# Journal of the Geological Survey of Brazil

# General aspects of continental margin sediments of the Ceará State, northeast Brazil, from mineralogy and principal component analysis

Wanessa S. Marques[1], Ronaldo G. Bezerra[1], Daniel P. Souza[2], George Satander de Sá Freire[2], Inacio O. de Lima Neto[2]

[1]Geological Survey of Brazil. Av. Antônio Sales, 1418, Bairro Joaquim Távora, Fortaleza, Ceará, Brazil, CEP: 60135-101
[2]Federal University of Ceará. Fortaleza, Ceará, Brazil

## Abstract

Granulometry, mineralogy, portable X-ray fluorescence (XRFp), portable X-ray diffractometry (XRDp), and principal component analysis (PCA) have been made in samples of two deep cores of the continental margin of the Ceará State, northeast Brazil, aiming to detail the general aspects of deep sedimentation, including mechanical dispersion of continental minerals, environmental chemistry, and clay identification. The samples comprised biogenic oozes, clays, coarse silt, and fine sand to a lesser extent. The granulometric composition suggests slow and calm sediment accumulation over time. XRDp analysis pointed out that pelagic clays consist of chlorite, kaolinite, nontronite, and vermiculite. High oxidation levels are suggested for the two core samples, represented by the light brown color 5YR 6/4 of the sediments. Traces of minerals existing at the continental shelf were found, although in the core SIS-454 at 160 to 164 cm depth, there is a total absence of both heavy and light continental minerals. In core SIS-515, the total absence of heavy and light minerals was found at the depth of 87 to 92 cm. The levels with absence of continental minerals are probably associated with the absence of mechanical dispersion due to transgression and regression events in the Ceará continental shelf. The high oxidation levels can probably be linked to shallow waters caused by sea level changes, or to large period of sedimentation in the slope. From the statistical analysis, it is suggested that element contents are related to each other according to the provenance setting, whereas the pelagic sediment has provenance from marine water, resurgence currents, wind transport, cosmic dust, and from slow transportation, originated from the continent. It was deduced that sedimentation in the area was affected by at least two events with absence of mechanical dispersion of continental sediments, associated with geochemical characteristics represented by antagonism between elements of terrigenous and biogenic origin. These events are possibly associated with small-scale regressions occurred during the Flandrian Transgression in the Ceará Basin.

## 1. Introduction

Marine sediments of the Brazilian coast were studied only from the 1970s onwards by DHN, CPRM, PETROBRAS and DNPM during the GEOMAR-I project. Surface sediments and north continental shelf physiography were studied (Chaves et al. 1979). Furthermore, detailed studies on the Ceará Basin concentrated in the Mundaú sub-basin (Morais Neto et al. 2003, Condé et.al. 2007), and addressed sedimentary and structural geology.

In order to contribute with the understanding of some aspects of the continental margin of northeastern Brazil, we performed analysis of heavy minerals, granulometry, mineralogy, portable X-ray fluorescence (XRFp), portable X-ray diffractometry (XRDp), along with principal component analysis (PCA) in samples of two deep cores of the continental margin of the Ceará State, northeast of Brazil, drilled at the continental slope (Figures 1 and 2). The deep cores are named SIS-515 and SIS-454, with the top located at 1473 and 2370 meters deep, and

are 1.64 and 1.62 meters long, respectively. Both cores were drilled at the water/sediment interface, and are located in the west part of the continental margin of the Ceará state, between the Piauí-Camocim and Icaraí sub-basins of the Ceará Basin. Sampling was performed by the Brazilian Agência Nacional do Petróleo (ANP - Petroleum Nacional Agency) in June and July 2011, and were donated by the Federal University of Ceará to the Geological Survey of Brazil.

Our study was carried out aiming to detail general aspects of the deep sediments of the continental margin of the Ceará state including mechanical dispersion of continental minerals, environmental chemistry, and clay identification.

## 2. Localization and geological setting

In the Ceará State, the continental area framework is mainly represented by igneous and metamorphic rocks that range in age from Precambrian to Phanerozoic (e.g. Arthaud et al. 2008).

Archean and Paleoproterozoic rocks are mainly represented by the Troia Massif (or Cruzeta complex) and the Canindé Complex, composed predominantly of TTG orthogneisses and high-grade paragneisses, respectively (Cavalcante et al. 2003; Arthaud et al. 2008). These associations are the basement for several Neoproterozoic granitoids and metasedimentary covers, respectively denominated Tamboril-Santa Quitéria and Ceará complexes (Arthaud et al. 2008). The Tamboril–Santa Quitéria Complex is an important Neoproterozoic granitic–migmatitic unit that developed from ca. 650 to 610 Ma, and the granitoids range in composition from diorite to granite, with predominance (up to 85%) of granitic to monzogranitic composition (Araújo et al. 2012; Costa et al. 2013). The Ceará complex is mainly composed of schists with lenses of quartzites, marble, calc-silicate rocks, and amphibolites, and probably developed in Neoproterozoic rift and passive margin settings around 750 to 650 m.y. ago (Arthaud et. al. 2015). The last magmatic events that occurred in the Ceará State were the emplacement of the Cretaceous Ceará-Mirim dikes related to the Atlantic Ocean opening (c. 130 to 134 Ma), and the Tertiary Messejana magmatism, occurring about 30 m.y. ago (Oligocene) (Almeida et al. 1988). The Messejana magmatic event includes phonolite, trachyte, and syenite (Almeida et al. 1988). This magmatism was responsible for the origin of small volcanic edifices in the state of Ceará, arranged in sectors of the continental margin onshore, and along the coastal zone of Fortaleza city (Almeida et al. 1988). Finally, recent (Neogene) sedimentary rocks and sediment cover were deposited along the coastline of the Ceará State, and mainly named as Barreiras Formation (e.g. Suguio and Nogueira 1999).

## 3. Methods

The deep cores were sawed longitudinally, moistened with distilled water, and cut by nylon line. Then, one half was analyzed and the other half was saved for subsequent observation. Each core was photographed and then sectioned according to the texture and color of the sediment, for interpretations about chemical and physical environmental variations. The color description was done using the Geological Rock-Color Chart (Munsell color 2009).

For the granulometric analysis, wet sieving was made using a 0.062 mm mesh sieve for fractions sand separation. For silt with clay, 50g of each sample was washed in running water, and the passing fraction was decanted into a recipient. After the decantation the excess water was withdrawn and the passing fraction and the fraction retained in the sieve were taken into a drying oven at 60°C. The dry sieving was later performed with the fraction retained in the sieve, in a set of sieves with mesh intervals according to Wentworth (1922). The material retained in each sieve was weighted and the data was processed with the software ANASED 5.0 Sedimentological Analysis (Lima et. al. 2001). To texturally classify the sediment, the triangular diagram of Shepard (1954) was used, and the fine particles calculation was performed using the pipet method according to the Stokes law.

