19)	14.14 (21)	17.35 (20)	4.58 (5)	0.36 (1)	1.85 (2)

Table 4 Siliciclastic and bioclastic composition, plus foraminiferal assemblages per station along the transect on the northern continental shelf of Rio Grande do Norte State

Stations	Siliciclastic Composition	Bioclastic composition	Foraminiferal assemblages
P05	84% - (Quartz 45%. Biotite 16%. little rock fragments).	16% - echinoderms. molluscs. worm tube and calcareous algae. ostracoda rarely.	*A. tepida. B. peruviana. M. subrotunda* and *Q. patagonica*
P12	70% - (Quartz 55%. Biotite 30%. rock fragments 15%).	30% - echinoderms. molluscs. worm tube. calcareous algae. benthic foraminifera and ostracoda rarely.	*Q. lamarckiana. T. earlandi. B. elegantissima. D. peruvianus* and *P. nasuta*
P20	92% - (Quartz 80%. rock fragments 10%. heavy minerals 2%).	8% - mollusks. calcareous algae. benthic foraminifera and worm tubes rarely.	*Q. lamarckiana. T. earlandi. B. elegantissima. D. peruvianus* and *P. nasuta, Uvigerina striata*
P25	Not described		*Q. lamarckiana. T. earlandi. B. elegantissima. D. peruvianus* and *P. nasuta*
P32	Not described		*B. striatula. B. marginata. T. trigonula. P. ringens and T. gramen Uvigerina striata*
P35	Not described		*B. striatula. B. marginata. T. trigonula. P. ringens* and *T. gramen, Uvigerina striata*
P55	37% - (Quartz 12%. rock fragments 25%).	63% - echinoderms. mollusks. worm tubes and calcareous algae.	*A. tepida. B. peruviana. M. subrotunda* and *Q. patagonica*

As detailed in Table 4 and Figure 4 the following Foraminifera were observed in those stations (P32 and P55) where carbonate, organic matter and silt, clay, and very fine sand values are higher and grains are poorly sorted: *Bolivina striatula, Bulimina marginata, Triloculina trigonula, Pyrgo ringens, Textularia gramen, Ammonia tepida, Buccella peruviana, Miliolinella subrotunda,* and *Quinqueloculina patagonica*. The sediments at Station P35 contain high carbonate and organic matter content and are different from Stations P32 and P55, by a larger amount of medium-grained sand (46.14%). Station P35, where silt and medium sand predominate, is composed mainly of *Bulimina striatula, Bulimina marginata, Triloculina trigonula, Pyrgo ringens* and *Textularia gramen.*

Quinqueloculina lamarckiana (an inner neritic to shelf indicator) and a coral reef endemic species (*Amphistegina* sp.) are found at the shallowest stations, P05 and P12, where the sediments are sandy. In contrast, *Q. patagonica* is typical of substrates with low organic matter and clay values, particularly at stations P12, P20, P35 (moderately sorted), and P55 (poorly sorted). The agglutinated species *Textularia earlandi* was found at stations where the sediment is moderately sorted (stations P12, P20, P25). Deeper-water sediments in the middle shelf contain *Bolivina striatula, Bulimina marginata, Triloculina trigonula, Pyrgo ringens,* and *Textularia gramen.* The shallowest sediments in the inner shelf contain *Ammonia tepida, Buccella peruviana, Miliolinella subrotunda,* and *Quinqueloculina patagonica.* The central parts of the transect along the inner shelf provide habitats for *Q. lamarckiana, Textularia earlandi, Buliminella elegantissima, Discorbis peruvianus,* and *Pyrgo nasuta.* The distribution of *Uvigerina striata* at two sedimentologically contrasting stations (P20 and P32) and the presence of *Buccella peruviana* at P05, P12, P32, P35, P55 indicates that their presence may be linked to water properties or other abiotic factors such as colder temperatures rather than the particular sedimentological features discussed above.

