



Integrated biozonation based on palynology and ostracods from the Neogene of Solimões Basin, Brazil

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ABSTRACT

Biostratigraphic analysis integrating spores-pollen and ostracods from boreholes 1AS-8-AM and 1AS-7D-AM, at Atalaia do Norte, Amazonas state, Brazil, allowed to infer Early to Late Miocene for studied sequences. Five palynological zones previously proposed for the Solimões Formation were identified: *Verrutricolporites* (Early Miocene), *Psiladiopites–Crototricolpites* (late Early to early Middle Miocene), *Crassoretitiletes* (Middle Miocene), *Grimsdalea* (late Middle to Late Miocene), and *Asteraceae* (Late Miocene). At the same time, four ostracods (*Cyprideis*) zones were identified but with limits modified: *C. sulcosigmoidalis* (late Early to early Middle Miocene); *C. caraionae* (late Middle to early Late Miocene); *C. minipunctata* (late Middle to Late Miocene); and *C. cyrtoma* (early Late Miocene). Furthermore, a new ostracod zone, *Cyprideis paralela* interval zone (Late Miocene), is formally proposed. Two main bioevents of *Cyprideis* radiation, related to marine incursions, have been identified: one at late Middle Miocene/early Late Miocene (*Grimsdalea* zone) and another at Late Miocene (*Asteraceae* zone). This study attests the viability and importance of using multiple microfossil for more accurate dating and correlation between basins.

1. Introduction

Studies based on the integration of sedimentological, stratigraphical, and paleontological data, carried out on sites from Peru, Colombia, and Brazil, allowed to infer late Early to early Late Miocene to the Neogene sequences of the Solimões and its correlated Pebas Formation (Hoorn, 1993; Hoorn, 1994a, 1994b; Muñoz-Torres et al., 2006; Wesselingh et al., 2006a, b). More recent palynological studies in boreholes from western Amazonia (Brazil) recorded a younger age for the top of the Solimões Formation, extending it to the Pliocene (Silva-Caminha et al., 2010; Kachniasz and Silva-Caminha, 2016; Leite et al., 2017).

The western Amazonia passed through important environmental changes during the Neogene, which are divided into distinct phases (Hoorn et al., 2010a, b): The Early Miocene landscape was characterized by fluvial and progressive lacustrine conditions, as well as marginal marine influence. Towards Middle Miocene, the maximum lacustrine conditions with marine incursions stands out, which is known

as Pebas Phase. Deltaic, estuarine and fluvial environments (Acre Phase) took place during the Late Miocene. During the Pliocene, essentially fluvial settings, similar to its current environment, have been established in Amazonia (Hoorn et al., 2010a; Latrubesse et al., 2010); although a controversial scenario in which marine incursions have taken place at this time was suggested by Kachniasz and Silva-Caminha (2016).

Paleontological studies have shown that similarities between microfossil assemblages (e.g. pollen, mollusks, and ostracod), rapid diversification of groups as well as marine incursions, indicate major bioevents and are relevant markers for correlations between sub-Andean basins of Peru and Colombia and the intracratonic Solimões basin of Brazil (Hoorn et al., 2010a; Roddaz et al., 2010; Boonstra et al., 2015; Gross et al., 2014; Salas-Gismondi et al., 2015; Antoine et al., 2016; Jaramillo et al., 2017; Linhares et al., 2017).

In this study we used an integrated biostratigraphical analysis with ostracods and spores-pollen from two boreholes located near Atalaia do Norte, northwestern Solimões basin, Brazil, aiming to contribute to a

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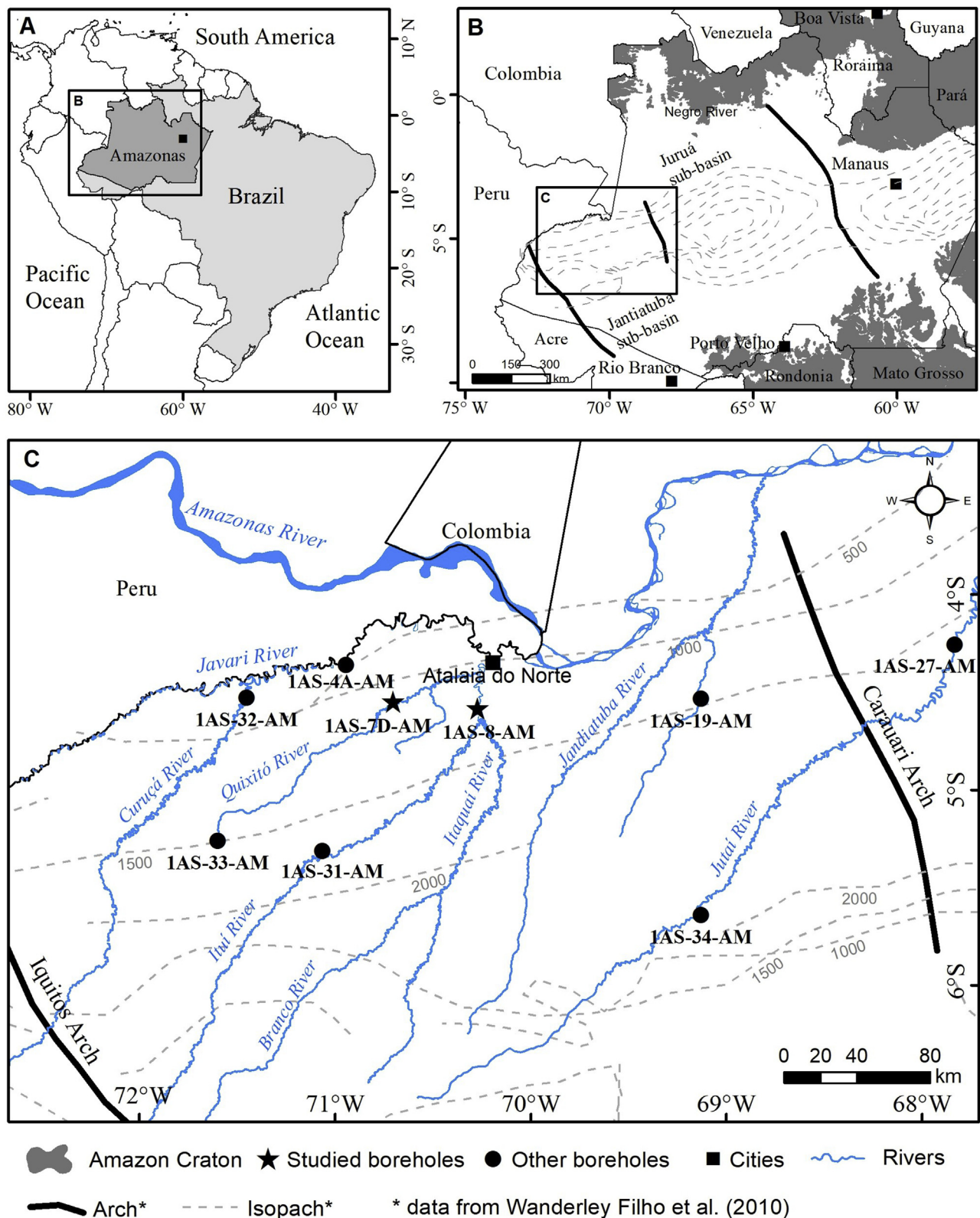


Fig. 1. Location of the study area. A) South America countries, contrasting Brazil and the Amazonas State. B) Subdivision of Solimões basin by the Caruaru Arch into the Juruá and Jantiatuba sub-basins. C) Study area, indicating boreholes used in this paper and from other biostratigraphic studies of the Solimões Formation. Source: adapted from Wanderley-Filho et al. (2010) and GeoSGB (Geological Survey of Brazil).

more reliable constraints and better correlation between the studied sections. The parallelism of two sets of zones based on two groups of microorganisms should increase the biostratigraphic resolution of studied sections (McGowan, 2005). This methodology has been applied to

other basins with satisfactory results in the identification of bioevents (Tantawy et al., 2001; Fauth et al., 2012; Beiranvand et al., 2014; Lehrmann et al., 2015).

