



New paleoenvironmental and palynostratigraphic data from Solimões Formation (Solimões Basin, Amazonas, Brazil)

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ABSTRACT

The Western Amazon was affected by tectonic events of great impacts, such as the uplift of the Andes during the Neogene. Such events promoted significant changes in the fluvial drainage system, in the climate, as well as in the ecosystems, triggering great irradiation of the Amazonian biota. Marine evidence recorded in the region also influenced the radiation of the biota. Despite advances in the paleoenvironmental and age models proposed for the Western Amazon deposits, we still observe conflicting results and interpretations on these aspects. Thus, here we analyzed the palynological content of three cores aimed to contribute with new paleoenvironmental and biostratigraphic data of the Solimões Formation. We presented new paleobotanical data from the 1AS-5-AM, 1AS-7D-AM, and 1AS-8-AM cores and correlated the biostratigraphic data already published with the data obtained here; were recognized five palynozones (*Verrutricolporites*, *Psiladiporites*, *Crassoretitrites*, *Grimsdalea*, and *Asteraceae*), reaching a range from the early to the late Miocene. The vegetation throughout the sequences studied includes elements of dryland forest next to zones of wetlands vegetation, including flooded forests and swamps; the floristic composition changed over time, predominating flooding vegetation during the early and part of the middle Miocene.

1. Introduction

The Neogene was a period of great importance for the paleoenvironmental evolution from the Amazon region, due to the tectonic events of great impact such as the Andes uplift. This dynamic event, from the end of the Mesozoic to Pliocene, caused climatic changes affecting the ecosystems, leading to the great biota irradiation (Hoorn et al., 2010; Lovejoy et al., 2010; Albert et al., 2011, 2018).

During the early Miocene, the hydrography in the western Amazon was distinct from today with the main drainage flowing in an east-west direction (Caputo and Soares, 2016). With the gradual increase in tectonic activity resulting in the Andean orogeny, large lakes and swamps were formed in the western Amazon, resulting in a complex ecosystem called the Pebas System, which led to the emergence of fauna and flora represented by several endemic species (Wesselingh et al., 2006; Wesselingh and Ramos, 2010). During this period, marine influence peaks are recorded in the region evidenced by microfossils such as microforaminiferal linings, mangrove pollen and dinoflagellates cysts (Hoorn et al., 2010; Linhares et al., 2011; Jaramillo et al., 2017; Leandro et al.,

2022).

Western Amazon stands out for the great diversity of its paleoflora since the beginning of the last century, when pioneering palynological studies contributed to the first biostratigraphic and paleoenvironmental models to the Neogene of Colombia and Brazil (Van de Hammen, 1954, 1956, 1957; Germeraad et al., 1968; Regali et al., 1974a,b; Hoorn, 1993, 1994a). Recent studies have reinforced this great palynological diversity, improving the paleoenvironmental interpretations and expanding the biostratigraphic framework through the study of outcrops and cores of different localities of the Solimões Formation (Silva-Caminha et al., 2010; Kachniasz and Silva-Caminha, 2016; Silveira and Souza, 2015, 2016, 2017; Leite et al., 2017, 2021; Jaramillo et al., 2017; Linhares et al., 2019; Gomes et al., 2021; Kern et al., 2020).

Despite advances in the paleoenvironmental and biostratigraphic knowledge of the Western Amazon deposits, still are observed conflicting results and interpretations on these aspects during the Neogene. Some studies still rule out the marine influence or even propose a different origin for the presence of marine/brackish microfossils in the region (Nogueira et al., 2013; Gross and Piller, 2020), while other

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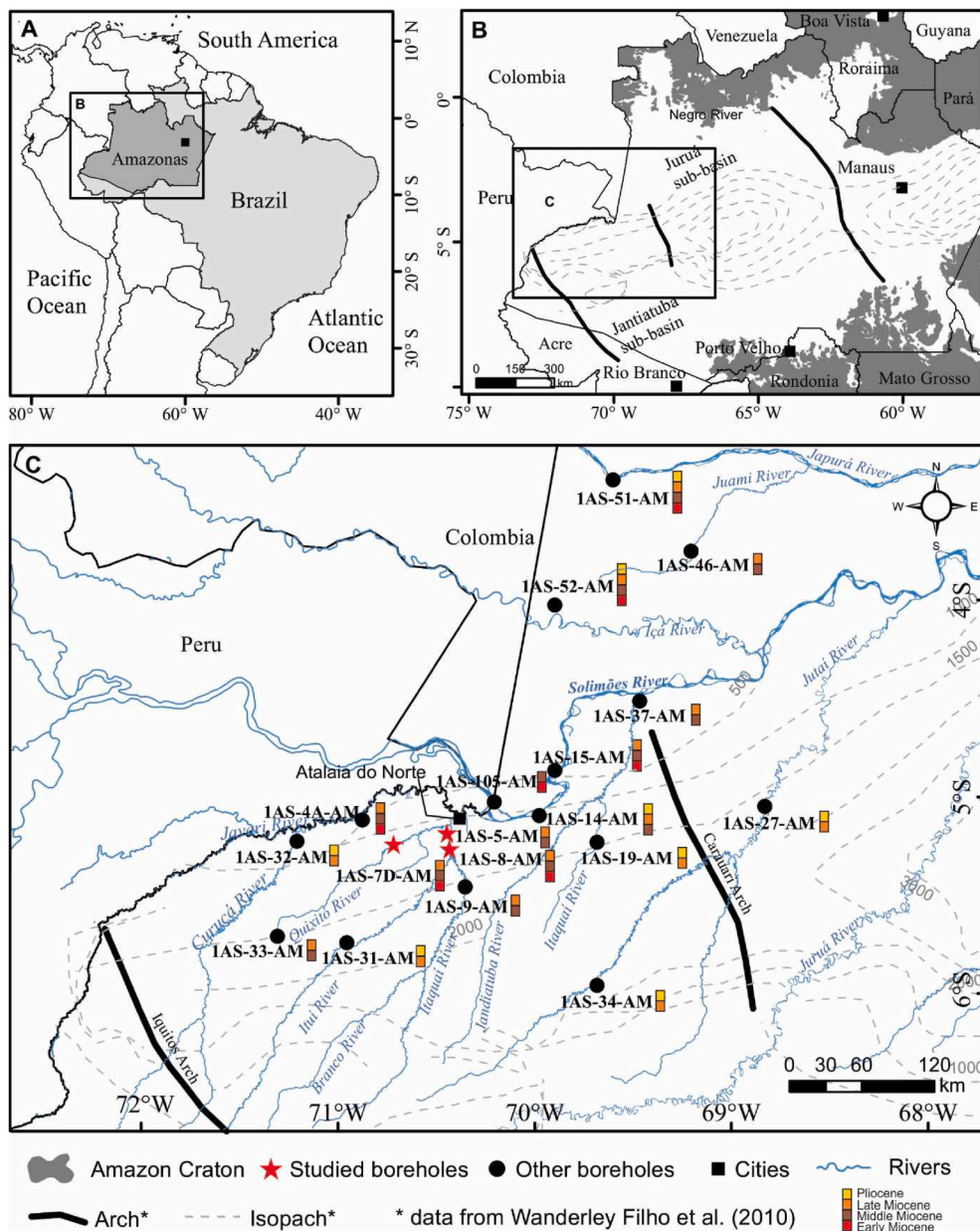


Fig. 1. Location of the study area. **A.** South America countries, contrasting Brazil and the Amazonas State. **B.** Study area, indicating the cores analyzed. **C.** Study area, the position and the age of the studied cores here and other cores from the previous palynological studies (Hoorn, 1993; Silva-Caminha et al., 2010; Latrubesse et al., 2010; Linhares et al., 2019; Kachniasz and Silva-Caminha, 2016; Jaramillo et al., 2017; Sá et al., 2020; Kern et al., 2020; Leite et al., 2021; Gomes et al., 2021; Espinosa et al., 2021; Leandro et al., 2022).

studies have pointed the marine influence in these deposits during the early Miocene and middle Miocene (Boonstra et al., 2015; Jaramillo et al., 2017), and more recently to the late Miocene (Antoine et al., 2016; Linhares et al., 2017, 2019; Espinosa et al., 2021; Leandro et al., 2022).