Cluster analysis applied to Foraminiferal abundances revealed three groups (Figure 4):

Group I: Stations P25 and P20 from the central parts of the transect located in the deeper inner shelf, with siliciclastic sediments and the following Foraminiferal assemblage; *Q. lamarckiana, T. earlandi, B. elegantissima, D. peruvianus,* and *P. nasuta.*

Group II: Stations P05 and P12 from the shallower inner shelf, with siliciclastic and silicibioclastic sediments associated with the Foraminiferal assemblage; *A. tepida, B. peruviana, M. subrotunda, Q. patagonica.*

Group III: Stations P32, P35, P55, with carbonate mud, silicibioclastic and biosiliciclastic sand sediments from channel, associated with the Foraminiferal assemblage; *B. striatula, B. peruviana, B. marginata, T. trigonula, P. ringens, T. gramen.*

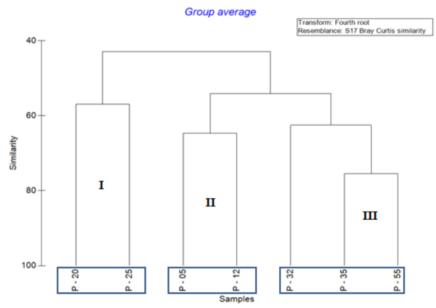

Figure 4 Cluster analysis based on Foraminiferal abundance data.

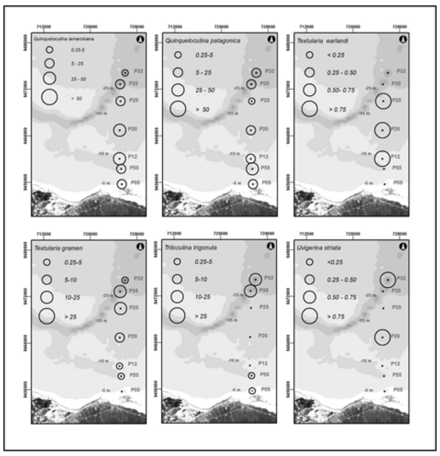

Figure 5 Map of relative frequency of Foraminifera microfauna in a stretch on the northern continental shelf of Rio Grande do Norte.

Citation: Nogueira MLS, Eichler PPB, Borges MEP, et al. Evidence of upwelling on the Brazilian continental shelf of Rio Grande do Norte. *J Aquac Mar Biol.* 2023;12(3):242–250. DOI: 10.15406/jamb.2023.12.00380

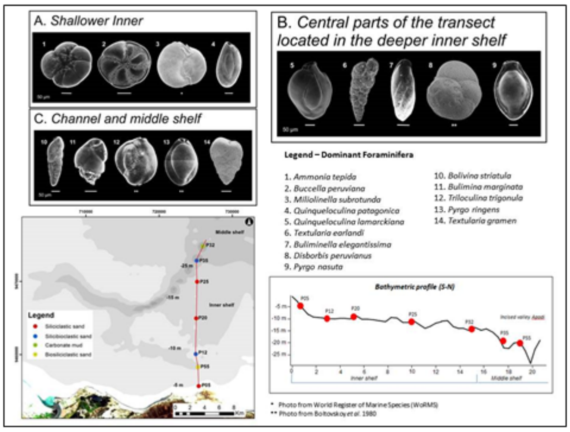

Figure 6 The distribution of dominant foraminifera microfauna along the transect on the northern continental shelf of Rio Grande do Norte.

Discussion

Our results shows that with the exception of Station P05, the stations from deep (Stations P32, P35) and shallow (Station P55) channels contain the highest values of organic matter and calcium carbonate, as found by Pessoa Neto[12] and Vital et al.[18,28] The calcium carbonate content in the sediments in our study also correlates with siliciclastic composition in the inner shelf and carbonate-siliciclastic in the middle shelf. The significant presence of calcium carbonate is due to the occurrence of bioclastic material (shell fragments, calcareous algae, among others).

The TOM distribution appears directly related to sediment grain size; the smaller particle size correlates with the higher amount of TOM, particularly at Stations P05, P32, and P55. The poor sorting of sediments at these three stations indicates close proximity to the rock matrix source. Our results match those of the above-mentioned studies of siliciclastic, silicibioclastic and biosiliciclastic sands in the inner shelf that are replaced by silicibioclastic and carbonate mud in the middle shelf. We note the presence of carbonate mud inside the deep channel of the incised valley.

