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An integrated analysis of palynofacies and diatoms in the Jucuruçu River valley, northeastern Brazil: Holocene paleoenvironmental changes

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ABSTRACT

This study demonstrates the usefulness of palynofacies as a tool for characterizing the origin, transport, and settling of particulate organic matter preserved in fluvial plain sediments and its integration with diatoms for inferring past depositional environments. Palynofacies, diatoms, and organic geochemistry (S, C/S) data from a sediment core (PR07) collected from the Jucuruçu River valley in coastal southern Bahia, northeastern Brazil were used to better understand ecosystem changes that occurred in the region during the last ~7.5k years. Elemental values (S: 0.15–5.9%; C/S: 0.12–41.5) suggest marine and fluvial influences in the valley during the Holocene, and organic matter was derived from freshwater and marine phytoplankton. The presence of heterolithic deposits, brackish/marine diatoms, predominance of amorphous group, non-opaque phytoclasts, pyrite crystals, and marine microfossils suggests that a tidal flat formed during a mid-Holocene sea-level highstand. A fluvial plain developed in the last 5k years, due to marine regression and an increase in fluvial sediment supply to the region.

1. Introduction

Coastal areas are very sensitive environments and their dynamic equilibrium results from several factors such as waves, winds, tides, and currents that provide energy to sediment transport and deposition (Bird, 2008). Also, sea-level oscillations, longshore transport of sands, climate change, and its effects on atmospheric circulation and rainfall are driving factors of coastal evolution (Martin et al., 1993a, 1998; Bittencourt et al., 2000).

A large number of proxies can be used for paleoenvironmental reconstruction in coastal regions, such as pollen, spores, foraminifera, diatoms, geochemical parameters, sedimentary facies, and particulate organic matter (Amaral et al., 2012). The analysis of particulate organic matter in rocks and/or sediments, introduced by Combaz (1964) as palynofacies, is a valuable proxy and an important record of past changes, including sea-level variations and fluvial inflow. The palynofacies concept has a more holistic approach than palynology and deals with all organic matter observed in unoxidized palynological preparations (Tyson, 1995).

In the last decades, more concern has been given to palynofacies in sediments deposited during the Holocene in Brazil. However, most of the palynofacies analysis was mainly applied to lacustrine sediments (e.g. Meyer et al., 2005, 2006; Sifeddine et al., 2011; Boussafir et al., 2012; Zocatelli et al., 2012; Lorente et al., 2014, 2018), and just a few were conducted on wetlands (e.g. Gadens-Marcon et al., 2014a,2014b,2014c; Souza et al., 2016). In an attempt to fill this gap, we studied organic components in river valley sediments located in a coastal area to understand the factors that acted during the production, accumulation, and preservation of the particulate organic matter.

The possible integration of palynofacies with different research interests such as diatoms is a great advantage for deducing past ecosystems (Tyson, 1995). Diatoms have been used in coastal evolution studies where marine and freshwater species alternate as a result of changes in marine and fluvial processes (Roe et al., 2009; Castro et al., 2013). These microorganisms can be excellently preserved and easily identified in the sedimentary record; they are sensitive to environmental changes, such

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as variations in salinity, tidal ranges, and depositional processes (Round et al., 1990; Denys and De Wolf, 2010; Espinosa and Isla, 2011). Thus, diatoms can provide valuable data about coastal dynamics and regressive and transgressive events.

Most studies on Brazilian coast reveal that a mid-Holocene sea-level highstand occurred in the eastern littoral region, and the sedimentary plains along the coast were mainly controlled by sea-level fluctuations and local sedimentary inflow (Angulo et al., 2006; Cohen et al., 2014). Fluvial valleys excavated during the Last Glacial Maximum (LGM; 21-18k years Before Present – yr. BP) were inundated during the Holocene transgression, which reached its maximum at circa 5k yr. BP, forming lagoonal-estuarine environments (Suguio et al., 1985; Suguio and Kohler, 1992) that favored the establishment of mangroves (Cohen et al., 2012, 2014; França et al., 2015). These mangroves are considered excellent indicators of environmental changes and their development is regulated by continent-ocean interactions (Cohen and Lara, 2003; Pessenda et al., 2012).

An earlier study about paleomangroves in the Jucuruçu River valley in Bahia State, northeastern Brazil by Fontes et al. (2017) recorded that between ~7.4 and ~5k yr. BP, the relative sea-level rose up to 1.35 m above the current level. After the mid-Holocene, the mangroves disappeared and fluvial plains formed. Allogenic processes are considered to be the main driving forces in mangroves dynamics, reinforcing the importance of the sedimentation in coastal evolution (Fontes et al., 2017; Moraes et al., 2017; Cohen et al., 2020). While all the studies in this region were based mainly on vegetation and its response to environmental changes, the uniting of particulate organic matter and diatoms in this study is novel for the region.

The present study uses palynofacies, elemental S analysis, C/S ratio, and diatoms from a sediment record collected in the northeastern of

