

Benthonic assembly and its correlation with the geodiversity of the east continental shelf of Ceará (Brazilian equatorial margin)

Assembleia bentônica e sua correlação com a geodiversidade da plataforma continental leste do Ceará (margem equatorial brasileira)

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Abstract

Bioclastic sediments have economic value due to their high concentration of calcium minerals and can be used as soil amendments in agriculture, in cement factories, for animal feed formulation, and in the cosmetic industry. In Brazil, they are widely exploited on the continental shelf. Although the sedimentary facies of the Ceará continental shelf are known, there is no information about the composition of bioclastic constituents, their diversity, and distribution. This study aims to identify the constituents of marine benthic communities and their relationship with abiotic factors such as depth, morphology, and sedimentary facies. To this end, analyses of remote sensing data, bathymetry, and sediment samples were conducted. Features such as submerged dunes (oblique, parallel, and transverse), beach sandstones, and paleochannels were observed, and, according to physiographic and morphological aspects, five zones were interpreted (1. suspended sediment zone, 2. transverse dune zone, 3. oblique dune zone, 4. reef construction zone, and 5. flatbed zone). Sedimentological analyses identified components with their respective relative frequencies: bryozoans (35.5%), calcareous algae (27%), foraminifera (12.3%), molluscs (12%), cnidarians (4%), echinoderms (3.9%), sponges (3.5%), and arthropods (1.7%). Principal component analysis (PCA) biplots showed a positive correlation between the biotic components (calcareous algae, sponges, and cnidarians) and the abiotic factors (depth 20-40 m, zones 2 and 4 (Z2 and Z4), and the bioclastic gravelly sand facies (BGS). Otherwise, arthropods tend to occur from 40 to 60 m depth and are commonly associated with the biolithoclastic sand facies (BLS), while echinoderms and molluscs tend to occur in shallower regions (0-20 m), associated with zone 1 (Z1) and to the bioclastic gravel (BG) and bioclastic sand with gravel (BSG). This research demonstrates the relationship between geology, geomorphology, and benthic marine life in the region and provides a valuable database for measuring and monitoring the area, which has attracted attention from various sectors of the Blue Economy, especially during the Decade of the Oceans.

Keywords: Seabed mapping, semi-arid continental shelf, biotic components, Principal Component Analysis, Brazilian Northeast.

Resumo

Os sedimentos bioclásticos possuem valor econômico devido à sua alta concentração de minerais de cálcio e podem ser utilizados como corretivo de solos em agricultura, fábrica de cimento, formulação de ração animal e indústria cosmética. No Brasil são amplamente explorados na plataforma continental. Embora as fácies sedimentares da plataforma continental cearense sejam conhecidas, não há informações sobre a composição dos constituintes bioclásticos, sua diversidade e distribuição. Este estudo tem como objetivo identificar os constituintes das comunidades bentônicas marinhas e sua relação com fatores abióticos, tais como, profundidade, morfologia e fácies sedimentares. Para tanto, foram realizadas análises de dados de sensores remotos, batimetria e amostras de sedimentos. Feições como dunas submersas (obíquas, paralelas e transversais), arenitos de praia e paleocanais foram observadas e, de acordo com os aspectos fisiográficos e morfológicos, cinco zonas foram interpretadas (1. zona de dunas longitudinais e sedimentos em suspensão, 2. zona de dunas transversais, 3. zona de dunas oblíquas, 4. zona de construções recifais e 5. zona de leito plano). A análise sedimentológica permitiu identificar componentes com as respectivas frequências relativas: briozoários (35,5%), algas calcárias (27%), foraminíferos (12,3%), moluscos (12%), cnidários (4%), equinodermos (3,9%), poríferos (3,5 %) e artrópodes (1,7%). As análises das componentes principais (ACP) apresentaram correlação positiva entre os componentes bióticos (algas calcárias, poríferos e cnidários) e os abióticos (profundidade 20-40 m, zonas 2 e 4 (Z2 e Z4) e a fácies areia bioclástica (BS). Já os artrópodes tendem a ocorrer de 40 a 60 m, na zona 3 (Z3) e são comumente associados à fácies areia biolitoclástica (BLS), enquanto que os equinodermos e moluscos tendem a ocorrer em regiões mais rasas (0-20 m), associados à zona 1 (Z1) e às fácies cascalho bioclástico (BG) e areia bioclástica com cascalho

(BSG). Esta pesquisa comprova a relação entre a geologia, a geomorfologia e a vida marinha bentônica da região e apresenta uma base de dados preciosa para mensurar e monitorar a área que tem atraído atenção de vários setores da Economia Azul principalmente durante a Década dos Oceanos.

Palavras-chave: Mapeamento do fundo marinho, plataforma continental semiárida, componentes bióticos, Análise de Componentes Principais, nordeste brasileiro.

1. Introduction

The bioclastic components habitually are produced in situ and conditioned by the sedimentary environment. The main part of the carbonate sediments is developed in the sea and the recognition of the physical and biological parameters is necessary to characterize the environment (Poggio et al. 2009, Rebouças 2010).

The sedimentation in shallow environments is generally related to the interaction between sediment supply, hydrodynamic regime (waves, tides, and currents), climate settings, relative sea-level changes, coastal morphology, and rock resistance (Nittrouer et al. 2007; Campos & Dominguez 2010; Muehe 2010). The continental margin of the western equatorial Atlantic (Northeast Brazil) presents a unique climate setting among regions on earth.

The continental shelf of Northeast Brazil is considered a tropical semi-arid shelf due to the climate, characterized by low annual temperature variation (26 to 30°C), low annual precipitation (< 1000 mm year⁻¹) and strong swell waves (6 to 11 m.s⁻¹) during most of the year (Coutinho & Morais 1970; Ximenes Neto et al. 2018a; 2018b; Morais et al. 2019; Pinheiro et al. 2020; Maia de Almeida et al. 2021; Soares et al. 2021).

The low input in the continental shelf has favored the development of a mixed deposition system on the shelf (Morais et al. 2019). Then, this semiarid continental shelf is characterized by a mixed siliciclastic carbonate sedimentation, showing evidences of modern supply of carbonates sediments (calcareous algae, mollusca and foraminifera) and siliciclastic relict sediments (quartz and lithic fragments) (Morais et al. 2019). The low influx of water from continent to ocean is a good factor to the development of bioclastic components specially the calcareous algae which require appropriate ecological conditions such as depth, light, temperature, salinity, currents, substrate and grain-size (Coutinho 1976; Costa 2015).

These carbonate sediments have attracted the mineral sector that aims to explore these granulates (Paiva et al. 2023; Maia et al. 2024) due to its high concentration of calcium minerals which can be used as a soil improver in agriculture, cement plants, animal feed formulation and cosmetic industry (Dias 2000). Besides that, the energy sector also has been attracted, aiming to install offshore wind farms due to the excellent wind potential of the region (Ortiz & Kampel 2011).

