MedCrave
Step into the World of Research

Journal of Aquaculture & Marine Biology

Research Article

Open Access

CrossMark

Marine sediments from mesophotic reefs as indicators of offshore vortex in the Açu reef (Northeast, Brazil)

Abstract

Shallow and deep-water oceanographic influences over shelf-edge environments affect the development of benthic habitats. We investigated the influence of an offshore vortex on a narrow (6 km wide) and shallow (25-80 m water depth) outer shelf with warm waters (27-30°C) through 84 sediment samples, CTD profiles, and underwater photographs. We analysed benthic foraminiferal content, organic matter, and carbonates in the inter-reef sediments of the newly discovered Açu reef in north-eastern Brazil between 25 m and the shelf edge closer to a recently described vortex. Benthic living *Buccella peruviana, Peneroplis carinatus, P. pertussis,* and the planktonic *Globigerina rubra* is directly associated with organically enriched sediments, and carbonate production where offshore vortices are likely to occur. The sedimentation pattern is evidenced by the deposition in one side and erosion in the other side on its forecasted pathway. Therefore, local vortices in thermocline associated with upwelling of cold waters in canyon heads on the Brazilian Equatorial shelf might be responsible for maintaining remains of living coral-algal systems on mesophotic outer shelves such as the Açu reef. Here we show that foraminifer-derived signatures at the sediment-water interface could serve as a potential tool to reconstruct paleo environmental and climate changes of habitats close to very dynamic water masses pathways.

Keywords: foraminiferal content, açu reef, production, sediment, ocean, water

Volume 13 Issue 1 - 2024

Patrícia Pinheiro Beck Eichler,[1,2] Helenice Vital,[1] Moab Praxedes Gomes[1]

[1]Programa de Pós-Graduação em Geodinâmica e Geofísica - PPGG, Universidade Federal do Rio Grande do Norte, Brazil
[2]EcoLogic Project, Boulder Creek, USA

Correspondence: Patrícia Pinheiro Beck Eichler, Laboratory of Marine Geology and Geophysics and Environmental Monitoring, Universidade Federal do Rio Grande do Norte (GGEMMA, CCET, UFRN), Campus Universitário, Lagoa Nova, Natal, RN, Brazil, 59072-970, Brazil, Email patriciaeichle@gmail.com

Received: January 02, 2024 | **Published:** January 23, 2024

Introduction

A vortex is a region in a fluid in which the flow revolves around an axis line, which may be straight or curved, and is a major component of turbulent flow. The distribution of velocity, vorticity (the curl of the flow velocity), and the concept of circulation are used to characterize vortices. In most vortices, the fluid flow velocity is greatest next to its axis and decreases in inverse proportion to the distance from the axis. Once formed, vortices can move, stretch, twist, and interact in complex ways. A moving vortex carries with it some angular and linear momentum, energy, mass and biogeochemical-associated features as well as its source site. These features influence global circulation, large-scale distribution of water bodies, and ocean biology. This influence involves not only the transfer of energy and properties associated with the vortex's place of origin, but also its marked effect on mixing processes, and the movement of the vortices across the oceans is influenced by three factors: intrinsic self-propulsion, feature which propels it westward; advection by external currents and the influence of nearby vortices. The encounter of hot and cold waters produces the formation of ocean vortices, which are the marine equivalents of atmospheric cyclones.

In the Southwest Atlantic Ocean, an important known area for air-sea interactions is the Brazil-Falklands convergence region. This area is characterized by the intense horizontal temperature gradient, due to the meanders and ocean vortices generated by the encounter of the hot and cold waters of the Brazilian and Malvinas currents, respectively. The thermal contrast between these currents causes the heat fluxes in the cold air masses moving from the continent to the sea to intensify. In addition, latent heat release plays an important role in the energy balance of cyclogenesis in this region.[1] The swirls of cold water appearing on the coast of Rio de Janeiro, sometimes more than 100 kilometers in diameter, are an intriguing phenomenon of the Brazilian territorial sea. "They come from the encounter of the predominant hot water in the region with a body of cold water that occasionally rises from the depths of the ocean near near Cabo Frio in Rio de Janeiro.