2. Study area

The study area is located in the intracratonic Solimões Basin, Amazonas state, Brazil (Fig. 1), that covers an area of approximately 450,000 km². The basin is bounded to the north by the Guiana Shield, to the south by the Brazilian Shield, to the east by the Purus Arch, and to the west by the Iquitos Arch; is subdivided by the Carauari Arch into the Juruá sub-basin to the east and the Jandiatuba sub-basin to the west and comprises five sequences: Ordovician, Upper Silurian – Early Devonian, Middle Devonian – Lower Mississippian, Upper Mississippian – Lower Permian, and Upper Cretaceous – Cenozoic (Wanderley Filho et al., 2007, 2010). The latter sequence comprises the Cretaceous Alter do Chão Formation and the Neogene Solimões Formation separated by the Neocretaceous regional unconformity (Eiras et al., 1994; Wanderley Filho et al., 2007, 2010).

The Solimões Formation is represented by siliciclastic deposits (mainly pelites and sandstones), with organic matter, fossils, and levels of lignite and carbonate (Hoorn, 1993; Latrubesse et al., 2010; Gross et al., 2014, 2013; Nogueira et al., 2013; Linhares et al., 2017; Jaramillo et al., 2017), which are interpreted as typically fluvio-lacustrine with short-lived events of marine ingression during the Miocene, which the pathway is mainly considered as derived from the Caribbean Sea (Hoorn, 1993; Wesselingh and Macsotay, 2006; Hoorn et al., 2010a, b; Linhares et al., 2011; Jaramillo et al., 2017; Linhares et al., 2017). More geological data of the studied area and specifically of the studied boreholes are detailed in Linhares et al. (2017).

The studied boreholes are 1AS-7D-AM (04°34'S; 70°41'W), located near the Quixito River, and borehole 1AS-8-AM (05°18'S; 71°02'W), near the Itacuaí River, Amazonas, Brazil (Fig. 1), both drilled by the Geological Survey of Brazil (Maia et al., 1977) and deposited at the office of Manaus. Borehole 1AS-7D-AM reaches a total depth of 304.70 m, in which the Solimões Formation occurs from the base to 5.7 m depth, where it is overlaid by Quaternary sediments. Borehole 1AS-8-AM reaches a depth of 405 m, but Solimões Formation overlies the Alter do Chão Formation at 368 m depth and is covered by recent sediments at 4 m depth (Linhares et al., 2017).

3. Materials and methods

A total of 196 samples were analyzed for palynomorphs and ostracods, 112 from borehole 1AS-7D-AM (04°34'S; 70°41'W), and 84 from borehole 1AS-8-AM (05°18'S; 71°02'W). Here we integrated biozonations based on ostracod and spores-pollen of both the boreholes to present composite data.

3.1. Ostracod procedures

Ostracods have been recovered following standard methodology for calcareous microfossils, in which 180 g of dry sediment were washed through sieves of 0.5 mm, 0.250 mm, 0.180 mm, and 0.125 mm; dried in an oven at 60 °C; and the residuals were separated for ostracods, using a stereo microscope, for subsequent identification. Photographs have been taken with an electronic scanning microscope (SEM) at the Museu Paraense Emílio Goeldi (LEO 1450VP) and at Geological Survey of Brazil (office of Belém), Brazil. Ostracods identification was based in Purper (1979), Purper and Pinto (1983, 1985), Purper and Ornellas (1991), Muñoz-Torres et al. (1998), and Gross et al. (2013, 2014; 2015). For ostracod counting, the following pattern was considered herein: 0–10 = rare; 11–30 = common; 31–50 = abundant and > 50 = very abundant.

For the biozonation of ostracods, we have followed Muñoz-Torres et al. (2006). Ostracod interval zones have been defined by the first and/or last appearances datum (FAD and LAD) of *Cyprideis* species.

3.2. Palynomorph procedures

Palynomorph extraction 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 material 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; at least three slides of the each sample were scanned and the specimens photographed under an optical microscope at 100x magnification.

For the establishment of palynological zones, 59 samples were examined through triplicated slides; pollen diagrams were constructed with the Tilia 2.0.41 program. For taxonomic identification specialized literature was used, such as 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), and Silva-Caminha et al. (2010). 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 qualitative and quantitative palynomorph data are listed in the supplementary material (Tables S1 and S2). 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 occurrence of marker species.

3.3. Repositories and institutional abbreviations

Figured specimens (Fig. 7.a–e and 7.I–VI) are deposited in the Micropaleontology Collection of the Museu Paraense Emílio Goeldi, Belém, Pará, Brazil, under numbers MPEG-846-M to MPEG-856-M.

4. Biostratigraphic background

The first palynological biozonation for the Solimões Formation was proposed by Hoorn (1993), who analyzed samples from borehole 1AS-4a-AM (near Atalaia do Norte, Amazonas, Brazil) and established five biozones, most of them correlated with the South America framework of Lorente (1986): 1- *Verrutricolporites*; 2- *Retitricolporites* (both Early Miocene); 3- *Psiladiporites/Crototricolpites* (late Early to Middle Miocene); 4- *Crassoretitiletes* (Middle Miocene), and 5- *Grimsdalea* (late Middle to early Late Miocene).

Further palynological studies extended the top of the Solimões Formation to the Pliocene, based on the presence of the *Psilatricolporites caribbiensis* zone (from late Late Miocene to Pliocene) in boreholes 1AS-19-AM, 1AS-27-AM, 1AS-31-AM, 1AS-33-AM, and 1AS-34-AM (Silva-Caminha et al., 2010; Kachniasz and Silva-Caminha, 2016; Leite et al., 2017), and by the presence of the *Echitricolporites-Alnipollenites* zone in these last three boreholes (Kachniasz and Silva-Caminha, 2016; Leite et al., 2017). Moreover, Latrubesse et al. (2010) recognized the *Grimsdalea* zone for borehole 1AS-32-AM, and although they found *Psilatricolporites caribbiensis* in some samples, the Pliocene has not been confirmed, because of uncertainties in the temporal definition of the palynological biochron (Fig. 2).

The ostracods biozonation presented in Muñoz-Torres et al. (2006), was based on species of *Cyprideis*; they proposed five zones for the Neogene deposits of Amazonia (Brazil, Peru and Colombia) and correlated them with the palynological zones proposed by Hoorn (1993): *Cyprideis aulakos* (late Early to early Middle Miocene); *C. caraionae*; *C. minipunctata*; *C. obliquosulcata* (all Middle Miocene), and *C. cyrtoma* zones (late Middle to early Late Miocene). This zonation has also been supported by mollusks, since Wesselingh et al. (2006a, b) proposed 12 mollusk zones covering Early to Late Miocene (Fig. 2).

Another biozonation using the ostracod genus *Cyprideis* was presented by Gross et al. (2014) for borehole 1AS-10-AM (from Atalaia do Norte), following Muñoz-Torres et al. (2006) (Fig. 2). The authors identified three biozones: *C. minipunctata*, *C. obliquosulcata*, and *C.*

Author		Palynology					Mollusk	Ostracod		
Age (Ma)		Hoorn (1993) 1AS-4a-AM	Latrubesse et al. (2010) 1AS-32-AM *	Silva-Caminha et al. (2010) 1AS-19-AM/1AS-27-AM	Leite et al. (2016) 1AS-33-AM	Kachniasz & Silva-Caminha (2016) (1AS-31-AM/1AS-34-AM)	Wesselingh et al. (2006a) 1AS-4a-AM	Muñoz-Torres et al. (2006) 1AS-4a-AM	Gross et al. (2014) 1AS-10-AM	Medeiros et al. (2017) 1AS-33-AM
3	Pliocene									
4										
5										
6	Miocene	Messinian								
7										
8										
9	Neo	Tortonian								
10										
11										
12	Meso	Serravalian								
13										
14										
15	Eo	Burdigalian								
16										
17										
18	Aquitanian									
19										
20										
21										
22										
23										

Fig. 2. Pollen, mollusk and ostracod biozonations proposed for the Solimões Formation.

cyrtoma, dating the studied interval as Middle to Late Miocene.

