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Morphological and sedimentary patterns of a semi-arid shelf, Northeast Brazil

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Abstract

The semi-arid shelf of Northeastern Brazil, adjacent to the State of Ceará, was analyzed using high-resolution seismic imaging, side-scan sonar imaging, sedimentary patterns, remotely operated vehicle (ROV), scuba dive surveys, and satellite images. Three geomorphic sectors were found according to physiographic, sedimentological, and morphological aspects: Coreaú, Mundaú, and Jaguaribe. The Ceará shelf is characterized by a mixed sedimentological pattern including a significant modern carbonate supply, relict siliciclastic grains, and a mixing of carbonates and siliciclastics. The modern siliciclastic supply is concentrated near the coast (shoreface/shoaling zone) and solid discharge from rivers is low due to a semi-arid climate. The subaqueous features (dunes, ripples, reefs, beachrocks, and incised valleys), both relict and modern, formed both as a result of sea-level changes (Wisconsin Glacial and Holocene transgression) and modern processes (longshore and wind-driven currents, waves, and tides).

Keywords Equatorial Atlantic · Semi-arid · Carbonates · Terrigenous · Paleogeography

Introduction and methodology

The continental margin of the west equatorial Atlantic (Northeast Brazil) presents a unique climate setting amongst semi-arid regions on Earth (Molion and Bernardo 2002). The predominance of semi-arid environments during the late quaternary has been verified (Behling et al. 2000). However, terrestrial sediment pulses at the continental margin of Northeastern Brazil have occurred during humid periods (warm sea-surface temperature and increased precipitation) in the low sea-level periods of the Wisconsin Glacial (Arz et al. 1998; Nace et al. 2014). Such conditions have favored the development of a mixed depositional system on the continental shelf, represented by both modern and relict sediments in the form of bioclastics and siliciclastics (Ximenes Neto et al. 2018a). The main geomorphological features found in the area are beachrocks, subaqueous dunes, incised valleys, escarpments, abrasion platforms, aligned features, and reefs or bioherms (Freire 1985; Monteiro 2011; Morais 1998; Silva 2015; Ximenes Neto et al. 2018b).

The continental shelf of Ceará State (Northeastern Brazil) was analyzed as the focus of this study to identify, classify, and correlate morpho-sedimentary aspects using compiled data from seismic profiles (2–16 kHz and 0.5–8 kHz), sedimentary samples (900), remotely operated vehicles (ROV), satellite images (Landsat 5 and 8), side-scan sonar (410 kHz), and scientific Scuba dives. The facies classification has been performed by the X-ray fluorescence (XRF), grain size (the sieve-pipette method), calcium carbonate (Bernard method, Lamas et al. 2005), sorting (Folk and Ward 1957), and grains components (siliciclastic x bioclastic).

The first studies that aimed to understand the sedimentological nature of the Brazilian equatorial margin were performed by Coutinho & Morais (1968 and 1970) and Kempf et al. (1970). Subsequent research has been carried out, mainly concerning sedimentation and geomorphology (Freire 1985; Monteiro 2011; Soares 2012; Farrapeira Neto 2013; Moura 2014; Barros 2014; Ciarlini and Morais 2014; Silva 2015). This study uses the sedimentological and morphological information for a better understanding of the seabed of these

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semi-arid shelves that are characterized by low siliciclastic input. A geomorphic sectorization was established, Fig. 1.

Results

Morphology

The geomorphological settings according to physiography/morphostructures were classified into three sectors as follows: Coreaú (from the mouth of the Timonha-Ubatuba to the Itapagé Inflexion), Mundaú (from the Itapagé Inflexion to the Fortaleza Headland), and Jaguaribe (from the Fortaleza Headland to the Manibú mouth), fig.1. The Ceará shelf includes a natural zonation according to its morphology and sedimentology, comprised of an inner shelf (< 20 m), a middle shelf (20–40 m), and an outer shelf (> 40 m to shelf break, ~ 60–70 m).