Although, several researches were carried out on the abiotic aspects of the continental shelf of Ceará to

understand the seabed morphology and sedimentation (Freire & Cavalcanti 1998; Maia et al. 1997; 2008; Silva Filho et al. 2007; Maia de Almeida et al. 2016; Lima et al. 2018; Ximenes Neto et al. 2018a; Morais et al. 2019; Maia de Almeida et al. 2021), then the regional geomorphology and the distribution and composition of sedimentary facies of the Ceará continental shelf is regionally known (Freire 1985, Silva Filho et al. 2007, Cavalcanti 2011, Maia de Almeida et al. 2016, Morais et al. 2019, Maia de Almeida et al. 2021), the Ceará semiarid shelf is very poorly known in respect to its geohabitats and marine benthic communities.

It is worth highlighting that Pinheiro et al. (2019) studied the marine habitats of a very local area (the continental shelf of Iracema beach in Fortaleza, Ceará). They affirm that integrating the biotic and abiotic components is essential for conservation and management of marine areas, especially those with anthropogenic activities.

Recognizing the benthic community of the continental shelf east of Ceará is very important, as it will help in identifying marine biodiversity, which can be considered as an indicator of the health of the ecosystem (Salas et al. 2006; Rice 2003). Changes in the composition and abundance of these communities may reflect environmental impacts (Noble-James et al 2017). Furthermore, they provide important ecosystem services as they have pharmaceutical potential, as they have medicinal properties, as well as in agriculture and cosmetics (Dias 2000; Cavalcanti 2020; Maia et al. 2024). Therefore, understanding and monitoring the benthic community is essential for the sustainable management of marine ecosystems and to ensure long-term human well-being.

The nature of the substrate, the geomorphology and the depth are most important factors that may help to understand the way of distribution and abundance of the marine benthic organisms. Mapping the geomorphic features on the seafloor is useful to understand the benthic habitats which can be considered as a powerful surrogate for associated communities (Harris et al. 2014; Jerosch et al. 2015). Currently, there is no comprehensive information combining spatial data to explain the geo and biodiversity and the distribution of the marine benthic communities of the Ceará continental shelf. Quantitative information about diversity, relative abundance, frequency of occurrence, and the relationship between the types of organisms and the abiotic factors does not exist.

This study aims to identify and quantify the constituents of the benthic community of the eastern

Ceará continental shelf and understand its geodiversity, in order to comprehend the relationship between the benthic marine life and its geohabitats. This can provide important information for the sustainable use, the conservation and management of the marine ecosystem along the semi-arid continental shelf of Ceará.

2. Study area and regional setting

The study area is located in the Potiguar Basin in Northeast Brazilian continental shelf, between the capital city of Ceará (Fortaleza) and the municipality of Icapuí with a width of approximately 63 Km. The limits of the study area are: on the West by the city of Fortaleza, to the East by the State of Rio Grande do Norte, to the South by the coastline of Ceará; and on the North by shelf break occurring at in 60-70 m (Fig. 1).

The Northeast Brazilian continental shelf represents one of the few areas in the world with an open and stable shelf almost completely covered by biogenic

calcium carbonate sediments with a mixed sedimentological pattern, including a modern carbonate supply and relict siliciclastics grains (Manso et al. 2004, Cavalcanti 2011).

Coutinho & Morais (1968) subdivided the continental shelf of Ceará into three parts according to their sedimentological and morphology characteristics: the inner shelf, from coastline up to 20 m, the middle shelf from 20 to 40 m, and the outer shelf, from 40 m until the shelf break which occurs around 60-70 m of water depth.

Morais et al. (2019) divided the continental shelf of Ceará into three sectors with the study area located within the Jaguaribe sector, characterized by a high number of high-energy unconsolidated bedforms. Maia de Almeida et al. (2016) mapped several zones in the Ceará continental shelf (suspended sediment zone, oblique dunes and flatbed zone, transverse dunes zone, carbonate sediments zone, besides reef construction and beach sandstone). However, their study area is restricted to the shelf adjacent to the Jaguaribe River.