An independent biozonation with ostracod was presented by Medeiros et al. (2017) that established a new biostratigraphic zonation with ostracods from borehole 1AS-33-AM (also from Atalaia do Norte), and proposed three biozones: *Cyprideis caraionae* (Middle Miocene); *Cyprideis multiradiata* (late Middle to Late Miocene); and *Cyprideis sulcosigmoidalis* (Late Miocene – Pliocene), including the subzone *Rhadinocytherura amazonensis* (Fig. 2).

5. Results

We recognized five palynozones in boreholes 1AS-8-AM and 1AS-7D-AM (Figs. 3 and 4): *Verrutricolporites* (Early Miocene), *Psiladiporites-Crototricolpites* (late Early to Middle Miocene), *Crassoretitiletes*, (Middle Miocene), *Grimsdalea* (late Middle to early Late Miocene), and *Asteraceae* (Late Miocene). The markers were easily recognized, however the palynological association is quite different from the Venezuelan zones of Lorente (1986), resembling more closely the Brazilian zonation scheme of Hoorn (1993) (Tables S1 and S2). Generally, the biozones present high diversity, yet the *Grimsdalea* zone shows low diversity, as indicated by Lorente (1986). Unlike other zones, *Grimsdalea* is present in both boreholes, but their species association is partially different.

5.1. Palynological zones of borehole 1AS-8-AM

5.1.1. *Verrutricolporites* Acme zone sensu Lorente (1986) (368–323.40 m) Aquitanian – Burdigalian

The *Verrutricolporites* zone is defined by the first occurrence of the *V. rotundiporus* van der Hammen and Wymstra (1964). This zone is characterized by the occurrence of *Zonocostites ramonae* Germeraad et al. (1968) and *Retitricolporites guianensis* van der Hammen and Wymstra (1964). The associated assemblage comprises *Psiladiporites sarmientoi* Hoorn (1993), *Mauritiidites franciscoi* (van der Hammen, 1954) van Hoeken-Klinkenberg (1964), *Psilamonocolpites amazonicus* Hoorn (1993), *P. nanus* Hoorn (1993), *Deltoidospora adriennis* (Potonié and Gellertich, 1933) Frederiksen (1983), *Perisyncolporites pokorny* Germeraad et al. (1968), *Heterocolpites incomptus* Hoorn (1993), *H. rotundus* Hoorn (1993), *Magnastriatites grandiosus* (Kedves and Solé de Porta, 1963) Dueñas (1980), *Echiperiporites akanthos* van der Hammen and Wymstra (1964), *Perforicolpites* sp. González-Guzmán (1967),

Verrucatosporites usmensis Germeraad et al. (1968), *Psilamonoletes tibui* van der Hammen (1954), among others (Table S1). At 323.40 m there is occurrence of mangrove palynomorphs, microforaminiferal linings and agglutinated foraminifera (*Miliammina fusca*) (Linhares et al., 2017).

5.1.2. *Crassoretitiletes* interval zone sensu Lorente (1986) (246.76–141 m) Langhian – Serravallian

The lower limit is determined by the first appearance of *Crassoretitiletes vanraadshoovenii* Germeraad et al. (1968), and the upper limit is placed by the first appearance of *Grimsdalea magnaclavata* Germeraad et al. (1968). In this zone there is the first occurrence of *Ilexpollenites* sp. Thiergart (1937) ex Potonié (1960) and *Bombacacidites baculatus* Müller et al. (1987). Moreover, *Retitricolporites irregularis* van der Hammen and Wymstra (1964), *Retitricolpites simplex* González-Guzmán (1967), *Psilastephanocolpites schneideri* Hoorn (1993), *Psiladiporites crassoexinatus* Hoorn (1993), *Psiladiporites atalayensis* Hoorn (1993), *Psiladiporites minimus* Regali et al. (1974), *Retimonocolpites maximus* Hoorn (1993), *Crototricolpites* sp. Leidelmeyer (1966) among others, occur (Table S1). The interval is marked by high abundance of *Laevigatosporites* spp. Ibrahim, 1933, *Verrucatosporites usmensis*, and *Psilamonoletes tibui*. At 165.20 m there are marine palynomorphs represented by microforaminiferal linings.

5.1.3. *Grimsdalea* interval zone sensu Lorente (1986) (141–32 m) Serravallian – Tortonian

The lower limit of this biozone is defined by the first appearance of *Grimsdalea magnaclavata*. The associated assemblage is mainly represented by *Bombacacidites bellus* Frederiksen (1983) and *Horniella morenoi* Silva-Caminha et al. (2010). Furthermore, there is an increase in *Magnastriatites grandiosus*, *Heterocolpites incomptus*, and *Deltoidospora adriennis*, while others occur exclusively in this zone, as *Bombacacidites muinaneorum* Hoorn (1993), *Psilaperiporites* sp. Regali et al. (1974), *Psiladiporites labiatus* Hoorn (1993) and *Bombacacidites fossulatus* Silva-Caminha et al. (2010). *Laevigatosporites* spp., *Verrucatosporites usmensis*, and *Psilamonoletes tibui* show moderate abundance (Table S1).

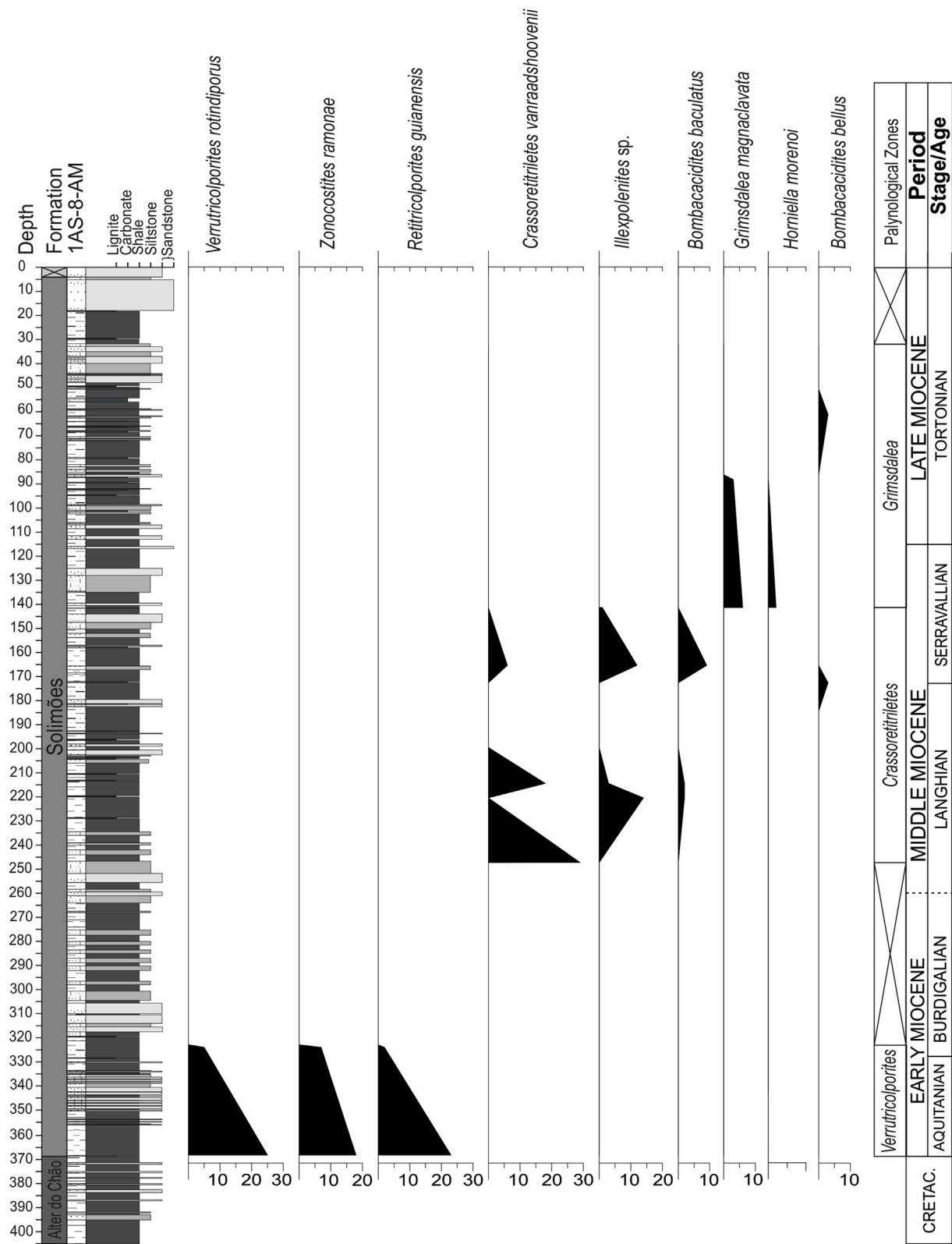


Fig. 3. Pollen diagram with the distribution of main index taxa and associated species, with the palynological zones in borehole 1AS-8-AM.