Figure 8 is a graphical abstract and summarizes data on abiotic and biological findings. Foraminiferal assemblages from Stations P12, P20, and P25 contain *Q. lamarckiana, T. earlandi, B. elegantissima, D. peruvianus,* and *P. nasuta,* which are characteristic of sediments with high TOM content. The occurrence of *B. elegantissima* is likely out of place, and probably due to organic contamination, see "Culver and Buzas".[29] According to Eichler et al.,[22] the polyhaline environment (18-30 PSU) of some parts of Bertioga Channel (SP, Brazil) contains both muddy and sandy sediments, with TOM varying from 1.2 to 9.5 mg/g and most stations have high sulfur content (>10 mg/g). It includes Foraminiferal assemblages dominated by *Q. milletti, A. mexicana, P. cananeiaensis, A. beccarii,* and *B. elegantissima.* The foraminiferal assemblage of poorly flushed marine bottom waters of inner parts of the bay Guanabara Bay, Rio de Janeiro,[5] is composed by *B. elegantissima, B. striatula,* and *B. elongata,* which are known to dominate in organic-rich substrate beneath low-oxygen water columns. Thus, the species distribution in the northern continental shelf compare strongly to recent highly organic deposits at Stations P32 and P55 (and possibly others). The porcelaneous genus *Quinqueloculina* can also be associated with normal marine salinities, high water clarity, good circulation,[30] and intrusion of marine waters Eichler et al.[22]

Depth and sediment type influenced the Foraminiferal assemblage, particularly at (a) the shallower inner shelf and in the shallow channel stations (Stations P5 and P55), where *A. tepida, B. peruviana, M. subrotunda,* and *Q. patagonica* are common, and (b) in the deep channel (Stations P32 and P35), with *B. striatula, B. marginata, T. trigonula, P. ringens,* and *T. gramen. Buccella peruviana* was described by Boltovskoy as a cold-water species from Malvinas current. Years later, in summer samples from the Brazilian continental shelf the presence of cold upwelled water masses was showed by the correlation between $\delta^{13}C$ from benthic foraminifera and water depth weakens, reflecting a less stratified water mass associated with upwelling and the distribution of *Buccella peruviana*, indicator of the Sub Antartic Shelf Water.[31]

The presence of *Buccella peruviana* in the Northernmost part of Rio de Janeiro was described by Stevenson et al.,[32] as a temperature water species typical to the Argentina province. In the South of Brazil, Eichler et al.,[33] has associated *B. peruviana* to upwelling of colder waters from Sub Antarctic shelf water. More recently, organically enriched sediments and foraminiferal species from the Açu Reef, have also indicated the presence of upwelling in NE Brazil.[34]

Shallow (Station P55) and deep channels (Station P32 and P35) contain the highest values of carbonate content (more than 40%), with the shallow channels even showing oil impregnation in some Foraminiferal tests. In contrast, the two stations located in the deep channels of the mid continental shelf have low carbonate context and very abundant autochthonous microfauna. *B. striatula, B. marginata, T. trigonula, P. ringens,* and *T. gramen* inhabit sediments with medium mud and medium sand at Station P35 whereas Station P32 has the highest content of mud, organic matter, and silt. *B. striatula, B. marginata, T. trigonula, P. ringens,* and *T. gramen* inhabit sandy and muddy sediments inside the deep channel.

The Foraminiferal species *B. striatula* is present at locations where carbonate, organic matter, silt, and clay values are higher and grains are poorly sorted (Stations P32 and P55).

The presence of *Amphistegina* sp. (a coral reef endemic Foraminiferal species) at Stations P05 and P12 revealed that the shallower stations are comprised of allochthonous material from a not very distant coral reef.[26] *Q. patagonica* and *Q. lamarckiana* are characteristic of sediments with both low organic matter and clay values, such as those from Stations P12, P20, and P35 (moderately sorted) and Station P55 (poorly sorted). The agglutinated *Foraminifera*, *T. earlandi* was found at stations where the sediment is moderately sorted (Stations P12, P20, P25).

Following the geomorphology and sedimentation patterns, Vital et al.[18] and Gomes and Vital[19] divided this continental shelf into 1. Inner shelf, dominantly siliciclastic sediments (up to 15m isobath), 2. Middle shelf, with siliciclastic-carbonate sediments (15 to 25m deep), and 3. Outer shelf, formed by carbonate sediments (25 to 40m deep). The Foraminiferal distribution is distributed basic in shallow and deep sediments as follows: 1. the shallowest sediments in the inner shelf contain *A. tepida, B. peruviana, M. subrotunda,* and *Q. patagonica.* Central parts from the deepest inner shelf provide habitats for *Q. lamarckiana, T. earlandi, B. elegantissima, D. peruvianus,* and *P. nasuta*, 2. Deeper-water sediments in the middle shelf contain *B. striatula, B. marginata, T. trigonula, P. ringens, and T. gramen.* For a late Pliocene assemblage, Resig[35] concluded that a 33% frequency of *B. elegantissima* is characteristic of the middle shelf and are in agreement with our findings. Moreover, our results are in agreement with the distribution of *Uvigerina striata* at two stations with contrasting sedimentological features (Stations P20 and P32) indicating that its occurrence may be linked to water properties or other abiotic factors such as colder temperatures, instead of the studied sedimentological features discussed here. Further confirming our conclusions, the genus *Uvigerina* has been reported as a cold water-tracer suggesting the influence of South Atlantic Central Water (SACW) nutrients brought up by upwelling in the Brazilian Continental shelf[36] and *U. striata* has been shown to be indicative of current-generated deposition in the lower upper bathyal counter current regime of paleo environments off Peru[35]. The distribution of *U. striata* in our work is also possibly linked to the occurrence of an upwelling phenomenon not yet described in the literature for the area. The cold waters would reach the shelf through the head canyons observed on the slope (Figure 1). Almeida et al.[37] mapped these canyons and identified that the Apodi canyon head reaches the shelf break at 106 m and suggested that Apodi-Mossoro canyons were probably connected to the incised valley and or shelf drainage system.[38]