Bernal et al. (2019), analyzing phylogeny data from current plants, also reports possible conditions of marine incursions in the region, indicating that some coastal and/or estuarine species, found today in Amazon forest, like fern *Acrostichum danaeifolium* (Pteridaceae), the tree *Cespedesia spathulate* (Ochnaceae), the shrub *Chrysobalanus icaco* (Chrysobalanaceae), the climber *Guilandina bonduc* (Fabaceae), the palm *Manicaria saccifera* (Arecaceae), and the creeping herb *Sphagnetica trilobata* (Asteraceae), may have their dispersion affected by fluctuating conditions, which can be associated with marine incursions events during the Miocene in western Amazon.

Recently, Gomes et al. (2021) developed a comparative study using cores sedimentary samples from the Miocene and Holocene for the Solimões Basin, not identifying significant differences in the diversity of the palynoflora between them; however, pointed to a great difference in the composition, founding Miocene less heterogeneous in pollen

composition than the Holocene samples.

Due to the large extension of Neogene deposits in the Solimões Basin, data about the chronostratigraphic limits and paleoenvironmental reconstruction still require greater attention and deepening. Thus, the present study aims to contribute with new biostratigraphic data from core 1AS-5-AM, in addition to integrating paleoenvironmental data between cores 1AS-5-AM, 1AS-7D-AM, and 1AS-8-AM, complementing the studies realized by Linhares et al. (2017, 2019).

2. Study area

The study area is located in the Solimões Basin, northeastern of the Amazonas state (Fig. 1), where several cores were drilled by the Geological Service of Brazil (CPRM) as part of the “Coal in the Solimões Rise” project (Maia et al., 1977); among these, three cores studied here: 1AS-5-AM (lat. 04° 29’S – long. 70° 17’W), 1AS-7D-AM (lat. 04° 34’S – long. 70° 41’W), and 1AS-8-AM (lat. 04° 36’S – long. 70° 16’W), on the banks of the Quixito and Ituí River, Atalaia do Norte town.

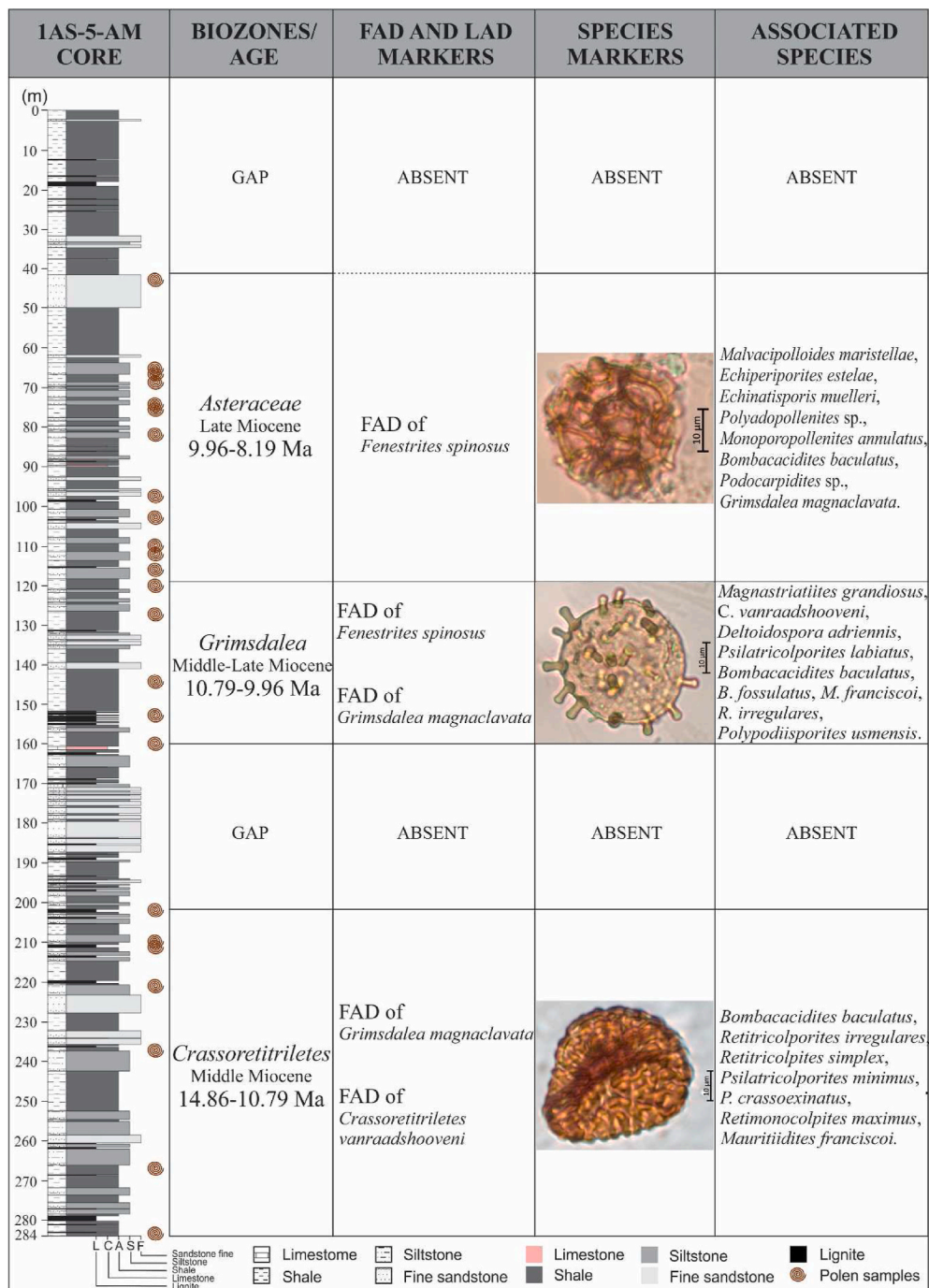


Fig. 2. Palynological zones established in the 1AS-5-AM core: *Crassoretitritiles*, (middle Miocene), *Grimsdalea magnaclavata* (middle-late Miocene), and *Asteraceae* (late Miocene).

2.1. Geological setting

The studied area is located at the northern limit of the Solimões basin. This basin, located in the Amazon craton and geographically located in the State of Amazonas, has an area of approximately 450.000 km² (e.g. Wanderley Filho et al., 2010), covered by the Amazon rainforest. The substrate on which it was implanted consists of igneous, metamorphic and sedimentary rocks, the latter from ancient Proterozoic rifts (see Lisboa et al., 2013). The basin is subdivided by the Carauari arc into two sub-basins: Juruá, to the east and Jandiatuba, to the west; the first reaches 3.100 m and the second 3.800 m thick. Its stratigraphic framework is divided into five depositional sequences limited by

regional unconformities, the last being the Neogene Sequence (Javari Group) that corresponds to the fluvio-lacustrine mudstones and sandstones of the Solimões Formation (Wanderley Filho et al., 2007, 2010).

