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Evaluation and assessment of the northern shelf adjacent to the Apodi River incised valley, Rio Grande do Norte (RN), Brazil

Abstract

This study was conducted in the area adjacent to the Apodi River Incised Valley, near the city of Areia Branca, RN, Brazil. The objective was to evaluate the responses of foraminiferal associations to environmental aspects. Ten surface sediment samples were collected from the northern shelf of the state of Rio Grande do Norte, along with the measurement of abiotic parameters. Granulometry (represented by silt content) was found to have the least influence on the dispersion of foraminiferal species, while physical water variables, mainly depth, showed a greater impact. An important observation in the northern region of the state was the absence of a single species dominating all stations. Instead, some stations were dominated by *Quinqueloculina lamarckiana*, while others were dominated by *Amphistegina gibbosa*.

Keywords: foraminifera, bio indicators, incised valley, Apodi River, abiotic data.

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Luísa Cardoso Marinho,[1] Patrícia Pinheiro Beck Eichler,[2] Allany de Paula Uchôa Andrade,[2] Moab Praxedes Gomes,[2] Helenice Vital[2]

[1]Undergraduate Student at UFRN, Brazil
[2]Postgraduate Program in Geodynamics and Geophysics, Department of Geology, Federal University of Rio Grande do Norte, Brazil

Correspondence: Patrícia P. B. Eichler, Programa de Pós-Graduação em Geodinâmica e Geofísica (PPGG), Universidade Federal do Rio Grande do Norte (UFRN), Campus Universitário, Lagoa Nova, 59072-970, Natal, RN, Brazil, Email patriciaeichler@gmail.com

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Introduction

Foraminiferal associations are influenced by various abiotic factors such as salinity, temperature, substrate type, organic carbon content, pH, tidal energy, and nutrient availability, which allow for paleo environmental reconstruction of a region.[1–3] The morphological characteristics of foraminiferal shells used for classification include test composition, shape, chamber arrangement, suture lines, the number and position of foramina, and ornamentation, which provide insights into the environment and the influence of marine waters on coastal settings.[4,5] Additionally, the diversity of foraminifera decreases with increasing sediment coarseness, with macro foraminifera typically dominating coarser sediments and leading to lower overall diversity in these environments.[6] Foraminiferal associations are influenced by various abiotic factors such as salinity, temperature, substrate type, organic carbon content, pH, tidal energy, and nutrient availability. These data allow for the paleo environmental reconstruction of a region.[2,3,7]

The morphological characteristics of foraminiferal shells used for classification include test composition, shape, chamber arrangement, suture lines, the number and position of foramina, and ornamentation.[3] These features provide information about the environment and the influence of marine waters on coastal settings.[4,7]

According to Araújo et al.[6] the diversity of foraminifera decreases with increasing sediment coarseness, with macro foraminifera typically dominating coarser sediments, leading to lower overall diversity in these environments.

Benthic foraminifera are strongly influenced by abiotic factors in their distribution across various habitats.[1] According to Vilela et al.,[3] benthic foraminiferal associations allow the creation of species distribution models for the Recent based on geological past conditions. Additionally, it is noted that the more sensitive taxa are suppressed first, while more tolerant taxa are the last to be eliminated from impacted areas.[5] Combined with their preservation potential, short life cycle, and ease of sampling -where even small samples can contain numerous specimens[3] -foraminifera are considered environmental indicators.[8]

This study aims to provide information about environmental quality and support preservation programs while also offering explanations for existing pollution-related problems. We also seek to qualify the distribution of microorganisms in relation to the physical and sedimentological aspects of the area.

Study area characterization

The study area is located on the outer shelf near the Apodi River incised valley (Figure 1), in the northern coastal region of Rio Grande do Norte, close to the city of Areia Branca, Brazil.

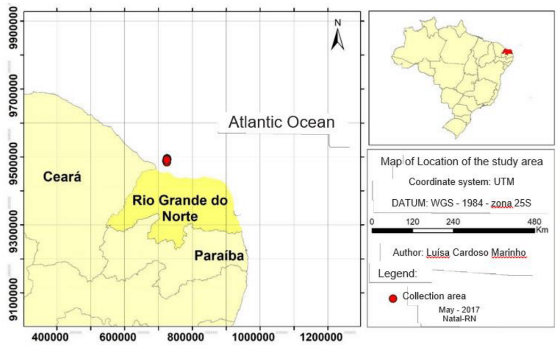

Figure 1 Location map of the study area.