5.2. Palynological zones of borehole 1AS-7D-AM

5.2.1. Psiladioporites–Crototricolpites range zone sensu Hoorn (1993) (296–184 m) Burdigalian – Langhian

The lower limit is defined by the first occurrence of *Crototricolpites annemariae* Leidekmeyer (1966), and the upper limit is defined by the

first occurrence of *Grimsdalea magnaclavata*. Other species also have their first appearances: *Psilatricolporites magniporatus* Hoorn (1993) and *Echiperiporites* sp. van der Hammen and Wymstra (1964). Moreover, *Polypodiaceoisporites potonie* Kedves and Solé de Porta, 1963, *Mauritiidites franciscoi*, *Magnastriatites grandiosus*, *Psilamonocolpites nanus*, *Deltoidospora adriennis*, *Psilamonocolpites amazonicus*, *Retimonocolpites*

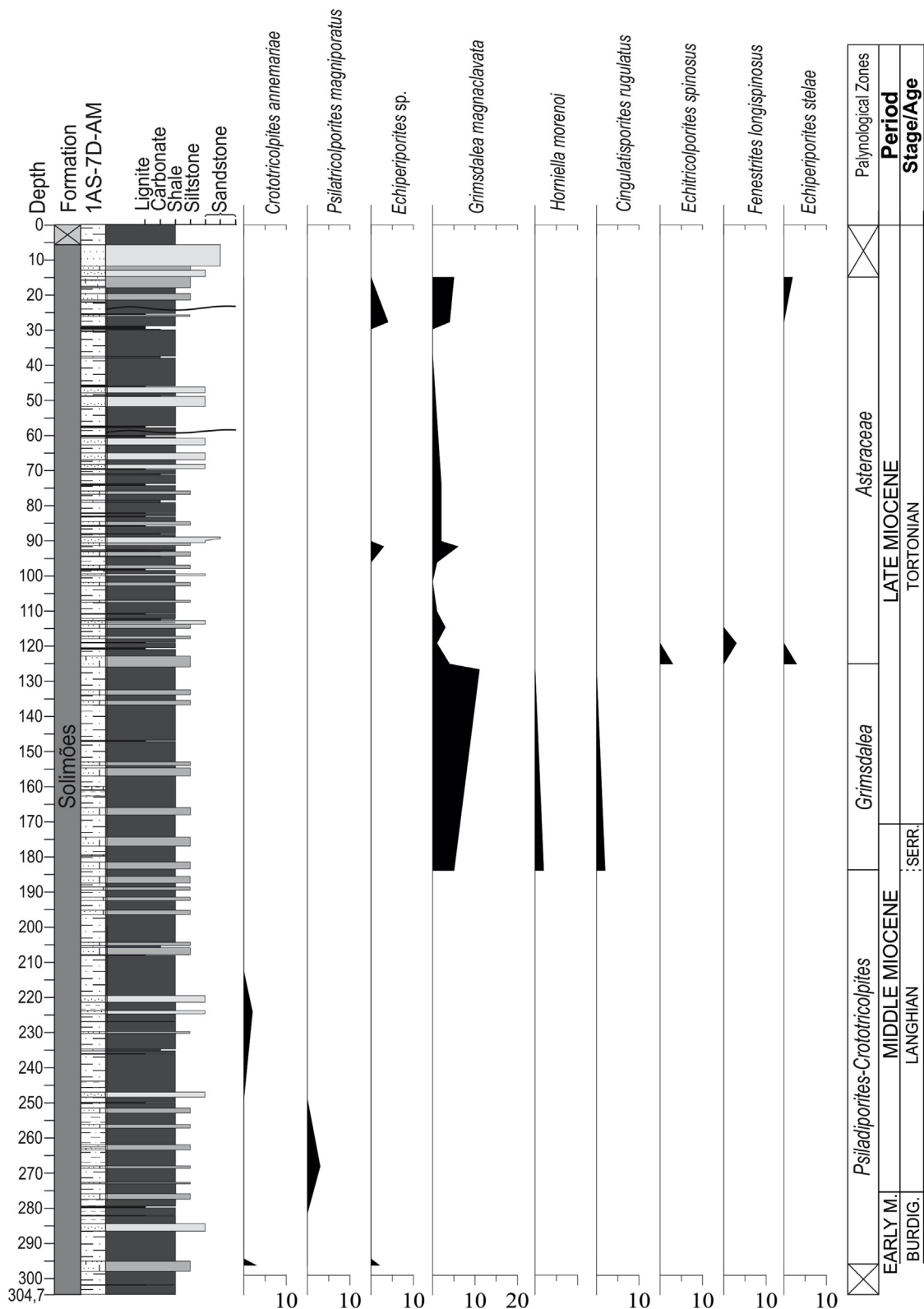


Fig. 4. Pollen diagram with the distribution of main index taxa and associated species, with the palynological zones in borehole 1AS-7D-AM.

maximus, *Perforitricolpites digitatus* González-Guzmán (1967) and *Striatricolpites catatumbus* González-Guzmán (1967) occur. This interval is dominated by abundance of *Verrucatosporites usmensis*, among other less frequent taxa (Table S2). At 268 m there is the occurrence of marine palynomorphs represented by microforaminiferal linings.

5.2.2. Grimsdalea interval zone sensu Lorente (1986) (184–125 m) Serravallian – Tortonian

The lower limit is defined by the first occurrence of *Grimsdalea magnaclavata*, and the upper limit is marked by the first occurrence of *Asteraceae* zone elements. The association is marked by the occurrence of *Horniella morenoi* and *Cingulatisporites rugulatus* Silva-Caminha et al.