A major mechanism of sediment suspension by organized vortices produced under violent breaking waves in the surf zone was identified through physical, biological, and geological approaches. Counter-rotating flows within obliquely descending eddies produced between adjacent primary roller vortices induce transverse convergent near-bed flows, driving bed load transport to form regular patterns of transverse depositions. The deposited sediment is then rapidly ejected by upward carrier flows induced between the vortices forming a unique sedimentation signature. This mechanism of vortex-induced suspension is supported by experimental evidence that coherent sediment clouds are ejected where the obliquely descending eddies reach the sea bed after the breaking wave front has passed. In addition to the effects of settling and turbulent diffusion caused by breaking waves, the effect of the vortex-induced flows was incorporated into a suspension model based on vorticity dynamics and parametric characteristics of transverse flows in breaking waves.

Here we show Benthic living *Buccella peruviana, Peneroplis carinatus, P. pertussis,* and the planktonic *Globigerina rubra* are directly associated with organically enriched sediments, and carbonate production where offshore vortices are likely to occur. The sedimentation pattern derived from vorticity dynamics is evidenced by the deposition in one side and erosion in the other side on its forecasted pathway. Therefore, local vortices in thermocline associated with the upwelling of cold waters in canyon heads on the Brazilian Equatorial shelf might be responsible for maintaining remains of living coral-algal systems on mesophotic outer shelves such as the Açu Reef (Figure 1).[2]

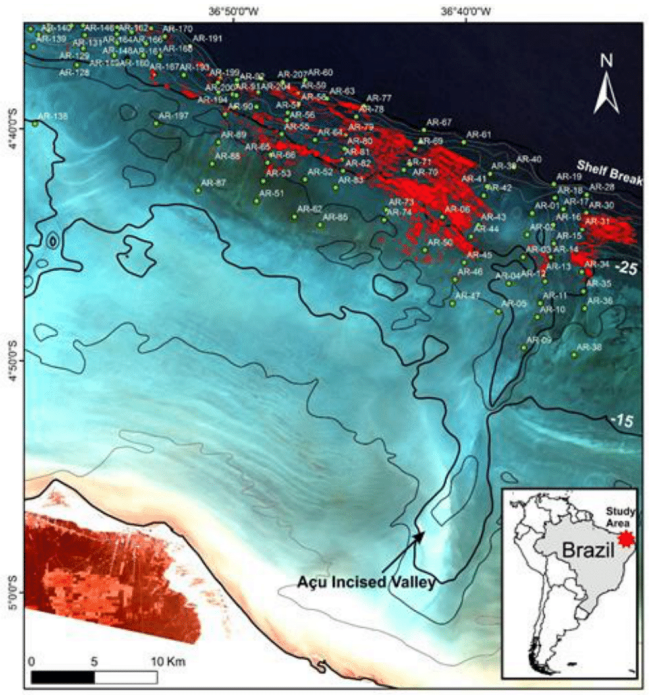

Figure 1 Samples collected along the Brazilian equatorial shelf. Mesophotic outer shelves of the Açu Reef (in red). Retired from Eichler et al.[2]

Foraminifer-derived signatures at the sediment-water interface could serve as a potential tool to reconstruct paleo environmental and climate changes of habitats close to very dynamic water masses pathways.

Study area

A newly offshore vortex was described in the Açu Reef northeastern of Brazil, and Krelling[3] verified that besides the effect of the vortex translation across the region, the conexion in mean velocity field between the retroflexions North Brazilian Current and South Equatorial Countercurrent (and NBC-SEC), and North Equatorial countercurrent (NBC -NECC) occur due to the extension of superficial retroflexion, in certain periods, at medium thermoclinical levels, distinguishing the fate of the waters from each retroflexion.