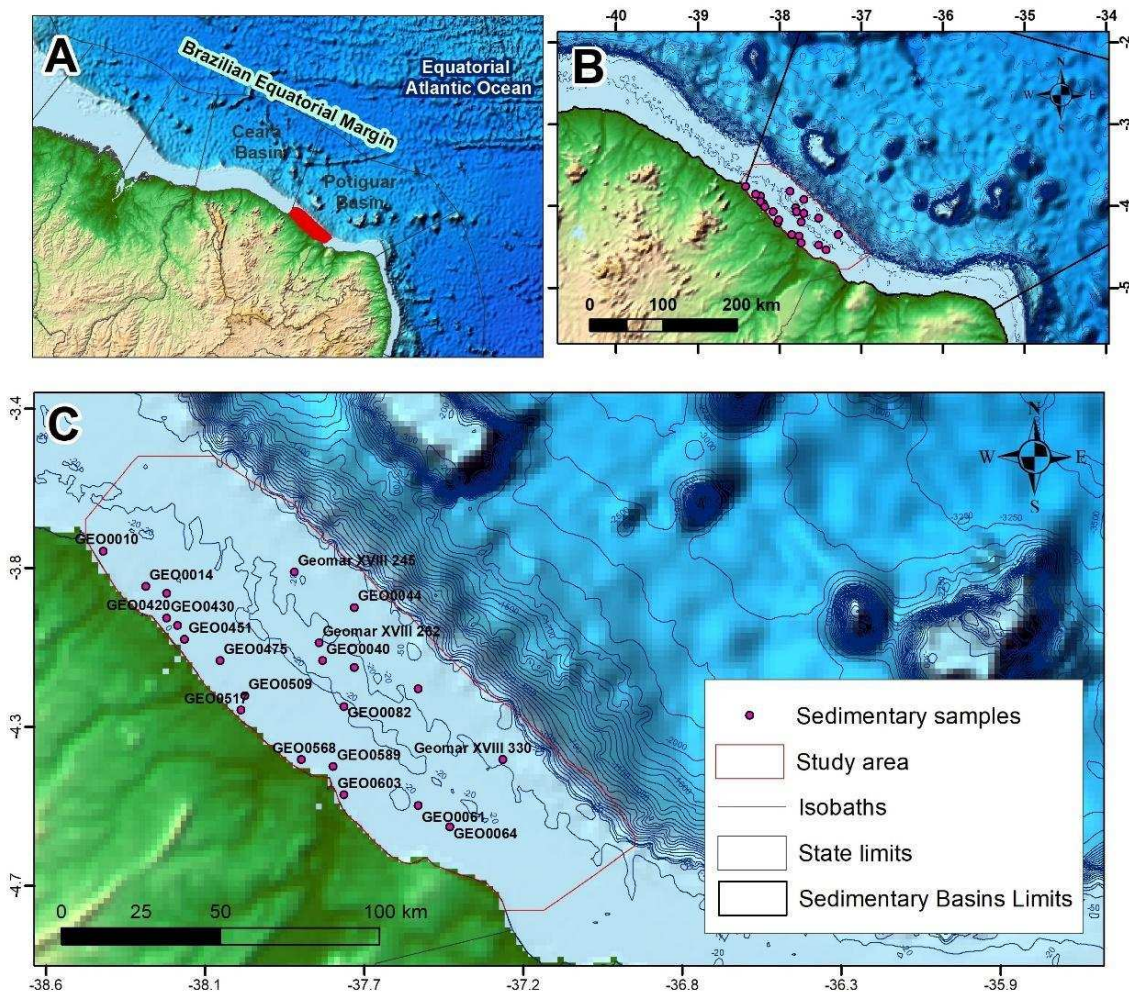


Figure 1: Map showing the study area with 22 sedimentary samples data available for this research along the eastern continental shelf of Ceará, Brazilian Equatorial Margin. Source: Marine and Energy-applied Geology and Geophysics Laboratory (LGMA), ETOPO, Brazilian National Agency of Petroleum (ANP), Brazilian Geological Survey (SGB).

For the eastern continental shelf of Ceará, Assis et al. (2007) defined two sedimentary provinces (carbonate and siliciclastic) based on several parameters, including texture, CaCO₃ content, carbonate associations, relative proportion of feldspar and mineralogical composition of siliciclastic components. Maia de Almeida et al. (2021) presents the sedimentary facies of the all Ceará continental shelf. The main facies of the eastern continental shelf are bioclastic sand (BS), bioclastic sand with granules (BSG), biolithoclastic sand (BLS), lithobioclastic sand (LBS), lithoclastic sand (LS), lithoclastic sand with gravel (LSG), bioclastic gravel (BG), lithobioclastic gravel (LBG), lithoclastic gravel (LG), terrigenous mud (TM) and carbonate mud (CM).

3. Materials and methods

3.1 Acquisition and processing of bathymetry data

The bathymetric data were obtained through the pre-existing data of the General Bathymetric Chart of the Oceans (GEBCO) in 2021. These data were processed using QGIS software in order to produce the bathymetric map and profiles. They were very useful to characterize the marine relief and geomorphology of the study area (Fig. 2).

3.2 Acquisition and Treatment of Landsat 8 images data

Two images of Landsat were acquired from the USGS (United States Geological Survey) database site with the Path/Row reference of 216/63 and 217/62. The choice of this sensor was due to the existence of the ultra-blue band (band 1), which is most commonly used for coastal studies and submerged environments (USGS 2018). The images were processed and georeferenced using QGIS software. Digital image processing was used to improve and assist in the visual analysis of submerged features. Shelf zones were interpreted based on Maia de Almeida et al. (2016).

3.3 Acquisition and processing of the sedimentological samples

At all, 22 marine sedimentary samples were collected from 1993 to 2003 by Geocosta I, Geocosta III, and Geomar XVIII projects in partnership with the of Marine and Energy-applied Geology and Geophysics Laboratory (LGMA) of the Federal University of Ceará (UFC). These samples are distributed along the entire eastern continental shelf of Ceará with depths varying from 7 to 51 m (Fig. 1). The grain-size analyses were realized using 100g of each sediment sample which were washed and dried at 60°C. Subsequently, the samples were sieved in an interval from 0.062 to 4 mm, in order to keep only the gravel and sand fractions. After the dry sieving, 300 species were selected on the sand fraction (0.177 and 0.125 mm) conforming the methodology proposed by Tinoco (1989). The biotic components were analyzed through a binocular stereomicroscope in order to identify the main constituents of the sediments (Fig. 3).

The benthic communities were plotted on the geohabitat map (Fig. 4) and the facies map that uses the classification adapted of Larssonneur (1977) adapted by Dias (1996) and Freire et al. (1997). The facies map was adapted from Maia de Almeida et al. (2021) (Fig. 5).

3.4 Statistical treatment

Statistical analyses were made conforming to the classification of Dajoz (1983) in order to show the mode of distribution and abundance of the species using relative analysis and frequency of abundance.

The interpretation of the results was carried out based on the values obtained for each component according to Dajoz (1983): principal (frequency above 5%); accessory (between 5 and 1%) and trace (less than 1%).

After these calculations, the species were grouped into three categories according to the Dajoz classification (1983): Constants (species present in over 50%); accessories (occurring between 25 to 49% of the samples) and accidental (present in less than 25% of the samples).

Multivariate statistical analyzes were used to show how the constituents are related to each other as well as to evaluate their correlations with abiotic factors such as depth, sedimentary facies and shelf zones. The biplots principal component analysis (PCA) method was performed using Past software (Hammer et al. 2001).

4. Results and discussion

4.1 Seabed geomorphology as an indicator of marine biodiversity

The bathymetric model and profiles show the irregularity of the seabed morphology of the eastern Ceará continental shelf (Fig. 2). Some features are also observed in Landsat images (Fig. 4). The A-A' profile presents morphologies that are a dune field (15 m), a submerged reef (15 m) and a paleovalley (18 m) which displays a U-shape. The B-B' profile presents submerged dunes distributed between depths of 25 and 32 m and a reef construction at 25 m. The C-C' is a transversal profile that shows an irregular relief with the presence of features like an erosive depression surface at the depth of 15 m and a reef construction at 35 m of depth.

Five zones were identified based on the depth and the seabed morphology based on Maia de Almeida et al. (2016) (Fig. 4). In this research, we expanded the area to englobe all the continental eastern shelf of Ceará. Benthic community analysis revealed eight taxonomic groups along the study area: calcareous algae fragment of the genus *Halimeda* and *Lithothamnium*, Bryozoa (fragments), Cnidaria (coral fragments), Arthropoda (Crustacea and Ostracoda), Echinodermata (Echinoidea - sea urchin spines), Foraminifera, Mollusca (*Bivalvia* and *Gastropoda*) and

Porifera (sponge spikes) (Fig. 3 and Table 1). The spatial distribution of the biogenic components is presented in Fig. 4 showing the different geohabitats of the area. This figure shows that with the increasing depth and the variety of shelf zones, there is a differentiation in composition and abundance of the benthic communities.