Referring to the chemical analysis, the method used was portable XRF analysis, which is cost-effective and provides essentially instantaneous information on sample composition, and has good precision for most elements
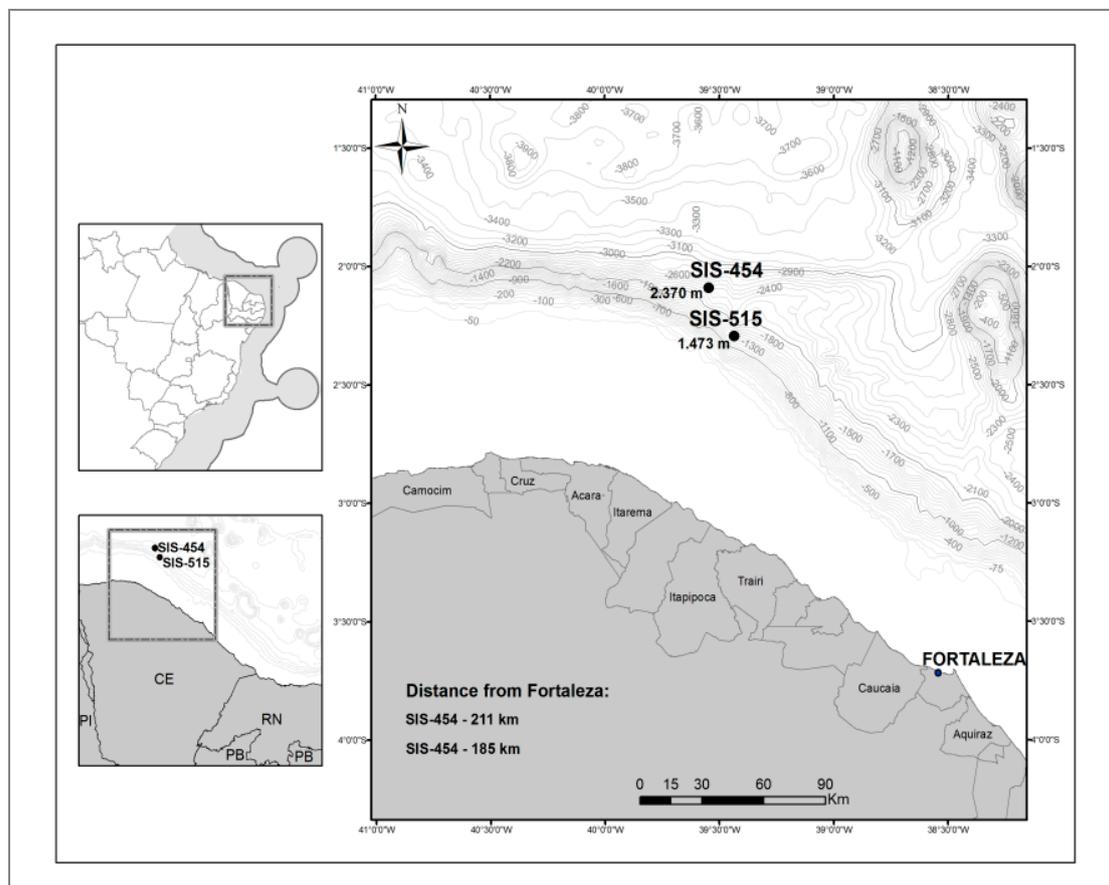


FIGURE 1 – Localization of deep cores SIS-515 and SIS-454 at the continental margin of the Ceará State, Brazil
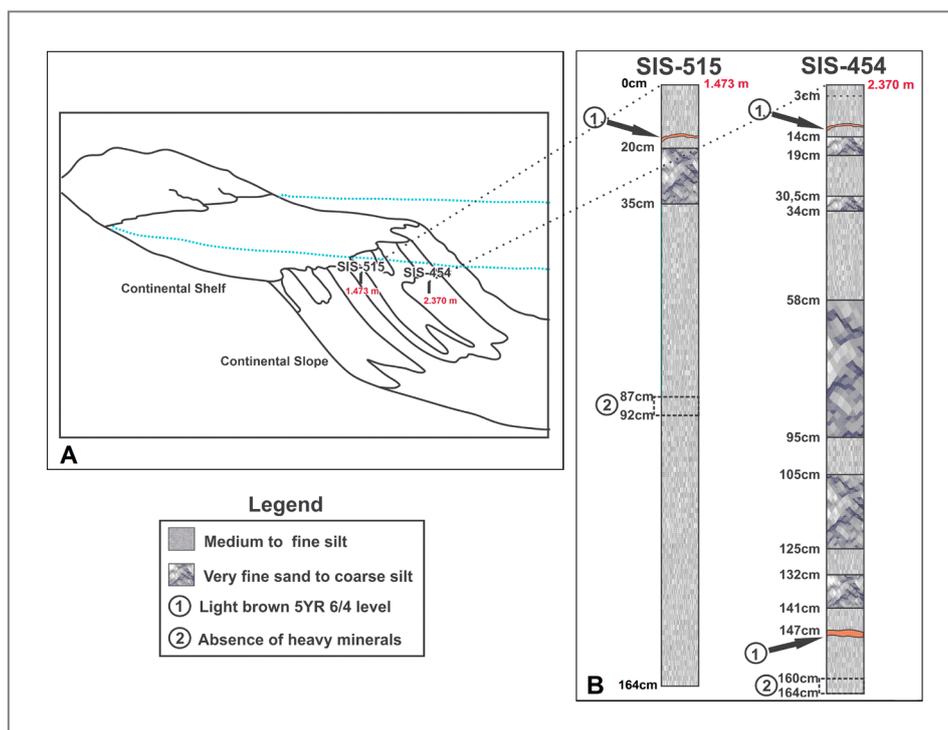
**FIGURE 2** – Schematic stratigraphy of the SIS-515 and SIS-454 cores.

(Piercey and Devine 2014). Semi-quantitative analysis was performed with three measurements made for each sample, and then, the mean was calculated. Previous analysis of the inXitu#94008 quartz standard was made to identify false contents of elements. The samples were analyzed using the 2-beam Mining Plus mode, with InnovX-550025-Olympus, with calibration verified in factory, using Alloy Certified Reference Material, produced by Analytical Reference Materials International (ARMI). The material analyzed was all 200 mesh powder. Analyses were conducted on paper stack, according to Gazley (2011), and the check for possible analytical interferences from any paper composition was done by separated analysis of 5cm stack of the same paper. From the data, a correlation matrix was produced, the content of the elements being in percentage, and log-transformed to guarantee a normal distribution. The principal component analysis was also performed to verify the maximum variances in the contents in the data base. The contents below the detection limit were considered to be half of the minimum detection content (Reimann et. al. 2008). Thus, the values are estimated within a range of real values.

Regarding to the heavy minerals analysis, the procedures of (Parfenoff et al. 1970) were followed. In the densimetric separation, bromoform (CHBr3; density of 2.89) was used with the samples previously treated by the densimetric separation with water by the method of Souza and Castro (2010), for removal of clays and part of the light minerals. Then, followed the drying of samples and the magnetic separation with handheld magnet. To the identification of mineral species a Olympus stereomicroscope was used, taking into account brightness, cleavage, color and crystallization habit. Because the remaining sample aliquot was very small with only a few grains of heavy minerals being present, the magnetic separation phase with the Frantz electromagnet separator was skipped. The mineralogical identification of clays

was carried out by a rock and mineral analyzer Terra-240, Inxitu, portable X-ray diffractometer (XRDp) with Co tube producing ionizing radiation.

## 4. Results and discussions

### 4.1. Granulometric analysis and description

The pelagic sediments of cores SIS-454 and SIS-515 comprise biogenic oozes, in the most part foraminifera microfossil, clays, and siliciclastic fine sand to a lesser extent. XRDp analysis pointed out that pelagic clays are constituted by chlorite, kaolinite, nontronite and vermiculite. The clays and siliciclastic fine sand account for less than 1wt.% of the sediment composition.

Chlorite is the result of weathering of metamorphic and igneous rocks containing Fe- and Mg-bearing silicates such as pyroxenes, amphiboles, biotite and garnet. Kaolinite originates from the weathering of aluminum silicates, particularly feldspars. Vermiculite originates from biotite alteration. Nontronite may derive from volcanic glass and magmatic basic rocks alteration (Klein and Hurbult 1997). It is suggested that the terrigenous part of the pelagic sediments of the studied area is the result of weathering of continental rocks with various compositions, as well as of continental rocks of other states of northeastern Brazil. Fluvial deposits formed at the extensive coastal plain across the continental shelf during low sea level at the end of the Pleistocene were drowned by the Holocenic marine transgression and have partially been reworked and redistributed in the transgressive sands that covered part of the Ceará continental shelf (Silva 2000).