Figure 2 shows a current at/on the right side of NBC, in the opposite direction. The presence of this current is the expression in the temporal mean of a region of vortex translation, in a manner similar to what occurs on the surface and thermocline. It is also noted the presence of NBC recirculations, representing the mesoscale activity present in this portion from the water column. These recirculations are evidenced in the middle field in the circle. possibly due to the lower magnitude of the currents in this region of the water column. A most intense vortex of the midfield in this region of the water column occurs in approximately 47° W, possibly indicating a place where vortices remain more lasting. Spatial-temporal evolutions of vortices are shown in Figure 3. Maps from Figures 2 and 3 were based on data from Martin et al.,[17] and Krelling et al.[18,19]

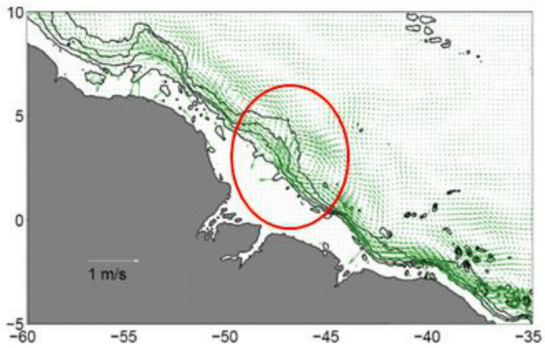

Figure 2 Mean velocity field in sub termocline. NBC follows over the slope of the north coast of South America, presenting recirculation evidenced in the middle field in the circle, expression of the mesoscale activity present in the region.[3]

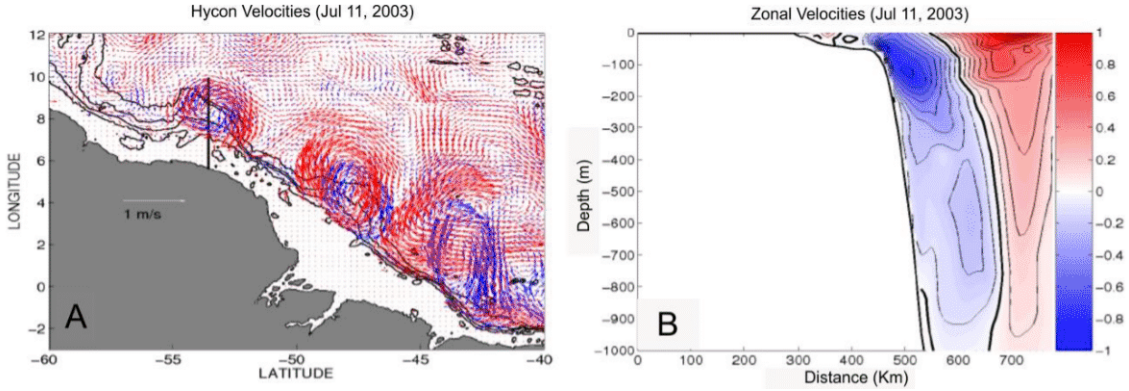

Figure 3 Spatial-temporal evolution of vortices. A: Fields of surface speed (red) and thermocline (blue). B: speed sections whose location is indicated by the figure on the left. In black, the speed isolines with interval of 0.1 m / s. The thick line corresponds to the velocity isoline zero zone.[3]

Materials and methods

Sample collection and laboratory procedures

We used a dataset obtained from 84 seafloor surface sediment samples collected from the outer shelf. The samples were collected during oceanographic cruises in July 2015 and March 2016 (months of calm sea weather in the study area) with the support of the Brazilian Navy hydrographic ship (Com. Manhães H-20). We used a van Veen grab sampler adapted with a metal frame support to provide vertical stabilization to the grabber. Sediment samples were collected along transects of approximately 10 km, perpendicular to the shelf break, across the Açu Reef[4,5] on the outer shelf. Surface sediment samples were collected for foraminiferal studies in transects using a van Veen sampler in water depths of 40 and 65m (Figure 4).

Citation: Eichler PPB, Vital H, Gomes MP. Marine sediments from mesophotic reefs as indicators of offshore vortex in the Açu reef (Northeast, Brazil). *J Aquac Mar Biol.* 2024;13(1):1–6. DOI: 10.15406/jamb.2024.13.00389