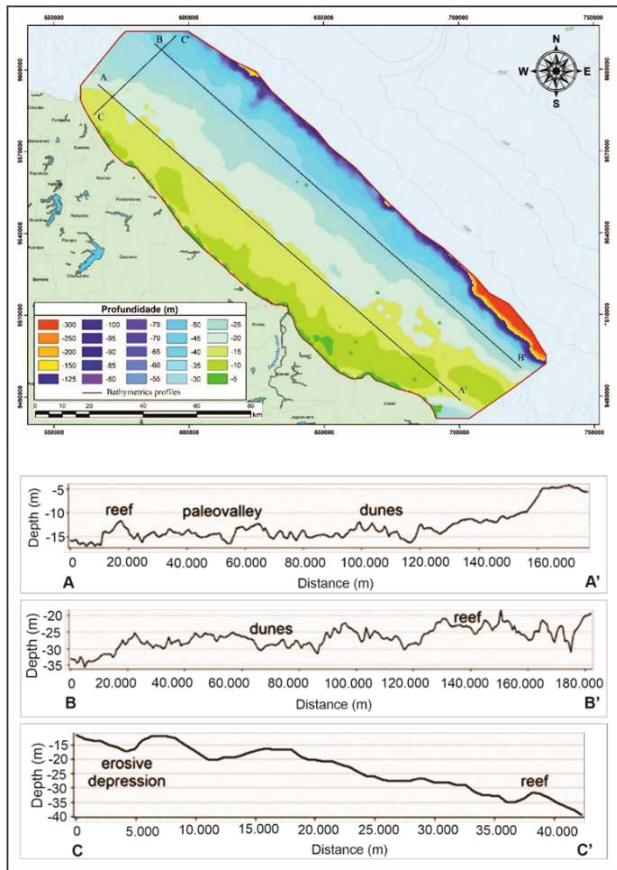


Figure 2: Bathymetric model of the eastern continental shelf of Ceará using GEBCO 2021 data. Longitudinal (A-A', B-B') and transversal (C-C') bathymetric profiles are presented highlighting features such as dunes, reef and paleovalley.

The sedimentary facies map analysis shows the occurrence of the biotic components (Calcareous algae, Bryozoa, Arthropoda, Cnidaria, Echinodermata, Foraminifera, Mollusca and Porifera) in very different sedimentary facies mainly Bioclastic Sand (BS), Biolithoclastic Sand (BLS), Bioclastic sand with gravel (BSG) and Bioclastic gravel (BG) (Fig. 5).

Zone 1 includes the inner continental shelf (0 - 20 m). It is characterized by being a zone of sediment in suspension (Maia de Almeida et al. 2016) and it presents a longitudinal dune field in front of Icapuí. In this zone, all eight taxonomic groups of the benthic community (calcareous algae, arthropoda, bryozoan, echinodermata, foraminifera, cnidaria, mollusca and porifera) were identified in the study area. The facies map indicates that this zone presents BS, BSG, BLS, LBS and LS.

Zone 2 is constituted of oblique dunes observed between the depth of 15 and 25 m (Maia de Almeida et al. 2016). There are seven of the eight biotic components. Only cnidaria is not present in this zone. This region is extremely heterogeneous and Monteiro (2011) identified features like sandy plains, sandy patches and corals reefs. The sedimentary facies are mainly BS, BSG, BS, LBS and LS.

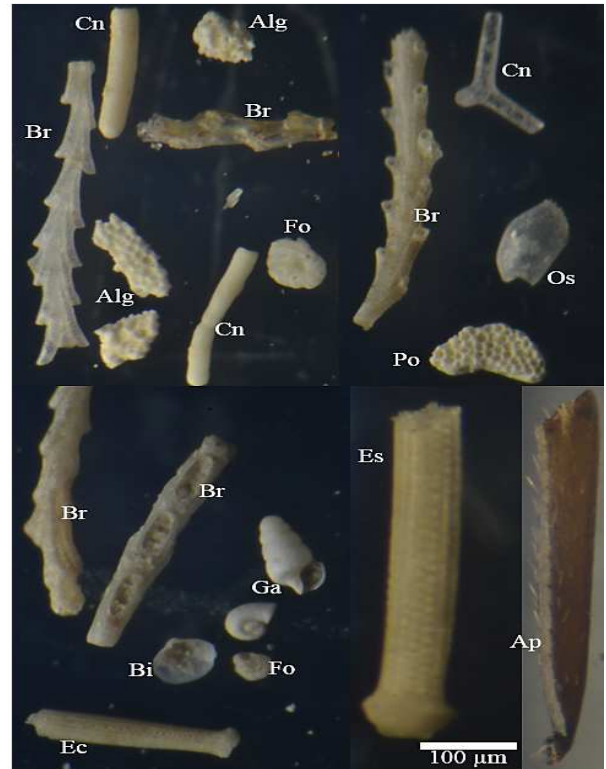


Figure 3: Biogenic components found on the eastern shelf of Ceará. Alg: Calcareous algae, Br: Bryozoa, Fo: Foraminifera, Cn: Cnidaria, Os: Ostracoda, Po: Porifera, Ga: Gastropoda, Bi: Bivalve, Ec: Echinoidea, Es: Spine of Hedgehog, Ap: Crustacean appendix.

Zone 3 is composed of transversal dunes which have a good representation along the continental shelf between 25 and 40 m (Maia de Almeida et al. 2016). The biotic components are represented in this zone by five taxonomic groups: arthropoda, calcareous algae, bryozoa, foraminifera and porifera. BS, BSG, BLS and LBS facies constitute the seabed.

Zone 4 is classified as a zone of reef constructions and presents cnidaria assembly near to Fortaleza. It also can be found near to the municipality of Icapuí at the outer continental shelf, a reef with the occurrence of foraminifera, calcareous algae and bryozoa.

The last one, zone 5 at 40-60 m is characterized by a seabed with a rough texture and reflectance with dark tones. No sample was collected in this zone. There is an extensive carbonate bank in a flatbed (Maia de Almeida et al. 2016). The facies are mainly BSG and BS, LBS also occurs in the NW of the area.

Table 1: Qualitative analyses performed on 22 biogenic sediments showing what biotic components are present in each sample.

Taxonomic Group	Samples																						
	10	14	40	44	47	61	64	82	246	262	318	330	420	430	439	451	475	509	517	568	589	603	
Calcareous algae			x	x	x		x	x	x	x		x	x				x	x	x	x			
Bryozoa	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Cnidaria				x	x		x	x	x	x	x	x		x		x	x	x	x				
Arthropoda				x	x			x		x	x			x									
Foraminifera	x			x			x			x	x	x	x	x	x		x		x	x	x	x	
Mollusca (Bivalvia)	x																					x	
Mollusca (Gastropoda)	x	x					x						x	x	x	x	x	x	x		x	x	
Echinodermata	x	x												x	x	x	x		x		x	x	
Porifera					x			x	x	x		x	x							x			

