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I dedicate it to my parents

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Summary

During the Holocene, the environment in northeastern Brazil has changed mainly due to climate dynamics, human activities, and in the coastal area, sea-level oscillations. However, little is known about the environmental history of this region due to a lack of palaeoenvironmental studies. To improve the understanding of these impacts, a multi-proxy analyses have been conducted and discussed in this thesis focused on the long-term changes.

In the eastern part of northeastern Brazil, a palaeoenvironmental study has been developed in a mire at the Catimbau National Park, State of Pernambuco, to reconstruct the climate changes and the human impact during the last 2800 cal yr BP. The study site is located in the semi-arid Caatinga dry forest, and the results distinguished three distinct environmental periods. From 2800 to 2150 cal yr BP, the vegetational composition had a predominance of *Cecropia*, indicating a dry condition in a strong disturbed environment. The indicators suggested a presence of humans in the region since the beginning of the record, which became more intense in the followed period from 2150 to 450 cal yr BP. In this interval occurred an increase of arboreal vegetation indicating wetter conditions. Conditions which were favorable for the local community expansion and, as consequence, their stronger influence on the environment. The evidence of humans was corroborated with the presence of pollen grains of *Phaseolus* (beans) and *Orbignya* palm (babaçu). After 450 cal yr BP, the analysis showed a return of drier conditions associated with more open vegetation, and a decline of the local population.

The northern part of northeastern Brazil, two studies were carried out in the Maranhão State coastal zone to understand the climate change, sea-level oscillations, and the human impact. The study areas are located more than 120 km far from the current coast. However, the records showed a presence of mangrove coastal ecosystem since around 8000 cal yr BP, suggesting the

transgression of the Atlantic Ocean during the early to mid-Holocene. The palynological, mineralogical and chemical parameters indicated a highstand of the sea-level between 5500 and 5020 cal yr BP. The mangrove displacement had also been influenced by the climate changes, which showed a tendency for the drier condition from around 8000 until 5000 cal yr BP. After 5000 cal yr BP, the sea-level dropped, the freshwater supply increased, and the arboreal vegetation, typical from Amazon rainforest, expanded due to wetter conditions. Those conditions were responsible for the abandonment of the mangroves from the study area. Since around 2500 cal yr BP, the records suggested the presence of Amerindians in the study areas. Both sites were the first palaeoenvironmental reconstruction of archaeological sites in the region to understand their impact on the landscape. Unique anthropological evidence suggested that the Amerindians were living upon the rivers and the lakes in stilt-house settlements, making those evidence the only ones found from the pre-colonial period in South America.

CHAPTER 1

1.1 Introduction

1.1.1 Mangroves and sea-level oscillations in Brazil

Mangrove is a coastal ecosystem of transition between terrestrial and marine environments, subject to constant tidal influence and characteristic of tropical and subtropical regions. Its latitudes' distribution is limited where the coldest monthly mean temperature is above 20°C, and the annual thermal amplitude is less than 5 °C (Giri et al., 2011), therefore, cold temperatures have limited its distribution limits in the northern to around 30°N, and in the southern to 30°S (Giri, 2016). The total mangrove forest area of the world in the year 2000 was 137,760 km^2 in 118 countries and territories, accounting for less than 1% of total tropical forests of the world (Giri et al., 2011).

The ecological term “Mangrove” referred to a taxonomically diverse assemblage of trees and shrubs that are formed by the dominant plant communities in tidal and saline wetlands (Blasco et al., 1996). Its substrate is composed of muddy sediments rich in organic matter and, the main variables that define the degree of development of mangroves are the temperature, soil type, salinity, duration and frequency of inundation, accretion of silt, tidal and wave energy, besides some periodic factors as cyclones or floods (Lugo et al., 1974). The growth of mangrove forests is the result of the best combination of these variables, under ideal conditions, forests can achieve up to 45 meters in height, for example in Ecuador, Cameroon, Thailand, and Malaysia. In contrast, where less favorable conditions are found, mangrove communities may reach maturity at heights of around 1-2 meters like on the arid coasts of the Arabian Gulf, Rajasthan, South Madagascar, Australia, and New Zealand (Blasco et al., 1996).

In Brazil, mangroves occupy an area of approximately 8000 km^2 (Souza Filho, 2005) found from the extreme northern Brazilian coast in the Oiapoque River (04°20′N) to Laguna, State of Santa Catarina (28°30′S) on the southern coast (Schaeffer-Novelli, 2000). Due to wide diversified environmental conditions along the Brazilian coast, the characteristics of the mangrove can be very different. For example, in the north of Brazil, where the environmental conditions are good for its development, *Rhizophora* taxa can be found up to 40 m high. On the other hand, in the south of the country, the same taxa can be found at a 1.5 m high (Schaeffer-Novelli et al., 1990). Along the Brazilian coast, there are occurrences of only four genera and seven species of mangroves. The main genera are *Rhizophora*, *Laguncularia*, and *Avicennia*, which occur as shrubs and trees, and have a different pattern of occurrence. *Rhizophora*, mostly occupies areas with higher tidal influence, at lower levels, and with high frequency and duration of inundation. *Avicennia* and *Laguncularia* colonize higher levels areas, with lower frequency and duration of tidal inundation, however, *Laguncularia* can be found mostly in recent sedimentation areas (Schaeffer-Novelli et al., 1990). Mangrove has also special physiological and morphological adaptations that allow it to grow in intertidal environments, which makes this ecosystem be used as a good indicator of coastal environmental change (Blasco et al., 1996). Therefore, its characteristics are widely used by palaeoecologists to understand the variations in sea-level.

Figure 1.1 World mangrove distribution and its maximum canopy height modified from Simard et al. (2019).

Mangroves can be a key ecosystem to understanding the sea-level oscillations along the Quaternary. During the Last Glacial Maximum, about 21,000 cal BP, the Atlantic sea-level was around 120 m lower than today (Shackleton and Opdyke, 1973). Nevertheless, during the early Holocene, the Atlantic sea-level started to rise, achieving higher levels until it inundated the Brazilian coastal shelf. In Brazil, many palaeoecological studies have used mangrove dynamics to reconstruct the environment during the Holocene (Behling, 2001; Behling et al., 2004; Behling and Costa, 2001, 1997; Fontes et al., 2017; França et al., 2015, 2013; Guimarães et al., 2012b, 2012a). However, its variation is still not under complete agreement.

Along the coast of the northeast and southeast Brazil, the mangroves have been controlled mainly by sea-level oscillations. In the Bahia State, Fontes et al. (2017) showed that during the mid-Holocene occurred a progressive increase in the sea-level with marine incursion up to 34 km inland. This transgression was responsible to form an estuarine system with tidal flats colonized by mangroves around 7400 and 5350 cal yr BP, reaching its highstand about 5350 cal yr BP with 2.7 ± 1.35 m. Afterward, the sea-level fell and, in consequence, the mangroves were reduced. On the Rio Grande do Norte coast, the sea-level reached the current level at ~7000 cal yr BP (Ribeiro et al., 2018), while the highstand, with about 1.3 m high, was reached at ~5900 cal yr BP (Boski et al., 2015). Further south, in Espírito Santo State, the sea-level rise also caused a marine incursion, developing an estuarine system dominated by mangroves during the early to mid-Holocene. The mangroves have been replaced by other arboreal and herbaceous vegetation between around 5252 and 1355 cal yr BP when the sea-level fell (França et al., 2015, 2013).

Variations in sea-level during the Holocene also have been proposed by other authors using different tools such as sedimentary deposits, vermetids, shellmounds ("sambaquis"), among others (Angulo et al., 2006; Bezerra et al., 2003; Caldas et al., 2006; Martin et al., 2003; Suguio et al., 2013). Martin et al. (2003) have proposed that the coastline of Salvador (NE Brazil) was in the submergence phase until achieve the present zero for the first time in the Holocene at about 7800 cal yr BP. Around 5600 cal yr BP, the relative sea-level went through the first maximum of 4.7 ± 0.5 m above the present level, followed by the sea-level regression. However, the authors proposed that the sea-level did not fall continuously, which suggests sea-level under the present zero in two more main events, followed by emergence phases (between 3500-2800 and after 2100 cal yr BP). For the coasts of Pernambuco and Paraíba, Suguio et al. (2013) suggested the sea-level crossed the current level at approximately 7400 cal yr BP and achieved its maximum between 4000-5000 cal yr BP with 3 m above sea-level. Afterward, the sea-level dropped to the current level with two slight oscillations phases. The same envelope curve patterns have also been proposed by Bezerra et al. (2003) in Rio Grande do Norte. On the other hand, Caldas et al. (2006) and Angulo et al. (2006) proposed a transgression of the sea-level achieving its maximum and followed by a constant fall without oscillations until the current level. Following the proposal of Caldas et al. (2006), the sea-level reached the present position in the Rio Grande do Norte at approximately 6700 cal yr BP, and its highstand was 1.3 m higher than the modern sea-level at around 5900 cal yr BP.

In northern Brazil, the ancient lower elevated coastal ecosystems were destroyed and new ecosystems, such as mangroves developed, replacing the former Amazon rainforest. The first occurrence of mangrove pollen in sediment reflects the early Holocene sea-level rise close to modern levels, with some phases of expansion and shrinkage of mangroves (Behling, 2011). The mangroves started to colonize close to Lagoa da Curuça between 8080 and 6380 cal yr BP, at Lago do Aquiri between 8280 and 7570 cal yr BP, and near Lago Crispim between 8370 and 7520 cal yr BP (Behling, 2001; Behling and Costa, 2001, 1997). In the Aquiri region, about 120 km inland from the modern coastline, the presence of mangroves suggests a significant early Holocene transgression with mangrove vegetation since the beginning of the record, however, the authors suggest an interruption of the sedimentation as a consequence of the marine regression after 6700 yr BP (Behling and Costa, 1997). In Bragança Peninsula, the presence of mangroves at Campo Salgado, the highest elevated site on the peninsula, suggests that the sea-level rose until stabilized close to the current level at 5100 cal yr BP (Behling et al., 2001; Cohen et al., 2005). A more recent study in Bragança Peninsula showed that mangroves were occupying the region from around 6250 to 5850 cal yr BP due to a combination of dry conditions and high sea-level stand (0.6±0.1 m). However, a sea-level fall over the past 4300 cal yr BP and wetter conditions restricted the mangroves to the lowest tidal flats (Cohen et al., 2021). Differently, on Marajó Island, the mangrove vegetation started to colonize the region just during the late Holocene after 2880 cal yr BP (Behling et al., 2004; Guimarães et al., 2012a). Nevertheless, sea-level changes may not be the only factor to influence the mangrove dynamics in coastal regions. Changes in the climate have influenced the regional precipitation and consequently, the freshwater discharges in the rives (e.g., Amazon River; Guimarães et al., 2012b) play an important role in the mangrove's displacements and environmental conditions.

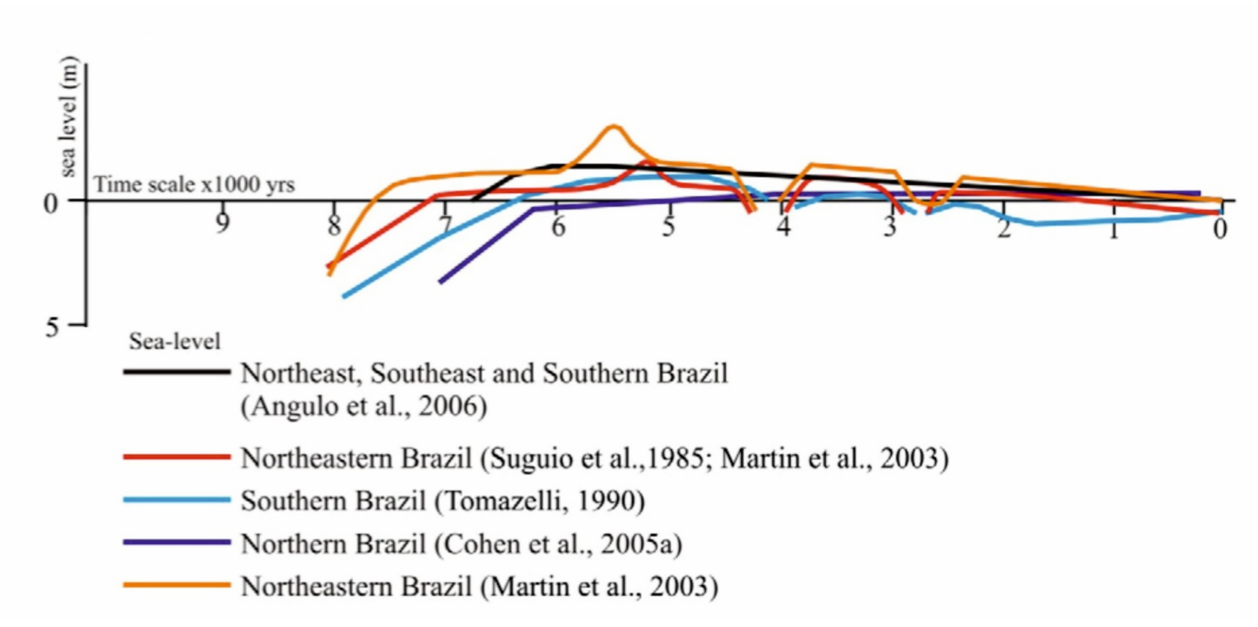

Figure 1.2. Sea-level curves comparison for Brazilian coast during the Holocene, modified from França et al. (2015).

1.1.2 Climate changes during Holocene in northeast Brazil

In Brazil, the climate history during the Holocene has followed different patterns depending on the location. Due to different atmospheric and oceanic circulations, the NE of Brazil has been distinguished into two different climatic areas (Jennerjahn et al., 2004; Wang et al., 2004). The first concerns the eastern coastal area, which is subject to a winter rainy season created by the trajectory of the cold Benguela Current southward along the Brazilian coast. The second concerns the inland and northern part of the NE, which is subject to the Inter Tropical Convergence Zone (ITCZ) seasonal shift and a summer rainy season (Ledru et al., 2006). During summer times, the ITCZ migrates to the southward due to the warming conditions of the continent dividing the year into two main seasons in northern NE: a rainy and a dry season (Martin et al., 1997). Its variations in position are determined by the temperature gradient between the pole and the equator, allowing the convergence zone stays in the warmest hemisphere. However, this seasonal feature can change depending on the position of the South Atlantic Convergence Zone (SACZ) at mid-latitudes in Central Brazil (Ledru et al., 2006). This seasonal configuration is the same that rules the climate in the eastern Amazonia (Behling, 2011).

In the northern NE, the early to mid-Holocene was marked by a tendency to drier conditions (Guimarães et al., 2021; Jacob et al., 2004; Pessenda et al., 2005; Sifeddine et al., 2003). In Maranhão State, Pessenda et al. (2005) showed, through soil isotopes, that the vegetation was dry and open from approximately 10,000 to 6000-5000 yr BP. Likewise, in the same region, intense fires and forest regression have been recorded by (Ledru et al., 2006). In the Carajás, the mid-Holocene was marked by a rapid shift from wetter to drier environmental conditions between 10,000 and 3000 cal yr BP (Guimarães et al., 2021). However, a different scenario has been proposed for the eastern NE during the early to mid-Holocene (Cruz et al., 2009; De Oliveira et al., 1999; Pessenda et al., 2010).

The Mid-Holocene has been characterized by lower incoming summer insolation in the Southern Hemisphere, although the opposite occurred in the Northern Hemisphere. This event reduced land-sea temperature contrast and, therefore, weakened South American monsoon system circulation. The consequence was a water deficit scenario in most parts of eastern South America (SA), with the exception of northeastern Brazil (Prado et al., 2013). Through speleothem study in Rio Grande do Norte, Cruz et al. (2009) indicated that from 10,500-5000 yr BP the climate was marked by wetter conditions over NE. Further south, the same tendency has been recorded in Botuverá Cave, which showed that the transition from early to mid-Holocene was marked by wetter conditions in southeastern Brazil. However, it occurred because of the increased proportion of Amazonian precipitation (Bernal et al., 2016). In studies using speleothem from Paraíso Cave in eastern Amazon lowlands, (Wang et al., 2017) showed that precipitation has been approximately 142% stronger than modern levels about 6000 years ago.

The transition from mid-to late Holocene in northern NE and northern Brazil showed a tendency to wetter conditions. Records from Maranhão showed this transition after about 4000 yr BP when the climate conditions became progressively more humid due to changes in the intensity and the displacement of the ITCZ (Pessenda et al., 2005). The same occurred for Carajás region after 3000 cal yr BP (Guimarães et al., 2021, 2016; Sifeddine et al., 2003). Other studies showed an Amazon rain forest expansion, reflecting a change to wetter climatic conditions, with higher precipitation rates and more extended wet periods, since mid and especially during the late Holocene (Behling et al., 2010; Behling and Hooghiemstra, 2001). Despite the late Holocene being recorded as wetter conditions in northern NE and Amazonia, to the eastern NE most of the studies have shown that during this period the climate was marked by dry conditions (Cruz et al., 2009; De Oliveira et al., 1999; Novello et al., 2012). This trend allowed the typical taxa from Cerrado and Caatinga to increase, mainly after 4000 yr BP, forming the biome boundaries known nowadays. This opposing climatic signal is possibly related to increased ENSO-like phenomena, coupled or not to a northward displacement of the ITCZ (De Oliveira et al., 1999).

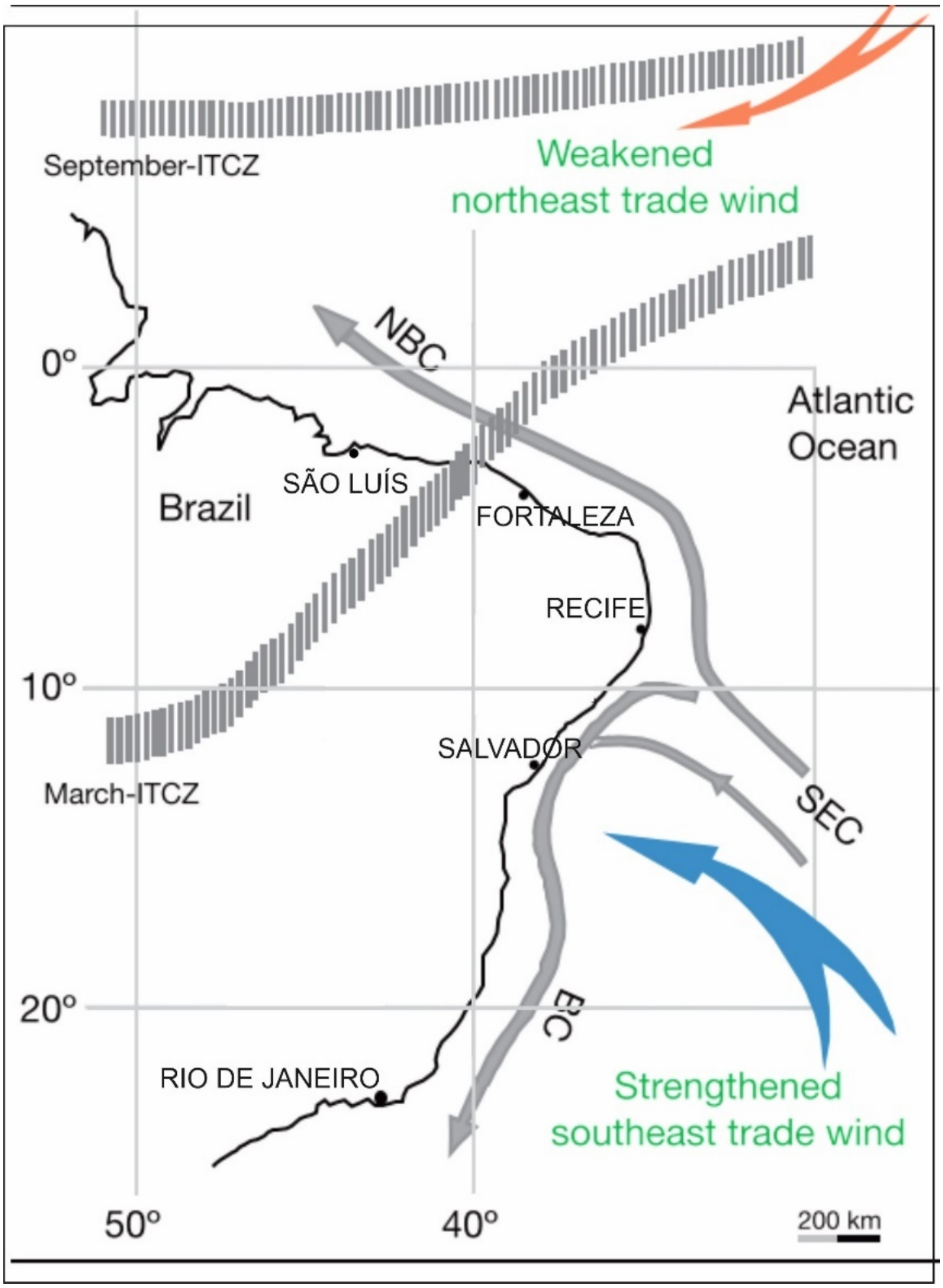

Figure 1.3. Map of coastal zone of Brazil with the present ITCZ seasonal positions, dominant wind directions, and ocean surface currents. Grey arrows indicate dominant surface and near-surface ocean currents: NBC, North Brazil Current; BC,

Brazil Current; SEC, South Equatorial Current. The blue arrow shows the current relatively strong southeast trade wind; the orange arrow represents the currently relatively weak northeast trade wind. Modified from (Wang et al., 2004)

1.1.3 Human influence in northeast Brazil

The first occupation in NE Brazil is still controversial, however, Heredia (1994) suggested that the first inhabitants arrived between 30,000 and 25,000 yr BP in the southeast of the State of Piauí. Other studies indicate that the first evidence of humans in NE Brazil dates from the late glacial, about 12,000 yr BP (Prous and Fogaça, 1999). The most accepted way of coming is from the north, which is now submerged due to sea-level transgression after LGM. Thus, the sites where the man would have exploited the rich marine resources until 7000 BP, are no longer available. Due to wetter conditions during the Holocene, part of the continental sediments was eroded, making it difficult for records preservation. Therefore, few places such as caves, where the sedimentary setting might protect Pleistocene layers from erosion, can preserve the archaeological sites (Prous and Fogaça, 1999).

In the State of Pernambuco, the first evidence is found in Pedra do Caboclo, dating back 11,000 yr BP, in the flat "Agreste" region, situated between huge rocks which formed shelters and small caves (Heredia, 1994). The CNP is considered the second-largest archaeological park in Brazil (Solari and Da Silva, 2017) because of its geological and geomorphological characteristics, making it suitable for human occupation. In the National Park, it is possible to find several rocky shelters with rupestrian paintings, engraving, and other pieces of evidence of prehistoric occupation. Evidence of human influence on the regional environment has been found through the records of palm vegetation such as (e.g., *Orbignya*), which were frequently used by Amerindians (Medeiros et al., 2018; Nascimento et al., 2009; Oliveira, 2001). According to (Medeiros et al., 2018), this human impact probably started around 9000 cal yr BP, however, it has increased during the 16th century with the arrival of Europeans and Africans (Arnan et al., 2018).

In the coastal zone of Maranhão, there is evidence of Amerindians' establishment in the period between 7000 and 2000 yr BP, when they became more fishermen and built houses on a shellmound known as "sambaquis" (Roosevelt et al., 1991). Another strong evidence of human occupation pre-colonization was the stilt-house settlements (Navarro, 2018a, 2018b). In the estuarine area of Maranhão, the Amerindians may have lived in stilt villages. They probably lived within the lakes and rivers of this region. Archaeological excavations obtained evidence from 6736-6530 yr BP in an archaeological site inside the lake in Maranhão lowland (Roosevelt and Navarro, 2021). The pile dwellings were lacustrine houses constructed with wooden pillars (stumps or trunks of trees) which supported constructions on top. Entire villages were placed on top of the pilings for protection and to avoid flooding (Roosevelt and Navarro, 2021). That stilts-houses evidence can be found just in this region in South America.

1.1.4 Aims and objectives of the project

This research aims to understand the environmental changes in NE Brazil during the Holocene. The major factors of those changes were related to vegetation dynamics, climate changes, fire history, human impact, and, in the coastal zone, the sea-level oscillations. To pursue this objective, multi-proxy analyses such as sedimentological description, palynology, charcoal fragments, human evidence, XRF, XRPD, and LOI have been conducted in sediment cores extracted from three different areas to answer the addressed questions:

- Identify the main drivers of the environmental changes in the study areas.
- Reconstruct the vegetation dynamics in three different environments in NE Brazil.
- Reconstruct the sea-level oscillations in the coastal zone of Maranhão State.
- Identify since when and how strong humans have influenced the environment in NE Brazil.

- Understand the context of the sediment input in the studied deposit along the Holocene

1.2 Study sites

1.2.1 Catimbaú National Park

The Catimbau National Park (CNP) is located in Pernambuco State, in northeast (NE) Brazil and has an area of 62.294 ha (Ministério do Meio Ambiente, 2022), which includes the cities of Buíque, Ibimirim, Arcoverde, and Tupanatinga. The national park has been created through decree 913/12 of 2002 with the objective of preservation of the ecosystems and the geology of the region. Its area is part of the São Francisco drainage basin and pursues a rich archaeological speleological heritage, as well as one of the last regions which can find Caatinga vegetation well-preserved.

The relief of the region is represented by two morpho-structural domains. The first domain corresponds geologically to the Recôncavo-Tucano-Jatobá Sedimentary Basin, and the second domain is based on the tectonostratigraphic terrains of the Transversal Zone of the Borborema Province (Ferreira et al., 2017). The sediments from Jatobá Basin are represented by Siluro-Devonian fluvial sandstones from Tacaratu Formation, which form the plateau that composes the landscapes (Ferreira et al., 2017). The climate in CNP is semi-arid and is located in one region also known as the "drought polygon" (polígono das secas) Following Köppen climate classification, the climate in the park is classified as BShs', semiarid with a low precipitation rate. The average temperature is 23ºC and the mean annual precipitation ranges from 480 to 1100 mm, mainly concentrated from March to July (Rito et al., 2017).

The predominant vegetation in the region is part of the Caatinga biome, however, due to relieve variations and micro-climate, is there also occurrence of species from cerrado and Atlantic Forest (Ferreira et al., 2017). The Caatinga biome is known as the largest tropical dry forest in

South America, which covers around 734000 km^2 of the semi-arid region of NE Brazil (da Silva et al., 2004). The most common vegetation are herbs and shrubs, with presence of succulents and Cactaceae, the typical family of Caatinga (Araújo et al., 1999). Related to CNP vegetation, (Andrade et al., 2004) have described 158 species, mostly represented by Fabaceae, Asteraceae, Myrtaceae, Rubiaceae, Euphorbiaceae, Malpighiaceae, Malvaceae, and Bignoniaceae. However, in a large part of the park area, much of the native vegetation has been replaced by pastures, and for use in agriculture based on cyclical crops such as beans and corn (Ferreira et al., 2017).

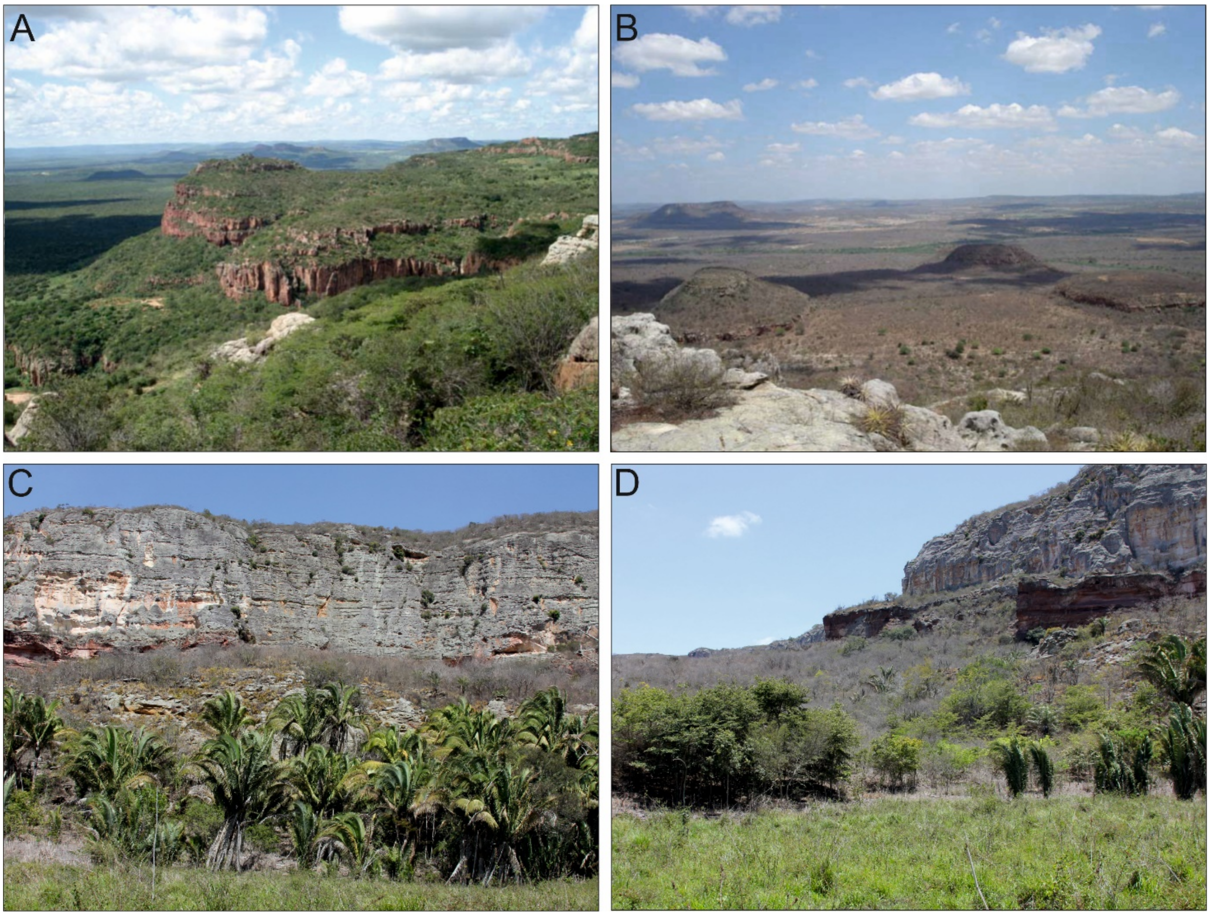

Figure 1.4. Images from Catimbaú National Park showing in A) and B) the border of the Jatobá basin in the contact zone with the Sertaneja Depression ("Depressão Sertaneja") from (Ferreira et al., 2017); C) and D) the study area Pingadeira valley region where the local environment is characterized by humid conditions in the middle of the semi-arid biome.

1.2.2 Maranhão coastal zone

The Coastal Zone of the Maranhão State can be separated in 5 different sectors: (i) Gulf of Maranhão (Golfão Maranhense); (ii) Eastern coast; (iii) Western coast; (iv) Maranhão lowland and (v) Manuel Luís Marine Park (El-Robrini et al., 2018). Regarding the study areas, the Cabeludo site is located in the western zone and Lago Formoso in the Maranhão lowland. The western coast is known as the region of "Reentrâncias Maranhenses" (Indentations of Maranhão) and is characterized by deep estuaries dominated by mangroves. This area shows intense erosion through the old coastline, marked by palaeocliffs and ancient "rivers" where several estuaries such as Turiaçu, Maracaçumé, and Tromaí flow, in addition to tidal channels. Its tidal cycle is semi-diurnal, with the occurrence of macrotide that can achieve up to 8 m in height. The Maranhão lowland is characterized by flat low-relieve with smooth ripples that are under constant flooding during the rainy season. During the wetter season occur the formation of large regional lakes such as Açu, Cajari, Bacuri, Formoso, and Viana. Those lakes are connected by a drainage system with the rives Mearim, Grajaú, Pindaré and Pericumã (El-Robrini et al., 2006). The area's vegetation is mainly composed of gallery forests, grasslands, and mangroves. The tidal cycle is distinguished as semi-diurnal with the occurrence mesotide that occurs with a height between 3,83 and 1,57 m (El-Robrini et al., 2018).

In this region, located in the equatorial region, the climate is hot and humid, with two very distinct seasons of precipitation: (i) the dry season from September to November and (ii) the rainy season from February to May. The mean annual temperature is around 26 °C, and the average annual precipitation is around 1700 mm (Climate-Data.org, 2021). The regional climate is controlled seasonally by the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ). When SACZ is absent, the warm and moist equatorial air masses remain close to the coast, causing heavy rainfalls. When SACZ is present, moisture is transported from the equatorial Atlantic towards Amazonia (Ledru et al., 2002).

Geologically, the coastal zone of Maranhão has lithostratigraphic units from Pre-Cambrian until Cenozoic. The Quaternary deposits, it is characterized by a fluvial-lacustrine environment composed of unconsolidated and semi-consolidated sand, and silt clay, which outcrops in riverbanks with a higher topographic level than the current fluvial plains (Correia Filho, 2011).

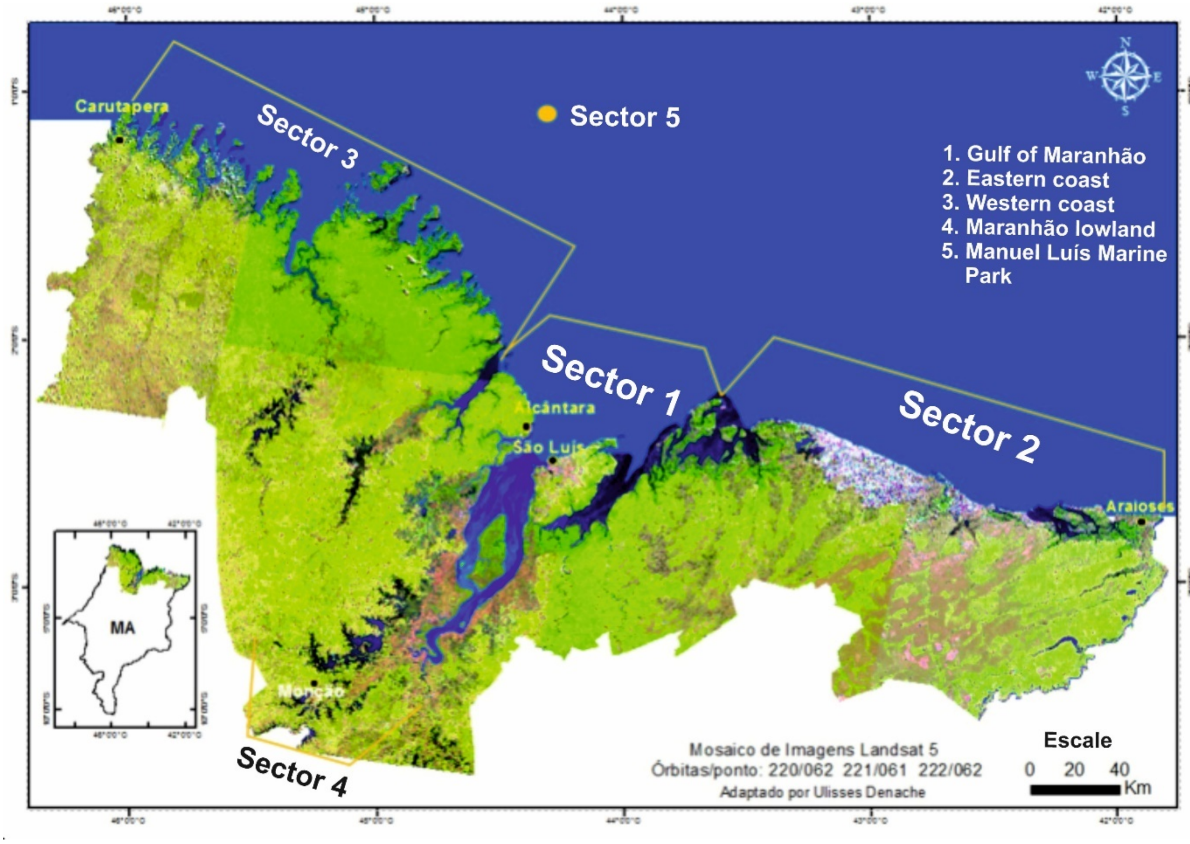

Figure 1.5. Map of the coastal zone of Maranhão State with the sectors zones. Modified from Ministério do Meio Ambiente (1996).

1.3 Sediment core analysis

1.3.1 Pollen and spore analysis

Palynology is the science of palynomorphs, which is a term for entities such as pollen, spores, cysts, and diatoms, among others (Halbritter et al., 2018). Though, pollen grain is the dominating object of the palynomorph spectrum. The palynological studies are one of the most used to reconstruct the environment during the Quaternary, since this analysis can be used to understand the past and the present vegetation composition. Pollen grains and spores, when deposited in good environmental conditions of preservation, can record millions of years. The taxonomic study of palynomorphs can reveal elements of the vegetation that were present throughout geological history. Pollen and spore grains can be deposited near their source area, under certain normal conditions, or can be carried reaching other distant areas (Salgado-Labouriau, 2007).

Prior to processing, one tablet with exotic marker *Lycopodium clavatum* (with 20,848 ±1546 spores) was added to each sample for calculation of pollen concentration (grains/cm^3) and pollen influx (grains/cm^2/yr). Afterward, samples were treated with a solution composed of 10% Hydrochloric acid (HCl) to dissolve the *Lycopodium* tablet and remove the carbonates (CO_3) compounds. Then, the samples were treated with 70% Hydrofluoric acid (HF) for 24 hours to remove the silicates. Subsequently, the samples were dehydrated with acid acetic (CH_3COOH), to avoid water contact with the next step (acetolysis), since the Sulfuric acid used for acetolysis is highly reactive to water. In acetolysis, 9 parts of acetic anhydride ($C_4H_6O_3$) were added to 1 part of Sulfuric acid (H_2SO_4) to remove the cellulose and polysaccharides. During this procedure, the samples were heated (ca. 90 °C) for 10 minutes. At the last step, the samples were sieved through a 120 µm mesh, to finally store them in an Eppendorf to prepare the slides for counting. Then, under a microscope, a minimum of 300 terrestrial pollen grains were counted per subsample. This sum was used for the calculation of pollen percentages. Fern spores, algae, and NPPs have been counted as well, however, their percentages are based on the pollen sum. After the counting procedure, the results were calculated and illustrated using the programs TILIA, TILIAGRAPH, and CONISS for cluster analysis to establish the pollen zones(Grimm, 1987).

1.3.2 Charcoal analysis

The charcoal fragments are produced when a fire incompletely combusts organic matter. In a depositional environment (e.g., a lake), its accumulation depends on the amount of charcoal that has been produced and the transportation process (Whitlock and Larsen, 2001). The charcoal analysis is used to reconstruct long-term variations in fire occurrence, and its records found in the sediments can be an important tool to understand the fire story of the region. The use of charcoal and pollen data from the same cores are widely used to analyze the connections between climate, vegetation changes, fire, and sometimes anthropogenic activities in the past (Whitlock and Larsen, 2001).

In order to reconstruct the environment in the study areas, macro and micro-charcoal analyses have been conducted. For macro-charcoal analysis, subsamples with 0.5 cm^3 were taken continuously along the core according to (Stevenson and Haberle, 2005) method. The samples were processed using 10% of Potassium hydroxide (KOH) and 6 % of Hydrogen peroxide (H_2O_2) to remove the organic matter. Afterward, all samples were sieved with a mesh of 64 µm width. The remained charcoal particles were counted using a Zeiss stereomicroscope and the results were analyzed with CharAnalysis version 1.1 (Higuera et al., 2009).

For micro-charcoal analysis, the charcoal particles have been counted on the pollen slides, following the methods used by several authors (Clark, 1983; Guyette and Dey, 1995; Swain, 1973; Whitlock and Larsen, 2001). The total of counted charcoal fragments was separated into two classes of particle size: 25 – 100 µm, suitable for the determination of regional fires, and >100 mm, better to determine local fire regimes. Then, the charcoal concentrations and influx were calculated in TILIA software (Grimm, 1987).