At the northeastern continental margin of Brazil, hydrodynamic agents which influence the sediments mechanical dispersion

have been well studied on the continental shelf. There, the wave system, currents, and winds generate sediment drifts and act as modeling agents of the coastal zone (Silva 2005; Aguiar Neto et.al. 2016; França et.al. 1976). In some areas of the western continental shelf of the Ceará State, surface marine currents reach an average velocity of 0.24 m/s and NW direction, while in the bottom they reach an average velocity of 0.21 m/s and W-direction (Aguiar Neto et.al. 2016). The incidence angle of these marine currents determines the velocity and trajectory of the sediment transport (Silva 2005). At the slope of the studied area, the sediment transport is probably controlled by gravitational processes, wind transport, and larger marine currents. The larger marine currents at the northeast of Brazil are represented by Brazilian North Current, with oxygenated and saline waters, and the westbound South Equatorial Current (Freire 1985). The granulometric analysis results showed changes between medium to fine carbonate silt to coarse silt and very fine carbonate sand. About the sorting degree, it ranged from poorly to very poorly sorted. Then, it was observed poorly sorting referring to the grain type and size, varying from angular grains of terrigenous sand to remains of shells of marine organisms and rounded grains of planktonic Foraminifera. Possibly, the poor sorting of grains with depth in the cores can be related to hydrodynamic and sediment input changes at the area, despite slow sediment accumulation over time. Additionally, those changes can be possibly related to sea level changes.

SIS-454 has five thick silt intervals at 14 to 19 cm, 30.5 to 34 cm, 58 to 95 cm, 105 to 125 cm, and 132 to 141cm (Figure 3). SIS-515 has only one thick silt granulometric variation at 20 to 35 cm depth, with the remainder of the sediment being medium to fine silt. The granulometric composition of sediment suggests slow sediment accumulation over time at the studied area.

Regarding to the colors, SIS-515 has presented light olive gray 5Y 5/2 from the top to 6 cm. From 6 cm depth on, it is pale yellowish brown 10YR 6/2. At about 15 and 16 cm it is light brown 5YR 6/4, which could mean a higher oxidation level of the sediment caused by shallower waters environment, or large period of sedimentation. SIS-454 presents light olive gray 5Y 5/2 at 10-14 cm. At 12 cm depth, it is light brown 5YR 6/4. Greyish green colors appear throughout the core, intercalated with brown colors. At about 149 cm depth, SIS-454 is again light brown 5YR 6/4 (Figure 4). The color of the sediments has long been interpreted as a qualitative measure of in situ redox conditions, and red or brown hues are attributed to oxidized (ferric ion) environments, whereas green or green-gray colors to more reducing conditions (ferrous iron) (Lyle 1983; Mooby and Cronan 1983). More recently, marine sedimentologists have observed that a brown (oxidized) sediment layer often can be found above green (reduced) layer, especially in hemipelagic deposits. The variation in thickness of the brown layer is hypothesized to be a measure of organic matter and clays flux to the sea floor, along with the rate of its burial (Lyle 1983). Then, at high rates of organic matter and clays deposition and burial, oxygen is rapidly consumed in the sediments and the brown layer is expected to thin or disappear. At low rates of organic matter deposition or very low sedimentation rates, the diffusion of oxygen into the sediments exceeds its consumption during degradation of organic matter. In this case the sediments remain brown (Lyle 1983). The natural drying of the analyzed sediments at the study area may have caused whitening in the colors, however, it was possible to observe environment oxidizing conditions through the light brown color.
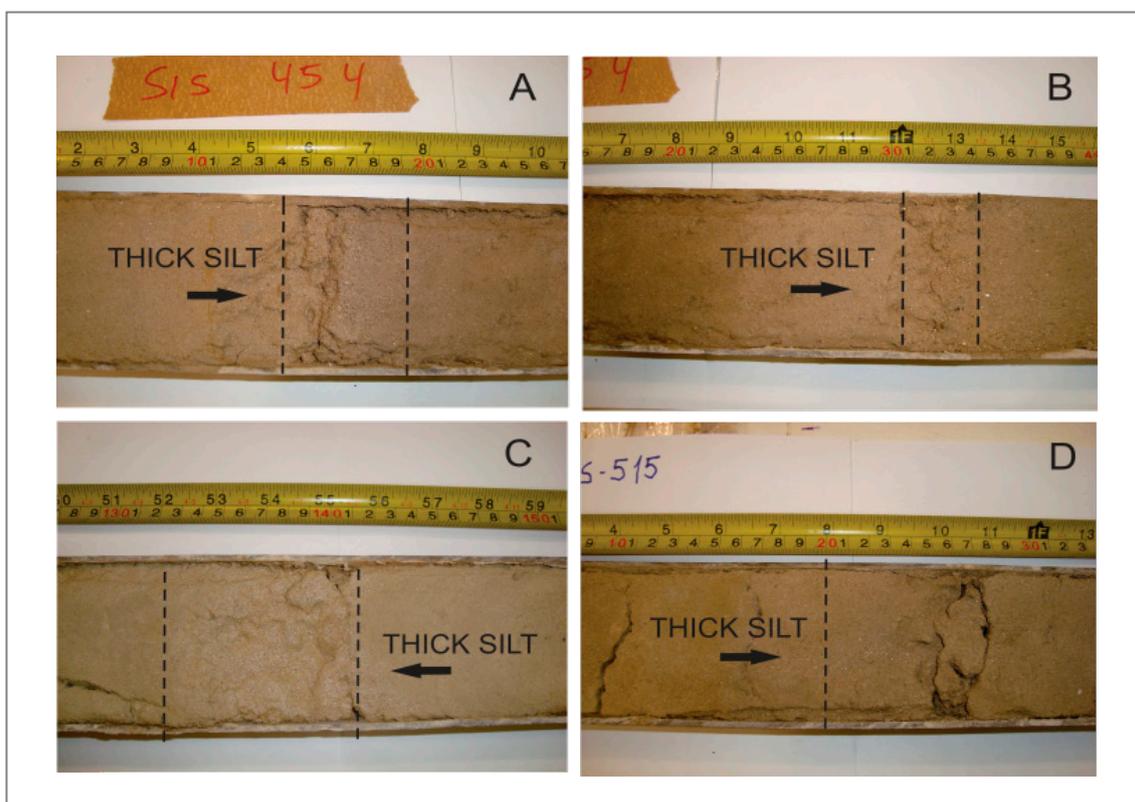


**FIGURE 3** — SIS 454 thick silt intervals (A) 14 to 19 cm, (B) 30.5 to 34 cm, (C) 132 to 141cm, and SIS 515 (D) 20 to 35cm.
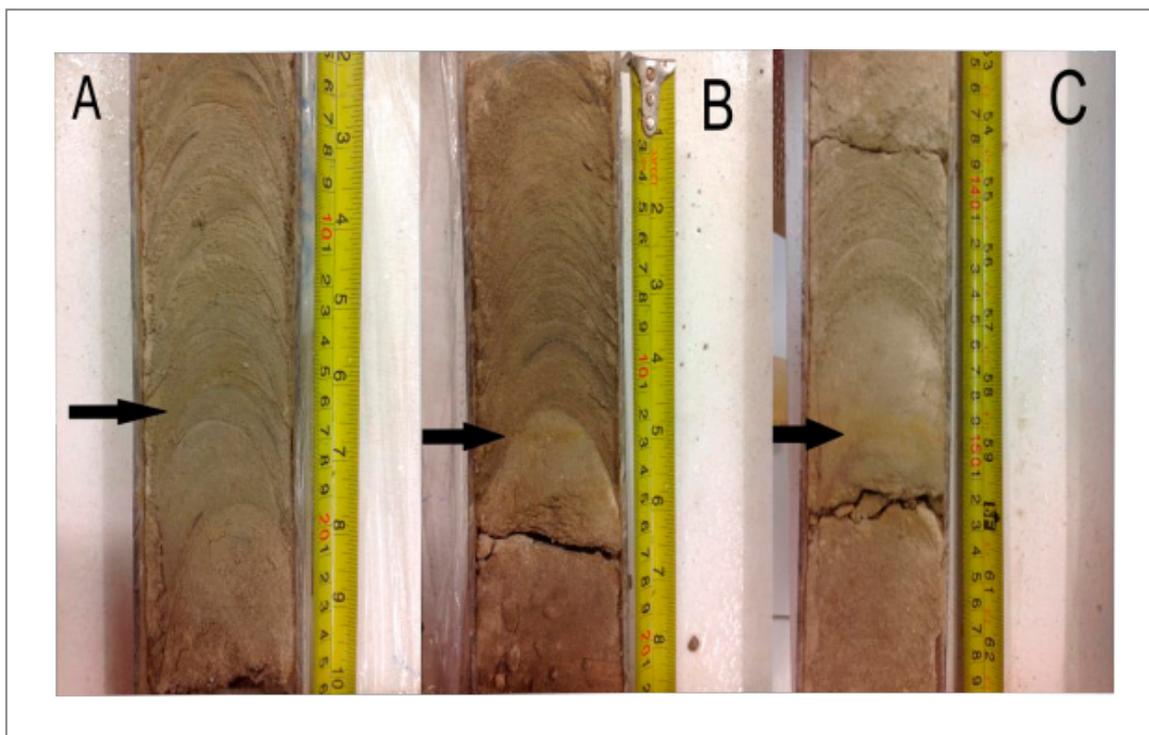
FIGURE 4 – (A) Light brown color 5YR 6/4 about 15 and 16 cm. SIS-515. (B) Light brown color 5YR 6/4 at 12 cm depth. SIS-454. (C) Light brown 5YR 6/4 about 149 cm depth. SIS-454.