Coreaú sector

This area is the largest semi-arid shelf of the equatorial Atlantic (~ 100 km in width, off the Coreaú Mouth), with an extensive inner shelf (40–50 km in width), since the Brazilian semi-arid shelf extends from the Rio Grande do Norte to Piauí. These morphological patterns reflect the physiographic changes related to the Itapagé Inflexion, the Parnaíba platform (inner shelf–shallow basement), the Ceará high, the Atlantic high, the Camocim fault and Piauí-Camocim sub-basin faults, and the Romanche fracture zone (extending to the outer shelf), Fig. 1.

The inner shelf includes principal morphological systems such as the Coreaú incised valley (Fig.1(2, 10)) and subaqueous dunes (Fig. 1(12)). In the sector containing the Itapagé inflexion, the Acaraú sub-basin favored the formation of a shallow seabed, which is associated with the Acaraú High (Fig. 1(12, 13)) known as Costa Negra (Ximenes Neto et al. 2018b). Around the 20-m and 40-m isobath range, escarpments often occur, sometimes with rocky floors such as reefs and beachrock. The main feature in the middle shelf is the Itapagé Bank. Rocky floors and outcrops occur frequently on the inner shelf, such as the Barreiras Group (fluvial sandstones and conglomerates) and submerged aeolianite or beachrock. Rhodolith beds, bioherms, and seagrass fields are common (Fig. 1).

Mundaú sector

This sector has a shelf of ~ 50 km width that enlarges to ~ 65 km towards the northwest at the Itapagé Inflexion. The inner shelf exhibits an increase in the slope as well as the presence of a shallow basement called the Fortaleza platform. Near the 20-m isobath lie escarpments and several linear features parallel to the coastline that consist of a rocky floor in the form of beachrocks and/or reefs. The State Marine Park of the Pedra da Risca do Meio lies in front of the Fortaleza city (Fig. 1(11)). The Fortaleza High occurs in the outer shelf. A crystalline basement outcrops on the inner shelf (e.g., Pecém region) (Fig. 1(7, 8)). In the inner to middle shelf between Coreaú and Mundaú sectors, some rough surfaces were verified (Fig. 1(5)). They may be related to the reefs and/or the beachrocks when they are parallel to the coast. On the other way, they may be related to the subaqueous dunes and/or erosive escarpments when oblique to the coast. Rhodolith beds occur off the Aracatimirim Mouth (Fig. 1(1)).

Jaguaribe sector

The narrowest shelf of the Ceará (~ 40 km in width), this section lies in front of Tremembé, Icapuí, and displays the greatest number of high energy unconsolidated bedforms in the form of subaqueous dunes, as identified by satellite imagery (Fig. 1(6)). These features can be parallel, transverse, or oblique to the coastline and occur mainly at the inner and middle shelf. The greatest diversity occurs between Beberibe and Icapuí. In the middle shelf, the rocky floor mainly exhibits features parallel to the coastline, such as beachrocks and/or reefs. At Icapuí, the Barreiras Group, which is of continental origin, occurs in the inner shelf (abrasion platform, stump, and stack). Halimeda banks are very common, mainly associated with the subaqueous dunes (Fig. 1(3)). Sponge bed occurs in the outer shelf of the Fortaleza (Fig. 1(4)) (Monteiro 2011).

Facies characteristics

Three sedimentological patterns are found at the Ceará shelf: carbonate, siliciclastic, and mixed. These are subdivided into eight facies and granulometric settings, as shown in Table 1.

Fig. 1 Morphological settings of the semi-arid shelf of the Ceará State with morphostructural aspects (CPRM 2003; Morais Neto et al. 2003; Silva Filho 2004; Ximenes Neto et al. 2018b) and geomorphic sectorization (Coreaú, Mundaú, and Jaguaribe). 1, Rhodolith bed from Scuba dive (Mundaú sector). 2, RGB composition of the Landsat 5 satellite of the Coreaú incised valley (Coreaú sector). 3, ROV image in a Halimeda bank (Jaguaribe sector). 4, ROV image in a rigid substrate with sponge (Jaguaribe sector; Monteiro 2011). 5, Rough surface (Coreaú sector). 6, Rocky floor and subaqueous dunes in inner and middle shelf—RGB composition of the Landsat 5 (Jaguaribe sector). 7, Side-scan sonar in a crystalline basement (Mundaú sector). 8, High-resolution seismic of the Pecém harbor with mud and shallow basement (Mundaú sector). 9, High-resolution seismic of the access channel of the Mucuripe harbor with fluid mud (Mundaú sector). 10, High-resolution seismic of the Coreaú incised valley (Coreaú sector). 11, High-resolution seismic of reef related to the State Marine Park of the Pedra da Risca do Meio (Mundaú sector). 12, RGB composition of Landsat 8 of the Costa Negra (Coreaú sector). 13, Digital bathymetric model of the Coreaú sector (inner shelf)