In geological terms, the study area is part of the Potiguar Basin, situated within the Borborema Province.[9] The basin is related to a series of Lower Cretaceous basins, dating back approximately 135 million years.[10] The main geomorphological features of this basin include the incised valleys of the Açu and Apodi-Mossoró rivers.[11–13]

Materials and methods

Physical parameters: Samples were collected between 17 y and 23 March 17 and 23, 2016, using a Van Veen grab or scientific divers. Ten surface samples were taken (Figure 2), and the top two centimetres were transferred to vials containing Bengal Rose stain for later biological analysis. A portion of each sample was also set aside for granulometric analysis.

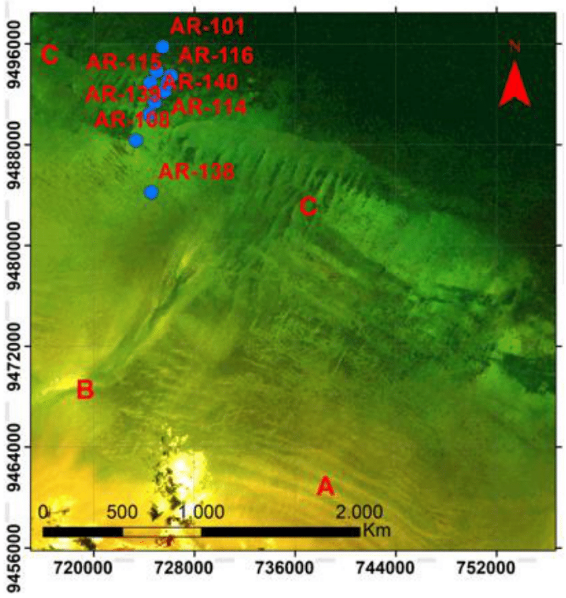

Figure 2 Location of sampling stations.

Biological parameters: According to Eichler et al.,[1] Bengal Rose stain, prepared with 70% alcohol prior to fieldwork, is used to stain the protoplasm, indicating that the individual was alive at the time of collection, while the alcohol protects against microbial attack. Afterward, the samples underwent wet sieving (through successive sieves of 0.500 and 0.0062 mm) to remove silt and clay fractions and were then dried at 50°C for 72 hours. The samples were quartered to obtain a satisfactory amount for foraminiferal sorting and species identification based on bibliographic material by Boltovskoy et al.[14]

Sedimentological parameters

The sedimentological processing was divided into four stages:

Washing and aliquot separation: The samples were washed to remove salts, repeating the process three times. Next, they were dried at 50°C, homogenized, quartered, and aliquots were separated for subsequent stages: 10g for organic matter analysis, 10g for carbonate content, and 100g for granulometry.

Granulometric analysis: Each sample was placed in a series of sieves (8.0mm, 4.00mm, 2.00mm, 1.00mm, 0.500mm, 0.250mm, 0.125mm, 0.0063mm, and PAN) and subjected to agitation for 15 minutes. The samples were then weighed, and the data were entered into the GGEMMA laboratory database.

Carbonate content analysis: Carbonate content was determined at the Sedimentology Laboratory by adding 10% hydrochloric acid to a beaker containing the sample. The material was filtered, dried at 50°C, and weighed again, with the results recorded in the GGEMMA database.

Organic matter content analysis: The organic matter analysis was carried out in the Geochemistry Laboratory at UFRN. Initially, empty crucibles were weighed, and then the samples were weighed and placed in an oven at 100°C for 24 hours to remove moisture. After cooling in a desiccator, the samples were re-weighed and then placed in a muffle furnace for 6 hours (initially at 300°C for 15 minutes, then at 600°C). After cooling, the samples were re-weighed and the results were recorded in the GGEMMA laboratory database.

After obtaining the sedimentological data, it was processed using the Granulometric Analysis System (SAG), developed by Gilberto T. M. Dias & Clarisse B. Ferraz, which provided the statistical calculations and sedimentological classifications, including mean grain size, Folk, and Larsonneur classifications for each sample.