## 4.2. Heavy minerals

Continental shelves exposed during glacial periods are harbors to sedimentary deposits carried out by rivers. In this case, the rivers can either sculpt channels or deposit continental sediment during periods of sea level regressions, and the northeastern continental shelf of Brazil is inserted in this context (Aguiar Neto 2015). The west part of the continental shelf of the Ceará State, despite the predominance of biogenic carbonates, presents important concentrations of heavy minerals, and the terrigenous sediments remains on the internal shelf, up to 20 meters deep (Aguiar Neto 2015). The terrigenous sediments are probably carried out to the continental margin by coastal dynamics through natural channels. Thus, it is understood that the lower the sea level, the greater the mechanical dispersion of the sediments towards the continental margin. Freire (1985) pointed out that the continental shelf of the Ceará State has the most part of contribution from terrigenous sedimentation along the Brazilian Northeast, and this terrigenous contribution predominates throughout the internal shelf, and in front of the city of Fortaleza (capital of the Ceará State, Fig. 1), it reaches the external continental shelf.

Komar and Wang (1984) pointed out that hydrodynamic processes like waves and currents, both parallel and transversely to the coastline, select the heavy minerals according to their size, density and shape. These factors are, therefore, controllers of the mechanical dispersion of the heavy minerals along the continental margin. The mechanical dispersion at the studied area has association with eustatic variations of the sea level throughout the Quaternary period (Silva 2000; Freire and Cavalcanti 1998).

The grains of heavy minerals that originated in the continent can be transported to the oceans by glacial, fluvial and eolian processes, where they are reworked and concentrated by marine processes such as wave energy during transgressions and regressions (Aguiar Neto 2015). Aguiar Neto (2015) analyzed sediment samples from rivers and compared with marine placers from the Ceará continental shelf, calculating the percentage of heavy minerals, relative abundances (%), mineralogical association, the Zircon/Tourmaline/Rutile (ZTR) and Rutile/Zircon (RZi) indexes, and performed chemical analysis. Aguiar Neto (2015) pointed out that the heavy mineral assembly at the western part of the continental shelf of the Ceará State is formed by ilmenite, tourmaline, epidote, hornblende, monazite, staurolite, sillimanite, rutile, magnetite, zircon, andalusite, kyanite, garnet, leucoxene, diopside, apatite, spinel, and cassiterite. According to Aguiar Neto (2015), the occurrences of heavy minerals at the continental shelf of the studied area are closely related to the eustatic sea level variations that occurred throughout the Quaternary period. Aguiar Neto (2015) suggested that there are regional contributions of reworked sediments of the Barreiras Formation and the mineral paragenesis existing at the Ceará continental shelf is typical of regional metamorphism of aluminum-rich rocks, and are correlated with the Ceará Complex rocks. The author also pointed out that the Ceará Complex rock occurs close to the coast as they appear directly on the continental shelf.

We found traces of almost all the heavy minerals cited by Aguiar Neto (2015) in the two cores (Figures 5 to 8). Those that were not mentioned by the author, and that appear as traces in the SIS-454 and SIS-515 analyzed sediments were muscovite, biotite, monazite, pyrite, and ferruginous aggregates. The light
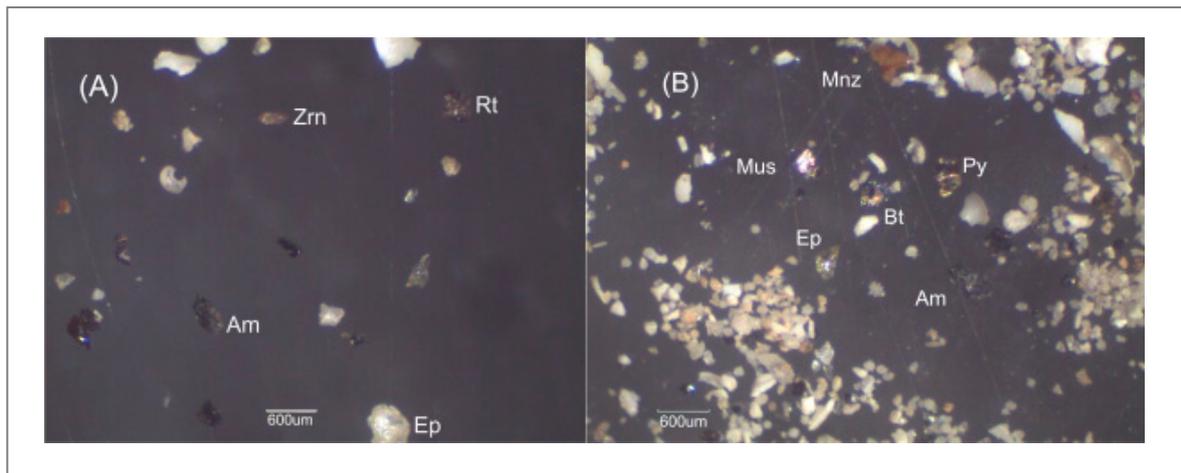
FIGURE 5 − (A): Heavy minerals at 0-3 cm depth-SIS-454. Zrn-zircon, Rt-rutile, Am-amphibole, Ep-epidote. (B): Heavy minerals at 10-14 cm at SIS-454. Mnz-monazite, Mus-muscovite, Bt-biotite, Ep-epidote, Py-pyrite, Am-amphibole. Acronyms according to the Subcommittee on the Systematics of Metamorphic Rocks by IUGS. The scale bar corresponds to 600 μm.
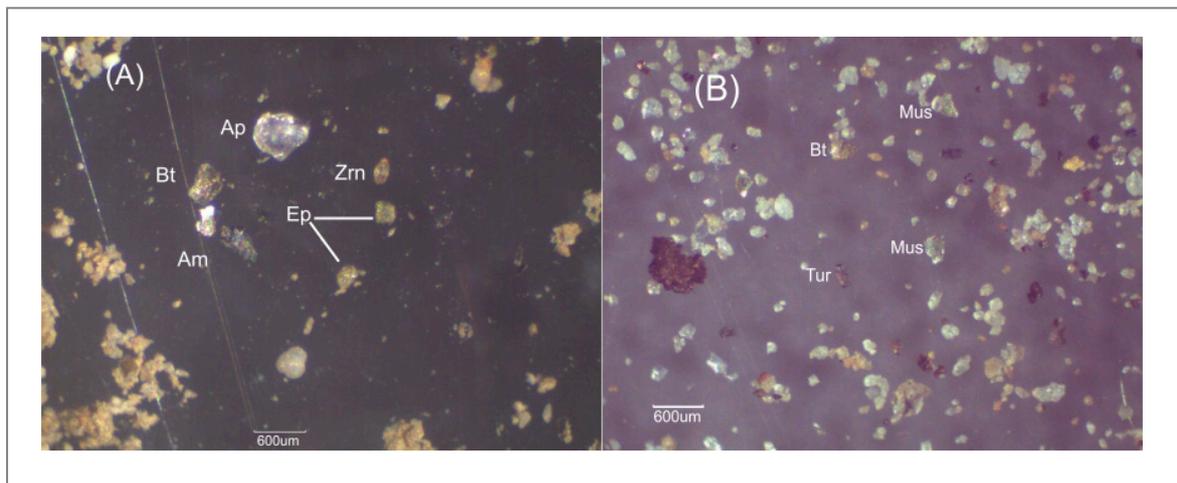