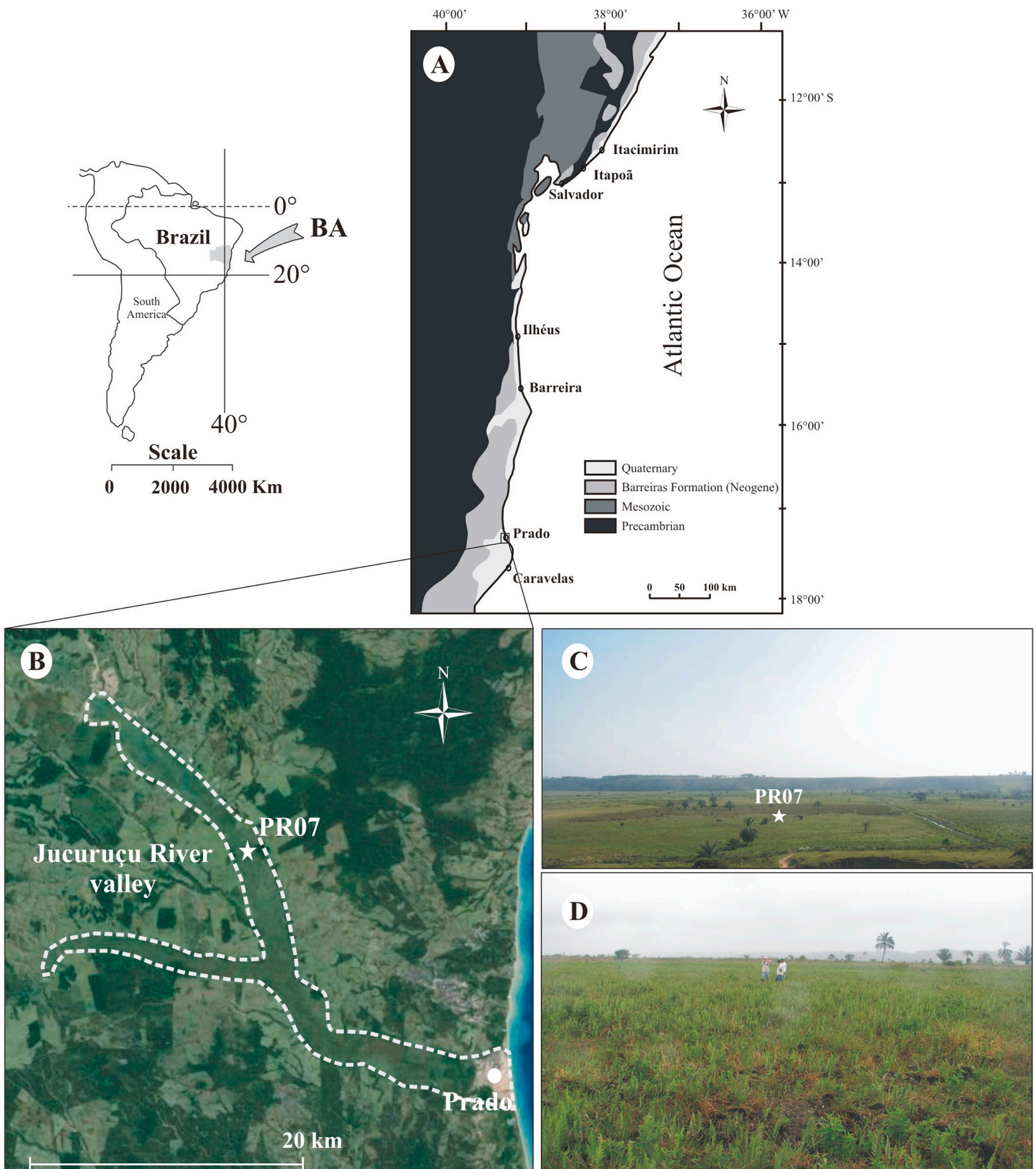

Fig. 1. Location of the study area. BA: Bahia State. **A.** Simplified geologic map of the coast of Bahia State (modified from Boas et al., 2008). **B.** Study area image. **C-D.** Modern photographs of the sampling area. The dashed area delineates the Jucuruçu River valley, and the star indicates the location of the PR07 core.

Brazil. Our goal is (1) understand how ecological, biogeochemical and sedimentological processes control the origin, transport, and settling of particulate organic matter in the Jucuruçu River valley during the Holocene, (2) to identify diatoms in the sedimentary record and to integrate them with palynofacies, and (3) to correlate our data with those previously published for the region.

1.1. Study site

The study area is located in the floodplain valley of the Jucuruçu River (Fig. 1), which is adjacent to the *Parque Nacional do Descobrimento* (PND; 17°08′42.2″S/39° 25′13.1″W) and close to the coastal town of Prado, southern Bahia, Brazil. The region is characterized by climate Af according to Köppen classification (1948), which is tropical humid or super-humid, with rains distributed during the year and periods of one to three drought months can occur annually (Mori et al., 1983; Martin et al., 1998). Annual precipitation average is 1360 mm, and temperature average varies from 24 °C to 25 °C yearly (Mori et al., 1983; EMBRAPA, 2003).

Cold fronts, trade winds and the Intertropical Convergence Zone (ITCZ, a tropical belt of deep convective clouds that migrates towards a hemisphere according to warming gradients) control the climate and ocean processes on the Brazilian coast (Dominguez, 2006). The coast of Bahia in northeastern Brazil is situated within the trade wind belt, where the atmospheric circulation is mainly controlled by the South Atlantic semi-stationary anti-cyclone (Martin et al., 1998). During the winter, the Atlantic Polar Front generates strong winds from the SSE, while during the summer the high-pressure zone returns to the ocean, modifying the wind patterns and direction (Bittencourt et al., 2000). Moreover, the eastern-northeastern Brazilian coast is also influenced by the ITCZ, the position of which varies seasonally from 9°N to 2°N over the Atlantic and Pacific oceans (Schneider et al., 2014).

Although the Holocene climate is considered relatively more stable compared to previous geologic periods, the seasonal and meridional distribution of solar radiation in the last 10k years has changed and consequently, the ITCZ position was altered (Sachs et al., 2018). ITCZ displacements have influenced northeast Brazil and a seasonal cycle of rainfall is the main signal (Viana et al., 2014). In the same context, rainfall anomalies and changes in wind patterns in South America during the Holocene can be related to strong El Niño Southern Oscillation (ENSO) events. The anomalous tropical heat sources associated with ENSO are responsible for high precipitation in southern Brazil and drier climatic conditions in the regions located northward. Reversals of longshore sand transport were observed on the Brazilian coast for the last 5k years suggesting a long-duration El Niño-like condition (Martin et al., 1993b; Evangelista et al., 2007).

The vegetation of southern Bahia is classified as Atlantic Forest - AF, but areas of grasslands also occur, as well as mangroves along the coast (Mori and Boom, 1981). According to Moraes et al. (2017), LANDSAT optical images indicate Atlantic Forest, plantation/pasture and bare ground covering the plateau, while floodplains are herb-dominated.

In the geological context (Fig. 1), sediments of the Barreiras Formation (Neogene) characterize the coastal tablelands. These coastal tablelands spread at about 70 m above mean sea level and extend from the coastal plain to fluvial valleys along the continent (Ferraz, 2006). Quaternary sediments comprise the coastal plain where marine and estuarine sediments can be found, including lagoons, wetlands, beaches and marine terraces (Andrade and Dominguez, 2002).

2. Material and methods

Information relating to sediment coring, grain size analysis, ^{14}C dating, and stable C and N isotopes analysis was previously published and can be found in more detail in Fontes et al. (2017).

2.1. Organic geochemistry (S, C/S)

Plant fragments were removed from the samples for elemental S analysis. The samples were dried at 50 °C, homogenized, and sent to the Nutrient Cycling Laboratory at CENA-USP, where they were weighed (~100 mg), combusted and analyzed by infrared detection using S 144DR-LECO equipment. Total sulfur (S) values were expressed in percentage by dry weight and precision of 0.09%. From the elemental results, C/S (weight/weight) ratios were calculated for the sediment samples. The data obtained through C/S were used to provide information about the origin (marine or freshwater; Berner and Raiswell, 1984) of the organic matter preserved in the fluvial valley sediments and integrated the results with $\delta^{13}C$, $\delta^{15}N$ and C/N data previously published by Fontes et al. (2017).

2.2. Diatoms

Samples of 1 cm^3 each were pretreated with 30% H_2O_2 and 10% HCl, and mounted on standard microscope slides using *Naphrax*. The diatom identification was based on frustule patterns and ornamentations (Round et al., 1990; De Oliveira and Steinitz-Kannan, 1992; Houk, 2003; Bigunas, 2005). For quantitative analysis at least 200 valves for each sample were counted, and the sum and percentage calculated by the programs Tilia, Tilia GView 2.0.2 and CONISS (Grimm, 1987).