Results

Hydrographic Parameters: Hydrographic data, acquired with the help of a CTD device, enabled the construction of Table 1 and the creation of contour maps using ArcGIS 10.2, which supported data analysis. Stations in the northern shelf region range in depth from 16 meters at station 108 to 57 meters at station AR-101, showing that the farther north and away from the incised valley, the deeper the stations. Temperature data show that surface temperatures (Figure 3.A) have very similar values, with a standard deviation of just 0.295°C, and maximum and minimum values at stations AR-114 (28.533°C) and AR-138 (27.684°C), respectively. Despite these similar values, it can be observed that, generally, temperatures decrease further north in the study area. In contrast, bottom temperatures (Figure 3.B) reveal an inverse pattern, with maximum and minimum values at stations AR-139 (29°C) and AR-103 (28.9°C), respectively. Bottom temperatures tend to increase further north in the study area, except for stations AR-101, AR-139, and AR-140. Lastly, salinity shows similar values across stations. However, as seen in Figure 3.C, station AR-139 (37.31) presents a lower value, indicating a reduction in salinity in the central area compared to surrounding stations.

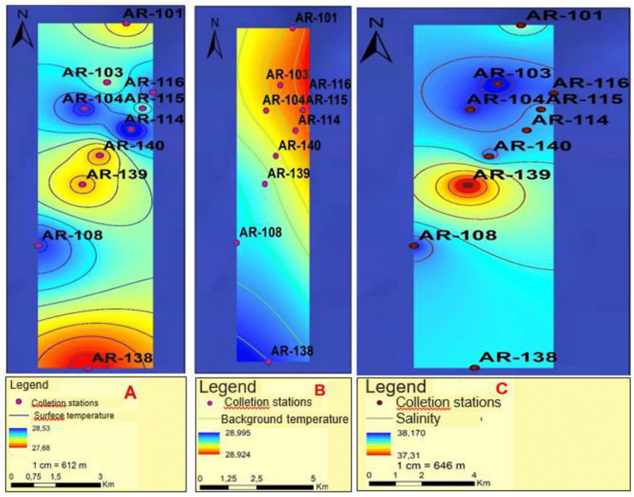

Figure 3 Physical-chemical data of sampling stations.

By analysing the hydrographic data, we observe that the stations further away from the Apodi River incised valley are deeper and warmer, particularly in the northern part of the study area. Bottom temperatures are higher near the incised valley.

Citation: Marinho LC, Eichler PPB, Andrade ADPU, et al. Evaluation and assessment of the northern shelf adjacent to the Apodi River incised valley, Rio Grande do Norte (RN), Brazil. *J Aquac Mar Biol.* 2024;13(3):124–131. DOI: 10.15406/jamb.2024.13.00407

Table 1 Abiotic data for the stations, highlighting the maximum, minimum, mean, and standard deviation for each collected parameter

Simple frequency classification										
Sample	**Gravel**	**Ver coarse sand**	**Coarse sand**	**Medium sand**	**Fine sand**	**Very fine sand**	**Silt**	**Clay**	**CacO$_2$**	**Organic matter**
AR-101	2,21	4,81	15,75	21,89	36,07	16,21	3,08	0,00	72,68	3,64
AR-103	52,99	7,90	7,88	4,71	4,20	13,35	8,97	0,00	90,23	8,48
AR-104	12,81	42,96	34,84	5,15	3,42	0,62	0,20	0,00	33,63	2,33
AR-108	20,98	12,34	16,86	36,12	13,55	0,15	0,01	0,00	46,07	3,11
AR-114	2,03	9,25	25,07	27,80	29,49	4,48	1,89	0,00	19,22	2,19
AR-115	26,44	10,85	8,22	6,00	21,19	15,15	12,14	0,00	71,97	7,83
AR-116	29,05	9,81	9,70	7,87	14,87	18,50	10,20	0,00	73,58	7,31
AR-138	0,76	2,08	57,74	37,96	0,00	1,44	0,03	0,00	5,26	0,36
AR-139	30,81	15,60	12,44	13,59	22,69	3,19	1,67	0,00	60,92	3,86
AR-140	38,32	21,94	25,28	11,89	2,09	0,47	0,01	0,00	69,10	5,06
Maximum	**52,99**	**42,96**	**57,74**	**37,96**	**36,07**	**18,50**	**12,14**	**0,00**	**90,23**	**8,48**
Minimum	**0,76**	**2,08**	**7,88**	**4,71**	**0,00**	**0,15**	**0,01**	**0,00**	**5,26**	**0,36**
Mean	**21,64**	**13,754**	**21,378**	**17,298**	**14,757**	**7,356**	**3,820**	**0,000**	**54,266**	**4,417**
Standard deviation	**17,678**	**11,799**	**16,036**	**13,229**	**12,622**	**7,442**	**4,638**	**0**	**30,632**	**2,882**

