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Transgressive deposits and morphological patterns in the equatorial Atlantic shallow shelf (Northeast Brazil)

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ABSTRACT

The aim of this work is to identify and characterize the Late Quaternary morphological patterns of the west coast of the Ceará shelf, Northeast Brazil, based on Landsat 8, sedimentology, and seismic data. The shallow shelf has three regions: the Acaraú high (AH), unconsolidated floor (UF), and Itapagé bank (IB). The AH occurs in the inner shelf (0–5 m water depth) and shows various bedforms and in part a rocky bottom. The UF (>5 m) has many subaqueous dunes with bioclastics, structures for catching lobsters, and an escarpment. The IB is an extensive feature (delimited by the 20-m isobath) with large dunes and a shipwreck. Three seismic boundaries were identified as follows: transgressive surface (TS), subaerial exposure (SE), and miscellaneous surface (MS = TS + SE). Four seismic units were defined as follows: U1 — transparent facies with low amplitude, underlying the SE; U2 — chaotic to parallel facies with moderate to high amplitude, overlying the SE and underlying the TS; U3 — chaotic facies above the SE or TS and below the TS or sea floor, with the largest spatial extension; U4 — periodically occurring chaotic facies above the TS and below the seafloor. U1 is probably related to the falling stage systems tract or previous highstand systems tract. U2 and U3 belong to the transgressive systems tracts and U4 is associated with bedforms of the highstand systems tract. Ancient topography favored the development of transgressive deposits and modern bedforms. The AH, escarpment, and IB are morphostructures influenced by Acaraú sub-basin faults. The inner shelf is characterized by shallow geomorphology strongly influenced by structural inheritance (Precambrian and post-breakup of Pangea), bedrock control, and the Holocene transgressive systems tract (the largest thickness occurs with subaqueous dunes).

1. Introduction

Helland-Hansen et al. (2012) divided the continental shelf into three main groups: sedimentary shelves, combined structural–sedimentary shelves, and structural shelves. The stratigraphy and morphological patterns of shelves are controlled by the relationship between accommodation space and sediment supply (Posamentier and Allen, 1999; Van Wagoner et al., 1990). Autogenic and allogenic factors provide conditions for the development of a systems tract (Catuneanu et al., 2011; Posamentier et al., 1988).

Shelf sediments are represented mainly by carbonates, siliciclastics, mixed, and relicts (Carneiro and Morais, 2016; Emery, 1968; Gomes et al., 2015). Swift (1974) describes the sediments of the shelf as allochthonous (modern sediments supply) and autochthonous (reworking of recent sediments *in situ*) in accordance with the transgression process (type, rate, and sediment supply) during the Holocene.

Older and modern processes (tides, waves, currents, and sea level changes) are continuously reworking the sea floor and create bedforms (Falco et al., 2015; Kenyon, 1970; Lolacono et al., 2010). Beyond the hydrodynamic agent, biogenic features are common, such as coral reefs and the bioherms (Hillis, 1997; Hine et al., 1988; Tucker and Wright, 1990).

Bedform classification ranges according to scale: macrofeatures and microfeatures (Amos et al., 1988; Ashley, 1990; Testa and Bosence, 1999). Many macrofeatures were created during sea level rise, but then subsequently modified by modern processes in the shelf (Dyer and Huntley, 1999).

Many features on shelves are associated with structural control, such as, aligned ridges and valleys, displacement of topographic features, pronounced breaks, and linear scarps (Gomes et al., 2016; Moslow et al., 1989; Stewart and Hancock, 1994). However, the hydrodynamic processes smooth the topographic relief (Harrison et al., 2003) and these features may be recognized only at a regional

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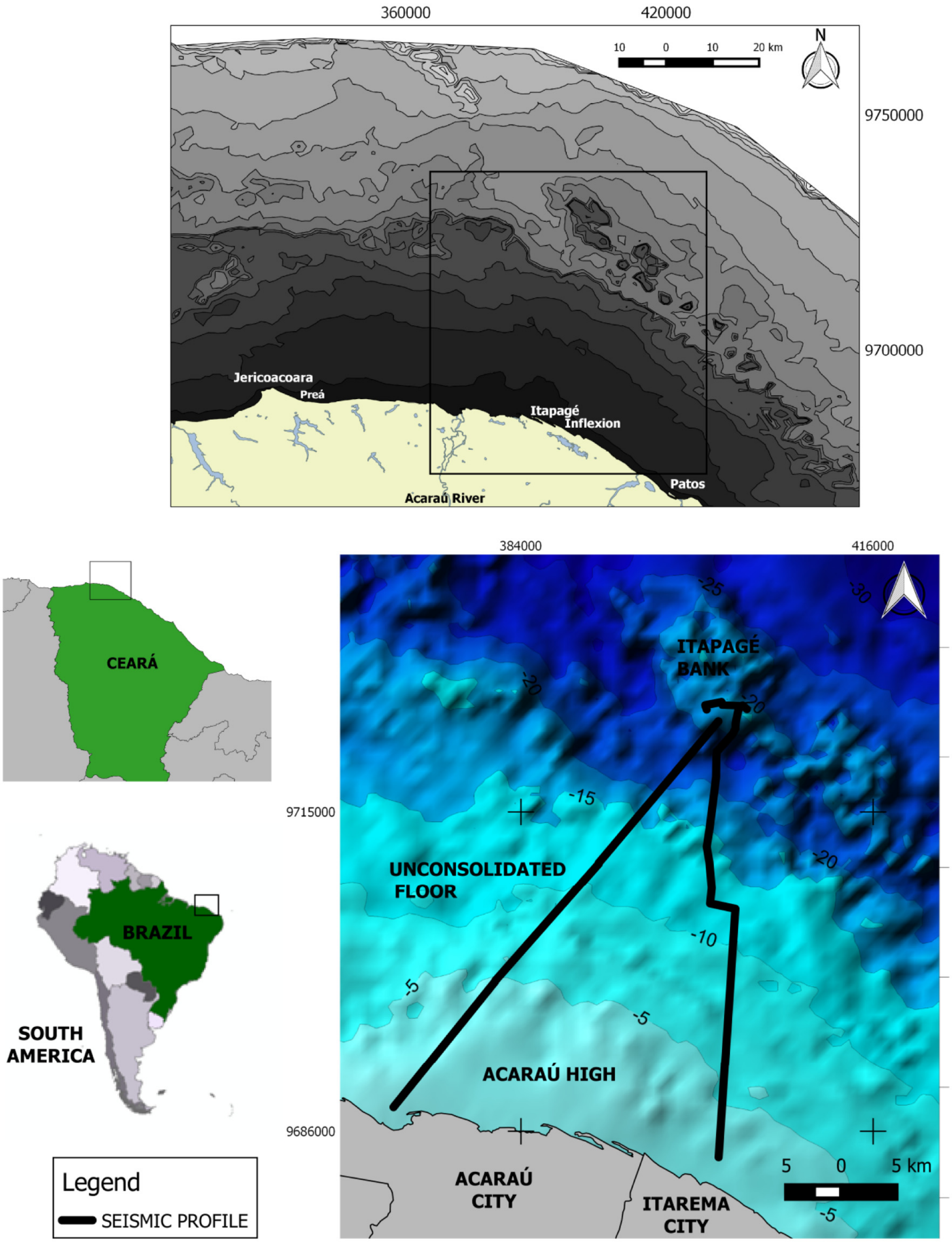


Fig. 1. Study area at the West Coast of Ceará shelf (Itarema and Acaraú) and seismic data survey.
Source: CPRM; DHN; PRONEX; IBGE.

scale (Helland-Hansen et al., 2012). Traces of neotectonic activity may be observed in seismic sections of Quaternary sediments including sedimentary thickening, divergence, and concavity of reflectors (Moslow et al., 1989).

The aims of this study are to identify the Holocene/Late Pleistocene key-surfaces and seismic units (deposits) and characterize the morphological patterns of the shelf offshore to the Itarema and Acaraú/West coast of Ceará (Northeast Brazil). The physiographic limits are the Jericoacoara and Patos headlands (Fig. 1).