2.3. Palynofacies analysis

About 5 g of bulk sediment from each sample were processed following non-oxidative palynological procedures (Tyson, 1995; Mendonça-Filho, 1999). These procedures consist of using HF and HCl to eliminate the silicate and carbonate fractions, respectively, and $ZnCl_2$ (d = 1.9–2 g/cm^3) to separate the organic fraction (particulate organic matter - POM) from the inorganic fraction. Centrifuging was not used to avoid breakage of particles that can occur with opaque phytoclasts (i.e., carbonized particles). The isolated organic matter was sieved at 5 μm and the slides used for microscopy were mounted using glycerol-jelly and *Entellan* as a mounting medium.

Palynofacies analysis was performed under transmitted white light microscopy, and the identification of different components of particulate organic matter Fig. 2 was based on the model proposed by Tyson (1995) and Mendonça-Filho (1999) with adaptations. The particulate organic matter components were grouped three main categories: (AG) amorphous group, (NOP and OP) phytoclasts and (PAL) palynomorphs. Amorphous group represents all structureless organic material derived from microbiological degradation of bacteria, phytoplankton or land plants tissues. Phytoclasts are plants and fungal tissues, that can be separated into non-opaque (un-biostructured, biostructured, cuticles, membranes, and fungal hyphae) which are yellow, brown or dark brown particles, and opaques (equidimensional, elongates and corroded particles) that includes charcoal produced by natural pyrolysis, and the oxidized land plant tissues. Palynomorphs include sporomorphs (pollen grains and spores), freshwater phytoplankton (*Botryococcus braunii* and other algae), dinoflagellate cysts, foraminiferal test linings, and fungal spores. For more details, see Tyson (1995).

A total of 500 organic matter particles were counted under the microscope. Percentage calculations and cluster analysis by similarity index were undertaken using the Tilia software package (Grimm, 1987). Palynofacies associations generated by CONISS (Grimm, 1987) were used for paleoenvironmental interpretation. The presence or absence of pyrite crystals was noted in parallel to the palynofacies analysis. Organic matter-iron interactions are important to pyrite growth in marine sediments (Morse and Wang, 1997), and the presence of this mineral in the sediments can be used to provide past environmental conditions.

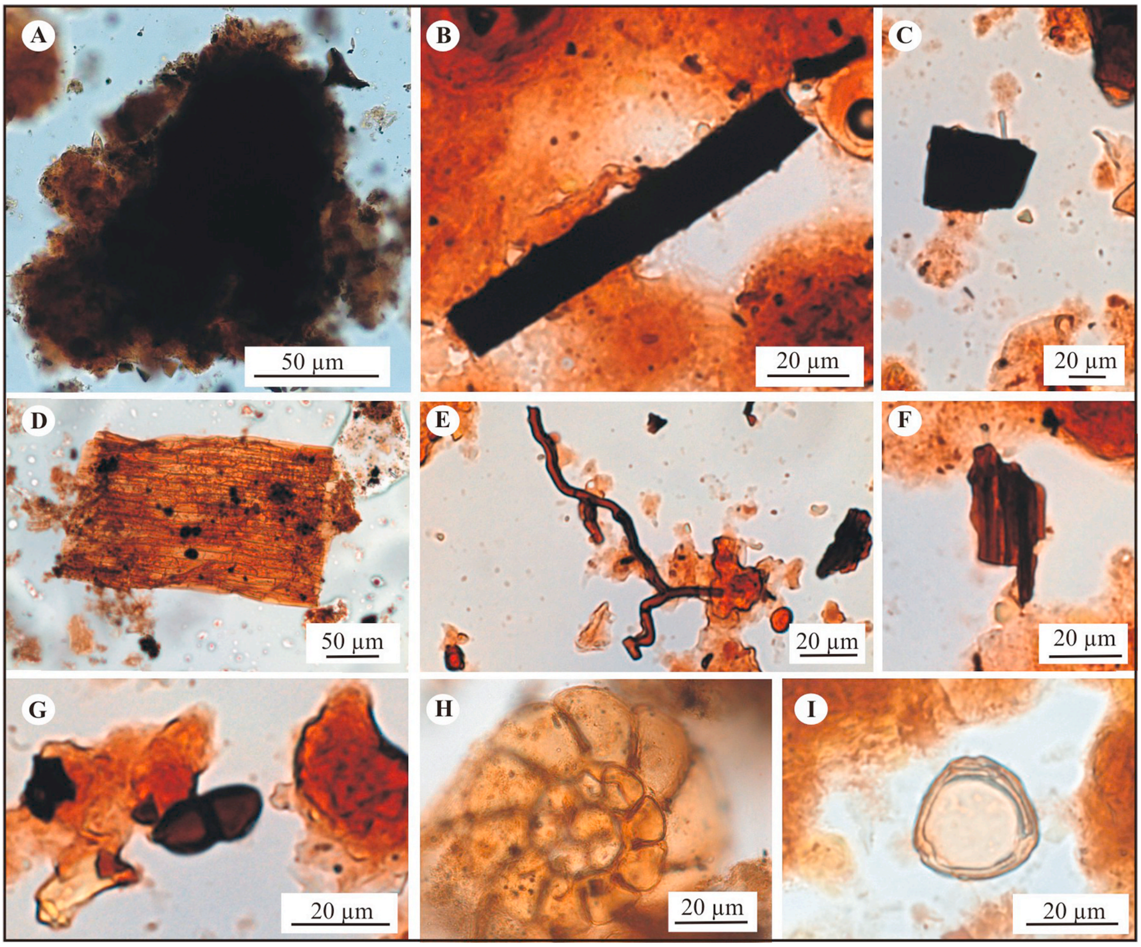

Fig. 2. Particulate organic matter viewed components under transmitted white microscopy. **A.** Amorphous group. **B.** Elongate opaque phytoclast. **C.** Equidimensional opaque phytoclast. **D.** Cuticle. **E.** Fungal hyphae. **F.** Biostructured striped non-opaque phytoclast. **G.** Fungal spore. **H.** Foraminiferal test lining. **I.** Pollen grain.

3. Results

3.1. ^{14}C dating

Although the ^{14}C ages for PR07 has already been published by Fontes et al. (2017), we maintained the radiocarbon ages as a separate item in this study to facilitate the understanding of the core chronology Table 1. The oldest age for the core is recorded at 447 cm (~7.4k cal yr. BP), and mean ages calibrated for the other samples were ~7.3k cal yr. BP (393 cm), ~6.3k cal yr. BP (213 cm), ~5.3k cal yr. BP (171 cm), ~3.8k cal yr. BP (107 cm), and ~2.4k cal yr. BP (53 cm). No age inversions are observed and the averages of the calibrated ages are used throughout the text. Sedimentation rates range from 0.22 to 11 mm/yr.

3.2. Organic geochemistry

Total sulfur concentration (S) values range between 0.15% (180 cm) and 5.9% (420 cm), and C/S ratios vary from 0.12 (440 cm) to 41.5 (10 cm). C/S ratios were calculated using total organic carbon data published by Fontes et al. (2017). Figs. 3 and 4 illustrate the S and C/S results.