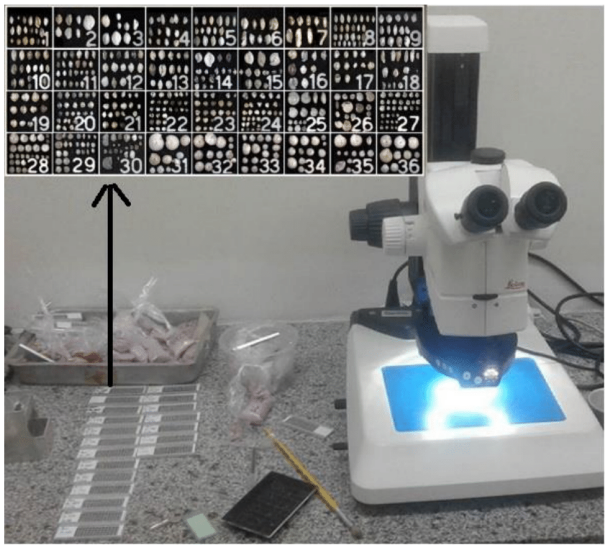

Figure 4 Laboratory stage, which included separation of the foraminifera after screening, using a petrographic magnifying glass, on a slide with a black background (next to the brush). The samples, after being quartered, were separated into plastic bags to obtain these data. At least 100 individuals of the same or different species were glued onto the smaller slides, for an absolute count of the specimens later. In the detail above, a slide as an example of the distribution of foraminifera.

After collection, the uppermost layer of the sediment sample (about 1 cm) was scraped off and kept in ethanol. A solution of Rose Bengal in ethanol was used for staining live specimens. After staining for 48h, a fixed volume of 10 cm3 of sediment was washed through a 0.063mm sieve. The quantitative analysis of the primary dataset is based on counts of living specimens. If a sample had too many tests, the content was split with a micro splitter, but a minimum of 100 tests of foraminifera was obtained, when quartering samples. Species identification and counting of dry specimens were done under an optical microscope. Scanning electron micrographs were taken to help with problematic identifications. Absolute and relative abundances were computed for each species. The grain-size analysis of the sediment samples was performed in ,accordance with the method of Suguio[7] following the Wentworth[8] classification of grain sizes, where 30 g of sediment was dried in an oven at 60°C and served as the reference weight. Next, the carbonate content of the sample was eliminated by treatment with 10% hydrochloric acid. Samples were sieved underwater through a 0.063mm sieve, and the material retained on the sieve was dried again in the oven and weighed. This coarser residue was fractionated in a RO-TAP siever by using a set of sieves with meshes from 2.0 to 0.063 mm. The amount of organic carbon was calculated by removing calcium carbonate from the sediment with hydrochloric acid (10%) and drying 1g of the remaining residue in a centrifuge tube. After the samples were rinsed in distilled water and dried, aliquots were used to measure total organic carbon (TOC) content using a 2400 CHN Perkin Elmer Elemental Analyzer. We used the sedimentary facies classification proposed for the Northeastern Brazilian continental shelf by Vital et al.[9]

ArcGis 10.3

The use of ArcGis 10.3 was essential for visualizing the distribution of results throughout the study area, as well as comparing the distribution of the most relevant foraminiferal species for the research and also integrating them with sedimentary and abiotic data, in order to establish a direct correlation of results. These results were obtained by adding the values contained in the tables, interpolating them using the IDW (Inverse Distance Weighting) method, since this interpolation method is one of the only ones that best represents data distributed in an irregular grid, as was the case with the points sample collection. The generated products characterize distribution maps of each foraminifera and abiotic data throughout the study area, in which the highest and lowest values are distinguished by color classes.

Results

Figure 5 shows Foraminifera species associated to the vortex region of the Equatorial margin. The only recognized planktonic species, *Globigerina rubra*, is an indicator of a deeper marine environment, therefore they are tolerant to temperature, salinity and water density, and may even indicate upwelling.

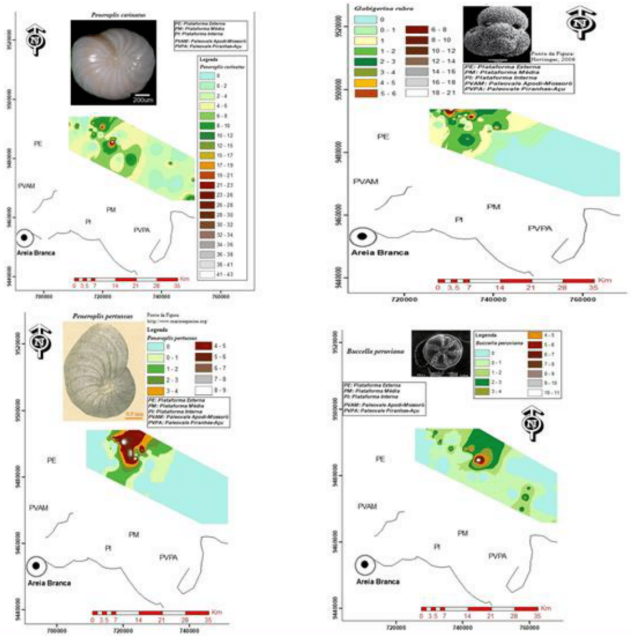

Figure 5 Vortex region and its Foraminifera species associated.