In the Ceará basin, there is a lack of research regarding transgressive deposits and their key-surfaces (ravinement, transgressive, marine flooding, and sequence boundary). In other areas, several similar features have been identified as follows: the transgressive large dunes, Adriatic shelf (Correggiari et al., 1996); sand bodies, Gulf of Lion (Rabineau et al., 1998); transgressive sand ridges, South Korea (Park et al., 2003); mixed siliciclastic–carbonate bedforms, Northeast Brazil (Vital et al., 2008); sorted bedforms over transgressive bedform, Sardinia margin (Falco et al., 2015).

1.1. Physical settings

The equatorial Atlantic Ocean opening in Aptian times is responsible for the Brazilian Equatorial Continental margin formation and genesis of the Ceará basin (Peulvast and Bétard, 2015). The Ceará basin is delimited by the Romanche fracture zone (to the north), crystalline basement (to the south), the Tutoia high (to the west), and the Fortaleza high (to the east). It has four sub-basins: the Mundaú, Icaraí, Acaraú, and Piauí-Camocim (Morais Neto et al., 2003). It is divided into three tectono-sedimentary systems: rift (Mundaú Formation), post-rift (Paracuru Formation), and drift (Ubarana, Tibau, Guamaré Formations). Beyond the Barreiras Group and coastal–fluvial sediments deposited during the Neogene and Quaternary, respectively (Condé et al., 2007). The study area is in the Acaraú sub-basin, situated in a transpressive domain, where the main structural traces occur in E–W and NE–SW directions (Morais Neto et al., 2003). The Itapagé inflexion divides the coastal physiography in NW–SE to E–W (Morais, 1998).

The equatorial continental shelf of Northeast Brazil shows two main types of sediments: biogenic (autochthonous) and siliciclastic (allochthonous), whereas the studied shelf is of a mixed type (Coutinho and Morais, 1968; Freire and Dominguez, 2006; Vital et al., 2008; Gomes et al., 2015).

The equatorial Atlantic of Northeast Brazil includes the north Brazil current, a major marine current that circumvents the Ceará shelf and influences the outer shelf of the West Ceará (Freitas, 2015). The shelf circulations and waves are mainly associated with the trade winds and north Brazil current (Morais et al., 2006).

The Ceará State coast (NNE Brazil) is in the intertropical convergence zone where rainfall remains only for four months (from February to May) (Molion and Bernardo, 2002). The semi-arid rivers of north-northeast Brazil experience intermittent low sediment discharge only in the rainy season (Pinheiro and Morais, 2010).

2. Materials and methods

The data included Landsat 8 satellite images, side-scan sonar and sub-bottom profiling, bathymetric data and a compilation of sedimentary samples. Landsat 8 satellite images (30 m of resolution) were used for identification of submersed macro-features on the inner shelf. Bands 1 (0.43–0.45 μm) and 2 (0.45–0.51 μm) were selected for digital image processing in Envi 5.3 software, in addition to the composition Red–Green–Blue (RGB) — 4 (0.64–0.67 μm), 3 (0.53–0.59 μm), and 2 bands in Qgis 2.12 software.

High resolution shallow seismic and side-scan sonar data were performed using device 512C chirp sonar (*Edgetech*). Two functions were used during the acquisition: sub-bottom profiler (0.5–8 kHz) and side-scan sonar (125–410 kHz). In the Discover software, time varying gain (TVG) was applied to improve the view of the reflectors in sub-bottom and echo-character patterns. Two transverse profiles (100 km) were performed with the objective of identifying the Quaternary morpho-sedimentary patterns. The seismic stratigraphy methodology was applied to analyze the key-surfaces/reflectors and seismic units/facies (Catuneanu, 2006; Catuneanu et al., 2011; Mitchum Jr. et al., 1977; Vail et al., 1977; Van Wagoner et al., 1990). The classification of unconsolidated bedforms was based on Ashley (1990).

The bathymetric data was based on the Diretoria de Hidrografia e Navegação (DHN) of the Brazilian Navy from a nautical chart (21700) and board page (600). The grid framework was established between the Acaraú River and Patos headland. The delimitation was between the coastline and the 25-m isobath. Digital bathymetric models and perpendicular profiles were performed using the Surfer 11 software.

Sedimentological data to validate the seismic survey were compiled from CPRM, Dias et al. (2007), Moraes (2012), Geocosta, and the project "Potencialidades e Manejo para a Exploração de Granulados Marinhos na Plataforma Continental do Ceará" (PRONEX) (Fig. 2).

3. Results

Three regions were identified in the shallow shelf, the Acaraú high (AH), unconsolidated floor (UF), and Itapagé bank (IB), according to the bedforms and seismic stratigraphy (Table 1). The AH is represented by a shallow sector (0–5 m water depth). The UF occurs below the AH and it is characterized by bedforms (large and small features). The IB is well delimited by the 20-m isobath.

3.1. Bathymetry

The continental shelf of the West Ceará is situated in a position of physiographic coastal change (NW–SE to E–W at Itapagé). This feature shows geomorphic modification in the sea floor. The shelf shows a heterogeneous bottom, 75-km wide and a shelf break at approximately-70 m. The West Ceará shelf is divided into three areas according to the coastal physiography: the western area comprises the right margin of Acaraú River, the central area includes the Itapagé, and the eastern area the Patos headland. This framework reflects the geomorphic pattern related to the Itapagé inflexion.

The Patos headland has a landward shift of the 5-m isobath (higher slope) and it becomes shallower in front of the bay. Between Itapagé and the Acaraú River there is a seaward shift of the 5-m isobath (very shallow). The incongruence of coastal physiography with the distance of isobaths along the coast is the outcome of structural control (Figs. 3 and 4). There are great subaqueous dunes at approximately 15–20-m isobaths, however, in front of the Acaraú River, such dunes appear below 10 m. From Itapagé, a large transverse dune field occurs at approximately 5 m depth.

The 20-m isobath marks the transition of the inner to outer shelf (Freire, 1985) and acts as a pronounced escarpment (Fig. 5). This area presents macrofeatures termed the IB, where a large population of calcareous red alga occurs (Figs. 2 and 5).

3.2. Morphologic patterns

A rocky substrate between Itapagé and Acaraú River was observed. The outcrops show irregular discontinuous blocks, an alignment cap, and a tabuliform. The alignment cap in the Acaraú region is in a NW–SE direction and in Itapagé the patterns are irregular. It reaches up to 1m in height. The rocky substrate occurs as well as in the transverse dune field (Fig. 6); low tide terrace, inlet, and coastal barriers occur at the coast. This locality was termed the AH and is known as the "dark coast". Dunes migration possibly occurs on the rocky floor (at least offshore of the Acaraú River). The beaches of Preá (stump) and Jericoacoara (headland, cliff, shore platform) are formed on Precambrian rocky outcrops.

The aligned features appear as possibly influenced by morphostructural control and are parallel to the major faults of the Acaraú sub-basin. Subaqueous dunes, mainly transverse, occur and overlap the aligned features (Fig. 7). A pattern in V-shaped of aligned feature was identified.

The main micro-features types are ripples (common in all sectors), a flat bottom (discontinuous space), a shipwreck, and obstacles (structures for fishing). The acoustic response was predominant with high backscattering from the gravelly and sandy biogenic sediments. Sand patches inside the small ripple fields were observed (Fig. 8). Their spatial distribution is irregular and they occur associated with finer sediments.