The Solimões Formation extends over approximately 500.000 km² (Maia et al., 1977) in western Brazilian Amazonia, covering the Solimões and Acre basins, separated by the Iquitos Arch (Wanderley Filho et al., 2007). Its lithology consists mainly of red, gray and variegated clays, levels of siltstones, sandstones, limestones and conglomerates, representing higher energy facies, while the low energy facies would be composed of green to grayish-green sediments and planar stratification or massive structure (Caputo et al., 1971; Latrubesse et al., 1997). The unit is characterized by frequent plant remains and intercalations of

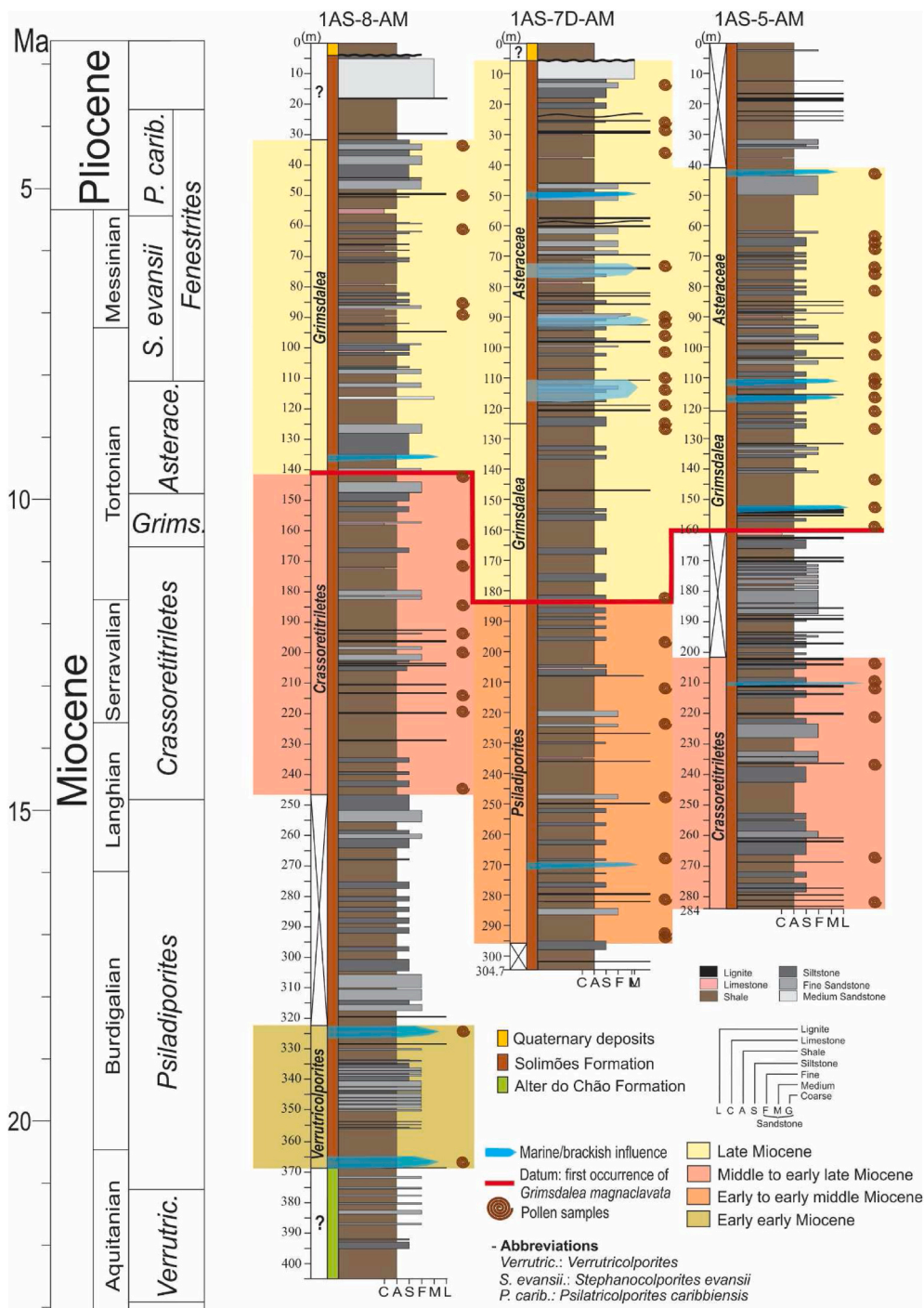


Fig. 3. Stratigraphic correlation between the cores 1AS-5-AM, 1AS-7D-AM, and 1AS-8-AM, with the respective zones, the limits of each palynological zone followed Lorente (1986).

lignite, carbonaceous clays and limestone, in addition presents abundant and well-preserved fossiliferous content, indicating a reducing and low energy environment, evidenced by abundant carbonaceous levels and fine sediments (e.g. Hoorn, 1993).

3. Palynological contributions to the Western Amazon

3.1. Paleoenvironments

Palynomorphs are widely used to determine paleoenvironments, ages, and correlation between sedimentary basins, being a useful tool for

elucidating geological issues (Silveira and Souza, 2017). The first palynological studies in the Neogene deposits from South America began in the late 1960s (Germeaad et al., 1968; Regali, 1971a,b; Lorente, 1986; Müller et al., 1987), recording a diverse assemblage of pollen and spores contributing to biostratigraphic resolutions and paleoenvironmental reconstructions.

The paleoenvironments evolution in the Western Amazon has been interpreted mainly based on paleontological studies, including palynology, ostracods, benthic and planktonic foraminifera, mollusks, barnacles, dinoflagellates, and marine ichnofossils (Hoorn, 1993, 1994a,b; Gingras et al., 2002; Vonhof et al., 2003; Hoorn et al., 2010; Boonstra

et al., 2015; Antoine et al., 2016; Jaramillo et al., 2017; Linhares et al., 2011, 2017; Kern et al., 2020; Sá et al., 2020; Leite et al., 2021; Espinosa et al., 2021). These studies point to significant environmental and geographical changes in Amazonia mainly influenced by Andean uplift (Hoorn et al., 2010), providing the formation of a very dynamic depositional system. From these records, the environment was interpreted as megawetlands with sporadic marine incursions during the Miocene (Hoorn et al., 2010; Linhares et al., 2011; Espinosa et al., 2021).

3.2. Age

The age range for the Western Amazon Neogene, both in Brazil, Peru, and Colombia, have been the subject of several discussions since it is difficult to establish the chronostratigraphic limits using only surface samples, due to its generally reaching only the uppermost intervals or layers of the Solimões Formation (less than 100 m thick). An alternative that has been widely used to solve this problem is the use of cores samples, which cover a more complete range giving more precise results (e.g., Hoorn, 1993; Leandro et al., 2022).

Despite the advance in biostratigraphic studies of the Solimões Formation, there is no consensus between the age range of the different localities and the correlation is not clear, needing greater integration between the biostratigraphic frameworks. Another question is the use of different palynostratigraphic frameworks utilized to compose the biostratigraphic models of the Amazon in Brazil as from Venezuela (Lorente, 1986) and Colombia (Jaramillo et al., 2011).