The species *Amphistegina gibbosa, Archaias angulatas, Borelis melo, Heterostegina depressa, Amphisorus hemprichii, Laevipeneroplis proteus, Peneroplis pertussus, P. carinatus* are symbionts (carry algae), typical of shallow environments up to 50 m, and are likely bioindicators of proximity of clean waters in reef environments, in addition to having a Caribbean affinity.[10]

In addition to CaCO3 production, another important parameter observed for environmental processing, it consists of marine upwelling zones, which in turn also contributes to carbonate processing. As demonstrated by the work of Stevenson et al.,[11] and Eichler et al,[12] the occurrence of the benthic *Buccella peruviana* in this environment is a bioindicator of upwelling, that is, marine nutrients brought by currents, thus being an important indicator of shelf health.

The presence of *Buccella peruviana*, *Globigerina rubra,* and *Uvigerina striata* is probably related to the intrusion of colder marine waters, taking into account that the shallow equatorial North Rio Grande do Sul shelf has warmer waters. Being related to cold water intrusions, therefore, the organisms mentioned above are not related to sedimentological characteristics, like the other assemblages, but are probably related to marine currents. Possibly, these foraminifera also indicate upwelling phenomena or another important characteristic of the water masses acting in the system.

Sedimentological data

Analysis of sedimentological material collected from the marine substrate of the outer shelf portion revealed variations in the sizes of unconsolidated grains, ranging from gravel to very fine sand. The granulometry corresponding to the silt and mud fractions was not very representative, while, in greater proportions, the gravel, coarse sand, and medium sand fractions were recognized. Through the granulometry and nature of its material- biochemical, siliciclastic, or mixed- it is possible to recognize 6 (six) main sedimentary facies, as well as subdivide them into a group of 14 subfacies in a careful way, based, on the main parameters, on the calcium carbonate content and granulometry. Essentially, three large Sedimentary Facies are distributed in the area, which allowed the identification of six Facies, defined basically through Calcium Carbonate content and total organic matter (MOT) (Figure 6).[13] The identification of the Subfacies took into account, in addition to the carbonate content, as well as the grain size of the sediments. MOT content exceeded its importance in correlating with biotic data, not interfering in the characterization and/or definition of facies/subfacies.

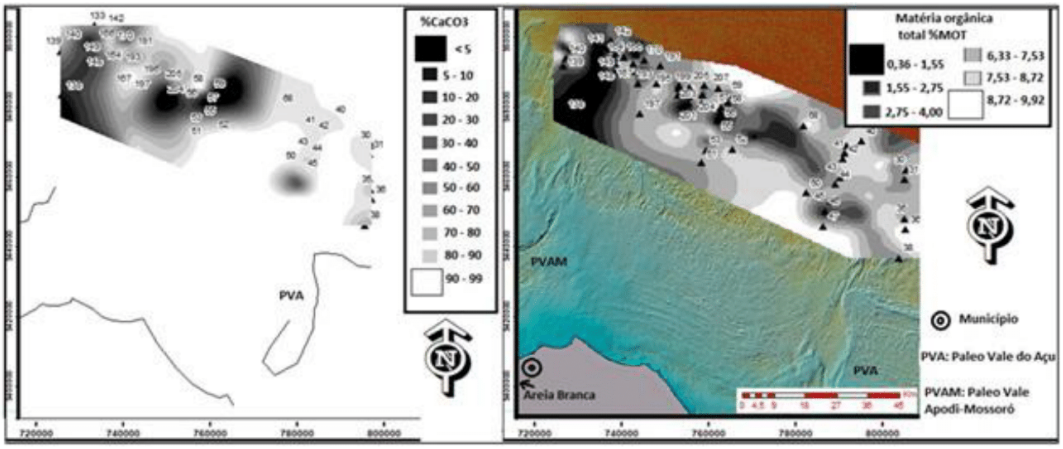

Figure 6 Similar distribution patterns of organic matter and calcium carbonate contents.