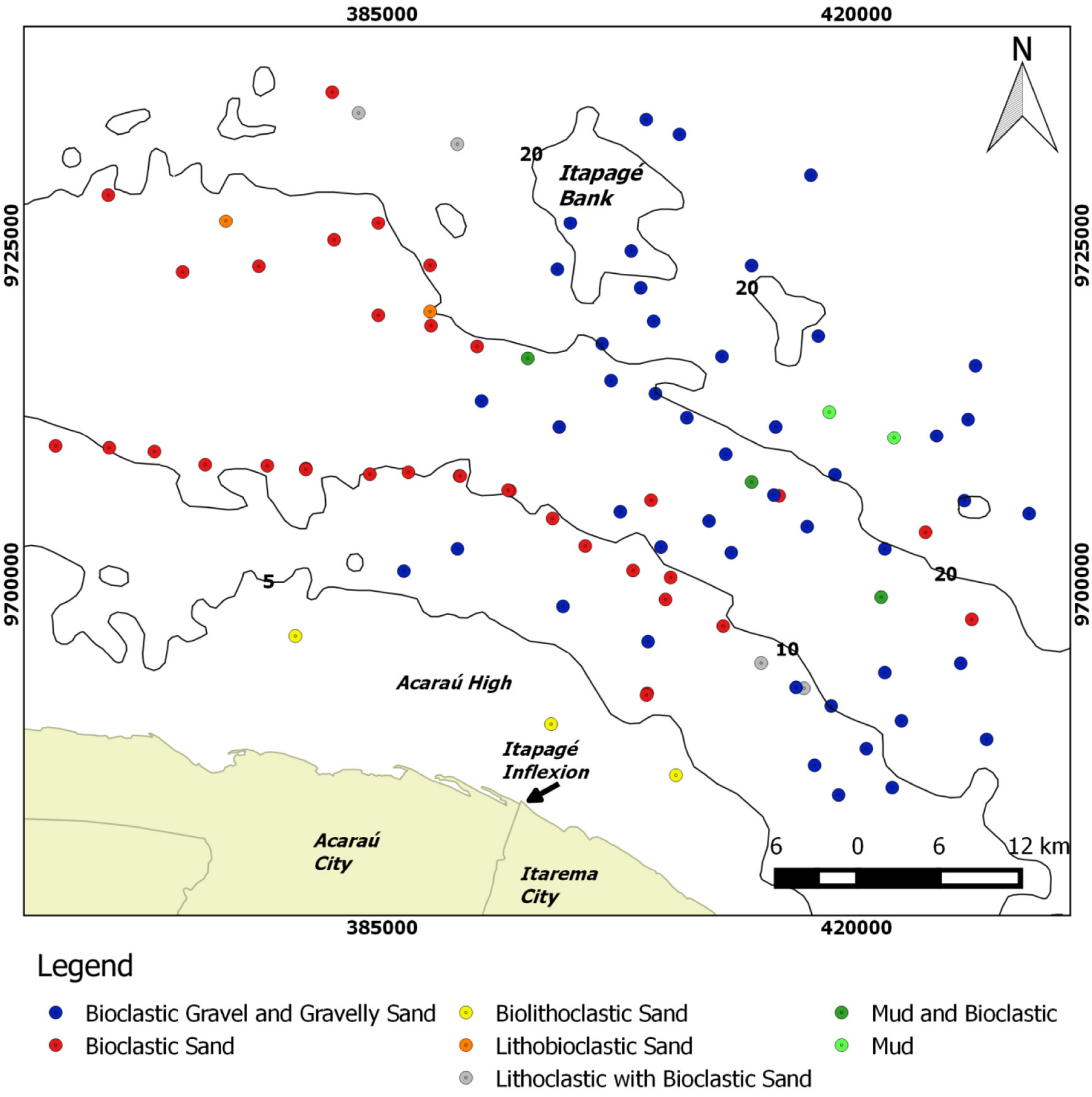


Fig. 2. Sedimentology of the shallow shelf. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: CPRM, Dias et al. (2007), Moraes (2012), Geocosta, and PRONEX.

Table 1
Regions and main characteristics.

Depths	Regions	Bedforms	Surfaces[a]	Seismic units
0–5m	Acaraú High	Rock, dunes, ripples	Sea floor	–
>5m	Unconsolidated floor	Ripples, dunes, traps, stepped surface	SE, TS	U1 and U3
~20m	Itapagé Bank	Ship, ripples, dunes, stepped surface	SE, TS, C	U1, U2, U3 and U4

[a] SE — Subaerial Exposure; TS — Transgressive Surface; C — Channel.

In the inner shelf, the presence of seagrass and small ripples (mixed sediments — siliciclastic and bioclastics) was verified (Fig. 5). In the middle shelf, a shipwreck (40 km from the coastline) and a sedimentary accumulation were identified resulting from the shipwreck as it acts as an obstacle to currents and downdrift deposition occurs (Fig. 8). The ship is ~130 m in length and 5 m in height. Large ripples (~2 m of spacing) and subaqueous dunes surround it. The ripple flow directions show complex vectors: SW, NW, W, and S. Large ripples in the carbonate sediments were very common, beyond the large dunes with a superimposition of large and small ripples. The origin of the ripples are waves (symmetrical) and mainly currents (asymmetrical). Trap structures for catching lobster are found in the inner shelf on small ripples.

The macrofeatures are large dunes with superposition of microfeatures (small dunes and ripples), (Fig. 8). They are 80–450 m in width (average of ~200 m) and 2–7 m in height (average of 4.5 m), (Fig. 8). The greatest heights and widths are associated with dune complexes (at least three dunes) which are more frequent offshore of the Itapagé region. Major dune fields were found at the 15-m isobath. They show two-stepped surfaces (terraces).

The term "bank" was applied only to the high bathymetric (IB) as far as 40 km from the coast. The IB is composed of coralline algae, and it has a size of approximately 85 km^2 (considering the 20-m isobath). This macrofeature has large superimposed dunes. An erosive escarpment occurs at approximately 20 m with a smooth slope.

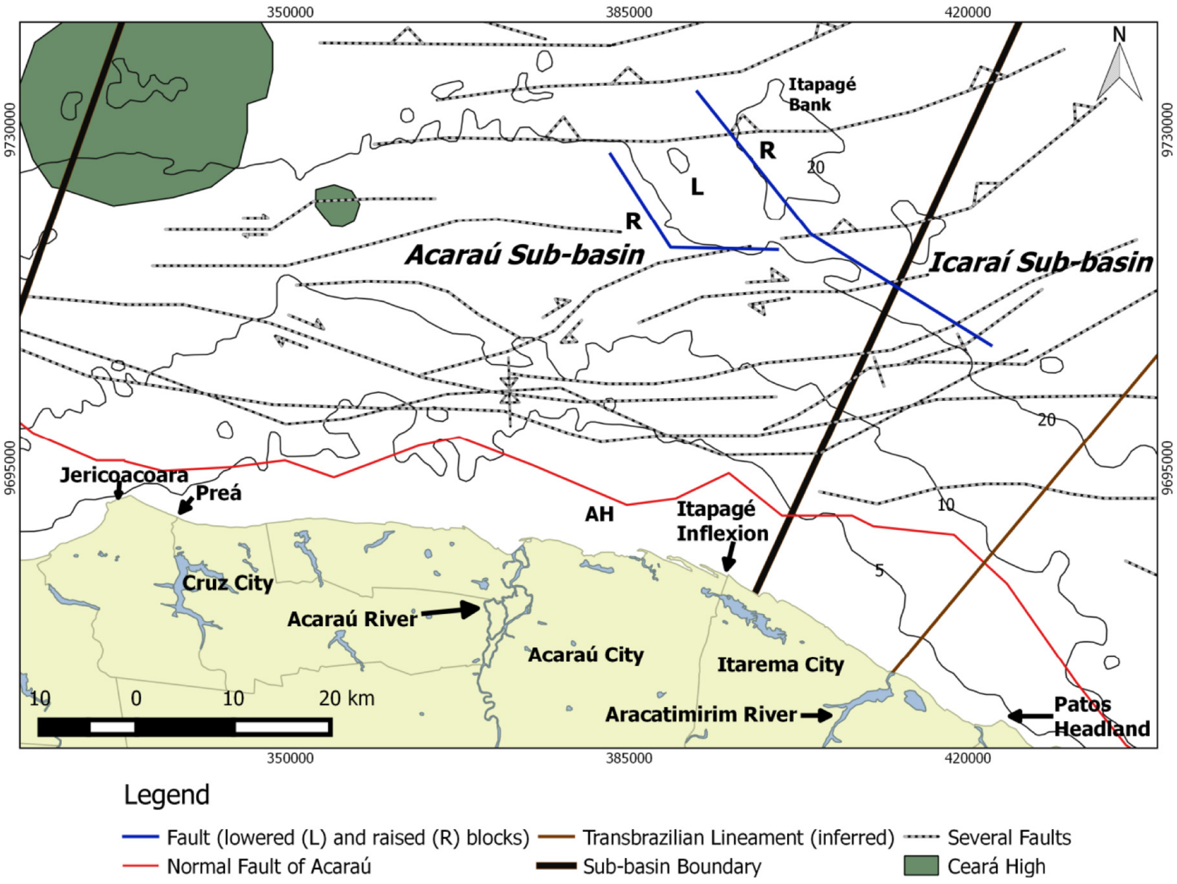


Fig. 3. Structural settings of the shallow shelf.
Source: Morais Neto et al. (2003); Silva Filho (2004); DHN.