3.3. Diatoms

Twenty-one diatom taxa were identified, 13 of which can be found in marine and/or brackish water environments. Three zones are recognized (Fig. 5) at intervals 450-360 cm (Zone I), 360-290 cm (Zone II), and 290-200 cm (Zone III). No diatoms were recovered in the uppermost 200 cm and no exclusively freshwater diatoms were described from the core.

3.3.1. Zone I (450-360 cm: ~7.4k cal yr. BP to ~7.1k cal yr. BP – interpolated age)

This zone consists mainly of brackish/marine, and to a lesser extent,

Table 1
^{14}C ages and sedimentation rates of the PR07 core (modified from Fontes et al., 2017).

Laboratory Number	Depth (cm)	Sample	Age conventional (^{14}C yr. B.P.)	Age (cal yr. BP, 2σ)	Mean calibrated age (cal yr. BP)	Deposition time (mm/yr)
UGAMS20331	53	Sediment	2380 ± 20	2347–2459	~2400	0.3
UGAMS20332	107	Sediment	3550 ± 20	3822–3900	~3861	0.4
UGAMS20333	171	Sediment	4760 ± 30	5325–5411	~5350	0.5
UGAMS20334	213	Sediment	5550 ± 25	6274–6355	~6300	1.7
LACUFF140149	393	Sediment	6488 ± 100	7244–7575	~7350	11
LACUFF140004	447	Sediment	6536 ± 38	7415–7513	~7400	

UGAMS = University of Georgia, USA; LACUFF = Fluminense Federal University, Brazil.

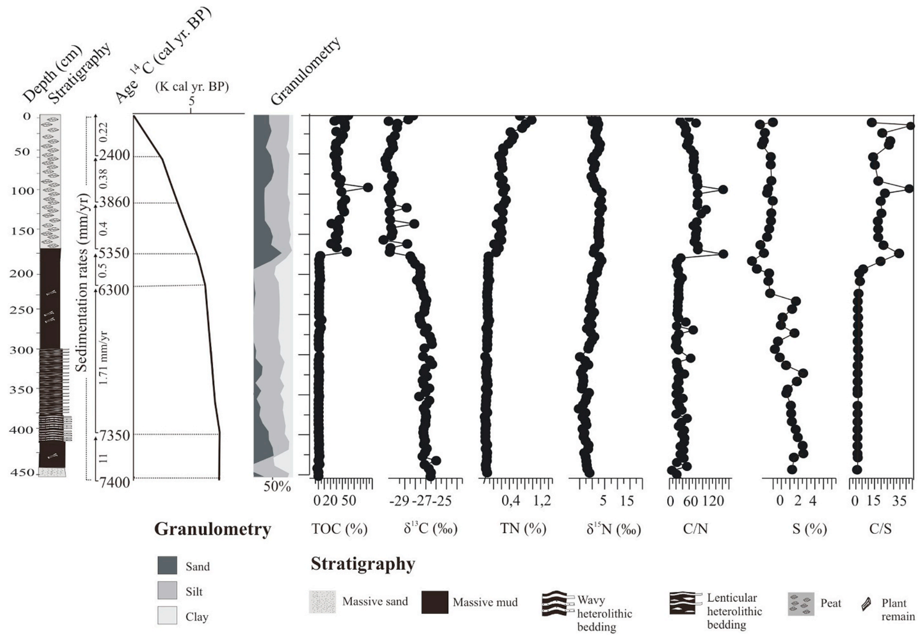

Fig. 3. Stratigraphy, sedimentation rates and ^{14}C ages, granulometry, total organic carbon (TOC), δ^{13}C, total nitrogen (TN), δ^{15}N, C/N (weight/weight), total sulfur (S), and C/S (weight/weight) values.

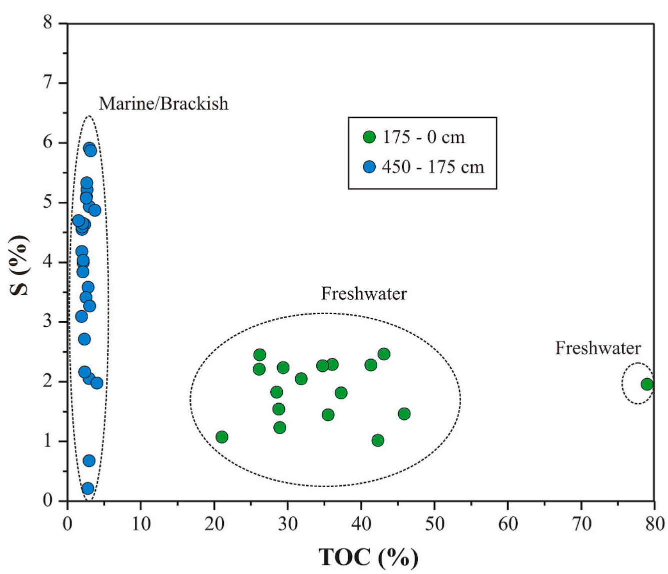

Fig. 4. S vs. TOC of PR07 organic matter. The interpretation was based on data by Berner and Raiswell (1984).

marine diatoms (Fig. 5). The most abundant species are *Diploneis gruendleri* (28–45%), *Paralia sulcata* (15.7–43%), and *Tryblionella granulata* (5–28%). *Cyclotella meneghiniana* (1.2–8%), *Tryblionella granulata var. elongata* (0.9–6%), *Actinoptychus senarius* (0.4%), and *Diploneis smithii* (0.7–3%) are also present. Marine diatom is represented mainly by *Cymatotheca weissflogii* (0.6–5%).

3.3.2. Zone II (360-290 cm: ~7.1k cal yr. BP to ~6.7k cal yr. BP – interpolated ages)

Mainly brackish/marine diatoms (Fig. 5) also characterize zone II. *Diploneis gruendleri* (14–51%) is the most abundant species, although its numbers are fewer compared to Zone I. *Tryblionella granulata* (17–34%) significantly increases in comparison to Zone III. *Paralia sulcata* is also present (4–20%). *Tryblionella granulata var. elongata* (1.9–7%) and *Cyclotella meneghiniana* (3–6%) are more prominent compared to the Zone I. *Cymatotheca weissflogii* (0.7–27%), *Coscinodiscus radiatus* (0.2–7%) and *Trachyneis aspera* (0.7–2.7%) represent the marine taxa.

3.3.3. Zone III (290-200 cm: ~6.7k cal yr. BP to ~6k cal yr. BP – interpolated ages)

Brackish/marine taxa remain the most common taxa (Fig. 5). *Diploneis gruendleri* dominates this zone with percentage values between 10% and 79%. *Tryblionella granulata* (17–34%) and *Paralia sulcata* (0.4–24%) are present. *Tryblionella granulata var. elongata* (4–9%) occurs throughout the entire zone. The marine diatom species *Cymatotheca weissflogii* (0.4–43%) shows a significant increase compared to the previous zones.