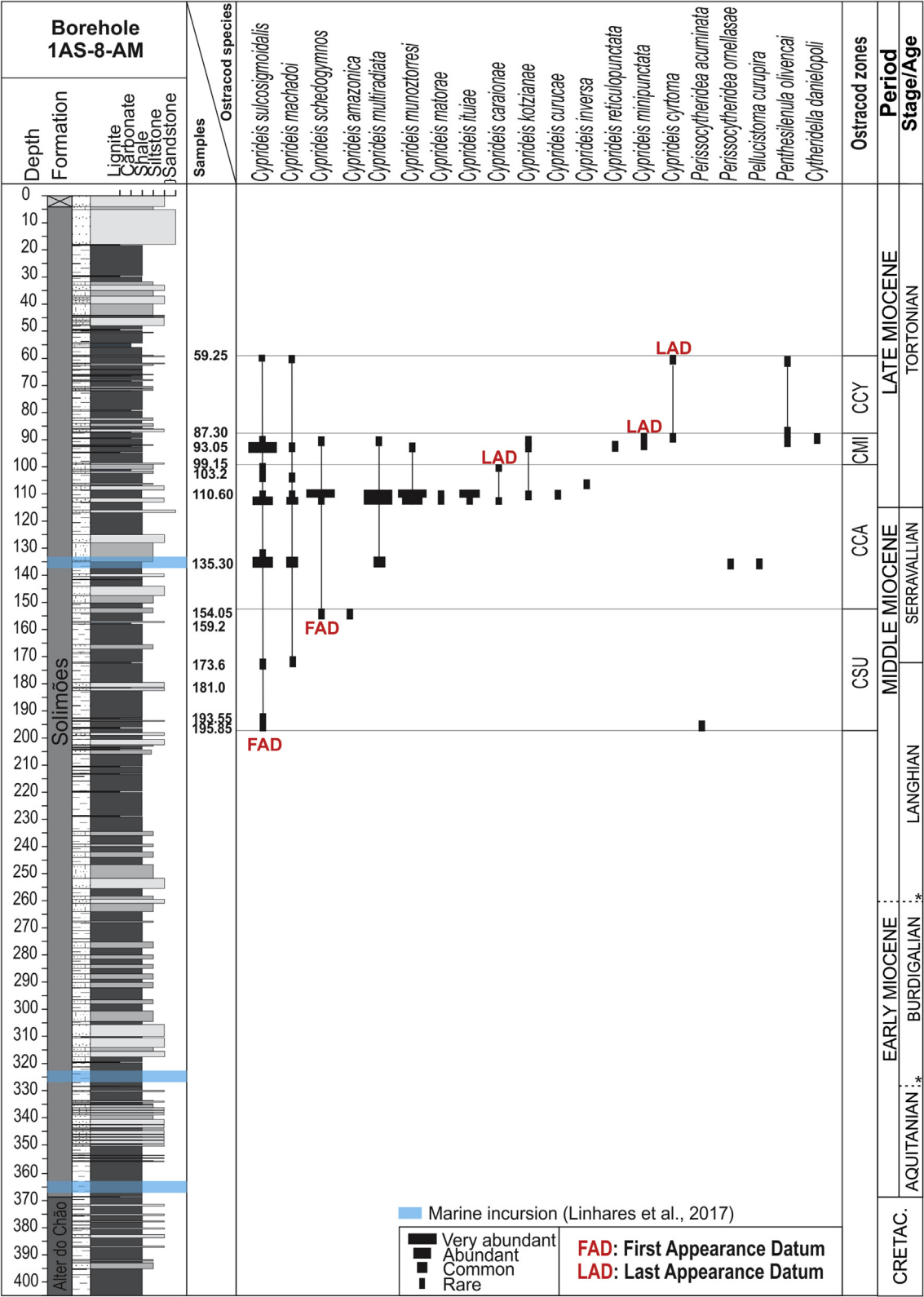


Fig. 5. Stratigraphical distribution of ostracod species in borehole 1AS-8-AM and ostracod zones. CSU: *C. sulcosigmoidalis* (= *C. aulakos*), CCA: *C. caraionae*, CMI: *C. minipunctata*, CCY: *C. cyrtoma*. *: inferred from palynological zones.

(2010). The assemblage demonstrates relative low abundance, but moderate diversity, including *Crototricolpites* sp. [Leidelmeyer \(1966\)](#), *Crassoretitrites vanraadshooveni*, *Retitricolporites irregularis*, *Retitricolporites simplex*, *Malvacipolis spinulosa* [Frederiksen \(1983\)](#), *Psilatricolporites labiatus*, *Monoporopollenites annulatus* ([van der Hammen,](#)

[1954](#)) [Jaramillo and Dilcher \(2001\)](#), among other taxa ([Table S2](#)).

5.2.3. Asteraceae zone - interval zone sensu [Lorente \(1986\)](#) (125–14.80 m) Tortonian – interval subzone of *Bombacacidites ciriloensis*
The subzone is characterized by the first appearance of

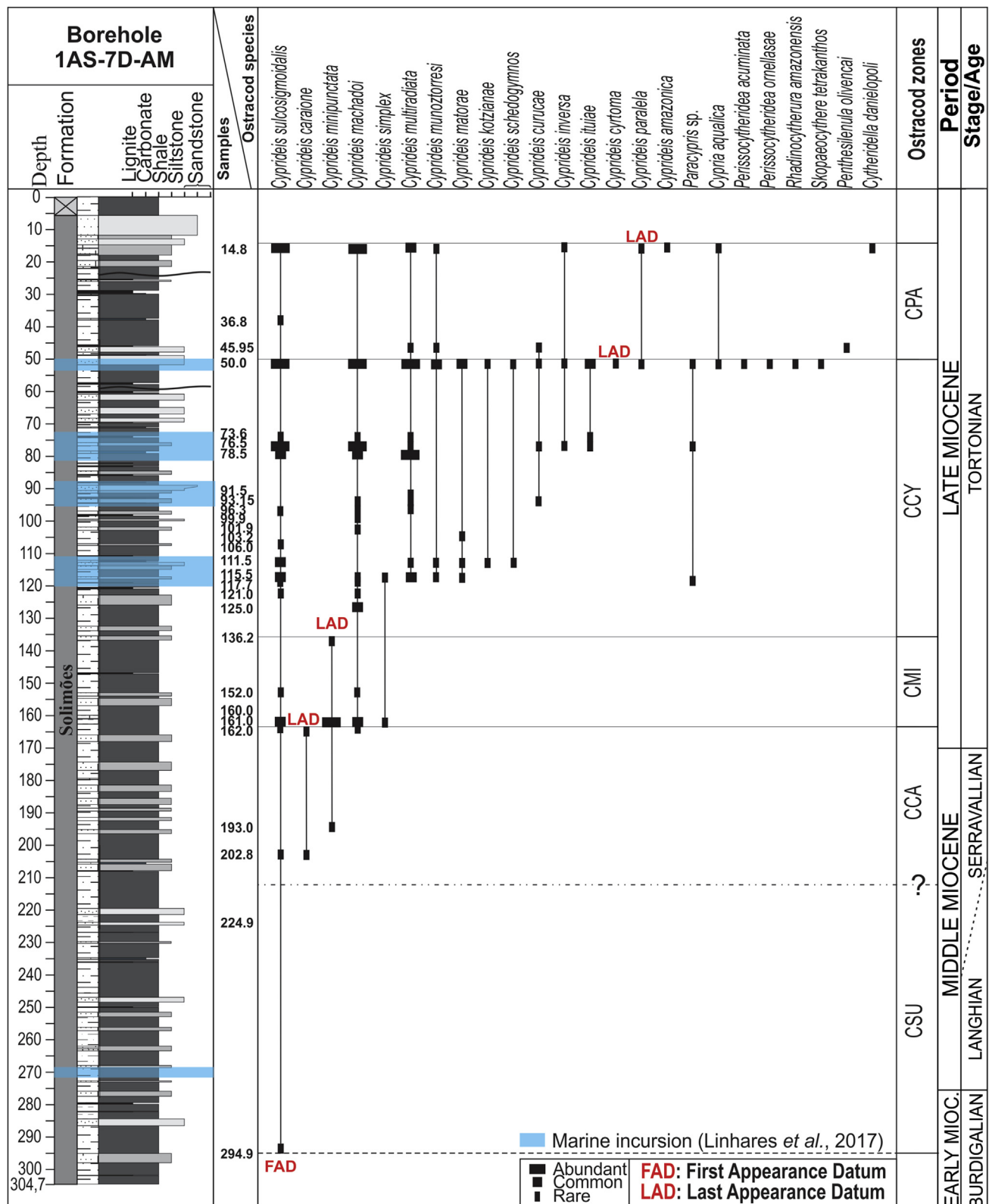


Fig. 6. Stratigraphical distribution of ostracod species in borehole 1AS-7D-AM and ostracod zones. CPA: *C. paralela*; Other abbreviations see Fig. 5.

Echitricolporites spinosus van der Hammen (1954) ex Germeraad et al., 1968 together with *Cichoreacidites longispinosus* (Lorente, 1986) Silva-Caminha et al. (2010). There is an increase of *Monoporopollenites annulatus*. Several species also have their first appearances, as *Echitricolporites stelae* Germeraad et al., 1968, *Fenestrites* sp. van der Hammen (1954), *Podocarpidites* sp. (Cookson, 1947) Couper, 1953, *Proxapertites*

sp. van der Hammen (1954), *Echinosporis* sp. Krutzsch (1967), *Malvacipolloides maristellae* (Müller et al., 1987) Silva-Caminha et al. (2010), *Echitricolporites* spp. (van der Hammen, 1954) Germeraad et al. (1968), *Polyadopollenites macroreticulatus* Salard-Cheboldaef (1974), among other taxa (Table S2). This subzone is characterized by abundance of *Verrucatosporites usmensis* and *Monoporites annuloides*. *Grimsdalea*

Table 1
Ostracod zones found in borehole 1AS-8-AM.