3.3. *Seismic stratigraphy*

3.3.1. *Seismic boundaries*

Shallow penetration and high resolution provided for the visualization of key reflectors in the seismic stratigraphy interpretations. These are transgressive surface (TS) and subaerial exposure (SE). SE and TS occur in most of the area and they may be amalgamated in a single surface (miscellaneous surface, MS). This reflector was formed by a succession of processes: subaerial and transgressive erosion. In the filled incised valley, the surface SE is termed channel C because of the channel shape.

The deepest reflectors with high amplitude and lateral continuity (erosive unconformity pattern) were termed SE. The SE shows regional extension with high acoustic impedance contrast (a product of velocity and density) at a sector from 20 to 45 km offshore. SE reflectors occur between 1 and 6 m below the sea floor; however, when large dunes overlap the SE they occur at 10–12 m underlying the sea floor (dune crest). The SE appears on the sea floor, between the escarpments (∼20 m), the IB (∼20 m), and near 5 m. In the incised valley, the surface C occurs from 4–8 m below the modern sea floor.

The TS shows a moderate-to-high amplitude and lateral continuity related to the top of the filled incised valley and occurring above the SE. The TS occurs between 1 and 4 m beneath the sea floor (Fig. 9).

The MS reflectors result from the lateral continuity of TS to SE on top of the filled incised valley and near the sea floor; which favors the occurrence of mixed surfaces. MS is more frequent in the Acaraú shelf.

3.3.2. *Seismic units*

Four seismic units (U) were identified as follows: U1 is associated with more ancient sedimentary systems than marine isotope stage (MIS) 2; it is limited on top by SE, MS, or sea floor and presents transparent facies (low-amplitude) (Fig. 9). U2 is represented by the infill of the incised valley and limited on top by TS and SE at the base. U2 has chaotic and parallel-to-sub-parallel facies with high-amplitude reflectors. U3 is limited on top by sea floor or TS and SE or TS on the base, and it shows chaotic facies. U4 occurs only in one site in the middle shelf, and it is associated with the modern sedimentation pattern and is limited by TS (base) and sea floor (bedform). It is acoustically chaotic. Low-amplitude facies (transparent) near the bottom occur periodically. U3 has the greatest spatial distribution in Itapagé and the Acaraú shallow shelf.

4. Discussion

4.1. *Physiography and bedforms on the shallow shelf*

The geographic position of the AH has a strong morphostructural control between Itapagé and the Preá tombolo/Jericoacoara headland in the physiography of the inner shelf (Figs. 3 and 4). The rocky outcrops occur below 5 m water depth and near the Acaraú Fault (Fig. 6). This substrate may be related Precambrian rocks of the Preá beach. Morais (1998) found a similar pattern associated with the Barreiras Formation (Neogene–Quaternary). However, a biogenic origin or ancient coastal deposit (beachrock) cannot be ruled out.

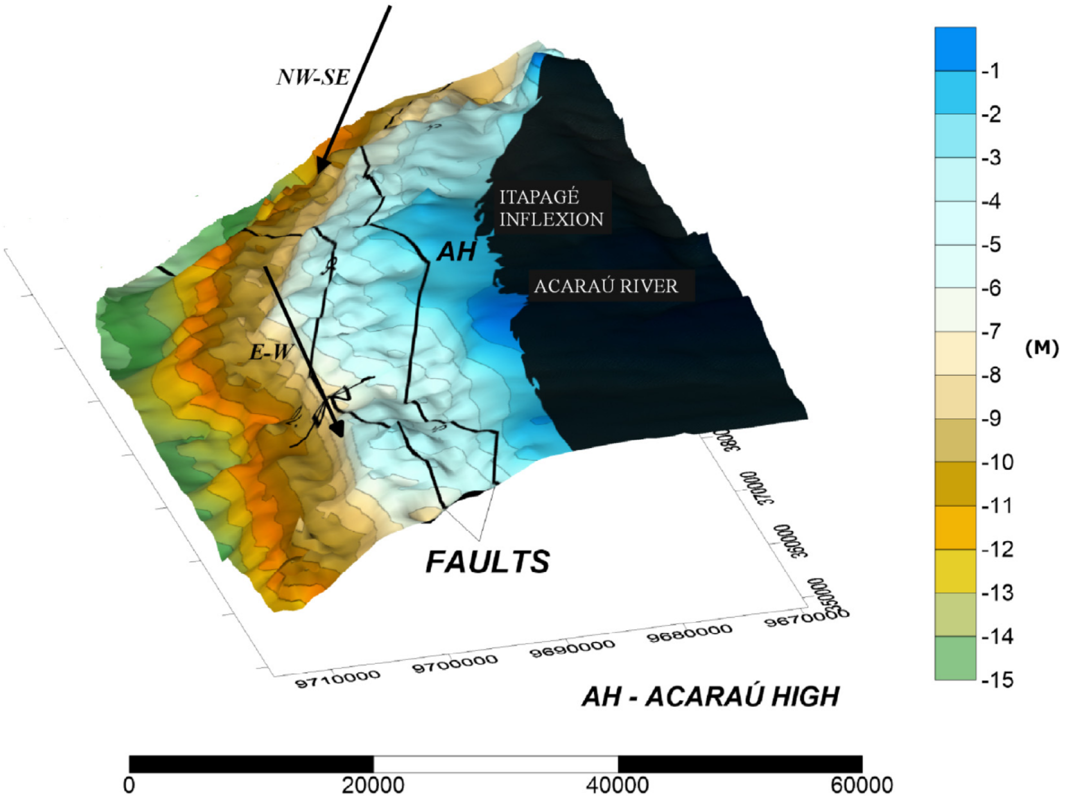


Fig. 4. Itapagé inflexion and morphostructural control on bathymetric patterns.

The extensional and strike-slip faults of the inner shelf are an inheritance of the Pangea supercontinent break-up during the Cretaceous (Gomes et al., 2014; Peulvast et al., 2008; Silva Filho et al., 2007). The Itapagé inflexion is divided into two sectors of the shelf: West — high bottom and East — low bottom (Curu incised valley) (Silva Filho, 2004). The bathymetry is influenced by differential elevation of tectonic blocks cut by normal faults buried on the shelf (Carvalho et al., 2005). An extensional fault occurs approximately at the 5-m isobath (Silva Filho, 2004). Furthermore, the main agent for modern morpho-sedimentary modifications is the local coastal dynamics. The East sector (between Patos and Aracatimirim River) has a steeper slope because of physiographic changes and the consequent repercussion on hydrodynamics. Between Itapagé and the Acaraú River it is smoother because of more intense surface and coastal processes (Fig. 4).

The coastal-inner shelf morphodynamics is directly influenced by morphostructural control between the Aracatimirim River and Preá tombolo (Fig. 3). In this sector, the inner shelf acts as a large platform (Fig. 5) because of an elevated sea floor associated with the bedrock outcrops on the coast and shelf. The barrier coastal systems and shallow macro-features on the inner shelf were formed by erosional and depositional processes (Fig. 6). Two main factors are responsible for these features: modern (longshore current, residual circulation, wind, waves, tides, and sediment gravity flow) and ancient (sea level change) processes (Dyer and Huntley, 1999; Freitas, 2015; Gao and Collins, 2014).