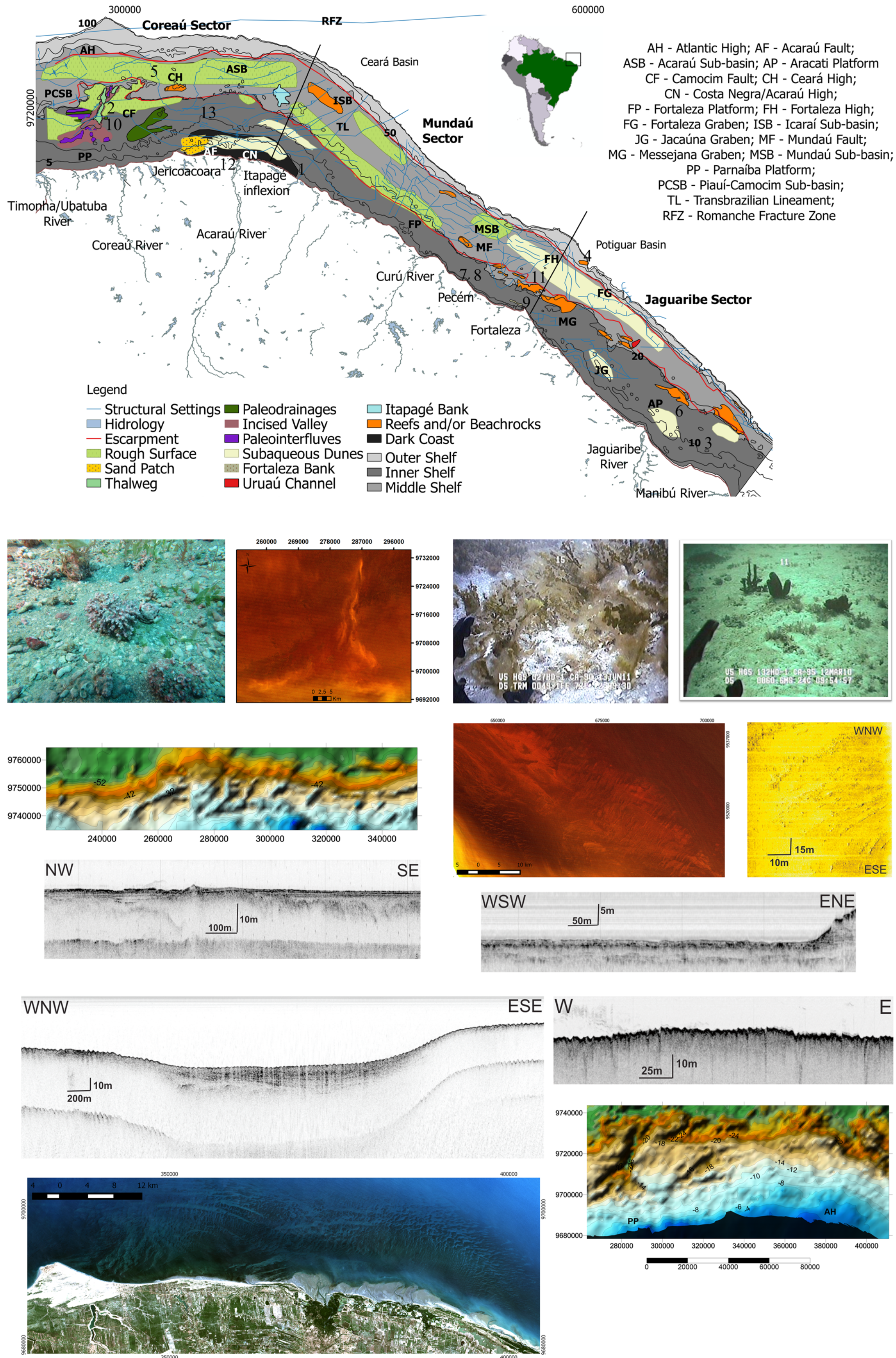

300000
600000
9720000
100
Coreaú Sector
RFZ
Ceará Basin
AH
ASB
CH
PCSB
CF
ISB
TL
50
Mundaú Sector
PP
AF
CN
Jericoacoara
Itapage inflexion
Timonha/Ubatuba River
Coreaú River
Acaraú River
Curú River
Pecém
Fortaleza
FP
MSB
MF
FH
Potiguar Basin
FG
Jaguaribe Sector
MG
JG
AP
Jaguaribe River
Manibú River
AH - Atlantic High; AF - Acaraú Fault;
ASB - Acaraú Sub-basin; AP - Aracati Platform
CF - Camocim Fault; CH - Ceará High;
CN - Costa Negra/Acaraú High;
FP - Fortaleza Platform; FH - Fortaleza High;
FG - Fortaleza Graben; ISB - Icaraí Sub-basin;
JG - Jacaúna Graben; MF - Mundaú Fault;
MG - Messejana Graben; MSB - Mundaú Sub-basin;
PP - Parnaíba Platform;
PCSB - Piauí-Camocim Sub-basin;
TL - Transbrazilian Lineament;
RFZ - Romanche Fracture Zone
Legend
Structural Settings
Hidrology
Escarpment
Rough Surface
Sand Patch
Thalweg
Paleodrainages
Incised Valley
Paleointerfluves
Subaqueous Dunes
Fortaleza Bank
Uruaú Channel
Itapagé Bank
Reefs and/or Beachrocks
Dark Coast
Outer Shelf
Inner Shelf
Middle Shelf
NW
SE
10m
100m
WSW
ENE
5m
50m
WNW
ESE
15m
10m
WNW
ESE
10m
200m
W
E
25m
10m
9760000
9750000
9740000
240000
260000
280000
300000
320000
340000
9740000
9720000
9700000
9680000
280000
300000
320000
340000
360000
380000
400000
0
20000
40000
60000
80000

Table 1 Facies distribution of the Ceará shelf

		Facies	Granulometric settings (*)
Sedimentological patterns	Siliciclastic	Quartzous	Gravel and sand