Conclusion

The results show that this transect is dominated by four facies: siliciclastic sand, silicibioclastic sand, carbonate mud and biosiliciclastic sand.

Siliciclastic sand encompasses P5, P20, and P25 stations. P5 is the shallowest station, comprised poorly sorted sediments, high percentage of silt and very fine sand, and allochthonous material from a not very distant coral reef and the presence of *Buccella peruviana and A. tepida*. *M. subrotunda* and *Q. patagonica*. P20 has *Q. patagonica*, *Q. lamarckiana*, *Uvigerina striata, T. earlandi, B. elegantissima, D. peruvianus,* and *P. nasuta* from low organic matter and clay values. P25 station has moderately sorted sediments with the presence of *Q. lamarckiana*. *T. earlandi*. *B. elegantissima*. *D. peruvianus* and *P. nasuta*.

Silicibioclastic sand groups P12 and P35 stations. Station P12 has *Q. patagonica* and *Q. lamarckiana, T. earlandi. B. elegantissima. D. peruvianus* and *P. nasuta*, sediment moderately sorted, low organic matter and clay values. P35 is also moderately sorted sediments with the high concentration of carbonate. Both have *Buccella peruviana.* P35 has *B. striatula. B. marginata. T. trigonula. P. ringens*, *T. gramen*, and *Uvigerina striata*.

Carbonate mud at P32 station has *B. striatula. B. marginata. T. trigonula. P. ringens*, *T. gramen Uvigerina striata*, and *Buccella peruviana* from poorly sorted sediments with high concentration of carbonate, organic matter, and high percentage of silt and very fine sand.

Biosiliciclastic sand at P55 station, poorly sorted sediments high concentration of carbonate and organic matter, high percentage of silt and very fine sand and the presence of *B. peruviana, A. tepida, B. peruviana, M. subrotunda,* and *Q. patagonica.* The carbonate content ranged between 5.83% to 85% and organic matter content 1.16% to 27.05%. The mineralogical description identified a predominance of siliciclastic content (37% to 92%) over bioclastic content (8% to 63%). These features are in accordance with the geomorphological divisions of northern continental shelf of Rio Grande do Norte State. The Foraminiferal distribution data show that the shallowest sediments in the inner shelf contain *A. tepida, B. peruviana, M. subrotunda,* and *Q. patagonica.* The central parts from the deepest inner shelf contain habitats for *Q. lamarckiana, T. earlandi, B. elegantissima, D. peruvianus,* and *P. nasuta.* Deeper sediments in the middle shelf contain *B. striatula, B. marginata, T. trigonula, P. ringens,* and *T. gramen.* The distribution of *U. striata* and *B. peruviana* are possibly linked to water properties or colder temperatures and upwelling rather than sedimentological features and should therefore be investigated. The sediment type, composition, and relation with the benthic biological community show that foraminifera are critical in coupling shelf systems with geological and hydrodynamic processes.

Acknowledgements

We gratefully thank the PRH-ANP 22 (Brazilian National Oil Agency and PETROBRAS) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the scholarship to M.L.S.Nogueira and to CNPq by the productivity research grant to H.Vital. The second author is thankful for CAPES for the PostDoc Fellowship at the Laboratório de Geologia e Geofísica Marinha e Monitoramento Ambiental da Universidade Federal do Rio Grande do Norte (GGEMMA-UFRN-Brazil) through the Edital Ciências do Mar [207/2010], and to CNPq - Chamada MCTI/CNPq [Nº 23/2011], Apoio Técnico para Fortalecimento da Paleontologia Nacional). Thanks are also to GGEMMA (DG/PPGG /UFRN) group, in special Canindé for field assistance under rough sea environmental conditions. Authors are grateful for the English review done by Christofer Barker from EcoLogic project.