1.3.3 Core chronology

Providing ages and building an accurate age-depth model is essential for comparing proxy records and, therefore, understanding the environmental history of an area. In general, the age-depth relationship is estimated from a relatively small number of dated levels using an age-depth model. Trachsel and Telford (2017) compared in their work, the most used age-depth modeling routines (CLAM, OxCal, Bacon, and Bchron), with varve sediments, all of them produced mean age-depth models close to the estimated deposition age. The chronology of the cores has been processed using the Accelerator Mass Spectrometry (AMS) for ^{14}C ages. Samples from Cabeludo have been sent to Poznań Radiocarbon Laboratory in Poland, while samples from CNP to Laboratory Beta Analytic, in Miami, USA. The samples have been calibrated using the Southern Hemisphere calibration curves (SHCal13.14C; Hogg et al., 2013). Thus, the age-depth model was constructed with the software R version 3.5.1 (R Development Core Team, 2018), using the classical age-depth modeling method CLAM, with the 2.3.8 package (Blaauw, 2010).

1.3.4 Chemical analysis by X-ray Fluorescence and mineralogical analysis by X-ray Powder Diffraction

The X-ray Fluorescence (XRF) scanning is a powerful tool to trace the variation in elemental and other sediment properties of a core in high resolution, meaning that even the shortest of events can be captured (Croudace et al., 2006). Samples from LF have been XRF scanned at GEOPOLAR Bremen University in Germany. The sediment core was scanned to detect major and trace elements with a Cr-tube using a 0.5-mm step size and a 10-s count time for each step. Settings of the tube were set to 30-kV voltage and 50-mA current for all sections. Samples from Cabeludo were analyzed using a Bruker S2 Ranger XRF spectrometer at the Federal University of Pará, Brazil.

Regarding the mineralogical composition determined by X-ray Powder Diffraction (XRPD), fifteen most representative samples from LF were collected systematically along with the core, dried at 40ºC for around 48 hours, to have their relativity humidity accounted for, and carefully grounded in an agate mortar. The finely grounded samples were prepared by backloading them into 16 mm-diameter sample holders. Afterward, the analyses were carried out by X-ray Powder Diffraction (XRPD) using a PANalytical X'Pert Pro MPD X-ray diffractometer (Cu anode), in the laboratories of mineralogy at the Institute of Geosciences of the Martin Luther University of Halle-Wittenberg, in Germany. The diffractometer was equipped with a linear X'Celerator RTMS detector set in the θ-θ Bragg-Brentano-Geometry, and the measuring conditions were under 5-70° 2θ angular range, with 0.013° step size, and a counting time of 38 seconds per step. Then, the characterization was performed with aid of the software HighScore Plus 4.5, using the Powder Diffraction Files mineral database from the International Center for Diffraction Data.

For the Cabeludo site, 10 most representative samples were collected along with the core and were performed using a Bruker D2 Phaser X-ray diffractometer, equipped with a Cu anode and a Ni-kβ filter, at the Federal University of Pará, Brazil. The diffractometer was set in the θ-θ Bragg-Brentano geometry with a Linear Lynxeye detector. The selected samples were ground in an agate mortar and measured in reflection mode from 5 to 70°2θ range with 0.02° step size and 38.4 seconds per step counting time. To execute the analysis has been used the software HighScore Plus 5.0, with aid of the database of the Powder Diffraction Files from the International Center for Diffraction Data.

1.3.5 Aerial images analysis and multivariate analysis

To characterize the individual vegetation and geological units of the study areas, images of RADAMBRASIL (Brasil, 1973), obtained from the Brazilian Institute of Geography and

Statistics – IBGE website (www.mapas.ibge.gov.br) have been taken and processed in QGIS software, version 2.18 Las Palmas (QGIS Development Team, 2016).

To investigate the relationship between the identified pollen taxa, Principal Component Analysis (PCA) was carried out on pollen percentages, showing the most representative taxa. The multivariate ordination analysis was performed with software Canoco 5.0 (Braak and Smilauer, 2012), to highlight the most important taxa suitable for interpretation.

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CHAPTER 2

Late Holocene climate dynamics and human impact inferred from vegetation and fire history of the Caatinga, in Northeast Brazil

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Abstract

Holocene vegetation changes are good indicators of climate change/and or human impacts. The environmental history in the semi-arid region with Caatinga vegetation in Northeast Brazil has been still little studied. A 420 cm-long sediment core collected in a mire at the Catimbau National Park, State of Pernambuco, has been analyzed for pollen, spores, charcoal, and sedimentological characteristics. The core is dated by three AMS radiocarbon dates and is at the bottom of the core about 2800 cal yr BP old. Results indicate three different periods of sedimentological and environmental characteristics. The first period from 2800 to 2150 cal yr BP is characterized by the dominance of the pioneer tree *Cecropia*, and high charcoal amounts, indicative of strong environmental disturbances due to frequent fires. The vegetation compositions with less frequent ferns suggest the predominance of relatively dry conditions. In the following period between 2150 and 450 cal yr BP, the Moraceae-dominated forest with ferns suggesting wetter conditions. The increased occurrence of the *Orbignya* palm, as well as the bean *Phaseolus,* combined with abundant charcoal, suggest even stronger influence of Amerindians in the area. During the last period, after 450 cal yr BP, arboreal species were replaced by herbaceous taxa, indicating more open vegetation. The fire regime has been reduced. This evidence points to the return of drier conditions and the complete decline of the Amerindian population in the area, after the arrival of European colonizers.

Keywords: Palaeoclimate; Fire History; Northeast Brazil; Palynology; Human influence; Late Holocene

2.1 Introduction

The semi-arid dry forest in the hinterland of Northeast (NE) Brazil, called Caatinga, covers an area of 912,000 km^2 and is one of the most important world's areas of drylands, which sustains a considerable richness of species, including a vast range of unique plant lineages (Silva et al., 2017). Palaeoecological studies in NE Brazil are still relatively scarce, probably due to the absence of perennial lakes. However, since this region marks a particular semi-arid zone near-equatorial latitude in South America, its study is important for tracking past environmental changes across the continent. Some authors point out that NE Brazil is fundamental for understanding tropical climate, as the region is influenced by the El Nino-Southern Oscillation (ENSO) and by seasonal displacements of the Intertropical Convergence Zone (ITCZ) (Cruz et al., 2009; Kousky et al., 1984; Ledru et al., 2002; Martin et al., 1997). Furthermore, it is also an interesting region regarding the past floristic connections between the Amazonian and Atlantic rain forest areas (Andrade-Lima, 1982; Cole, 1960).

Based on marine pollen records (GeoB 3104-1), (Behling et al., 2000) indicate the predominance of Caatinga vegetation in NE Brazil from 42,000 yr BP to 8500 yr BP, reflecting semi-arid conditions during most of the time. However, several humid phases occurred during this recorded time. The period between 15,500 and 11,800 cal yr BP is the wettest recorded in NE Brazil. This is associated with Heinrich event 1, which brings evidence to the general association between previous Late glacial humid phases in southern Hemisphere and Heinrich events in the northern (Jennerjahn et al., 2004).

(De Oliveira et al., 1999) studied vegetation and climatic changes in a Caatinga/Cerrado ecozone at the Icatu River Valley. Their results suggest very humid climatic conditions and lower temperatures from 10,990 to 10,540 yr BP, during the early Holocene. A humid climate persisted from early to the middle Holocene, between 10,500 and 6790 yr BP, briefly shifting to semi-arid conditions from 6790 to 6230 yr BP and returning to a moister climate from 6230 until 4535 yr BP. Afterward, a marked semi-arid condition evolve into the late Holocene, from 4535 yr BP to the present.

Carbon isotope studies in the State of Ceará indicate an expansion of savanna vegetation (C_4 plants) during the early to the middle Holocene (Pessenda et al., 2010). This change suggests drier conditions (or less humid than the previous period), with a maximum between around 3200 and 2000 cal yr BP. The period is also marked by the high presence of charcoal fragments in the soil record, indicating palaeofires. Afterward and up to the present the carbon isotope record indicates the expansion of forest vegetation (C_3 plants), suggesting the predominance of more humid conditions.

The Catimbau National Park (CNP) is probably one of the most protected areas in the state of Pernambuco, NE Brazil (Jesus et al., 2008; Rito et al., 2017). Despite its location within the Caatinga biome, the park possesses local wetlands that are suitable for palaeoecological research. A study on the pollen record of a wetland within the CNP area was conducted by (Medeiros et al., 2018), which shows the predominance of arboreal vegetation in a humid environment from 10,000 to 6000 cal yr BP. This humid condition is mostly associated with a local spring, created by the surfacing of groundwater throughout geological fault systems. A long-term sedimentation hiatus occurs in the record between 6000 and 2000 cal yr BP, and is taken as indicative of the long dry phase previously recognized in the Icatu pollen record, from Bahia state (De Oliveira et al., 1999). A humid environment occurred again after 500 cal yr BP, although showing a gradual decrease in taxa adapted to high levels of humidity.

Our study analyses a more detailed record of pollen, spores, and charcoal in a sediment core collected at the bottom of a shallow canyon within the CNP. This canyon is locally known as the Pingadeira valley. The site studied by (Medeiros et al., 2018) is nearby, but lies outside the canyon (Fig. 2.1), and locates within a local topographic depression established on the top of the pediments that frame the transition between the park's dissected mesas and the surrounding planation surfaces. Thus, both sites are locally humid, fed by the surfacing of groundwater, and provide limited areas of humidity within the semi-arid Caatinga. Our analysis of pollen and spores enables us to determine vegetation and associated climatic changes, while the charcoal record allows for the reconstruction of the area's palaeofire history during the late Holocene. In addition, our record will shed light on the character and timing of human influence on the environment, raised on how and when humans have eventually influenced the recorded environmental changes in the area.

2.2 Study area

2.2.1 Geology and topography

The site under study is a swampy area in the CNP (8°32'54"S / 37°12'47"E), in the State of Pernambuco, in NE Brazil. The mire occupies about 4 ha in the vegetated bottom of a relatively short and deep canyon that was carved at the border of the tabular landforms and associated sites protected by the park. Palm trees cover most of the bottom of the canyon, except for the wet area where herbs predominate. Palm trees also cover a ring of pediments marking the transition between the mesa cliffs and surrounding planation surfaces. On the mesa plateaus and lower planation surfaces, the Caatinga dry forest is predominant (Fig. 2.1). The bottom of the study canyon lies at 727 m above sea level, framed by the mesa tops about 200 meters higher.

As the origin of the mire is associated with the outcropping of groundwater, in Silurian-Devonian sedimentary rocks, through Mesozoic/Cenozoic-age faults (Nascimento et al., 2009), it classifies as a fen, or minerotrophic peatland, referred to by locals as the Pingadeira site (leaking spot). The frequent presence of water across the fen favors the accumulation of peat deposits, which eventually mix with siliciclastic sediments, transferred from surrounding slopes by flash floods. As a result, the study fen finally classifies as a peat-forming spring fen

(Charman, 2002). Due to the spring`s yearlong sustained discharge, the Pingadeira site is also an important source of freshwater for local communities.

Geologically, the study area is part of the Borborema Province, inserted at the Jatobá Sedimentary Basin. The stratigraphy starts with the Meso to Neoproterozoic orthogneisses and migmatites of the Belém de São Francisco complex and associated Ediacaran granites (Ferreira et al., 2017). The sedimentary rocks that outcrop around the study fen are sandstones and conglomerates of the Tacaratu Formation, deposited from the Silurian to the Devonian and interpreted as characteristic of fluvial braided systems, associated with alluvial fans. Quaternary colluvial, alluvial, and eluvial deposits complete the local geology (Gomes, 1995). Across the whole Catimbau area, geological faults and zones of groundwater outcropping are responsible for maintaining surface waters and the formation of local mires (Gomes, 1995; Nascimento et al., 2009) (Fig. 2.1).

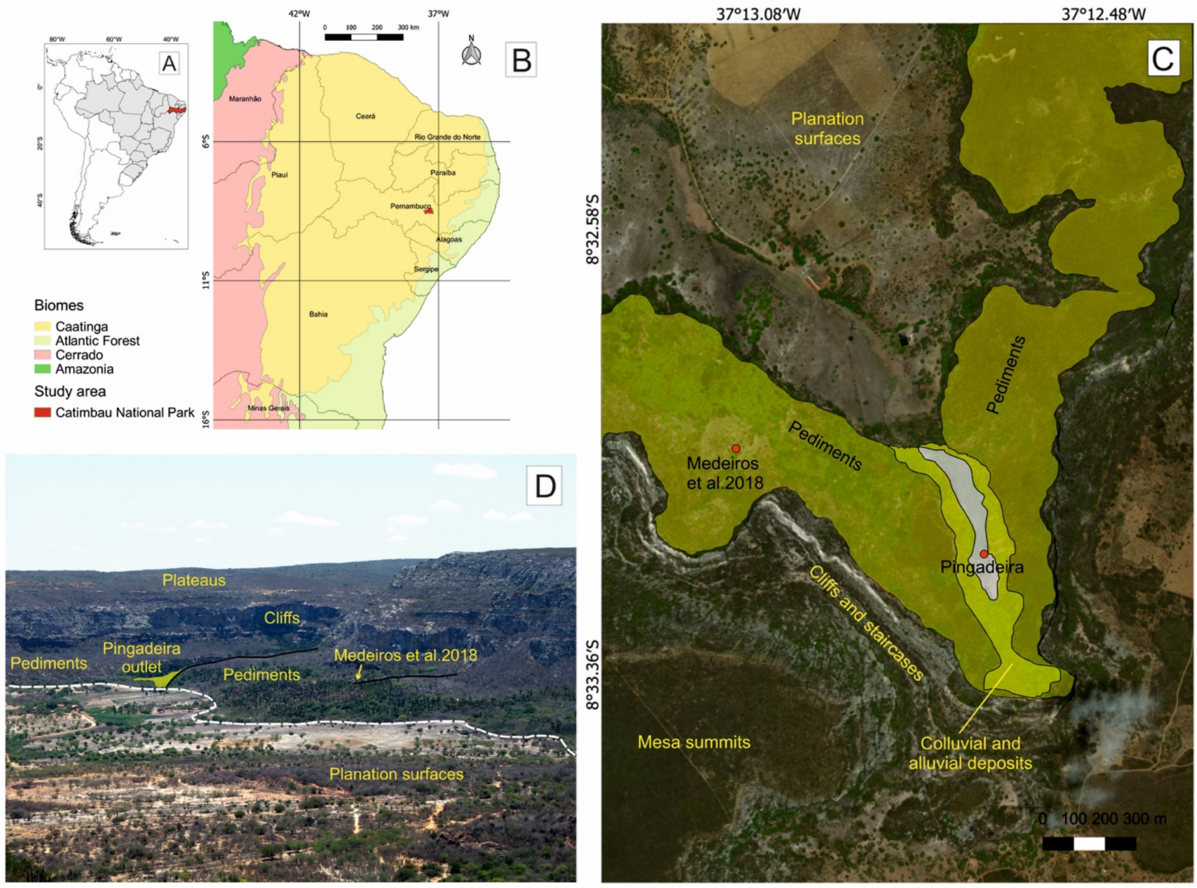

Figure 2.1. Map of South America showing Brazil in gray and Pernambuco State in red. (B) Biome map of Northeast Brazil showing the location of Catimbau National Park (CNP) in red. (C) Satellite image of collection site showing the studied swamp with the Pingadeira coring site (8°32′54″S / 37°12′47″E). (D) Geomorphologic structures around the collection site.

2.2.2 Climate

The study area is located in the semi-arid region, also known as NE-Brazil "drought polygon" (polígono das secas) as redefined by (Nacional, 2005). The climate is semi-arid, with an average temperature of 23ºC and annual precipitation ranging from 480 to 1100 mm, mainly concentrated from March to July (Rito et al., 2017)

2.2.3 Vegetation

The Caatinga formation represents the largest tropical dry forest in South America, occupying about 734,000 km^2 in the semi-arid region of NE Brazil (da Silva et al., 2004). Its vegetation structure is related to hydric and nutrients availability, besides the human influence (Gariglio et al., 2010). Besides the predominance of herbaceous vegetation, succulents are also common in the shrub-tree layer, particularly of the Cactaceae family (Araújo et al., 1999).

In the CNP, (Andrade et al., 2004) have listed 158 species distributed in 50 families, mostly represented by Fabaceae, Asteraceae, Myrtaceae, Rubiaceae, Euphorbiaceae, Malpighiaceae, Malvaceae, and Bignoniaceae, which have a wide distribution in the Neotropics. (Athiê-Souza et al., 2019) provide an inventory of the main angiosperms present in the area. Most species-rich families are Fabaceae, Poaceae, Euphorbiaceae, Asteraceae, Convolvulaceae, Malvaceae, Myrtaceae, Apocynaceae, Malpighiaceae, and Cyperaceae. Species of Cactaceae, associated with the Caatinga, are common in the area. At the Pingadeira site, the vegetation within the mire is mainly composed of different species of Cyperaceae, Poaceae, and Asteraceae. At the borders of the mire, herbaceous species and palm trees like *Orbignya* (babaçu) are dominant.

2.2.4 Land use

Evidence for the first occupation of humans in the Caatinga is still controversial. (Heredia, 1994) suggest that humans were already in NE Brazil by 25,000-30,000 yr BP. Other studies suggest that the first evidence of humans in NE Brazil dates from the Lateglacial, about 12,000 yr BP (Prous and Fogaça, 1999). In the State of Pernambuco, the first settlers have arrived around 11,000 yr BP, establishing in sites at the base of cliffs, in shelters and small caves sculptured by differential erosion of sedimentary plateaus (Heredia, 1994).

The CNP and the surrounding areas show a large number of rocky shelters, associated with archaeological sites with rupestrian paintings, engravings, and other pieces of evidences of prehistoric occupation. An instance of these sites is the Pedra do Caboclo, situated about 200 km from the Pingadeira site (Heredia, 1994). The set of evidence in the CNP area makes it the second-largest archaeological park in Brazil (Solari and Da Silva, 2017).

The rock shelters bear evidence of hunter-gathering groups exploring the Catimbau valley during the Holocene, between 6000 and 2000 yr BP (Solari and Da Silva, 2017). A study based upon rupestrian records (engravings and paintings) at the Alcobaça archeological site, in the Buíque municipality (Martín, 2005), shows that the area around the Pingadeira mire was continually occupied by humans from 5000 to 900 yr BP, probably impacting the local environment. According to (Arnan et al., 2018), this influence has increased with the arrival of Europeans and enslaved people from Africa during the 16th century.

2.3 Material and methods

2.3.1 Coring, radiocarbon dating and age-depth-modeling

A sediment core of 420 cm length, called Pingadeira, was collected in sections of 50 cm, using a Russian Corer. The sediments were sealed and taken to a laboratory and stored under dark and cold conditions. The sediment core was described by its textural characteristics and color following the Munsell color chart (Color, 2009).

Based on the first pollen results, three organic sediment samples (1 cm^3 each) were selected along the core and sent for Accelerator Mass Spectrometry (AMS) radiocarbon dating at the Laboratory Beta Analytic, in Miami, Florida. The calibrated ages and age-depth model have been done with software R version 3.5.1 (R Development Core Team, 2018), using the CLAM package (Blaauw, 2010).

2.3.2 Palynological analysis

Forty-four pollen samples of 0.5 cm^3 were collected in intervals of 5-10 cm along the core, from the depth of 420 to 70 cm. The uppermost 70 cm of the core is consisting of washed sands with no sign for the preservation of organic material within. Prior to processing the sediment subsamples, one tablet with the exotic marker *Lycopodium* spores (concentration of 20,848 +/- 1546) was added to each sample for calculation of pollen concentration (grains/cm^3), and pollen influx (grains/cm^2/yr). The samples were processed in the laboratory following the methods of (Faegri and Iversen, 1989), using the chemical processes (10% HCl, 40% HF and acetolysis) to separate palynomorphs.

Pollen and spore identification was made after reference to collections from the Department of Palynology and Climate Dynamics; to a palynological atlas (Lorente et al., 2007), and to the Neotropical Pollen Database (Bush and Weng, 2007). A count of 300 terrestrial pollen grains was made in each of the 44 samples. Percentages were calculated on the sum of the terrestrial types, excluding fern and moss spores. Some samples (at core-depth 230, 310, and 370 cm) were not included because of the very low pollen content.

The pollen and spore taxa are grouped into trees and shrubs, herbs, palms, ferns, and mosses, respectively. The calculation and illustration of the data were made through the programs TILIA and TILIAGRAPH (Grimm, 1987). The zonation of the pollen diagram has been done by the cluster analysis of the percent data from all pollen taxa included in the pollen sum, using CONISS (Grimm, 1987).

2.3.3 Micro-charcoal analysis

In order to track the role of fire in the study area, a micro-charcoal analysis was carried out on all pollen slides, following the methods used by several authors (Clark, 1983; Guyette and Dey, 1995; Swain, 1973; Whitlock and Larsen, 2001). The total of counted charcoal fragments are separated into two classes of particle-size: 25 – 100 µm, to determine regional fires, and >100 mm, to determine local fire regimes. Charcoal concentrations and influx are also calculated in TILIA software.

2.3.4 Data analysis

Percentages obtained on the 44 samples from the Pingadeira core were submitted to Principal Component Analysis (PCA) in order to investigate the eventual correlation between the identified taxa. Multivariate ordination analysis was performed with software Canoco 5.0 (Braak and Smilauer, 2012), in order to highlight the most important taxa suitable for interpretation (Fig. 2.2). The illustration containing the study area and site maps was made in QGIS software, version 2.18 Las Palmas (QGIS Development Team, 2016).

2.4 Results

2.4.1 Description of sediments in the core

The detailed sedimentological description of the Pingadeira core is shown in Table 2.1. Sediments in the 420 cm-long core were split into 18 units according to their predominant characteristics. Sediments are mainly composed of alternating grayish muds and black peat layers in the lower parts.

From 420 to 380 cm depth sands and muddy peats alternate in equivalent amount and interval. From 380 to 300 cm, only 20 cm consist of peat overlain by 20 cm of dark olive-gray muddy fine sands, and by 30 cm of coarser dark gray sand at the top of the set.

From 300 to 105 cm occur 4 sets of black peat covered by thin to medium layers of sands and muds. Plant remains are frequent in the peat deposits. At 105 cm, the black sandy peat sediments are covered by 35 cm of reddish-black organic sands. Flash flood sands compose the uppermost 70 cm of the core (Fig. 2.2).

Table 2.1. Textural description of the sediment core from Pingadeira.

Depth (cm)	Description	Munsell color
0-70	Washed sands formed by flash flows	No data
70-105	Reddish black organic sands	2,5Y 2.5/1

105-125	Black sandy peat	10 YR 2/1
125-155	Black peat	5 Y 2.5/1
155-165	Dark gray medium sands	5 Y 4/1
165-200	Black peat with a thin layer of sand at level 200 cm	5 Y 2.5/1
200-225	Black peat	5 Y 2.5/1
225-240	Gray sands mixed with peat	5 Y 5/1
240-300	Black peat with vegetal remains	5 Y 2.5/1
300-315	Very dark gray sands grading to peat	5 Y 3/1
315-330	Dark gray medium to coarse sands with inverse grading to coarse sands	5 Y 4/1
330-350	Dark olive gray muddy fine sands grading to sandy muds	5 Y 3/2
350-360	Black sand muds	5 Y 2.5/2
360-380	Black peat	5 Y 2.5/2
380-390	Very dark gray muddy peat	5 Y 3/1
390-400	Olive gray fine sandy peat	5 Y 4/2
400-410	Very dark gray muddy peat	5 Y 3/1
410-420	Olive gray medium sandy peat	5 Y 4/2

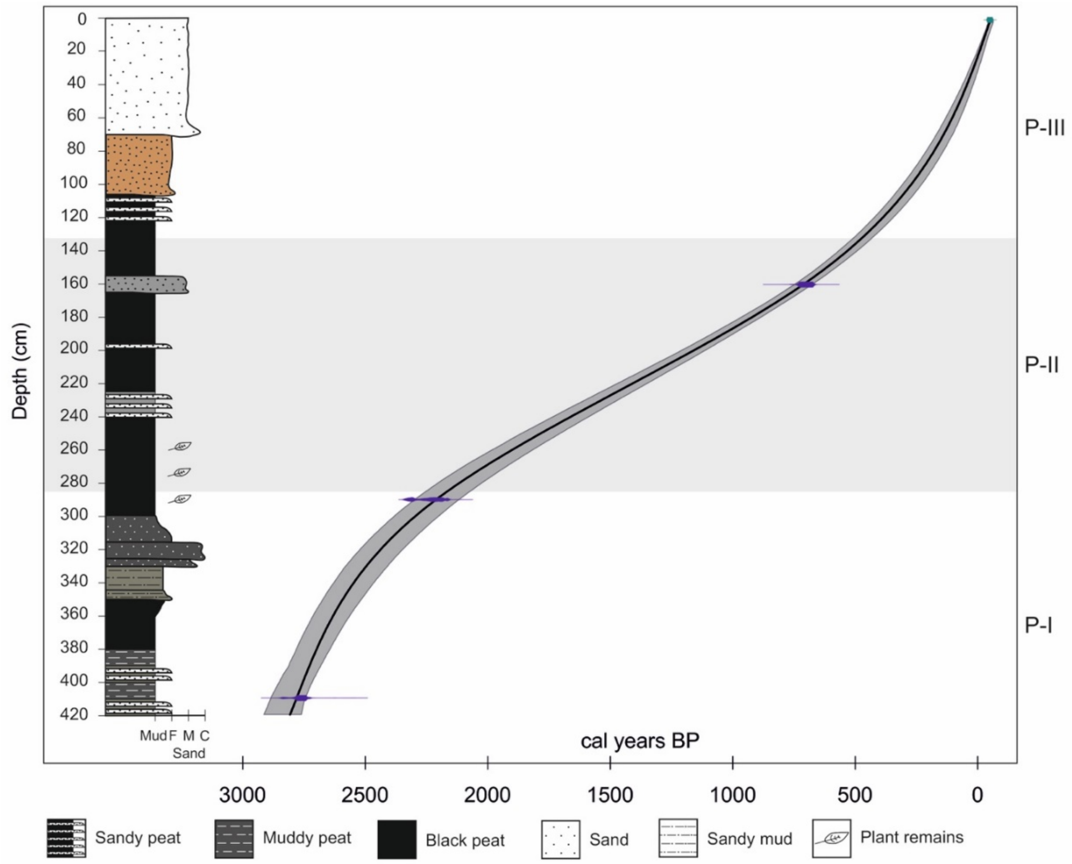

Figure 2.2. Stratigraphic description of the Pingadeira core showing textural characteristics and structures as well as the age-depth-model.

2.4.2 Radiocarbon dating and sedimentation rates

Table 2.2 shows the results for three AMS radiocarbon dates. The core chronology indicates that the deposits accumulated during the late Holocene. The base of the core, at 420 cm depth, has an extrapolated age of 2800 cal yr BP. Sedimentation rates were calculated for the different depth slices defined by the zonation of the pollen diagrams (see Fig. 2.4, for instance). Sedimentation rate is 2.8 mm/yr (420-285 cm) for pollen zone P-1; 0.9 mm/yr (285-132, 5 cm) for pollen zone P-II, and 1.8 mm/yr (132, 5-70 cm) for pollen zone P-III. The upper 70 cm of the core (washed sands) was not included in the pollen analysis and has an extrapolated age that ranges from 150 cal yr BP up to the present.

Table 2.2. List of the radiocarbon dates for the Pingadeira core.

Laboratory code	Sample/depth (cm)	^{14}C age (yr BP)	^{14}C age (cal yr BP)
Beta - 525101	CTB/160 cm	820 ± 30 BP	667-736 (700)
Beta - 525100	CTB/280 cm	2.280 ± 30 BP	2.157-2.275 (2.160)
Beta - 370004	CTB/410 cm	2.679 ± 30 BP	2.723-2.799 (2.760)

2.4.3 Palynological and charcoal results

In total 93 pollen and spore taxa have been identified: 44 tree and shrub taxa, 33 herb taxa, 4 types of palms, and 12 types of fern spores. According to major changes in the pollen assemblages and the CONISS cluster analysis the pollen record has been recognized into three pollen zones (P-I; P-II and P-III) (Fig. 2.4 and 2.5).

2.4.3.1. Pollen zone P-I (420-285 cm; 12 samples; 2,800-2,150 cal yr BP)

This zone is characterized by the dominance of tree and shrub pollen (43-85%), mainly by *Cecropia* (16-70%) and less frequent Moraceae (9-19%). Other trees and shrub pollen are Euphorbiaceae, *Mimosa*, *Acalypha,* and *Byrsonima* with values up to 5% (Fig. 2.5). Palms (<5%) are presented by a few pollen grains of *Orbignya*, Arecaceae, and *Euterpe*/*Geonoma*. Less frequent herbaceous pollen (14-49%) include Cyperaceae (3-28%), Poaceae (3-15%), Asteraceae (4-23%), and a few *Phaseolus*, *Borreria*, Amaranthaceae and *Solanum* pollen (Fig. 3.4). Ferns spores are well-represented (6-23%), mainly by Monolete psilate (1-20%). The pollen concentration ranges from 28,125 to 128,514 grains/cm^3 and the influx from 42,650 to 469,071 grains/cm^2/yr.

The charcoal concentration achieved its highest values compared to other zones, varying from 18 to 520 particles/cm^3 for the size 25-100µm, and 9 to 225 particles/cm^3 for the size >100µm. The influx of the small particles ranges from 46 to 1900 particles/cm^2/yr, while that of large particles varies from 22 to 830 particles/cm^2/yr (Fig. 2.5).

2.4.3.2. Pollen zone P-II (285-132,5 cm; 19 samples; 2,150-450 cal yr BP)

This middle zone has the highest number of different pollen types and is marked by high values of arboreal and low values of herbaceous pollen. Trees and shrubs (16-85%) are represented mainly by Moraceae (between 0 and 83%) and by lower percentages of *Cecropia*, Euphorbiaceae, *Mimosa,* and Melastomataceae. In particular in the upper part Moraceae reaches very high values (up to 83%). Palm pollen (1-12%), are represented mainly by *Orbignya* (1-9%), Arecaceae (0-3%) and *Euterpe*/*Geonoma* (0-3%). The herbs group (10-77%), is mainly represented by Cyperaceae (5-55%), Poaceae (3-24%) and Asteraceae (3-27%), while *Borreria* and Amaranthaceae occur in lower values <5% (Fig. 3.4). *Phaseolus* occur in this zone with values between 0 and 5%, much higher than in the previous zone. Fern spores (8-56%) present markedly higher values in this zone. The pollen concentration is between 6,346 and 345,295 grains/cm^3 and influx between 5,535 and 334,157 grains/cm^2/yr.

The charcoal concentration decreases for both classes, with values between 24 and 150 particles/cm^3 for the finer class, and between 10 and 95 particles/cm^3 for the large coarser. The influx for small particles remained almost the same as before, ranging from 370 to 1900 particles/cm^2/yr, while large particles influx increased, ranging from 102 to 1150 particles/cm^2/yr (Fig. 2.5).

2.4.3.3. Pollen zone P-III (132.5-70 cm; 13 samples; 450-150 cal yr BP)

In the upper zone, trees and shrubs (17-37%) taxa present lower values of Moraceae, *Cecropia,* Euphorbiaceae, *Byrsonima*, Melastomataceae, and Myrtaceae. Values of Moraceae decreased markedly compared with the previous zone, where it was the dominant taxa. *Orbignya*, Arecaceae, *Euterpe*/*Geonoma*, and *Mauritia* occur only in values <5%. The herbaceous taxa dominate (49-80%) with Cyperaceae (16-39%), Poaceae (15-33%), Asteraceae (7-16%), Amaranthaceae (0-3%) and *Solanum* pollen (0-28%). Ferns spores a decrease markedly (3-32%). The pollen concentration has values from 7,752 to 309,296 grains/cm^3 and the influx from 10,767 to 475,841 grains/cm^2/yr (Fig. 2.5).

The charcoal concentration and influx in this zone strongly decrease. The concentration for the particles with 25-100 µm ranges from 5 to 75 particles/cm^3, and from 2 to 10 particles/cm^3 for particles >100µm the influx values for small particles range between 20 and 430 particles/cm^2/yr, and between 14 and 60 particles/cm^3 for the large ones.

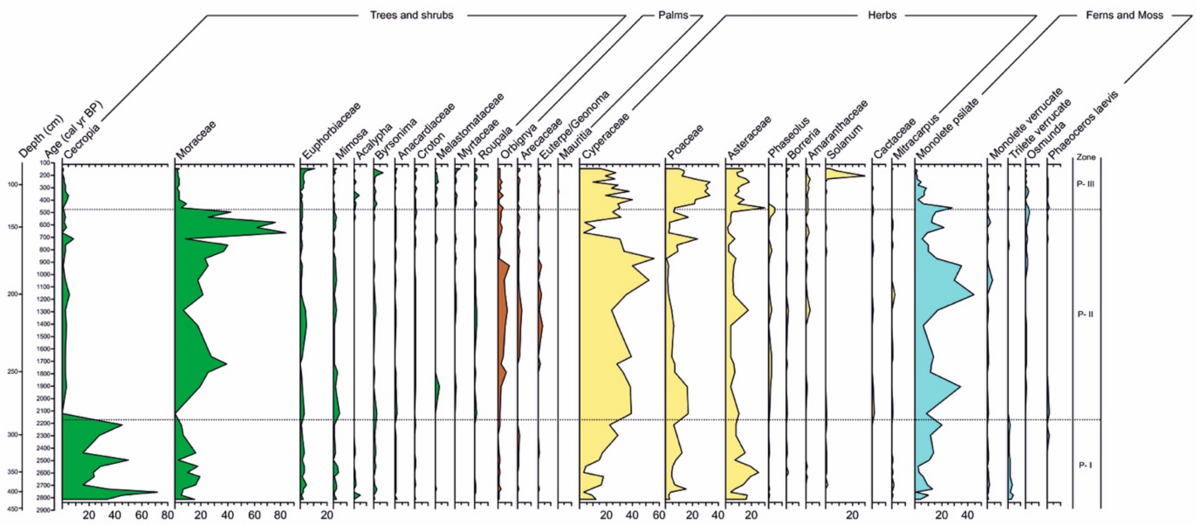

Figure 2.3. Pollen percentage diagram of the frequent and most important taxa of the Pingadeira record of the Catimbau Nacional Park (CNP) grouped into Trees and shrubs, Herbs, Palms, and Ferns and Moss.

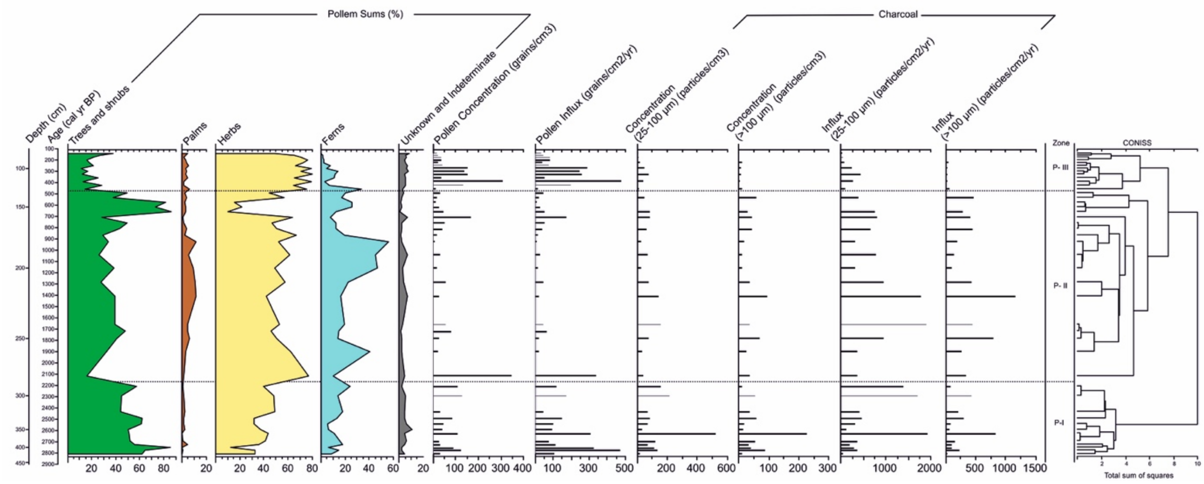

Figure 2.4. Summary pollen diagram of the Pingadeira record in Catimbau National Park (CNP) core, showing the age scale, stratigraphy, ecological groups, pollen sum, pollen concentration and influx, charcoal concentration and influx and the cluster analysis dendrogram.

2.4.4 Principal Component Analysis (PCA)

The PCA indicates the ecological differences of the 22 most important taxa in the 44 subsamples during this late Holocene record, between 2800 and 150 cal yr BP (Fig. 2.3). PC1 (positive values) comprises mainly samples from pollen zone P-II, represented especially by moisture-adapted species as Moraceae, *Orbignya, Phaseolus* and Cyperaceae. The PC2 is characterized by samples of zone P-I (positive values) and of zone P-III (negative values). Taxa with positive values on PC2 relate either to disturbed or to dry vegetation and are mainly represented by trees/shrubs of *Mitracarpus, Cecropia*, and Meliaceae. The negative values on PC2 are associated to dry vegetation taxa including Amaranthaceae, *Solanum*, *Roupala* and Poaceae.

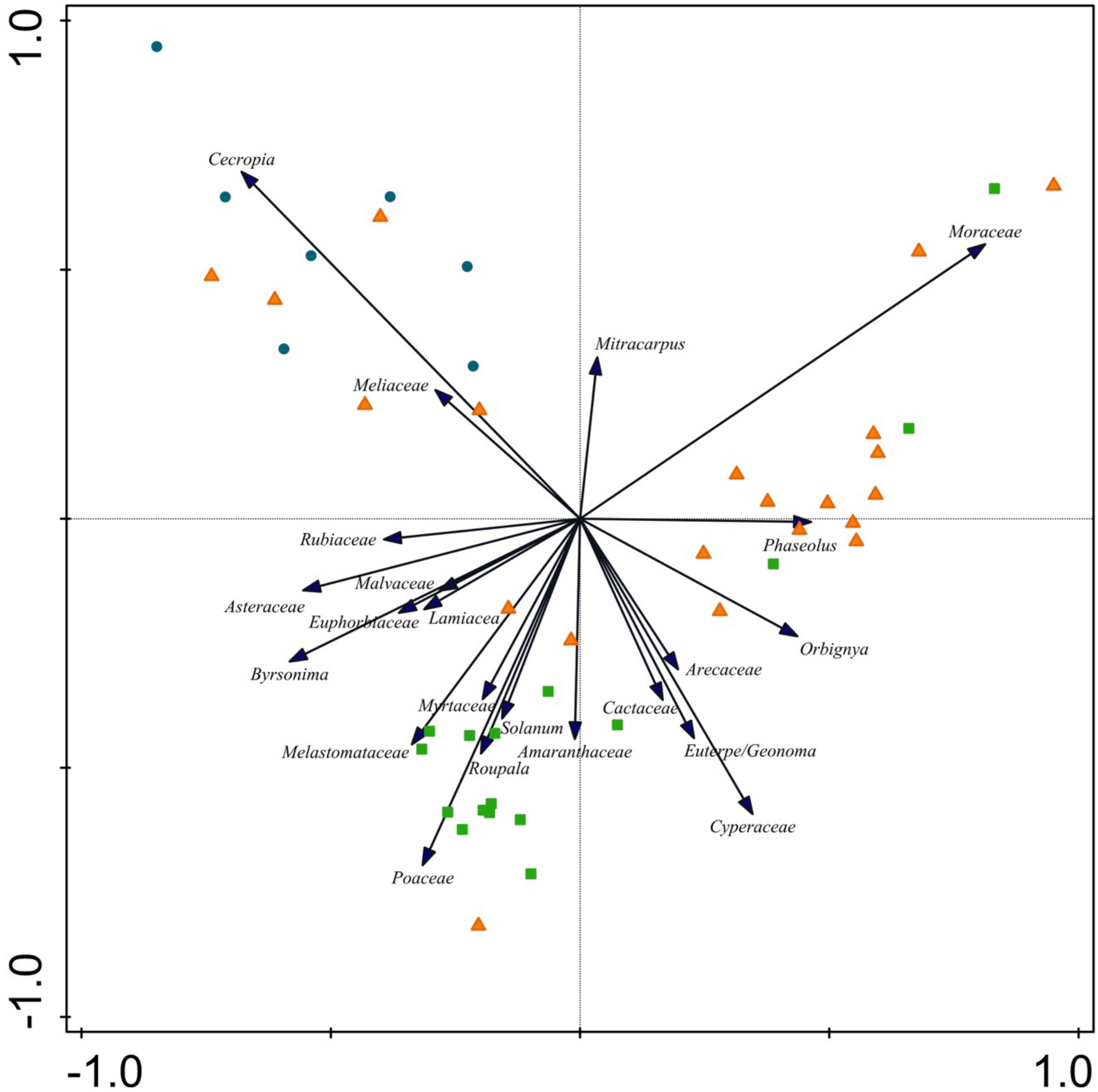

Figure 2.5. Principal Component Analysis (PCA) from the Pingadeira record. The blue circles are the samples from pollen zone P-I; the orange triangles represent the samples from zone P-II, and the green squares show the samples from zone P-III.