Granulometric parameters: The gravel and coarse sand content (Figures 4.A and 4.B) show inverse patterns, with station AR-138 displaying the highest coarse sand content (57.47%) and the lowest gravel content (0.76%), while station AR-103 has the highest gravel content (52.99%) and the lowest coarse sand content (7.88%). Similarly, the medium sand fraction follows the pattern of gravel, with maximum values at station AR-138 (37.96%) and minimum values at station AR-103 (4.71%) (Figure 4.C). The very coarse sand fraction shows minimum values at station AR-138 (2.08%) and maximum values at station AR-104 (42.96%) (Figure 5.A). Fine sand is absent at station AR-138 and shows maximum values at station AR-101 (36.07%) (Figure 5.B). Table 2 presents the sedimentological data.

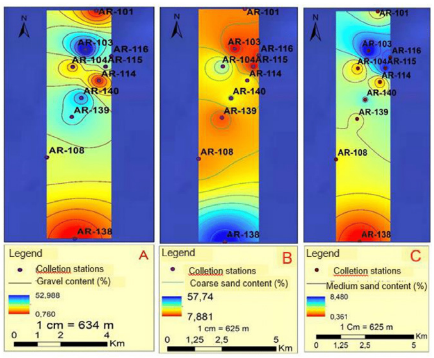

Figure 4 Contour maps of sedimentological data from the northern shelf area of RN. A- Gravel; B- Coarse sand; C- Medium sand.

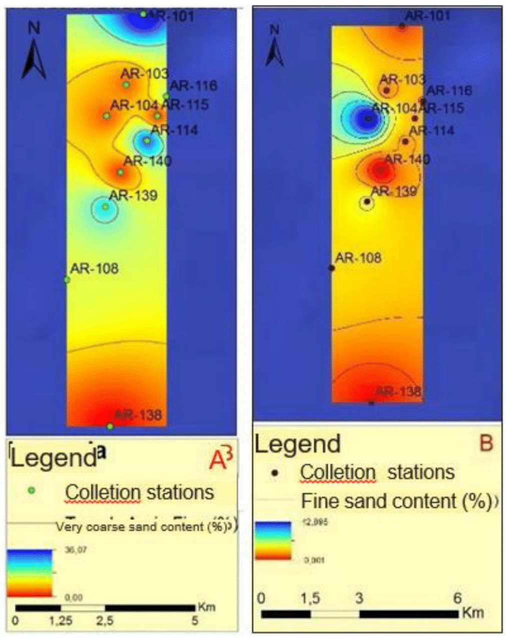

Figure 5 Contour maps of sedimentological data from the northern shelf area of RN. A- Very coarse sand; B- Fine sand.

Table 2 Sedimentological data of the study area, highlighting the maximum, minimum, mean, and standard deviation for each collected parameter

Sample	**Depth**	**Background temperature**	**Background conductivity**	**Bottom salinity**	**Surface temperature**
AR-101	57,00	28,98	60235,71	37,83	27,95
AR-103	28,00	28,91	60709,31	38,17	28,11
AR-104	30,00	28,93	60625,96	38,11	28,44
AR-108	16,00	28,96	60628,14	38,11	28,41
AR-114	35,00	28,92	60437,43	37,98	28,53
AR-115	36,00	28,92	60418,64	37,96	28,16
AR-116	40,00	28,93	60553,26	38,06	28,36
AR-138	25,00	28,99	60352,68	37,92	27,68
AR-139	27,00	29,00	60615,61	37,31	27,87
AR-140	50,00	28,97	60514,91	38,03	27,84

Table 2 Continued..

Sample	Depth	Background temperature	Background conductivity	Bottom salinity	Surface temperature
Maximum	57,00	29,003	60709,309	38,171	28,533
Minimum	16,00	28,914	60235,711	37,307	27,684
Mean	31,273	26,319	55008,332	34,499	25,578
Standard deviation	12,158	0,033	146,731	0,247	0,295

The clay fraction is absent at the collected stations. The very fine sand and silt fractions (Figures 6.A and 6.B) show similar behaviour, with minimum values at station AR-108 (0.15% for very fine sand and 0.01% for silt) and maximum values at station AR-116 (18.5% and 10.2%, respectively).