		Clay minerals	Terrigenous mud
	Carbonate	Calcareous red algae	Pebble to sand
		Calcareous green algae	Pebble to sand
		Biodetritic	Sand
		Biogenic mud	Carbonate mud
	Mixed	Lithobioclastic	Sand
		Biolithoclastic	Sand

*Predominance

In the Ceará shelf, the sedimentological characterization of the seabed has been carried out since the 1960s. In this period, the use of several terminologies with different geographic zoning for the facies has been verified (Fig. 2(A, B, C)). In this work, the use of a structured approach favored the overall understanding of the facies in a semi-arid shelf. The mixed and carbonate patterns should be broader than those cited for Coutinho and Morais (1970), Freire (1985), and Morais (1998) (Fig. 2(1, 2, 3); CGA, BL, and BM). The previous maps (Coutinho and Morais 1970; Freire 1985; Morais 1998) have been shown the overestimated presence of siliciclastic patterns, mainly in the inner and middle shelf, where in reality in some places there is a mixed or carbonate pattern (Fig. 2, CGA and BL).

Carbonates

Calcareous algae (green/Chlorophyta and red/Rhodophyta) supply the greatest sedimentary contribution; predominantly represented by rhodoliths/lithothamnion/maerl, halimeda, and geniculate corallines. Areas of calcareous green algae tend to be poorly (~ 80%) sorted, calcareous red algae are moderate (35%) to poorly (51%) sorted, biogenic mud is very poor to poorly sorted, and the biodetritic area is moderately sorted (75%).