2.5 Environmental reconstruction and discussion

2.5.1 Late Holocene between 2800 – 2150 cal yr BP (Pollen zone P-I)

Sediments of the core from this period are mainly formed by sand embedded with muddy layers. Together, deposits of sand and muddy, black peat indicate higher energy compared to the following period (Fig. 2.2 and Table 2.1). Considering the overall configuration of the mire and core location, near the canyon's valley head, deposition of sands and muds mixed with peats indicates the predominance of inputs of siliciclastic sediments during the period, probably related with flash floods that were more frequent than today. The period also shows the highest sedimentation rates in our record (2.8 mm/yr), probably associated with a stronger runoff production due to little vegetation cover.

The pollen record (Figs. 2.3 and 2.4) shows a relatively high proportion of arboreal vegetation, composed of trees and shrubs of *Cecropia*, Moraceae, Euphorbiaceae, *Mimosa*, *Acalypha*, and *Byrsonima*. However, the local vegetation at the Pingadeira site was dominated by the pioneer taxon *Cecropia*, which is predominant in secondary vegetation, commonly associated with disturbed environments (Lorenzi, 1998). The ecological difference for this period is evidenced in the PCA analysis, from which pollen samples of this period are exclusively related to *Cecropia*, indicating environmental disturbance. The Caatinga surrounding the canyon is composed of shrubs and herbs (mainly represented by *Mimosa*, Asteraceae, and *Borreria*), suggesting the predominance of relatively dry conditions during the period, which is also supported by the relatively low occurrence of ferns in wetter areas. Despite that pollen of Cactaceae occurs in low values during the whole record, it also supports that the environment around the valley was composed of the semi-arid Caatinga during the recorded periods. *Mitracarpus* is associated with rocky soils in the Caatinga (Souza et al., 2010), and its presence in the record suggests that pollen grains have been transported to the Pingadeira site from the surrounding sandstone cliffs and plateaus, which were then probably composed of the same Caatinga vegetation as nowadays.

The charcoal record for this period shows the abundant input of small and large particles, indicating that fire was frequent on local and regional scales.

The local condition of the swamp was likely still relatively moist, due to the continuing outcropping of groundwater, enable by the geological setting. Despite these local moist conditions, however, local fires were also frequent, which caused disturbance (abundance of *Cecropia*). This suggests that these frequent local and regional fires were probably triggered by local land-use practices of humans.

The occurrence of a few pollen grains of *Phaseolus* (beans), which is unknown in Brazil (Debouck, 1986), suggests cultivation by Amerindians, who traditionally burn vegetation when managing crops. The use of *Cecropia* by locals was probably the same as it is in Amazonia today, where people often exploit its wood to make a fire for cooking ((Rocque, 1968).

Supporting our interpretation, the soil isotopic and charcoal record from Ceará state in NE Brazil ((Pessenda et al., 2010) suggests the occurrence of strong dry conditions between 3200 and 2000 cal yr BP. Also, the pollen record from (De Oliveira et al., 1999) in Bahia State indicates an increase of Caatinga taxa and high fire frequency since 4535 yr BP, suggesting the predominance of semi-arid conditions in NE Brazil.

2.5.2 Late Holocene between 2150– 450 cal yr BP (Pollen zone P-II)

In this period, the sedimentological characteristics indicate a more stable local environment with minor contributions from external runoff, which are mainly composed of peat, with siliciclastic materials contributing only about 15% of the sediments. The deposit was probably fed mostly by subsurface water under a denser vegetation cover and wetter conditions. Sedimentation rates are lower than previously (0.9 mm/yr) and may be associated with three factors: i) an increase in the area of the mire, as a consequence of water table rising, also protecting the coring site from the inputs of surrounding siliciclastics sources; ii) the expansion of arboreal taxa, protecting the local slopes from erosion, and iii) an increase in root density in the mire, related with more abundant forest taxa. Concerning the last factor, studies showed that in general the presence of vegetation increases the sedimentation rate due to a combination of reduced water velocity and decreasing resuspension of sediments (Braskerud, 2001; Dieter, 1990; Sand-Jensen, 1998), the opposite in what is seen in the study area. However, vegetation may also trap sediments from resuspension (Braskerud, 2001). Then, the increase of dense forest (in our study site in particular of Moraceae), probably is responsible for the trapping of organic sediments, thus reducing the sedimentation rate. Plant remains are also well evident in the core between 300 and 250 cm, probably due to the denser vegetation cover that increased the deposition of particulate matter by slowing down-water velocities (Carpenter and Lodge, 1986; Harlin et al., 1982; Stevenson et al., 1988).

During this period, the pioneer *Cecropia* decreased markedly, and a forest expanded, mainly represented by species of Moraceae. This family is indicative of moist conditions (Berg et al., 2006; Honorio Coronado et al., 2014). This change was also documented by (Behling, 1995) in the record of Lago do Pires, in SE Brazil.

The record for palms is also worth mentioning. The *Orbignya* palms was more frequent during this period, but other palm taxa increased as well. Since the *Orbignya* palm was frequently used by Amerindians in Brazil (even today it is frequently used by local communities), mainly for food, weapons, and materials for dwelling construction (Anderson, 1977), its higher occurrence is probably related to a stronger presence of humans which favored the occurrence in the study area. (Nascimento et al., 2009; Oliveira, 2001) proposed the presence of *Orbignya* in the region is associated with human influence since around 4500 yr BP. Likewise, (Medeiros et al., 2018) show the presence of *Orbignya* pollen in the Catimbau area, suggesting that it was under the influence of humans since as early as 9000 cal yr BP.

The abundant of Cyperaceae, which is common on waterlogged soils (Souza and Lorenzi, 2005), indicates that the water within the swamp was saturated. The relatively high occurrence of ferns during the period also supports evidence more wetter conditions, whereas the decrease of Poaceae and Asteraceae indicates the relative of open vegetation.

Phaseolus occurs in higher frequencies throughout this period, suggesting an even stronger presence of Amerindians around the site. (Gepts, 1990) showed that this taxon is native from America, with distribution from northern Mexico to western Argentina mountainous areas, however there is no record of native *Phaseolus* in Brazil. The archeological evidence indicates the common exchange of its seeds between central and south American native populations, either by trading or by migration, but its regional origins are difficult to determine (Freitas, 2006). Seeds of the same species have been found in Europe after the arrival of Europeans in South America (Pinto et al., 2007). However, the increase in *Phaseolus* spectra at the end of this period may be associated with more abundant cultivation around 500-450 cal yr BP to serve European trade.

Interesting is the marked increase of Moraceae and a reduction of the palm *Orbignya* as well as *Phaseolus* at the end of this period. This recorded strongest forest expansion by Moraceae, and the reduction of anthropogenic indicators could be related to a decline of the indigenous population. The spread of disease, due to the arrival of European in NE Brazil may have been the reason for that. The agricultural abandonment by indigenous would mean that the vegetation in this area would have undergone secondary succession. This vegetation succession may have occurred in general in the Americas after European arrival (Koch et al., 2019). This event, called the Great Dying, may have had a strong consequence in the earth`s climate system due to decline in global atmospheric CO_2 concentration as consequence of forest recovery in Americas (Koch et al., 2019). This happening has also been evidenced in several other studies in Brazil (Bush et al., 2000; Jeske-Pieruschka et al., 2010) and in Ecuador (Niemann et al., 2013).

The ecological groups determined by PCA analysis for this period are associated with the positive axis of PC1. The *Phaseolus*, Moraceae, *Orbignya*, and Cyperaceae group together, indicating the predominance of humid conditions.

With the increase of precipitation, the water table increased as well, making the region more appropriate to human life in the context of the semi-arid Caatinga region. Then, with more resources to survive, more people came to live in this, area and, as a consequence, they had even more influence on the vegetation (e.g., by fire).

As demonstrated by the charcoal record (Fig. 2.4) local fires increased during the period, suggesting an even stronger presence of humans in the study area. Regional fires, however, maintain almost the same pattern as in the previous period. Although we cannot discard natural causes for regional fires, perhaps both local and regional fires during this period are associated with human exploitation of the Caatinga landscape.

2.5.3 Late Holocene between 450-150 cal yr BP (Pollen zone P-III)

Sandy material prevailed during the period, even with higher proportions compared to the first period (Zone P-I). These deposits may reflect a return to drier conditions in the area, as also indicated by the increase in herbaceous vegetation. However, we have also to consider the influence of human occupation on sediment deposits and vegetation, as stressed below. Sedimentation rates are twice the values of the previous phase (zone P-2), and 1/3 smaller than rates during the first period (zone P-1). This increase in sedimentation rates may reflect drier conditions and more open vegetation, favoring further inputs of siliciclastics to the swamp. Indeed, the uppermost 70 cm-thick layer of washed sands indicates an increase of flash flood events from 450 cal yr BP up to present, favored by local aggradation on the coring site, where the peat deposits occur buried below the surface.

Another explanation for this increase of sand inputs to the mire can be associated with the arrival of Europeans about that time, as colonial land-clearing practices are shown to accelerate sedimentation rates on wetlands ((Orson et al., 1992).

The vegetation reconstruction for this period shows an abrupt decrease in arboreal species and an abrupt increase of herbaceous vegetation. Taxa in the Moraceae family were primarily affected, showing a marked decrease, after the strong increase during the end of the last period. The replacement of this family by herbs as Poaceae, Cyperaceae, and Asteraceae suggests the predominance of drier conditions in the region. In spite of it, the presence of *Cecropia*, Moraceae, and *Orbignya,* although in smaller percentages, indicates that the mire was still wetter than the surrounding Caatinga, as it stands still today.

The environmental conditions changed probably because of a decrease in the human occupation, as a consequence of less water availability and the arrival of Europeans in Brazil. Land-use associated with the arrival of Europeans has probably contributed to the environmental changes, as suggested by a decline of palm trees, and an increase of Euphorbiaceae, *Acalypha*, *Byrsonima*, and *Solanum* (Fig. 2.3). The analysis realized by PCA indicates that samples from this period are related mainly to the axis PC2 (negative values) represented by Amaranthaceae, *Solanum, Roupala*, and Poaceae, indicating their relationship with another period of drier conditions.

The charcoal record indicates a decrease in local and regional fire regimes in comparison to prior zones. The stronger decline in local fires (Fig. 2.4) probably reflects a decrease in the Amerindian population during the period.

In accord to other studies in the Caatinga (De Oliveira et al., 1999; Nascimento et al., 2009; Novello et al., 2012), the climate was marked by arid conditions in the late Holocene, but these results showed climatic oscillations in scales of thousands of years, which makes it difficult to relate it to the role of human influence. (Medeiros et al., 2018) also showed a gradual decrease in taxa adapted to high levels of humidity in the last 500 years, which is in agreement with the dry conditions found on the Pingadeira site.

As a matter of fact, (Flantua et al., 2016) showed a significant change in land-use in Amazonia after the first contact of native people with Europeans, around 500 yr BP, implying a sudden decrease in induced fires. A reduction in fires and an increase in reforestation are also documented by (Nevle and Bird, 2008) and (Koch et al., 2019) in different regions of tropical America, after the collapse of native populations associated with the arrival of Europeans.

2.6 Summary and Conclusion

The multi-proxy analysis of a sediment from a mire located in the semi-arid Caatinga dry forest, in the CNP area, provided a reconstruction of vegetation, climate, and fire history depicting local and regional environmental changes and their association to human impact on the landscape for the last 2800 yr cal BP. The palaeoecological reconstruction encompasses three distinct periods. The first, between 2800 and 2150 cal yr BP, records a relatively high proportion of arboreal vegetation with a predominance of *Cecropia*, indicative of dry conditions and strong disturbance environment, which is associated with frequent fires. These local fires are associated with human activity, as the rare occurrence of pollen grains of *Phaseolus* (beans) indicates. During the second period, from 2150 to 450 cal yr BP, the higher frequencies of Moraceae and ferns, indicate a change to wetter environmental conditions. Again, the continuous occurrence of the *Orbignya* palm and of the bean *Phaseolus*, together with frequent fires, suggest an even stronger influence of native Amerindians in the area. At the end of this period (between 700 and 450 cal yr BP), a marked increase of Moraceae and a reduction of *Orbignya* suggests a decline of the Amerindian population, probably related to the arrival of Europeans in NE Brazil. At last, between 450 and 150 cal yr BP, the arboreal vegetation was replaced by herbaceous taxa, indicating the return of drier conditions and/or stronger human impact associated with more open vegetation. These environmental condition changes are related to the decrease in human occupation of the study area.

During the last 2800 yr cal BP there is no abrupt regional climate change recorded for the Caatinga dry forest, although the record from the Pingadeira site demonstrates that even little changes in the regional climate may propitiate important environmental changes when associated with human activity.

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CHAPTER 3

Holocene coastal environmental changes inferred by multi-proxy analysis from Lago Formoso sediments in Maranhão State, northeastern Brazil

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Abstract

Little is known about the history of the coastal environment in the northern part of northeastern Brazil and the role of sea level and climate change, as well as the human impact during the past. In order to shed more light on coastal ecosystem dynamics and its influencing factors, a 300 cm long sediment core has been taken from Lago Formoso (LF), located around 150 km distance from the present-day coast in Maranhão State. The core has been radiocarbon dated and analyzed by pollen, spores, charcoal, X-Ray Fluorescence (XRF), X-ray Powder Diffraction (XRPD), LOI, and sedimentary characteristics. During the period from 7520 to 6230 cal yr BP occurred a dominance of mangrove vegetation, and a high relative sea level (RSL), indicating that the coast of the Atlantic Ocean was very close to the study area. The following period is characterized by an increased input of marine sediment into LF and vegetational succession, indicating a highstand of RSL between 5500 and 5020 cal yr BP. From 5020 to 2580 cal yr BP, dominant sandy sediments show chemical and mineralogical characteristic typical of continental sources. The study area was represented mainly by herbaceous and arboreal vegetation, while mangroves were absent, indicating an RSL decrease. The period between 2580 and 1350 cal yr BP is marked by the lower water table and the stronger presence of rainforest vegetation, and an increasing presence of palm trees, indicating the beginning of the human settlement. The last period, after 1350 cal yr BP, is marked by an even stronger anthropogenic influence in the study area, as the records of the stilt-house settlements also evidence it. These records together with others from the same region are the only evidence of stilts-houses from the pre-colonial period in South America.

Keywords: Holocene, Northeast Brazil, Multi-proxy analysis, Vegetation and climate dynamics, Mangrove, Fire history, Sea level oscillation, Human influence

3.1 Introduction

During the Holocene, environmental changes in coastal zones can be associated with natural forces as climate changes and sea level oscillations, as well as anthropogenic influences. Lago Formoso (LF) lies in the coastal area of Maranhão state (MA), about 150 km to the south of the modern coastline (Fig. 3.1). The studied lake is situated in the transition zone of the Amazon rainforest to the west, Caatinga (dry forest) to the east, and Cerrado (savanna) to the south. This pattern indicates that any environmental changes around this area suggest in shifting of biome boundaries. Coastal environmental changes are strongly influenced by relative sea level (RSL) oscillations and climatic changes, which makes mangroves a key environment to understand these changes (Behling et al., 2001; Behling and Costa, 2001, 1997; Cohen et al., 2005). Several studies on sea level oscillations have been carried out on the eastern (Angulo et al., 2006; Bezerra et al., 2003; Caldas et al., 2006; Martin et al., 2003; Suguio et al., 2013), and the northern Brazilian coast (Behling, 1996; Behling and Costa, 2001, 1997; Cohen et al., 2005).

During the late Pleistocene, Northeastern (NE) Brazil has faced some abrupt short-term climatic changes (Bouimetarhan et al., 2018; Ledru et al., 2006; Pessenda et al., 2005). Between 15,000 and 13,500 cal yr BP, marked forest expansion was found around Lake Caçó, indicating wetter conditions (Ledru et al., 2006). From 12,800 to 11,000 cal yr BP, a forest regression at Lake Caçó was caused by Younger Dryas (YD) climatic reversal. A study located offshore of Parnaiba River by (Bouimetarhan et al., 2018), indicates drier conditions around 12,900 to 12,300 cal yr BP, in the marine sediment core GeoB16205-4, with more heterogeneous vegetation, and increased fire activity. The marine core also suggests a second YD phase from about 12,300 to 11,600 cal yr BP, with increased precipitation in the drainage basin of Parnaíba River. Together with a latitudinal displacement of Intertropical Convergence Zone (ITCZ), the climatic conditions became wetter than in the previous phase, which is suggested by the expansion of tropical rainforest in the hinterland, and development of mangrove. Around 300 years after the end of the YD, a return to more open and dry vegetation occurred (Bouimetarhan et al., 2018). Using stable carbon isotopes, (Pessenda et al., 2005) suggest a dry and open landscape from approximately 10,000 to 6000-5000 yr BP (= uncalibrated years Before Present) at the area of Lagoa do Caçó. After about 4000 yr BP, the climate became progressively more humid due to changes in the intensity and the displacement of the ITCZ.

The first study on coastal environmental changes is from Lago do Aquiri (45 km from LF) (Behling and Costa, 1997), which is located closer to the coastline than LF. The pollen record shows mangrove vegetation at that site since the beginning of the recorded period at 7450 yr BP. The stratigraphy suggests an interruption of the sedimentation due to the marine regression after 6700 yr BP. The recorded late Holocene period from 150 yr BP until present-day, shows a very different environment with seasonally inundated swamp savannas, and secondary forests.

In order to understand detailed past environmental changes in the coastal zone of MA such as vegetation change, climate changes, and sea level oscillations as well as the human impacts, we conducted this study on sediment deposits from LF. To shed more light on the regional palaeoenvironmental changes, we applied multi-proxy analysis. This study has the following specific research questions: 1) How were the dynamics of vegetation in the study area? 2) How sea level and climate influenced the coastal environment since the mid-Holocene? 3) When occurred the Atlantic Ocean regression? 4) Since when and how strong did humans have influenced the environment in the LF region?

3.2 Study area

3.2.1 Location and geological characteristics

The study site, Lago Formoso (LF) (3°15'14"S / 45°23'10"W), is in the region of Penalva county, about 140 km from São Luís, capital of MA state, eastern of Amazonia in NE Brazil (Fig. 3.1). The lake has an area of approximately 500 ha and is inserted into the coastal plains of MA (Fig. 2). During the rainy season (in May is the maximum) the lake is seasonally inundated with the highest water stand of up to 8 m, while during the dry season the shallow lake has 1.3 m water depth (observation by the co-author Navarro). The relief of this area is characterized by a gently sloped landscape with flood plain areas between 3 and 10 m above sea level (asl), formed by a mixture of fluvial and marine deposits (IBGE, 1984). The coastal plains of MA are characterized by significant dynamics, mainly because it is a transgressive coast dominated by a macro-tide (up to 6 m) (El-Robrini et al., 2006). The extensional neotectonics regime and sea level fluctuations control the evolution of the landscape of this coastal plain (Souza Filho and El-Robrini, 1998).

Geologically, it is inserted in the Paleozoic-Mesozoic Parnaiba sedimentary basin. The Quaternary fluvial-lacustrine deposits are composed of unconsolidated and semi-consolidated sand and silt-clay that outcrop in riverbanks with a higher topographic level than the current alluvial plains. Generally it is covered by vegetation which its evolution is ruled by the river dynamics (Correia Filho, 2011).

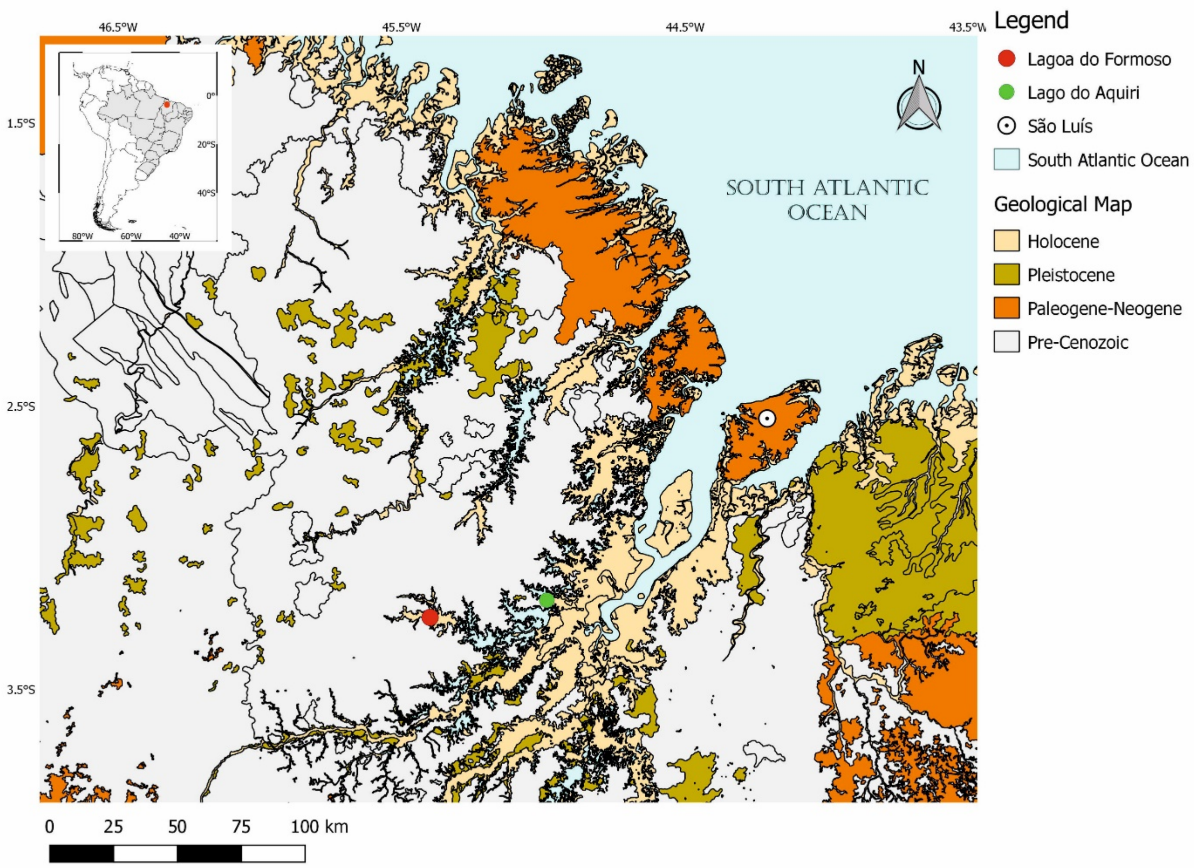

Figure 3.1. Geological map of the region where the Lago Formoso (LF) is located showing the Cenozoic's rock formations and sediments related to their Periods and Epochs besides the Pré-Cenozoic´s. The geological map was adapted from RADAMBRASIL.

Figure 3.2. Photo of the study area Lago Formoso (3°15'14"S / 45°23'10"W). The lake has an area of approximately 500 ha and is situated 10 m above sea level of elevation.

3.2.2 Climate

The Penalva region is characterized by an Equatorial monsoon climate (Am) according to the Köppen-Geiger classification. The average annual precipitation rate is 1860 mm with two distinct periods: a dry season of 5 months with low rainfall rates which occurs from July to November, and a wet season that occurs between December and June. The average annual temperature is 27.3°C (Climate-Data.org, 2021).

The regional climate is seasonally controlled by latitudinal shifts of the ITCZ. These seasonal changes also depend on the position of the South Atlantic Convergence Zone (SACZ) in Central Brazil. When SACZ is absent, the warm and moist equatorial air masses remain close to the coast causing heavy rainfalls. When SACZ is present, moisture is transported from the equatorial Atlantic towards Amazonia (Ledru et al., 2002).

3.2.3 Modern vegetation

The vegetation of MA has a strong gradient as it is in a transitional zone. The region is limited by the Atlantic Ocean in the north, Amazon rainforest to the west, Caatinga dry forest to the east, and Cerrado savanna from to the south. Today, LF is surrounded by pioneering herbaceous vegetation, as it is typical in the surroundings of lakes and fluvial plains. Secondary vegetation is mainly composed of dense ombrophilous forest and palms in the open ombrophilous forest (Fig. 3.3).

Throughout floristic phytosociological sampling realized in LF, the lake has been described by floating islands (aterrados) and not-floating islands, which are characterized by its occurrence of palms as *Euterpe oleracea* Mart. (juçara) and *Mauritia flexuosa* (buriti) (Araujo and Pinheiro, 2012; Souza, 2010). The authors also have mentioned the representative occurrence of Piperaceae, Araceae, Arecaceae, Myrsinaceae, *Cecropia*, and Anacardiaceae.

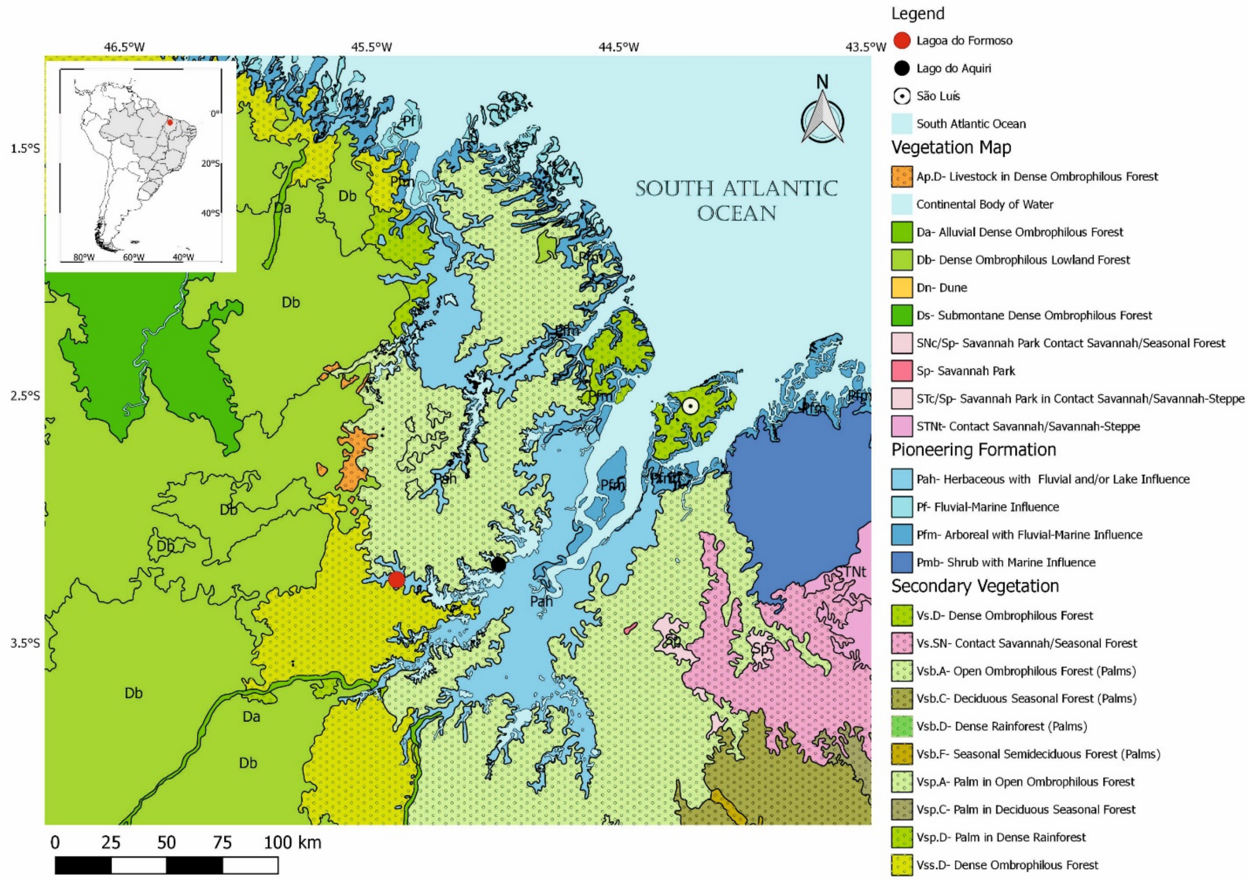

Figure 3.3. Vegetational map of Lago Formoso (LF) showing the current coastal vegetation in Maranhão State, northeastern Brazil. The vegetation map was adapted from RADAMBRASIL.

3.2.4 Human impact

Eastern Amazonia has been occupied since the Pleistocene in which the Amerindians, who were hunter-gatherers, developed extensive communication networks, built sophisticated lithic tools, and rock art in the rivers of the region. One of the oldest human occupations, dating back to 13,000 yr BP, has been found in the caves of Monte Alegre, in eastern Amazonia (Roosevelt et al., 1991).

During the period between 7000 and 2000 yr BP, the Amerindians in South America lowlands became fishermen and built houses on a shellmound. Those shells were usually collected from mangroves, which along the time turned into shellmound known as sambaquis (Roosevelt et al., 1991). This human evidence dated from 6700 yr BP has also been found in MA (Navarro, 2018a).

During the late Holocene, another strong archaeological evidence of pre-colonial occupation in the MA is the stilt-house settlements. These archaeological sites formed by stilts uplifted inside rivers and lakes, which served as support for the wooden pillars or pillars of the indigenous villages, is a peculiar type of pre-colonial occupation in the MA lowlands (Navarro, 2018a, 2018b). In that region, these records have been found in Caboclo (1120 yr BP), Boca do Rio (1150+-30 BP), Cabeludo (1160 yr BP), Trizidela (1140 yr BP), Lontra (1150 yr BP), and Jenipapo (1210 yr BP), making those the only evidence of stilts-houses from the pre-colonial period in South America.

3.3 Material and methods

A 300 cm-long sediment core was obtained using a Russian peat corer in the shallow lake of LF during the dry season. The 50 cm long sediments sections were sealed and taken to a laboratory and stored under dark and cold conditions at 4 °C in the Department of Palynology and Climate Dynamics, Goettingen University. Afterwards, the 300 cm-long core has been described according to its predominant sediment characteristics and color (Color, 2009).

3.3.1 Radiocarbon dating and age-depth model

Six bulk samples (1 cm^3 each) of organic matter were selected along the core based on changes in the pollen record and sent for Accelerator Mass Spectrometry (AMS) radiocarbon dating at Poznań Radiocarbon Laboratory in Poland.

The Marine Reservoir Effect could play an important role in the lower part of the sediment core. However, this period was dominated by mangrove vegetation, which is characterized using carbon dioxide from the atmosphere during photosynthesis. Therefore, this environment typically does not require reservoir corrections (Sefton et al., 2021). Therefore, the radiocarbon dates were calibrated using the Southern Hemisphere calibration curves (SHCal13.14C, (Hogg et al., 2013). The age-depth model was constructed with the software R version 3.5.1 (R Development Core Team, 2018), using Clam 2.3.8 package (Blaauw, 2010) with linear interpolation.

3.3.2 Qualitative Chemical analysis by XRF-scanning and LOI evaluation

X-Ray Fluorescence (XRF) scanning was carried out using an ITRAX XRF core scanner, COX analytical systems (Croudace et al., 2006), at GEOPOLAR, Bremen University in Germany. The sediment core was scanned to detect major and trace elements with a Cr-tube using a 0.5-mm step size and a 10-s count time for each step. Settings of the tube were set to 30-kV voltage and 50-mA current for all sections. Semi-quantitative element data were obtained for Si, Al, K, Rb, Ti, Fe, and S. XRF-scanning data were normalized by cps.

The loss on ignition was carried out as follows: approximately 2g of dried (40 °C) sample was heated to 1000 °C and kept in this temperature for 1 hour. The weight mass difference (expressed in weight percent) between the sample at 40 °C and 1000 °C is here related as LOI. It is important to point out that the determined LOI values do not represent only the loss of volatile due to the decomposition of organic matter (Santisteban et al., 2003), but also the structural water of minerals (clay minerals).

3.3.3 Mineralogical characterization by XRPD

Mineralogical analyses were performed by X-ray Powder Diffraction (XRPD) using a PANalytical X’Pert Pro MPD X-ray diffractometer (Cu anode), in the laboratories of mineralogy at the Institute of Geosciences of the Martin Luther University of Halle-Wittenberg, in Germany. The diffractometer was equipped with a linear X’Celerator RTMS detector set in the θ-θ Bragg-Brentano-Geometry, and the measuring conditions were under 5-70° 2θ angular range, with 0.013° step size, and a counting time of 38 seconds per step.

Fifteen representative samples were collected from the core, dried at 40ºC for approximately 48 hours to have their relativity humidity accounted for, and carefully grounded in an agate mortar. The finely grounded samples were prepared by backloading into 16 mm-diameter sample holders. The mineral characterization was performed with aid of the software HighScore Plus 4.5, using the Powder Diffraction Files mineral database from the International Center for Diffraction Data.

3.3.4 Palynological and macro-charcoal analysis

For pollen analysis, 40 subsamples of 0.5 cm^3 have been taken in intervals of 4 to 8 cm along the 300 cm-long core. Prior to processing, one tablet with the exotic marker *Lycopodium clavatum*, each with 20,848 +/-1546 spores, was added to each sample for calculation of pollen concentration (grains/cm^3) and pollen influx (grains/cm^2/yr). Chemical preparation included 10% HCl, 10% KOH, 40% HF, and acetolysis (Faegri and Iversen, 1989).

Pollen and spore identification was carried out with the reference collections from the Department of Palynology and Climate Dynamics, a palynological atlas (Roubik and P., 1992), and with the Neotropical Pollen Database (Bush and Weng, 2007). At least 300 terrestrial pollen grains were counted per subsample. This sum was used for the calculation of pollen percentages. Fern spores and algae have been counted as well, and their percentages are based on the pollen sum.

The pollen and spore taxa were grouped into mangroves, herbs, trees and shrubs, palms, ferns, and algae. The calculation and illustration of the data used the programs TILIA, TILIAGRAPH, and CONISS for cluster analysis to establish the pollen zones (Grimm, 1987).

For macro-charcoal analysis, samples with 0.5 cm^3 were taken continuously along the core at intervals of 1 cm. The samples were processed using 10% KOH, 6 % H_2O_2, and a sieve (mesh width 64µm) according to (Stevenson and Haberle, 2005). The remained charcoal particles were counted using a Zeiss stereomicroscope and the results were analyzed with CharAnalysis version 1.1 (Higuera et al., 2009). Background charcoal was separated from the charcoal record to permit the identification of main fire events. The charcoal counts were transformed to charcoal accumulation rates (CHAR; units: cm_2/yr) with interpolation to the median sample resolution of this record (18 years).

Low-frequency charcoal $CHAR_{background}$ was calculated by use of moving median defined by 300-yr intervals. Locally defined peaks within this interval were estimated by subtracting $CHAR_{background}$ from CHAR and $CHAR_{peak}$ identification via base threshold values on a noise distribution determined by a Gaussian mixture model. A $CHAR_{peak}$ represents a fire episode of one or more large fire events in the catchment of LF within 18-year intervals (Higuera et al., 2009; Mustaphi and Pisaric, 2014).

3.3.5 Data analysis

To elaborate the thematic map from the studied area in MA, vegetational and geological maps were taken from RADAMBRASIL (Brasil, 1973), obtained from the Brazilian Institute of Geography and Statistics – IBGE website (www.mapas.ibge.gov.br) and processed in QGIS software, version 2.18 Las Palmas (QGIS Development Team, 2016).

In order to investigate the possible correlation between the identified pollen taxa, Principal Component Analysis (PCA) was carried out on pollen percentages obtained on the 40 subsamples, showing the most representative taxa. Multivariate ordination analysis was performed with software Canoco 5.0 (Braak and Smilauer, 2012), to highlight the most important taxa suitable for interpretation.

3.4 Results

3.4.1 Sedimentological description of the core

Through textural description of the LF core (see supplementary material), have been identified 14 different units (Fig. 3.4). From 300 to 196 cm, the deposit was composed only of compact light gray silt/clay, with the presence of vegetation fragments. Between 196 and 122 cm occurred a transitional zone, in which brownish and dark gray mud sediments were found interbedded. From 122 to 81 cm, banded sediments composed of compact brownish-gray silty sand were predominant. Between 81 and 48 cm occurred smoothly banded sediments, composed of grayish brown to brownish-black silt. Brown silt and thin sand sediments with a strong presence of ceramic fragments (anthropological influence) composed the uppermost 48 cm part of the core. In general, the core presented a coarsening upward, switching from compact gray silt-clay sediments at lowermost layers to brown sand-silt sediments at uppermost layers.

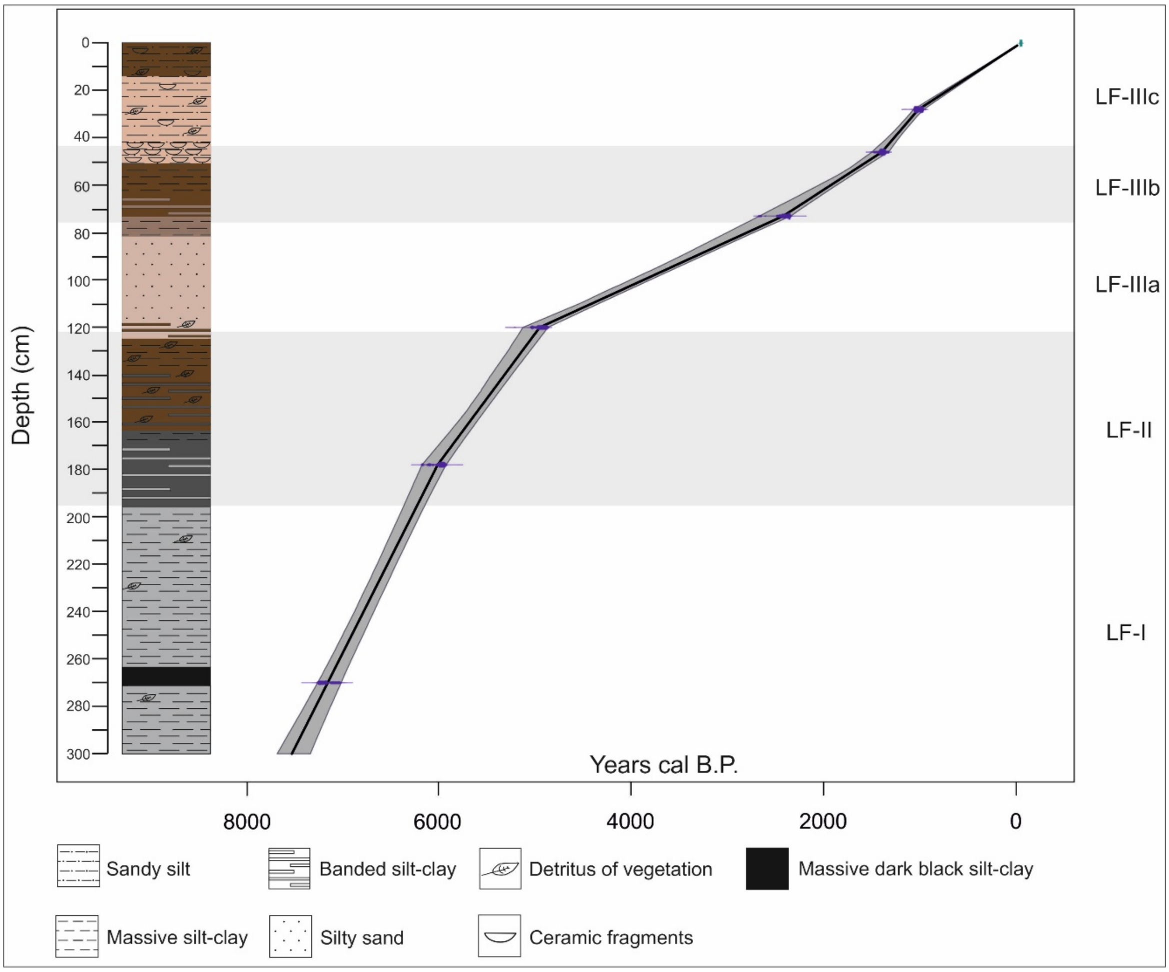

Figure 3.4. Age-depth-model and stratigraphic description of Lago Formoso core exhibiting the textural characteristics, structures, human influence and the radiocarbon-dated samples.