Bedform patterns at the AH are mainly related to longshore circulation (Figs. 6 and 7). In the coastal-inner shelf interaction, relict and modern sediments may be reworked in three main directions (waves and currents): parallel, oblique, and transverse to the coast. Wave-driven resuspension events are typical in many continental shelves and are important in transport, deposition, and sorting across-shelf (Harris and Wiberg, 2002).

Continental (interannual changes in rainfall) and shallow-marine (wave-driven resuspension events and shelf currents) processes interfere in coastward migration of bioclastic facies. Prolonged dry periods (4, 5 yr) occur at the hinterland (Pessoa, 2015). Thus, the low solid discharge of river sediments favors the advance of calcareous sedimentation (Carneiro and Morais, 2016; Ciarlini and Morais, 2014; Morais, 1998; Moura, 2014; Paula et al., 2009; Ximenes Neto et al., 2018). A mixed pattern (siliciclastics and bioclastics) is typical of the inner shelf, but above the wave base calcareous red alga predominates.

Sand patches (Fig. 8) in carbonate sediments are related to the suspension process of fine grains and subsequent deposition in low energy sectors (Moscon and Bastos, 2010). At the West Ceará region carbonate mud was observed, mainly associated with biochemical and physical processes. Thus, during storm events, fine sediments are suspended and dispersed along the shelf and deposited in sectors with favorable bathymetry (irregular morphology) and energy (low).

The morpho-sedimentary dynamics of the unconsolidated substrate are remarkable, as observed in ripple migration towards the shipwreck on the middle shelf (Fig. 8). The current velocity ranges from 0.8 to 0.4 cm/s (internal sector) and 1 to 1.6 cm/s (external sector) in the residual tidal currents, and the direction in this sector is approximately perpendicular (flood and ebb) to the coast (Freitas, 2015). The wind-driven current velocity mainly ranges from 0 to 0.2 m/s with predominant directions of WNW and NW; it is more significant during July to December (Freitas, 2015). This velocity is not sufficient to move large dunes (only ripples) because the mean velocity of the currents must be greater than 0.4 m/s, the grain size larger than 0.15 mm (however, the carbonate sediments show lower density than quartz), and the water depth greater than 1 m (Ashley, 1990). Complex directions of flow including SW, NW, W, and S were verified (Fig. 8). Symmetrical ripples formed by wave action, mainly in the inner shelf and over dunes in the middle

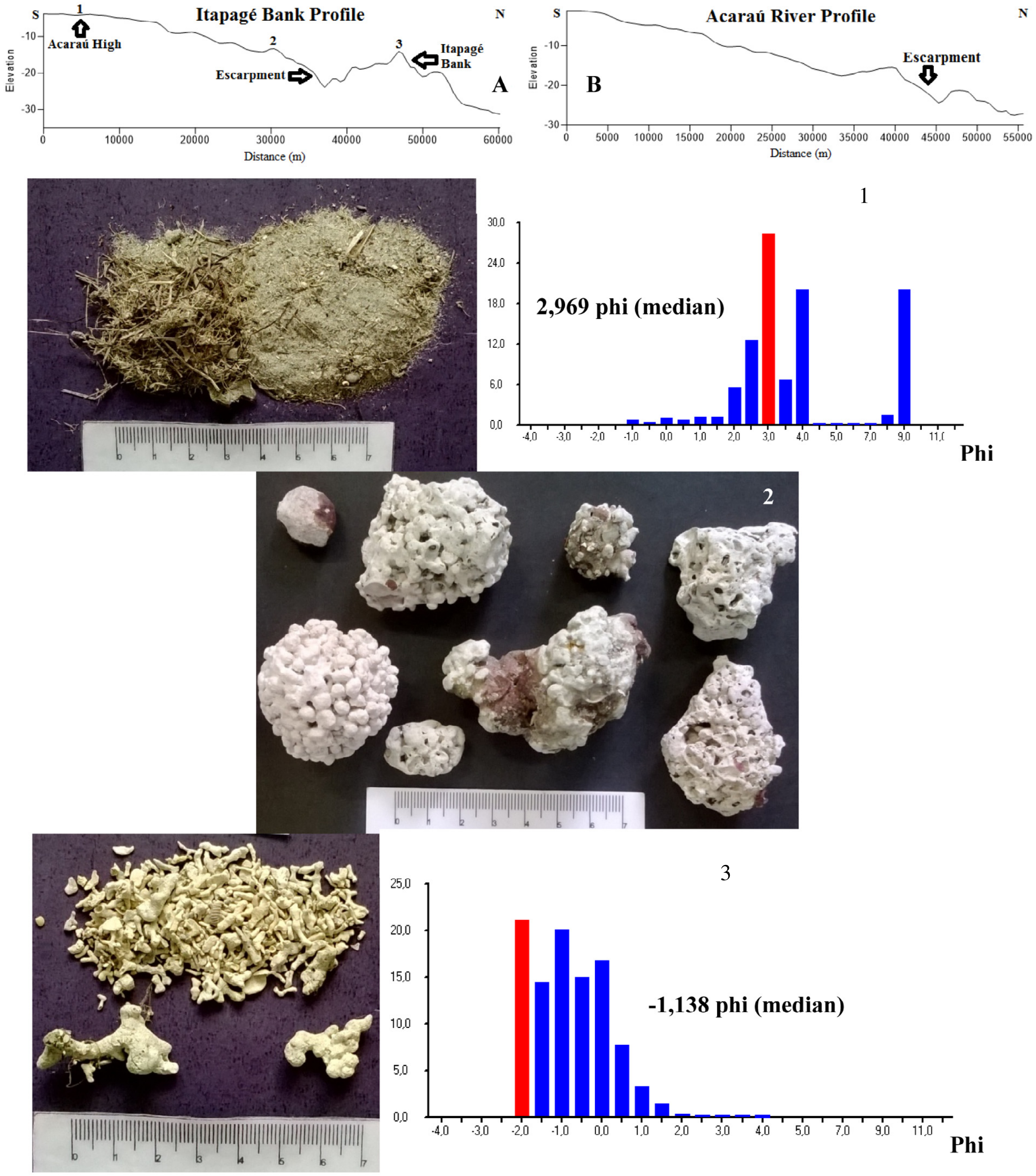


Fig. 5. Bathymetric profiles and main types of sediments: (A) Bank profile with presence of AH, escarpment, and IB; (B) Acaraú profile with sharp presence of escarpment surrounding 20-m isobath; (1) AH — muddy sand with seagrass algae; (2) rhodolite and (3) bioclastic gravel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sector (Fig. 8 and 9). Superimposed bedforms may occur suggesting that several currents with different directions interact in the area; indicating a hydrodynamically complex environment (Lobo et al., 2010).

The escarpments found near the 20-m isobath are related to transgressive deposits (Figs. 5 and 9). Thus, these features do not represent only the erosional pattern of the Ceará shelf, contrary to what was pointed out by Freire (1985) and Morais (1998). In the Brazilian shelf, the escarpments correspond to the pauses of the Holocene transgression (Coutinho, 1976; Freire, 1985; Corrêa, 1990; Morais, 1998; Silva Filho, 2004). The punctuated transgressions occurred by coastal retrogradation and regression alternation (Cattaneo and Steel, 2003). Local factors in a short time present a key role, such as, neotectonic activity, geoid changes, sediment supply, and accommodation space. Reis et al. (2011) analyzed the erosive levels of the Fluminense continental shelf (Southeastern Brazil) and provided an interpretation as erosional features formed during forced regression (periods of falling sea level or stable during the Wisconsin).