3.4. Palynofacies analysis and resulting associations

Two associations of particulate organic matter components were identified and grouped by cluster analysis (Fig. 6). The details of each association are described in the following.

3.4.1. Association I

The amorphous group (AG: $\bar{x}$ = 69.9%) is the main component of association I (460-175 cm: ~7.4k to ~5.3k cal yr. BP), followed by non-opaque phytoclasts (NOP: $\bar{x}$ = 24.5%), opaque phytoclast (OP: $\bar{x}$ = 3.2%), and palynomorphs (PAL: $\bar{x}$ = 2.2%). Among non-opaque phytoclasts, non-biostructured particles and cuticles are predominant. Fungal hyphae and striped non-opaque phytoclasts also are well represented, averaging 6% and 2.2%, respectively. Biostructured non-opaque phytoclasts appear occasionally. Pyrite crystals are present in all samples in this association.

Mainly fungal spores ($\bar{x}$ = 1.1%) and pollen grains ($\bar{x}$ = 1%) characterize the palynomorph group. Fern spores (triletes, monoletes, ornamented and not ornamented), pollen grains (porates and colpates), freshwater phytoplankton and Botryococcus braunii occur with average relative abundances not exceeding 1%. It is worth noting that the occurrence of foraminiferal test linings ($\bar{x}$ = 0.47%) and dinoflagellate cysts ($\bar{x}$ = 0.05%) in this association suggest marine influence. Lastly, among opaque particles, the equidimensionals ($\bar{x}$ = 2.3%) and elongates ($\bar{x}$ = 1.1%) are predominant, while corroded and biostructured are

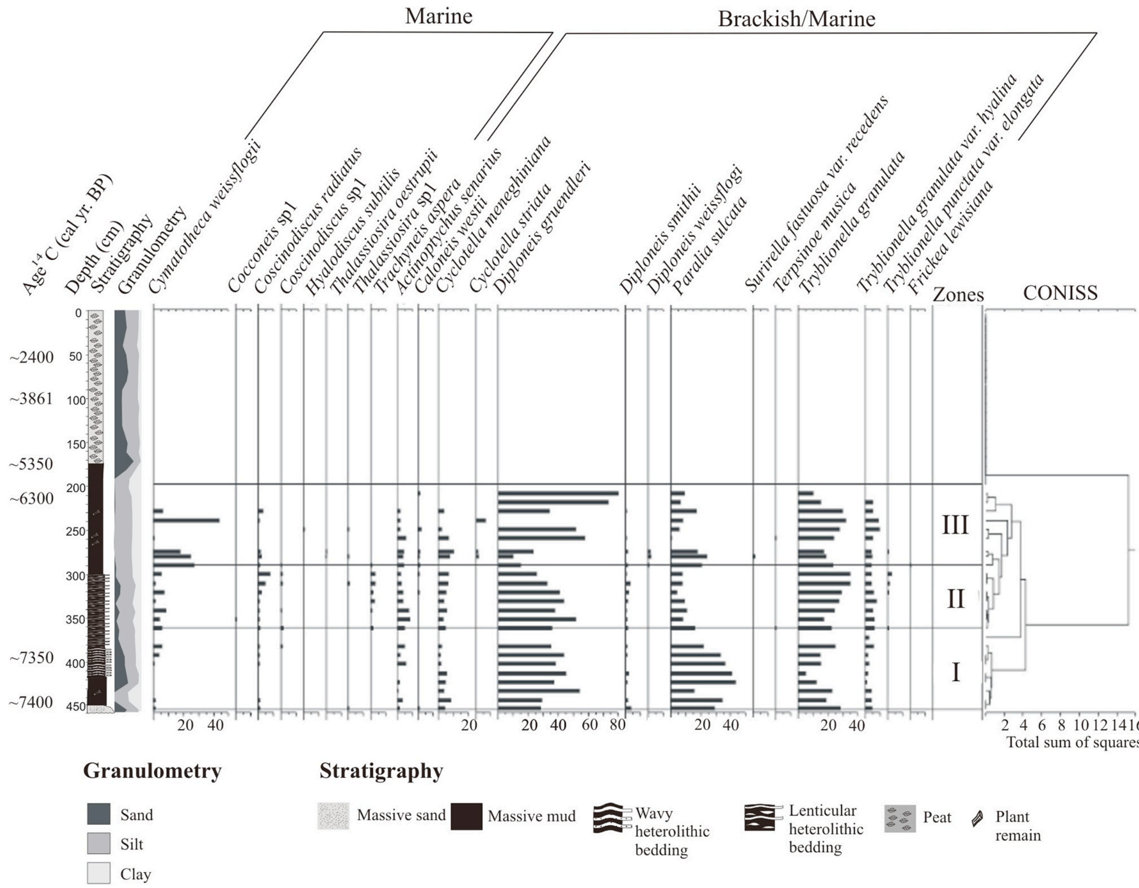

Fig. 5. Relative frequencies (%) of diatoms.