Radiocarbon dating and sedimentation rates

Six bulk samples have been AMS Radiocarbon dated as shown in Table 3.1. The chronology indicates that the sedimentation occurred continuously since the mid-Holocene (Fig. 3.4). The base of the core, at 300 cm depth, has an extrapolated age of 7520 cal yr BP. The sedimentation rates have been calculated according to the zonation of the pollen diagram (see next section). The sedimentation rate for pollen zone LF-I is 0.8 mm/yr (300–196 cm); for LF-II 0.6 mm/yr

(196–124 cm); for LF-IIIa (124–76 cm) 0.2 mm/yr; for LF-IIIb (76-44 cm) 0.25 mm/yr, and for LF-IIIc (44–0 cm) 0.31 mm/yr.

Table 3.1. List of the radiocarbon dates for core LF.

Depth (cm)	Lab. No.	Material (1 cm^3)	^{14}C age years, BP	Calibrated (cal yr BP)
28	**Poz-132086**	Bulk sediment	**1160 ± 30**	1014
46	**Poz-111300**	Bulk sediment	**1555 ± 30**	1394
73	**Poz-119189**	Bulk sediment	**2410 ± 30**	2419
120	**Poz-115847**	Bulk sediment	**4415 ± 35**	4947
178	**Poz-111301**	Bulk sediment	**5270 ± 40**	6006
270	**Poz-111302**	Bulk sediment	**6280 ± 40**	7148

3.4.2 Chemical composition and LOI

We selected Si, Al, K, Rb, Ti, and Fe as the most representative elements to determine the continental output, as well as the S element to characterize the marine influence into LF. Other elements (for example Ca), besides ratios, have been analyzed, but they did not show relevant trend results. The relevance of these elements can also be evidenced by the mineralogical composition of the studied site (Fig. 3.5).

The electronic counts for Si, Al, K, Rb, and Ti demonstrate similar trends with higher contents at the base of the core (LF-I), followed by a slight decrease at the lower portion of LF-II until the minima from 160 to 120 cm. Elements in the uppermost core section (15 to 0cm) show variable patterns. Sulfur counts oscillate between 300 and 200 cm (LF-I), with noticeable higher counts at about 270 cm and 200 cm. In the upper portion of LF-II, from approximately 160 to 120 cm, sulfur depicts its maximum counts (contents). S contents decrease abruptly to a fairly constant minimum from 120 cm until surface level.

LOI sampling was carried out in lower frequency and therefore gives results only for selected samples of the core (Fig. 3.5). It varies only from 12 to 14% from 300 to 200 cm (LF-I), with the clear exception of the sample at 270 cm (26%). From 160 to 130 cm (upper part of LF-II) the LOI sharply increases to a maximum of 67%, before decreasing to 6 and 7%, at respectively 110 and 90 cm (LF-IIIa). At 70 cm (LF-IIIb) it increases to 26%. From 40cm to the top of the profile (LF-IIIa), the LOI increases from 16 to 26%.

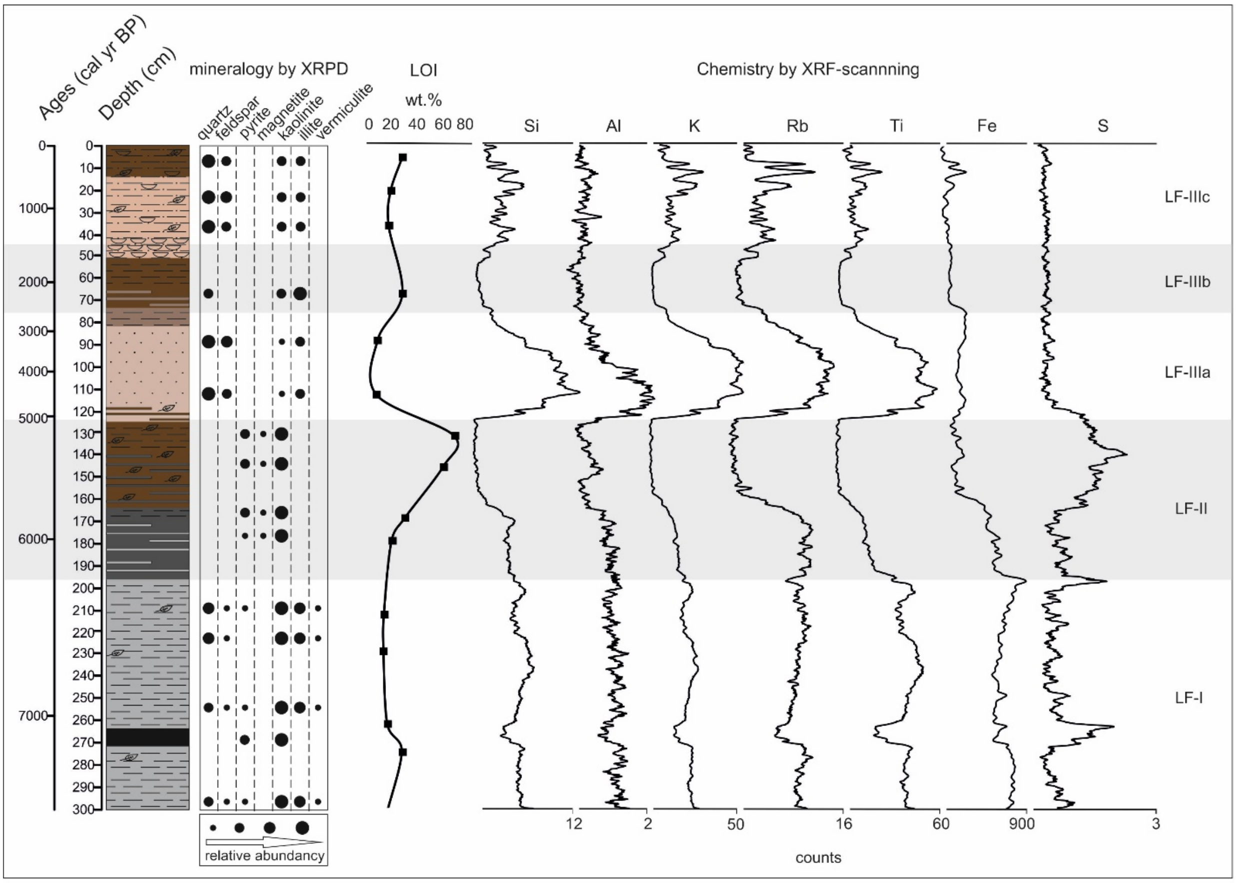

Figure 3.5. Selected results of the mineralogical (XRPD), LOI and chemical analyses (XRF) of the Lago Formoso core. The mineralogy by XRPD is represented relative to the mineral abundancy, showing the most abundant as bigger circles. The LOI analysis are expressed as weight percentages (wt.%). The chemistry by XRF-scanning is expressed as counts per second (cps), and every element have been multiplied by 10^3.

3.4.3 Mineralogical composition

Kaolinite and illite are the most abundant minerals in the lower part of the core (300-200 cm, LF-I) which make up the clayey fraction of it, while minor contents of quartz, feldspar, pyrite, and vermiculite are present (Fig. 3.5). The clear exception is again at 270 cm, where only kaolinite and pyrite were identified. In the middle part of the profile (LF-II), kaolinite and pyrite are the main phases, besides some magnetite. From 120 cm to the top of the core, the mineral assemblage of the sediments changed, with the disappearance of pyrite and magnetite (LF-III). Quartz and feldspar are the most abundant minerals at 110 and 90 cm (LF-IIIa) forming the sandy fraction of the sediments, while lower contents of the clay's kaolinite and illite are still present. At 70 cm (LF-IIIb) the clay minerals kaolinite and illite turn abundant again, with still considerable quartz. The mineralogy of the core becomes fairly homogeneous along its uppermost silty-sandy part (LF-IIIc), essentially composed of quartz and feldspar, besides less abundant kaolinite and illite.

3.4.4 Description of pollen, spore, and charcoal data

In total 96 different pollen, spores and algae have been identified: 1 mangrove taxon, 23 herb taxa, 53 trees and shrubs, 5 palms, 12 types of spores, and 2 types of algae. According to major changes in the pollen assemblages and the CONISS cluster analysis, the pollen record has been zoned into three pollen zones (LF-I, LF-II, and LF-III) (Fig. 3.6 and 3.7). The uppermost zone is divided into three pollen subzones (LF-IIIa, LF-IIIb, and LF-IIIc). The local fire events and temporal changes in the fire regime are shown by the charcoal influx (Fig. 3.7). In total, there have been detected 28 main (local) fire events (Fig. 3.7 and 3.8).

Pollen zone LF-I (300–196 cm; 14 samples; 7520–6230 cal yr BP) is marked by a predominance of mangrove pollen represented by *Rhizophora*, which is almost the unique taxon on some levels. Specifically, at the depth of 270 cm, occurs a stronger decrease in mangrove pollen. Pollen of herbs are represented mainly by Cyperaceae and Poaceae. The group of trees and shrub pollen such as Moraceae and Fabaceae (psilate) are the most representative, but in low concentration. Palms are almost absent. Ferns are marked by low values. Algae are absent. The pollen influx ranges from 2246 to 14838 grains/cm^2/yr. The

Macro-Charcoal influx has a marked maximum at 270 cm core depth, while in the other parts of the zone occur in low influx.

Pollen zone LF-II (196–124 cm; 9 samples; 6230–5020 cal yr BP) is characterized by a marked decrease of mangrove pollen, whilst herbaceous and trees and shrub pollen increase at different times. This succession is represented by a marked decrease in *Rhizophora* pollen and an increase in herbs such as Cyperaceae, Poaceae, *Borreria*, Asteraceae, and *Polygonum*. Trees and shrub pollen such as Moraceae, Euphorbiaceae *Mabea*, and Fabaceae (psilate) are increased. Palm pollen occurs in a low amount and is represented by *Euterpe/Geonoma*. Fern spores increase strongly, mainly represented by the typical mangrove fern *Acrostichum* at the end of the zone. Algae is represented by *Botryococcus* in low concentration. Pollen influx ranges from 875 to 82729 grains/cm^2/yr, achieving the highest amount. The macro-charcoal influx is markedly higher in this zone, and fire magnitude has its highest peaks at this zone.

Pollen zone LF-IIIa (124–76 cm; 6 samples; 5020–2580 cal yr BP) is marked by low values of mangrove with a slight increase of *Rhizophora* pollen at the beginning of the zone but much lower compared to the first zone. There is a marked decrease of *Acrostichum* spores at the beginning of the zone. The herbs maintain relatively high values and are mainly represented by Cyperaceae and Poaceae. Trees and shrubs increase due to higher values of Moraceae, *Cecropia*, and *Alchornea* pollen. Regarding ferns, which were almost represented by *Acrostichum* in the previous zone, have a slight increase in Monolete psilate and Monolete verrucate spores. Algae is represented by *Botryococcus*. The pollen influx varies from 1028 to 4065 grains/cm^2/yr. Macro-charcoal influx is marked by small values.

Pollen zone LF-IIIb (76–44 cm; 4 samples; 2580–1350 cal yr BP) is characterized by small amounts of mangrove pollen. Herbs increase gradually, mainly due to Cyperaceae and Poaceae values. Trees and shrubs slightly decrease in comparison to the last zone, represented mainly by Moraceae and *Cecropia*. Palms trees which are almost absent in the previous zones increase markedly mostly by *Mauritiella*, *Mauritia*, and *Euterpe/Geonoma*. Ferns spores have a gradual increase due to the values of Monolete spores. Algae are represented by *Botryococcus* and *Pediastrum*, the latter occurs only in this zone and in high values. Pollen influx ranges from 620 to 2709 grains/cm^2/yr. The Macro-charcoal influx is still low in this zone, but with a gradual increase in the transition to the next zone.

Pollen zone LF-IIIc (44–0 cm; 7 samples; 1350 cal yr BP –Present) is marked by the same small values of mangrove pollen compared to the last zone. Herbs decrease slightly, characterized mainly by Cyperaceae, Poaceae, and Asteraceae pollen. Trees and shrubs increase mainly due to higher *Cecropia* values, besides the presence of Moraceae and *Alchornea*. The palm pollen increases markedly, represented by *Mauritiella*, *Mauritia*, *Euterpe/Geonoma*, and *Orbignya*. Fern spore values remain stable in this zone, and Algae are only represented by *Botryococcus*. The pollen influx varies from 293 to 1737 grains/cm^2/yr. The Macro-charcoal influx and fire magnitude have markedly increased in the entire zone.

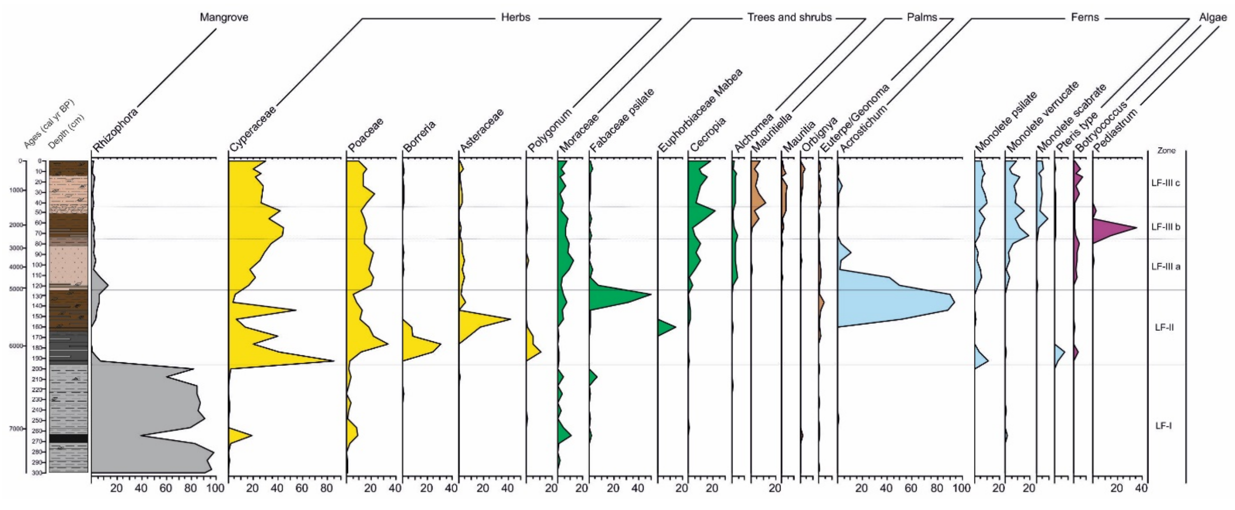

Figure 3.6. Pollen percentage diagram of the frequent and most important taxa of Lago Formoso (LF) core grouped into mangrove, herbs, trees and shrubs, palms and ferns associated with the stratigraphic description.

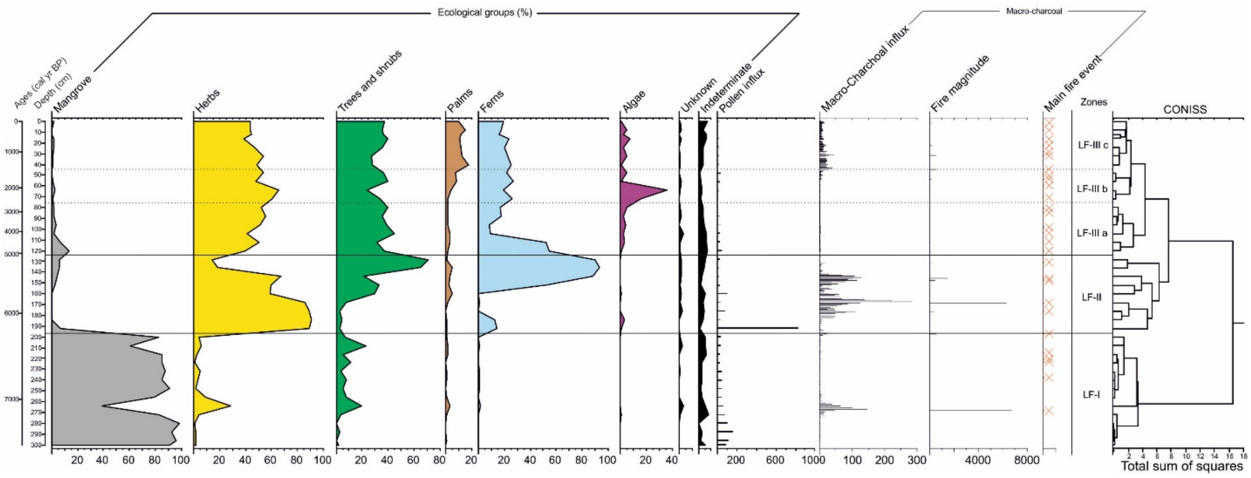

Figure 3.7. Summary pollen diagram of Lago Formoso (LF) core, showing the age scale, ecological groups, pollen influx, macro-charcoal and the cluster analysis dendrogram.

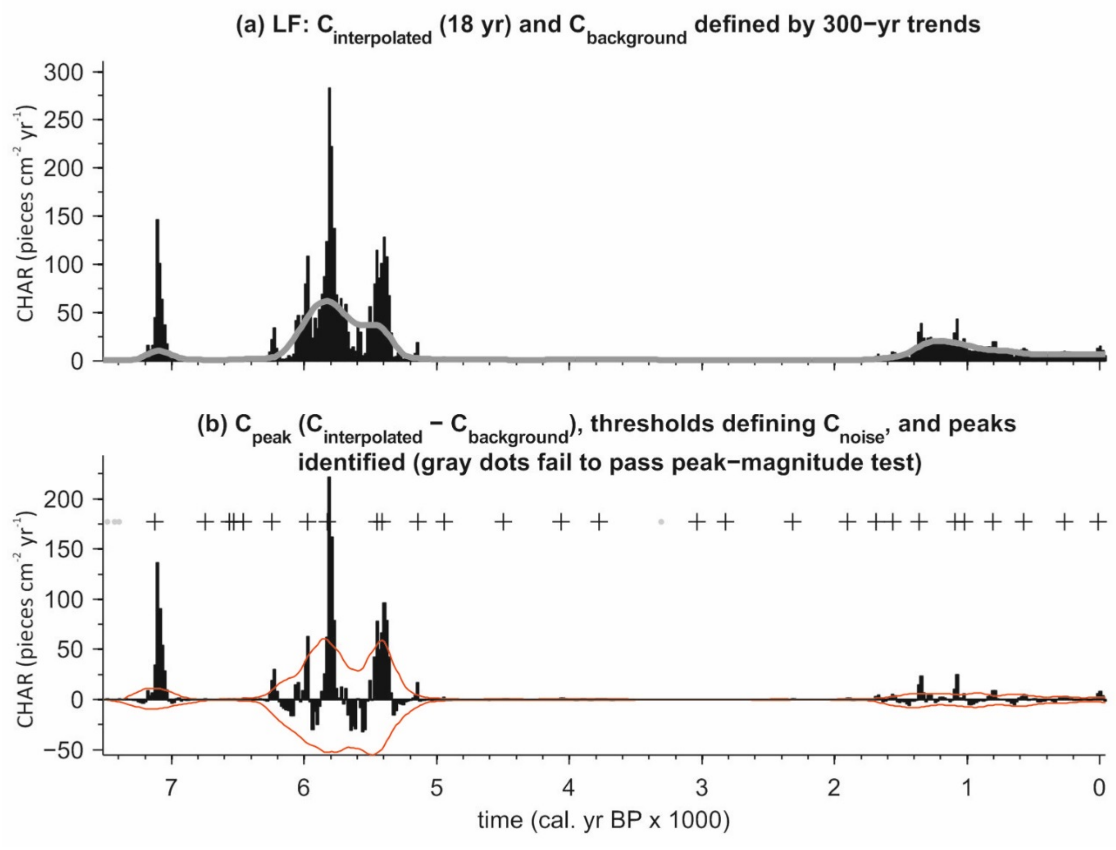

Figure 3.8. CHARAnalysis diagram presenting (a) the interpolate charcoal counts ($C_{interpolated}$) (18 yr) and the background charcoal noise ($C_{background}$, gray line) defined by 300-yr trends, and (b) C_{peak} ($C_{interpolated}$ + $C_{background}$), threshold defining C_{noise} black line), and the main fire events (peak ID, +).

3.4.5 Principal Component Analysis (PCA)

The PCA is shown by its most representative taxa (22) in the 40 subsamples of the period from 7520 cal BP to the present time (Fig. 3.9). The Axis1 has a cumulative percentage variance comprise 49.1 from a total variation of 622.77. The positive axis is composed almost unique by samples from the LF-I zone, represented especially by mangrove environment as *Rhizophora*, besides the presence of Fabaceae (psilate), *Polygonum*, and *Sebastiana*. The negative axis comprises the transition to LF-II with an ecological succession to more open vegetation represented mainly by Cyperaceae, Asteraceae, and Poaceae.

Axis 2 has a cumulative percentage variance consist of 61.75. The positive axis is represented by samples from LF-II, composed mainly of Rubiaceae, *Borreria*, and Euphorbiaceae. On the other hand, the negative axis is represented mostly by samples related to LF-III, which is composed mainly of arboreal species as *Alchornea*, Fabaceae reticulate, *Euterpe*, *Mauritiella*, Moraceae and, *Cecropia*.

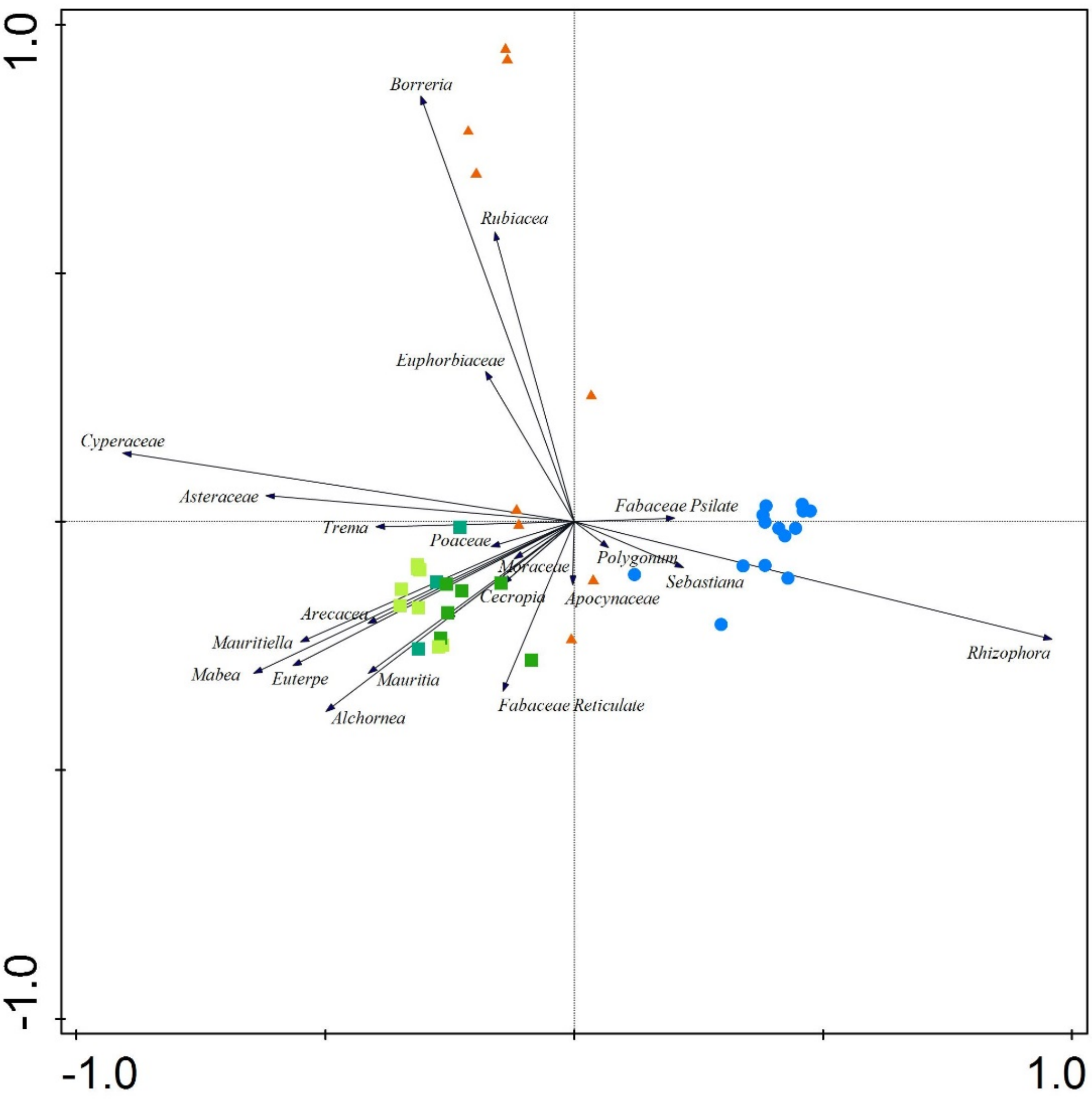

Figure 3.9. Principal Component Analysis (PCA) from Lago Formoso (LF) core. The blue circles represent samples from zone LF-I; the orange triangles are samples from zone LF-II; and the varieties of green squares from zone LF-III.

3.5 Interpretation and Discussion

3.5.1 Mid-Holocene period from 7520–6230 cal yr BP (Pollen zone LF-I)

The gray silt-clay sediment deposits have the highest sedimentation rates, with 0.8 mm/yr, in the core during this period (Fig. 3.4). These sediments show average counts (relative contents) for Si, Al, K, and Rb compared to the following periods, whereas Fe and S display slightly variable counts. The chemical data correspond with the mineralogical composition, which shows a predominance of clay minerals (kaolinite, illite, and vermiculite), feldspar, besides quartz, and pyrite (Fig. 3.5). The high counts of Fe may be due to a terrigenous contribution, and S indicates marine influence, coming from the reduction of dissolved marine water sulphate. These sediment deposits show as well continental as marine run-off at the study site, as indicated by kaolinite, iron (probably previous iron oxyhydroxides), and some quartz. Those characteristics suggest that during this period, the site was under tidal influence due to a high RSL. Marine transgression during this period has also been reported from the eastern part of NE Brazil. Accordingly, the current sea level was exceeded at approximately 7000 cal yr BP, and reached its maximum between 5900 and 5000 cal yr BP (Bezerra et al., 2003; Caldas et al., 2006; Martin et al., 2003; Suguio et al., 2013).

The pollen records show the predominance of *Rhizophora* for this period, indicating that mangroves occurred at the study site. As the mangrove establishment depends on tidal influence, and the studied site is far distant from the current coastal zone (Fig. 3.1 and Fig. 3.3), it indicates that the ocean extended deep inland, enabling the landward migration of mangroves into estuaries, embayments, and lagoons in the coastal zone of MA. Therefore, during this period the LF was probably located in the mangrove zone as part of a tide-dominated estuary system. The development of mangroves landwards as a consequence of rising RSL has been reported since the early Holocene in the northern part of NE (Behling and Costa, 1997; Ledru et al., 2006). In northern Brazil, the mangrove expansion has been documented from 8370 to 7520 cal yr BP in Lago Crispim (Behling and Costa, 2001), and between 8080 and 6380 cal yr BP in Lagoa da Curuça (Behling, 2001, 1996).

Recorded herbs such as Cyperaceae, Poaceae, and Asteraceae were very rare. Palm trees such as *Mauritiella* and *Mauritia* and trees that belong to the Amazon rainforest such as Moraceae, *Cecropia*, and *Alchornea* also were rare due to the local dominance of mangrove vegetation (Fig. 3.7).

Interesting is a strong short event that was recorded at about 7150 cal yr BP (270 cm core depth). During this event occurred a clear decrease of the chemical counts for Si, Al, K, Rb, and Ti, respectively indicating a decrease or disappearance in the contents of clay minerals, feldspars, and Ti oxides. The iron counts remain practically unchanged. On the other hand, S sharply increases (as for pyrite), as well as charcoal particles. Moreover, LOI, which is fairly regular for this entire period, also increased. Its variation might be associated with the higher abundance of charcoal particles (Fig. 3.7 and 3.8). This disturbance event could be caused by a lower influx of continental coarser sediments (mainly composed of quartz and feldspar), or an increase of marine influence to the study site. This short-term markedly reduction of mangrove vegetation, and increase of herbs, might indicate an event of severely dry conditions. The recorded strong fires at this time might be related to drier conditions and/or human activities, the latter is a possibility that cannot be excluded. However, so far the oldest evidence of Amerindian colonization and their interaction with mangroves in the MA lowlands has been dated at 6700 yr BP (Navarro, 2018a).

The predominance of mangrove in the study area makes it difficult to indicate the local climatic conditions at LF during this period. However, previous palaeoecological studies suggested that the mid-Holocene was marked by drier conditions, as shown in MA State (Pessenda et al., 2005), and southeastern Amazonia (Guimarães et al., 2021; Hermanowski et al., 2012a).

3.5.2 Mid-Holocene period from 6230–5020 cal yr BP (Pollen zone LF-II)

The interbedded brownish and dark gray mud sediments, together with a high sedimentation rate, indicate a heterogeneous environment during this period. A sharp decrease of Si, Al, K, Rb, and Ti elements reflect lower contents or the absence of quartz and feldspar, indicating a minor terrestrial input to the study site (Fig. 3.5). On the other hand, the constant presence of kaolinite, a typically continental mineral and indicator of warm and humid climate, may suggest that the study site`s surroundings were more humid, and the transport energy had lost in strength, being able to transport only clay, invaded by fruitful vegetation and incursions of marine waters to the younger part of this period (upper zone of LF-II). Additionally, in this younger part, the increase in the S values reflects that the marine inputs played a major role during this phase. The exclusive presence of magnetite in LF-II may demonstrate that the partial source of terrestrial minerals has changed, with weathering of rocks carrying magnetite, or the local drainage has been changed and reached areas with magnetite. Magnetite and/or titanomagnetite is a frequent mineral found in beach deposits on the coast of MA (Costa et al., 1977). The LOI maximum occurred between 6000 and 5020 cal yr BP, suggesting the formation of organic deposits probably caused by the increase of the local water table. These records suggest that the Atlantic Ocean kept moving towards the continent, allowing an influence on the LF site.

The mangroves with *Rhizophora*, which dominated the last period, strongly decreased (Fig. 3.6). The reason for its marked decline at the study site can be related to two main reasons: i) an increase of the deposition causing a higher topographic elevation, which became a natural barrier to mangroves keeping contact with the marine brackish water; and/or ii) an increase in freshwater into the floodplains, transported from the continent as a consequence of higher precipitation rates.

The marked increase in Cyperaceae, besides *Polygonum*, ferns, and *Botryococcus* at the beginning of this period, suggests the formation of a saltmarsh/swamp environment. This environment occurred probably due to an increase in freshwater at the study site as a consequence of higher rainfall with a shortened dry season, marked by a short wet event from 6230 to 6000 cal yr BP. Evidence of higher precipitation rates has been recorded about 6000 yr BP in Amazon lowlands (Wang et al., 2017). Suggestions of dry periods alternating with slightly wetter periods have been proposed also for southeastern Amazonia (Hermanowski et al., 2012b; Sifeddine et al., 2001), in contrast to the idea of permanent dry conditions (Absy et al., 1991).

Between 6000 and 5500 cal yr BP, occurred a decrease in Cyperaceae, ferns, and the algae *Botryococcus*. Species of Poaceae, Asteraceae, and *Borreria* increased, suggesting a different phase with drier conditions (Fig. 3.6). This environment-related to more open vegetation may be due to a lowering of the precipitation rates. The high abundance of carbonized particles shows that fires were intense during this period, affecting the vegetation.

Between 5500 and 5020 cal yr BP occurred a strong increase in the mangrove fern *Acrostichum*, besides the slight return of *Rhizophora*. The marked maximum in Fabaceae (psilate) and the increase in Moraceae and the palm *Euterpe/Geonoma* can be related to succession phases as well as a slight rainforest expansion (Fig. 3.6). The increase in S reflects the marine influence. The RSL probably achieved its highstand in this phase, allowing a return of mangrove further inland, colonizing areas which were at somewhat higher elevated areas. Studies from eastern NE Brazil indicate the highest RSL achieving from 1.3 to 4.7 m above current sea level between 5900 and 5000 cal yr BP (Bezerra et al., 2003; Caldas et al., 2006; Martin et al., 2003; Suguio et al., 2013). However, the RSL was apparently not that high in northern NE for a full establishment of mangroves (Behling and Costa, 2001). The highstand of the RSL for northern Brazil has been reported in Bragança Peninsula at 5100 cal yr BP, however, the RSL never achieved above current sea level (Cohen et al., 2005).

3.5.3 Mid- to late Holocene period from 5020–2580 cal yr BP (Pollen zone LF-IIIa)

The sediments are predominant characterized by silty-sand and decrease in sedimentation rates, with an overall minimum of 0.2 mm/yr. There is a relatively sharp count increase of Si, Al, K, Rb, Ti, and Fe. The first four elements correspond to the relative abundance of quartz, feldspar, and illite (Fig. 3.5). Together with the decrease of kaolinite, this environment suggests a climate in the direction of dry conditions. This was probably a consequence of the intensity's loss of the tropical weathering, which reduced the production of kaolinite, and produced much more illite, and concentrating feldspars, indicating a continental influx to the LF site. The higher counts for Ti and Fe also reinforce the continental influx of detrital minerals (Rothwell and Croudace, 2015). The lower S contents, and consequently of pyrite, confirms the absence of marine influence. The decreasing LOI values are related to the lesser content of clay minerals and organic matter, reinforcing the drier conditions. This different environment has been formed mainly as a consequence of RSL fall, and therefore, the shift of sediment run-off predominance from marine to continental. Event of RSL regression (after around 5000 cal yr BP) has been also suggested in eastern NE as well as in northern Brazil.

Mangrove vegetation represented by *Rhizophora* and *Acrostichum* markedly decreased during the beginning of this period. Their few pollen grains and spores respectively must have been transported by wind from the more distant coastal region. Herbs such as Cyperaceae, Poaceae, and Asteraceae are well represented, indicating open non-forested areas, probably due to seasonal inundation with freshwater. The arboreal vegetation increased mainly represented by Moraceae, *Cecropia,* and *Alchornea* (Fig. 3.6). These trees are common on fertile soils in tropical rainforests (Marchant et al., 2002a), and in contrast to the chemical and mineralogical composition, it suggests an increase of Amazon rainforest species in the LF area. The increase of ferns may also be related to these moister conditions. The increase of the algae *Botryococcus* suggests a shallow and temporarily stagnant lake. The macro-charcoal influx has been represented in low values, indicating a low fire regime (Fig. 3.8).

After this period, LF became a freshwater lake with some Amazon rainforest trees in the surroundings. The formation of the lake could be associated to the local drainage system, which has very little water and sediment discharge. Meanwhile the sediment deposition in the inner part of estuarine system (the large São Marcos Bay) was probably substantial. Thus, the infilling at the inner part of estuary was advancing rapidly during the mid-late Holocene due to the association of fluvial discharges coming from the rivers Mearim, Pindaré and Grajaú, which at certain point blocked those smaller systems at the west bank of the Bay, whereas LF became a lake.

A moderate and progressive increase in arboreal vegetation was also suggested, since approximately 4000 yr BP, around Lake Caçó (Pessenda et al., 2005), and around 3000 yr BP in southeast Amazonia (Carajás region) (Guimarães et al., 2021; Hermanowski et al., 2012a), indicating changes to wetter conditions.

3.5.4 Late Holocene period from 2580–1350 cal yr BP (Pollen zone LF-IIIb)

This period is composed of finer sediments also poor in organic matter. Elements such as Si, Al, K, Rb, and Ti decreased likewise quartz and feldspar, while clay minerals as kaolinite and illite increased. The LOI values increased in comparison to the last phase (Fig. 3.5). Altogether, these parameters suggest that the regional environment was wetter and warmer without marine connection.

Rhizophora pollen was recorded in low values, indicating mangrove presence even further distant to the study site. The amount of Cyperaceae increased, while the occurrence of Poaceae remained stable. The appearance of Amazon tree species such as Moraceae, Fabaceae, and *Alchornea* indicate wet conditions, suggesting a freshwater lake environment like the previous phase.

Interesting is the beginning of palm tree expansion mainly of *Mauritiella* and *Mauritia*. *Mauritia* occurred in a low frequency since the beginning of the Holocene in lake Caçó (Ledru et al., 2006). Although the presence of these palm trees are due to this warm and flooding environment (Marchant et al., 2002b), their increase in abundance may be related to human activities, as evidenced in other studies through Amazonia (Behling and Costa, 1997; Ledru et al., 2006; Maezumi et al., 2018a; Morcote-Ríos and Bernal, 2001). *Cecropia* is predominant in secondary vegetation and often associated with disturbed environments (Lorenzi, 1998). Its abrupt increase at this interval, together with high amounts of carbonized particles, indicate disturbance by fire. A similar pattern with enrichment of *Mauritiella* and *Mauritia,* together with an increase in fires has been recorded in eastern Amazon around 2500 cal yr BP as a consequence of the intensification of human activities (Maezumi et al., 2018b). Using charcoal and pollen analysis, the authors indicated the onset of fire activity and crop cultivation around a lake in eastern Amazonia approximately 4500 cal yr BP. However, after 2500 cal yr BP, Amerindians have altered the vegetation composition through the enrichment of edible plants, primarily by palm fruits of *Mauritiella* and *Mauritia.*

The presence of the algae *Botryococcus* and *Pediastrum* indicates a freshwater environment. *Pediastrum* inferring lake level changes have been used in other palaeoenvironmental studies in South America (Gosling et al., 2008; Whitney and Mayle, 2012), and its higher occurrence in this period may indicate a lowering of lake levels. As the vegetation indicated that the climatic conditions kept wet during this interval, one reason for a shallower lake level could be related to the decrease of the RSL. In the eastern NE, a RSL oscillation has been proposed instead of a direct decrease until the current sea level, which suggested that RSL was continuously low between 4200 and 2100 cal yr BP ((Bezerra et al., 2003). Regarding the northern coast of Brazil at the Bragança Peninsula, (Cohen et al., 2005) suggested a maximum decrease of about 1 m below the modern RSL between 1800 and 1400 yr BP. The higher amount of freshwater and shallower water table could be the trigger for the human establishment in the LF area.

Between 7000 and 2000 yr BP, Amerindians in eastern Amazon lowlands became more fishermen and built houses on a shellmound, called sambaquis (Roosevelt et al., 1991). The oldest sambaquis can be found in the eastern Amazonia, in the region of Monte Alegre, Santarém, and Taperinha, which belong to the Mina Tradition (Roosevelt et al., 1991). Shellmounds of this tradition have been found spread along the littoral from the states of Pará to MA (Simões, 1981a). In MA lowlands, (Navarro, 2018a) found first evidences dated back to 6700 yr BP. Nevertheless, the shellmounds of this region have not been studied, with exception of archaeological sites from São Luís (Bandeira, 2013). Likewise, the shellmounds from Paço do Lumiar (2500 yr BP) and Maiobinha (2000 yr BP) (Simões, 1981a) are characterized by intense exploitation of the aquatic resources of mangroves. If at some point the people who lived on stilts were also builders of sambaquis, would be necessary to investigate of these sunken sites in LF.

3.5.5 Late Holocene period from 1350 cal yr BP – present (Pollen zone LF-IIIc)

The sandy silt sediments deposited in this last period are rich in vegetational detritus and ceramic fragments (found in high amounts between 48 to about 40 cm core depth). The overall chemical counts for Si, Al, K, Rb, Ti, and Fe are in general higher than in the previous periods, however slightly below their pattern in the lowermost pollen zone (LF-I) and are marked by intense oscillating values (Fig. 3.5). Probably these more variable count values reflect the variability of ceramic fragment abundance in this interval. Quartz and feldspar are the most abundant minerals in the coarser fraction, which represent normally the mineralogy of archaeological ceramic fragments (Costa et al., 2004; Rodrigues and da Costa, 2016), and the sediments. Nevertheless, the chemical and mineralogical data are possibly strongly affected by the human activities in the lake by using and discharging ceramic and lithic fragments into the lake.