In Brazil, the age of the Solimões Formation was established through paleontological studies, mainly through palynological data (e.g. Regali et al., 1974a,b). One of the first palynological studies with the use of cores was developed by Hoorn (1993), with the 1AS-4a-AM core, located Atalaia do Norte town, in which the author, based on the proposal of Lorente (1986), established five palynological zones dated from the early Miocene to the earlier late Miocene: *Verrutricolporites*, *Retitricolporites*, *Psiladiporites-Crototricolporites*, *Crassoretitrites*, and *Grimsdalea* zone. This age interval was later reinforced by studies with mollusks and ostracods (Wesselingh et al., 2006; Muñoz-Torres et al., 2006).

Further proposals using palynological data indicate late Miocene to Pliocene to the 1AS-32-AM, 1AS-33-AM, and 1AS-34-AM cores (Atalaia do Norte town, Amazonas State), expanding the stratigraphic range to Solimões Formation (Silva-Caminha et al., 2010; Silveira and Souza, 2015; Kachniasz and Silva-Caminha, 2016; Leite et al., 2017). Later, Leandro et al. (2018) proposed early Miocene to Pleistocene to the stratigraphic range of Solimões Formation using two cores (1AS-51-AM and 1AS-52-AM). More recently, the reevaluation of the 1AS-33-AM core and the analysis of the 1AS-37-AM core demonstrate an age between middle Miocene to late Miocene (Leite et al., 2021). Espinosa et al. (2021) analyzed the core 1AS-9-AM and compared it with two nearby cores (1AS-105 and 1AS-33 a.m.), recording an age from middle to late Miocene which agrees with Leite et al. (2021). Although these data range on the local age, they pointed to a regional stratigraphical extension from early Miocene to Pliocene to the Solimões Formation. The different stratigraphic ranges proposed to the cores in the Solimões Basin could be related to geographic position of these and to the topographical irregularity in the basin, but it is not clear yet.

4. Materials and methods

A total of 86 sedimentary samples from the three cores were processed: 1AS-5-AM, 284m total depth; 1AS-7D-AM, 304.70 m; and 1AS-8-AM, 405 m. To the palynomorphs extraction we followed the procedure of Uesugui (1979) in which 30 g of dry sediment were submitted first to hydrochloric acid (32%) for 2 h and then to hydrofluoric acid (40%) for 12 h; the samples was washed with distilled water and sieved in 10 µm, followed by extraction of light residue which was spread on palynological thin sections for study; three slides of each sample were scanned and the specimens photographed under an optical microscope at 100×

magnification.

For the establishment of palynological zones, 25 samples were examined through triplicated slides from core 1AS-5-AM; for the paleoenvironmental interpretations we used the 86 samples from the cores 1AS-5-AM, 1AS-7D-AM, and 1AS-8-AM, being surveyed botanical affinity of pollen grains and spores to provide information for data interpretation; pollen diagrams were constructed with the Tilia 2.0.41 program. Taxonomic identification was based on Van der Hammen (1954), van der Hammen and Wymstra (1964), Germeraad et al. (1968), Lorente (1986), Müller et al. (1987), Hoorn (1993), Jaramillo and Dilcher (2001), Silva-Caminha et al. (2010), Jaramillo et al. (2017), and D'Apolito et al. (2021).

Palynostratigraphic analysis was based mainly on the zonation presented by Hoorn (1993) for the Neogene of Amazonia and on the South American biostratigraphical framework of Lorente (1986). The definition of biozones was based on the North American Stratigraphic Code (2005), and the limits of each palynological zone followed Lorente (1986), which mainly considers the first appearance Datum (FAD) and Last Appearance Datum (LAD). Was used here the first occurrence of *Grimsdalea magnaclavata* as datum to correlate the studied cores (Fig. 3). The ages of the zones were calibrated according to the geological time scale of Gradstein et al. (2012).

4.1. Statistical analysis (non-metric multidimensional scaling and cluster analysis)

All statistical analyses were carried out on language R (version 4.1.2; R Core Team, 2021). The functions 'metaMDS,' 'adonis,' and 'decostand' in the package 'vegan' (Oksanen et al., 2020), and 'ggplot' in the package 'ggplot2' (Wickham et al., 2021), were used to perform NMDS, and 'hclust' in package 'cluster' (Maechler et al., 2021) to perform Cluster analyses. For a zonation of the phases, we used cluster analysis through the ward.D2 and euclidean distance methods, an agglomerative hierarchical clustering method. Furthermore, to compare the vegetation between all core and show the Bray-Curtis similarity we use non-metric multidimensional scaling; the nMDS analysis was performed using data transformed through the 'Hellinger transformation', suitable for abundance data (Kruskal, 1964). Some samples were removed to avoid possible error which statistical analysis because of unknown ecological data. NMDS has been used for the appropriate ordination method in ecology (Minchin, 1987) and has been applied to palynological data in previous studies (Lenz and Wilde, 2018; Moshayedi et al., 2020; Gomes et al., 2021).

5. Results and discussions

5.1. Biozonation

A total of 4656 specimens of pollen, spores, microforaminiferal linings, diatom, and dinoflagellates cysts were recognized (Table 1–3, supplementary material), with 4617 pollen and spore grains identified. Based on the occurrence of grains of pollen and spore, we recognized three palynozones in the 1AS-5-AM core (Fig. 2), based on the definitions of Lorente (1986) and their markers for the Neogene of South America: *Crassoretitrites* interval zone (284–202.2 m), Langhian–Serravallian; the base of this zone is marked by the first appearance (FAD) of the species *Crassoretitrites vanraadshooveni*, while the top of the zone is marked by the first of *Grimsdalea magnaclavata*. *Grimsdalea* interval zone (160–120.7 m), Serravallian–Tortonian; the base of this zone is marked by the first appearance (FAD) of the species of *Grimsdalea magnaclavata* and the top is marked by the first appearance (FAD) of the species *Fenestrites spinosus*. *Asteraceae* zone interval zone (120.7–41 m), Tortonian; the base of this zone is marked by the first appearance (FAD) of the species of *Fenestrites spinosus*, while the top of the zone is undefined due to the absence of marker species.