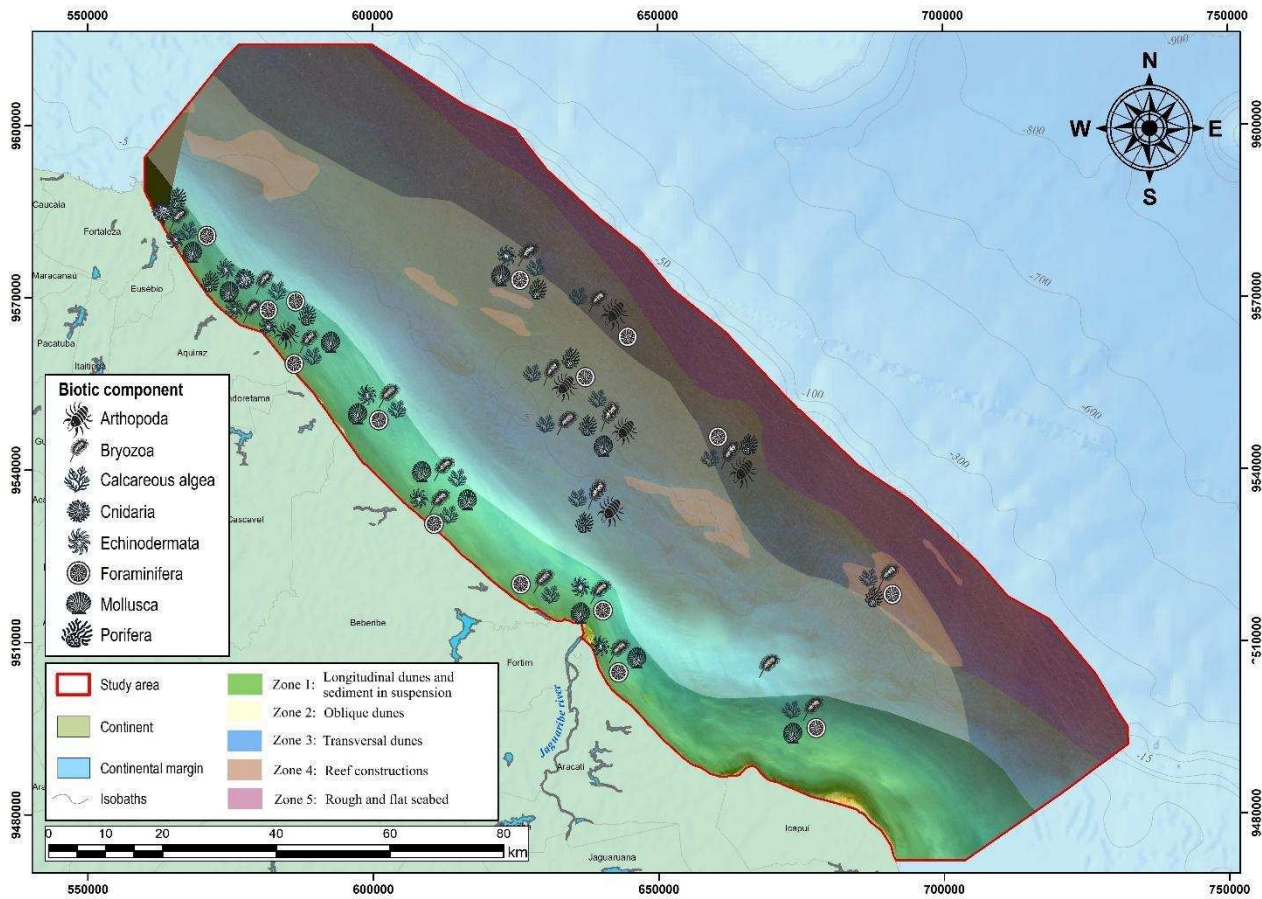


Figure 4: Geohabitat map of the continental shelf of Ceará adapted of Maia de Almeida et al. 2016. Different zones present diverse morphological and sedimentary features such as oblique and transverse dunes and reef constructions.

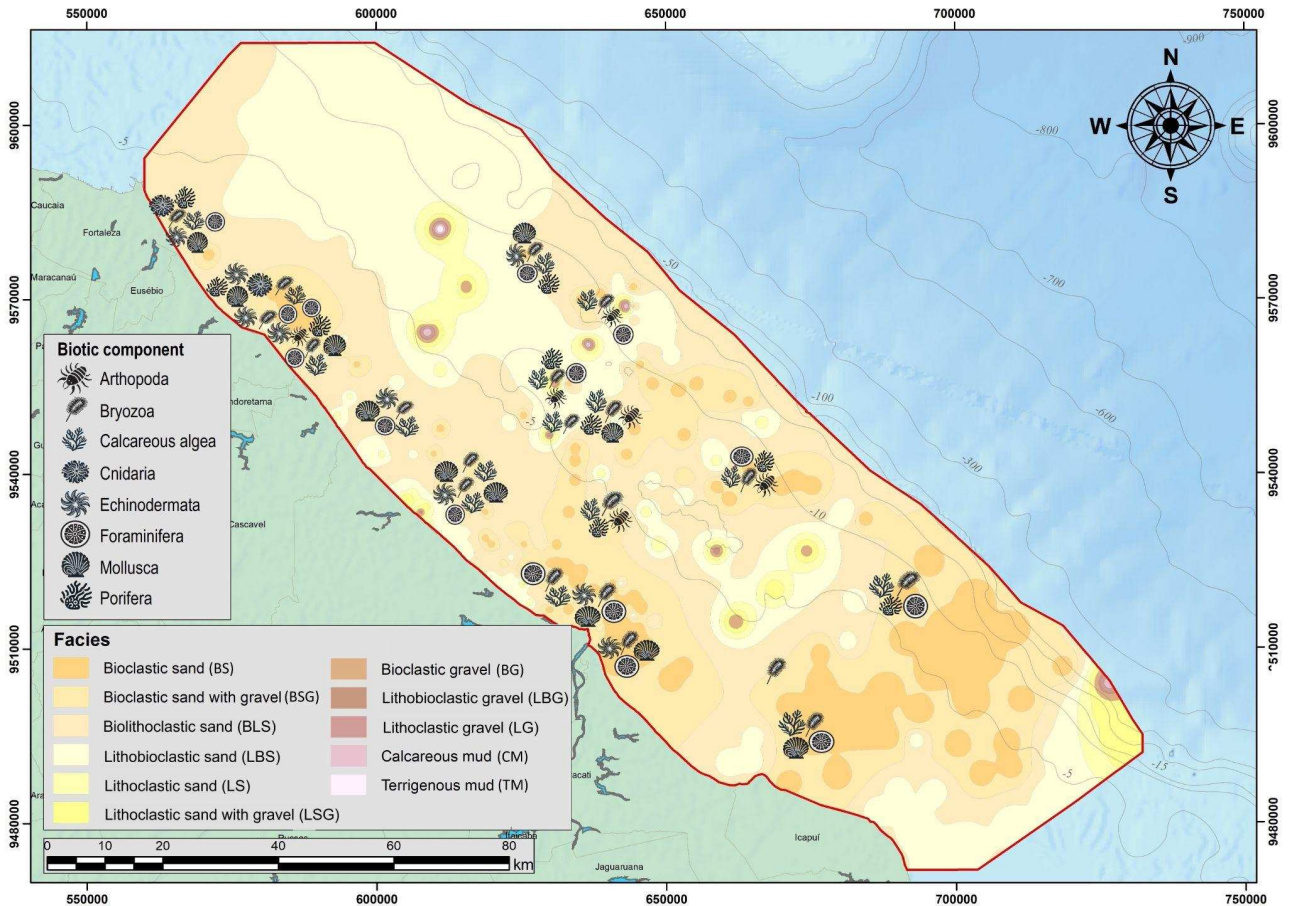


Figure 5: Facies map adapted of Maia de Almeida et al. (2021) showing the distribution of eight biogenic components identified along the eastern continental shelf Ceará.