FIGURE 6 − (A): Heavy minerals at 38-43 cm depth SIS454. Ap-apatite, Bt-biotite, Ep-epidote, Zrn-zircon, Am-amphibole. (B): SIS-454, 120-126cm depth. Tur-tourmaline, Mus-muscovite, Bt-biotite. Presence of iron aggregate.

minerals are traces of detrital quartz and biogenic carbonate. A ferruginous mollusk shell was found in the SIS-515 core, at the 156-162 cm depth (Figure 8). An explanation would be films of Fe oxides and hydroxides precipitated under rich water conditions and then transported to the deeper zones, or the iron presence in the formation environment, being this element encompassed in the organism metabolism.

In the SIS-454 core, at 160 to 164cm depth, there is a total absence of both heavy and light minerals level below the oxidation level represented by the light brown 5YR 6/4 color. The total absence of heavy and light minerals was also observed in core SIS-515, at the depth of 87 to 92 cm. The levels lacking continental minerals in cores SIS-454 and SIS-515 are probably associated with the absence of mechanical dispersion due to transgression and regression events at the Ceará State continental shelf.

Due to a low sedimentation rate (1mm x 1000-1y), pelagic sediments tend to suffer high oxidation rates (Li and Schoonmaker 2003). The presence of ferruginous aggregate and ferruginous shell can probable be associated with the sediment oxidation, or mixture of shallow and deep sediments due to hydrodynamic processes at the studied area.

According to Condé et al. (2007), absence of terrigenous sedimentation (pelagic sedimentation predominance), anoxic conditions and total organic carbon preserved are related to transgressive events. According to Parfenoff et al. (1970), changes in the mechanical dispersion of heavy minerals often indicate limits caused by a paleogeographic evolution. Then, levels with total absence of continental minerals in the two cores are possibly associated with non-achievement of continental terrigenous contribution associated with periods of marine transgressions. The intense oxidation levels are possibly associated with slow pelagic sedimentation periods, or regressive periods of sea level. Freire and Cavalcanti (1998) pointed out that although there is no information regarding the absolute dating of the sediments of the Ceará Basin, the Flandrian Transgression in this basin did not proceeded continuously and was interrupted several times by small-scale regressions.

### 4.3. Chemical analysis

According to chemical analysis, at SIS-454, 72-78 cm depth, there is a clear antagonistic tendency in both elements originated from terrigenous sediment (Si 13.77%, Fe 3.08%, Al
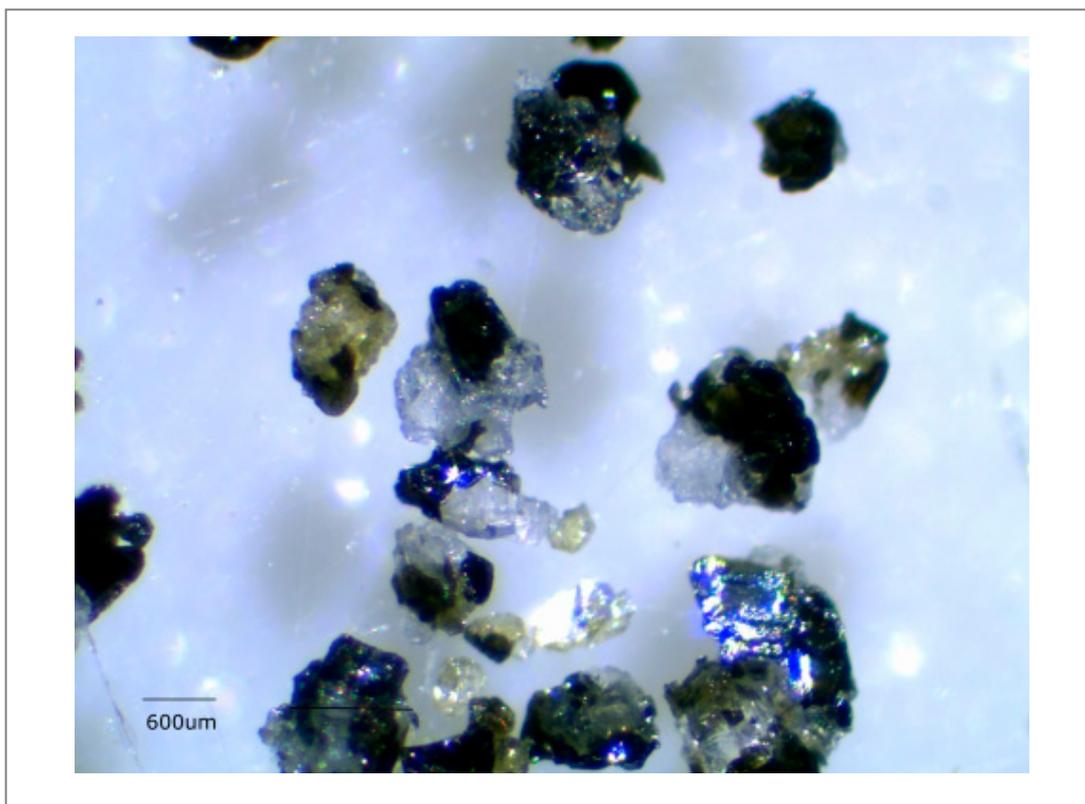
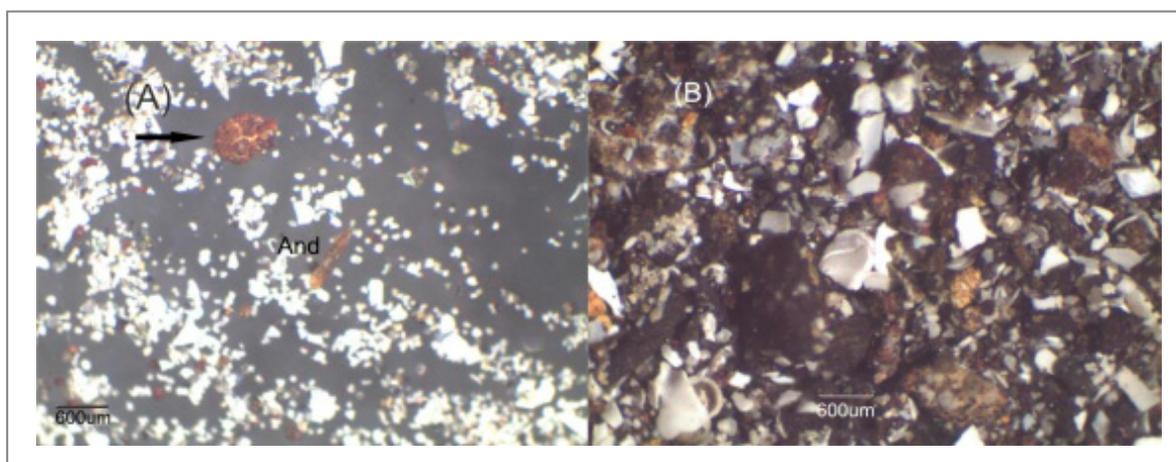**FIGURE 7** − SIS-454-72 cm depth. Light minerals are quartz and biotite.