The dynamic process of the vortex generation, growth, ejection, and finally being swept over a sandy ripple bed can also is well represented by the numerical model. The sediment trapping–lifting process associated with the formation–ejection process of vortices has also been demonstrated by Chen and Yu.[13] The observed vortex leaves a mark on the sediment and it was evidenced by the maps generated by the Arc Gis.

Discussion

The shelf environment close to the slope generally presents a diverse marine fauna, with both benthic and nektonic habits. Planktonic organisms come from deeper marine environments, from the open sea, and when they occur in shallower portions, they can indicate the formation of vortex and upwelling, that is, the action of winds helping in marine hydrodynamics, taking deeper waters to shallow marine portions, bringing phytoplankton (great sources of nutrients). Upwelling is a rare and occasional phenomenon in nature, and when it occurs, it brings a series of benefits to the marine habitat.[14,15] The outer portion of the shelf tends to be more naturally favourable for the circulation of marine nutrients and the vortex formation, essential for the balance where this ecosystem lives, as it can also increase carbonate sedimentation rates, which is also beneficial. The external portion of the RN Equatorial shelf, a reef environment located between the incised valleys Apodi-Mossoró (to the West) and Piranhas-Açu (to the East), presents mixed Neogene sedimentation (carbonate and siliciclastic sediments). The particle size varies, in increasing order, from fine sand to gravel, with coarse sand occurring in practically all samples.

The sedimentological data were of great importance to correlate with the biota, as the type of sedimentary material directly influenced the diversity and/or dominance of groups of species and individuals, as well as their distribution in the environment in which they lived and were deposited next to the substratum. Carbonate marine sedimentation is enriched by the shells of dead organisms, which are deposited on the substrate. This relationship between the sedimentary environment and the organisms that inhabit it can be better understood through foraminifera. Their wide geographic distribution, and diversity of species, with their shells being very sensitive –and adaptable –to the environment allows such protists to be used as a tool for geosciences. Through the sensitivity of the tests, which react to abiotic variables such as salinity, temperature, pH, conductivity, density, depth, as well as having a direct or indirect relationship with the levels of organic matter in addition to having a direct relationship with the production rate of calcium carbonate, thus contributing to the construction of geo-habitats, for example, reefs (shelters for different beings). The living coral reef lies on a fossilized, or "deactivated" reef constructions, and is under vortex influence due to the great rise in sea level caused by the last deglaciation that occurred at the end of the Pleistocene.

In the portions of the area where foraminifera have high diversity, the levels of organic matter and $CaCO_3$ are the highest, also indicating a relationship with the carbonate sedimentary facies. On the other hand, the dominant macro foraminifers, highlighting *Quinqueloculina lamarckiana, Amplistegina gibbosa,* and *Peneroplis carinatus*, occur in practically all recognized sedimentary facies. However, the presence of *Q. lamarckiana* and Pyrgo are dominant in the siliciclastic sedimentary facies and suggests that this type of terrigenous material disadvantages species diversity, since there is less variety in the terrigenous facies. The robust shells of these organisms favoured their proliferation in the highest energy sedimentary facies. Ecological indices, together with the influence of abiotic variables on foraminifera, must be used with caution. Previous studies in shelf reef environments, for example, the work in Abrolhos carried out by Araújo & Machado[16] and Pessoa Neto et al[6] showed high levels of diversity associated with granulometry, essential in these studies. The identified foraminiferal associations also appear to be different in these studies, for direct correlation with the present work.

On the external equatorial shelf adjacent to the RN area, between the Piranhas-Açu and Apodi-Mossoró incised paleovalleys, it was

observed that opportunistic and dominant foraminiferal species tend to concentrate in the portions with the lowest calcium carbonate contents.

While in the portions where there are higher carbonate levels (carbonate to mixed facies), assemblages of symbiotic foraminifera prevail. These results led to the conclusion that, where there is greater diversity of symbiotic species, there is greater environmental quality, favoring the production of calcium carbonate.