4.2 Representation and distribution of the benthic communities in the Ceará continental shelf

Eight different groups of organisms were identified on the analyzed samples with predominance of bryozoa (35.5%), calcareous algae (27%), foraminifera (12.3%), mollusca (12%), cnidaria (4%), echinodermata (3.9%), porifera (3.5%) and arthropoda (1.7%) (Fig. 6A). Four of them (bryozoa, calcareous algae, foraminifera and mollusca) were the most abundant and classified as principal (5%) according to Dajoz (1983). The other components were classified as accessory (4.99 and 1%): cnidaria, echinodermata, porifera and arthropoda.

By examining the frequency of occurrence of each biogenic component, it was observed that five groups were classified as constant: bryozoa (95.45%), calcareous algae (72.73%), cnidaria (59.09%), foraminifera (72.73%) and mollusca (59.09%) (Table 2) according Dajoz (1983). While the echinoderms (45.45%), porifera (40.91%) and arthropoda (27.27%) were classified as accessory (Fig. 6B and Table 2).

The bryozoa is very abundant in the study area with a percentage of 35.5% of relative frequency (Fig. 6A) and a frequency of occurrence of 95.45% (Fig. 6B). Considering that the bryozoans are the most abundant biotic component found on the Eastern Ceará

continental shelf, this result is similar to the study of Santos et al. (2019) which showed that the most abundant biogenic components of another continental shelf in South Atlantic (Sergipe and Alagoas states) are foraminifera, red algae and bryozoans. According to Almeida (2011), the continental shelf environments are the place where highest values of diversity and richness of bryozoans occur. Then, this research is in conformity with Almeida (2011). The same results are showed in the continental shelf of Santa Catarina and Bahia by Gré (1989) and Poggio et al. (2009) who registered values of bryozoans in abundance. In contrast, other authors (Oliveira 2012, Nascimento 2016) found less than 5% in the continental shelf of Pernambuco.

Calcareous algae are the second most abundant with 27.06% (accessory) of relative frequency and 72.73% (constant) of occurrence frequency. They can be branched or not, free or fixed and are the most abundant in northeastern Brazil with an important role in carbonate production (Dias 2000, Lemos & Terra 2005). In the study area, they are type Rhodophyta (red algae) and Chlorophyta (green algae). In accordance, Pinheiro et al. (2019) found mainly shells and biodebris mostly constituted of calcareous algae and fragments of molluscs (bivalves) in the continental shelf of Iracema, Fortaleza.

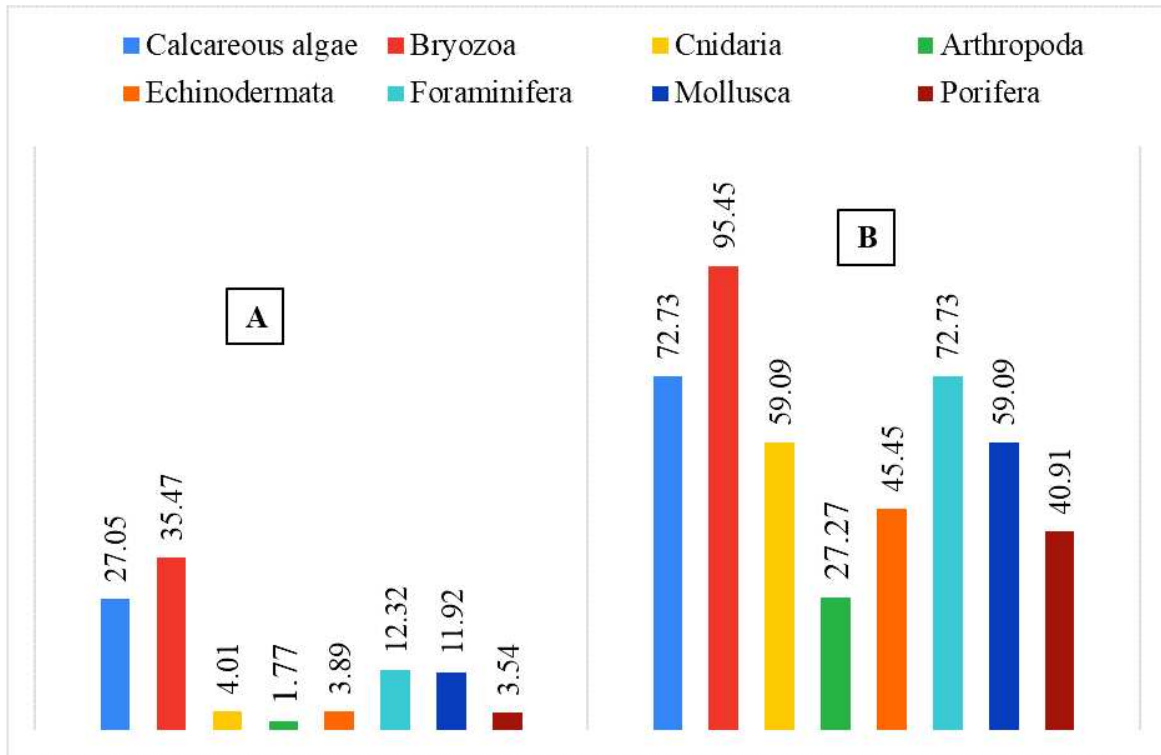


Figure 6: Distribution of the biotic components. A) Relative frequency (RF) of the main groups of organisms identified on the analyzed bioclastic sediments; B) Occurrence frequency (OF) of biotic components showing the predominance of each group.

Table 2: Occurrence frequency (%) and classification (Dajoz 1983) of the biotic components. p = number of stations in which each of the biogenic occurred; P= total number of stations; FO= occurrence frequency.

Biogenic components	p	P	FO (%)	Classification
Calcareous algae	16	22	72,73	constant
Bryozoa	21	22	95,45	constant
Cnidaria	13	22	59,09	constant
Arthropoda	6	22	27,27	accessory
Echinodermata	10	22	45,45	accessory
Foraminifera	16	22	72,73	constant
Mollusca	13	22	59,09	constant
Porifera	9	22	40,91	accessory

Foraminifera are the third most abundant in the study area with a representation of 12.32% and 72.73% conforming to the relative and occurrence frequency, respectively. Benthonic foraminifera is a group that contributes considerably to the composition of the biogenic sediment on the Eastern continental shelf of Ceará. It is classified as a constant and principal group.

The mollusca are represented by the gastropods and bivalve classes. They present a relative frequency of 11.62% that classified it as a principal group. In relation to the occurrence frequency, they represent 59.09% being classified as a constant group. Similar studies developed on continental shelf of Rio Grande of Sul, Santa Catarina, Bahia and Pernambuco have found mollusca as the most abundant group (Lopes & Buchmann 2008; Gré 1989; Poggio et al. 2009; Oliveira 2012).