**FIGURE 8** − (A): SIS-515, 156-162 depth, andalusite and oxidized mollusk shell. (B): ferruginous aggregates and mollusk shell SIS-515, 156-162.

8.09%, and K 1.04%) against Ca (22.67%), the latter interpreted as being from marine biogenic origin (Figure 9). This trend may be related to a time which allowed the advance of terrigenous material from the continent to the slope, although this trend was not detected in SIS-515, where the contents of the analyzed elements are directly proportional. At 105 a 110 cm depth (SIS-454) there is the maximum Ca content (31.44%), and low contents of Si, Fe, K and Al (6.18%, 1.31%, 0.45% and <1% respectively). This feature refers to little influence of terrigenous material environment, and high planktonic and benthic organism proliferation that are biogenic calcium carbonate producers.

From the results of chemical analysis, the Pearson's correlation coefficient was obtained with the elements that presented variations in their contents, measuring the degree of correlation between the variables (Table 1). Furthermore, the Principal Component Analysis (PCA) was performed, with elements distributed in groups, representing paragenesis related to the same chemical conditions formation in the environment (Figure 10).

The Pearson's correlation of the contents of the elements gave us a first notion about the mineral assemblages in the studied environment. We interpret that the element contents are related to each other according to the provenance environment. Al, Si, Ti, V, Fe, K, Hf, Pb, and Ni have correlation with each other and are elements of continental provenance. Calcium in the marine environment usually does not have a strong correlation with continental origin elements. The Ca correlation with Mn, V, and Zr is possibly associated with the mixture of
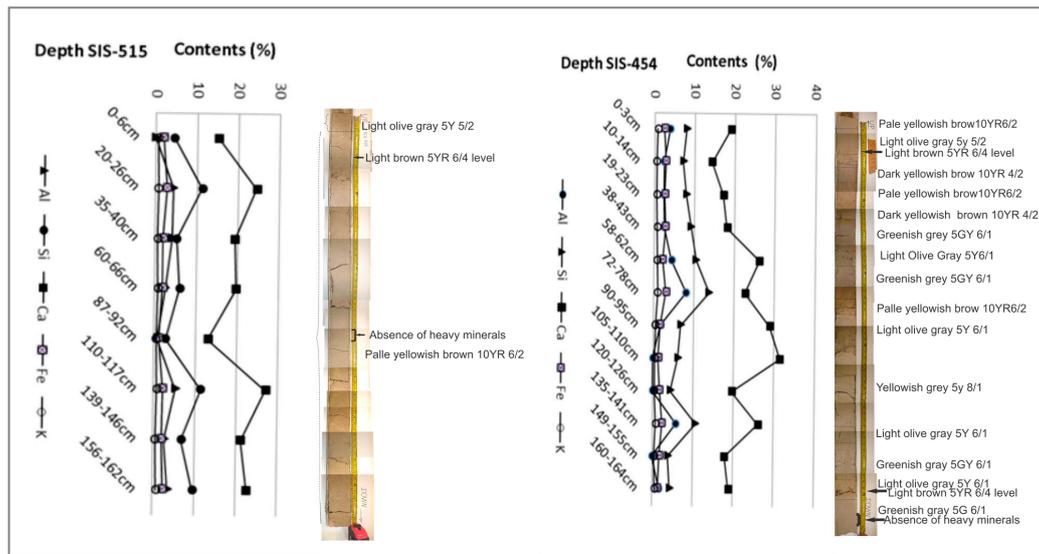
**FIGURE 9** — Features of cores SIS-454 and SIS-515 including Al, Si, Ca, Fe and K contents and colors

**TABLE 1** — Correlation matrix of element contents of cores SIS-515 and SIS-454

| | $Al_2O_3$ (wt.%) | $SiO_2$ (wt.%) | S (ppm) | Cl % | CaO (wt.%) | $TiO_2$ (wt.%) | V (ppm) | $Cr_2O_3$ (wt.%) | MnO (wt.%) | $Fe_2O_3$ (wt.%) | Ni (ppm) | $K_2O$ (wt.%) | Zr (ppm) | Sn (ppm) | Hf (ppm) | $W_2O_3$ (wt.%) | Pb (ppm) | Bi (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Al_2O_3$ (wt.%) | 1.00 | | | | | | | | | | | | | | | | | |
| $SiO_2$ (wt.%) | 0.87 | 1.00 | | | | | | | | | | | | | | | | |
| S (ppm) | -0.15 | -0.23 | 1.00 | | | | | | | | | | | | | | | |
| Cl % | -0.25 | -0.44 | 0.48 | 1.00 | | | | | | | | | | | | | | |
| CaO (wt.%) | 0.35 | 0.50 | -0.35 | -0.45 | 1.00 | | | | | | | | | | | | | |
| $TiO_2$ (wt.%) | 0.74 | 0.83 | -0.33 | -0.60 | 0.44 | 1.00 | | | | | | | | | | | | |
| V (ppm) | 0.57 | 0.68 | -0.56 | -0.67 | 0.62 | 0.77 | 1.00 | | | | | | | | | | | |
| $Cr_2O_3$ (wt.%) | 0.42 | 0.54 | 0.11 | -0.21 | 0.45 | 0.36 | 0.23 | 1.00 | | | | | | | | | | |
| MnO (wt.%) | 0.24 | 0.36 | -0.57 | -0.66 | 0.69 | 0.42 | 0.60 | 0.16 | 1.00 | | | | | | | | | |
| $Fe_2O_3$ (wt.%) | 0.67 | 0.78 | -0.12 | -0.49 | -0.03 | 0.71 | 0.43 | 0.29 | 0.14 | 1.00 | | | | | | | | |
| Ni (ppm) | 0.44 | 0.66 | -0.25 | -0.38 | 0.55 | 0.70 | 0.72 | 0.22 | 0.53 | 0.37 | 1.00 | | | | | | | |
| $K_2O$ (wt.%) | 0.86 | 0.85 | 0.07 | -0.05 | 0.25 | 0.60 | 0.40 | 0.46 | 0.02 | 0.68 | 0.47 | 1.00 | | | | | | |
| Zr (ppm) | 0.26 | 0.52 | -0.47 | -0.79 | 0.71 | 0.59 | 0.66 | 0.41 | 0.84 | 0.33 | 0.61 | 0.09 | 1.00 | | | | | |
| Sn (ppm) | 0.46 | 0.37 | -0.58 | -0.74 | 0.41 | 0.58 | 0.70 | 0.13 | 0.51 | 0.35 | 0.18 | 0.13 | 0.55 | 1.00 | | | | |
| Hf (ppm) | 0.59 | 0.59 | 0.04 | 0.03 | 0.55 | 0.45 | 0.40 | 0.55 | 0.24 | 0.20 | 0.61 | 0.66 | 0.29 | 0.16 | 1.00 | | | |
| $W_2O_3$ (wt.%) | 0.48 | 0.51 | -0.12 | -0.22 | 0.41 | 0.52 | 0.63 | 0.38 | 0.29 | 0.25 | 0.45 | 0.30 | 0.37 | 0.40 | 0.48 | 1.00 | | |
| Pb (ppm) | 0.55 | 0.60 | 0.01 | -0.02 | 0.09 | 0.38 | 0.08 | 0.64 | 0.01 | 0.53 | 0.05 | 0.51 | 0.21 | 0.01 | 0.21 | 0.28 | 1.00 | |
| Bi (ppm) | 0.45 | 0.64 | -0.23 | -0.13 | 0.53 | 0.53 | 0.46 | 0.49 | 0.25 | 0.29 | 0.61 | 0.53 | 0.47 | 0.14 | 0.57 | 0.30 | 0.46 | 1.00 |

continental and pelagic sediments due to sea level changes events, hydrodynamic processes, and ocean currents.