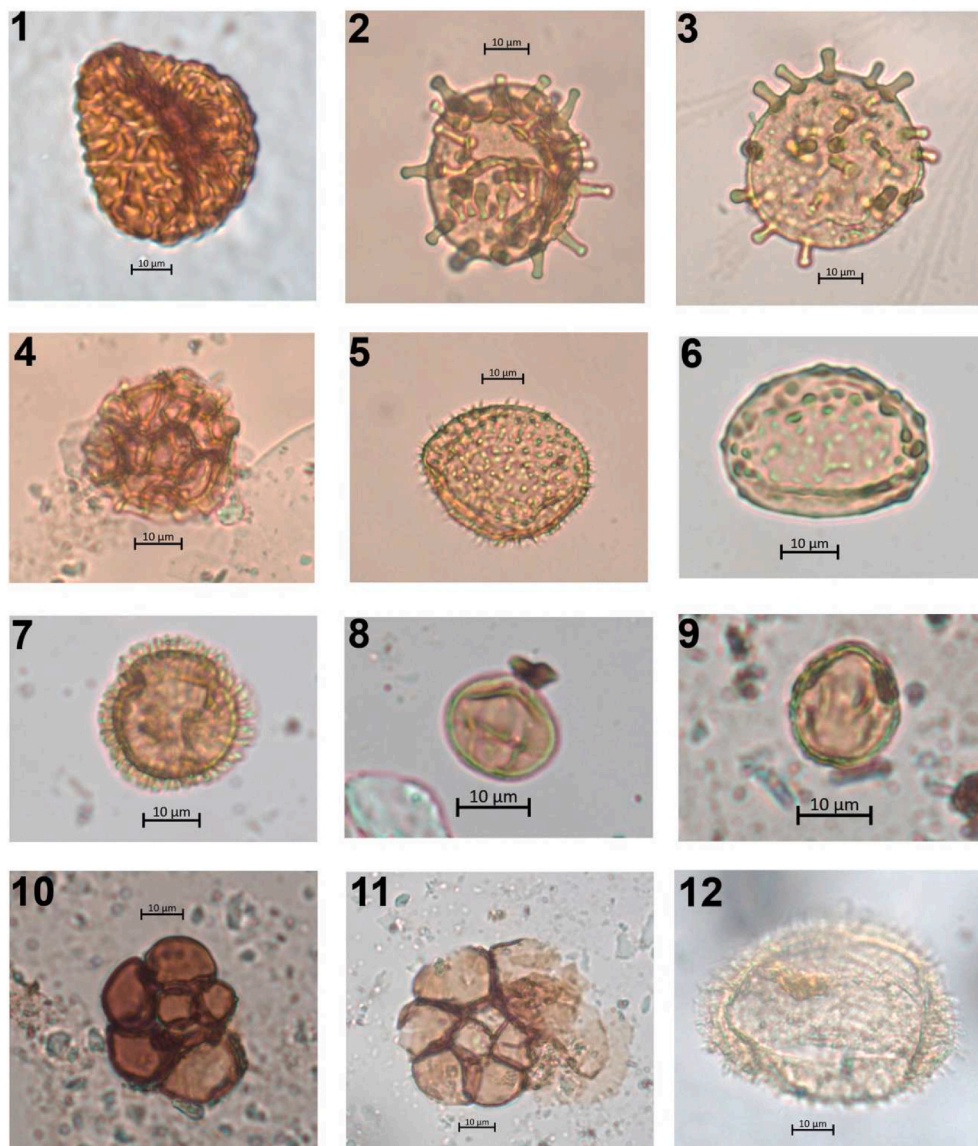


Fig. 4. Selected species from 1AS-5-AM core, Solimões Basin, Amazonas, Brazil – Time markers (Lorente, 1986): 1- *Crassoretitriletes vanraadshooveni*; 2,3- *Grimsdalea magnaclavata*; 4- *Fenestrites spinosus*. High abundance: 5- *Mauritiidites franciscoi*; 6- *Polypodiisporites usmensis*; 7- *Retitrescolpites irregularis*. Marine elements: 8,9- *Zonocostites ramonae*; 10,11- Microforaminiferal linings; 12- Dinoflagellate cysts.

5.2. Data integration and age correlation between cores

To the chronostratigraphic correlation between the three studied cores (Fig. 3), we used the results obtained by Linhares et al. (2019) to the AS-7D-AM and 1AS-8-AM cores. The results obtained were based on the integration between palynology and ostracods data allowed the recognize three palynozones to the 1AS-8-AM: *Verrutricolporites* (early Miocene), *Crassoretitriletes* (middle Miocene), and *Grimsdalea* (late middle to early late Miocene); while in the 1AS-7D-AM were recognized the palynozones: *Psiladiporites* (late early to middle Miocene), *Grimsdalea* (late middle to early late Miocene), and *Asteraceae* (late Miocene); besides were recognized five zones of ostracods: *Cyprideis sulcosigmoidalis*, corresponding to *Psiladiporites* zone, *Cyprideis caraionae*, corresponding to part of the *Grimsdalea* zone, *Cyprideis minipunctata*, corresponding to *Grimsdalea* zone, *Cyprideis cyrtoma*, corresponding to part of the *Grimsdalea* and *Asteraceae* zones, and *Cyprideis paralela*, corresponding to part of the *Asteraceae* zone.

The integrated study of the three cores allowed to date the Solimões Formation (Atalaia do Norte town, Amazonas State) from early to late Miocene. We used here the first occurrence of *Grimsdalea magnaclavata*

as a datum to correlate the cores. The 1AS-8-AM has the oldest age range, from Aquitanian (~23 Ma) to early Tortonian (~10.8 Ma). The 1AS-7D-AM reaches a slightly wider range than the other cores from late Aquitanian (~21.1 Ma) to part of the Tortonian (~8.1 Ma), while the 1AS-5-M presents the youngest range, from part of the Langhian (14.8 Ma) to part of the Tortonian (~8.1 Ma).

5.3. Paleoenvironmental context

Data obtained from three studied cores allowed confirming the abundance and diversity of the palynomorphs from the Solimões Formation (e.g., Fig. 4). From the paleovegetation data found in the study area (Fig. 5; Supplementary Material: Tables 1–3 and Figs. 1–3) we initially carried out an approach to paleoenvironmental evolution individually in each studied core, and subsequently an integrated analysis, thus making it possible to observe the similarities and discrepancies between the palynological content from the three cores (Fig. 6), and its different phases (Fig. 7).

In the 1AS-5-AM core, the first phase occurs between 284 m and 202 m (*Crassoretitriletes* zone; Figs. 2 and 3), in which a little more than

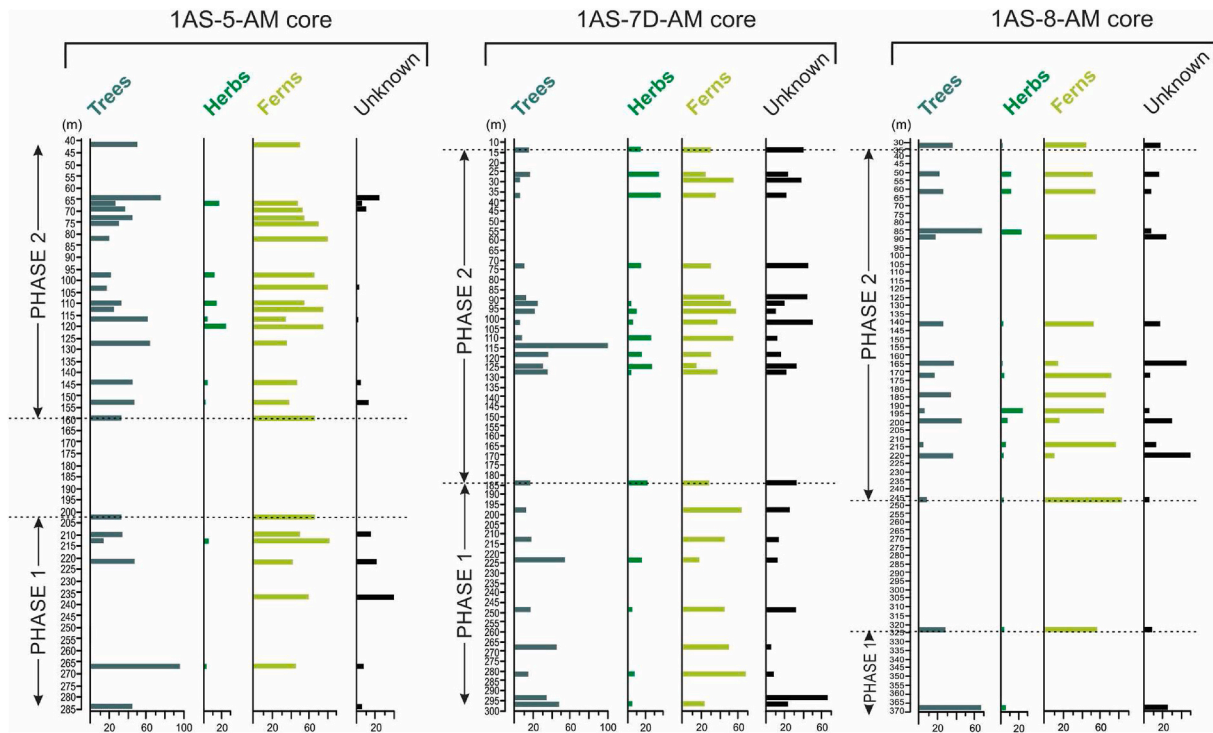


Fig. 5. Diagram of percentage for life forms from studied cores: trees (forest green); herbs (green); ferns (yellowish-green); unknown (black). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