The subaqueous dunes identified can be classified into two patterns: modern and relict. The dunes located at the Acaraú High are modern, related to the shallow water depth and coastal physiographic change in the area and favored by the longshore flow. The dunes located between AH and IB are likely relict, as a

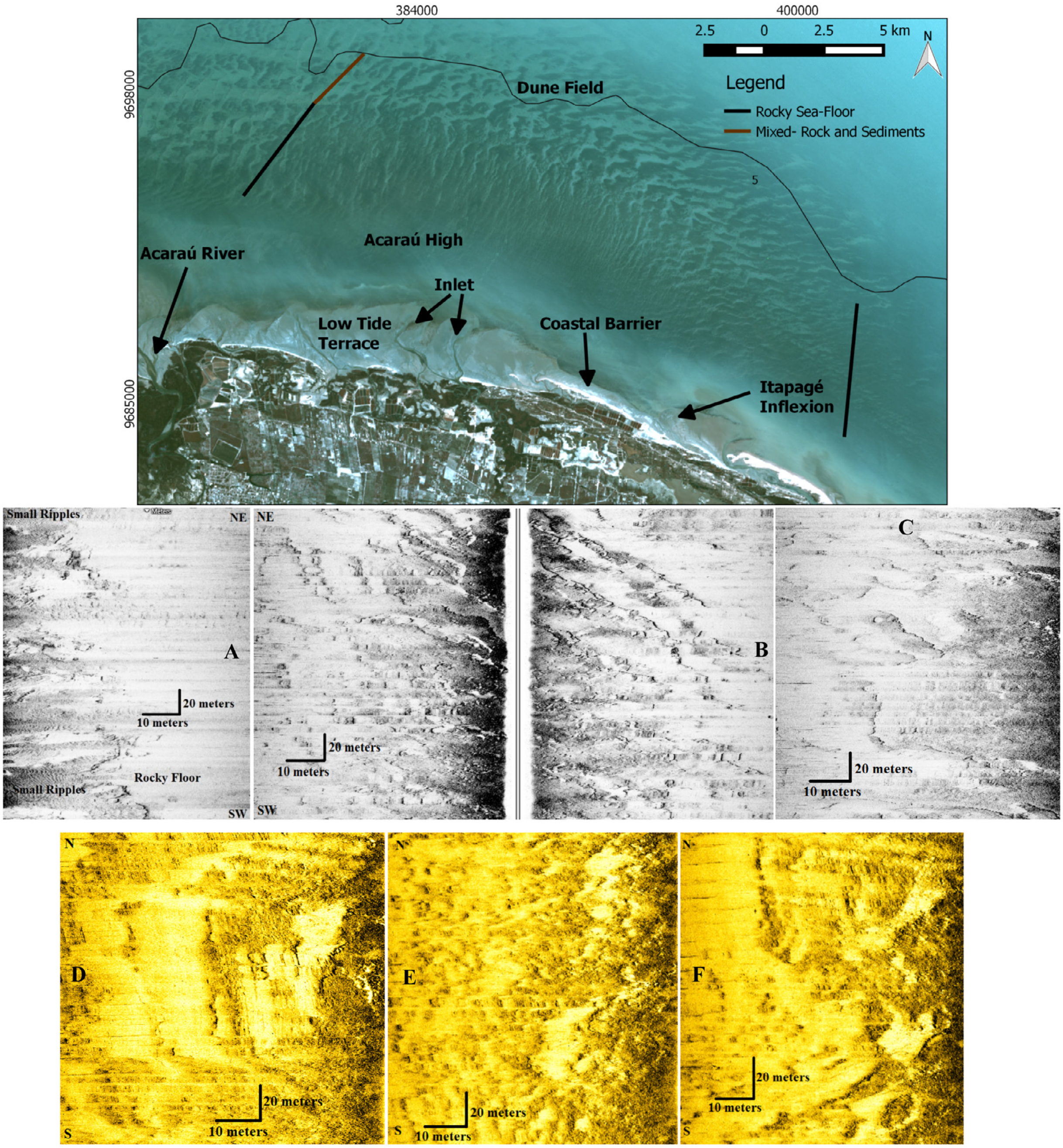


Fig. 6. Acaraú High shows several features patterns — at the coast: low tide terrace, inlets, coastal barriers (bar, spit, and island), and estuary (satellite image); at the shelf: transverse dunes and rocky floor (side-scan sonar). The main types of rocky features are: tabuliform (a, c, d and f); alignment cap (b); irregular and discontinuous (e). Acaraú: a, b, and c; Itapagé: d, e, and f.

result of increasing water depth and thickness (up to 10 m). In this region, according to the hydrodynamic data reported by Freitas (2015), it can be verified that the large and thick subaqueous dunes are not explainable by the "modern" dynamic alone. However, the bedform surface is fully controlled by modern hydrodynamics, with superposition of micro-features. Their modern biogenic sedimentation may be overlaying or mixed with terrigenous sediments (Figs. 2 and 5). Bedforms of large scale (2D and 3D subaqueous dunes) in the shelf are generated by currents, tides, and occasional storm events (Ashley, 1990). Wave action forms only ripples (Testa and Bosence, 1999).

The geomorphic evolution of the shallow features is associated with hydrodynamic processes and morphostructural control, mainly the IB and AH. The IB is in the morphostructural domain of the Acaraú exterior and represents a positive relief anomaly (faults and a centrifugal anomaly) (Silva Filho, 2004).

4.2. Late quaternary surfaces and deposits

The SE (Fig. 9) shows a seismic pattern similar to the sub-bottom horizontal reflector at the base of ridges in the Well Bank by Houbolt (1968) and Middelkerke Bank by Berné et al. (1994). This reflector may be a TS and/or an MS (Table 2). The depositional pattern below the SE may be related to the falling stage systems tract (FSST) or highstand systems tract (HST).

The sequence boundary (SE) was formed during the Wisconsin period. At the base of the transgressive deposits, a complex polygenetic surface may have formed (subaerial erosion and ravinement

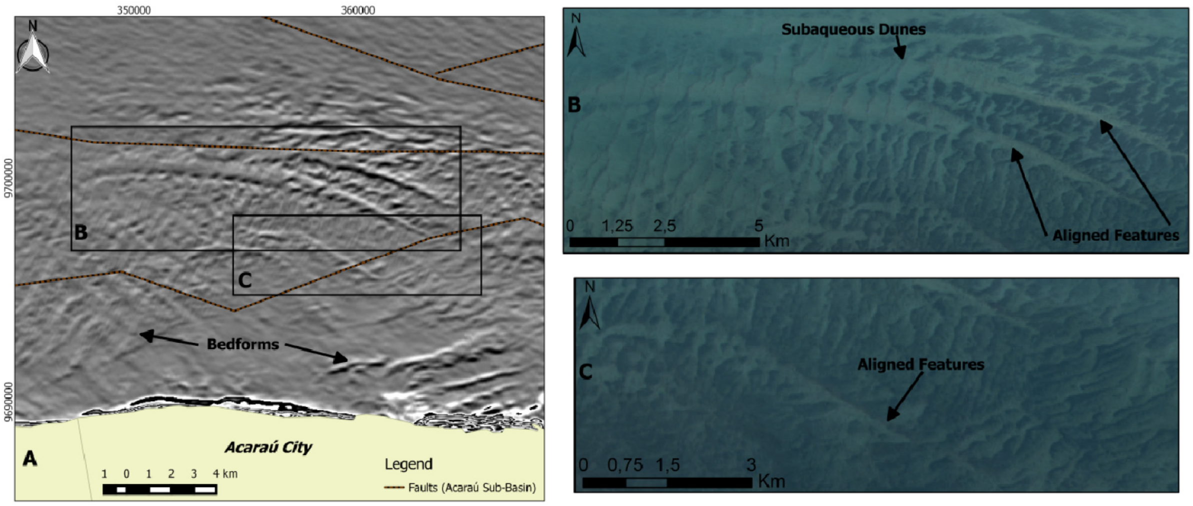


Fig. 7. Structural features identified in satellite images (Landsat 8), Band 1 (A) and RGB (B and C). A: aligned features, bedforms, and major faults of the Acaraú Sub-Basin; B: aligned features (parallel to fault) with subaqueous dunes overlapped; C: aligned features with V-shaped.