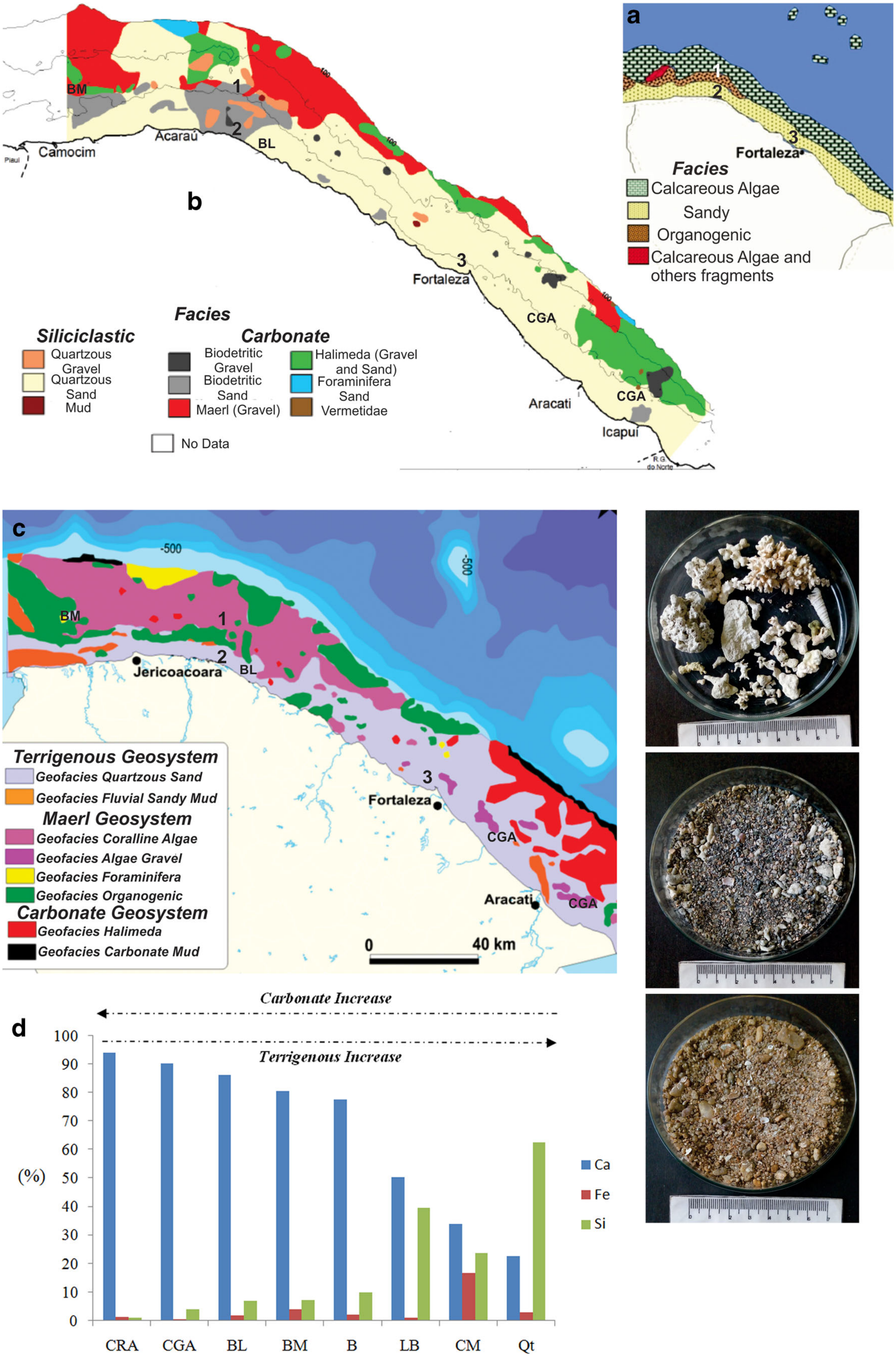
Chemical elements associated with these facies show little difference overall. The predominant chemical elements found are Ca, Si, Cl, Fe, and Sr. Ca is related to the carbonate marine sediments, but in both the calcareous red algae and biogenic mud facies, Sr is also found to be associated with marine sediments. The calcareous red algae facies contain the greatest carbonate accumulation. The calcareous green algae and biodetritic regions exhibit a mixture with terrigenous sediments. Biogenic mud and biodetritic shows the greatest terrigenous influence (~ 10%), but the main element was Ca (80.5% and 75%, respectively) (Fig. 2(D)). In the Mundaú and Coreaú sectors, the calcareous red algae are common; the rhodolith beds also occur on the inner shelf (Fig. 1(1)). In the Jaguaribe sector, the calcareous green algae are common and associated to the unconsolidated bedforms (banks and dunes) (Fig. 1(3, 6)). The biogenic mud tends to appear in punctual sites, mainly in the stratigraphic traps (e.g., incised valleys) (Fig. 2, BM). Biodetritic facies are mainly related to the shallow areas, as the Coreaú sector.