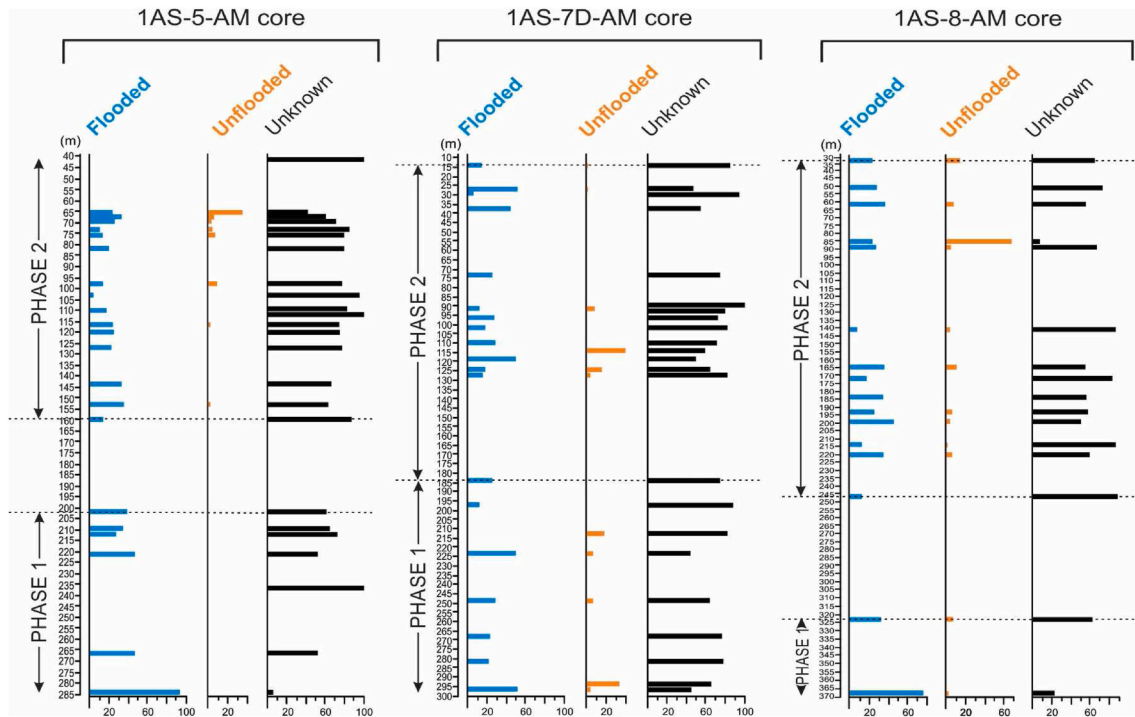


Fig. 6. Diagram of percentage for ecological groups: flooded: swamp, mangrove, etc. (blue); unflooded: dryland forests, montane (orange); unknown (black). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

50.6% is composed of spores and the rest composed of pollen; standing out the abundance of the *Mauritiidites franciscoi* species, which demonstrates its ecological importance, as it is a palm tree belonging to the Arecaceae family, occurring mainly in flooded environments such as floodplains and swamps (Leite et al., 2017, 2021). In smaller values we have occurrences of *Zonocostites ramonae*, belonging to the

Rhizophoraceae family; it is a mangrove pollen environment, although the occurrence of this pollen in low abundance and the absence of the other associated coastal elements may not indicate the presence of a mangrove swamp, as pollen dispersion occurs by air transport and consequently reaches regions farther from the source (Tomlinson, 1986; Nadia and Machado, 2014). At depth 221 m *Retitrescolpites irregularis*

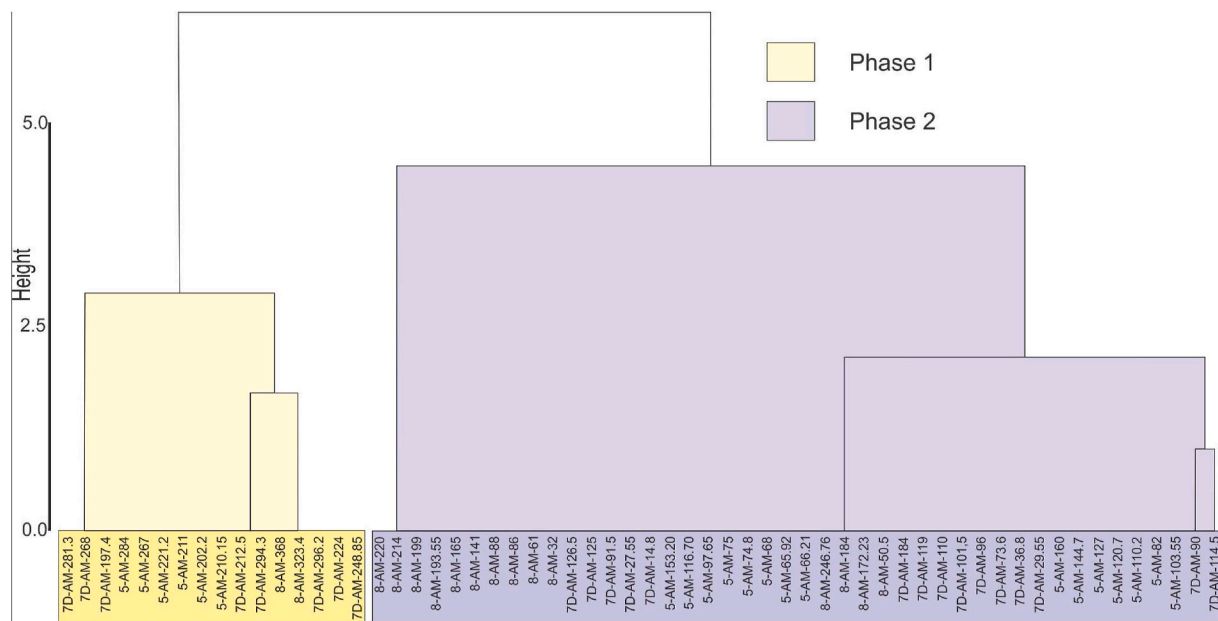


Fig. 7. Zonation of phases of the studied cores through cluster analysis, by ward.D2 and Euclidean distance methods, an agglomerative hierarchical clustering method, showing phases 1 and 2.