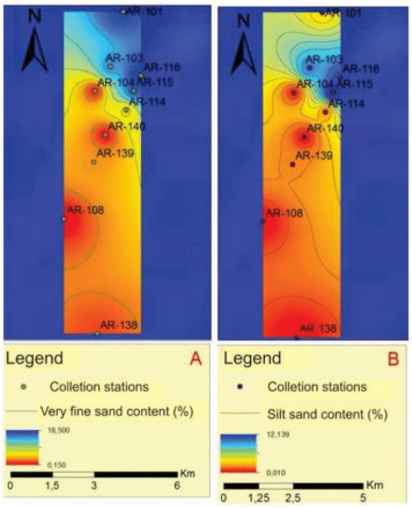

Figure 6 Contour maps of sedimentological data from the northern shelf area of RN. A- Very fine sand; B- Silt.

Calcium carbonate content (Figure 7.A) and organic matter content (Figure 7.B) follow similar trends, with maximum values at station AR-103 (90.25% and 8.48%) and minimum values at station AR-138 (5.26% and 0.36%, respectively).

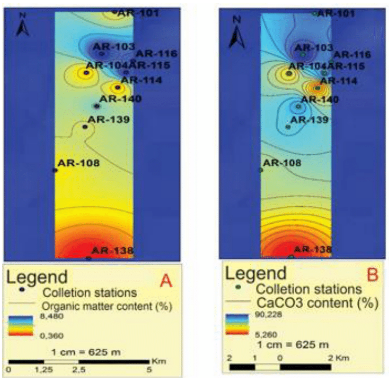

Figure 7 Contour maps of sedimentological data from the northern shelf area of RN. A- $CaCO_3$ content; B- Organic matter content.

Figure 8 shows the ternary diagram based on the granulometric analysis, indicating that the samples are distributed in the sand and gravel fields.

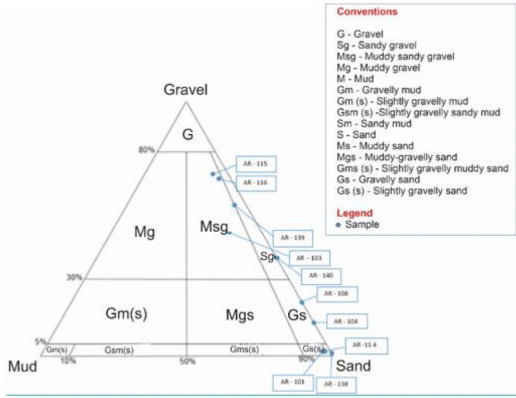

Figure 8 Ternary diagram of the samples from the northern shelf area of RN.

Based on the mean grain size classification, a sedimentological map was created (Figure 9). The map reveals a gradation in granulometry from north to south, transitioning from medium sand to very coarse and coarse sand, which may be a result of changes in the region's hydrodynamics due to the presence of the Apodi River incised valley.

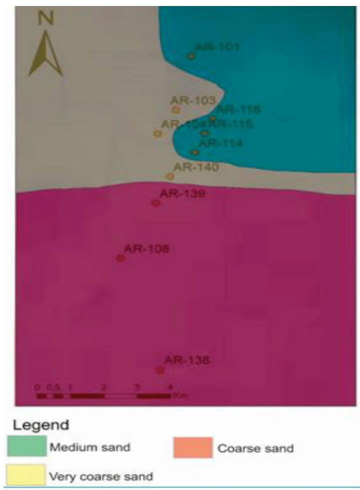

Figure 9 Sedimentation map of the Northern shelf.

Biological parameters: In the Northern Shelf area, a total of 13,126 individuals were identified across 33 species (Table 3). The main species found in this area were *Quinqueloculina lamarckiana* (2,672 individuals), *Amphistegina gibbosa* (2,856 individuals), *Peneroplis carinatus* (1,664 individuals), Pseudononium atlanticum (1,172 individuals), Quinqueloculina patagonica (1,072 individuals), and Buccella peruviana (216 individuals) (Figure 10).