Financial support to field and laboratory works was provided by SISPLAT (REDE 05/FINEP/CTPETRO/ CNPq/ PETROBRAS), CAPES Ciências do Mar I (207-10) and TBEM IODP/CAPES-Brasil (88887.123925/2015-00). This is a contribution to INCT AmbTropic (CNPq/FAPESB/CAPES) and TBEM IODP/ CAPES-BRASIL.

Conflicts of interest

The authors declare that there are no conflicts of interest.

References

1. Gehrels WR. Using foraminiferal transfer functions to produce high-resolution sea-level records from salt-marsh deposits, Maine, USA. *The Holocene*. 2000;10(3):367–376.
2. Edwards RJ, Van De Plassche O, Gehrels WR, et al. Assessing sea-level data from connecticut, USA, using a foraminiferal transfer function for tide level. *Marine Micropaleontol.* 2004;51(3–4):239–255.
3. Horton BP, Edwards RJ. The application of local and regional transfer functions to the reconstruction of Holocene Sea levels, north Norfolk, England. *The Holocene.* 2005;15(2):216–228.
4. Araújo FMT, Machado AJ. Análise sedimentar e micropaleontológica (foraminíferos) de seções quaternárias do talude continental superior do Norte da Bahia, Brasil. *Revista Pesquisas em Geociências.* 2008;35(2):97–113.
5. Eichler PPB, Eichler BB, Miranda LB, et al. Benthic foraminiferal response to variations in temperature, salinity, dissolved oxygen and organic carbon, in the guanabara bay, Rio de janeiro, Brazil. *Anuário do Instituto de Geociências.* 2003;26:36–51.
6. Phleger FB, Soutar A. Production of benthic foraminifera in three east Pacific oxygen minima. *Micropaleontology*. 1973;19(1):110–115.
7. Belanger CL. Evaluating taphonomic bias of paleoecological data in fossil benthic foraminiferal assemblages. *Palaios*. 2011;26(12):767–778.
8. Belanger CL. Coastal dysoxia accompanies early miocene warming based on benthic foraminiferal and sedimentary records from Oregon. *Marine Micropaleontol.* 2011;80(3–4):101–113.