<i>Cyprideis sulcosigmoidalis</i> (= <i>C. aulakos</i>) interval zone (CSU)	
Interval	195.85–154.05 m
Definition	Lower limit marked by first appearance of <i>Cyprideis aulakos</i> = <i>Cyprideis sulcosigmoidalis</i> (Purper, 1979). Upper limit is defined by the first appearance of <i>Cyprideis schedogymnos</i> Muñoz-Torres et al. (1998).
Associated species	<i>Cyprideis amazonica</i> Purper (1979), <i>Cyprideis machadoi</i> (Purper, 1979) and <i>Perissocytheridea acuminata</i> (Purper, 1979).
Palynological zone	<i>Crassoretitrites</i> zone sensu Lorente (1986)
Age	Middle Miocene
<i>Cyprideis caraionae</i> interval zone (CCA)	
Interval	154.05–99.15 m
Definition	Lower limit marked by first appearance of <i>C. schedogymnos</i> . Upper limit is defined by the last appearance of <i>Cyprideis caraionae</i> Muñoz-Torres et al. (1998).
Associated species	In this interval the species <i>Cyprideis matorae</i> Gross et al. (2014), <i>Cyprideis ituiiae</i> Gross et al. (2014), <i>Cyprideis curucae</i> (Purper, 1979), <i>Cyprideis inversa</i> (Purper and Pinto, 1983), <i>Perissocytheridea ornellae</i> (Purper, 1979) and <i>Pellucistoma curupira</i> Gross et al. (2015) has its first and last appearance.
Palynological zone	<i>C. sulcosigmoidalis</i> , <i>C. machadoi</i> , <i>C. schedogymnos</i> , <i>C. multiradiata</i> (Purper, 1979), <i>Cyprideis munoztorresi</i> (Muñoz-Torres et al., 1998) and <i>Cyprideis kotzianae</i> (Purper and Ornellas, 1991).
Age	Part of <i>Crassoretitrites</i> and of the <i>Grimsdalea</i> zone sensu Lorente (1986) Middle Miocene to early Late Miocene
<i>Cyprideis minipunctata</i> interval zone (CMI)	
Interval	99.15–87.3 m
Definition	Lower limit marked by last appearance of <i>C. caraionae</i> . Upper limit is defined by the last appearance of <i>Cyprideis minipunctata</i> (Purper and Ornellas, 1991). <i>Cyprideis reticulopunctata</i> (Purper, 1979) is rare and has its first and last appearance in this interval.
Associated species	<i>C. sulcosigmoidalis</i> , <i>C. machadoi</i> , <i>C. schedogymnos</i> , <i>C. multiradiata</i> , <i>C. munoztorresi</i> , <i>C. kotzianae</i> , <i>Cytheridella danielopoli</i> Purper (1979) and <i>Penthesilenula olivencai</i> (Purper, 1979).
Palynological zone	<i>Grimsdalea</i> sensu Lorente (1986)
Age	early Late Miocene
<i>Cyprideis cyrtoma</i> interval zone (CCY)	
Interval	87.3–59.25 m
Definition	Lower limit marked by last appearance of <i>C. minipunctata</i> . Upper limit is defined by last appearance of <i>Cyprideis cyrtoma</i> Muñoz-Torres et al. (1998).
Associated species	<i>C. sulcosigmoidalis</i> , <i>C. machadoi</i> and <i>P. olivencai</i> .
Palynological zone	<i>Grimsdalea</i> sensu Lorente (1986)
Age	early Late Miocene

magnaclavata presents moderate abundance, decreasing up-section. At 91.5 m there is the occurrence of marine diatoms and fish remains (e.g. selachian dermal denticles, otoliths *Genidens*; Linhares et al., 2017).

5.3. Ostracod zones

The stratigraphical distribution of *Cyprideis* species from boreholes 1AS-8-AM (Fig. 5) and 1AS-7D-AM (Fig. 6) allowed to propose a new zone *Cyprideis paralela* and to recognize four ostracod zones established by Muñoz-Torres et al. (2006) (Tables 1 and 2). However, a review in the extension of the boundaries of these zones is presented below. The ostracod zones here identified were adjusted with the palynological zones.

In the biozonation proposed by Muñoz-Torres et al. (2006) the *C. aulakos* zone is inferred to be equivalent only to the *Crassoretitrites* palynozone and extending from Burdigalian to Serravallian (Muñoz-Torres et al., 2006, page 83, Fig. 6). However, the *Crassoretitrites* palynozone spans from Langhian to Serravallian (Middle Miocene), not reaching the Burdigalian (Early Miocene) according to Hoorn (1993). This incorrect dating of *Crassoretitrites* zone resulted into a mistake in the limits of the correspondent ostracod zone *C. aulakos* also in subsequent studies (Wesselingh and Ramos, 2010; Linhares et al., 2011; Gross et al., 2014). In the present study we observed that this zone extends from *Psiladioprites*-*Crototricolpites* to the base of *Crassoretitrites* palynozones, thus actually reaching the interval between late Early and late Middle Miocene (Burdigalian to Serravallian) (Fig. 7).

C. aulakos zone was renamed herein to *C. sulcosigmoidalis*, as the *C. aulakos* species is synonymous of *C. sulcosigmoidalis*, according to Gross et al. (2014), due to the variation in the ornamentation pattern, from slightly punctuated (*C. sulcosigmoidalis* morphotype) to smooth (*C.*

aulakos morphotype), was not enough to classify them as two different species.

Besides the adjustments at the limits of *C. aulakos* zone, we also extend the limits of the other ostracod zones according to the stratigraphic distribution of the index species in the studied boreholes and its correlation with the palynozones here identified.

Thus, the next *Cyprideis caraionae* zone had its amplitude extended – both lower and upper stratigraphic limits – reaching the interval between the Middle Miocene (Serravallian) and early Late Miocene (Tortonian), equivalent to part of the *Crassoretitrites* and *Grimsdalea* zones. Muñoz-Torres et al. (2006) indicate this zone restricted to Middle Miocene and exclusively to the correspondent *Crassoretitrites* zone. In borehole 1AS-8-AM, the *Cyprideis caraionae* zone presents the higher diversity of *Cyprideis* species, in which some species have their FAD and LAD (*C. ituiiae*, *C. caraionae*, *C. matorae*, *C. curucae*, and *C. inversa*).

The range of the *C. minipunctata* zone was also extended here to *Grimsdalea* palynozone, extending the upper limit from late Middle to early Late Miocene. Muñoz-Torres et al. (2006) pointed this zone restricted to late Middle and correlate to the *Crassoretitrites* zone.

Cyprideis cyrtoma zone was extended to a younger age (Tortonian) then previously proposed, reaching not only the *Grimsdalea* zone but also the lower part of *Asteraceae* zone.

Furthermore, Muñoz-Torres et al. (2006) mentioned that a likely marine species *Skopaeocythere tetrakanthos* Whatley et al. (2000), which is associated with foraminifera *Elphidium*, is restricted to the *C. obliquosulcata* zone, not recorded here. Gross et al. (2014) also recorded this species associated with *Elphidium* in borehole 1AS-10-AM, but related to the *C. cyrtoma* zone. We also observed this species in *C. cyrtoma* zone (1AS-7D-AM, at 50 m depth), associated with the foraminifera

Table 2
Ostracod zones found in borehole 1AS-7D-AM.