Mixed

The mixed facies shows evidence of modern sediment supply in the form of carbonates and relict sediments in the form of siliciclastics. The main bioclastic components are calcareous algae, mollusks, and foraminifera, while the lithoclastic components consist of quartz and lithic fragments. Biolithoclastic shows poor to extremely poor (64%) sorting whereas lithobioclastic has poor (50%) sorting and moderate (33%) sorting. The biolithoclastic is the least sorted because of the considerable bioclastic contribution, and the lithobioclastic is better sorted because of the large quartz contribution in the form of fine to very fine sand.

The chemical elements associated with facies present large differences. The main elements are Ca, Si, Cl, K, Fe, and Al. Ca is a unique element correlated with marine sedimentation (bioclastics) (Fig. 2(D)). The Si, K, and Al are associated with terrigenous sedimentation. Other elements (trace), such as Cd, Zr, Ti, Ag, Tc, and Rh, are also found. The biolithoclastic facies is characterized high concentrations of Ca (~ 86%) and low amounts (~ 11%) of siliciclastics (Si, Al, and K). It is noteworthy that the Fe element can be correlated with

Fig. 2 Sedimentological mapping evolution in the last five decades to the Ceará shelf. A, First sedimentary map of Ceará shelf elaborated for Coutinho and Morais (1968, 1970). B, Faciology of the Ceará shelf elaborated from Freire (1985), Freire and Cavalcanti (1998), and Silva Filho (2004). C, Geofacies map elaborated for Morais (1998). In this paper proposes the sedimentological patterns, as follows: 1, carbonate; 2, mixed; and 3, siliciclastic. D, Main chemical elements of the sedimentological patterns. The carbonate influences increase from siliciclastic pattern to calcareous algae facies. CRA, calcareous red algae; CGA, calcareous green algae; BL, biolithoclastic; BM, biogenic mud; B, biodetritic; LB, lithobioclastic; CM, clay minerals; Qt, quartzous. In the ancient maps, some facies were plotted (BM, CGA, and BL) to demonstrate differences in mapping ▶


a
Fortaleza
Facies
Calcareous Algae
Sandy
Organogenic
Calcareous Algae and others fragments
b
BM
1
2
3
Acaraú
BL
Camocim
Fortaleza
CGA
Aracati
Icapui
Facies
Siliciclastic
Quartzous Gravel
Quartzous Sand
Mud
Carbonate
Biodetritic Gravel
Biodetritic Sand
Maerl (Gravel)
Halimeda (Gravel and Sand)
Foraminifera Sand
Vermetidae
No Data
c
-500
BM
Jericoacoara
BL
Fortaleza
CGA
Aracati
Terrigenous Geosystem
Geofacies Quartzous Sand
Geofacies Fluvial Sandy Mud
Maerl Geosystem
Geofacies Coralline Algae
Geofacies Algae Gravel
Geofacies Foraminifera
Geofacies Organogenic
Carbonate Geosystem
Geofacies Halimeda
Geofacies Carbonate Mud
0 40 km
d
Carbonate Increase
Terrigenous Increase
(%)
100
90
80
70
60
50
40
30
20
10
0
CRA
CGA
BL
BM
B
LB
CM
Qt
Ca
Fe
Si

siliciclastics. The lithobioclastic facies, which exhibits high siliciclastic content (~ 44%), but a significant carbonate influence, is still found (~ 54%). The Fe is highly correlated with carbonate sedimentation in this facies. The Al and K are frequently associated with the Si in terrigenous sedimentation but correlation for this is not found. These two mixed sedimentological patterns are related mainly to the inner shelf (Fig. 2, BL).