Mangrove pollen transported over distances remained low. The herbs showed a decrease, mainly related to the lower occurrence of Cyperaceae. Arboreal vegetation increased, mostly correlated with the pioneer *Cecropia,* indicating disturbances. Palm trees increased mainly represented by *Mauritiella* and *Mauritia*. Differently from the previous periods, occurred an increase of *Orbignya* and *Euterpe/Geonoma* (Fig. 3.6). *Orbignya* palms occurrence can be related to Amerindian activities (Moran, 1993), which have been used mainly for food, weapons, and materials for dwelling constructions during the Holocene (Anderson, 1977). Similar evidence has been also recorded by other palaeoenvironmental studies in Brazil (De Oliveira et al., 1999; Moraes et al., 2020). Fires markedly increased, probably due to a stronger presence of humans in the area. Ceramics in the studied deposits, the increase of *Cecropia* as well as palms, and the fire intensification can be directly associated with stronger human influence in the landscape.

The presence of *Botryococcus* algae indicate the same freshwater environment as in the previous period, however, the abrupt decrease in *Pediastrum* suggests lake level changes. Different to the previous period, the lake level has risen until the present-day level (Fig. 3.2). The co-author Navarro has observed that nowadays during the rainy season, the lake is seasonally inundated with the highest water stand up to 8 m, while during the dry season, the shallow lake has 1.3 m water depth.

This anthropogenic-influenced period is marked by the building of the dwellings which are archaeological sites formed by stilts-houses constructed inside of rivers and lakes. This type of occupation has been found in others sites in MA lowlands (Navarro, 2018a, 2018b), making these stilts-houses from the pre-colonial period the unique evidence in South America. Evidence of these larger settlements (Lopes, 1924; Simões, 1981b), and their amount of artifacts, show that these people had achieved greater social complexity than the previous ones, and occupied this study area for a longer period (Navarro, 2018a).

In the São Luís Island there is also evidence of a greater social complexity during this period, marked by archaeological sites on black earth. However, they did not live in stilts-house settlements like in the Paço do Lumiar (908 yr BP) and the Panaquatira (1245 yr BP) sites (Simões, 1981b). They suggest larger human populations in the MA lowlands and São Luís Island for that period. The ceramic material found in the uppermost layer of LF, which is much more elaborate than that of the sambaquis, is quite different from that of its shellmonund builders' predecessors. They used it to cook, store, and serve food and liquids, indicating that they were horticultural people and non-fishermen as the previous people. Therefore, these pieces of evidence suggest that humans were the principals responsible for the environmental changes in LF for this period. The moment of Amerindians' abandon of the study site could not be properly estimated and need more investigations. However, the risen of the lake's water level, as indicated by this zone parameters, could be one of the triggers.

3.6 Summary and conclusion

This study carried out at Lago Formoso in northern NE Brazil indicates an environment dominated by Rhizophora as a consequence of a high RSL between 7520 and 6230 cal yr BP. At present time, the mangroves are established only at the current coastline about 150 km distant from the study site, showing that a mangrove landward displacement occurred due to mid-Holocene RSL transgression. The sediment's chemical and mineralogical composition from this phase indicates terrigenous as well as marine influence. Short-term higher precipitation rates turned the study site into a saltmarsh/swamp environment between 6230 and 6000 cal yr BP. From 6000 to 5500 cal yr BP, dry conditions shaped the environment as showed by the predominance of open vegetation, and high concentration of charcoal particles. Highstand of the RSL is suggested between 5500 and 5020 cal yr BP, with a subsequent decrease. The continental element indicators decreased while an increase in S values occurred, reflecting an increase in marine inputs. The predominance of kaolinite confirms the loss of transport energy from the continent. Between 5020 and 2580 cal yr BP, the lower marine influence due to RSL regression and higher continental sediment depositions turned the study site into a freshwater lake, which is corroborated by a relatively sharp count increase of Si, Al, K, Rb, Ti, and Fe, and the consequent abundance of quartz, feldspar, and illite. From 2580 to 1350 cal yr BP occurred a lowering of the lake level due to a maximum RSL decrease. The increase in *Cecropia*, and palm trees as *Mauritiella*, *Mauritia*, and *Orbignya* are related to human influence on the LF environment. The predominance of clay minerals as kaolinite and illite joined with the other parameters, suggest a wetter and warm environment without marine connection. This environment could be the trigger for the human establishment in LF. The Amerindians from this time had the tradition to build houses on a shellmound, called sambaquis, and they are characterized by intense exploitation of the aquatic resources of mangroves. After 1350, vegetation related to human disturbance as *Cecropia* and palm trees like *Mauritiella*, *Mauritia*, and *Orbignya* increased as well as the fire regime, indicating an even stronger presence of humans in the study site. An interesting anthropological layer of ceramic material suggests a more complex civilization as compared to the previous period. This phase, in which there are possibly no more sambaquis in the region, corresponds to the expansion of the people who lived in the stilt villages. These are exactly the stilts, vestiges of the old villages, which spread over Lago Formoso today. The chemical and mineralogical counts represent the ceramic and lithic fragments found in the lake due to human manipulation. Besides the human establishment and the change in local civilization been suggested, the moment of their abandonment still needs more evidence to be estimated.

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Data accessibility

The data used in the analyses are available at PANGAEA https://doi.org/10.1594/PANGAEA.938173.

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Supplementary material

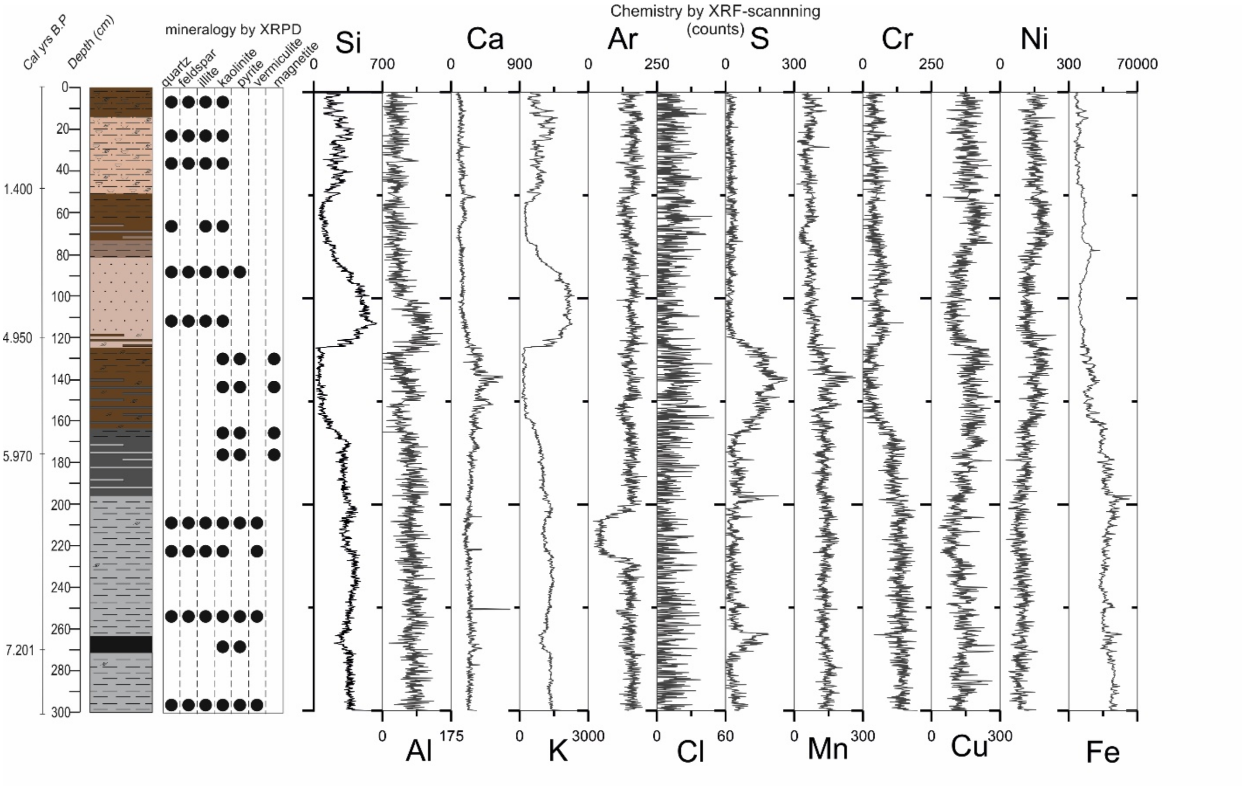

Figure 3.3.10. Supplementary elements included in the chemical analyses (XRF) related to Figure 5.

Depth (cm)	Description	Munsell color
0-11	Dark brown silt and fine sand with Presence of anthropological influence (ceramic) and detritus of vegetation.	5 YR 2/1
11-47.8	Light brown silt and fine sand with a strong presence of anthropological influence (ceramic) and detritus of vegetation. In the 20 and 26 cm depth levels there is the presence of big vegetation fragments	5YR 5/2
47.8-64	Dark brown massive silt	5 YR 2/1

64-73	Dark brown silt smooth banded with Grayish brown silt	5 YR 2/1 and 5YR 3/2
73-81	Grayish brown massive silt	5YR 3/2
81-121.6	Brownish gray silty sand, smoothly banded, mainly in the lower portion	5YR 4/1
121.6-125	Brownish gray sand interbedded with Brownish black silt marking a transitional zone. Presence of detritus of vegetation.	5YR 4/1 and 5 YR 2/1
125 - 139.8	Brownish black Silt / Clay. Presence of sands in form of irregular micro-lens.	5 YR 2/1
139.8 - 163	Silt / Clay sediments banded with one material composed of Brownish color and another of Dark gray color. Presence of detritus of vegetation.	5 YR 2/1
163 -168 cm	Dark gray massive Silt / Clay sediments.	N3
168 - 196	Silt / Clay sediments banded with one material composed of Dark gray color and another of Medium gray color.	N5
196 – 263	Medium light gray massive Silt / Clay. Punctual presence of vegetation fragments.	N5
263-271 cm	Thin layer of Dark black massive Silt / Clay.	N1
271-300 cm	Medium light gray Silt / Clay with bands or waves marks in the lower portion. Between the levels 273-274 cm is possible to recognize vegetation fragments.	N6

Table 3.2. Textural description of sediment core.

CHAPTER 4

Holocene vegetation, climate, sea-level oscillation, and human impact inferred from the archaeological site Cabeludo in Maranhão State, NE Brazil

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Abstract

This study provides an environmental reconstruction of an archaeological site in the northern part of northeastern Brazil. To understand how the climate, relative sea-level (RSL), and human activities triggered environmental changes in Maranhão State during the Holocene, a multi-proxy analysis has been done in a 450 cm long sediment core. The core has been radiocarbon dated and analyzed by its content of pollen, spores, micromorphological and spot chemical analyzes by Scanning Electron Microscope (SEM), multi-element chemical analyzes, X-ray Powder Diffraction (XRD), charcoal, Loss on Ignition (LOI), and sedimentary characteristics. The site was a tidal channel, part of an estuarine system surrounded by mangrove vegetation between 7920 and 7500 cal yr BP. For this period, the mineralogical and chemical composition showed sediments inputs also coming from marine sources, indicating a transgression of the ocean. The combination of marine transgression and dry environmental conditions allowed mangroves to colonize areas further inland. From 7500 to 1800 cal yr BP, the study site turned into the current freshwater tributary river surrounded by lowlands arboreal and herbaceous vegetation while the Amazon biome expanded. The moister conditions and the RSL regression displaced the mangroves to the current coastal bays about 120 km to the north. The sediment run-off was predominantly continental, as showed by mineralogical and chemical analysis. After 1800 cal yr BP, human influence is noted by increased charcoal and fragmented ceramics in the sediment. Archaeological studies at this region showed that Amerindians built stilt-house villages upon the rivers and lakes, which played stronger role in the environment. These pre-colonial stilt-houses Maranhão lowland are the only ones found South America.

Keywords

Holocene; Vegetation and climate dynamics; Sea-level oscillations; Human impacts; Cabeludo archaeological site; Northeastern Brazil.

4.1 Introduction

In tropical regions occur mangrove ecosystems in the transition zone between continental and marine environments. The dynamic of this ecotonal zone, during the past can be related to both climate changes and RSL oscillations (Behling, 2001a; Behling and Costa, 2001, 1997; Cohen et al., 2021, 2005; Fontes et al., 2017; Moraes et al., 2021). The coastal area of State of Maranhão, encompassing Pará State, has the largest continuous mangrove belt in the world, which covers 56.6% of mangroves in Brazil (Souza Filho et al., 2006). However, in the past mangroves colonized regions further inland of the continent during the mid-Holocene marine transgression (Behling and Costa, 1997; Moraes et al., 2021). Studies for eastern Brazil have proposed sea-level transgression of 1.3 to 4.7 m above present between 5900 and 5000 cal yr BP (Angulo et al., 2006; Caldas et al., 2006; Fontes et al., 2017; Martin et al., 2003; Moraes et al., 2021; Ribeiro et al., 2018; Suguio et al., 2013). In northern Brazil studies on past mangroves suggests that the maximum transgression occurred during the mid-Holocene around 5000 cal yr BP (Behling, 2001a; Cohen et al., 2021, 2005). In Bragança Peninsula, the RSL highstand and regional dry climate conditions allowed the mangrove to colonize the highest elevations between 6250 and 5850 cal yr BP. After RSL decreased and the climate became wetter, the mangroves shifted to the lower and coastal regions (Cohen et al., 2021). Our study area is located in the northern part of Northeastern (NE) Brazil, where little is known about the RSL oscillations. The first study on coastal environment changes, related to RSL in Maranhão, is from Lago do Aquiri, and more recently Lago Formoso (LF; Behling and Costa, 1997). In Aquiri, mangrove vegetation was colonizing the area since the beginning of the recorded period at 7450 yr BP (= uncalibrated years Before Present). After 6700 yr BP a sedimentation gap, suggests an interruption in sedimentation due to the RSL lowering (Behling and Costa, 1997). In LF, mangroves were established around the study area, located about 150 km inland from the actual coast, by 7520 cal yr BP (Moraes et al., 2021). Between 5500 and 5020 cal yr BP, RSL reached the highest levels, after which the RSL dropped to the current level. In the coastal zone of Maranhão, there is evidence of Amerindians' presence from 7000 to 2000 yr BP, after that time they became more fishermen and built houses on shellmounds known as “sambaquis” (Roosevelt et al., 1991a). By 1800 cal yr BP, still houses settlements were built upon lakes and rivers (Navarro, 2018a, 2018b). Pre-colonial stilt-house villages evidence, in South America, can be found only in the Maranhão lowland region, which makes the present study of archaeological site Cabeludo important to understanding the interactions between environment and humans during the Holocene. Here we present palaeoenvironmental results obtained from the Cabeludo archaeological site in the Maranhão coastal area. We integrated our records with other palaeoecological studies of the region as well as from different coastal areas in Brazil, to understand how the climate, sea-level, and human activities triggered environmental changes during the Holocene.

4.2 Regional setting

4.2.1 Location and Geomorphological characteristics

The studied sediment core was taken from Cabeludo archaeological site (2° 17’27.8” S / 45º 24’28.7” W, 4 m above sea-level (asl)). The site lies along the Paruá River, a tributary of the Turiaçu River, close to Santa Helena town, approximately 120 km to the west of São Luís, capital of Maranhão state in NE Brazil (Fig. 4.1). This lowland region is characterized by marked environmental dynamics, mainly due to its location along a transgressive coast dominated by a macro-tides (up to 8 m; (El-Robrini et al., 2018).

The study area has no detailed geomorphological studies, which makes it difficult to understand the modern environment of the study area. Besides Cabeludo site being currently fed by a tributary (Paruá River), it behaves geomorphologically as a "lake", once Paruá decreases its flows (Fig. 4.2).

The physiographical morphology of this region is classified as Amero-trailing edge coast and is characterized by flat topography and wider continental shelf (El-Robrini et al., 2018). Moreover, this area is also marked by extensive estuaries (known as "Reentrâncias Maranhenses"), where mangroves colonize the coastal plains.

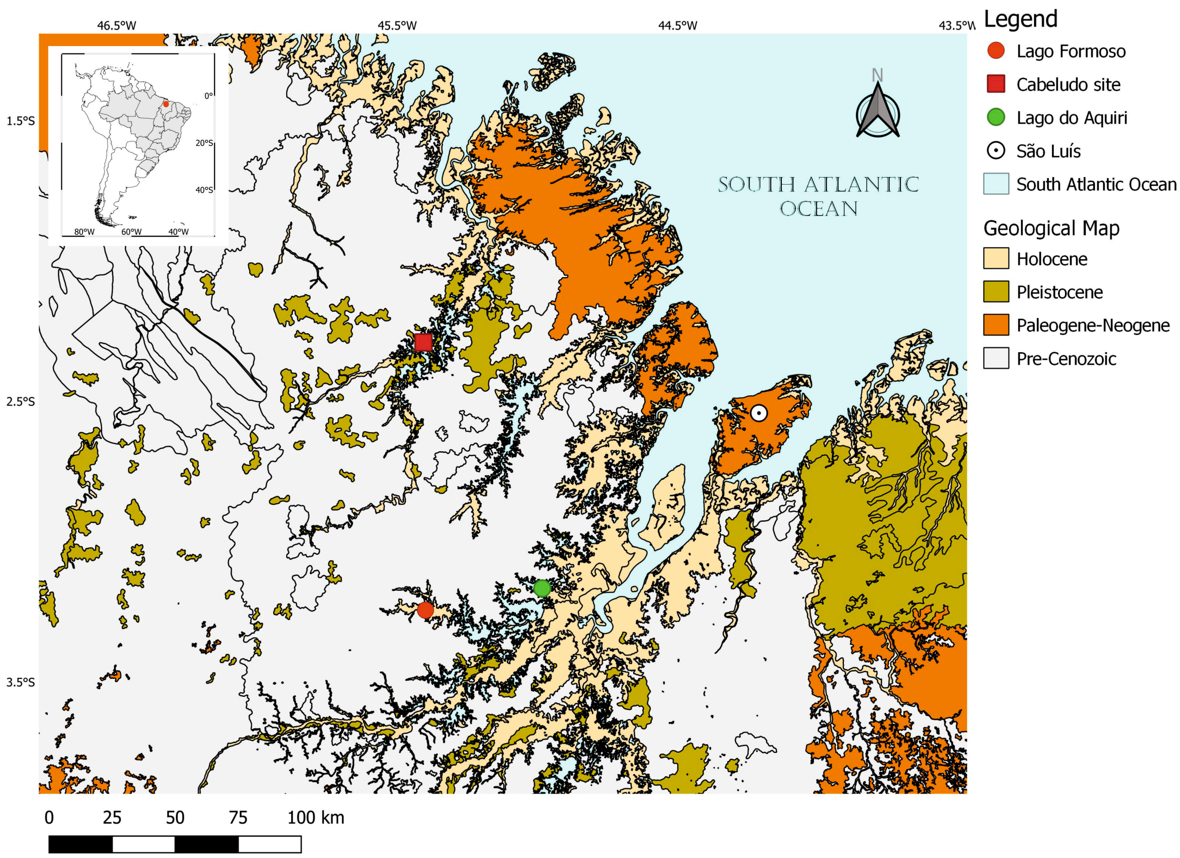

Figure 4.1. Regional geological map of Cabeludo site with the others local palaeoecological studies mentioned in this work. The original map was adapted from RADAMBRASIL.

Figure 4.2. Aerial photo of Paruá River with the Cabeludo archaeological site in the center (2° 17’27.8” S / 45º 24’28.7” W). The site is located 4 m above sea-level (asl). Photo taken by Alexandre Navarro in December 2018.

4.2.2 Climate

The climate in the Santa Helena region is tropical and, according to the Köppen-Geiger, is classified as Aw. The mean annual temperature is 28.1 °C, with November as the warmest month during the year. March is the coldest month of the year, with a temperature of 25.5 °C. The precipitation in October is characterized as the lowest of the year with an average of around 19 mm, while March is the month with the highest precipitation, showing an average of 352 mm (Climate-Data.org, 2021).

The precipitation over tropical South America is controlled mainly by the seasonal movements of the Intertropical Convergence Zone (ITCZ). During summer times, the ITCZ migrates southward due to the warming conditions of the continent (Martin et al., 1997).

4.2.3 Modern vegetation

Maranhão State lies in a transitional zone between the Amazon rainforest to the west, Caatinga dry forest to the east, and the Cerrado savanna to the south. However, the study site is in the coastal region, which receives influence from continental and marine environments. Nowadays, the human influenced vegetation surrounding Cabeludo is characterized by pioneering vegetation composed of herbs. The secondary vegetation is characterized mainly of open ombrophilous forest composed of palms; and of dense ombrophilous lowland forest, typical of Amazon rainforest (Fig. 4.3).

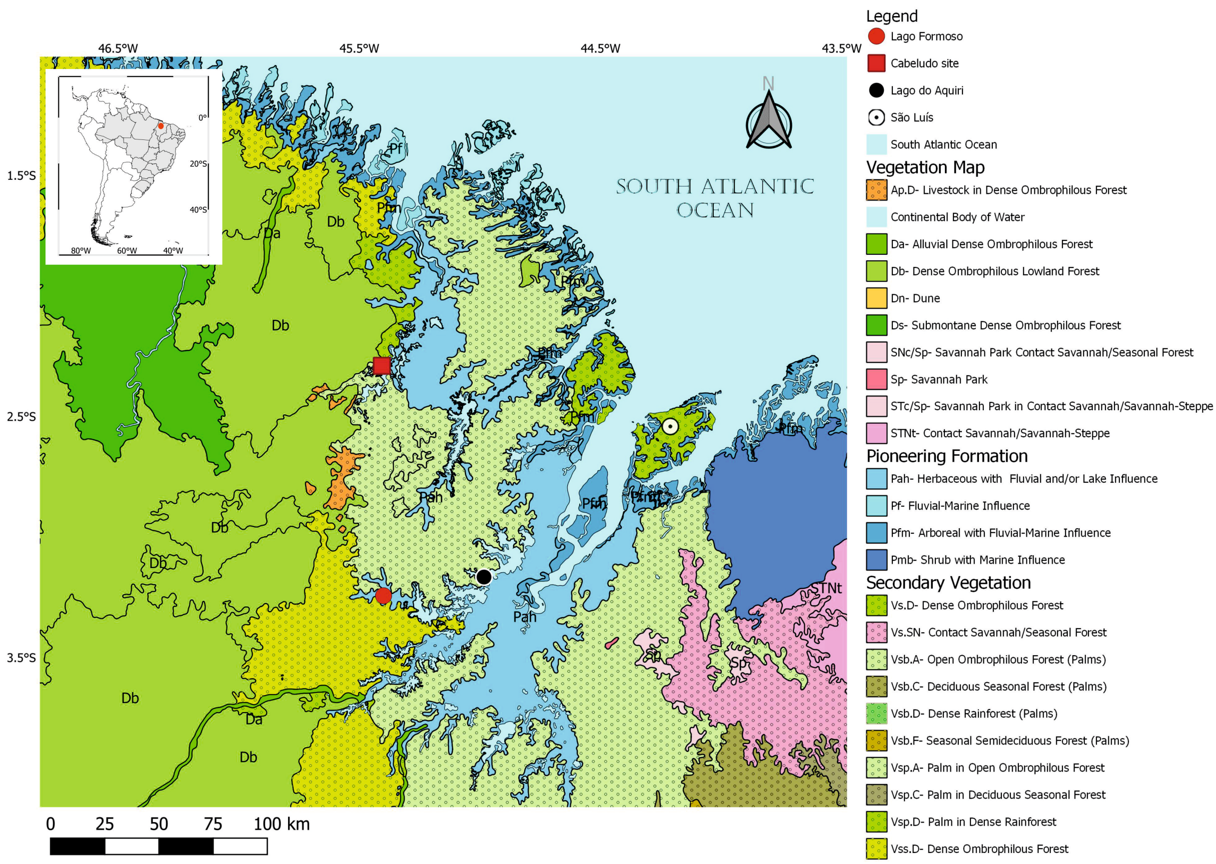

Figure 4.3. Regional vegetation map showing the location of the Cabeludo site and other palaeoecological studies mentioned in this work such as Lago Formoso and Lago do Aquiri. The original map was adapted from RADAMBRASIL (1973).

4.2.4 Archaeological and settlement history

The first human occupation of the eastern Amazonia region is still under debate due to scarce evidence left by the Amerindians. However, Roosevelt et al. (1991) found in the caves of Monte Alegre that humans were living in that region since the late Pleistocene, dating back 13,000 yr BP. During this period, the Amerindians were living as hunter-gatherers in the Amazonia region (Simões, 1983). Nevertheless, between 7000 and 2000 yr BP, these people had started to become fishermen building houses on a shell mounds in the lowland regions. Afterward, these shell mounds, mainly build by shells collected from mangroves, became what is called sambaquis (Roosevelt et al., 1991). Concerning the human presence in MA lowlands, the oldest archaeological evidence has been found dated from 6700 yr BP (Navarro, 2018b).

Regarding the late Holocene, recent studies found stilt-house settlements in MA lowlands, evidence of pre-colonial occupation in that region (Fig. 4.4). Around the world, stilt-house settlements are found in a variety of archaeological contexts built on lakes, rivers, and coastlines.

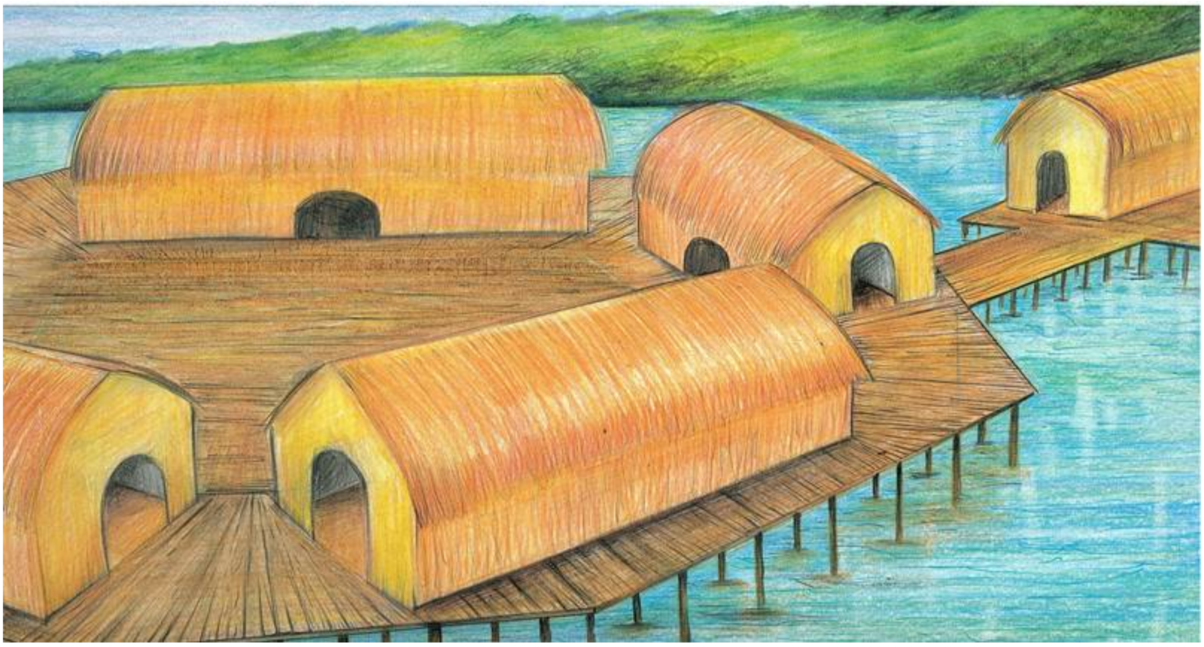

Figure 4.4. Hypothetical reconstruction of stilt villages in Maranhão lowland (Navarro, 2018c).

The Cabeludo site, the largest stilt village in the Turiaçu basin, is located in the Paruá River, a tributary of the Turiaçu, and is situated in the middle of the river canal. It extends over 0.74 hectares, with 1150 stilts, has an elliptical shape, and is oriented towards the northeast. The largest nucleus is an area of approximately 55 × 15 m, oriented northeast to southwest. Seven smaller clusters of piles, on a broadly similar alignment, lie to the east and northeast. The main concentration appears to have been connected by a bridge or causeway to the cluster located closest to it; the other clusters may also have been connected, although the accumulation of large quantities of sand means that this cannot be verified.

At the time of the flood, bathymetric measures have been conducted in the Turiaçu River. The Cabeludo site has a water depth of 5.08 meters at the time of the flood. On the other hand, in the dry season, when water levels are low, the pillars of the stilt houses can be observed above water (Fig. 4.5a). Radiocarbon dating carried out on the stilts and pottery can be found in table 1.

Table 4.2. Radiocarbon dating from archaeological evidence found in Cabeludo archaeological site. The samples were dated in the Beta Analytic.

Lab. No.	**Material**	**^{14}C age years, BP**
430864	wood	1160+-30 BP
458479	wood	1200+-30 BP
492361	soot	1020+-30 BP
458480	soot	1050+- 30 BP
515391	wood	1130+-30 BP
515390	wood	930+-30 BP
515392	soot	1990+-30 BP

Archaeological finds include complete and broken ceramic vessels, ceramic figurines, ceramic griddles (many with basketry and leaf marks) used for cooking food, spindle whorls, lithics (e.g., polished small axes), and various wooden remains, which include an ax-haft, and either an oar or a borduna (mace or club). Burnt seeds from the babaçu tree (*Orbignya*) and other palms were also recovered from within some ceramic vessels, which themselves were dated to the pre-colonial period. A large quantity of charcoal was also found in a dense concentration within these vessels (Fig. 4.5b). This peculiar pre-colonial occupation was also recorded in other parts of the region (Navarro, 2018b, 2018a).

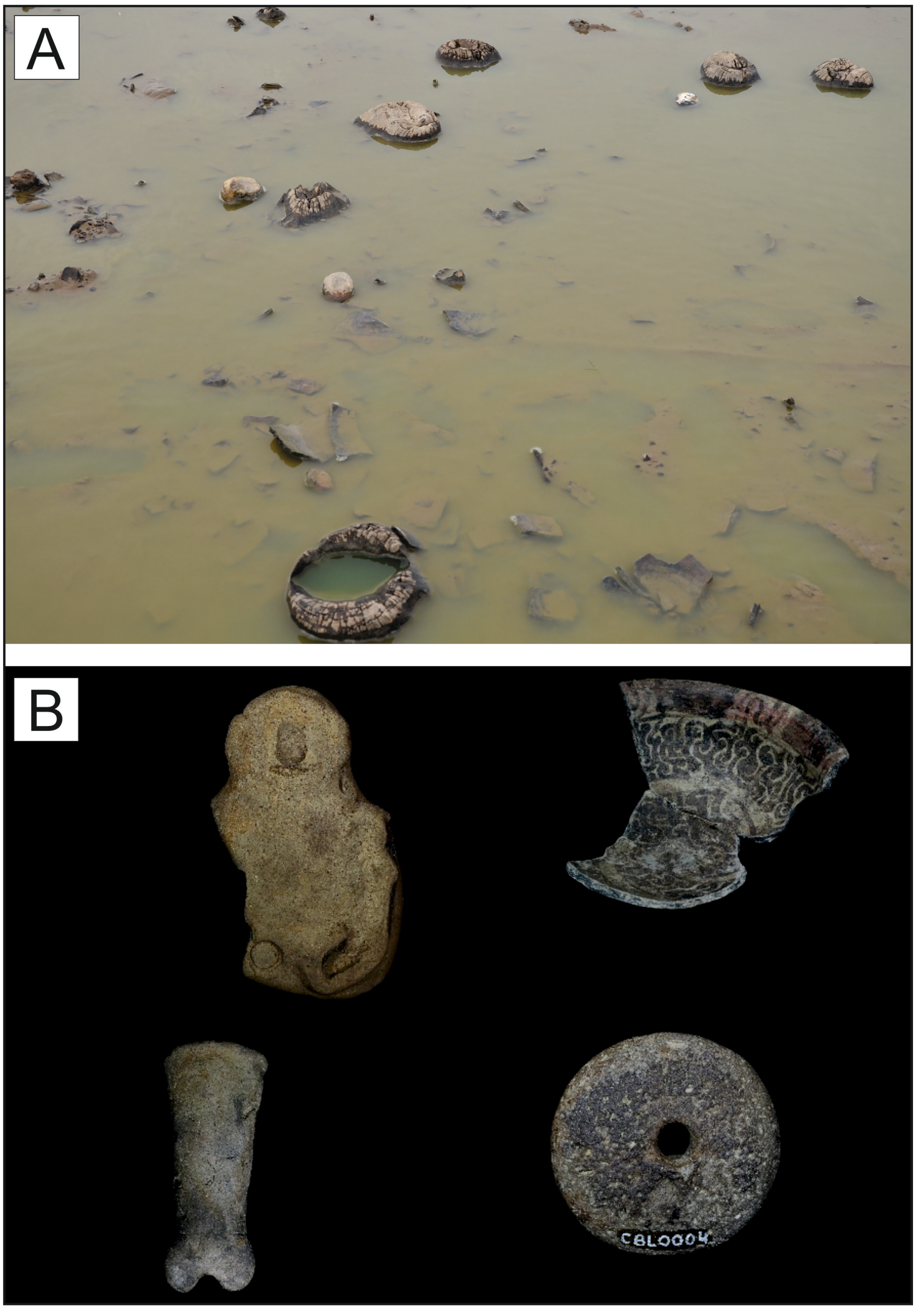

Figure 4.5. Human evidence found in Cabeludo archaeological site A) pieces of evidence found in situ; B) pottery material from Cabeludo stilt village. From left to right, figurine, painted vessel, pipe and spindle whorl.

4.3 Material and Methods

The studied 450 cm-long core has been collected using a Russian peat corer in 50 cm-long sections during the dry season in December 2018. Core sections have been put in split PVC tubes, sealed, and transported to a laboratory in the Department of Palynology and Climate Dynamics, Göttingen University. The material has been stored in a cold and dark room at 4°C.

The core has been described according to its main textural sediment characteristics and color (Color, 2009). For the chemical and mineralogical analysis, 10 selected samples from representative intervals of 410 – 400, 360 – 350, 310 – 300, 260 – 250, 230 – 220, 200 – 190, 140 – 130, 100 – 90, 80 – 70, 57 – 50 cm, were collected along the core.

4.3.1 Radiocarbon dating and age-depth model

Along the core, three bulk samples (1 cm^3 each) of organic matter were taken, based on changes in the textural characteristics as well as on changes in the pollen records, and sent for Accelerator Mass Spectrometry (AMS) radiocarbon dating at Poznań Radiocarbon Laboratory in Poland. The marine reservoir effect is a parameter to be considered in the age-depth model as the study site was influenced by the Atlantic Ocean. However, during the marine influence phase, mangrove vegetation dominated the study area, which is characterized by using carbon dioxide from the atmosphere during photosynthesis. Consequently, this environment typically does not require reservoir corrections (Sefton et al., 2021). Then, the radiocarbon dates were calibrated using the Southern Hemisphere calibration curves (SHCal13.14C; Hogg et al., 2013). The age-depth model was constructed with the software RStudio (RStudio Team, 2021), using Clam 2.4.0 package (Blaauw, 2010) with linear interpolation.

4.3.2 Mineralogical analysis by X-ray Powder Diffraction

Mineralogical analyses were performed by X-ray Powder Diffraction (XRD) using a Bruker D2 Phaser X-ray diffractometer, equipped with a Cu anode and a Ni-kβ filter, at the Federal University of Pará, Brazil. The diffractometer was set in the θ-θ Bragg-Brentano geometry with a Linear Lynxeye detector. Ten selected samples were ground in agate mortar and measured in reflection mode from 5 to 70°2θ range with 0.02° step size and 38.4 seconds per step counting time. The mineral characterizations using the obtained diffractograms were performed using the software HighScore Plus 5.0, with aid of the database of the Powder Diffraction Files from the International Center for Diffraction Data.

4.3.3 Micromorphological and spot chemical analyzes by Scanning Electron Microscope (SEM)

To obtain images and semi-quantitative (spot and chemical mapping) chemical analysis, a Hitachi TM3000 Scanning Electron Microscope (SEM) coupled to a Swift ED300 Energy Dispersive X-ray Fluorescence Spectrometer (EDX) was used, with voltage acceleration from 5 to 15kV and with SDD detector (161 eV Cu-Kα) from the Institute of Geosciences of the Federal University of Pará. The analyses were performed under low vacuum and without metallization.

4.3.4 Whole rock chemical analysis

Whole rock multi-element chemical analyzes (major, minor and trace elements, including rare earth elements) were performed in the laboratories of ALS Ltd in Peru for 10 samples (depth intervals in cm: 50-57, 70-80, 90-100, 130-140, 190-200, 220-230, 250-260, 300-310, 350-360, 400-410). The major and minor elements represented by their respective oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, TiO_2, P_2O_5, Na_2O, K_2O, MnO) were determined by ICP-OES after multi-acid digestion (HCl + HNO_3 + HF + $HClO_4$). Loss on Ignition (LOI) was determined by calcination at 1000°C and gravimetry. Trace elements, including rare earth elements were determined by ICP-MS after fusion with lithium borate ($LIBO_2$). Total C and total S concentrations were determined by the LECO system.

4.3.5 Palynology

The sediment core was subsampled (0.5 cm^3) at 10 cm intervals, with a total of 45 samples. All samples were prepared using tablets of the exotic marker *Lycopodium clavatum* spores (each

9,666±212), for the calculation of pollen concentration (grains/cm^3) and pollen influx (grains/cm2/yr), proceeding to the standard analytical techniques for pollen (Faegri and Iversen, 1989), including 10% HCl, 10% KOH, 40% HF, and acetolysis treatment.

The pollen and spore identification were carried out with the reference collections from the Department of Palynology and Climate Dynamics, a palynological atlas (Roubik and Moreno, 1992), and with the Neotropical Pollen Database (Bush and Weng, 2007). A minimum of 300 pollen grains was counted per sample, with the exception of the depths of 30, 90, and 110 cm due to low pollen concentrations. The sum was used for the calculation of pollen percentages. Fern spores, algae, and non-pollen palynomorphs (NPP) have been counted as well, however, their percentages are based on the pollen sum. Afterwards, the taxa were grouped into mangroves, herbs, trees and shrubs, palms, ferns, algae, and NPPs. The calculation and illustration of the data used the programs TILIA, TILIAGRAPH, and CONISS for cluster analysis to establish the pollen zones (Grimm, 1987).

4.3.6 Macro-charcoal analysis

Subsamples with 0.5 cm^3 were taken along the core at intervals of 2 cm for macro-charcoal analysis. Those samples were processed using 10% KOH, 6 % H_2O_2, and a sieve (mesh width 125 µm) according to (Stevenson and Haberle, 2005). The remained charcoal particles were counted using a Zeiss stereomicroscope and the results were analyzed with CharAnalysis version 1.1 (Higuera et al., 2009). Background charcoal was separated from the charcoal record to permit the identification of main fire events. The charcoal counts have been transformed to charcoal accumulation rates (CHAR; units: cm^2/yr) with interpolation resolution of the record as 50 yr.

Low-frequency charcoal $CHAR_{background}$ was calculated by use of moving median defined by 300-yr intervals. At this interval, the locally defined peaks were estimated by subtracting

$CHAR_{background}$ from CHAR and $CHAR_{peak}$ identification via base threshold values on a noise distribution determined by a Gaussian mixture model. A $CHAR_{peak}$ represents a fire episode of one or more large fire events in the catchment of Cabeludo within 500-year intervals (Higuera et al., 2009; Mustaphi and Pisaric, 2014).