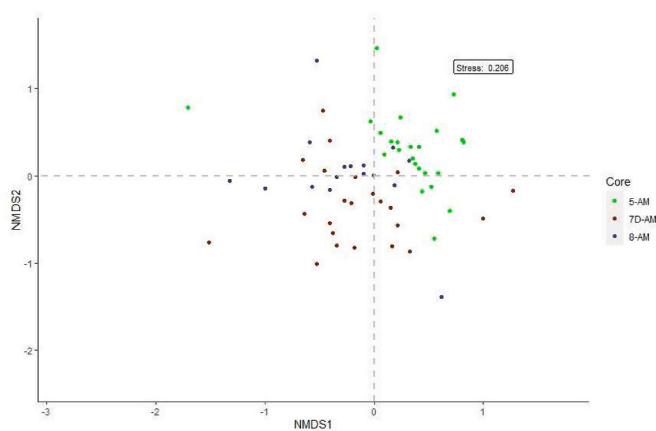


Fig. 8. Non-metric multidimensional scaling (NMDS) of palynological data of studied cores samples from the Solimões Formation. The vegetation was compared between all them; to show the Bray-Curtis similarity we use non-metric multidimensional scaling, the nMDS analysis was performed using data transformed through the 'Hellinger transformation', suitable for abundance data (Kruskal, 1964). The color represents samples from three different cores. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

occurs, which is associated with *Amanoa* (Euphorbiaceae), a genus that grows in floodplain forests along rivers (Lorente, 1986; Leite et al., 2017).

After the first phase, there is a gap of 42 m, making it impossible to recover paleovegetation elements. After this interval, we consider a second phase which occurs between 160 m and 41 m (*Grimsdalea* and *Asteraceae* zones, Figs. 2 and 3), in which 47.6% correspond to spores. This phase is dominated by pollen grains of *Grimsdalea magnaclavata* (54%), which is already extinct and belongs to the Arecaceae family (Pocknall and Jarzen, 2012), and its ecologic affinity is not well defined, however; Jorge et al. (2019) associate the occurrence of this species to shallow lakes, lake margins or swamps environments. Besides, the pollen content includes *Mauritiidites franciscoi*, *Zonocostites ramonae*, and *Retitrescolpites irregularis*. In addition to these, is recorded the species

Psilamonocolpites amazonicus, *Perforicolpites digitatus*, and *Perisyncolporites pokorny* that grow in floodplains, and still are observed some occurrences, such as *Corsiniipollenites collaris*, typical of swamps and lakes (Marchant et al., 2002); as well as *Bombacacidites baculatus*, *Crassoretitrites vanraadschooveni*, and *Deltoidospora adriennisi* occurring in flooded environments such as swamps, rivers, and marshes (Sá and Carvalho, 2017). Despite the partial similarity of pollen content between it and the previous phase, the first occurrence of *G. magnaclavata* (datum) on the base of this phase, besides its abundance throughout the phase, points to a consistent difference of the palynological association, besides indicates another age interval (late Miocene). The brief and punctual occurrence of marine elements in the two phases described above is also registered, with microforaminiferal linings, dinoflagellate cysts, and mangrove pollen (*Zonocostites ramonae*). After this phase there is a gap of 41 m towards the top of the section. The paleovegetation in the 1AS-5-AM core indicates a transition from floodplain environments and swamps (phase 1) to an environmental context composed of representatives from different environments, such as lakes, rivers, swamps, and marshes (phase 2).

In the 1AS-7D-AM core, the first phase occurs from 296.2 m to 184 m, (*Psiladiporites* zone; Fig. 3), 49.2% being spores. Regarding the pollen grains with the highest occurrence, we have a predominance of species with arboreal affinity such as *Crototricolpites annemariae*, *Retitricolporites guianensis*, *Psilamonocolpites nanus*, *Psilamonocolpites amazonicus*, *Foveotricolpites simplex*, *Perisyncolporites pokorny*, *Retistephanopites crassianulatus*, *Verrutricolporites rotundiporus*, *Polyadipollenites mariae*, and *Malvacipoloides maristellae*, besides we observed *Heterocolpites incomptus* as representatives of dryland environments. Still occurs *Mauritiidites franciscoi*, which appears throughout the interval as a typical example of a floodplain environment (Marchant et al., 2002; Leite et al., 2017, 2021; Jorge et al., 2019; Espinosa et al., 2021); and punctually at depth 268m, occurs the mangrove pollen *Zonocostites ramonae* (Hoorn, 1994a, 1994b). Other important highlights in this interval are the herbaceous representatives, which occur in lower abundance: *Corsiniipollenites oculunocit*, *Monoporites annuloides*, *Monoporipollenites annulatus*, and *Perforicolpites digitatus* (Leite et al., 2017, 2021).

The second phase spans from 184 m to 14 m of depth (*Grimsdalea* and *Asteraceae* zones; Fig. 3), with 38.6% of spores. With greater representation, we have *Monoporites annuloides* and *Monoporipollenites annulatus* as herbaceous representatives of the Poaceae family (Leite

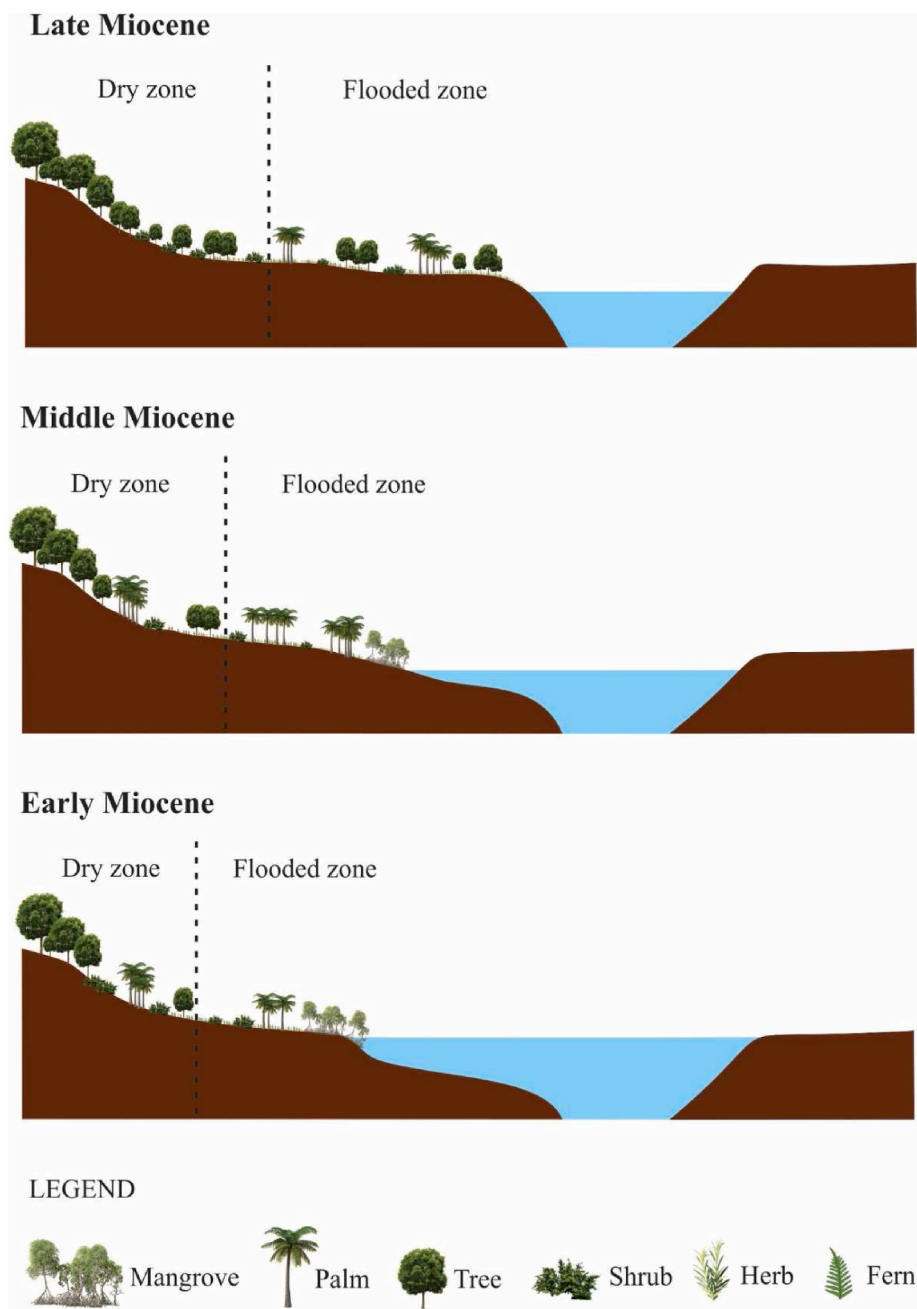


Fig. 9. Schematic model of paleovegetation distribution throughout the Miocene in the study area.