The PCA of the data has given 73.36% of explanation for the covariance of the element contents of the analyzed dataset, including the main factors 1, 2, and 3 (Figure 10). This method of multivariate analysis reveals structures in the database that can be indicative of certain geochemical processes (Reimann et. al. 2008). It gives an explanation of the co-variances between the variables in terms of a smaller number of data, allowing them to reduce the database size with minimal loss of information.

Regarding to factor 1, there are two opposite variances data set. One formed by Cl and S, and the other formed by all other elements. It is suggested that possibly Cl and S, present in the sediments analyzed, were originated exclusively in the marine environment, with Cl originated exclusively from

marine water and S originated probably from resurgence currents and deposited in pelagic sediments. The second group, formed by all other elements, suggests they originated not only by wind transport, but also by slow transportation, and coming from the continent.

Regarding to factor 2, we have a paragenesis linked to transport from the continent, being the set Si, Ti, Ni, W, Bi, and Fe in intermediate position indicating, probably, origin from both the continent, as from cosmic dust, and seawater itself in the case of biogenic silica. The other paragenesis, formed by Mn, Zr, Ca, Sn, and V may indicate origin in the marine environment, and probably cosmic dust and wind transport.

Regarding to factor 3, the paragenesis indicates that elements such as Hf, Bi, Cr, Ni, Zr, and W, associated with the element of biogenic origin Ca, have their origin not only from the continent, but also probably from cosmic dust and wind
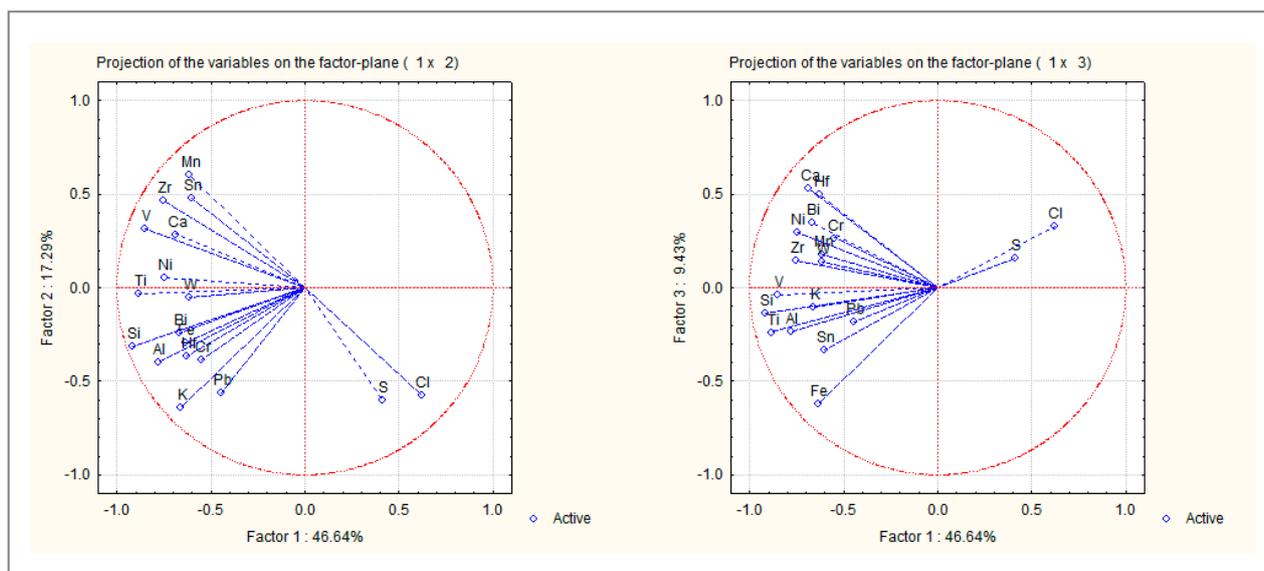
FIGURE 10 – Principal Component Analysis of the contents of elements of pelagic sediments of the continental margin of the Ceará State, Brazil.

transport. The principal component analysis has suggested the three origin environments for the pelagic sediments of the continental margin of Ceará, which are the continental, cosmic, and marine environment itself. The Appendices 1, 2 and 3 show the chemical analysis results and photographs of the cores.

From the SIS-454 and SIS-515 analysis, it was deduced that sedimentation in the slope of the continental margin of the Ceará State was affected by at least two sedimentation events with absence of mechanical dispersion of continental sediments, associated with geochemical characteristics represented by antagonism between elements of terrigenous and biogenic origin. These events are possibly associated with the small-scale regressions occurred during the Flandrian Transgression in the Ceará Basin as measured by Freire and Cavalcanti (1998).

## 5. Conclusions

The pelagic sediments of the SIS-454 and SIS-515 cores comprise biogenic oozes, in the most part foraminifera, clays, and continental fine sand to a lesser extent. XRDp analysis pointed out that pelagic clays consist of chlorite, kaolinite, nontronite, and vermiculite. The clays and siliciclastic fine sand account for less than 1wt.% of the sediment composition.

The granulometric analysis showed changes between medium to fine carbonate silt to coarse silt and very fine carbonate sand. About the sorting degree, it has been found that it ranged from poorly to very poorly sorted. Then, it was observed the same variety with respect to the grain type, varying from angular grains of marine organism shells debris, to rounded grains of planktonic foraminifera. Possibly, the poor sorting of grains with depth in the cores can be related to hydrodynamic and sediment input changes at the area, despite slow sediment accumulation over time. Additionally, these changes can be related to sea level changes. Regarding to the colors, light brown 5YR 6/4 was found at SIS-515 at 15 cm, and SIS-454 at 12 and 149 cm depth, which could mean a higher oxidation level of sediment caused by shallower waters environment, or large period of sedimentation.

In the two cores traces of almost all heavy minerals existing at continental shelf were found. These are ilmenite, tourmaline, epidote, hornblende, monazite, staurolite, sillimanite, rutile, magnetite, zircon, andalusite, kyanite, garnet, leucoxene, diopside, apatite, spinel, and cassiterite, along with minor muscovite, biotite, pyrite, and ferruginous aggregate. The light minerals correspond to traces of detrital quartz and biogenic carbonate formed by foraminifera shells. A ferruginous mollusk shell was found at SIS-515, 156-162 cm depth. An explanation would be films of Fe oxides and hydroxides precipitated under rich water conditions and then transported to the deeper zones, or the iron presence in the formation environment, being this element encompassed in the organism metabolism.

At SIS-454 160 to 164cm depth, heavy and light minerals are lacking below the oxidation level represented by light brown 5YR 6/4. A total absence of both heavy and light minerals was also found in SIS-515, at depths of 87 to 92 cm. The levels with absence of continental minerals are probably associated with the absence of mechanical dispersion due to transgression and regression events at the Ceará continental shelf.

According to chemical analysis, at SIS-454, 72-78 depth, there is a clear antagonistic tendency in both elements originated from terrigenous sediment (Si 13.77%, Fe 3.08%, Al 8.09% and K 1.04%) against Ca (22.67%), this being from marine biogenic origin. This trend may be related to a time which allowed the advance of terrigenous material from the continent to slope, although this trend was not detected in SIS-515.

From the statistical analysis, it was understood that the element contents are related to each other according to the provenance environment, and the pelagic sediment of studied area has provenance from marine water, resurgence currents, wind transport, cosmic dust, and from slow transportation, originated from the continent.

From the SIS-454 and SIS-515 analysis, it was deduced that sedimentation in the slope of the continental margin of the Ceará State was affected by at least two sedimentation events with absence of mechanical dispersion of continental sediments, associated with geochemical characteristics represented by antagonism between elements of terrigenous

and biogenic origin. These events are possibly associated with the small regressions occurred during the Flandrian Transgression in the Ceará Basin.

## Acknowledgements

## Appendices

Supplementary data to this article can be found online at https://doi.org/10.29396/jgsb.v2.n2

## References

Aguiar Neto A.B. 2015. Ocorrências de minerais pesados na plataforma continental interna/média oeste do Ceará. PhD Thesis, Centro de Ciências, Departamento de Geologia, Universidade Federal do Ceará, Fortaleza, 115 p.