4.3.7 Geological and vegetational maps and data analysis

The thematic maps from the studied area in MA have been built in QGIS software, version 2.18 Las Palmas (QGIS Development Team, 2016). The images were taken from RADAMBRASIL (Brasil, 1973), obtained from the Brazilian Institute of Geography and Statistics – IBGE website (www.mapas.ibge.gov.br)

The Principal Component Analysis (PCA) was carried out on pollen percentages to investigate the possible correlation between the most representative identified pollen taxa. The multivariate ordination analysis was performed with the software Canoco 5.0 (Braak and Smilauer, 2012), to highlight the most important taxa.

4.4 Results

4.4.1 Sedimentological description of the core

The textural description of the core indicates 9 different units with specific characteristics (Table 4.1). From 400 to 150 cm core depth, the deposit was marked by compact mud, with the presence of plant remains at some levels. Between 150 to 57 cm within the compact mud a few layers of fine sand occur. From 57 cm to the top of the core the material is sandy mud material, rich in organic matter with a few plants remains and ceramic fragments representing the archaeological layer (Fig. 4.6).

Table 4.3. Textural description of Cabeludo sediment core.

Depth (cm)	Description

0-57	Dark gray sandy mud material, unconsolidated, and rich in organic matter partially decomposed. Presence of plant remains as palm seeds and ceramic fragments.
57 - 93	Dark gray compact mud
93 - 125	Dark gray fine sand interbedded with lens of mud.
125 - 146	Dark gray compact mud
146 – 150	Dark gray fine sand
150-200	Dark gray compact mud with presence of plant remains, including micro roots, in the intervals between 150-155 and 194-195 cm.
200 - 250	Dark gray compact mud material smooth banded with light gray in the interval between 200-214 cm. Presence of plant remains between 200-203, 231, and from 240 to 250 cm.
250-400	Dark gray compact mud with presence of plant remains, including fine roots, between 275-280, 304-314, 318-331, 368-374 and 390-392 cm.
400-450	Dark gray compact mud.

4.4.2 Radiocarbon dating and sedimentation rates

Three bulk samples have been submitted to AMS radiocarbon dating as shown in Table 4.2. The chronology indicates that occurred two distinct periods of sedimentation along with the core. The first cycle begins at the base of the core at 450 cm depth, with an interpolated age of 7920 cal yr BP, and ends at approximately 155 cm depth, at about 7500 cal yr BP. This period is marked by a sedimentation rate of 6,9 mm/yr and includes probable gaps in sedimentation.

The second period occurs from 155 cm depth up to the top. The base of this layer has an interpolated age of 7500 cal yr BP, and the sedimentation rate is 0,2 mm/yr.

Table 4.4. List of radiocarbon dates of the Cabeludo core.

Depth (cm)	Lab. No.	Material (1 cm^3)	^{14}C age years, BP	Calibrated (cal yr BP)
20	Poz-149116	Charred nut	955 ± 30 BP	±800
57	Poz-141108	Bulk sediment	1430 ± 30	±1300
125	Poz-149805	Bulk sediment	5180 ± 40 BP	±5850
158	Poz-149806	Bulk sediment	6870 ± 40 BP	±7600
200	Poz-141109	Bulk sediment	6930 ± 40	±7740
450	Poz-141110	Bulk sediment	7130 ± 40	±7915

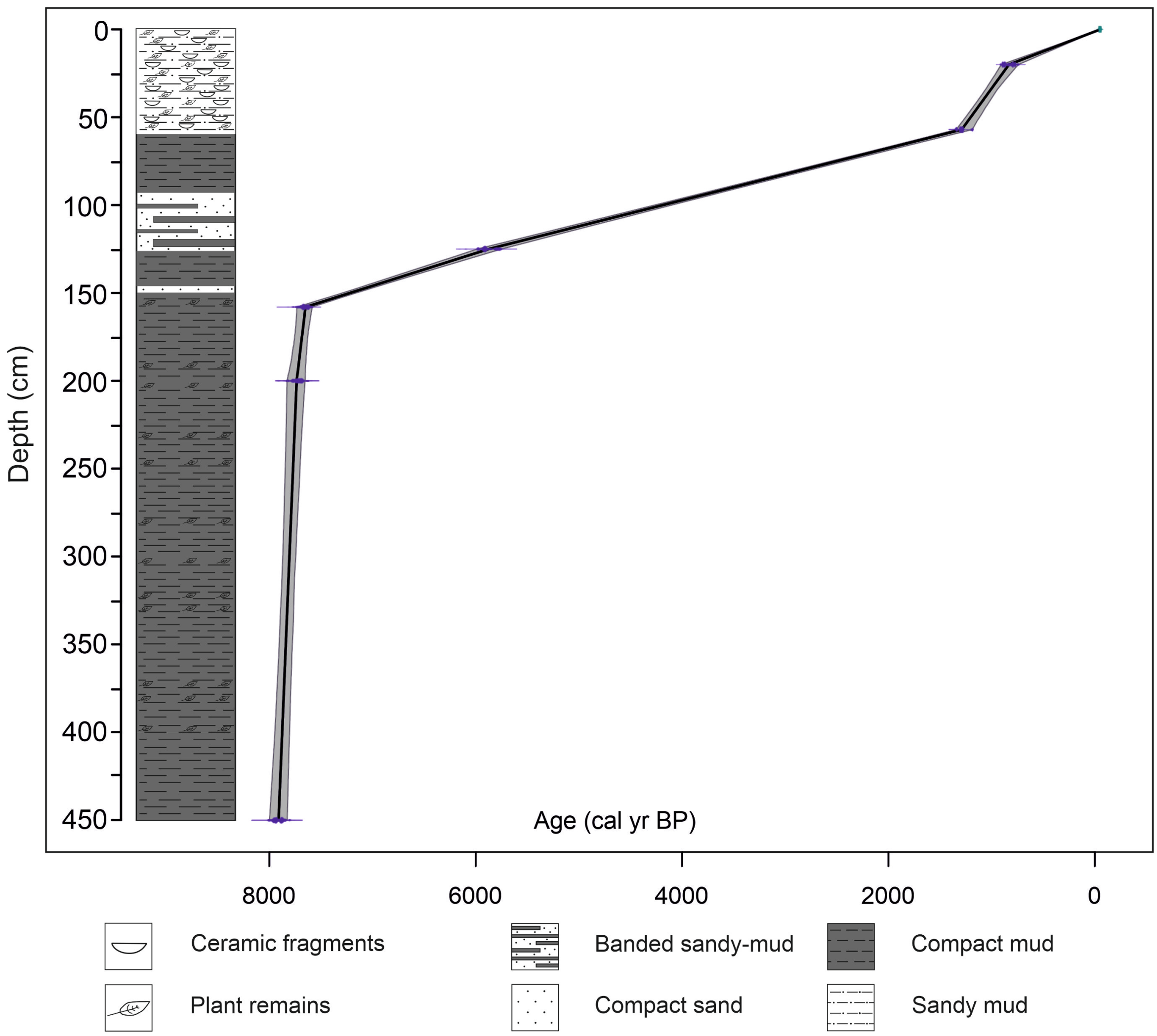

Figure 4.6. Age-depth-model and stratigraphic description of the Cabeludo core exhibiting the textural characteristics, structures ceramic fragments, and the radiocarbon-dated samples.

4.4.3 Mineralogical composition

The minerals identified along the sedimentary succession of Cabeludo core show that their abundance and distribution are intrinsically linked to the main stratigraphic layers. The main minerals are quartz, kaolinite, K-feldspar (microcline), plagioclase (andesine), illite/muscovite, clinochlore, and pyrite; accompanied by gypsum and anatase. All have been identified after XRD (Fig. 4.7). Using the SEM/EDX, it was possible to identify barite, native sulfur, florencite, zircon, tourmaline, ilmenite, and magnetite, which are at the trace level.

The compact mud layer (zone C-I) stands out for its high levels of kaolinite and illite, and, on the other hand, relatively low occurrence of quartz. High levels have been identified for clinochlore, pyrite, native sulfur, and gypsum. Native sulfur is frequent and was characterized by SEM/EDS (crystal morphology and elemental chemical microanalysis; Fig. 4.8). This layer also has the higher content of organic matter (OM) in the core.

The transitional upper layer (C-II) quartz dominated with high concentrations together with andesine plagioclase, and microcline (Fig. 4.7). In contrast to the lower layer, the upper layer is poor in kaolinite, illite, and clinochlore, as well as pyrite, and gypsum. The SEM/EDS analysis identified presence of barite and fluorencite as well as higher levels of zircon. The presence pf muscovite and microcline are also evident in this layer.

Lastly, a discrete peak of the mineral anatase (TiO_2) was identified in all the samples.

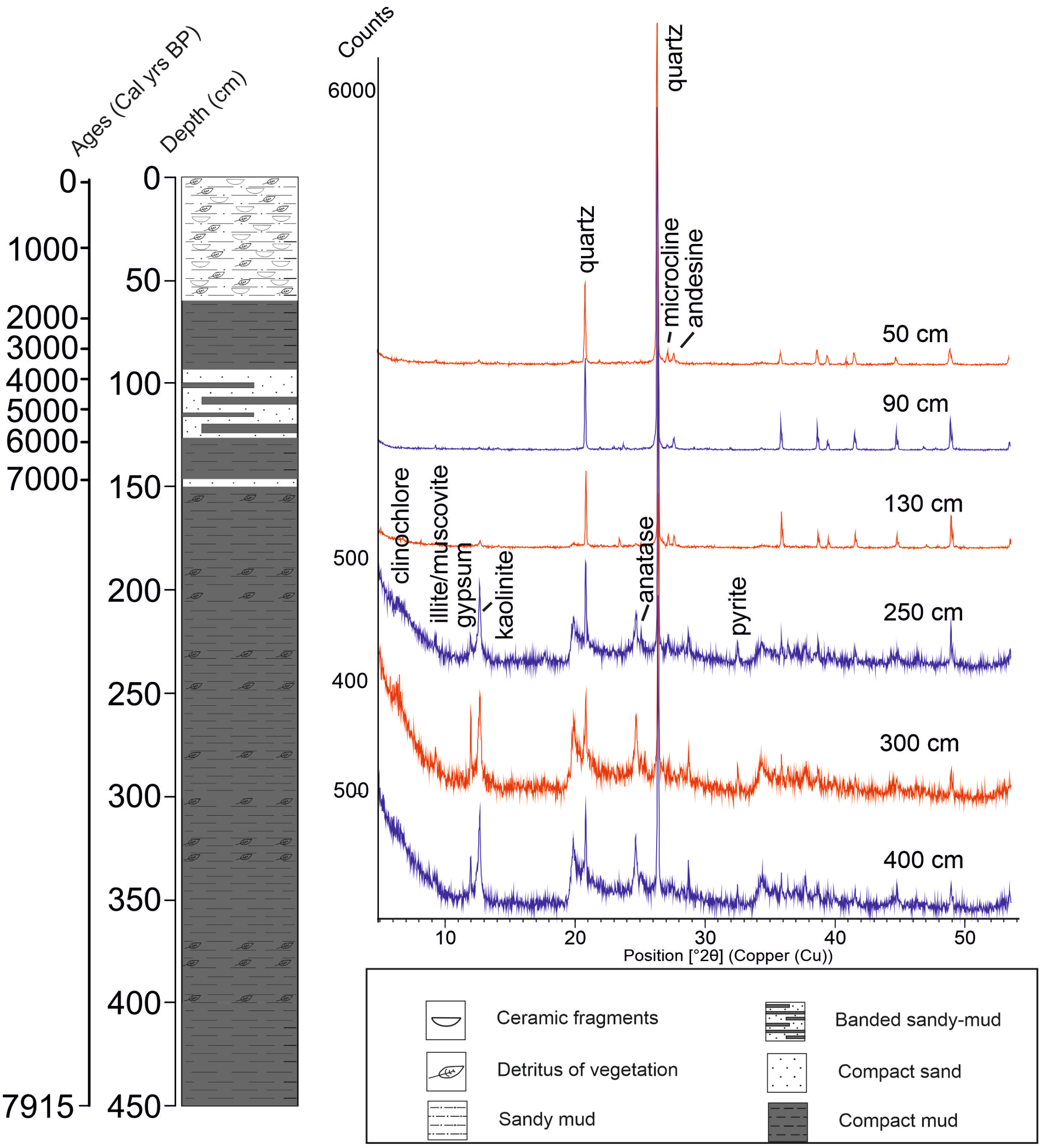

Figure 4.7. Results of the mineralogical analysis (XRPD) of the Cabeludo core showing the relative abundance of the most representative minerals.

4.5 Chemical composition

The distribution of the major and minor chemical elements, some trace elements (Zr and REE), as well as the values of LOI, C and S (Fig. 4.8 and table S4.1-see supplementary material) clearly highlight the two layers: compact mud (C-I) and compact fine sand (C-II). The results allowed to characterize the main changes in the content's distribution (in %) of SiO_2, Al_2O_3,

Fe_2O_3, MgO, Na_2O, C and S; in the values of LOI and in the concentrations in ppm of Zr and REE. The SiO_2, Na_2O and Zr contents are relatively higher in the upper compact fine sand layer, portraying the dominance of quartz (as SiO_2), the presence of albite (as Na_2O) and zircon (as Zr). However, the contents of Al_2O_3, Fe_2O_3, MgO, C, S and LOI, as well as REE, are more concentrated in the lower layer (C-I) and decrease drastically towards the top of the sequence (C-II). These chemical elements and LOI results are corroborating with the dominance of aluminosilicate as clay minerals (kaolinite and illite), clinochlore (as MgO and Fe_2O_3), plant remains (as C and LOI), pyrite and Fe sulphide precursors (Fe and S) and florencite (for REE). The comparison between the mineralogical and chemical composition can been seem in the dendrogram after single linkage Euclidian distances for 10 variables (Fig. 4.9).

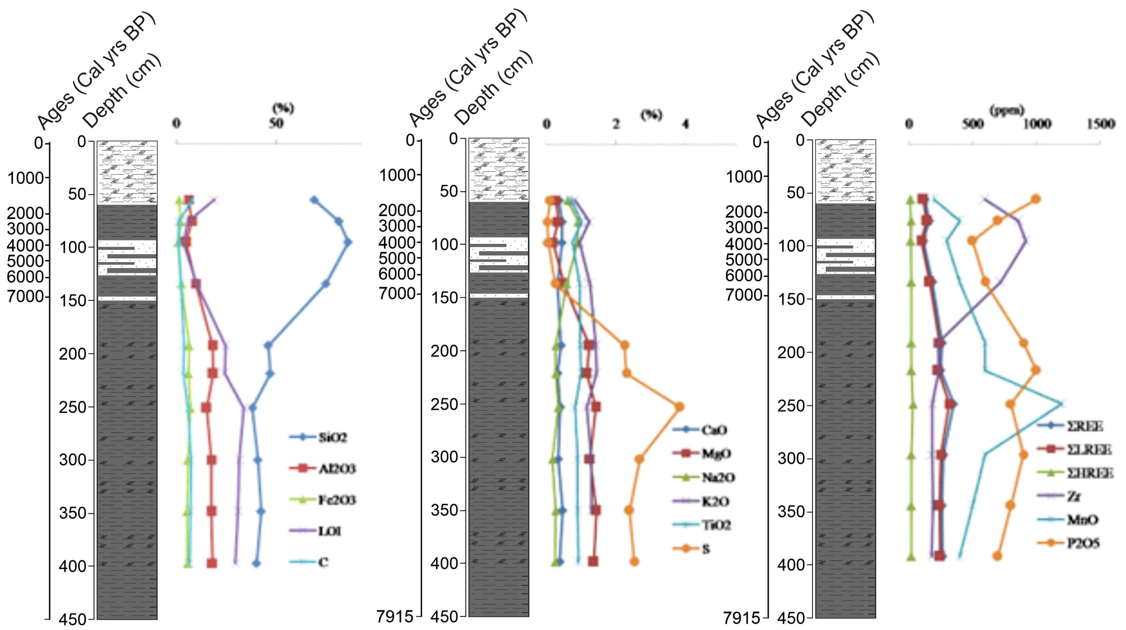

Figure 4.8. Distribution of concentrations of analyzed chemical elements (major and minor in Wt.% and some trace elements in ppm) along the Cabeludo core profile.

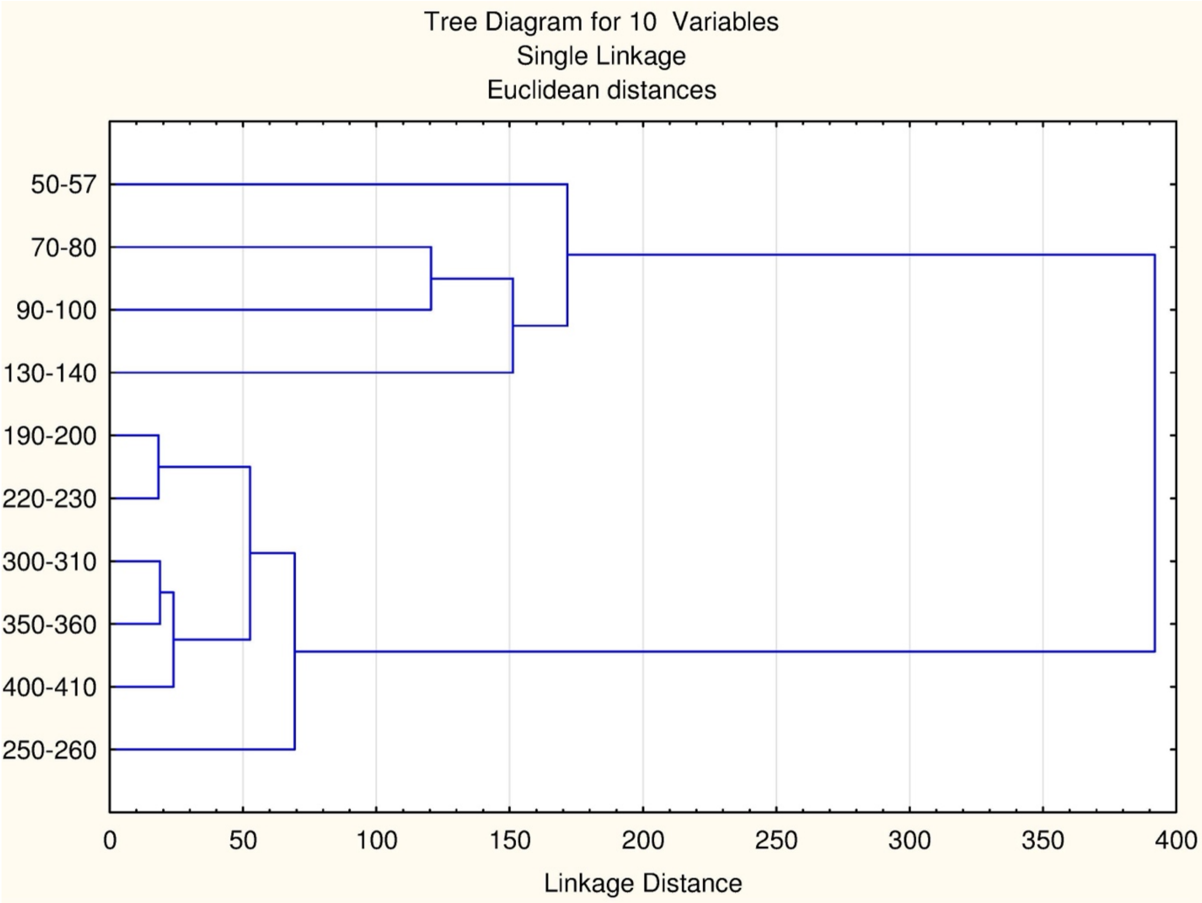

Figure 4.9. The dendrogram after single linkage Euclidian distances for 10 variables (core samples) using the results of chemical analyzes (major, minor and trace elements) allow to distinguish the two main beds or units: compact mud and compact fine sand (C-I and C-II).

4.5.1 Palynological and charcoal description

We identified in the pollen record: 2 mangrove taxa, 22 herb taxa, 46 tree and shrub taxa, 5 palm taxa, 10 types of spores, 2 types of algae and 8 different types of NPPs. Using CONISS cluster analysis, the major changes in pollen assemblages distinguish two pollen zones (C-I and C-II) (Fig. 4.10 and 4.11). The upper zone (C-II) has been split into two subzones (C-IIa and C-IIb). The local fire events and their change in time is shown in Fig. 12. In total, 18 main fires events have been recorded.

Pollen zone C-I (450-155 cm; 30 samples; 7920 – 7500 cal yr BP) is characterized by a predominance of mangrove pollen composed mainly of *Rhizophora* and a few pollen of *Avicennia*, which is present only in this zone. Herb pollen such as Asteraceae, Asteraceae II, Poaceae and Cyperaceae occur in low percentages. Pollen of trees and shrubs are represented mainly by *Alchornea*, *Sebastiana*, Euphorbiaceae, Fabaceae and Moraceae occurring in low percentages. Specifically, at the core depth of 190 cm, *Rhizophora* pollen are low, and herb taxa mainly Poaceae and Cyperaceae are high. During the same short interval, trees, and shrubs also increase, represented mainly by *Sebastiana*. Palms, Ferns, and NPPs are almost absent, marine Foraminifera are present only in this zone.

Pollen zone C-IIa (155-65 cm; 9 samples; 7500 – 1800 cal yr BP) is marked by an abrupt decrease of mangrove taxa, *Rhizophora*. Pollen of herbs, mainly represented by Poaceae, Cyperaceae and Asteraceae, strongly increase. Trees and shrubs including mainly *Sebastiana*, *Alchornea,* Anacardiaceae, *Byrsonima*, Euphorbiaceae, Fabaceae and Moraceae increase. Palm tree pollen Arecaceae, *Euterpe*/*Geonoma*, *Mauritia*, *Mauritiella* and *Orbignya*, but in very low percentages. Ferns spores are present in very low percentages and Algae are absent. Among NPPs, *Anabaena*, and *Turbellaria neorhabdacoela* have their main occurrences.

Pollen zone C-IIb (65-155 cm; 7 samples; 1800 – Present) *Rhizophora* occurs in low percentages. Poaceae decreased, while Cyperaceae and Asteraceae maintained stable. The increase in trees and shrubs is mainly related to higher values of *Sebastiana*, *Alchornea*, *Astronium*, *Byrsonima*, Euphorbiaceae, Fabaceae, Moraceae and Myrtaceae. Pollen of palms are most frequent in this zone with Arecaceae and *Euterpe*/*Geonoma*. Presence of *Mauritia*, *Mauritiella* and *Orbignya* pollen also occurred but in very low percentages. Monolete psilate fern spores have higher percentages in this zone but are relatively low. NPPs such as *Anabaena* and *Turbellaria neorhabdacoela* decrease.

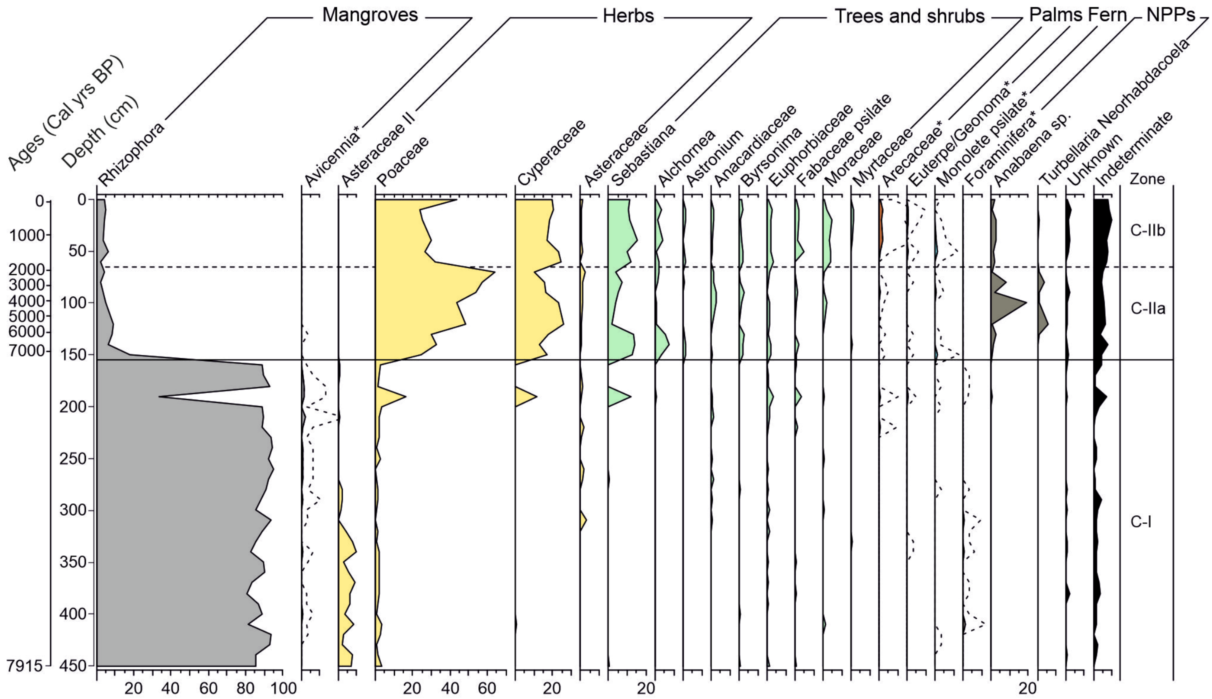

Figure 4.10. Pollen diagram showing the percentages of the frequent and most important taxa of Cabeludo site core grouped into mangrove, herbs, trees and shrubs, palms, ferns, and NPPs associated with the stratigraphic description. *Taxa are with exaggeration factor 10x.

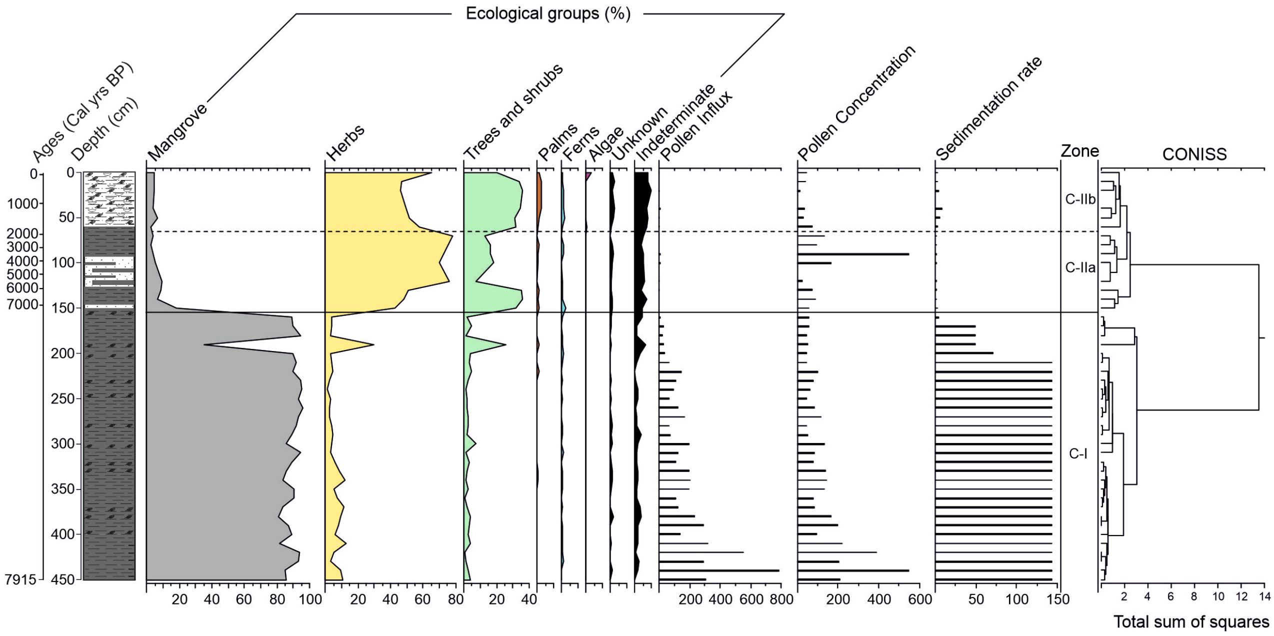

Figure 4.11. Summary pollen diagram of Cabeludo site core, showing the age scale, ecological groups, pollen concentration, pollen influx sedimentation rate, and the cluster analysis dendrogram.

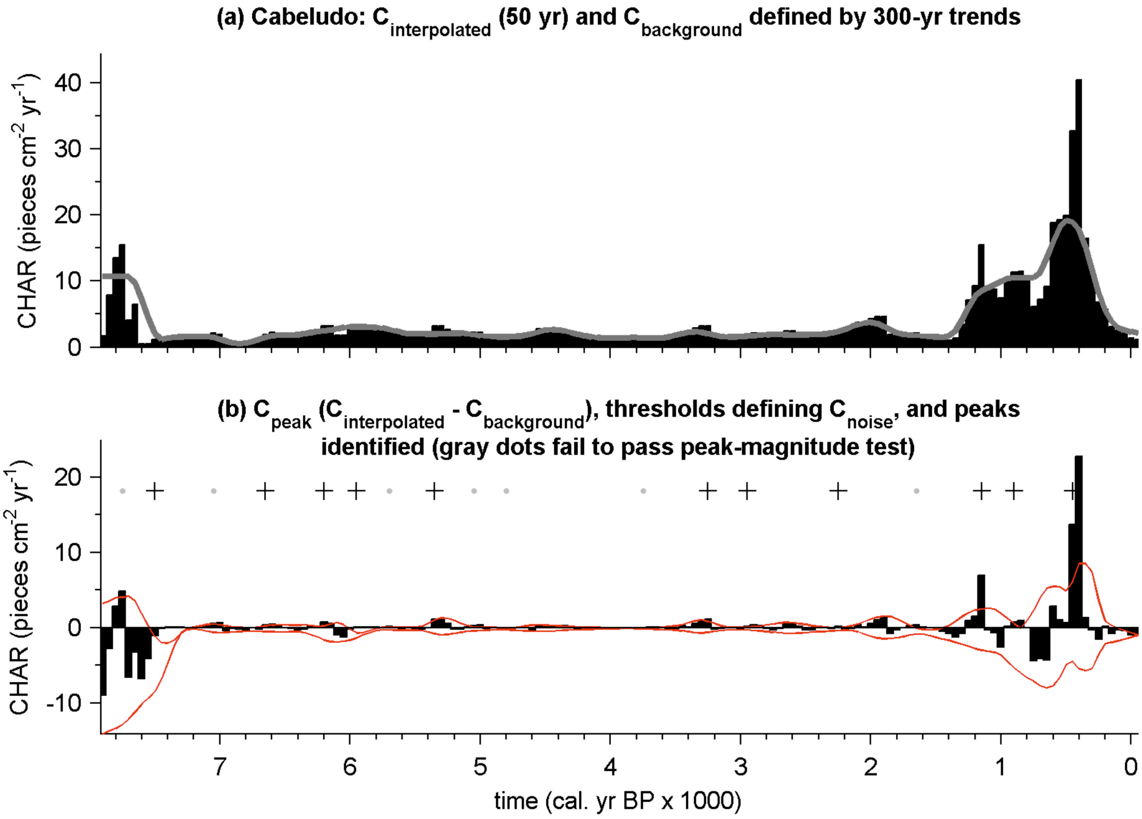

Figure 4.12. CHARAnalysis diagram from Cabeludo site presenting (a) the interpolate charcoal counts ($C_{interpolated}$) (50 yr) and the background charcoal noise ($C_{background}$, gray line) defined by 300-yr trends, and (b) C_{peak} ($C_{interpolated}$ + $C_{background}$), threshold defining C_{noise} black line), and the main fire events (peak ID, +)

4.5.2 *Principal Component Analysis (PCA)*

The most representative taxa (19) have been defined by PCA for the period from 7920 cal yr BP until the present (Fig. 4.13). Axis1 has an eigenvalue of 0.746 and its positive axis is composed of samples from the C-II zone represented by most of the taxa as Cyperaceae, Poaceae, *Sebastiana*, *Alchornea*, Anacardiaceae, Euphorbiaceae, Moraceae, *Byrsonima*, and *Euterpe*. The negative axis comprises samples from the lower unit C-I zone, represented mainly by *Rhizophora*. Axis 2 has an eigenvalue of 0.0582 and its positive axis is composed mainly of Asteraceae and *Avicennia*. The negative axis is represented predominantly by Asteraceae II.

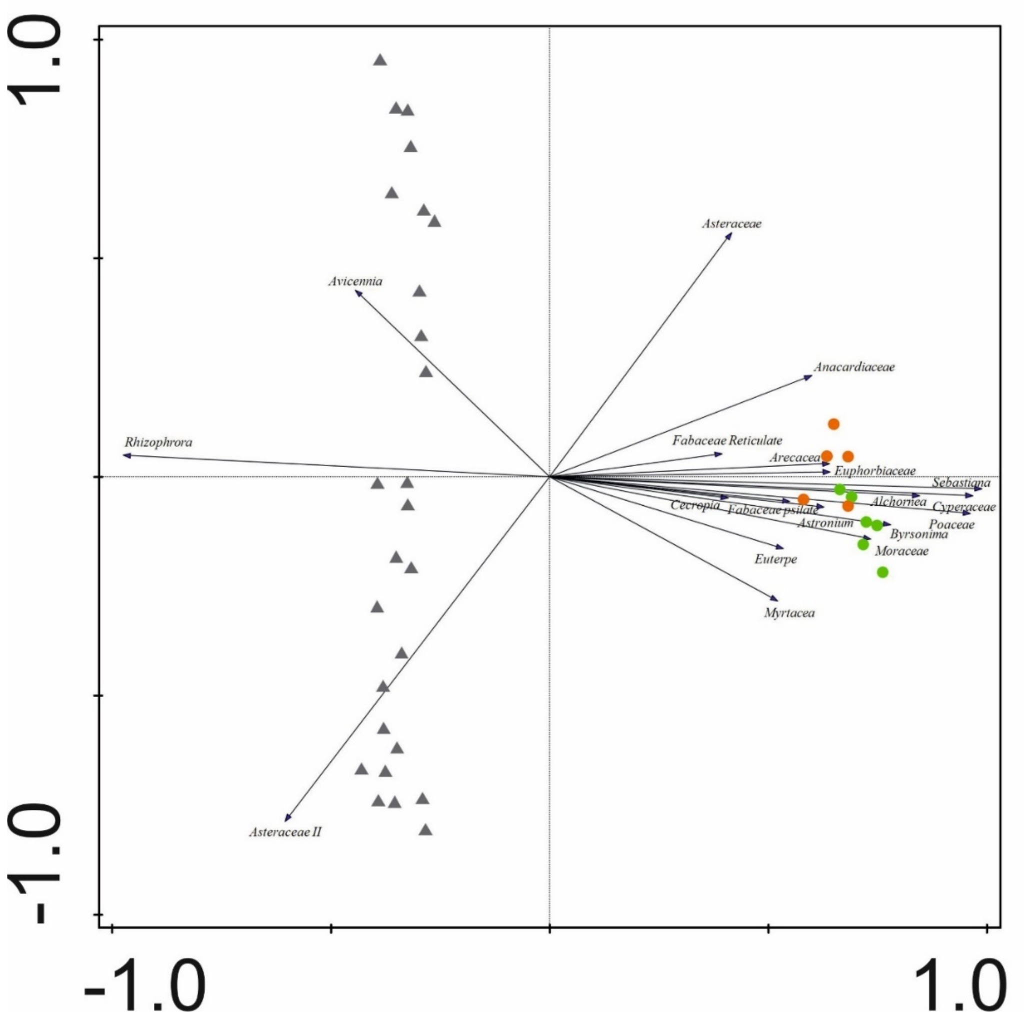

Figure 4.13. Principal component analysis (PCA) from Cabeludo core. The gray triangles represent samples from zone C-I; the orange circles are samples from zone C-IIa; and the green circles represent samples from the zone C-IIb.

4.6 Discussion

4.6.1 Mid-Holocene period from 7915 to 7500 cal yr BP (pollen zone C-I)

This period was composed of compact mud sediments with the highest sedimentation rate (6,9 mm/yr). The mineralogical composition for this period was marked by high levels of kaolinite and illite/muscovite, as well as clinochlore, pyrite, and gypsum. Quartz occurred in low frequency. The OM contents were the highest in comparison to the rest of the core, which in the XRD spectra would correspond to the amorphous fraction (Fig. 4.7). The images and spot chemical analyses of SEM/EDS allowed the delineation of the microstructures of plant remains, freshwater and brackish sponges and diatoms like "cauixi" (Fig. 4.8). Sponges and diatoms were predominantly constituted by amorphous silica, and therefore also constituted part of the amorphous fraction indicated by the XRD spectra. The presence of pyrite, and gypsum, in addition to sulfur, illite, and clinochlore suggest that this environment was influenced by marine waters (presence of ions $(SO4)^{2}$-, Ca^{2}+, Mg^{2}+, in addition to Na+ and K+).

Pyrite appeared in frambohedral formations as isolated crystals, occupying cavities and spaces of the OM plant tissue in addition to surrounding the fragments of iron oxyhydroxide microfragments (SEM/EDS), therefore formed after sedimentation. The incursion of marine waters made the environment slightly neutral and favored the neoformation of illite and clinochlore at the expense of part of the deposited kaolinite. As the abundance of plant debris increased, the environment became reducing, favoring the reduction of sulfur from sulfate ions in interstitial waters and iron from its oxyhydroxides, leading to extensive formation of pyrite and other Fe sulfides precursors (greigite and mackinawite) and even sulfur associated with vegetable remains. In turn, masses of these sulfides involve possible micrometric fragments of Fe oxyhydroxides (goethite or hematite) coming from the continental area.

Gypsum, also frequent, but with a more irregular distribution, formed clusters in rosettes or similar of tabular euhedral crystals, occupying cavities. The microscopic textual observations showed that Gypsum succeeds pyrite, and its formation showed that locally the interstitial waters became alkaline and partially dehydrated, in addition to barite, $BaSO_4$, calcite, $CaCO_3$, and florencite, a REE phosphate (Rare Earth Elements). These mineralogical assemblages, the very fine granulometry and richness in OM, in addition to the presence of diatoms and sponges from fresh to brackish water, indicated that the mud clay layer may represent a sequence of mangrove deposits in diagenetic change.

The chemical results were in agreement with the mineralogical data, which was even more evident in the dendrogram applying single linkage Euclidian distances for 10 variables (Fig. 4.9). During this period, dominated Al_2O_3, Fe_2O_3, MgO, C, S and LOI, as well as REE, while the SiO_2, Na_2O and Zr are relatively lower. The relative higher values of MgO, K and S corroborate with the contribution of marine waters, while Al_2O_3, Fe_2O_3, C, LOI and REE are in accordance with the strong continental influence from the surroundings. Therefore, the mineralogical and chemical composition indicate that, at this period, the study area was under both marine and continental influence, under conditions of warm and local humid climate, deposited in locally low-energy environment (mangroves and/or lakes) due to the deposition and accumulation of clay, and OM at relative high rate. Although by now, the site was located about 120 km inland, the high RSL suggest continuing tidal influence. The same sediment composition pattern has been found in LF, a site that is located even further inland (Moraes et al., 2021).

Palynological evidence showed a predominance of *Rhizophora* during this period, indicating that mangroves dominated in the study area. *Avicennia* was also present in low percentages during this phase, probably because this taxon is pollinated by insects, differently from *Rhizophora* which is wind-pollinated (Behling, 2011). Mangroves do not occur in the study area nowadays, being restricted to coastal bays (Fig 4.3). The markedly constant occurrence of Asteraceae II and Poaceae, besides the low occurrence of Cyperaceae, might be related to the drier conditions in the surrounding area. Trees and shrubs, mainly represented by *Alchornea*, *Sebastiana*, Euphorbiaceae, Fabaceae and Moraceae characteristic for the rainforest were rare and also suggest drier conditions.

The predominance of mangroves surrounding the Cabeludo site provides a strong local signal, masking the regional vegetation. However, other regional studies showed that the mid-Holocene was marked by drier conditions in the northern NE Brazil and southeastern Amazonia (Guimarães et al., 2021; Pessenda et al., 2005; Sifeddine et al., 2003). Pessenda et al. (2005) studied an area about 240 km distant from the Cabeludo site and recorded a dry and open landscape from approximately 10,000 to 6000-5000 yr BP. Studies from Carajás (Guimarães et al., 2021; Hermanowski et al., 2012) suggested that the mid-Holocene was markedly drier also in southeastern Amazonia.