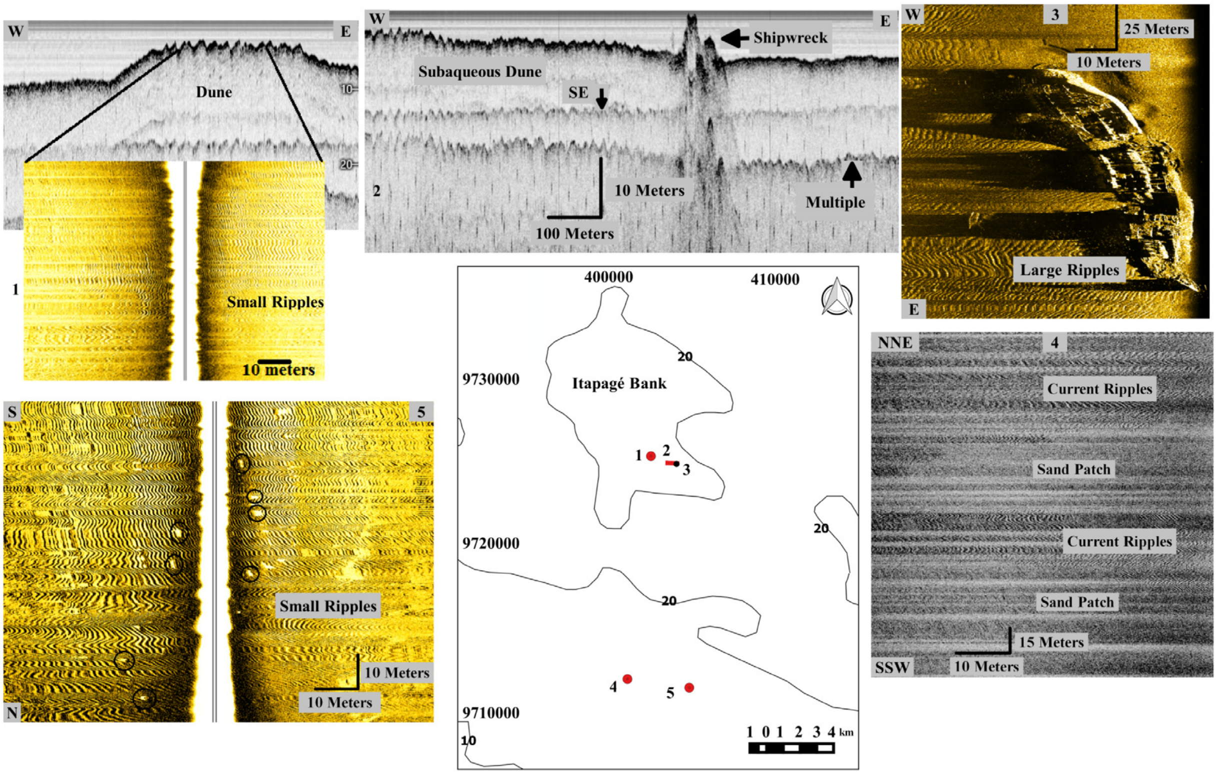


Fig. 8. Seismic and sonographic sections. 1: small ripples superimposed on dunes, 2: morpho-sedimentary control, 3: shipwreck, 4: sand patches, 5: traps structures (lobster)

surfaces). However, the same surfaces should also be considered as a sequence boundary (Cattaneo and Steel, 2003).

The reflector dividing these two units may be the same as that found by Freire (1985), where on the outer Ceará shelf it characterizes the base of 10 m thick biogenic gravels marking the transition from the Pleistocene to the Holocene. During low sea level, the West Ceará shelf was exposed to subaerial processes, and a hiatus in sedimentation is present in the forming the sequence boundary.

An MS was formed by erosive processes of subaerial and subaqueous dynamics created by low and transgressive sea levels, respectively. The ravinement surface is an erosional surface created and displaced by beach face erosion and sea level rise, causing reworking of old and new sediments, and migration of the coastline towards the mainland (Catuneanu, 2006; Swift, 1968). Residual deposits can cover the ravinement surface (lag) from the reworking of waves.

The relationship between gradient, sediment supply, paleotopography, and hydrodynamics plays a key role in the configuration and internal geometry of transgressive deposits (Gao and Collins, 2014) and the spatial relationships between the sequence boundary and wave ravinement surface determines the degree of preservation of the transgressive deposits (Belknap and Kraft, 1985; Cattaneo and Steel, 2003).

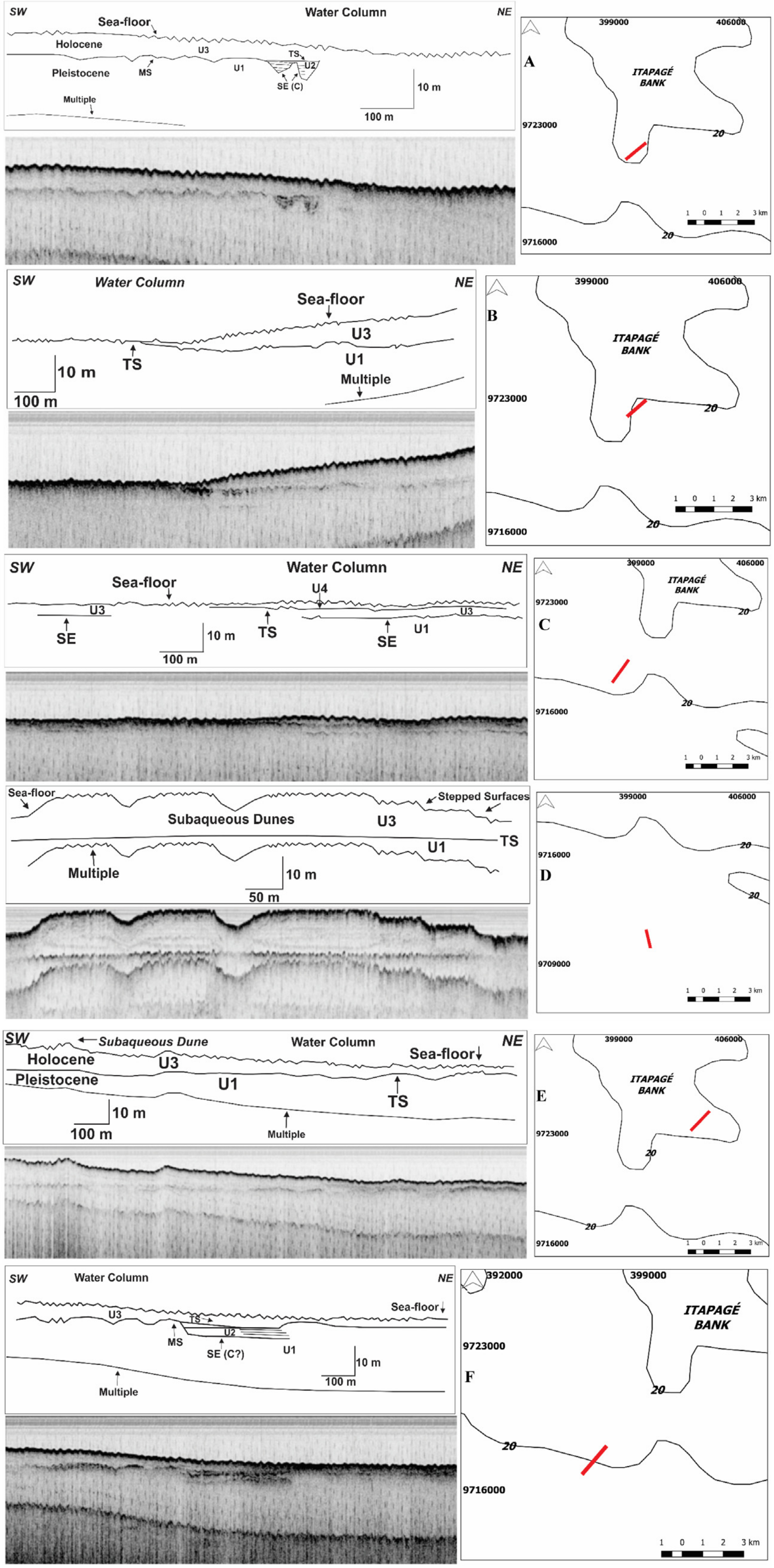
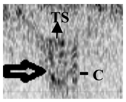
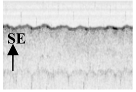
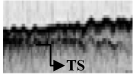
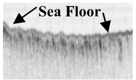


Fig. 9. Key surfaces, Seismic Units, and Holocene features. Paleovalley (A and F), subaqueous dunes and transgressive deposits (B, D, E, F), and modern sedimentation (C).