<i>Cyprideis sulcosigmoidalis</i> interval zone (CSU)	
Interval	224.9–184 m
Definition	Lower limit marked by first appearance of <i>C. sulcosigmoidalis</i> . The upper limit is not clearly defined in this section.
Palynological zone	<i>Psiladioporites–Crototricolpites sensu Hoorn (1993)</i>
Age	late Early Miocene to early Middle Miocene
<i>Cyprideis caraionae</i> interval zone (CCA)	
Interval	~ 184–162 m
Definition	Upper limit is defined by last appearance of <i>C. caraionae</i> . The lower limit is not clearly defined in this section.
Associated species	<i>C. sulcosigmoidalis</i> , <i>C. minipunctata</i> and <i>C. machadoi</i> .
Palynological zone	Part of the <i>Grimsdalea sensu Lorente (1986)</i>
Age	late Middle Miocene to early Late Miocene
<i>Cyprideis minipunctata</i> interval zone (CMI)	
Interval	162.00–136.20 m
Definition	Lower limit marked by last appearance of <i>C. caraionae</i> . Upper limit is defined by last appearance of <i>C. minipunctata</i> .
Associated species	<i>C. sulcosigmoidalis</i> , <i>C. machadoi</i> and <i>Cyprideis simplex</i> (Shepard and Bate, 1980).
Palynological zone	<i>Grimsdalea sensu Lorente (1986)</i>
Age	early Late Miocene
<i>Cyprideis cyrtoma</i> interval zone (CCY)	
Interval	136.20–50 m
Definition	Lower limit marked by last appearance of <i>C. minipunctata</i> . Upper limit is defined by last appearance of <i>C. cyrtoma</i> .
Associated species	<i>C. sulcosigmoidalis</i> , <i>C. machadoi</i> , <i>C. simplex</i> , <i>C. multiradiata</i> , <i>C. munoztorresi</i> , <i>C. matorae</i> , <i>C. kotzianae</i> , <i>C. schedogymnos</i> , <i>C. curucae</i> , <i>C. inversa</i> , <i>C. ituaie</i> , <i>Cyprideis paralela</i> (Purper, 1979), <i>C. amazonica</i> , <i>Paracypris</i> sp., <i>Cypria aqualica</i> Shepard and Bate, 1980, <i>Perissocytheridea acuminata</i> , <i>Perissocytheridea ornellae</i> , <i>Rhadinocytherura amazonensis</i> Shepard and Bate, 1980 and <i>Skopaeocythere tetrakanthos</i> Whatley et al. (2000).
Palynological zone	Part of the <i>Grimsdalea</i> and of the <i>Asteraceae sensu Lorente (1986)</i>
Age	early Late Miocene
<i>Cyprideis paralela</i> interval zone (CPA) This Study	
Interval	50–14.8 m
Definition	Lower limit marked by the last appearance of <i>C. cyrtoma</i> . Upper limit is defined by the last appearance of <i>C. paralela</i> .
Associated species	<i>C. sulcosigmoidalis</i> , <i>C. machadoi</i> , <i>C. multiradiata</i> , <i>C. munoztorresi</i> , <i>C. curucae</i> , <i>C. inversa</i> , <i>C. amazonica</i> , <i>C. aqualica</i> , <i>P. olivencai</i> and <i>C. danieolopoli</i> .
Discussion	The top of the reference section used by Muñoz Torres et al. (2006) is undefined. The last ostracode zone recognized is <i>C. cyrtoma</i> correspondent to <i>Grimsdalea</i> palynozone. Our data show that the LAD of <i>C. cyrtoma</i> extends to the <i>Asteraceae</i> palynozone, which was not defined in the preceding biozonation. Thereby, the previous recognition of a zone above, defined here as <i>C. paralela</i> , would not be possible.
Palynological zone	Part of the <i>Asteraceae sensu Lorente (1986)</i>
Age	Late Miocene
Reference section	Borehole 1-AS-7D-AM, Atalaia do Norte, Amazonas, Brazil (04°34'S; 70°41'W)

Ammonia, besides the occurrence of marine and transitional species as *Paracypris* sp., *Pellucistoma curupira*, *Perissocytheridea acuminata*, *Perissocytheridea ornellae* and *Rhadinocytherura amazonensis* (1AS-7D-AM, at 50 m depth). In borehole 1AS-7D-AM, this zone presents the higher diversity of *Cyprideis*, in which some species have their FAD and LAD (e.g. *C. ituaie*, *C. kotzianae*, *C. matorae*, and *C. schedogymnos*).

The new zone proposed herein, *C. paralela* (interval zone), defined by successive last occurrence of *C. cyrtoma* and *C. paralela* (Fig. 6, Table 2), occurs exclusively at the top of borehole 1AS-7D-AM and is equivalent to part of the *Asteraceae* palynological zone (Tortonian). The lower limit of this zone is defined by the last appearance of *C. cyrtoma* and the upper limit is defined by last appearance of *C. paralela*. Although Muñoz Torres et al. (2006) have not identified this zone they indicated an undefined zone for the top of 1AS-4a-AM, above *C. cyrtoma*, corresponding to *Grimsdalea* palynozone. However, our data show that the LAD of *C. cyrtoma* extends to the *Asteraceae* palynozone and is coincident with the base of *C. paralela* zone. Other species (*C. ituaie*, *C. kotzianae*, *C. matorae*, and *C. schedogymnos*) have their LAD at the base of this zone, indicating a representative distribution datum.

6. Discussions and correlations

Integrated biostratigraphy analysis using ostracods and spores-pollen from two boreholes allowed to date the studied sequence from Early Miocene (Aquitian) to Late Miocene (Tortonian) (Fig. 7). The

oldest *Verrutricolporites* pollen zone was herein reported at the base of the 1AS-8-AM and is correlated to the base of the 1AS-4a-AM. However, we recognized the *Asteraceae* zone (Late Miocene) in the upper strata of the 1AS-7D-AM, not recognized by Hoorn (1993) to the 1AS-4a-AM, but recognized by Leite et al. (2017) to borehole 1AS-33-AM. This palynozone is here correlated to *Cyprideis paralela* ostracod zone.

We did not recognized the *Psilatricolporites caribbiensis* and *Echitricolporites-Alnipollenites* zones (Pliocene) in the upper layers of our two boreholes, as otherwise indicated for boreholes 1AS-31-AM, 1AS-33-AM and 1AS-34-AM, from the southernmost regions of the Jandiatuba sub-basin (Kachniasz and Silva-Caminha, 2016; Leite et al., 2017), as well as for boreholes 1AS-19-AM and 1AS-27-AM, close the Caruari Arch, to the east (Silva-Caminha et al., 2010), and outcrop areas near Coari region (Silveira and Souza, 2015).

The different range or even hiatus of biozones have been attested from several localities inside western Amazonia (Figs. 2 and 8). This is probably related to the regional ecological settings controlling the distribution of ostracods and palynomorphs. Although a wider or more restricted stratigraphical range is locally observed for some species of *Cyprideis* (Fig. 8), the biozonation is regionally accepted, as the index species distribution allow identify the biozones over vast geographic areas during the Neogene in the Amazonia (Figs. 7 and 8), showing the validity of the integrated analysis of ostracods and spores-pollen for the establishment of age, recognition of bioevents and the regional correlation between the coeval and adjacent units in Brazil, Peru and

Period	Stage/Age	Palynological Zones Lorente (1986)	Palynological Zones Hoorn (1993)	Palynological Zones This Study	INDEX TAXA	Muñoz-Torres et al. (2006) 1AS-4a-AM	Ostracod Zones This Study	INDEX TAXA
MIOCENE	LATE	MESSINIAN			e			VI
		TORTONIAN			d	Undefined		V
	MIDDLE	SERRAVALLIAN			c	C. cyrtoma	Cyprideis cyrtoma	IV
		LANGHIAN			b	C. obliquosulcata	Cyprideis minipunctata	III
	EARLY	BURDIGALIAN			a	C. caraionae	Cyprideis caraionae	II
		AQUITANIAN				C. aulakos	Cyprideis sulcosigmoidalis = (Cyprideis aulakos)	I
		1AS-7D-AM						
		1AS-8-AM						
			Palynological Zones Lorente (1986)	Palynological Zones Hoorn (1993)	Palynological Zones This Study			
			<i>F. longispinosus</i>					
			<i>Stephanocolpites evansii</i>					
			Asteracea	Undefined	Asteracea			
			Grimsdalea	Grimsdalea	Grimsdalea			
			Crassoretitrites	Crassoretitrites	Crassoretitrites			
			Psiladiopites	Psiladiopites - Crototricolpites	Psiladiopites - Crototricolpites			
			Verrutricolporites	Retitricolporites	Undefined			
				Verrutricolporites	Verrutricolporites			

Fig. 7. Correlation of the palynological and ostracod biozonation proposed in this study with the previous palynological (Lorente, 1986; Hoorn, 1993) and ostracod zones (Muñoz-Torres et al., 2006). Pollen index taxa: a. *Verrutricolporites rotundiporus*; b. *Crototricolpites annemariae*; c. *Crassoretitrites vanraadshooveni*; d. *Grimsdalea magnaclavata*; e. *Echitricolporites spinosus*. Ostracod index taxa: I. *Cyprideis sulcosigmoidalis*; II. *C. schedogymnos*; III. *C. caraionae*; IV. *C. minipunctata*; V. *C. cyrtoma*; VI. *C. paralela*. Pollen scale bar: 20 µm. Ostracod scale bar: 100 µm.