The presence of foraminifera, even in low percentages, is a good indicator of marine influence in the study site, in agreement with the RSL transgression during the mid-Holocene in Maranhão. After the LGM, the Atlantic sea-level started to rise until it reached the highest level around 7000 yr BP on the eastern coast of Brazil (Angulo et al., 2006; Caldas et al., 2006; Martin et al., 2003; Suguio et al., 2013). In consequence, mangrove expanded inland during the early to mid-Holocene. The occurrence of mangroves further inland has also been found for this period in other regions of NE and Northern Brazil related to marine transgression (Behling, 2001a, 1996; Behling and Costa, 2001, 1997; Cohen et al., 2021, 2005; Fontes et al., 2017; Moraes et al., 2021; Ribeiro et al., 2018). Regional studies showed that mangroves were colonizing areas further inland as early at 8080 cal yr BP in an area close to Lagoa da Curuça, since 8280 cal yr BP at Lago do Aquiri, and since 8370 cal yr BP near Lago Crispim (Behling, 2011, 2001b; Behling and Costa, 2001, 1997). Although the mangrove's expansion is mainly related to the RSL transgression, the drier regional conditions during the early Holocene (Behling and Hooghiemstra, 2000; Pessenda et al., 2010, 2005) also might have been a reason for the further inland shift of mangroves, in response of reduced river flows.

As a consequence of an RSL transgression and drier climate conditions, the study area had become a tidal channel surrounded by mangroves as part of a tide-dominated estuarine environment. Nowadays, Cabeludo archaeological site is under the influence of the freshwater Paruá river, which is a tributary of the Turiaçu river. However, the river behaves as a lake, once the water flows decrease in energy, as evidenced by the sediment textural characteristics and organic matter preservation. Nevertheless, the presence of mangroves was responsible for the changes in the hydrodynamic of the channel, reducing, even more, the tidal flows. In addition, the mangrove behaves like a sediment trap-inducing deposition (Van Santen et al., 2007), as is evidenced by the higher sedimentation rate during this phase (Fig. 4.6).

4.6.2 Mid- to late Holocene period from 7500 to 1800 cal yr BP (pollen zone C-IIa)

This transitional layer composed of dark gray fine sand was dominated by quartz, and higher relative proportions of K-feldspar (microcline), plagioclase (albite), especially in the sand and fine sand fraction (Fig. 4.7). There were lower occurrence of clay minerals (kaolinite, illite and clinochlore) and OM content decreased strongly, while heavy and resistant minerals such as zircon, ilmenite, chromite, and magnetite increased. Although at low levels (ppm), Zr increases dramatically in this layer (maximum of 917 ppm versus maximum of 235 ppm in lower layer), and thus strengthens the identification of this mineral. Contrary to the lower layer (C-I), the concentration of pyrite, and gypsum was lower during this interval. The anatase values are on the order of 1% detected by XRD only in the lower layer. However, the total TiO_2 contents are identical for the two layers (Fig. 4.8). According to SEM/EDS analyses, ilmenite grains are frequent in the upper layer, perhaps compensating for the similar values of TiO_2 corresponding to anatase in the lower layer. Magnetite, chromite and tourmaline according to SEM/EDS still occur. Cauixi spicules were found in both layers, but decreased towards the top of upper layer, while diatom fragments occur only at the lower. This mineralogical constitution notably reflects the dominance of the sand fraction and strong continental contribution. The occurrence of beach deposits rich in ilmenite, magnetite and perhaps chromite on the coast of Maranhão is notable. The contents of SiO_2, Na_2O and Zr are relatively higher, portraying the dominance of quartz (as SiO_2), the presence of albite (as Na_2O) and zircon (as Zr).

Those characteristics suggest continental source under less humid climatic conditions, with a transport agent with higher energy, probably fluvial and/or tides and waves. The rare fragments of sponges at the top suggest moments of energetic acquiescence and/or materials carried from other sources. On the other hand, this period was marked by more continental influence with high energy indicated by accumulation of sand and little OM, under low rate of deposition and/or high erosion level. The water depth is certainly shallow, mainly towards the top, demonstrated by the decrease or absence of sponges and diatoms. Thus, this period suggests that the sediment run-off was predominantly continental, probably due to RSL regression.

Mangrove vegetation, which was predominant in the lower layer, sharply decreased. The continuing presence in the deposit might be a consequence of wind transportation from the distant coastal area. Herbs taxa represented mainly by Poaceae, Cyperaceae and Asteraceae strongly increased, indicating some open non-forested areas, probably due to seasonal inundation with freshwater. The arboreal vegetation is mainly represented by *Sebastiana*, *Alchornea*, Anacardiaceae, *Byrsonima*, Euphorbiaceae, Fabaceae and Moraceae. Their increase indicates an expansion of moister vegetation. Moraceae species are frequent on fertile soils in the Amazon tropical rainforest, and *Alchornea* occurs commonly as large trees in Amazonian forests (Marchant et al., 2002), which suggests an expansion of the Amazon biome during this period. On the other hand, the presence of *Byrsonima*, common in grass/savanna habitats, and *Astronium*, mostly present in dry forests (Marchant et al., 2002), might indicate the occurrence of Cerrado near the area as well.

In this period the earlier tidal channel surrounded by mangrove wetlands turned into freshwater river environment surrounded by arboreal and herbaceous lowlands vegetation. The abrupt decrease in mangrove around 7500 cal yr BP (150 cm depth) occurred when the sedimentologic texture changed to coarser sediments, indicating stronger river flow. The increase in freshwater might be related to higher rainfall with a shortened dry season, like occurred in LF around 6000 cal yr BP.

The shift of environmental conditions at beginning of this phase could be related to a combination of factors related to RSL and climate changes. In eastern Brazil, studies proposed that the RSL achieved its highstand between 5900 and 5000 cal yr BP, reaching 1.3 to 4.7 m above current sea-level (Angulo et al., 2006; Caldas et al., 2006; Fontes et al., 2017; Martin et al., 2003; C. A. Moraes et al., 2020; Ribeiro et al., 2018; Suguio et al., 2013). Afterwards, RSL fell, restricting the mangroves to the current coastal zone (Fontes et al., 2017; Moraes et al., 2021). In LF, the highstand of the RSL was proposed between 5500 and 5020 cal yr BP, when *Acrostichum* mangrove species expanded, and marine indicators increased (e.g., Sulfur and pyrite). In northern Brazil, the RSL was apparently not that high to result in a full establishment of mangroves (Behling et al., 2001; Cohen et al., 2021, 2005). In Bragança Peninsula the mangroves occupied the highest tidal flats between around 6250 and 5850 cal yr BP as a consequence of a combination of dry conditions and high RSL, which reached its highstand at 5000 cal yr BP at 0.6±0.1 m above sea-level. Afterwards, RSL fell and wetter conditions over the past 4300 cal yr BP restricted the mangroves to the lowest tidal flats (Fig. 4.14; Cohen et al., 2021).

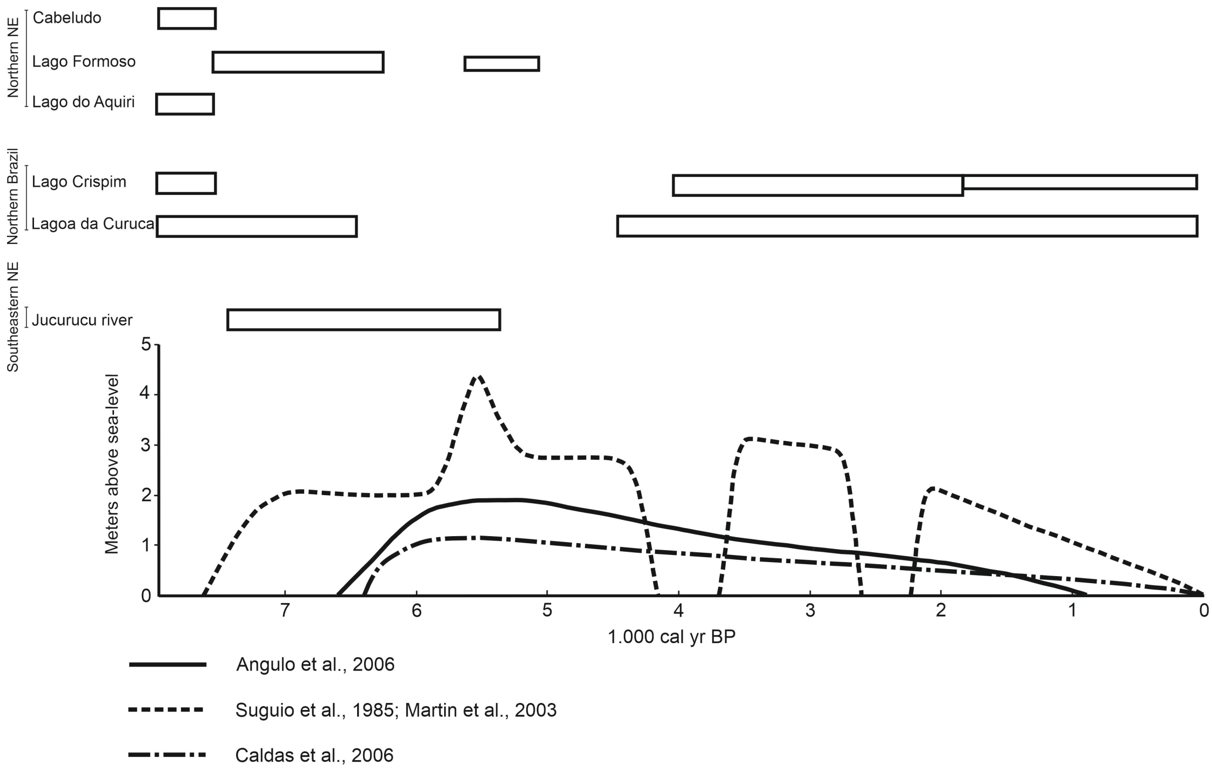

Figure 4.14. Graph summarizing the mangrove vegetation dynamics in comparison to the sea-level curves proposed for the eastern Brazil during the Holocene.

4.6.3 Late Holocene period from 1800 to Present (pollen zone C-IIb)

The upper zone is considered the archaeological layer due to the richness of human materials found in the sediments. Sandy mud sediments characterize the deposit with the presence of ceramic fragments, charcoal particles, and plant detritus. The mineralogical and chemical analyses have not been done for this layer. Like in LF, the archaeological layer is around 50 cm thick, and the chemical and mineralogical results in LF showed that the ceramic and lithic fragments strongly affected the chemical and mineralogical analyses.

The presence of *Rhizophora* is lower, suggesting longer distance transportation. Herbaceous vegetation mainly composed of Poaceae, Cyperaceae, and Asteraceae decreased. Meanwhile, arboreal vegetation such as *Sebastiana*, *Alchornea*, *Astronium*, *Byrsonima*, Euphorbiaceae, Fabaceae, Moraceae, and Myrtaceae expanded. Its increase might be related to Amazon rainforest expansion after 1800 cal yr BP. The taxa related to the Cerrado biome such as

Byrsonima and *Astronium* occured in the same percentages as the previous period. Palm trees such as Arecaceae, *Euterpe*/*Geonoma (Juçara?), Mauritia* (buriti), *Mauritiella*, and *Orbignya* (babaçu) expanded in this period indicating an increase in wetter conditions. Fern increased slightly probably also due to the wetter conditions. This shift in the plant taxa composition suggests that after 1800 cal yr BP conditions were wetter, although, humans could have affected the environmental dynamics.

In eastern Amazonia, Amerindians have been present since the late Pleistocene as hunters and gatherers. Afterwards, in the following period between 7000 and 2000 yr BP, the Amerindians became more fishermen and built houses on a shellmounds known as "*sambaquis*" (Roosevelt et al., 1991b). In the Maranhão lowland evidence of this tradition was found, exploiting aquatic sources of mangroves (Simões, 1981). In LF, during the interval between 2580 and 1350 cal yr BP evidence correlated to this establishment, when palms such as *Mauritia* and *Mauritiella*, started to increase (Moraes et al., 2021). At Cabeludo site, we did not find any evidence related to this period, or due to the lack of evidence, or because Amerindians from this tradition did not colonize the Cabeludo site during this time. Although the occurrence of palm trees was low, when correlated with the increase of charcoal contents in this period and the ceramics fragments (Figs. 4.11 and 4.12), is inevitable to correlate with human activities, as it has been evidenced in other palaeoecological studies in the north and NE Brazil (De Oliveira et al., 1999; Ledru et al., 2006; Maezumi et al., 2018; C. A. de Moraes et al., 2020; Moraes et al., 2021).

The upper layer of Cabeludo is characterized by abundant in archaeological evidence such as ceramic fragments, suggesting the beginning of human occupation after 1800 cal yr BP. This is similar to LF as the ceramic layer there started at around 1470 cal yr BP. For this time interval, the Amerindian community established in the Maranhão lowland was considered more developed than the previous tradition (*Sambaquis* tradition), as interpreted from the presence of stilt-house villages along rivers and lakes (Navarro, 2018b, 2018a). Stilt-houses were constructed with wooden pillars (stumps or trunks of trees) which supported constructions on top, where it was possible to place entire villages for protection and to avoid flooding (Fig. 4.4; Roosevelt and Navarro, 2021). The evidence of pre-colonial stilts-house villages can be found just in this region in South America. Comparing Cabeludo and LF archaeological layers, the beginning of stilt-house establishments in the region started between 1800 and 1470 cal yr BP.

4.7 Summary and Conclusion

The Cabeludo archaeological site provided new information about past environmental changes and human´s influence in the coastal zone of Maranhão State during the Holocene. The comparison with others regional palaeoecological studies showed comparable changes in climate changes, relative sea-level oscillations, and human environmental impacts in the northern part of northeastern Brazil. Between 7920 and 7500 cal yr BP, the study area was a tidal channel surrounded by *Rhizophora* due to a combination of marine transgression and dry environmental conditions, which allowed the mangroves to colonize areas further inland. During this period the study area was receiving sediment run-off from continental as well as marine sources as evidenced by the presence of quartz, clay minerals, pyrite, sulfur and among others. From 7500 to 1800 cal yr BP, the previous tidal channel in mangrove environment turned into the current freshwater river surrounded by lowlands arboreal and herbaceous vegetation by the expansion of the Amazon rainforest biome. The major changes were the consequence of a combination of relative sea-level fall and enhance in wetter conditions after 7500 cal yr BP. The mineral pyrite and the sulfur element decreased markedly, meanwhile the continental indicators increased, suggesting an interruption of sediments inputs from marine sources. After 1800 cal yr BP, Cabeludo was characterized by the wetter vegetational composition along the core. However, this period was mainly marked by the establishment of Amerindians in the study area. These people probably arrived at the beginning of this period, where they built stilt-house villages upon the river, like occurred in Lago Formoso and other sites in Maranhão lowland. The sediment layer is rich in anthropological evidence such as fragments of ceramics, high amount of charcoal particles, and higher amounts of pollen of palm trees. The increase of those evidences suggests that the establishment of the stilt-house villages community started at the begging of this period. The mineralogy and chemistry agree and mark very well the textural subdivision of the core, with a lower granulometric finer portion, where clay minerals (kaolinite and illite) and micas are present, as well pyrite-denoting marine influence. Whereas in the upper and granulometric coarser part of the core, there is a clear predominance of quartz, plagioclase, and feldspar.

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Supplementary material

Table S4.1. Chemical composition and LOI of the Cabeludo core.

Depth interval (cm)		***57-50***	***80-70***	***100-90***	***140-130***	***200-190***	***230-220***	***260-250***	***310-300***	***360-350***	***410-400***
SiO_2	%	69,2	81,6	86,3	75,2	46,2	47,1	38,2	40,9	42,6	40,3
Al_2O_3	%	6,23	7,92	5,04	9,82	18,3	18,5	15,25	17,7	17,6	18,1
Fe_2O_3	%	1,42	2,2	1,17	2,62	6,43	6,19	7,07	5,85	5,53	5,63
CaO	%	0,37	0,46	0,45	0,33	0,42	0,33	0,4	0,35	0,47	0,39
MgO	%	0,28	0,34	0,19	0,52	1,24	1,16	1,43	1,26	1,44	1,37
Na_2O	%	0,61	0,92	0,9	0,58	0,27	0,27	0,35	0,18	0,27	0,25

K_2O	%	0,83	1,24	0,96	1,26	1,43	1,44	1,17	1,29	1,3	1,39
TiO_2	%	0,72	1,01	0,75	0,97	0,98	1	0,83	0,9	0,91	0,92
MnO	%	0,02	0,04	0,03	0,04	0,06	0,06	0,12	0,06	0,05	0,04
P_2O_5	%	0,1	0,07	0,05	0,06	0,09	0,1	0,08	0,09	0,08	0,07
LOI	%	19,15	5,76	3,48	9,97	24,8	24,3	33,9	31,7	31	29,7
S	%	0,11	0,03	0,06	0,25	2,26	2,31	3,86	2,7	2,4	2,54
Sc	ppm	6	8	5	10	14	14	14	14	14	14
V	ppm	43	49	32	68	102	100	134	120	119	125
Cr	ppm	50	60	50	80	110	110	100	120	130	120
Co	ppm	10	10	8	20	11	10	19	12	12	13
Ni	ppm	13	13	8	22	23	26	30	26	26	23
Cu	ppm	11	11	7	33	16	15	16	16	16	15
Zn	ppm	89	44	30	56	61	56	80	63	62	63
Ga	ppm	7,7	9,6	6,3	11,7	22,5	22,2	18,5	21,2	21,1	22,3
As	ppm	0,9	0,2	0,3	1,5	13,1	12,9	13,3	13,1	11,2	19,1
Se	ppm	0,2	<0.2	<0.2	<0.2	0,2	<0.2	0,3	0,4	0,4	0,6
Rb	ppm	31,1	43,8	28,8	49,6	80,2	80,8	64,9	79,3	79,3	83
Sr	ppm	82,7	118,5	111	92,1	120	107,5	125	113	123	120,5
Y	ppm	22,1	31,8	25,4	33,4	32,9	29,1	45,2	31,7	31,2	30,9
Zr	ppm	598	860	917	718	230	235	186	183	192	182
Nb	ppm	11,3	16,5	11,9	16	18,8	19,3	15,9	17,5	17,2	17,8
Mo	ppm	<1	<1	<1	<1	2	3	2	4	3	4

Ag	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Sn	ppm	1	2	1	2	3	3	3	3	2	2
Sb	ppm	<0.05	<0.05	<0.05	<0.05	0,06	0,06	0,08	0,09	0,09	0,13
Cs	ppm	1,11	1,31	0,69	1,93	4,46	4,53	3,74	4,84	4,58	4,84
Ba	ppm	329	438	340	429	380	385	315	356	357	376
Hf	ppm	16	23,9	26,3	20,6	6,6	7	5,4	5,1	5,3	5,1
Ta	ppm	1	1,2	1	1,3	1,3	1,4	0,7	0,5	0,6	0,9
W	ppm	3	3	2	3	2	4	2	3	2	2
Tl	ppm	0,12	0,08	0,05	0,13	0,15	0,16	0,18	0,18	0,17	0,18
Pb	ppm	11	14	10	17	22	23	20	23	22	22
Bi	ppm	0,04	0,05	0,03	0,08	0,14	0,14	0,13	0,13	0,13	0,14
Hg	ppm	0,076	0,054	0,036	0,075	0,067	0,042	0,053	0,044	0,051	0,061
Th	ppm	7,91	10,75	8,58	10,8	17,15	16,35	21,1	16,95	15,4	16,45
U	ppm	2,38	3,35	2,97	3,3	4,01	3,93	5,92	5,06	4,83	4,45

CHAPTER 5 SYNTHESIS

The environmental changes during the Holocene in northeastern Brazil have been triggered mainly by climate changes, human activities, and in the coastal area, sea-level oscillations. To understand these dynamics, a multi-proxy analysis has been conducted in three sediment cores from two different regions, as described in the previous chapters. In this chapter, I synthesize the results to reconstruct the impacts of each parameter on the environment in a wider context, comparing them between each other and other regional studies.

5.1 Sea-level oscillations and mangroves dynamics in Maranhão coastal region

The sea-level curve for Brazil has been proposed by many authors, however, most are published for the eastern and southern coastal regions. The northern part of NE is still poor in data to determine precisely when and how strong the sea-level oscillated during this epoch. As used in many other palaeoecological studies, mangrove dynamics have been used (chapter 3 and chapter 4) to determine the relative sea-level variations for the coastal zone of Maranhão.

Nowadays, the State of Maranhão (encompassing Pará State) shelters the largest continuous mangrove belt in the world, which covers 56.6% of mangroves in Brazil (Souza Filho et al., 2006). Nevertheless, during the early to mid-Holocene, mangroves were colonizing different regions into the continent due to Atlantic transgression, as evidenced in Lake Aquiri since 7450 yr BP (Behling and Costa, 1997). In our study sites, the presence of mangroves occurred since the beginning of the records at 7520 cal yr BP in LF, and 7920 cal yr BP in Cabeludo.

Each study area is inserted in a different environmental context. The pollen and spores of mangrove found were *Rhizophora*, *Avicennia*, and *Acrostichum*. However, *Rhizophora* was the most representative taxon and *Avicennia* occurred just in Cabeludo. Lago Formoso (LF) is a lake situated around 150 km far from the coastline, while Cabeludo is in a tributary river around 120 km from the current coast. But like in Aquiri, both study sites do not have the occurrence of mangroves nowadays, meaning that the mangrove's previous presence was related to sea-level displacement inside the continent during the mid-Holocene. The study sites suggest an initial setting of mangroves since 7920 cal yr BP when the ocean was extending deep inland, due to marine transgression, allowing the mangroves to spread in continental regions. Correlating mangrove presence with chemical and mineralogical contents, it was possible to propose that the relative sea-level highstand occurred between 5500 and 5020 cal yr BP. Afterward, the relative sea-level fell after until the present. The pattern of the relative sea-level curve dropped could not be precisely determined with our data, however, a slight oscillation has been suggested between 2580 and 1350 cal yr BP, when occurred a lowering of lake level in LF.

5.2 Climate in northern NE Brazil

The climate history of the Maranhão coastal zone was reconstructed from Lago Formoso and Cabeludo archaeological sites, suggesting the climate changes during the mid- to late Holocene (Chapters 3 and 4). The almost 8000 years-old records showed a predominance of open vegetation related mainly to Cyperaceae, Poaceae, Asteraceae, *Borreria*, and *Polygonum*, and an intense fire regime. These conditions indicated a dry environment from the beginning of the record at 7920 cal yr BP until approximately 5000 cal yr BP. The same tendency for the drier condition has been recorded since the early Holocene in other palaeoecological studies from northern NE and southeastern Amazonia (Guimarães et al., 2021; Hermanowski et al., 2012; Jacob et al., 2004; Pessenda et al., 2005; Sifeddine et al., 2003). In the Lake Caço region, which is also located in the Maranhão coastal zone, (Ledru et al., 2006) indicated intense fires and forest regression in the early Holocene. Similarly, Pessenda et al. (2005) using soil isotopes, showed that the vegetation was dry and open from approximately 10,000 to 6000-5000 yr BP (= uncalibrated years Before Present), and became more humid after approximately 4000 yr BP. Climate reconstructions in Carajás (Guimarães et al., 2021; Hermanowski et al., 2012) suggested that the mid-Holocene was markedly dry when occurred a rapid shift from wetter to drier environmental conditions between 10,000 and 3000 cal yr BP.

The followed period from 5000 to 2500 cal yr BP was marked by an increase in freshwater flow into the study areas due to an increase in precipitation rates. The vegetation reconstruction from both sites showed an arboreal expansion represented mainly by Moraceae, *Cecropia*, and *Alchornea*, which are common trees on fertile soils in tropical rainforests (Marchant et al., 2002) indicating wetter conditions. After around 1800 cal yr BP, occurred a predominance of quartz and clay minerals as kaolinite and illite suggesting a moister and warm environment. The vegetational recons showed an enhancement of arboreal vegetation such as *Alchornea*, *Astronium*, *Byrsonima*, Euphorbiaceae, Fabaceae, Moraceae, and Myrtaceae, which are typical of the Amazonia biome. Those conditions were favorable to the rainforest expansion of its boundaries closer to the study areas.

5.3 Late Holocene climate changes in eastern Northeast Brazil

One study area was carried out in CNP, which is in the eastern NE Brazil. The climatic history in the study site followed a different pattern during the Holocene in comparison to the other two samples, located in northern NE Brazil, discussed in this work. Nowadays, CNP is inserted in the semi-arid Caatinga biome, and is located in one region also known as the "drought polygon" (Nacional, 2005). Besides the predominant vegetation in the region to be part of the Caatinga biome, due to relieve variations and microclimate provided by CNP geomorphological conditions, is there also an occurrence of species from Cerrado and Atlantic forests (Ferreira et al., 2017). Despite conducting a paleoenvironmental study in Caatinga being difficult because of the lack of environments that can preserve records (e.g., perennial lakes), CNP conditions were suitable for sediment preservation and collection. The Pingadeira (leaking spot) study site had an origin associated with the outcropping of groundwater, which behaves like an oasis-type environment. Then, besides the studied spot being located in the semi-arid context, the local conditions provided enough information to understand, in higher resolution, how the local and regional climate changed during the last 2800 cal yr BP.

Other authors proposed that after around 4000 yr BP the eastern NE was marked by drier conditions when the Caatinga species expanded (Cruz et al., 2009; De Oliveira et al., 1999; Novello et al., 2012). However, during this interval occurred slight oscillations in the climate, and these changes could have seemed in the Pingadeira record. In the interval between 2800 and 2150 cal yr BP, drier conditions have been suggested, indicated by the dominance of *Cecropia* and high charcoal fragments, and less frequent fern spores. Besides the human presence in the area since the begging of the record, the typical vegetation mainly composed of *Mimosa*, Asteraceae, and *Borreria* supported the idea of dry environmental conditions during this phase. From 2150 and 450 cal yr BP, the climate was marked by moister conditions when occurred an enhancement in Moraceae, palm trees, and ferns spores. The expansion of arboreal vegetation evidenced a moister condition, which turned the environment more suitable for humans and increase their community. After 450 cal yr BP the climate switched to drier conditions as showed by the shifting from arboreal to herbaceous species and increase in charcoal fragments. Besides humans playing a strong role in the local environment, the climate dynamics have been essential to their community establishment and expansion.

5.4 Human impact

The human impact on the environment in Brazil can be well distinguished between two different periods: Pre-colonial and Postcolonial. After the arrival of the Europeans in 1500 A.C., the human influence on the environment changed and, most of them, are commonly written recorded. However, before, Amerindians were leaving in Brazilian territory and their activities do not have written registers but can be found through environmental records. In our study areas, we could find evidence of human activities through vegetation dynamics, and high charcoal concentration.

Palms trees have been found in all the study areas, and together with the other proxies, they indicated anthropological handling. *Orbignya* species (babaçu) has been frequently used by Amerindians for food, weapons, and materials for dwelling constructions during the entire Holocene (Anderson, 1977). Its occurrence was most representatively in Pingadeira and LF, where it was present since 2800 cal yr BP and 1350 cal yr BP, respectively. *Mauritia* (buriti) incidence has been associated with pre-colonial human activities by many other palaeoecological studies in Brazil (Behling and Costa, 1997; Ledru et al., 2006; Maezumi et al., 2018b; Morcote-Ríos and Bernal, 2001). Its presence was more marked in LF core when it started to increase since 2580 cal yr BP together with the other humans' indicators. *Phaseolus* (beans) is not an endemic vegetation of Brazil (Debouck, 1986), suggesting cultivation by Amerindians, who commonly exchanged its seeds with other American native populations (Freitas, 2006). Its species have been found only in the Pingadeira record, mostly in the interval between 2150 and 450 cal yr BP. The increase in its signal close to the end of this phase can be an indicator of trade with the Europeans. *Cecropia* was very representative in Pingadeira (between 2800 and 2150 cal yr) and LF (mainly after 2580), and in both study areas, it was associated with strong fire frequency. Once it is a dominant species in secondary vegetation and frequently associated with disturbed environments (Lorenzi, 1998), its increase suggested the local Amerindian effect on the environment.

Strong fire frequency can occur due to dry climate conditions, but, during the Holocene, is also common to be associated with humans' impacts in South America as suggested by other authors (Maezumi et al., 2018a, 2018b; Pessenda et al., 2005). The charcoal fragments in this work were almost entirely associated with humans, once joined with the other proxies, the results corroborate that interpretation. In Pingadeira, in the period between 2800 cal yr BP and

2150 cal yr BP the charcoal contents were associated with the high presence of *Cecropia* to indicate the humans' activities. Afterward, from 2150 to 450 cal yr BP besides the phase being marked by moister conditions, the stronger presence of charcoal fragments was associated with palms and *Phaseolus* vegetation indicating that the Amerindian community increased in the study area. The same pattern has been found in the Maranhão coastal zone, with LF and Cabeludo after around 1400 cal yr BP. The charcoal contents increase was associated with the enhancement of palm vegetation and with the presence of ceramic fragments in a deposit interval that has been denominated as an archaeological layer

5.5 Concluding remarks and open questions

The results of this research showed that climate, sea-level, and humans triggered environmental changes, all on high scales, during the Holocene. Nevertheless, the human impact occurred only in the late Holocene in all study areas.

After analyzing two different areas, one correlated to the eastern NE Brazil and the other in the northern NE, it was possible to distinguish two different climate patterns during the late Holocene. In the eastern NE Brazil, the Pingadeira showed similar climate conditions to today since around 3000 years, when the region was facing dry conditions with the presence of the Caatinga biome characteristics. Besides Pingadeira did not cover the early to mid-Holocene, other regional studies showed a shifting from wetter to dry conditions (Cruz et al., 2009; De Oliveira et al., 1999). On the other hand, in northern NE, the other two study sites showed dry conditions from approximately 8000 cal yr BP until 5000 cal yr BP. Afterward, occurred a tendency to wetter conditions since around 5000 years, with an intensification of moister and warmer environment after 1500 cal yr BP.

This study provided new insights about the marine transgression, its highstand, and the subsequent regression for Maranhão coastal zone. So far, other studies have proposed sea-level curves for different parts of Brazil, but still lack evidence of the northern part of the northeastern. Through vegetation dynamics, mainly related to mangroves, this study could understand how strong the Atlantic transgression played a role in the landscape in the last 8000 years. However, more studies would be needed to build more precisely a sea-level curve and determine the magnitude of the marine transgression.

The presence of Amerindians in Maranhão lowland has been reported in other studies, however, their interaction with the environment was described for the first time in our study from Lago Formoso and Cabeludo. Our records showed their first recorded contact with the landscape occurred around 2500 cal yr BP, probably because of and decrease in the lake level, which allowed the people to build houses upon the fluvial system. Comparing our evidence with the previous literature, it was possible to distinguish two different communities' settlements, i) the people from sambaquis and ii) the people of stilt-houses. The first probably lived from the period from approximately 2500 until around 1500 cal yr BP, then the people of stilt-houses started to establish themselves from 1500 cal yr BP. Nonetheless, it was not possible to determine the time of their abandonment with our both studies. To understand better their abandonment, more palaeoecological studies in the region would be needed.

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I am grateful to my sponsor CNPq for the opportunity to provide the scholarship that allowed me to produce this project.

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For all the friends I have made in Göttingen that helped me in the good and bad moments of the life I had during this project time.

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And the last and the more important, I would like to express all my gratitude to my family. In special to my father and my mother. If not for them, I wouldn't achieve this point in my academic life, and wouldn't be who I am today. To them all my love.

Appendix 1: Table of identified pollen, spores and NPP taxa

Abbreviations for palynological records

P: Pingadeira

LF: Lago Formoso

C: Cabeludo

Pollen

Family	**Pollen type**	**Photo**	**Records**
Acanthaceae	*Justicia*	1	CNP, LF
	Avicennia	2	C
Alismataceae	Alismataceae		CNP, LF
	Sargittaria		C
Amaranthaceae	*Alternanthera*	3	CNP, LF, C
	Amaranthus	4	CNP, LF, C
	Gomphrena/Pfaffia	5	CNP, C
Anacardiaceae	Anacardiaceae	6	CNP, LF, C
	Astronium	7	C
Annonaceae	Annonaceae	8	CNP, LF
Apiaceae	Apiaceae	9	CNP, LF, C
Apocynaceae	Apocynaceae	10	CNP, LF, C
Aquifoliaceae	*Ilex*	11	LF, CNP
Araliaceae	*Schefflera*		LF, C
Arecaceae	Arecaceae		CNP, LF, C
	Mauritia		CNP, LF, C
	Mauritiella	12	LF, C

	Orbignya	13	CNP, LF, C
	Euterpe/*Geonoma*	14	CNP, LF, C
Asteraceae	Asteraceae	15	CNP, LF, C
	Ambrosia		CNP
	Cichorioideae		CNP
	Trixis		CNP
Begoniaceae	Begoniaceae		CNP, LF, C
Bignoniaceae	Bignoniaceae	16	CNP, C
Boraginaceae	*Cordia*	17	LF, C
Burseraceae	*Protium*		LF, C
Cabombaceae	*Cabomba*		LF
Cactaceae	Cactaceae	18	CNP
Calophyllaceae	Calophyllaceae		CNP
Cannabaceae	*Celtis*	19	CNP; LF
	Trema	20	CNP
Celastraceae	Celastraceae		LF
Clusiaceae	*Clusia*		C
Combretaceae	Combretaceae	21	LF, C
Convolvulaceae	*Ipomoea*		CNP, LF, C

Cyperaceae	Cyperaceae	22	CNP, LF, C
Dilleniaceae	*Curatella*		LF, C
	Doliocarpus		C
Elaeocarpaceae	*Sloanea*	23	CNP, LF, C
Euphorbiaceae	Euphorbiaceae	24	CNP, LF, C
	Acalypha	25	CNP, LF, C
	Alchornea	26	LF, C
	Croton	27	CNP
	Mabea	28	LF, C
	Sapium		CNP, LF, C
	Sebastiana	29	CNP, LF, C
	Sebastiana Type		C
	Sebastiana brasiliensis		C
	Sebastiana discolor		C
Fabaceae	Fabaceae	30	CNP, LF, C
	Clitoria		CNP
	Mimosa		CNP, LF, C
	Mimosa ceratonia		CNP, LF

	Mimosa Elliptica		CNP, LF
	Mimosa Enterobium sp		CNP
	Mimosa Stryphnodendron		CNP
	Mimosaceae	31	CNP, LF, C
	Mucuna		LF, C
	Phaseolus	32	CNP
	Zornia		CNP
Flacourtiaceae	*Flacourtiaceae*		CNP, LF
	Casearia		LF
Iridaceae	Iridaceae		LF
Lamiaceae	Lamiaceae	33	CNP, LF
Lentibulariaceae	*Utricularia*	34	CNP
Loranthaceae	Loranthaceae		CNP, LF
Lythraceae	*Cuphea carthagenensis*	35	CNP
	Cuphea flava		CNP
Malpighiaceae	Malpighiaceae	36	CNP, LF, C
	Byrsonima	37	CNP, LF, C

	Pteramdra		LF
Malvaceae	Malvaceae	38	CNP, LF, C
	Lueheopsis		LF
Melastomataceae	Melastomataceae	39	CNP, LF, C
	Miconia		LF
Meliaceae	*Meliaceae*		CNP
Menispermaceae	Menispermaceae		LF, C
Menyanthaceae	*Nymphoides*		LF
Moraceae	Moraceae	40	CNP
	Ficus		CNP
Myrtaceae	Myrtaceae		CNP, LF, C
Ochnaceae	Ochnaceae	41	CNP
Onagraceae	Ludwigia	42	CNP, LF, C
Phytolaccaceae	*Gallesia* Type	43	CNP, LF
Picramniaceae	Picramniaceae		CNP
Piperaceae	*Piper*		CNP, LF, C
Poaceae	Poaceae	44	CNP, LF, C
Polygalaceae	Polygalaceae		LF, C
Polygonaceae	*Polygonum*		LF, C

Potamogeton	*Potamogeton*		C
Proteaceae	*Roupala*	45	CNP
Rhamnaceae	Rhamnaceae		CNP, LF, C
Rhizophoraceae	*Rhizophora*	46	LF; C
Rubiaceae	Rubiaceae	47	CNP
	Borreria	48	CNP, LF, C
	Borreria Cupularis		C
	Diodella		CNP
	Emmeorhiza		C
	Mitracarpus		CNP
	Psychotria		CNP, LF
	Richardia		CNP
	Spermacoceae	49	CNP, LF, C
Rutaceae	*Zanthoxylum*		CNP, LF
Sapindaceae	Sapindaceae	50	CNP, LF, C
Sapotaceae	*Chrysophyllum*	51	CNP, LF, C
Solanaceae	*Solanum*	52	CNP
Sterculiaceae	Sterculiaceae		CNP
Symplocaceae	Symplocaceae		C

Tiliaceae	*Luhea*	53	CNP, LF
Typhaceae	*Typha*		LF, C
Urticaceae	*Cecropia*	54	CNP, LF, C
Verbenaceae	Verbenaceae		CNP

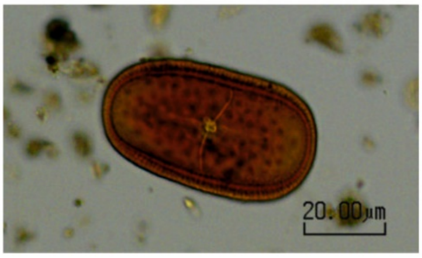
Spores

Family	**Spore type**	**Photo**	**Records**
Lycopodiaceae	Lycopodium alopecuroides	55	CNP
Notothyladaceae	Phaeoceros laevis		CNP
Osmundaceae	Osmunda	56	CNP
Pteridaceae	Acrostichum	57	LF, C
	Arachnoideum		CNP
	Pityrogramma calomelanos	58	CNP, LF
	Pteris		LF, C
Schizaeaceae	Schizaea attenuata	59	CNP

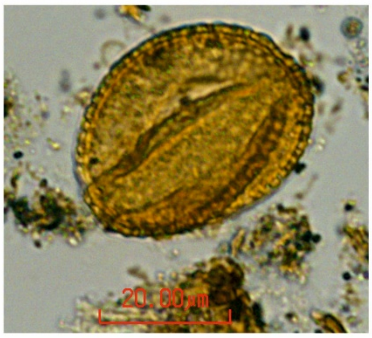
Non-pollen palynomorphs

NPP type	Photo	Records
Anabaena sp.		C
Botryococcaceae Botryococcus	60	LF
Lining of Foraminifera	61	C
Pediastrum	62	LF, C
Turbellaria Neorhabdacoela		C