Table 3 Total number of foraminifera collected for each sample in the Northern shelf

	AC - 101	AC - 103	AC - 104	AC - 108	AC - 114	AC - 115	AC - 116	AC - 138	AC - 139	AC - 140
Ammonia tepida	0	64	0	0	0	24	0	0	40	0
Amphistegina gibbosa	224	656	56	512	16	112	480	160	200	440
Articulina	0	16	0	0	64	0	0	0	0	0
Buccella peruviana	16	32	0	0	0	32	96	0	0	40
Cymbaloporeta sp 2	0	0	0	0	0	0	0	64	0	0
Discorbis sp.	0	0	0	16	0	8	0	32	0	0
Elphidiu sp 1	48	16	0	16	16	8	16	0	48	0
Elphidiun articulatun	0	16	0	32	80	144	16	234	16	0
Hanzawaia boueana	32	0	0	0	0	24	0	0	0	0
Heterostegina depressa	0	16	0	0	0	0	0	0	0	0
Miliolinella subrotunda	0	32	0	0	16	32	32	32	40	0
Patellina corrugata	0	48	0	0	80	0	0	32	0	0
Peneroplis carinatus	320	144	504	416	16	0	96	0	0	168
Peneroplis sp.	208	0	0	0	80	0	0	0	0	8
Peneroplis planatus	0	16	0	96	160	104	64	96	24	0
Peneroplis pertussis	0	0	48	0	0	0	0	0	0	0
Poroeponides lateralis	0	16	8	16	0	0	0	0	16	0
Pyrgo ringens	0	0	0	16	0	0	0	0	0	8
Pseudononion atlanticum	0	32	0	32	128	32	0	900	48	0
Quiqueloculina intricata	0	0	0	0	16	24	0	0	0	0
Quiqueloculina costata	0	0	16	0	0	0	0	0	0	0
Quiqueloculina lamarckiana	544	80	216	368	240	152	640	256	88	88
Quiqueloculina patagonica	0	32	8	16	240	224	112	320	120	0
Quiqueloculina polygona	0	0	8	0	0	0	0	64	24	24
Spiroloculina depressa	32	48	0	32	16	32	32	32	0	0
Textularia earlandi	0	16	0	0	0	16	48	288	80	56
Triloculina trigonula	16	16	0	0	16	8	16	0	0	0
Wiesnerella auriculata	0	16	0	0	0	0	0	32	16	0
Total	1440	1312	864	1568	1184	976	1648	2542	760	832

Figure 10 Plates of the main foraminiferal species found in the Northern Shelf area. (1) *Quinqueloculina lamarckiana*, (2) *Amphistegina gibbosa*, (3-4) *Peneroplis carinatus*, (5) *Pseudononium atlanticum*, (6) *Quinqueloculina patagonica*, and (7) *Buccella peruviana*.

Based on the identified species, five biofacies were distinguished in relation to dominant species (Figure 11): Biofacies 1 (stations AR-101 and AR-116), dominated by *Quinqueloculina lamarckiana*, Biofacies 2 (stations AR-114 and AR-115), dominated by *Quinqueloculina patagonica*, Biofacies 3 (stations AR-103, AR-108, AR-139, and AR-140), dominated by *Amphistegina gibbose*, Biofacies 4 (station AR-138), dominated by Pseudononium atlanticum, Biofacies 5 (station AR-104), dominated by *Peneroplis carinatus*

Figure 11 Biofacies map of the Northern shelf.

Discussion

The results of the BEST analysis indicate that depth is the most significant factor influencing foraminiferal associations, followed by bottom temperature, while the silt fraction has the least impact. This finding aligns with the work of Moura,[15] who similarly highlighted depth as a critical determinant of foraminiferal distribution in the study area. Further support comes from Havach & Collins, who also emphasized the importance of depth and temperature in shaping foraminiferal assemblages. However, contrasting studies, such as that of Araújo & Machado,[6] suggest that grain size can play a predominant role in foraminiferal distribution, demonstrating the complexity of environmental interactions in benthic ecosystems.

Equitability, a measure of the evenness of species distribution, is an important indicator of environmental stability. The high equitability observed in most stations, coupled with increased diversity and low dominance, suggests a relatively stable and healthy environment. However, certain stations (AR-104, AR-139, and AR-140) displayed reduced species richness, correlating with lower foraminiferal counts. Notably, station AR-139 exhibited the lowest salinity values, which may explain its lower species abundance, as salinity fluctuations can impose stress on marine biota. The connection between hydrographic conditions and biological assemblages highlights the sensitivity of foraminifera to environmental stressors.