Siliciclastic

The siliciclastics of the Ceará shelf are mainly relict grains deposited during low sea level and reworked during Holocene transgression. The quartzous facies is predominant. It is very common to find angular gravel, pebbles, or sand grains with iron and carbonate coatings in these areas. The quartzous facies show moderate to poor sorting and clay minerals are usually very well sorted, but poor sorting may occur because of mixed grain size fractions (e.g., sand and gravel).

The chemical elements associated with the facies showed important differences related to the grain size pattern. The main chemical elements are Si, Ca, Fe, K, Al, and Cl. In this sedimentological pattern, some correlations were not verified, such as Fe and Al with the siliciclastic group (Si, K). The main elements in the quartzous facies are Si (62.6%), Ca (22.7%), and K (7.5%) (Fig. 2(D)). However, in the clay mineral facies, Ca (34%), Si (23.8%), Fe (16.5%), and Al (8%) were found. Some elements, such as Ti, Rb, Mg, and Rh in minor proportions, were identified and are associated with terrigenous sedimentation. The Mn and Br elements occur in the clay minerals facies. Quartzous facies occur mainly in the inner shelf of the Mundaú and Jaguaribe sectors. In the Pecém and Mucuripe harbors (Mundaú sector), the clay minerals facies were found (Fig. 1(8, 9)).

Discussions and conclusion

The Ceará shelf is a mixed carbonate-siliciclastic shelf with modern and relict subaqueous features (Coutinho and Morais 1970; Ximenes Neto et al. 2018a, 2018b). Modern sedimentation consists mainly of autochthonous carbonate supply from calcareous algae (green and red), which in turn leads to the presence of ripples, dunes, banks, and reefs. Mixed facies are found in the shallow areas that are favorable for hydrodynamic reworking. The ancient sedimentation is represented by relict grains (mainly quartz) and palimpsest patterns. Low lithoclastic supplies occur because of the semi-arid climate (Freire 1985; Morais 1998; Morais et al. 2006; Dias et al. 2013). The clay minerals facies is related to terrigenous mud, both relict and modern. Modern siliciclastic supply for the shoreface and shoaling zone occurs only near the fluvial mouth, aeolian bypass zone, and the erosive unconsolidated cliff. The carbonate influence is greater in the clay minerals facies than in the quartzous facies because of the mixing of terrigenous mud (relict or modern) with modern bioclastic sedimentation.

This mixed carbonate-siliciclastic system is observed throughout the semi-arid shelf of the Brazilian equatorial margin (Piauí to Rio Grande do Norte shelf). It shows antecedent morphologies, biogenic reefs, incised valleys, bioherms, subaqueous dunes, and the large carbonate supply derived from the calcareous growth on the inner to outer shelf (Coutinho and Morais 1970; Testa and Bosence 1998; Vital et al. 2008; Gomes et al. 2014; Nascimento Silva et al. 2018; Ximenes Neto et al. 2018a, 2018b). Thereafter, the Ceará shelf is a modern carbonate supply system mixing with relict siliciclastics mainly from lower shoreface (~ 5-m depth) to shelf break (~ 60-m depth). However, during a maximum freshwater discharge, an estuarine plume advances 6 km (< 10-m depth) along the continental shelf off the Jaguaribe river (siliciclastic input) (Dias et al. 2013). At the Parnaíba River mouth (Piauí), the suspended sediment released approximately 2.54×10^6 tons (2008 year), which influences the inner shelf (~ 10 km from the mouth) (Aquino da Silva et al. 2015). In the Ceará inner shelf, a great accumulation of terrigenous mud predominantly occurs in the harbor areas due to the low hydrodynamic of the sheltered sectors (Pecém and Mucuripe Ports) (Fig. 1(8, 9)). In the others areas, the clay minerals are transported as suspended load, mainly by the longshore flow and North Brazil current for north-westerly direction (to the Amazon shelf) (Morais et al. 2006). In the inner shelf (< 10-m depth) off the mouths of Acaraú, Camocim, Aracatimirim, and Choró Rivers a modern carbonate growth was verified (Fig.1(1); Fig. 2, CGA, BL, and BM), unlikely what it is evidenced in other shelves, as in the Doce river shelf which has the typical marine carbonate sedimentation just in the mid-outer shelf (> 40-m depth) (Quaresma et al. 2015) and the North Queensland margin which shows siliciclastic cross-shelf transport to deep sea (Francis et al. 2007). In La Parguera (Puerto Rico), there shows little annual precipitation and low siliciclastic input to the shelf which favors the carbonate factory in shallow water (Ryan-Mishkin et al. 2009); similar patterns occur at Ceará shelf, allowing the formation of biogenic reefs.