The presence of *Buccella peruviana, Globigerina rubra,* and *Uvigerina striata* is most likely related to colder marine waters, because the shallow equatorial North Rio Grande do Sul shelf is warmer. The organisms mentioned earlier are not related to sedimentological characteristics, however are possible related to the marine dynamic of the currents. Possibly, these foraminifera also indicate upwelling phenomena or another important characteristic of the water masses movement influencing the system.

The abiotic variables $CaCO_3$ and organic matter were those that best related to foraminifera, followed by gravel, coarse sand, and medium sand. Other abiotic variables such as depth and finer particle size fractions were responsible for the species' variability. Therefore, the distribution and dispersion of species are strongly linked to high levels of $CaCO_3$ and organic matter, as already observed by Eichler et al[12] in shelf environments. Such observations also suggest that when associated with high levels of $CaCO_3$ and organic matter, the diversity of foraminiferal species contributes directly to shelf carbonate production.

In addition to $CaCO_3$ production, another important parameter observed for environmental processing, it consists of marine upwelling zones, which in turn also contributes to carbonate processing. As demonstrated by the work of Steverson et al.,[11] and Eichler et al,[12] the occurrence of the benthic *Buccella peruviana* in the South of Brazil is a bioindicator of upwelling, that is, marine nutrients brought by currents, thus being an important indicator of shelf health.

Conclusion

Organic matter and $CaCO_3$ content are the most influential variables on species diversity, and mud is among those with the least influence. $CaCO_3$ levels decrease with the presence of siliciclastic material, and there is greater dominance of the same species with less diversity of individuals. The opposite occurs where the carbonate content increases. Carbonate or mixed sedimentation environments (silicibioclastic and biosiliciclastic) have high carbonate content, with *Amphistegina gibbosa* and *Peneroplis carinatus* as indicator species. In muddy zones, there is low diversity and high dominance, with siliciclastic sedimentation, with the dominant species *Quinqueloculina lamarckiana*. The species *Archaias angulatus* and *Amphisourus hemprichii*, occurring in mixed portions, increase in places where the genera *Amphistegina* and *Peneroplis* decrease. Opportunistic and dominant foraminiferal species concentrate in environments with low levels of $CaCO_3$ while symbiotic foraminiferal associations prevail where there are higher carbonate levels (carbonate to mixed facies). Greater diversity of symbiotic species reflects the better environmental quality that favours carbonate production.

The presence of *Buccella peruviana, Globigerina rubra, Quinqueloculina patagonica, Peneroplis pertussus,* and *Amphisourus hemprichii* is probably related to the intrusion of warm waters which indicate the influence of differentiated masses of ocean water, probably linked to the balance of warmer ocean currents of the Tropical Gyre on the shelf. A phenomena of upwelling of cold water with greater nutrients enriching the shelf ecosystem can also be inferred by the presence of three species *Peneroplis pertussus*, *Globigerina rubra*, and *Quinqueloculina patagonica. Globigerina rubra*, an indicator of a deeper marine environment, tolerant to low temperatures, may also indicate upwelling to the west of the studied area. The distribution of *Buccella peruviana* in the central portion of the study area, correlating with the concentrations of $CaCO_3$ and organic matter, indicate an upwelling zone rich in nutrients that contribute to the quality of the shelf. Species with more robust shells, such as those of the genera *Amphistegina* and *Quinqueloculina*, confirm the high-energy environment with intense marine currents on the outer shelf portion.

The observed factors, such as symbiont species present, species diversity, direct correlations to carbonate facies, as well as the distribution of organic matter in its highest portions, corroborate a healthy environment with carbonate productivity associated with the interaction of shelf-breaking processes with external shelf reef environments.

Acknowledgments

We thank CAPES (Coordination for Improvement of Higher Level Personnel) through the project "Oceanographic processes in the breakdown of the continental shelf of the Brazilian Northeast: scientific foundations for marine spatial planning (Edital Marine Science 2 n° 43/2013, 23038.004320 / 2014 -11), for funding research and postdoctoral fellowship for P.P.B. Eichler at the Federal University of Rio Grande do Norte (UFRN-Brazil), at Moss Landing Marine Laboratories, San Jose State University (MLML/SJSU), and at the Ocean Sciences Department of the University of California at Santa Cruz (UCSC) (grants Nº88887.305531/2018-00, Nº88881.188496/2018-01). H. Vital and M.P. Gomes thanks CNPq for their research fellowships PQ nº 315742/2020-8, and nº 302483/2019-5. Thanks are also due to the Brazilian Navy (SECIRM/SSN-3) for the ship NB Comandante Manhães H-20 for collecting the data, and GGEMMA group for their support during the data acquisition, This work was carried out under the INCT AmbTropic phase II (CNPq process 465634/2014-1).