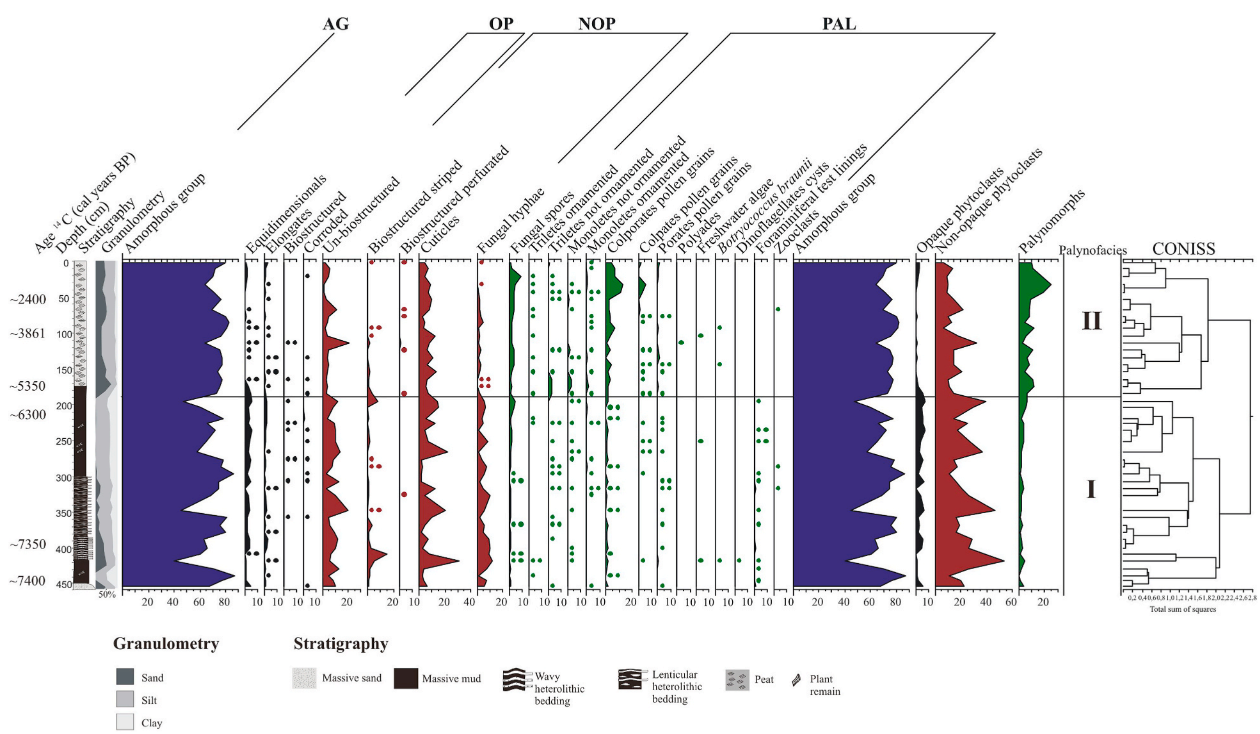

Fig. 6. Relative frequencies (%) of particulate organic matter components. AG: amorphous group. OP: opaque phytoclasts. NOP: non-opaque phytoclasts. PAL: palynomorphs.

underrepresented.

3.4.2. Association II

The particulate organic matter in association II (175-0 cm: ~5.3k cal yr. BP to present) is composed of the following components: AG ($\bar{x}$ = 72.1%), NOP ($\bar{x}$ = 16.7%), PAL ($\bar{x}$ = 8.7%), and OP ($\bar{x}$ = 2.3%). The frequency of amorphous group and palynomorphs is higher compared to association I. Among non-opaque phytoclasts, cuticles ($\bar{x}$ = 7.7%) and un-biostructured ($\bar{x}$ = 5.8%) remain predominant; however, the un-biostructured are much fewer compared to association I. No pyrite crystals were recorded.

For the palynomorphs group, colporate pollen grains ($\bar{x}$ = 3.4%) and fungal spores ($\bar{x}$ = 2.6%) have the highest percentages values in the core, followed by the colpate pollen grains ($\bar{x}$ = 1,2%). The other palynomorph components do not exceed 1%. Foraminiferal test linings occur in only three samples (193 cm, 233 cm, 248 cm), indicating marine influence in the basal samples of this association. Dinoflagellate cysts are not recorded. Among opaque phytoclasts, the percentages are fairly similar to those of association I. Equidimensionals ($\bar{x}$ = 1.8%) and Elongates ($\bar{x}$ = 1%) remain dominant, followed by corroded and bio-structured with 0.2% each.

4. Discussion

4.1. Tidal flat

The sedimentary facies between 460 and 175 cm depth was interpreted by Fontes et al. (2017) as tidal flat and correspond to the time interval between ~7.4k and ~5.3k cal yr. BP. These facies consists of massive muds, massive sands, and lenticular and wavy heterolithic beddings. Bioturbation signals and plant remains were also recorded. This depositional phase is defined as a tidal flat with sand deposition and well-developed wavy bedding at the base topped by intertidal muddy and lenticular bedded deposits. The fining-upward facies succession and accumulation of mud represents tidal channel abandonment (Fontes et al., 2017). Heterolithic bedding near littoral settings, in general, are commonly interpreted as intertidal deposits created by the deposition of sediments in low-energy coastal environments (De Backer et al., 2010), and shallow areas flooded during the high tide that emerge during low tide periods (Augustinus, 1995).

Mostly brackish/marine taxa such as *Diploneis gruendleri*, *Tryblionella granulata*, *Paralia sulcata*, *Tryblionella punctata* var. *elongata,* and *Cyclotella meneghiniana* represent the diatom assemblage in this sedimentary interval. These brackish and marine species can be found in tidal flats, which experience fluvial and marine influences (Augustinus, 1995). Most of the diatoms identified have well-preserved frustules without signs of redeposition, reworking, or any other conditions that are not favorable for their preservation (e.g., natural chemical dissolution, diagenesis, predation).

The dominant species, *Diploneis gruendleri* and *Tryblionella granulata*, have a benthic habit, a high degree of silicification and preservation of their valves, and in turn, tend to be better represented in the sediment samples. Both taxa occur in coastal wetlands such as mangroves and estuaries, and present salinity optimum of ~18‰ (Gaiser et al., 2005). *Paralia sulcata* is a tycoplanktonic polihaline diatom frequent in estuaries and lagoons with salinity ranging up to 22‰ (Hassan et al., 2009). *P. sulcata* was also recorded in Holocene estuarine sediments in coasts of Brazil, Argentina and Uruguay, which can indicate marine transgression and similar past environments with high salinity (García-Rodríguez et al., 2004; Medeanic et al., 2009; Hassan et al., 2009; Santos-Fischer et al., 2016). The centric diatom *Cyclotella meneghiniana* is a planktonic euryhaline species able to grow in estuarine salinity gradient (Roubeix and Lancelot, 2008).

The typical marine species recorded in the PR07 core (*Coscinodiscus radiatus*, *Cymatotheca weissflogii*, *Thalassiosira oestrupii*) are allochthonous planktonic forms transported into the tidal flat during periods of greater marine influence. These planktonic forms had intact frustules with details of their well-preserved ornamentations. Their preservation may be related to the more resistant characteristics of their valves, as well as the depositional environment. The deposition of clayey sediments under low energy conditions minimizes mechanical shocks between the sediments and diatom valves without causing physical damages and structural properties to the valves. According to Mitbavkar and Anil (2002), diatoms from the water column, represented by planktonic forms and deposited under low energy conditions, are less subject to the abrasion and dissolution processes in intertidal settings.

Components of the particulate organic matter described for this sedimentary interval corresponds to palynofacies association I, which is dominated by the amorphous group. Amorphous group generally dominates the organic matter assemblage in response to the environmental conditions of dysoxia-anoxia (Batten, 1996), but it can also be exposed to different oxygenation conditions during its deposition (Valdés et al., 2004). The dominance of AG in the tidal flat is mainly related to the biodegradation of land plants and can be associate with root and plant tissues which were oxidized in the presence of abundant water (Tyson, 1995). As a tidal flat environment receive fluvial and marine influence, we did not discard the amorphous organic matter derived from phytoplankton as well.

Non-opaque phytoclasts also has high percentages in this sedimentary interval and reflect the proximity of the fluvial source, oxic conditions, or sediments transported by surface runoff (Tyson, 1995). Un-biostructured non-opaque phytoclasts, identified in some studies as gellified particles (e.g. Boussafir et al., 2012; Zocatelli et al., 2012), and cuticles were predominant, suggesting the influx of freshwater organic matter into the sedimentary basin (Boussafir et al., 2012). In addition, non-opaque phytoclasts may have originated from the surrounding vegetation and transported by river currents. Another point worth mentioning is the occurrence of fungal hyphae as one of the most frequent elements in the non-opaque phytoclasts subgroup since they are generally associated with sediments rich in plant remains (Batten, 1996).