Aguiar Neto A.B., Marques W.S., Freire G.S.S. 2016. Distribuição espacial de minerais pesados nos sedimentos superficiais da plataforma continental oeste do Ceará, Nordeste do Brasil. Pesquisas em Geociências, 43(1), 69-83. https://doi.org/10.22456/1807-9806.78193

Almeida F.F.M., Carneiro C.D.R., Machado Jr. L.D., Dehira L.K. 1988. Magmatismo pós-paleozóico no Nordeste Oriental do Brasil. Revista Brasileira de Geociências, 18(4), 451-462.

Araújo C.E.G., Costa F.G., Pinéo T.R.G., Cavalcante J.C., Moura C.A.V. 2012. Geochemistry and 207Pb/206Pb zircon ages of granitoids from the southern portion of the Tamboril-Santa Quitéria granitic-migmatitic complex, Ceará Central Domain, Borborema Province (NE Brazil). Journal of South American Earth Sciences, 33(1), 21-33. https://doi.org/10.1016/j.jsames.2011.07.009

Arthaud M.H., Caby R., Fuck R.A., Dantas E.L., Parente C.V. 2008. Geology of the northern Borborema Province, NE Brazil and its correlation with Nigeria, NW Africa. In: Pankhurst R.J., Trouw R.A.J., Brito Neves B.B., Wit M.J. (eds.). West Gondwana: Pre-Cenozoic correlations across the South Atlantic Region. Geological Society of London, 294, 49-67. https://doi.org/10.1144/SP294.4

Arthaud M.H., Fuck R.A., Dantas E.L., Santos T.J.S., Caby R., Armstrong R. 2015. The Neoproterozoic Ceará group, Ceará central domain, NE Brazil: depositional age and provenance of detrital material. New insights from U–Pb and Sm–Nd geochronology. Journal of South American Earth Science, 58, 223-237. https://doi.org/10.1016/j.jsames.2014.09.007

Cavalcante J.C., Vasconcelos A.M., Medeiros M.F., Paiva I.G., Gomes F.E.M., Cavalcante S.N., Cavalcante J.E., Melo A.C.R., Duarte Neto V.C., Benevides H.C. 2003. Mapa geológico do estado do Ceará. Escala 1:500.000. Fortaleza, CPRM. Available on line at: http://rigeo.cprm.gov.br/jspui/handle/doc/2355

Chaves H.A.F., Zembruscki S.G., França A.M. 1979. Projeto REMAC: geomorfologia da margem continental brasileira e das áreas oceânicas adjacentes. Rio de Janeiro, PETROBRÁS, CENPES, DINTEP, 177 p.

Condé V.C., Lana C.C, Neto O.C.P, Roesner E.H., Neto J.M.M., Dutra D.C. 2007. Bacia do Ceará. Boletim de Geociências da Petrobrás, 15(2), 347-355.

Costa F.G., Araújo C.E.G., Amaral W.S., Vasconcelos A.M., Rodrigues J.B. 2013. U-Pb (LA-ICPMS) zircon ages and Nd isotopes for granitoids of the Tamboril-Santa Quitéria Complex, Ceará Central Domain: implication for neoproterozoic syncollisional magmatism in north Borborema Province. Geologia USP. Série Científica, 13(2), 159-174. https://doi.org/10.5327/Z1519-874X2013000200009

França A.M.C., Coutinho P.N., Summerhayes C.P. 1976. Sedimentos superficiais da margem continental nordeste brasileira. Revista Brasileira de Geociências, 6(2), 71-88.

Freire G.S.S. 1985. Geologia marinha da plataforma continental do estado do Ceará. MSc Dissertation, Programa de Pós-graduação em Geociências, Instituto de Geociências, Universidade Federal de Pernambuco, Recife, 108 p.

Freire G.S.S., Cavalcanti V. M.M. 1998. A cobertura sedimentar quaternária da plataforma continental do estado do Ceará. Brasília, DNPM, 39 p.

Gazley M. F. 2011. Metamorphism, geochronology and stratigraphy of an amphibolite-facies greenstone hosted gold deposit: plutonic gold mine, Marymia Inlier, Western Australia. PhD Thesis, Geology Department, School of Geography, Environment and Earth Sciences, Victoria University of Wellington, New Zealand. 164 p.

Klein C., Hurbult Jr. C.S. 1997. Manual de mineralogía. 4. ed. Spain, Editorial Reverté, 310 p.

Komar P.D., Wang C. 1984. Processes of selective grain transport and the formation of placer on beaches. The Journal of Geology, 92(6), 637-655. https://doi.org/10.1086/628903

Li Y.-H., Schoonmaker J. E. 2003. Chemical composition and mineralogy of marine sediments. Treatise on Geochemistry, 7, 1-35. https://doi.org/10.1016/B0-08-043751-6/07088-2

Lima S.F., Silva Filho W.F., Pinheiro R.D., Freire G.S.S., Maia L.P, Monteiro L.H.U. 2001. ANASED: programa de análises, classificação e arquivamento de parâmetros metodológicos. In: Congresso da Associação Brasileira De Estudos do Quaternário (ABEQUA), 13, 458-459.

Lyle M. 1983. The brown-green color transition in marine sediments: a marker of the Fe(III)-Fe(II) redox boundary. Limnology and Oceanography, 28(5), 1026-1033. https://doi.org/10.4319/lo.1983.28.5.1026

Mooby S.A., Cronan D.S. 1983. The geochemistry of hydrothermal and pelagic sediments from the Galapagos hydrothermal mounds fields. Mineralogical Magazine, 47(344), 291-300. https://doi.org/10.1180/minmag.1983.047.344.03

Morais Neto J.M., Pessoa Neto O.C., Lana C.C., Zalán P.V. 2003. Bacias sedimentares brasileiras: bacia do Ceará. Phoenix, 5(57), 1-6.

Munsell color. 2009. Geological Rock-Color Chart. Grand Rapids.

Parfenoff A., Pomerol C., Tourenq J. 1970. Les minéraux en grains, méthodes d'éthude et détermination. Paris, Masson et Cie., 578 p.

Piercey S.J., Devine M.C. 2014. Analysis of powdered reference materials and known samples with a benchtop, field portable x-ray fluorescence (pXRF) spectrometer: evaluation of performance and potential applications for exploration lithogeochemistry. Geochemistry: Exploration, Environment, Analysis, 14(2), 139-148. http://dx.doi.org/10.1144/geochem2013-199

Reimann C., Filzmoser P., Garrett R., Dutter R. 2008. Statistical data analysis explained-applied environmental statistics with R. England, John Wiley & Sons, 343 p.

Shepard F.P. 1954. Nomenclature based on sand-silt-clay ratios. Journal of Sedimentary Research, 24(3), 151-158. https://doi.org/10.1306/D4269774-2B26-11D7-8648000102C1865D

Silva C.G. 2000. Placeres marinhos. Revista Brasileira de Geofísica, 18(3), 327-336. http://dx.doi.org/10.1590/S0102-261X2000000300010

Silva C.M.A. 2005. Relações entre a dinâmica costeira e a meio-fauna dos sedimentos praiais do litoral da ilha de Itamaracá-Pe. PhD Thesis, Centro de Tecnologia e Geociências, Universidade Federal de Pernambuco, Recife, 139 p.

Souza F.J.C., Castro J.H.W. 2010. Treinamento em análise mineralógica de minerais pesados. Porto Alegre, CPRM, 44 p. Available on line at: http://rigeo.cprm.gov.br/jspui/handle/doc/14571

Suguio K., Nogueira A.C.R.1999. Revisão crítica dos conhecimentos geológicos sobre a Formação (ou Grupo?) Barreiras do Neógeno e o seu possível significado como testemunho de alguns eventos geológicos mundiais. Geociências, 18(2), 461-479.

Wentworth C.K. 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology, 30(5), 377-392.