9. Vital H, Furtado SFL, Gomes MP. Response of apodi–mossoro estuary–incised valley system (NE Brazil) to sea–level fluctuations. Braz J Oceanography. 2010;58:13–24.
10. Vital H. The north and northeast Brazilian tropical shelves. In: Chiocci FL, Chivas AR (Eds). *Continental shelves of the world: their evolution during the last glacio–eustatic cycle*. Geological Society Memoir. 2014;41(1):35–46.
11. Gomes MP, Vital H, Eichler PPB, et al. The investigation of a mixed carbonate–siliciclastic shelf, ne Brazil: side–scan sonar imagery, underwater photography, and surface–sediment data. *Italian J Geosci*. 2015;134(1):9–22.
12. Pessoa Neto OC. Estratigrafia de seqüências da plataforma mista neogênicana bacia potiguar, margem equatorial Brasileira. *Revista Brasil de Geociocências*. 2003;33:263–278.
13. Dominguez JML, Biitencourt ACSP, Martin L. Controls on quaternary coastal evolution of the east–northeastern coast of Brazil: roles of sea–level history, trade winds and climate. *Sedimentary Geology.* 1992;80:213–232.
14. Chaves MS, Vital H, Silveira IM, et al. Beach morphodynamics of the serra oil field (NE, Brazil). *J Coast Res.* 2006;39:594–597.
15. Caldas LHO. Late quaternary coastal evolution of the northern Rio Grande do Norte coast, NE Brazil. Ph.D. thesis, University of Kiel, Germany. 2002;99.
16. Araujo M, Vital H, Amaro VE, et al. Caracterização das forçantes hidrodinâmicas -correntes, ondas e marés – na região costeira de guamaré–rn. In: *proceedings of the II workshop Petrorisco*, Brazil. 2004.
17. Vital H, Silveira IM, Tabosa WF, et al. *Beaches of Rio Grande do Norte*, In: Short AD and Klein AH (eds), Brazilian Beach Systems. 2016;201–229.
18. Vital H, Stattegger K, Amaro VE, et al. Inner continental shelf off Northern Rio Grande do Norte, NE Brazil: A modern high-energy siliciclastic-carbonate platform. In: Hampson G, Dalrymple R (eds). Recent advances in ahoreline–shelf. *Stratigraphy*. SEPM Special 2008;90.
19. Gomes MP, Vital H. Revisão da compartimentação geológica da plataforma continental norte do Rio Grande do Norte -Brasil. *Revista Brasileira de Geociências*. 2010;40(3):321–329.
20. Lima SF, Vital H, 2006. Geomorphological and paleogeographic characterization of continental shelf of the Apodi–Mossoró River, RN–Brazil. *WIT Transac Ecol Environ*. 2006;88:351–360.
21. Gomes MP, Vital H, Macedo JWP. Aplicação da geoestatística na filtragem de dados batimétricos e altimétricos na Bacia Potiguar. *Revista de Geologia.* 2007;20(2):243–255.
22. Eichler PPB, Eichler BB, Miranda LB, et al. Modern foraminiferal facies in a subtropical estuarine channel, Bertioga, São Paulo, Brazil. *J Foraminiferal Res.* 2007;37(3):234–247.
23. Folk RL. *Petrology of sedimentary rocks*. Hemphill publishing company, Austin-Texas, EUA. 1974.
24. Freire GSS, Cavalcanti VMM, Maia LP, et al. Classificação dos sedimentos da plataforma continental do estado do ceará. in: *simpósio de geologia do nordeste*; Brasil. 2016;209–211.
25. Ellis BF, Messina A. Catalogue of foraminifera: *American museum of natural history and micropaleontology* project, Inc., New York (with supplements). 1940.
26. Javaux EJ, Scott DB. Illustration of modern benthic foraminifera from Bermuda and remarks on distribution in other subtropical/tropical areas. *Palaeontologia Electronica*. 2003.
27. Clarke KR, Warwick RM. Changes in marine communities: an approach to statistical analyses and interpretation. *Nat Environ Res Council*. 1994.
28. Vital H, Silveira IM, Amaro VE. Carta sedimentológica da plataforma continental braisleira area Guamaré a Macau (NE do Brasil), utilizando integração de dados geológicos e sensoriamento remoto. *Revista Brasileira de Geofísica*. 2005;23(3):233–241.
29. Culver S J, Buzas MA. The effects of anthropogenic habitat disturbance, habitat destruction, and global warming on shallow marine benthic Foraminifera. *J Foramin Res*. 1995;25(3):204–211.
30. Ishman SE, Graham I, D'Ambrosio J. Modern benthic foraminfer distributions in biscayne bay: analogs for historical reconstruction. *US Geological Survey Open-File Rep.* 1997;23:97–34.
31. Eichler PPB, Rodrigues AR, Eichler BB, et al. Tracing latitudinal gradient, river discharge and water masses along the subtropical South American coast using benthic Foraminifera assemblages. *Braz J Biol.* 2012;72(3 Suppl):723–759.
32. Stevenson MR, Dias–Brito D, Stech JL, et al. How do cold water biota arrive in a tropical bay near Rio de Janeiro, Brazil? *Continent Shelf Res.* 1998;18:1595–1612.
33. Eichler PPB, Pimenta FM, Eichler BB, et al. Living benthic foraminiferal species as indicators of cold-warm water masses interaction and upwelling areas. *Continent Shelf Res*. 2016;116(4):116–121.
34. Eichler PPB, do Nascimento Silva LL, de Andrade AU, et al. Organically enriched sediments and foraminiferal species from the Açu Reef, indicators of upwelling in NE Brazil? *Marine Geology.* 2019;417(3):106016.
35. Resig J. Benthic foraminiferal stratigraphy and paleoenvironments off Peru, Leg 1121. In: Suess, E., Von Huene, R., et al., *Proc Ocean Drilling Program Sci Results*. 1990;112.
36. Eichler PPB, Sen Gupta BK, Eichler BB, et al. Foraminiferal assemblages of the South Brazil: relationship to water masses and nutrient distributions. *Continent Shelf Res.* 2008;28(13):16741686.
37. Almeida NM, Vital H, Gomes MP. Morphology of submarine canyons along the continental margin of the Potiguar Basin, NE Brazil. *Mar Petrol Geol*. 2015;68(A):307–324.
38. Larsonneur C. La cartographie des dépôt meubles sur le plateau continental français: méthode mise au point et utilisée en Manche. *J Rech Oceanography.* 1977;234–39.