According to Lallier-Verges et al. (1998), un-biostructured non-opaque phytoclasts are common in areas of high mangrove concentration. These particles could have originated from the aerial roots of mangrove plants, such as *Rhizophora, Avicennia,* and *Laguncularia*. Fontes et al. (2017) interpreted this interval as a sub-environment of tidal flat associated with mangrove vegetation composed mainly of *Rhizophora* and *Avicennia*. Thus, the presence of un-biostructured non-opaque phytoclasts can be related with the presence of mangrove plants during this period.

The presence of foraminiferal test linings and dinoflagellate cysts (*Spiniferites* sp.) in palynofacies association I indicates marine influence in the sedimentary environment. Foraminiferal test linings are reliable indicators of marine conditions and occur in transitional environments such as estuarine systems (Tyson, 1995), which have similar stratigraphic characteristics with tidal flats. Dinoflagellates are mainly marine algae that are sensitive to environmental factors such as light, water temperature, salinity, nutrient levels, and circulation currents (Batten, 1996). The rare occurrence of these microorganisms in the core may be due to environmental variations, such as in salinity, which did not favor their proliferation and preservation in the sediments.

Oboh (1992) described particulate organic matter in the Middle Miocene of the Niger Delta, Nigeria, where the dominance of AOM and non-opaque phytoclasts, and abundant grass pollen and mangrove pollen grains indicated a lagoon/tidal flat and prodelta sub-environments, which are comparable to palynofacies association I in the PR07 core. In a particulate organic matter analysis performed on the island "Tierra del Fuego" (Argentina), Grill et al. (2002) identified two associations that represent a low energy, anoxic marginal marine environment located near the entrance of terrigenous material. They also recorded the predominance of AOM (60–70%) and the occurrence of dinoflagellates, foraminiferal test linings, and pyrite crystals, similar to palynofacies association I. In the process of sulfate reduction, the produced H_2S gas tends to react with iron forming pyrite, especially in anoxic environments. Pyrite crystals were present in all the samples in palynofacies association I. Pyrite is abundant in sediments with algae and amorphous organic matter of marine origin (Batten, 1996), which would also reinforce the marine influence in the studied sedimentary deposit.

Elemental and isotopic values indicate a mixture of terrestrial C_3 plants and freshwater and/or marine phytoplankton as the sources of the organic matter preserved in tidal flat sediments. Organic matter produced by C_3 land plants (Calvin-Benson pathway) has an average $\delta^{13}C$ value of −27‰ (−32‰ to −22‰; Meyers, 1997), which is comparable to the $\delta^{13}C$ values of −24‰ to −26.1‰ recorded. Similarly, the C/N values recorded (7.3–60.4) suggest autochthonous (phytoplankton: C/N < 10) and allochthonous (terrestrial plants: C/N > 20) organic matter in the sedimentary basin. The C/S ratio can be used to distinguish sediments of marine (C/S: 0.5 to 5) or freshwater (C/S > 10) origin (Berner and Raiswell, 1984). C/S values varied from 0.1 to 17.4 in the topmost sample of the sequence, and reflect an increase in freshwater influence toward the top of the interval. C/S can be calculated from the amount of dissolved sulfate available and the formation of pyrite in the samples, which corroborate with pyrite crystals noted in the palynofacies association I.

In our study area, a tidal flat along a fluvial valley developed with mangrove vegetation and estuarine organic matter between ~7.4k cal yr. BP and ~5.3k cal yr. BP (Fontes et al., 2017). Furthermore, studies reveal that the paleoenvironmental evolution of the south coast of Bahia was conditioned mainly by transgressions and regressions during the Quaternary (Fontes et al., 2017; Moraes et al., 2017; Cohen et al., 2020). During transgressive episodes, low river courses were drowned by the sea, forming estuaries, whereas the coastline developed and Pleistocene and Holocene marine terraces formed during regressive episodes (Martin et al., 1993b). According to Martin et al. (1993b), the current sea-level was above zero about 7.1k yr. BP between Caravelas and Nova Viçosa in Bahia (including Prado), and this agrees with the relative sea-level curve established for Salvador by Suguio et al. (1985). Fontes et al. (2017) suggested that the relative sea-level along the littoral zone of Prado was between 0 ± 1.35 m and 0.55 ± 1.35 m at circa 7.4k cal yr. BP, and a highstand of about 2.75 ± 1.35 m occurred during the mid-Holocene. The tidal flat would have evolved during this time interval of higher relative sea-level in the region, which explains the drowning of the fluvial valley and the formation of an estuarine system.

Sea-level changes are considered one of the most important driving forces in coastal depositional systems (Woodroffe et al., 2015). However, the climate component may prevail over the relative sea-level component in areas where there is fluvial discharge (Fontes et al., 2017). Therefore, it is important to consider the effects of these and other factors on coastal system dynamics, as described for estuarine environments during the Holocene (Cohen et al., 2012; Pessenda et al., 2012; França et al., 2015).

$\delta^{18}O$ isotopic variation in speleothems in Rio Grande do Norte State, northeastern Brazil, yielded the lowest values between 10.5k and 5k yr. BP when insolation was at its minimum. The climate was wet in northeastern Brazil during the early and middle Holocene, in contrast to the water deficit scenario for the same period in the majority of eastern South America (Cruz et al., 2009; Prado et al., 2013). A low austral summer insolation during the middle Holocene resulted in a decrease in precipitation over the South Atlantic Convergence Zone, which affected most of Brazil with the exception of the northeastern region (Prado et al., 2013).

North of Espirito Santo State, ~300 km from Prado, Buso Junior et al. (2013) verified through palynology of lake sediments high humidity levels between 7k yr. and 4k yr. BP. The humidity was probably maintained during the entire year due to the intensification of the monsoon system in the summer, and to the advection of polar air masses during the winter (Buso Junior et al., 2013). The polar advections probably provided enough humidity to maintain the tropical forest in the region.

The PR07 core was sampled ~23 km inland from the current coastline and with ~70 m of topographic difference between the fluvial terrace and the adjacent plateau, where Atlantic Forest dominates. Palynofacies and diatom analyses probably reflect an often-flooded environment with sufficient humid conditions. According to Fontes et al. (2017), there were no significant changes in the forest-covered plateau during the middle Holocene, since the humidity prevailed and the fluvial terrace ecosystems changed mainly driven by relative sea-level changes.

4.2. *Fluvial plain*

Massive dark gray organic mud with roots and leaves characterize the fluvial plain facies deposited between 175 cm and the top of the core, which corresponds to the last ~5.3k yr. BP (Fontes et al., 2017). The disappearance of diatoms in the topmost samples of the core is possibly due to the greater fluvial contribution and, consequently, the low adaptation of the diatoms to low salinity conditions. According to the estuarine salinity gradient (i.e. fluvial predominance zone, mixed zone, and marine predominance zone), the marine species become more dominant with salinity increase, and they decrease in areas with greater fluvial contribution (Kaiser, 2005).

