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Modern and relict sedimentary systems of the semi-arid continental shelf in NE Brazil

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ABSTRACT

This paper describes the carbonate–siliciclastic system of the equatorial continental shelf of NE Brazil (East Ceará) based on X-ray fluorescence (XRF), grain size, $CaCO_3$, shallow seismic and remotely operated vehicle (ROV) analyses. Data were obtained for two sectors: 1) *Halimeda* Bank (HB), inner shelf (−12 m), and 2) transverse profile (TP), inner to outer shelf-upper slope (−5 to −100 m). In total, 72 samples were collected, and 29 km of seismic lines (HB) and ROV profiles (HB and TP) were surveyed. The main chemical elements were Ca and Si (93%). These elements occur in two types of shallow marine sediments: carbonate (mainly autochthonous) and siliciclastics (terrigenous/allochthonous/relict). With respect to the chemical elements, a strong negative correlation was observed between calcareous (Ca and Sr) and siliciclastic (Si, Al, and K) components. Strontium does not always show a strong positive correlation with Ca. The average $CaCO_3$ contents of 81% and 91% were determined for the HB and TP, respectively. The profiles show a predominance of carbonate sediments; however, the HB demonstrates a greater continental influence (inner shelf). The grain size presents a prevalence of sand (82%) in relation to gravel (18%). This particle size variation is mainly due to the breakdown of *Halimeda* nodules, siliciclastic sediments in the finer fraction (>2.5Φ), and the presence of gravel with iron coating (relict). Two types of echo-characters have been identified. Both are associated with the large presence of carbonate sediments. Echo I shows the bottom surface with continuity in the sub-bottom without a subsurface reflector. Echo II presents a discontinuous subsurface reflector. The ROV allowed the observation of algae patches in higher floors and gravelly and sandy bioclastics in the lowest sectors. Large patches of calcareous green algae, *Halimeda*, occur in the inner shelf below the 15 m isobath, mainly due to the semi-arid climate (weak sediment supply from the mainland), geographical position (equatorial) and oceanographic conditions (hydrodynamic and biogeochemistry). It has been concluded that the seafloor of the semi-arid continental shelf of East Ceará (NE Brazil) shows modern predominance of carbonate deposition based on the lack of contaminants, geochemical purity of carbonate sediments, and high percentage of $CaCO_3$. The conditions for exploitation in the intermediate sector are provided. However, it would be ideal to perform punctual extraction and analyze the resilience and regeneration of *Halimeda incrassata* and the consequences for fisheries (important economic resource of the region).

1. Introduction

Continental shelves are mainly covered with carbonate and siliciclastic and mixed sediments (Johnson and Baldwin, 1996). Mixed systems are common in tropical areas (Ryan-Mishkin et al., 2009). The typical lithology of mixed sedimentary environments is characterized by sandstone and limestone sequences (Zecchin and Caffau, 2011; Moura, 2014). Large accumulations of *Halimeda* debris (bioclastic) have been found in shallow water worldwide (Rees et al., 2007). *Halimeda* bioherms in the southwestern Caribbean are 20–30 m high at depths of 40–50 m (Hine et al., 1998). Heyward et al. (1997) pointed out that *Halimeda* banks (HBs) with sizes ranging from 0.05 to 40 km^2 can be found in northwestern Australia (Timor Sea).

The mixed shelf in Northeast Brazil (NEB) is characterized by changes of the composition and grain size (muddy siliciclastics to coarse carbonate) from the inner to outer shelf (hydrodynamic and bottom physiographic interaction) (Gomes et al., 2015).

The middle and external sectors of the continental shelf in NEB

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predominantly contain bioclastic sediments, reflecting the breakdown of the calcareous algae *Halimeda* and *Lithothamnium* (Coutinho and Morais, 1968; Cavalcanti, 2011).

Marine granulates form shelf surface deposits that are of economic importance and easy to explore. They are represented by sand and gravel siliciclastics and carbonate, in addition to heavy minerals (Freire and Cavalcanti, 1998). Bioclastic granulates occur as free forms of calcareous algae (nodules, rhodoliths, and fragments) that are easily collected by dredging of unconsolidated sediments (Dias, 2000). The surface of the continental shelf in NEB is rich in carbonates and has high economic potential (Kempf, 1980; Coutinho, 1995; Dias, 2000; CPRM, 2007; Ciarlini, 2014).

The study area is located in the equatorial continental shelf of the NEB in the far east of Ceará State (Fig. 1), which is characterized by semi-arid climate with four/five rainy and seven/eight dry months. Intermittent solid discharge predominates in this region. The major river (Jaguaribe) discharges 43.767 t/yr (Cavalcante et al., 2006), which is very different from humid environments such as the Amazon River with a solid discharge of 1.161×10^6 t/yr (Carvalho and Cunha, 1998). The Intertropical Convergence Zone is a region that is characterized by southeastern and northeastern trade wind confluence; it is the major agent responsible for rain in NEB (Molion and Bernardo, 2002).