Table 2
Main characteristics of the seismic stratigraphy and sea level position correlation.

Seismic section	Seismic unit	Seismic facies	Boundary surface	Systems tract	Sea level position
	U1	Transparent	TS, SE and/or MS (above)	FSST or HST	Falling
	U2	Chaotic and parallel to sub-parallel	SE - C (below) and TS (above)	TST	Rising
	U3	Chaotic	TS, SE and/or MS (below) and TS or sea floor (above)	TST	Rising
	U4	Chaotic	TS (below) and sea floor (above)	HST	High
	U4	Transparent	Modern Sedimentation	HST	High

The AH has very thin transgressive deposits (lag). This is because of the decrease in the accommodation space, hydrodynamic action, and rocky sea floor. The ravinement surfaces (Fig. 9) in the sub-bottom occur mainly from AH basinward. Deposited sediments below the ravinement surface may belong to the coastal transgression and not necessarily to the previous FSST or HST (Cattaneo and Steel, 2003; Catuneanu, 2006).

The transgressive deposits are associated with the filled incised valley, the subaqueous dunes, and the lithosome. The filling of the valley may be related to channel deposits and muddy vertical accretion. The incised-valley system can be divided into three segments: seaward portion (marine, barrier, delta), middle portion (central basin), and inner portion (fluvial) (Boyd et al., 2006). In the Ceará Basin, Aquino da Silva et al. (2016) found a fluvial meandering system that formed incised valleys offshore of the Parnaiba delta; similar features have been observed in the Mekong River shelf, suggesting that deltas and estuaries around the world were subjected to similar processes during the LGM–Holocene.

Subaqueous dunes are transgressive deposits that accumulate with the relative sea level rise over short time scales (4th- to 6th-order cycles) (Cattaneo and Steel, 2003; Curray, 1964; Van Wagoner et al., 1990). A transgressive lithosome develops above the ravinement surface by waves in low-gradient scenarios. They are usually very thin, but thicken where the transgression was punctuated by a transgressive pulse or where it forms offshore sand ridges (Cattaneo and Steel, 2003).

Subaqueous dunes are associated with sea level fluctuations (Fig. 9). These macrofeatures may have originated from paleobathymetric irregularities and were formed during a period of high sediment availability (subaqueous banks and/or ancient coastal dune deposits) and/or in a high energy environment during a rising sea level phase (MIS 1). The material source was probably derived from erosion of the falling stage systems tract (120–20 kyr). Present-day sea level was reached 7 kyr BP (Suguio et al., 2013).

4.3. Shallow shelf systems: structural inheritance, sea level changes, and morphology

Three main factors determined the modern morphology of the shallow shelf: structural inheritance (Fig. 3), sea level changes (Fig. 9), and modern processes (Fig. 8).

Structural inheritance is represented along the coast and in the Acaraú sub-basin by rocky outcrops, structural highs, aligned features, and fault networks (Figs. 3 and 7). In the coastal zone, two rocky outcrops occur: Preá and Jericoacoara. Both consist of crystalline basement (Precambrian) belonging to the middle Coreaú domain (Brito Neves et al., 2000). The Trans-Brazilian lineament (eastern boundary) occurs in the Aracatimirim River (Silva Filho et al., 2007). This lineament is a discontinuity of continental extension that acted in the formation of the Gondwana supercontinent (Neoproterozoic/Early Paleozoic) (Almeida et al., 2000).

The AH (Fig. 4) genesis is associated with the fault reactivation during the Cretaceous and Cenozoic in the Acaraú sub-basin. The main structural traces are E–W and NE–SW oriented and are influenced by the directional movement associated with the transcurrent tectonics (Morais Neto et al., 2003). At approximately 5 m water depth one normal (Acaraú fault) and one transfer fault (Silva Filho, 2004) occur, where the site of a high block coincides with the AH.

The higher elevation of the AH originating from morphostructural inheritance is responsible for physiographic change, rocky outcrops (coast and shelf), and creation of favorable places for high morphodynamic bedforms (coastal barriers and subaqueous dune fields) (Figs. 4 and 6).

The Acaraú shallow shelf has superficial features that are controlled by a NE–SW Precambrian trend and present a weak negative gravity anomaly (Silva Filho, 2004). The neotectonic influence is inferred as a wrench-type with maximal horizontal stress sub parallel to the margin trend (inner shelf) and extensional with maximal horizontal stress perpendicular to the margin trend (outer shelf) (Silva Filho et al., 2007). Precambrian inheritance occurs in the inner shelf; however, in the outer shelf a Cretaceous inheritance is found (Silva Filho, 2004). Gomes et al. (2014) identified Quaternary fault reactivation in the siliciclastic–carbonate shelf systems (Potiguar Basin, Northeast Brazil). Almeida-Filho et al. (2009) found reactivation of basement faults in the Barreirinhas Basin (Northeast Brazil), which propagated through the entire sedimentary pile, from the Paleozoic to the Tertiary strata.

The rocky feature alignments of NW–SE (inner shelf) are perhaps not associated with the structural inheritance (NE–SW). These features on the rocky bottom may be a product of physical (hydrodynamic) and chemical processes changing the sea floor (Fig. 6).

The change in inclination at approximately the 20-m isobath is associated with both morphodynamic processes (erosive processes of sea level stabilization, still-stand) and inherited structural control (Fig. 5). These escarpments as well as those that surround the IB may be associated with the ravinement processes due to the irregular paleotopography favoring transgressive filling (Fig. 9).

The structural influence is mainly associated with the paleotopographic setting, as evidenced by faults and possible lowered and raised blocks. In this manner, there is no evidence of neotectonic processes after the Last Glacial Maximum (LGM) 20,000 years ago. Gomes et al. (2014) identified faults (Pescada Fault, Potiguar Basin) at similar depths. In the shallow shelf of West Ceará such faults occurred between the slope break (steps) and the IB.

The SE shows a regional extent and formed during the LGM, when sea level decreased by ∼120 m compared to that of today and created an erosive unconformity (sequence boundary). This key surface (sequence boundary) separates the Pleistocene and Holocene sedimentary systems. The Holocene filling above the SE/TS is interpreted as TST — incised valley fills, lithosome, and dunes (Fig. 9). AH region presents thin and/or absence of transgressive deposits which favored the rapid ravinement process and sea level rise. In this area, later the highstand in middle Holocene favored the subaqueous dunes development at AH due to the shallow water depth, longshore current, and Trade winds.

5. Conclusion

The continental shelf of the West Coast of Ceará shows a shallow shelf with heterogeneous morphology given the presence of unconsolidated bottom (macro- and microfeatures), escarpments, aligned features, the IB, and a rocky sea floor. It is a sedimentary shelf with structural inheritance control. The AH, because of physiographic and dynamic process change (NW–SE to E–W), favored the development of many subaerial (coastal barrier) and subaqueous (dunes) bedforms. Lower slopes and depths allow for high interaction between the inner shelf and land-based coastal systems. The escarpments played a key role in paleotopography, favoring the deposition of the TST. Therefore, the marine escarpments (terraces) acted as a product of erosion (FSST or HST) and redeposition (Holocene transgressive deposits). The paleotopography shows pronounced structural inheritance, as various faults occur and coincide with some features (escarpments, the IB, aligned features, and the AH). The scale factor is fundamental to an understanding of the modern (superposition of bedforms) and ancient (large dunes, the IB) features. It was found that previous features (FSST or HST, SE, and C) favored the development of transgressive deposits and modern bedforms (HST).

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