Colombia.

Muñoz-Torres et al. (2006) recorded the great radiation of *Cyprideis* to the Middle Miocene. In the present study, we checked peaks of *Cyprideis* radiation between the Serravallian and Tortonian, i. e. between the late Middle Miocene (*C. caraionae*/*Crassoretitrites* and *Grimsdalea* zones) and early Late Miocene (*C. cyrtoma* zone/*Grimsdalea* and *Asteracea* zones). Gross et al. (2014) recorded highest diversity between *C. minipunctata* and *C. cyrtoma* zones (equivalent to *Grimsdalea* zone) in borehole 1AS-10-AM.

In the borehole 1AS-8-AM the first peak of *Cyprideis* species radiation occurs in uppermost part of *C. caraionae* and in *C. minipunctata* zones, corresponding to the transition of the *Crassoretitrites*/*Grimsdalea* zones, just after the marine level of the late Middle Miocene (Figs. 5 and 8). Otherwise, in the borehole 1AS-7D-AM the increase the species diversity is progressive inside the *C. cyrtoma* zone, reaching its maximum in the upper limit of this zone, coincident with marine levels of the Tortonian/Late Miocene (Figs. 6 and 8). In the Peruvian and Colombian Amazonia, radiations of other groups throughout Miocene also have been associated with marine incursions, mainly in the interval between Middle and early Late Miocene (Monsch, 1998; Wesselingh and Ramos, 2010; Bloom and Lovejoy, 2011; Boonstra et al., 2015;

Antoine et al., 2016; Jaramillo et al., 2017).

Although we observed the importance of the marine events for ostracod radiation, the mangrove conditions of the Early Miocene (*Verrutricolporites* palynozone) also related to marine events did not triggered species diversity of calcareous microfossils as attested in the base of borehole 1AS-8-AM. This could be explained by the typically acidic mangrove environments, which might have favored only the organic wall microfossils, as palynomorphs and foraminiferal linings (Hoorn, 1993; Linhares et al., 2017; and in this research) and could have disadvantaged ostracod occurrences.

7. Conclusions

Biostratigraphic analysis using data from ostracods and palynology in two boreholes from the Solimões Formation (Atalaia do Norte region) proved to be a valuable tool, since it was possible to defined the sequence from Early to Late Miocene (Aquitania to Tortonian). In addition, several marine flooding events were identified, which affected ostracod radiations, especially between the late Middle Miocene and early Late Miocene. Our data confirm previous studies that point to the higher *Cyprideis* radiation triggered by marine influence between the

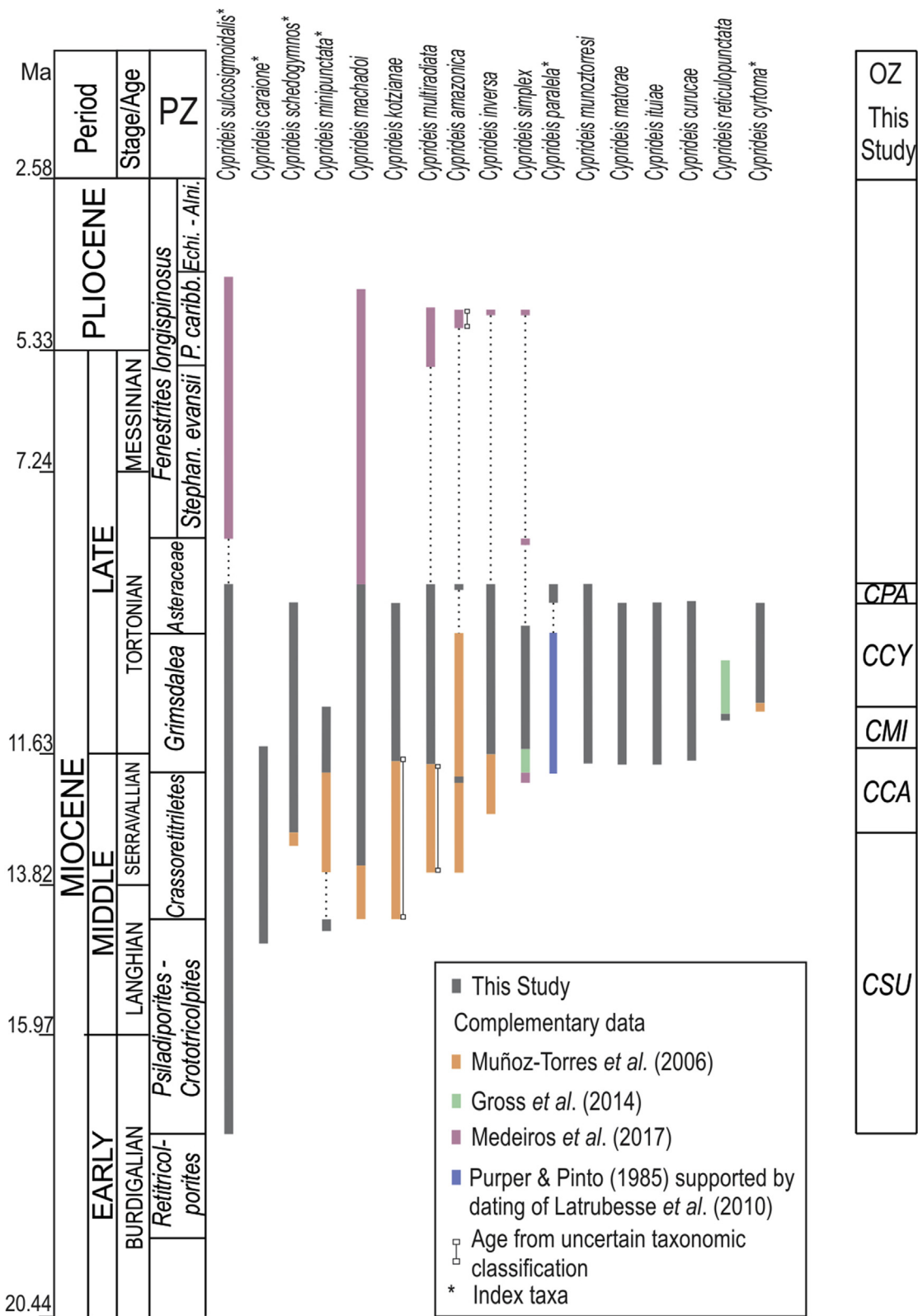


Fig. 8. Stratigraphic distribution of *Cyprideis* species of the Solimões Formation based on boreholes, as well as outcrops from the western Amazon. Complementary data plotted only where stratigraphic range is larger outside study area. PZ: Lorente (1986) and Hoorn (1993). OZ: ostracod zones in this study.

late Middle Miocene and early Late Miocene (Serravallian/Tortonian), correlated to the *Grimsdalea* and *Asteraceae* zones. Although our data do not indicate younger ages (Pliocene), as attested for other sites, we encourage further discussions about the different stages of the basin evolution and correlation between sections. This study attests the

viability and the importance of using more than one microfossil group as a tool to a more accurate dating and correlation between basins.

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Appendix A. Supplementary data

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