The inner continental shelf of East Ceará is predominantly composed of quartz (Freire, 1985; CPRM, 2007). Based on the isobath of 15 m, an advance of carbonate sedimentation is evident, which is mainly associated with green calcareous algae (*Halimeda)* and, secondarily, with calcareous red algae (*Lithothamnium*) (Freire and Cavalcanti, 1998). Mollusks and foraminifera also occur (Freire, 1985; Cavalcanti, 2011; Ciarlini and Morais, 2014). This shelf comprises calcareous algae patches and bioclastics (predominately between 12 and 25 m), which are associated with sandy ridges, sandy bars, barchanoid dunes, gravel banks, and sandy plains (Monteiro, 2011).

The continental shelf of Ceará is an important area for fisheries, mainly with respect to benthic organisms whose natural habitats should be monitored and/or protected and present marine granulates with economic potential (Fonteles-Filho, 2007; Colares, 2009; Monteiro, 2011; Ciarlini, 2014; Ciarlini and Morais, 2014). The aim of this work is to define the seafloor morphology and chemical composition and grain size of the sediments to identify the relationships among relict and modern sediments and analyze the exploitation potential of bioclastic facies.

2. Oceanographic settings

The oceanographic parameters of the equatorial continental shelf are linked to perpendicular and parallel circulation patterns. The former and latter are related to tides (semidiurnal and mesotidal regime) and the North Brazil Current (NBC) and winds, respectively (Morais et al., 2006; Freitas, 2015). The equatorial continental shelf of the NEB is influenced by the full strength of the westerly flowing south equatorial current, combined with high winds, moderate–high tidal range and/or waves (Vital, 2014).

The NBC carries from the Atlantic equatorial gyre into the subtropical gyre significant quantities of heat and mass (Condie, 1991). The NBC flows relatively parallel to the coast and seasonally interacts with the circulations of the outer shelf of Ceará (Vital, 2014; Freitas, 2015). The NBC shows velocities of 30–40 cm/s, overlain by tidal and wave components (Knoppers et al., 1999).

The waves occurs as sea waves ($1 \leq T \leq 9s$) and swell ($T > 10s$); sea waves dominate (80%) (Pinheiro et al., 2016). The residual tidal circulation in the Ceará shelf shows higher maximum velocities in the spring tide with 2.0 cm/s and weaker in the neap tide with 1.2 cm/s (both in the process of flood). The directions are well defined in the flood and ebb tides (Freitas, 2015).

The trade winds generate shelf circulations with a strong seasonality (higher velocities in second semester). The water masses are well mixed without any characteristic stratification. The wave pattern is conditioned by variations in the trade winds (Vital, 2014; Freitas, 2015).

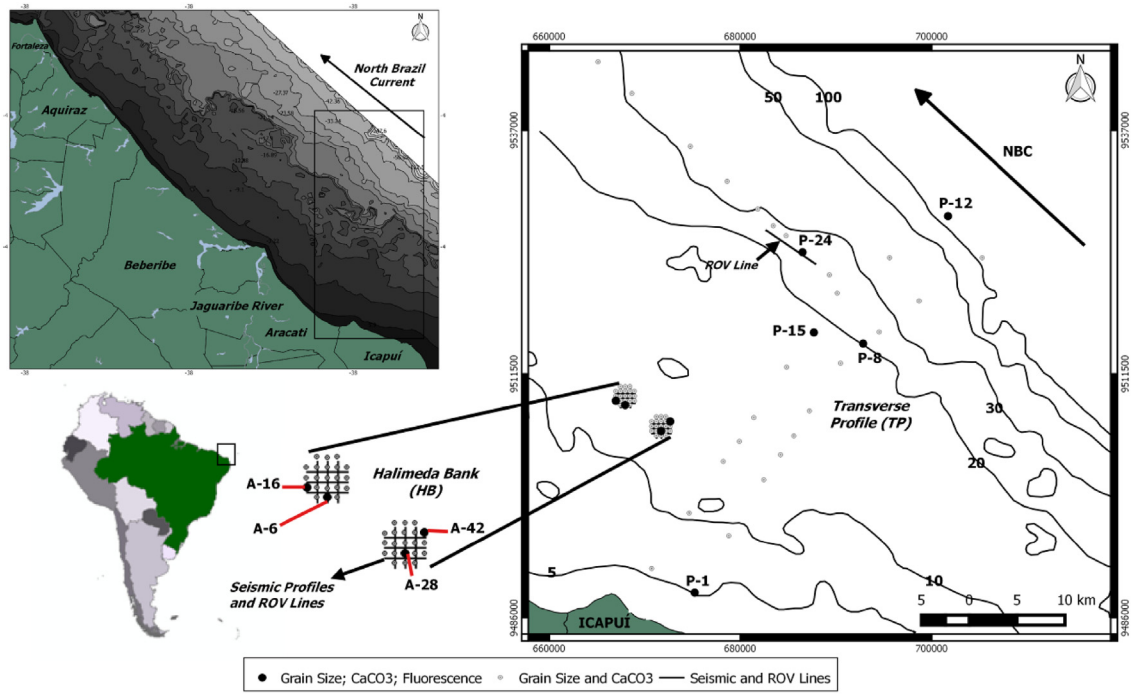

Fig. 1. Localization of the sedimentary samples (inner, middle and outer shelf), shallow seismic (inner shelf) and ROV lines (inner and middle shelf).