Cnidarians constitute 4.01% and 59.09 % of relative and occurrence frequency, respectively, being classified as an accessory and constant group.

Echinodermata presents 3.88% of RF and 45.45% of OF being considered an accessory both related to its frequency and its occurrence. Similarly, Porifera is classified as an accessory group in both frequencies with a percentage of 3.54% and 40.91% (OF).

Finally, the Arthropods represent 1.77% (RF) and 27.27% (OF) and also are considered accessory in both frequencies. They were identified by the subclasses Crustacea and Ostracode.

4.3 PCA: how the geodiversity and the benthic communities are related?

Quantitative analysis was carried out to understand what are the dominant and determinant variables that control the distribution of the benthic organisms. The PCA biplot of the variables (biotic components, depth, facies and zones) permit the interpretation of the correlation between them (Table 3 and Fig. 7).

Table 3: Factorial axes resulted of the PCA showing 3 axes with the eigenvalue >1. Cal: calcareous algae; Cni: cnidaria; Arth: arthropoda; Por: porifera; Bry: bryozoa; For: foraminifera; Echi: Echinodermata; Mol: mollusca, BSG: Bioclastic sand with gravel, BLS: Biolithoclastic Sand, BS: Bioclastic Sand, BG: Bioclastic Gravel, Z1: zone 1; Z2: zone 2; Z3: zone 3; Z4: zone 4.

Variable	PC 1	PC 2	PC 3	Variable	PC 1	PC 2	PC 3
Cal	0.66228	0.56152	0.010144	40-60m	0.43037	-0.66328	0.13787
Cni	0.39317	0.10836	-0.19718	BSG	-0.2774	-0.022161	0.048398
Arth	0.67362	-0.24346	0.24837	BLS	0.20634	-0.77641	-0.18234
Por	0.61757	0.55747	-0.23908	BS	0.13653	0.59663	0.30358
Bry	-0.15246	0.39868	-0.24549	BG	-0.48019	-0.095364	0.071964
For	-0.04914	0.25143	0.51711	Z1	-0.91658	0.029338	0.21985
Echi	-0.60361	0.053199	0.17418	Z2	0.57202	0.091729	-0.74133
Mol	-0.54841	0.3049	0.33274	Z3	0.48334	-0.43276	0.5585
0-20m	-0.87026	0.049726	-0.27729	Z4	0.2734	0.33189	0.29529
20-40m	0.83591	0.15083	0.4129				

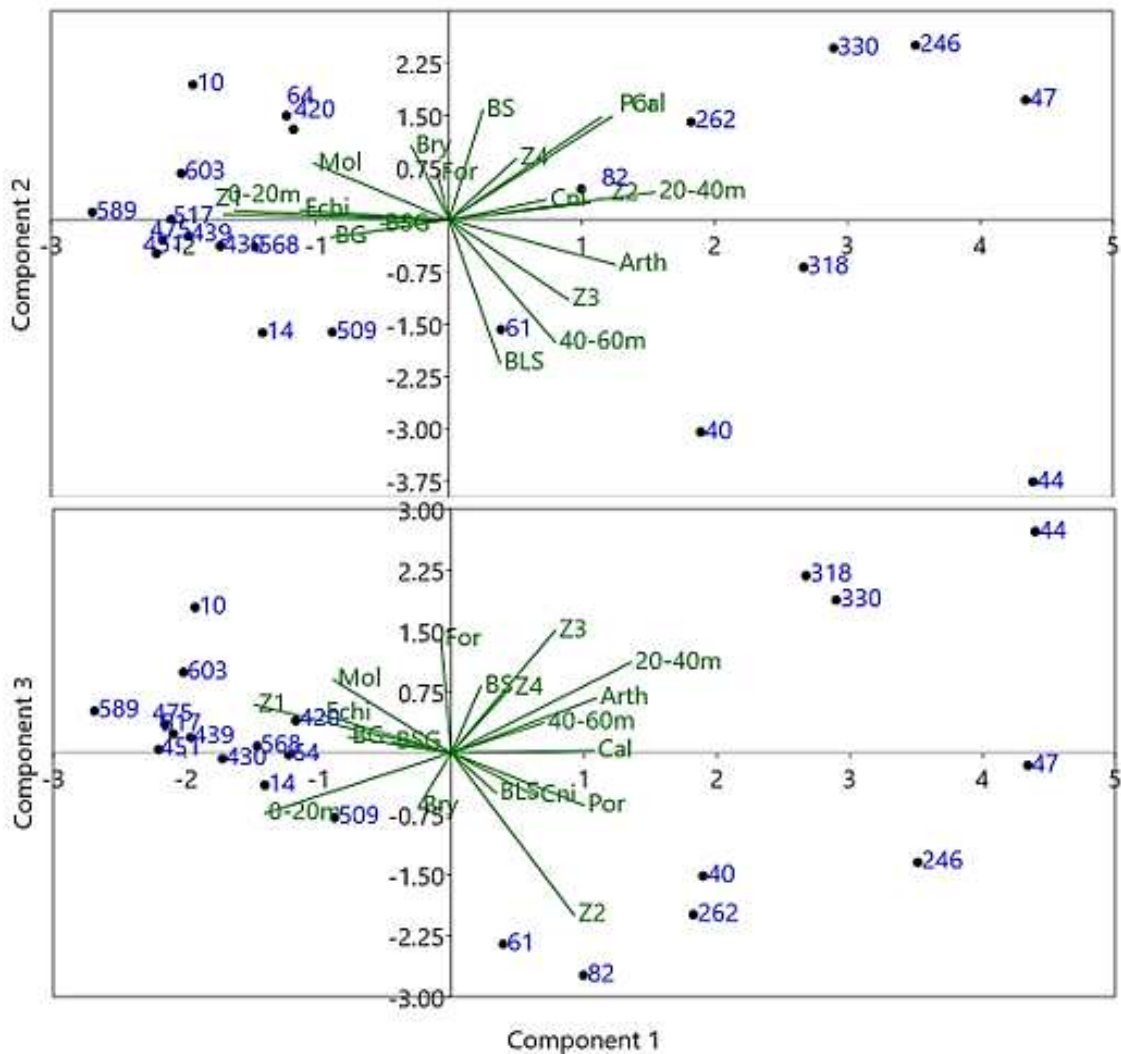


Figure 7: Principal Component Analysis (PCA) biplot for the biotic and abiotic variables of the eastern continental shelf of Ceará. PC1 explains 29,50% of the variation, PC2 14,50% and PC3 10,64%. Cal: calcareous algae; Cni: cnidaria; Arth: arthropoda; Por: porifera; Bry: bryozoa; For: foraminifera; Echi: Echinodermata; Mol: mollusca, BSG: Bioclastic sand with gravel, BLS: Biolithoclastic Sand, BS: Bioclastic Sand, BG: Bioclastic Gravel, Z1: zone 1; Z2: zone 2; Z3: zone 3; Z4: zone 4.