The Multidimensional Scaling (MDS) and CLUSTER analyses provide additional insight into the spatial patterns of foraminiferal distribution. Groupings identified in the MDS plot (Groups I and III) correspond to Group C4 of the CLUSTER analysis, sharing similar characteristics in terms of organic matter content, $CaCO_3$ concentration, depth, and bottom temperature. These groups also exhibited lower species diversity, suggesting that these stations are subject to more homogenous environmental conditions. Conversely, Group C1 of the CLUSTER analysis corresponds to Group VI of the MDS and Group P2 of the Principal Component Analysis (PCA), with stations AR-138 and AR-139 sharing similarities in bottom temperature and medium sand content. These findings reinforce the notion that sedimentological and hydrographic variables play a crucial role in shaping benthic communities.

Stations dominated by *Amphistegina gibbosa* were characterized by coarse granulometry, supporting the conclusions of Moura[15] that the prevalence of this symbiont indicates an ecologically healthy reef environment. Similar results have been documented in Caribbean reef systems, where *Amphistegina gibbosa* is associated with coarse sediment textures, typically found in areas subject to high turbulence and water movement.[16–19] The coarse grain sizes in these habitats facilitate the separation of finer sediments, which may otherwise hinder the establishment of symbiotic foraminifera.

The biofacies analysis further refines our understanding of environmental conditions across the study area. Biofacies 1 and 2 are characterized by their tolerance to fluctuations in physical parameters, likely due to the dominance of the genus *Quinqueloculina*, a genus often associated with stressed environments. Biofacies 3, dominated by *Amphistegina gibbosa*, indicates a healthy reef environment with limited anthropogenic or natural disturbances. Biofacies 4 reflects the influence of continental input, evidenced by high concentrations of silicate in the sediments, consistent with the findings of Eichler et al.[7] Finally, biofacies 5, which is more typical of the middle and outer shelf regions, shows characteristics aligned with previous studies of shelf sedimentology,[20] confirming the spatial differentiation in foraminiferal communities across the shelf. The integration of sedimentological, hydrographic, and biological data underscores the importance of both depth and bottom temperature as key drivers of foraminiferal distribution on the Northern Shelf. The presence of distinct biofacies, coupled with the high diversity and equitability of foraminiferal assemblages, suggests that this region maintains a relatively healthy ecological balance, though localized variations in environmental parameters, such as salinity and grain size, may impose stress on specific stations. These findings contribute to our broader understanding of the factors shaping benthic foraminiferal communities in tropical shelf environments and provide valuable baseline data for future environmental monitoring and management efforts

Conclusion

This study underscores the effectiveness of using foraminiferal assemblages as reliable indicators of environmental health in coastal and marine ecosystems. The Northern Shelf, adjacent to the Apodi River incised valley, demonstrated notable environmental heterogeneity, with depth emerging as the primary factor influencing the distribution of foraminiferal species. Granulometric analyses indicated that silt content played a relatively minor role in determining biological distributions, highlighting the dominant influence of other environmental parameters such as depth and temperature. The delineation of distinct biofacies in the study area provides a deeper understanding of environmental dynamics and offers a practical framework for integrating physical and biological variables in marine ecosystem management. The spatial variation in sediment granulometry reveals a shift from medium to coarse and very coarse sand from north to south, strongly influenced by hydrodynamic conditions and sediment distribution patterns shaped by the Apodi River incised valley. This predominantly coarse-grained environment is further characterized by its dynamic sedimentary system.

From a hydrographic and biological perspective, the study found a positive correlation between depth and bottom temperature, with deeper stations exhibiting higher seabed temperatures. This stratification may influence both sediment transport and biological distributions, with temperature gradients driving ecological responses. Localized variations in salinity, particularly in station AR-139, suggest hydrological processes such as continental runoff or oceanographic mixing, impacting sediment distribution and benthic habitats. The foraminiferal community was diverse and abundant, with species like *Amphistegina gibbosa*, *Quinqueloculina lamarckiana*, and *Peneroplis carinatus* thriving in specific environmental conditions. The correlation between biological and sedimentological data suggests that coarser sediments host more symbiotic foraminifera, with species like *Amphistegina gibbosa* favoring turbulent environments. The integration of biological, sedimentological, and hydrographic data highlights the complexity of the Northern Shelf and its importance for future monitoring and conservation efforts. This study underscores the effectiveness of using foraminiferal assemblages as reliable indicators of environmental health in coastal and marine ecosystems. The Northern Shelf, adjacent to the Apodi River incised valley, demonstrated notable environmental heterogeneity, where depth emerged as the primary factor influencing the distribution of foraminiferal species. Granulometric analyses indicated that silt content played a relatively minor role in determining biological distributions, highlighting the dominant influence of other environmental parameters such as depth and temperature. The delineation of the study area into distinct biofacies not only provides a deeper understanding of the environmental dynamics but also offers a practical framework for environmental monitoring, particularly for the integration of physical and biological variables in marine ecosystem management.