Acanthaceae

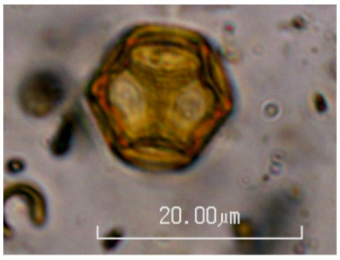


1) *Justicia*

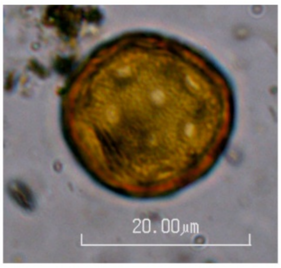


2) *Avicennia*

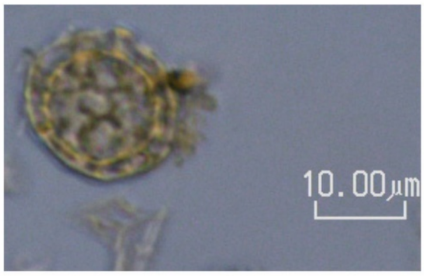
Amaranthaceae



3) *Alternanthera*



4) *Amaranthus*



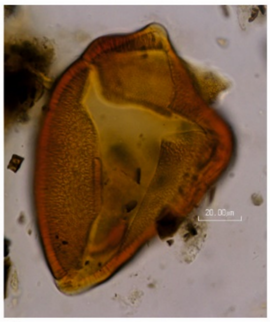
5) *Gomphrena/Pfaffia*

Anacardiaceae

6) Anacardiaceae

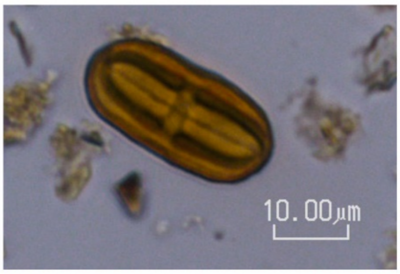
7) *Astronium*

Annonaceae



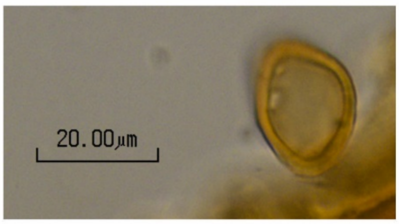
8) Annonaceae

Apiaceae



9) Apiaceae

Apocynaceae

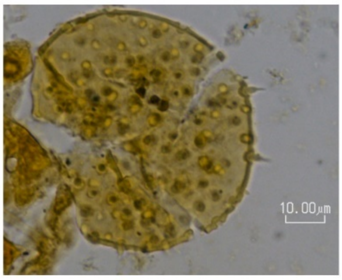


10) Apocynaceae

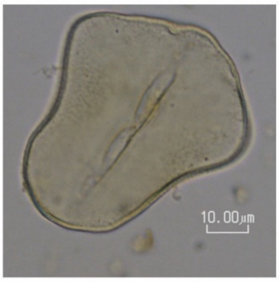
Aquifoliaceae

11) *Ilex*

Arecaceae



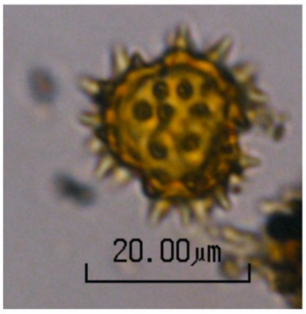
12) *Mauritiella*



13) *Orbignya*

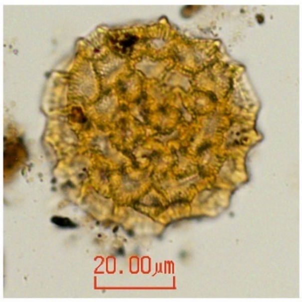
14) *Euterpe/Geonoma*

Asteraceae



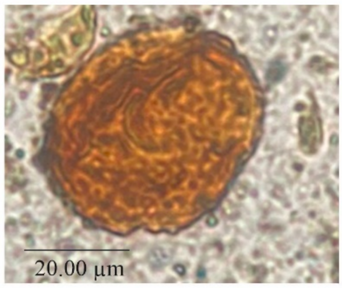
15) Asteraceae

Bignoniaceae



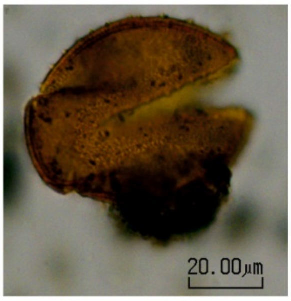
16) Bignoniaceae

Boraginaceae



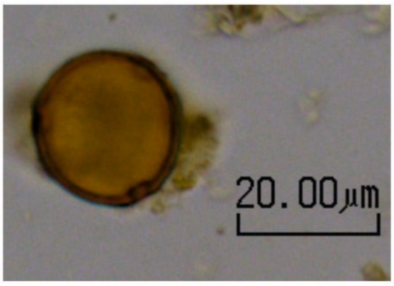
17) *Cordia*

Cactaceae

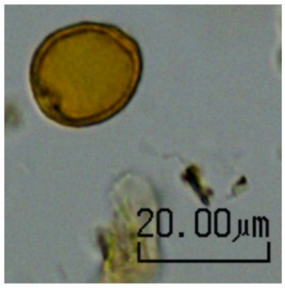


18) Cactaceae

Cannabaceae

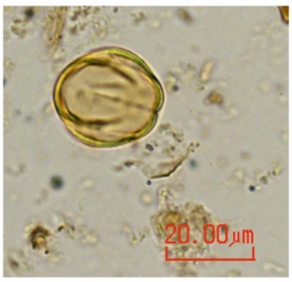


19) *Celtis*



20) *Trema*

Combretacae

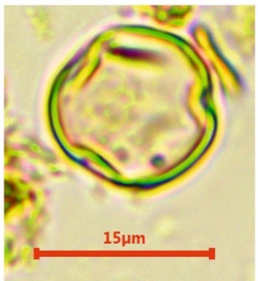


21) Combretaceae

Cyperacacae

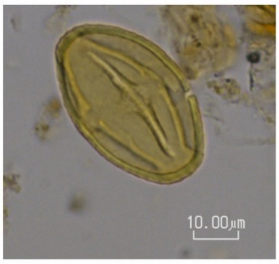
22) Cyperaceae

Elaeocarpaceae

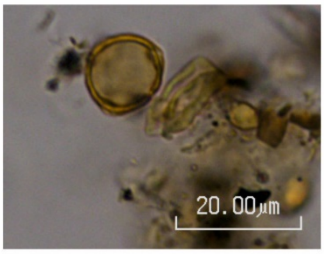


23) *Sloanea*

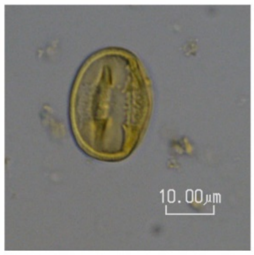
Euphorbiaceae



24) Euphorbiaceae



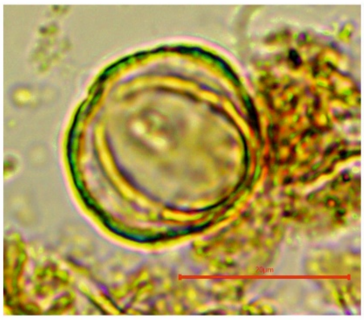
25) *Acalypha*



26) *Alchornea*

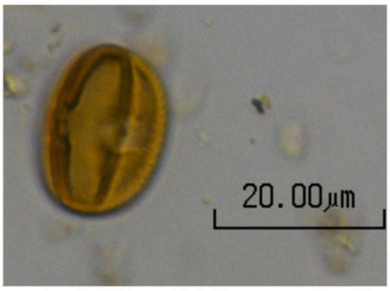
27) *Croton*

28) *Mabea*



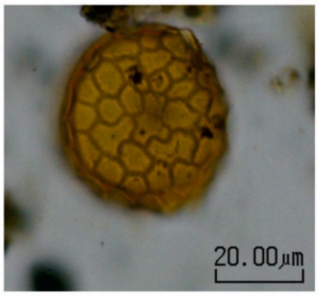
29) *Sebastiana*

Fabaceae



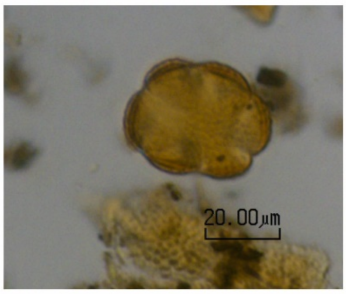
30) Fabaceae

31) Mimosaceae



32) Phaseolus

Lamiaceae

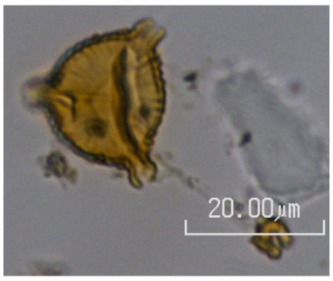


33) Lamiaceae

Lentibulariaceae

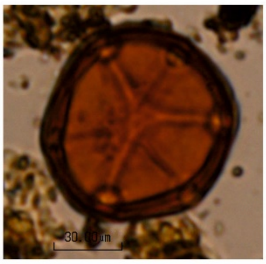
34) *Utricularia*

Lythraceae

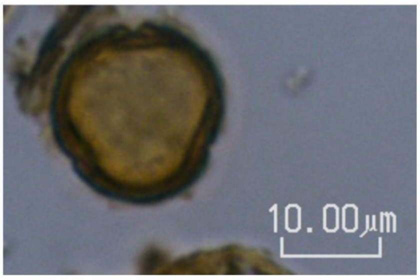


35) *Cuphea carthagenensis*

Malpighiaceae

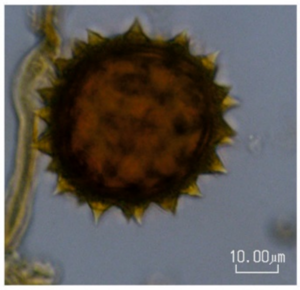


36) Malpighiaceae



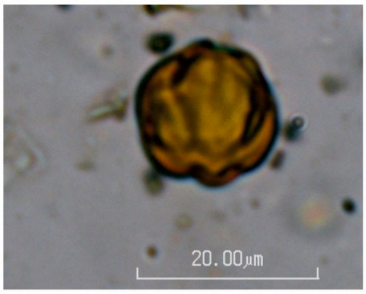
37) *Byrsonima*

Malvaceae



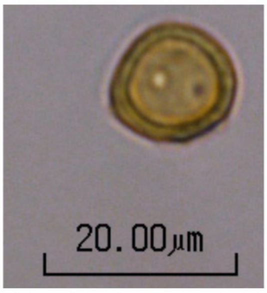
38) Malvaceae

Melastomataceae



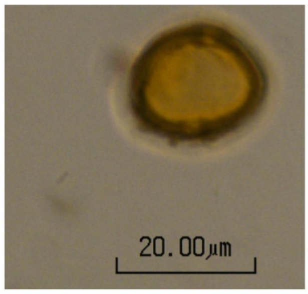
39) Melastomataceae

Moraceae



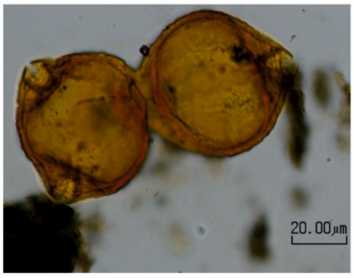
40) Moraceae

Ochnaceae



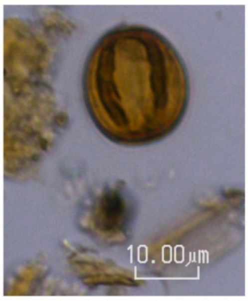
41) Ochnaceae

Onagraceae



42) *Ludwigia*

Phytolaccaceae



43) *Gallesia type*

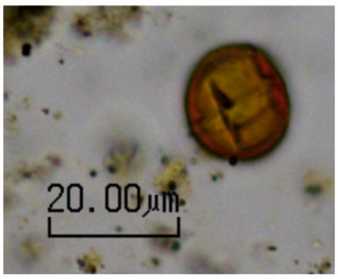
Poaceae

44) Poaceae

Proteaceae

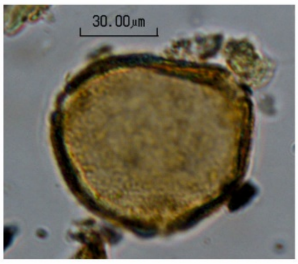
45) *Roupala*

Rhizophoraceae

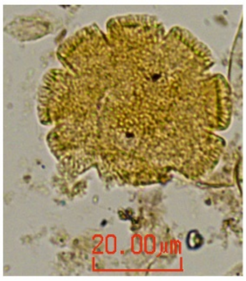


46) *Rhizophora*

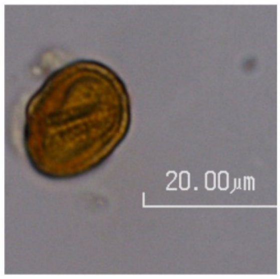
Rubiaceae



47) Rubiaceae

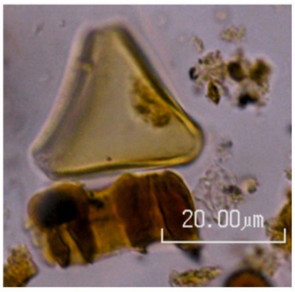


48) *Borreria*



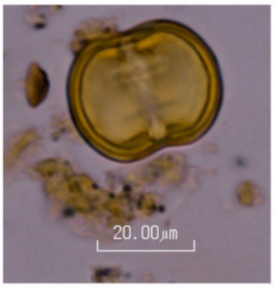
49) *Spermacocea*

Sapindaceae



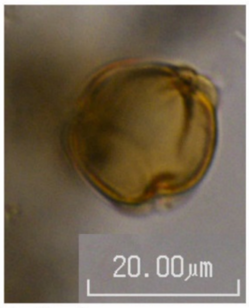
50) Sapindaceae

Sapotaceae



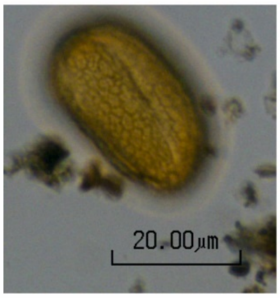
51) *Chrysophyllum*

Solanaceae



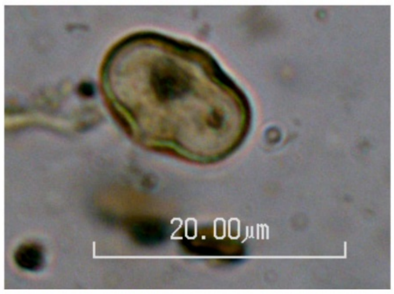
52) Solanum

Tiliaceae



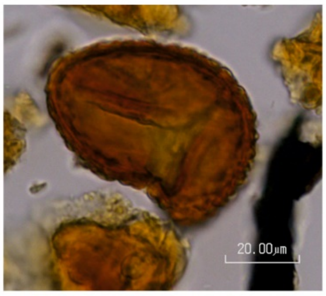
53) Luhea

Urticaceae



54) Cecropia

Lycopodiaceae

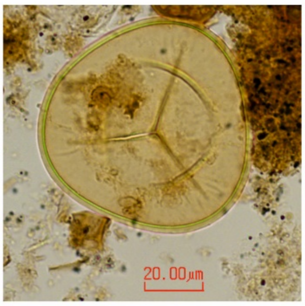


55) *Lycopodium alopecuroides*

Osmundaceae

56) *Osmunda*

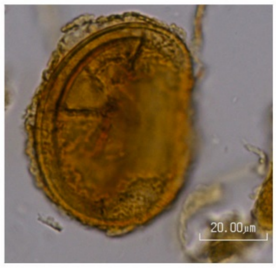
Pteridaceae



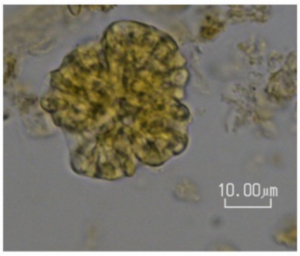
57) *Acrostichum*

58) *Pityrogramma calomelanos*

Schizaeaceae

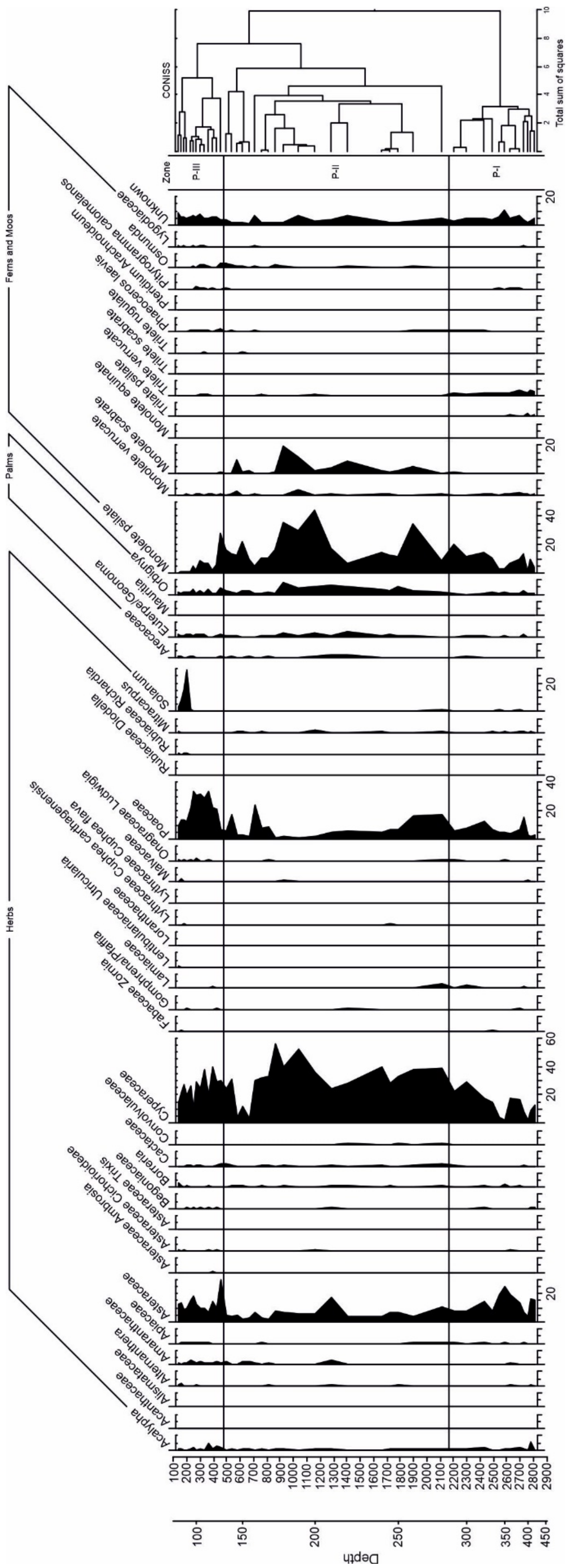


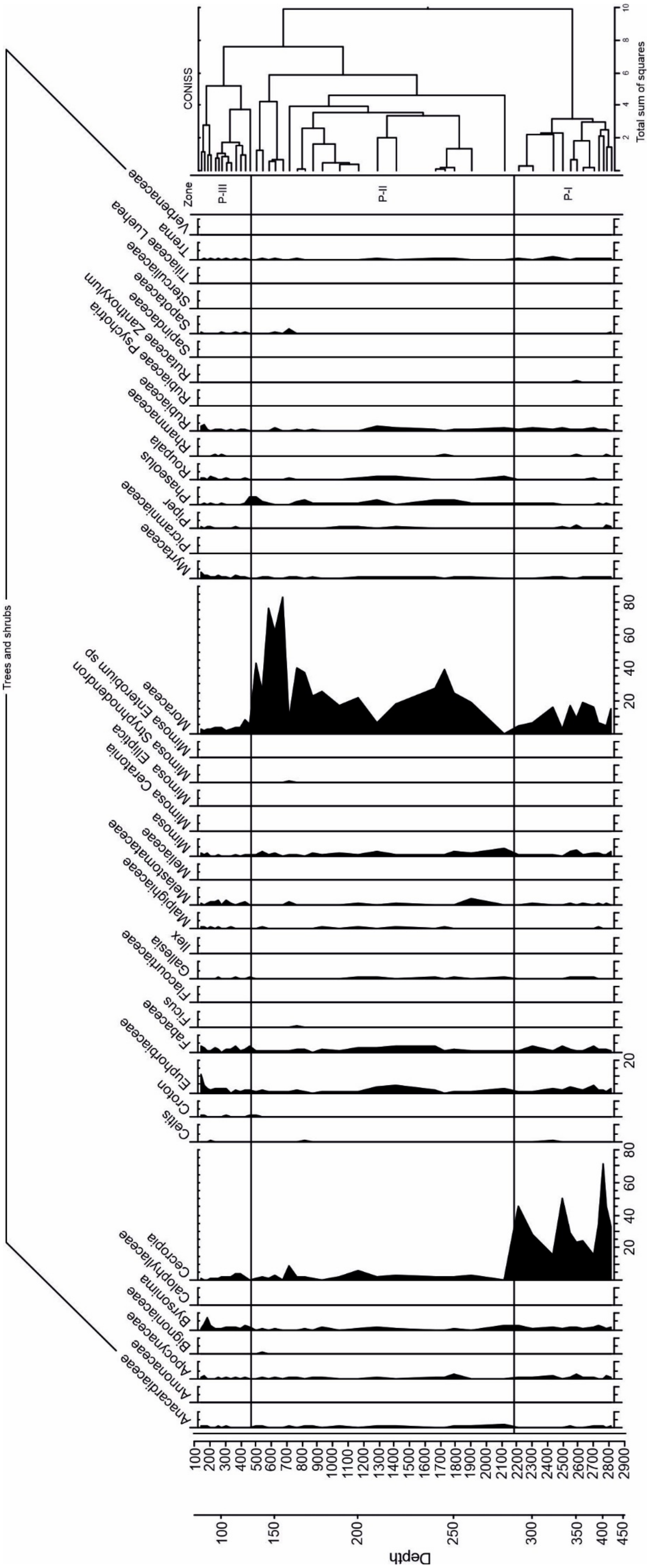
59) *Schizaeae attenuata*

Botryococcaceae	Lining of Foraminifera	Pediastrum
		
60) *Botryococcus*	61) *Foraminifera*	62) *Pediastrum*

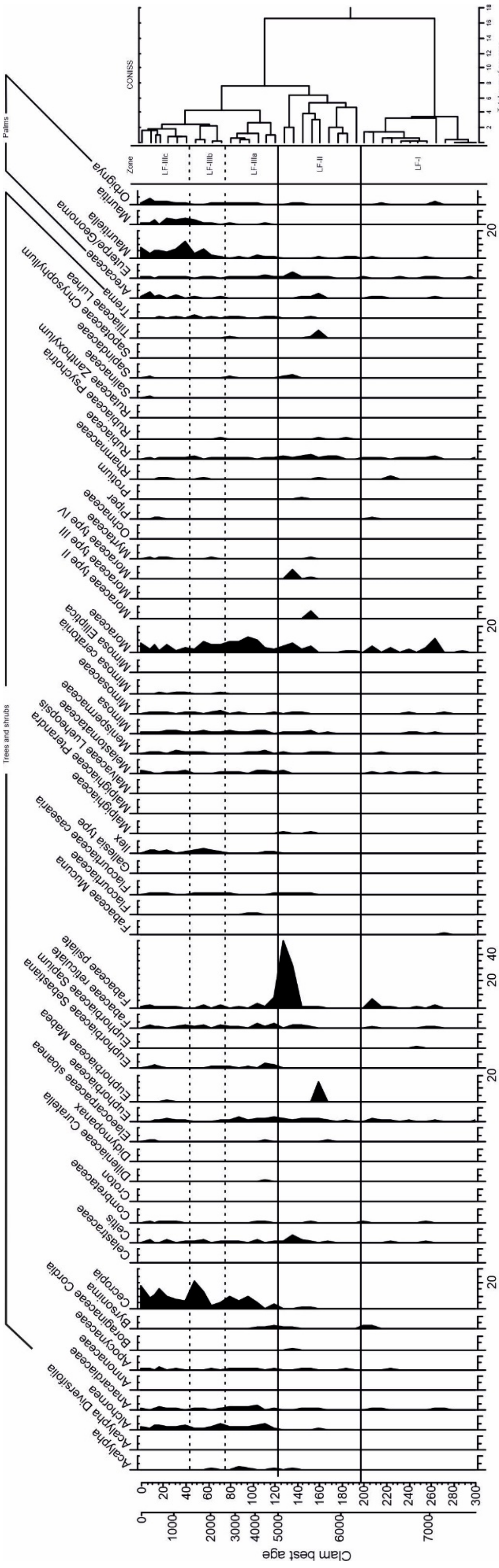
Appendix 2: Full pollen diagrams

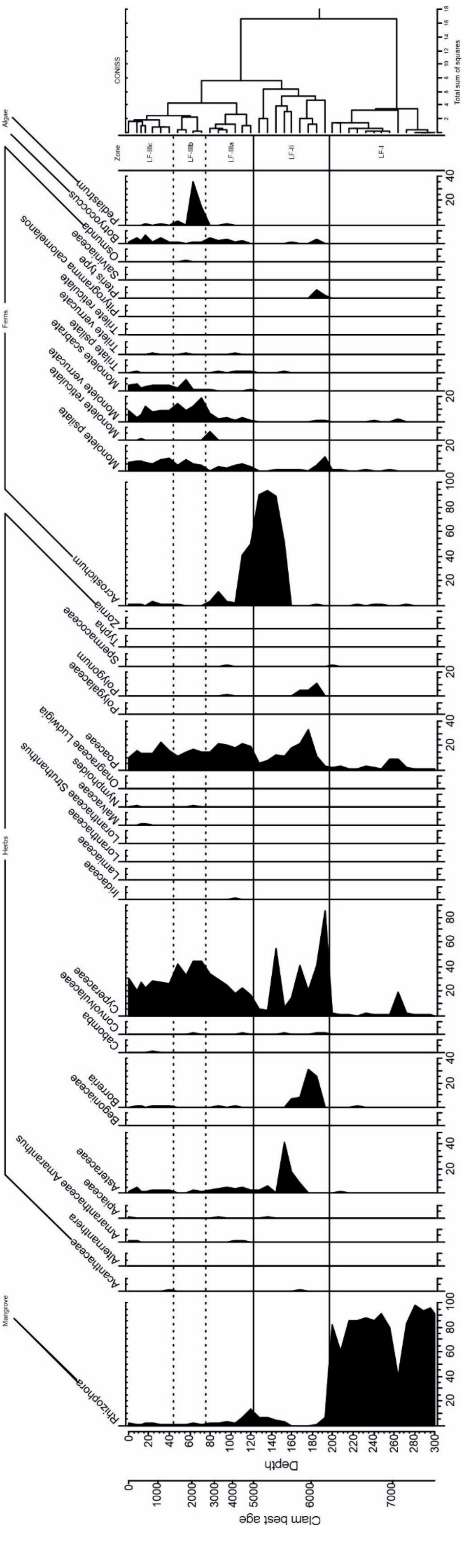
Pingadeira




Trees and shrubs
Anacardiaceae
Annonaceae
Apocynaceae
Bignoniaceae
Byrsonima
Calophyllaceae
Cecropia
Celtis
Croton
Euphorbiaceae
Fabaceae
Ficus
Flacourtiaceae
Gallesia
Ilex
Malpighiaceae
Melastomataceae
Meliaceae
Mimosa
Mimosa Ceratonia
Mimosa Elliptica
Mimosa Stryphnodendron
Mimosa Enterobium sp
Moraceae
Myrtaceae
Picramniaceae
Piper
Phaseolus
Roupala
Rhamnaceae
Rubiaceae
Rubiaceae Psychotria
Rutaceae Zanthoxylum
Sapindaceae
Sapotaceae
Sterculiaceae
Tiliaceae
Trema Luehea
Verbenaceae
Zone
P-III
P-II
P-I
CONISS
Total sum of squares
Depth

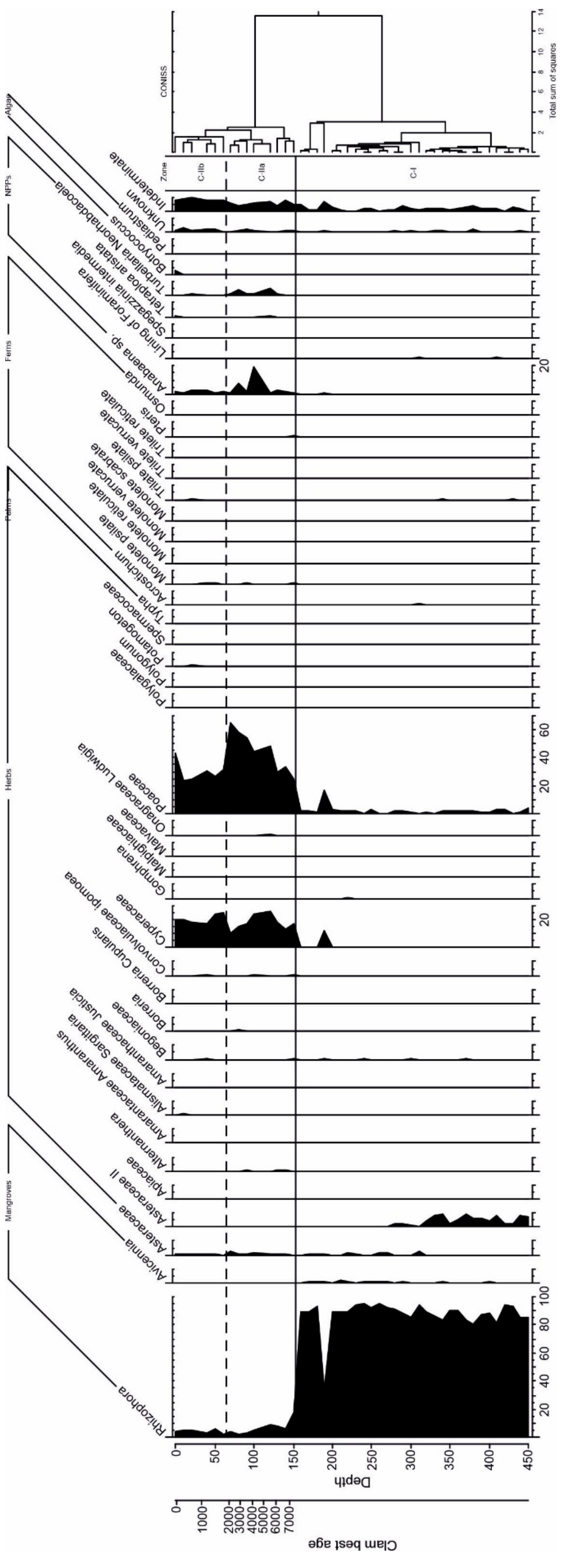
Lago Formoso

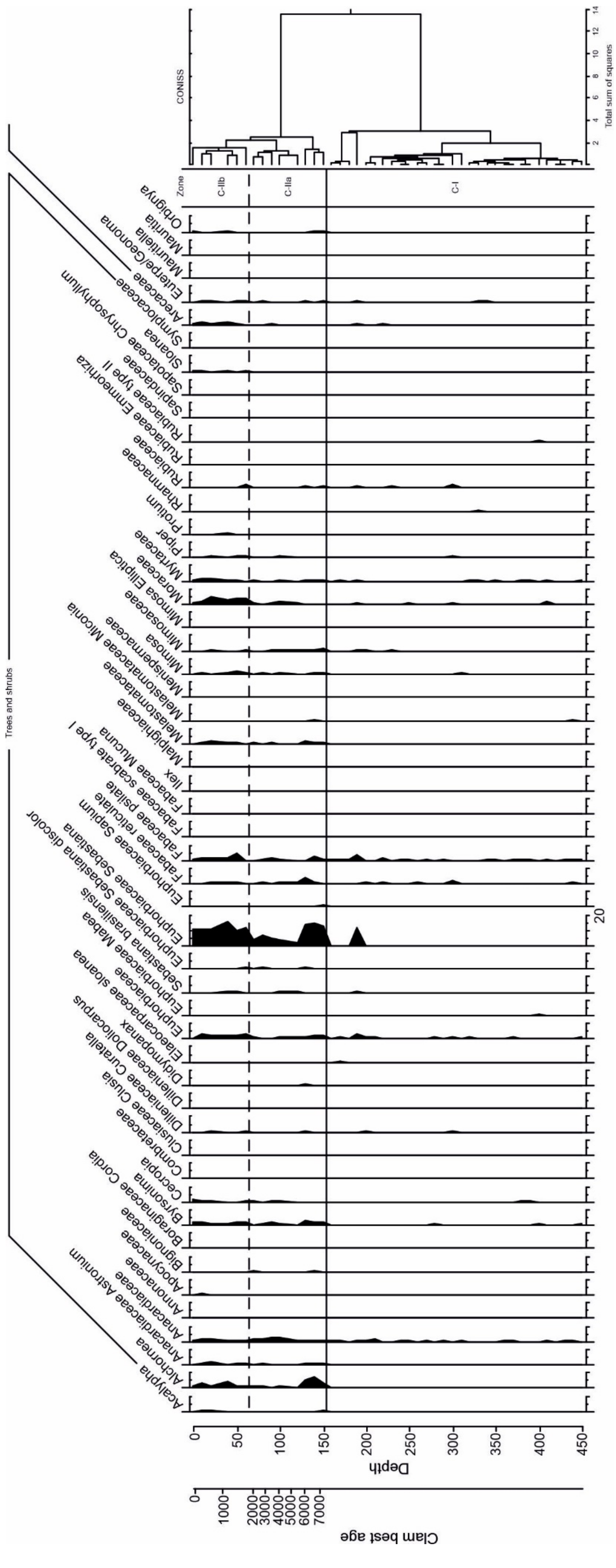




Mangrove
Herbs
Ferns
Algae
Rhizophora
Acanthaceae
Alternanthera
Amaranthaceae Amaranthus
Apiaceae
Asteraceae
Begoniaceae
Borreria
Cabomba
Convolvulaceae
Cyperaceae
Iridaceae
Lamiaceae
Loranthaceae
Malvaceae
Nymphoides
Onagraceae Ludwigia
Poaceae
Polygalaceae
Polygonum
Spermacoceae
Typha
Zornia
Acrostichum
Monolete psilate
Monolete reticulate
Monolete verrucate
Trilete scabrate
Trilete psilate
Trilete verrucate
Trilete reticulate
Pityrogramma calomelanos
Pteris type
Salviniaceae
Osmunda
Botryococcus
Pediastrum
Zone
LF-IIIc
LF-IIIb
LF-IIIa
LF-II
LF-I
CONISS
Total sum of squares
Depth
Clam best age

Cabeludo


CONISS
Total sum of squares
Zone
C-IIb
C-IIa
C-I
Algae
NPPs
Ferns
Herbs
Mangroves
Indeterminate
Unknown
Pediastrum
Botryococcus
Anabaena sp.
Osmunda
Pteris
Acrostichum
Typha
Poaceae
Cyperaceae
Asteraceae
Avicennia
Rhizophora
Depth
Clam best age


CONISS
Total sum of squares
Zone
C-IIb
C-IIa
C-I
Trees and shrubs
Depth
Clam best age

Curriculum Vitae

Personal Information

Full name	Caio Alves de Moraes
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Formal Education

2018 - 2022 **PhD in Mathematics and Natural Sciences** – Biological Diversity and Ecology

Georg-August-Universität Göttingen, Germany

Supervisor: Prof. Dr. Hermann Behling

With a scholarship from the CNPq foundation

PhD Thesis: *Impacts of Climate and Sea Level changes on Mangroves and Atlantic Forest of Northeastern Brazil during the Late Quaternary*

2014 - 2016 **Master's degree in Science** – Geology and Geochemistry

Universidade Federal do Pará, UFPA, Belém, Brazil

Supervisor: Prof. Dr. Marcelo Cancela Lisboa Cohen

With a scholarship from the Brazilian National Council for Scientific and Technological Development – CNPq

2008 - 2013 **Graduation – Bachelor's degree in Geology**.

Universidade Federal do Pará, UFPA, Belém, Brazil, with Exchange program in the Martin-Luther-Universität Halle-Wittenberg (Supervisors: Prof. Dr. Herbert Pöllmann and Prof. Dr. Marcondes Lima da Costa)

Supervisor: Prof. Dr. Afonso César Rodrigues Nogueira

Experience

Sept. 2010 – Jul. 2011 - Undergraduate research projects. Paleoenvironment of Permian deposits with fossilized wood of Pedra de Fogo Formation, Parnaíba Basin, region of Filadélfia-TO, Brazil. Scholarship holder of Brazilian National Council for Scientific and Technological Development – CNPq

Mar. 2011 – Jun 2011 – Teacher's Assistant of the course Sedimentology

Mar. 2012 – Jan 2013 - Exchange program during bachelor (2 semesters) in the Martin-Luther-Universität Halle-Wittenberg, Germany.

Mar. 2013 – Jun 2013 – Teacher's Assistant of the course Depositional Systems

Feb. 2018 – May. 2018 - Teaching assistant / Senior Intern – **German University of Technology in Oman – GUtech** – Department of Applied Geosciences

Languages

Portuguese	Native speaker
English	Fluent
German	Good communication and reading skills (B2 level)
Spanish	Good communication and reading skills

Software

Tilia – managing and graphing paleontological data

QGis – GIS mapping

C2 - managing and graphing paleontological data

CorelDRAW

Office Suite, incl. Word, Excel and PowerPoint

Canoco – multivariate statistical analysis

Software R

CharAnalysis - sediment-charcoal records analysis

List of Publications

Research Papers

ALVES DE MORAES, CAIO; LIMA DA COSTA, MARCONDES; GUIDA NAVARRO, ALEXANDRE; NUNES DA SILVA MENESES, MARIA ECILENE; BOIADEIRO AYRES NEGRÃO, LEONARDO; PÖLLMANN, HERBERT; BEHLING, HERMANN. Holocene coastal environmental changes inferred by multi-proxy analysis from Lago Formoso sediments in Maranhão State, northeastern Brazil. QUATERNARY SCIENCE REVIEWS, v. 273, p. 107234, 2021.

DE MORAES, CAIO ALVES; DE OLIVEIRA, MARCELO A.T.; BEHLING, HERMANN. Late Holocene climate dynamics and human impact inferred from vegetation and fire history of the Caatinga, in Northeast Brazil. REVIEW OF PALAEOBOTANY AND PALYNOLOGY, v. 282, p. 104299, 2020.

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FONTES, N. A.; **MORAES, C. A.**; COHEN, M. C. L.; ALVES, I. C. C.; PESSENDA, L. C. R.; FRANCISQUINI, M. I.; FRANCA, M. C.; BENDASSOLLI, J. A.; MACARIO, K.; MAYLE, F. The Impacts of the Middle Holocene High Sea-Level Stand and Climatic Changes on Mangroves of the Jucuruçu River, Southern Bahia - Northeastern Brazil. Radiocarbon, v. 1, p. 1-16, 2017.

MORAES, CAIO A.; FONTES, NEUZA A.; COHEN, MARCELO C.L.; FRANÇA, MARLON CARLOS; PESSENDA, LUIZ C.R.; ROSSETTI, DILCE F.; FRANCISQUINI, MARIAH I.; BENDASSOLLI, JOS? A.; MACARIO, KITA. Late Holocene mangrove dynamics dominated by autogenic processes. EARTH SURFACE PROCESSES AND LANDFORMS, v. 2017, p. 1, 2017.

MORAES, CAIO ALVES; DA COSTA, MARCONDES LIMA; NAVARRO, ALEXANDRE GUIDA; NEGRÃO, LEONARDO BOIADEIRO AYRES; DA SILVA VALENTE, GLAYCE JHOLY SOUZA; PÖLLMANN, HERBERT; BEHLING, HERMANN . Holocene vegetation, climate, sea-level oscillation, and human impact inferred from the archaeological site Cabeludo in Maranhão State, NE Brazil. PALAEOGEOGRAPHY PALAEOCLIMATOLOGY PALAEOECOLOGY, v. 608, p. 111292, 2022

Conference Abstracts

MORAES, C. A.; M. ACCIOLY TEIXEIRA DE OLIVEIRA; H. BEHLING. Impacts of climate and humans on vegetation in northeastern Brazil during the late Holocene. In: 25th Latin-American Colloquium of Geosciences, 2019, Hamburg. 25th Latin-American Colloquium of Geosciences, 2019.

LORENTE, F. L.; PESSENDA, LUIZ C.R.; FONTES, NEUZA A.; FRANCISQUINI, M. I.; COHEN, MARCELO C. L.; BENDASSOLLI, J. A.; ALVES, I. C. C.; **ALVES, C.**; MAYLE, F.; PICCOLO, M. Fluvial valley evolution in the southern coast of Bahia during the Holocene based on palynofacies and stable isotopes. In: XIV International Palynological Congress, 2016, Salvador. XIV International Palynological Congress, 2016., 2016. v. 14.

MORAES, CAIO A.; COHEN, M. C. L.; FRANCA, M. C. Efeitos dos processos autocíclicos na dinâmica dos manguezais no rio Jucuruçu, litoral sul da Bahia, durante os últimos 1000 anos. In: 48º Congresso Brasileiro de Geologia, 2016, Porto Alegre. Anais do 48º Congresso Brasileiro de Geologia. Porto Alegre: Sociedade Brasileira de Geologia, 2016. v. 48. p. 8283.

MORAES, CAIO A.; NOGUEIRA, A. C. R. Paleoambiente de depósitos permianos com madeira fossilizada da Formação Pedra de Fogo, Bacia do Parnaíba, região de Filadélfia. In: Seminário de Iniciação Científica da UFPA, 2011, Belém. XXII Seminário de Iniciação Científica da UFPA. Belém: Universidade Federal do Pará, 2011. v. 22. p. 1