Conflicts of interest

The authors declare that there are no conflicts of interest.

References

1. Pezzi LP, Souza RB, Dourado MS, et al. Ocean-atmosphere in situ observations at the Brazil-Malvinas confluence region. *Geophys Res Lett*. 2005;32(22):1–4.
2. Eichler PPB, Nascimento Silva LL, 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. Krelling APM. The Potiguar Eddy: a subsurface anticyclone associated with the North Brazil Undercurrent at 4ºS. Tese de Doutorado, Instituto Oceanográfico, Universidade de São Paulo, São Paulo. 2015.
4. Nascimento Silva LL, Gomes MP, Vital H. The Açu Reef morphology, distribution, and inter-reef sedimentation on the outer shelf of the NE Brazil equatorial margin. *Continent Shelf Res*. 2018;160:10–22.
5. Nascimento Silva LL, Gomes MP. Statistical approach on mixed carbonate-siliciclastic sediments of the NE Brazilian outer shelf. *Geo-Marine Lett*. 2020;40:1001–1013.
6. Pessoa Neto OC. Estratigrafia de sequências da plataforma mista neogênica na Bacia Potiguar, margem equatorial Brasileira. *Revista Brasileira de Geociências*. 2003;33(3):263–278.

7. Suguio K. Introdução à sedimentologia. São Paulo, Edgard Blucher. 1973;317.
8. Wentworth CK. A scale of grade and class terms for clastic sediments. *J Sedim Petrol*. 1984;30(5):377–392.
9. Vital H, Stattegger K, Amaro VE, et al. A modern high-energy siliciclastic-carbonate platform: continental shelf adjacent to northern Rio Grande do Norte State, northeastern Brazil. *J Sediment Res*. 2008;90:175–188.
10. 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. *Ital J Geosci*. 2015;134(1):9–22.
11. Stevenson R, Dias-Brito D, Stech JL, et al. How do cold water biota arrive in a tropical bay near Rio de Janeiro, Brazil? *Continental Shelf Res*. 1998;18(13):1595–1612.
12. Eichler PPB, Eichler BB, Sen Gupta B, et al. Foraminifera as indicators of marine pollutant contamination on the inner continental shelf of southern Brazil. *Mar Pollut Bull*. 2012;64(1):22–30.
13. Chen X, Yu X. A numerical study on oscillatory flow-induced sediment motion over vortex ripples. *J Phys Oceanogr*. 2015;45:228–246.
14. Boltovskoy E. Los Foraminiferos Recientes. Ed. Univ. Buenos Aires, Eudeba, Buenos Aires. 1965;510.
15. Boltovskoy, E. *Biotic interactions in recent and fossil benthic communities*. Topics in Geobiology 3. Michael J.S. Tevesz, Peter L. McCall (Editors). 1966;8:364–365.
16. Araújo TMF, Machado AJ. Foraminíferos da superfície do talude continental superior do Norte da Bahia, Brasil. *Revista de Geologia*. 2008;21(1):49–77.
17. Martin UD, Cintra MM, Gomes MP, et al. Interactions between the North Brazilian Undercurrent (NBUC) and the southwest atlantic margin. Implications for Brazilian shelf-edge systems. *Reg Stud Mar Sci*. 2022;54,102486,
18. Krelling APM, da Silveira ICA, Polito PS, et al. A newly observed quasi-stationary subsurface anticyclone of the North Brazil undercurrent at 4°S: the potiguar Eddy. *J Geophy Res Oceans*. 2020;125(10):e2020JC016268.
19. Krelling APM, Gangopadhyay A, Silveira I. et al. Development of a feature-oriented regional modelling system for the North Brazil Undercurrent region (1°–11°S) and its application to a process study on the genesis of the Potiguar Eddy. *J Operat Oceanograph*. 2020;15(2):69–86.