The PCA biplot diagram indicates that the PC1 holds the account for 29,50% of dataset variance. Some biotic components (calcareous algae, porifera and cnidaria), BS facies, 20-40 m depth and zone (Z2, Z4) are positively correlated according to PC1. The calcareous algae and porifera variables present the best correlations between them.

On the other hand, the echinodermata, mollusca, 0-20 m depth, BSG and BG facies and zone 1 (Z1) are negatively correlated.

PC2 presents positive correlations between bryozoan, foraminifera, and bioclastic sand (BS). Differently, Arthropoda, 40-60 m depth, zone 3 and biolithoclastic sand facies (BLS) are negatively correlated.

The PC3 accounts for 10,64% of variance and shows a positive correlation between calcareous algae and depth of 20-40 m. The arthropoda, 40-60 m depth and zone 3 are also positively correlated. It is worth mentioning that mollusca, echinodermata, zone 1 (Z1), BG and BSG facies are positively correlated.

In addition, the PC3 presents negative correlation between porifera, cnidaria and zone 2 (Z2).

Some groups of samples were identified conforming to the positive and negative correlations. Samples of group A (47, 82, 246, 262, 330) reflect the association which is strongly correlated with PC 1. It means that those samples are mostly enriched of calcareous algae, porifera and cnidaria and can be found in depths of 20-40 m and are well distributed in zone of oblique dune (Z2) and zone of reef constructions (Z4).

The group B (10, 64, 420, 517, 589, 603) presents echinodermata and mollusca and tends to occur in depths of 0-20m, in the zone 1 (Z1) correlated to the BG and BSG facies.

The group C (40, 44, 61 and 318) presents a negative correlation in PC2 and presents arthropoda, in an environment of 40-60 m with transversal dunes (zone 3), constituted of BLS facies. This means that groups B and C have an inverse correlation in PC1 which means that group B is poorly represented by the variables identified in group C and inversely.

Depth plays a significant role in the distribution of each variable. Group A occurs on the medium shelf (20-40 m). In contrast, group B is localized at 0-20 m in the inner shelf and group C occurs in the outer shelf at depth of 40-60 m.

The environmental conditions at each sample point (depth, temperature, pressure, currents, characteristics of the bottom of the water column, turbidity, among others) promote conditions for reproduction of those determined biotic groups. Group A is distributed in two specific zones which are zone 2 (zone of oblique dunes) and zone 4 (zone of reef constructions), while the group B occurs in the zone 1 (zone of longitudinal

dunes and sediments in suspension) and group C in zone 3 (zone of transversal dunes). Then, the depth and seabed morphology have influence in the distribution of the benthic organisms of the eastern Ceará continental shelf.

Similarly, the abiotic factor of the sedimentary facies also contributes to the heterogeneous distribution of the benthic communities. Porifera, calcareous algae, and cnidaria tend to occur in BS facies. In addition, the BSG and BG facies are favorable to the development of mollusca and echinodermata while the BLS, to the arthropoda.

As mentioned before, the groups B and C show an inverse correlation with each other. This means that, if one group exists, the other group tends not to exist or exist in a small amount. These results show that the physical environment (abiotic factors) can allow the development of only certain groups. The benthic communities can be influenced by environmental factors (Lundblad et al. 2006, Jerosch et al. 2015, Goes et al. 2019). Another hypothesis is that these two groups may generate some competition in the environment, not allowing the other group to exist or to reproduce (biotic factor) (e.g. Peterson 1980, Quinn 1982, Kohler 1992).

It is known that the benthic community distribution is controlled by physical (environmental) and biological processes (Cartes & Carrasson 2004, Locker et al. 2010, Kaskela et al. 2017). However, in the study area, localized in a tropical semiarid climate which has a particularity of low input of sediment, this research is the first approach about the heterogeneity and diversity of the seafloor and of the benthic community of the eastern Ceará continental shelf and their correlation.

The results of the present study reveal the importance for ecological studies, considered by Dartnell & Gardner (2004) as a basic data set, which describes the superficial characteristics of the seafloor as the baseline for habitat study. The combination of bathymetric data, seabed morphology and sedimentary facies reveals the great geodiversity of the eastern continental shelf of Ceará. Correlated to the knowledge about the benthic communities and their distribution influenced by environmental settings, this research may be considered an important study on the distribution of geohabitats throughout the studied area. Here, the first map of the benthic distribution of the eastern Ceará continental shelf was presented.

Similar to what was observed by Matthews-Cascon et al. (2018) regarding marine benthic communities affected by the Doce River (southwestern Atlantic), in Ceará continental shelf with the increasing distance from the coast, in addition to increasing depth, there is a differentiation in composition and abundance of the benthic communities. Furthermore, depth, seabed morphology and sedimentary facies are important factors that explain variations in composition and diversity across the continental shelf. The results

provide an invaluable baseline for measuring the possible future effects on shallow and mesophotic communities of the anthropogenic activities related to Blue Economy.

5. Conclusions

This research presents the main constituents of the benthic assembly of the eastern Ceará continental shelf that are: bryozoans, calcareous algae, foraminifera and mollusca. These organisms are responsible for the majority of the carbonate sedimentation of the study area. The calcareous algae are mainly of type Rhodophyta (red algae) and Chlorophyta (green algae) and the mollusca are represented by Gastropods and Bivalvia classes. Bryozoa showed the highest relative frequency of occurrence followed by calcareous algae, cnidaria, foraminifera and mollusca. These groups are constant while Cnidaria, Arthropods, Echinoderms, and Porifera are considered accessory constituents.

The PCA biplot analyses presented a positive correlation between calcareous algae, porifera, cnidaria, 20-40 m depth, zones 2 and 4 (longitudinal dunes and reef constructions), and BS facies (group A). In addition, Echinodermata, mollusca, 0-20 m depth, BSG and BG facies and zone 1 (sediment in suspension) (group B). Arthropoda, 40-60 m depth, zone 3 (transversal dunes) and the BLS facies also present correlation (group C). Groups B and C tend not to occur together.

This research identifies, for the first time, the relationships between the benthic community distribution and the abiotic factors of the marine environment. It presents essential results for quantitatively and qualitatively analyzes about the composition, frequency of occurrence, diversity of the benthic community of the Eastern continental shelf of Ceará. Depth, seabed morphology and sedimentary facies are important factors that explain variations in composition and diversity across the continental shelf.

These analyses revealed the real composition of the benthic assembly and its correlation with the geodiversity. Therefore, these results are considered an invaluable baseline for measuring and monitoring the impacts of possible future anthropogenic and industry activities related to Blue Economy in the semiarid continental shelf, subsidizing sustainable development.

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Credit author statement

P.N.N.N: Conceptualization; Data curation; Formal Analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing;

N.M.A.: Conceptualization; Formal Analysis; Investigation; Methodology; Resources; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing;

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