The relict sandy to gravelly quartz grains of the Ceará shelf demonstrates a typical pattern of semi-arid environments, which represents a predominance of bedload sediment transport rather than the suspended sediment transport (clay minerals) by the rivers. The rate of sediment concentration in the Jaguaribe River watershed does not exceed 500 mg L^{-1} (Cavalcante 2012). The solid discharge of the Jaguaribe is 4.3×10^4 to $7{,}4 \times 10^4$ t $year^{-1}$ (Cavalcante 2018). These values are very low in relation to humid systems, such as the Amazonas (810×10^6 t $year^{-1}$), Doce (1×10^6 t $year^{-1}$), Tocantins (3.06×10^6 t $year^{-1}$) (Guyot et al.

2005; Lima et al. 2005) and others semi-arid systems, such as the Isábena, Iberian Peninsula (1.84×10^5 t year^{-1}) (López-Tarazon et al. 2009).

The Amazon shelf and the eastern Brazilian margin are characterized by a significant terrigenous mud deposit, mainly in the inner shelf (Nittrouer et al. 1991; Bastos et al. 2015). However, the Ceará inner shelf is evidenced a predominance of mixed to siliciclastic patterns, being frequently found carbonate pockets—rhodoliths beds (Mundaú and Coreaú sectors), Halimeda bank (Jaguaribe sector), geniculate calcareous algae beds (Mundaú and Itapagé sectors), and biodetritic. In the Jaguaribe sector, a Halimeda-quartz cycle (sea-floor and sub-bottom) was verified in Halimeda banks (Moura 2014; Ciarlini and Morais 2014; Ximenes Neto et al. 2018a). This cyclic alternation of bioclastic and siliciclastic in sub-bottom demonstrate a cyclical occurrence of Halimeda banks, at least in the inner shelf (Fig. 1(3)). Halimeda zone between 15 and 30 m in the Jaguaribe sector was verified (Monteiro 2011). Rhodoliths and maerl (coralline algae) beds are very common in the middle to outer shelf between Fortaleza and Camocim (Cavalcanti 2011). However, some sectors of the inner shelf have a rhodolith bed below 10-m isobath (Fig. 1(1)).

The ancient shorelines (beachrocks) viewed in the inner to outer shelf, subaqueous dunes in the middle and outer shelf, and incised valleys are important paleogeographic morphologies created during low sea level and the Holocene transgression (Fig.1). However, the subaqueous dunes and ripples of the inner shelf are associated with modern processes, mainly longshore flow, wind-driven currents, and waves. Greater intensity of bottom currents (0.1 to 0.2 m/s.1) in the second semester (July to December) is verified due to the most intensity of the trade winds (Freitas 2015). The longshore current near the Fortaleza harbor carries ~ 860.000 m^3/year of sediments (Maia 1998). Nevertheless, the large amount of sediments is not justified solely by the modern sediment supply.

The major rigid substrates related to the beachrocks and/or reefs are located in the Mundaú and Jaguaribe sectors, such as the Pedra da Risca do Meio (Fortaleza), Aquiraz, Uruaú, Fortim, and Icapuí (Monteiro 2011; Silva 2015). The reefs and rhodoliths beds found in the middle and outer shelf of Ceará may be a continuation of the Amazon Reef system. This is located in the outer shelf between Amapá and Maranhão and it has a great complexity and diversity of habitats (reefs, rhodoliths, and sponges beds) (Francini-Filho et al. 2018). The rigid substrates in the Ceará shelf could have a connection with Holocene sea-level rise and flooding shelf due to the parallel shaped to the coastline. However, there is no up to date information about the composition of these rocky floors.

A complete sedimentary map should be made from samples collected in more areas, especially in the facies transitions, in addition to the standardization of a single terminology, as presented in this paper.

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