et al., 2021); in smaller amounts of representatives of herbs, *Perforicolpites digitatus*, *Corsinipollenites oculusnoctis*, *Echitricolporites "microechinatus"*, *Echitricolporites spinosus*, *Fenestrites* sp., and *Cichoreacidites longispinosus*. As arboreal representatives, we have *Retitricolporites guianensis* and *Grimsdalea magnaclavata*, being the last species the most abundant arboreal species and having its occurrence throughout the entire second phase collaborating with previous works (Leite et al., 2017, 2021; Jorge et al., 2019; Espinosa et al., 2021). The lowland environments species are represented by *Psilamonocolpites nanus*, *Psilamonocolpites amazonicus*, *Striatricolpites catatumbus*, *Foveotricolpites simplex*, and *Polyadopollenites macroreticulatus*. Besides, *Mauritiidites franciscoi* is also recorded. According to Jorge et al. (2019) it is a representative species of low-energy environments. The association represented in the 1AS-7D-AM core reflects energy dynamic change, with transition from a little more dynamic environment, with flooded and non-flooded environments species (phase 1) to more flooded

environments of low-energy (phase 2).

In the 1AS-8-AM core, the first phase reaches the range from 368 m to 323 m (*Verrutricolporites* zone; Fig. 3), in which 32.4% is composed of spores. In this association, there is a predominance of arboreal representatives, with emphasis on the representatives of lowland forests, such as *Perisyncolporites pokorny*, *Rhoipites guianensis*, *Psilamonocolpites amazonicus*, *Verrutricolporites rotundiporus*, *Striatopollis catatumbus*, *Polyadopollenites mariae*, *Mauritiidites franciscoi*, and *Psilamonocolpites nanus*. In addition, occur palynomorphs indicative of increased salinity in the region, as *Zonocostites ramonae* and microforaminiferal linings, both present in mangrove. Herbaceous representatives have a lower occurrence compared to the representatives of the aforementioned environments. There is a gap of 76.3 m until the second phase.

The second phase ranges from 246.7 m to 32 m in depth (*Crassoretitrites* and *Grimsdalea* zones; Fig. 3), with 49.34% of spores, with emphasis on *Crassoretitrites vanraadshoovenii*, which has a botanical

affinity with a type of vine fern (*Lygodium*) common in wetlands of West Africa and Indo-Malaysia, but currently absent in South America (Germeraad et al., 1968; Leite et al., 2017, 2021); at this stage, there is a predominance of elements of tree species, *Mauritiidites franciscoi* is the most abundant species and represents an element of the floodplain environment (Marchant et al., 2002; Leite et al., 2017, 2021; Espinosa et al., 2021). Lowland species like *Psilamonocolpites amazonicus*, *Striatopollis catatumbus*, *Polyadopollenites mariae*, *Psiladiporites minimus*, *Psilamonocolpites nanus*, and *Foveotricolpites simplex* also occur. Among the herbaceous representatives, we have *Monoporopollenites annulatus*, *Monoporites annuloides*, and *Echitricolporites "microechinatus"*. Besides, we observed the record of dryland species: *Heterocolpites incomptus*, *Heterocolpites rotundus*, and *Bombacacidites muinaneorum*.

The paleobotanical data demonstrate, in general, that the paleovegetation in all studied cores presents a certain similarity and is typical of the Amazon Forest. We identified that the first phase of the 1AS-7D-AM and 1AS-5-AM cores (from to part of the early to middle Miocene) are more correlated, especially due to the more occurrence of levels with elements typical of flooded forest, although 1AS-7D-AM shows considerable number of unflooded taxa; while that the first phase of 1AS-8-AM (early Miocene) also presents flooding conditions, although to a lesser extent than the other cores. The data were corroborated by NMDS analysis (Fig. 8). The second phase of the three cores (from part of the middle to late Miocene), records the predominance of low energy and more stable environments elements, and a greater abundance of arboreal elements, however with the permanence of flooded area elements.

We observed, along the sequences studied in the three cores, that the distinct phases occur predominantly in a sequence dominated mainly by claystones and siltstone lithology and lignite layers, that are normally related to low-energy environments such as lakes, floodplains, and abandoned channels as pointed out in previous studies of outcrops from the Solimões Formation (e.g. Gross et al., 2011, 2013; Nogueira et al., 2013). Along of the intervals of these phases, observed sporadically the occurrence of fine layers of sandstones and rare presence of limestones (Fig. 3).

6. Final considerations

The palynological data from the western Amazon in the study area provided us with new insights concerning the age and paleobotanical composition of this system. The sedimentary sequence analyzed in the study area points to an age range between the early and late Miocene and an evident variation in vegetation over this period (Fig. 9). Among the most abundant families, stand out Poaceae (grasses), Arecaceae (palms), Euphorbiaceae (tree), Malvaceae (herbaceous plants, trees), and Rhizophoraceae (mangrove plants). Besides, some aquatic grass taxa are also observed (Polygalaceae and Onagraceae). However, most plants belong to arboreal taxa, a rich tree assemblage, that includes seasonally flooded forest taxa and an abundance of ferns (Pteridaceae and Polypodiaceae), strongly indicative of floodplains, swamps, and dryland environment forests, pointing to a constant presence of hot and humid conditions, with some drier periods and salinity rate variations in the region during the Miocene.

The predominant vegetation throughout the sequences studied in the three cores includes elements of dryland forest next to zones of wetlands vegetation, including flooded forests and swamps; the floristic composition changed over time, predominating flooding vegetation during the early and part of the middle Miocene. From part of the middle and late Miocene, the predominant vegetation comprised characteristic elements of dryland forests, but still with flooded areas (Fig. 9). In some samples, between the early to early late Miocene, microforaminiferal linings co-occur together as mangrove pollen (*Zonocostites ramonae*) and/or dinoflagellate cysts. Although, its abundance is low; however, the occurrence of marine palynomorphs and carbonatic microfossils are widely recorded in some intervals from 1AS-7D-AM and 1AS-8-AM cores, dated between the early to middle Miocene (Linhares et al., 2017, 2019; Leandro

et al., 2022). Despite we cannot attest the more estuarine condition to these intervals, there is strong evidence of ecological changes that explain the presence of these elements typical of mangroves and brackish swamps.

CRediT authorship contribution statement

Yuri Souza Friaes: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Maria I. Feijó Ramos:** Writing – review & editing, Investigation, Conceptualization. **Ana Paula Linhares:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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