From a sedimentological perspective, the spatial variation in granulometry across the Northern Shelf reveals a clear gradation from medium to coarse and very coarse sand as one moves from north to south. This shift appears to be strongly influenced by the region's hydrodynamic conditions, with the Apodi River incised valley playing a pivotal role in sediment distribution patterns. The absence of clay and the limited presence of fine sediment fractions support the characterization of this shelf environment as predominantly coarse-grained, reinforcing the idea of a dynamic sedimentary system shaped by strong hydrological forces.

Hydrographic data provided further insights into the environmental variability of the Northern Shelf. A positive correlation between depth and bottom temperature was identified, with deeper stations exhibiting higher temperatures at the seabed. This stratification has potential implications for both sediment transport and biological distributions, as temperature gradients may drive differential ecological responses. Moreover, localized variations in salinity, particularly in station AR-139, suggest the influence of hydrological processes, possibly stemming from continental runoff or oceanographic mixing, which in turn impact sediment distribution and benthic habitats.

Biologically, the study identified a diverse and abundant foraminiferal community, consisting of over 13,000 individuals and 33 species. Dominant species, such as *Amphistegina gibbosa*, *Quinqueloculina lamarckiana*, and *Peneroplis carinatus*, were found across different biofacies, each associated with specific environmental conditions. The sensitivity of these species to factors like sediment grain size, depth, temperature, and salinity confirms their utility as bio indicators. The identification of five distinct biofacies highlights the spatial variability in environmental conditions across the shelf, with biofacies 1 and 2 associated with environments more tolerant to physical changes, while biofacies 3, dominated by *Amphistegina gibbosa*, reflects healthier, more stable reef environments.

The correlation between biological and sedimentological data suggests that sediment grain size significantly influences the composition of the benthic community. Stations characterized by coarser sediments, particularly those with high proportions of gravel and coarse sand, hosted greater numbers of symbiotic foraminifera, notably *Amphistegina gibbosa*, which thrives in environments subjected to strong hydrodynamic forces and sediment turbulence. This finding aligns with previous research on reef ecosystems, where such species are known to prefer coarse-grained habitats due to the turbulent conditions typical of these environments, driven by wave action and current movement.

The integration of MDS and CLUSTER analyses, supported by the BEST method, reaffirmed depth and bottom temperature as the key drivers of foraminiferal distribution across the Northern Shelf. This observation is consistent with other studies that have demonstrated the sensitivity of foraminiferal communities to environmental gradients, particularly depth and temperature. The relatively low impact of silt content on foraminiferal distribution reinforces the significance of coarser sediments in shaping the biological structure of this marine ecosystem.

In summary, this research demonstrates that the Northern Shelf of Rio Grande do Norte is a complex and dynamic environment, where sedimentary and hydrographic factors are intricately linked to biological diversity and distribution. The presence of healthy, ecologically stable biofacies, characterized by high species diversity and equitability, suggests that the area maintains a generally balanced ecological state. These findings contribute to a broader understanding of the interplay between sedimentary processes, hydrography, and benthic ecology in tropical shelf systems. The results offer a valuable baseline for future monitoring and conservation efforts aimed at safeguarding the health of these ecosystems.

Furthermore, the implications of this study extend to the broader management and conservation of marine ecosystems in the region. Given the sensitivity of foraminiferal species to environmental changes, they serve as crucial bio indicators for monitoring ecosystem health.

The continued observation of these species, alongside sedimentological and hydrographic data, will provide early detection of environmental stressors or degradation, offering a proactive tool for marine resource management. Additionally, understanding the natural variability within these systems is essential for predicting their responses to future environmental changes, whether from climate change, ocean acidification, or anthropogenic activities such as fishing, pollution, and coastal development.

In conclusion, the Northern Shelf of Rio Grande do Norte exhibits a dynamic and ecologically diverse marine environment, characterized by distinct sedimentological and biological patterns that are shaped by the region's hydrodynamics and sediment composition. The integration of biological, sedimentological, and hydrographic data provides a comprehensive understanding of the processes driving this important marine region. Future research should aim to expand on these findings, focusing on the effects of both natural and human-induced changes on the health and sustainability of shelf ecosystems.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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