AG and NOP were the dominant particulate organic matter components in the sediments. Similar to the previous phase, amorphous group is mainly indicative of land plants degradation, which is common in wetlands under wet conditions. Furthermore, the poor sand samples corroborate with this interpretation. Non-opaque phytoclasts were also recorded in abundance, and an inversely proportional relationship between AG and NOP was observed. High relative frequencies of phytoclasts could be reflective of both the proximity of the river source and the dispersion of the other components of particulate organic matter (Batten, 1996). Thus, the inversely proportional relationship noted between AG and NOP confirms periods of greater fluvial inflow, as occur in fluvial plains.

In a study in Argentina, Grill et al. (2002) defined AOM (~60%) as a predominant element in the particulate organic matter association of a fluvial environment. According to the authors, AOM may be related to degraded cuticles and/or poorly lignified tissues modified by bacteria in a subaquatic environment with reducing conditions. The main component of the non-opaque phytoclasts of association II were the cuticles, which could suggest a similarity to the origin of AOM recorded by Grill et al. (2002). In addition, un-biostructured non-opaque phytoclasts are abundant and likely indicative of biochemical oxidation related to bacterial and fungal activity in a subaquatic environment (Tyson, 1995; Grill et al., 2002).

There was an increase in the percentage values of palynomorphs, represented mainly by the pollen grains and fungal spores. According to Fontes et al. (2017), the pollen grains identified in the PR07 core reflects the proximity of parental vegetation, while fungal spores may be related to periodic floodings, such as experienced along rivers and streams (Grill et al., 2007). An increase in pollen grains of trees, shrubs, and palms occurred during the late Holocene, while mangrove pollen grains were absent (Fontes et al., 2017).

Lorente (1990) characterized organic matter components in a sub-flood plain under wet and dry conditions in the Orinoco River delta region, Venezuela. According to her, the predominant components of organic matter in the floodplain under wet conditions were the cuticles, fungal remains, equidimensionals opaque phytoclasts, and degraded material, while the dry season was characterized by oxidizing conditions, low sedimentation rate, and absence of delicately preserved tissues. Thus, association II of the PR07 core is similar to the wet season floodplain data described by Lorente (1990).

Isotopic and elemental results of this facies association indicated an increase in the organic matter concentrations (TOC: 4.1%–78.9%), a greater continental influence on sedimentary organic matter (NT: 0.1%; $\delta^{15}N$: 4.1‰–8.4‰, C/N: 29.5 to 152.9), predominance of C_3 plants

(δ^{13}C: 26‰ to −28.6‰), and no marine influence (S: 1.0%–2.4%, C/S: 10.6 to 41.5).

Although some studies show that the relative sea-level was above the current on the coast of Bahia in 4.5k yr. BP (e.g. Martin et al., 1993b), no indicators of marine influence were recorded for that period in the Jucuruçu River valley. Similarly, Fontes et al. (2017) did not record mangrove pollen grains in the fluvial plain facies' association. According to them, after ~5k a BP there was the retraction and local disappearance of the mangroves and higher rainfall rates likely influenced the plateau vegetation, since an increase of trees and shrubs pollen was recorded.

During the middle and late Holocene humidity conditions prevailed in southeast coast of Brazil, and that an increase in rainfall indexes resulted in the increase in fluvial flow (Cohen et al., 2014; França et al., 2015; Lorente et al., 2018). Therefore, the humid climate in south Bahia State led to the reduction of salinity, the retraction of mangroves, and the subsequent development of freshwater vegetation. Changes in rainfall caused variations in river discharge and due to a progressive reduction in water salinity, the mangroves receded to current tidal flats and the nearest coastal lagoons (Fontes et al., 2017).

Similar studies indicate that after ~5k yr. BP, estuaries that previously formed during the Holocene high stand in the northern coast of Espirito Santo, ~350 km south of the study site, gradually closed by the accumulation of sand in barriers at its mouth (Buso Junior et al., 2013; Castro et al., 2013; Cohen et al., 2014; Lorente et al., 2014). As the estuary was being closed, marine influence was reduced and replaced by greater fluvial influence in the basin. According to Cohen et al. (2014), the late Holocene in the northern coast of Espírito Santo was characterized by an increase in fluvial sediments and the formation of progradational deposits, with the reduction of mangroves and the expansion of marshy areas colonized by herbaceous vegetation.

The modern climate in the northern coast of Espirito Santo was established from 4k yr. BP when summer insolation reached values similar to the present, and the ITCZ migrated southward towards its present position (Buso Junior et al., 2013). The present study in the Jucuruçu River valley is comparable to the Espírito Santo data. Moreover, reversals of longshore sand transport were recorded in the Rio Doce coastal plain due to El Niño-like conditions during the last 5k years. During these events, the polar frontal systems are blocked in southern Brazil, which generates an anomalously high rainfall in the blocking zone and drought in the regions northward (Martin et al., 1993a). Although ENSO events were recorded for the late Holocene in the eastern Brazilian coast (Bittencourt et al., 2000), the resolution of our data is not adequate to affirm if these events played a role in the Jucuruçu River valley evolution. Palynofacies integrated with total S, C/S, and diatoms allowed us to reinforce that origin and deposition of the particulate organic matter in the studied area was influenced mainly by a highstand in the mid-Holocene, and posterior higher fluvial inflow in the last ~5k years.

5. Conclusions

Palynofacies, diatoms, total S and C/S on the PR07 sediment core collected in a fluvial valley in northeastern Brazil allowed us to describe the paleoenvironments during the Holocene for the region. The sediments deposited between ~7.4k yr. and ~5.5k yr. BP was characterized by amorphous group, non-opaque phytoclasts, pyrite crystals and marine/brackish organisms such as dinocysts, foraminiferal test linings, and diatoms. The establishment of the tidal flat under marine and fluvial influences occurred during the Holocene due to sea-level highstand. The last ~5k yr. BP reflect a regressive period, with the formation of a floodplain, increased river flow, and no marine influence recorded. The characterization of the particulate organic matter, in association with elemental S analysis, C/S ratios, and diatoms in this study is unprecedented for the southern region of Bahia State. Palynofacies analysis was shown to be an efficient tool in studying wetlands that were influenced by relative sea-level changes during the Quaternary and can be used as a correlating analysis with other different proxies due to its versality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Flávio Lima Lorente: Conceptualization, Investigation, Visualization, Writing - original draft. **Darciléa Ferreira Castro:** Investigation, Writing - review & editing. **Mariah Izar Francisquini:** Investigation, Writing - review & editing. **Luiz Carlos Ruiz Pessenda:** Supervision, Funding acquisition, Resources, Writing - review & editing. **Neuza Araújo Fontes:** Writing - review & editing. **Marcelo Cancela Lisboa Cohen:** Writing - review & editing. **José Albertino Bendassolli:** Resources. **Marisa de Cássia Piccolo:** Resources. **Kita Macario:** Resources.

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