



New contributions to the taxonomy of non-marine ostracods from the Neogene megawetlands, western Amazonas state, Brazil

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ABSTRACT

The taxonomic review of the ostracods from Solimões Formation in the western Amazonas State, Brazil, allowed the identification of eight genera and twenty-two species of the genus *Cyprideis* Jones, 1857. Two species are new: *Cyprideis goeldiensis* sp. nov and *Cyprideis javariensis* sp. nov.; and *Cyprideis* sp. 1 remains in open nomenclature. For the first time, the species *Cyprideis santaelenae* Sousa and Ramos 2023, originally described to the Pebas Formation, in Peru, was recorded in the Solimões Formation. A new morphotype of the species *Cyprideis matorae* Gross et al. 2014 is here identified. The stratigraphical distribution of the *Cyprideis* species in the borehole 1AS-32-AM permitted the identification of four ostracod zones: *Cyprideis caraionae* Zone, *Cyprideis minipunctata* Zone, *Cyprideis cyrtoma* Zone and *Cyprideis paralela* Zone, presenting a time range from the middle Miocene (Serravallian) to the late Miocene (Tortonian). Based on the ostracod assemblage, an environment of a semiconfined lake, with mesohaline features and sporadic marine influence is attested to the western Amazonia during the Miocene. The species turnover of *Cyprideis* occurred during the Tortonian.

1. Introduction

Taxonomic studies of the genus *Cyprideis* have been a challenge for specialists due to the large intra-specific morphological variation probably promoted by sympatric evolution forming “flocks” of speciation (Muñoz-Torres et al., 1998; Gross et al., 2014) during the formation of the megawetlands in the Neogene of western Amazonia, such as the mollusks (Wesselingh and Ramos, 2010).

The genus *Cyprideis* is euryhaline and highly eco-phenotypically plastic, commonly associated with lacustrine, estuarine, and coastal environments, thriving especially in brackish waters, due to unique morphological and biological characteristics. Its occurrence is recorded from the Oligocene to the present day (Gliozzi et al., 2017).

During the Neogene, the genus *Cyprideis* underwent a remarkable radiation never seen in other sedimentary basins, leading to exceptional morphological variability among species and posing significant challenges in their taxonomic classification (Muñoz-Torres et al., 1998; Whatley et al., 1998; Gross et al., 2013, 2014). Such diversity within the genus was mainly driven by the evolution and dynamics of environments established in Western Amazonia during this period, largely influenced by geological events such as the Andean orogeny and fluctuations in sea

level (Hoorn et al., 2010; Friaes et al., 2022; Leandro et al., 2022).

Many taxa are still in open nomenclature or in taxonomic review and most recent studies have been trying to unravel how many species have developed and which evolution pattern occurred during the process of this system. In the present study we review the taxonomy of ostracods from five boreholes drilled in the Solimões Formation, located in the western Brazilian Amazonia, Amazonas state (Fig. 1) previously studied by Purper and Pinto (1983, 1985, and references herein).

2. Geological settings

The Solimões Basin (Fig. 1) is classified as an intracratonic Paleozoic sedimentary basin with an east-west orientation that covers approximately 480,000 km² of sedimentary area, limited by the Guiana Shield (north), the Brazilian Shield (south), the Purus Arch (east), and the Iquitos Arch (west). It is subdivided into two sub-basins: the Jandiatuba sub-basin to the west, and the Juruá sub-basin to the east, both are separated by the Caruari Arch (Eiras et al., 1994; Wanderley Filho et al., 2007, 2010).

The Javari group represents the last sedimentary package deposited in the Solimões Basin, and includes the Solimões Formation, the object of the present study, which represents the Neogene period in the basin

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(Caputo et al., 1971; Maia et al., 1977).

The age of the Solimões Formation was inferred through palynostratigraphic studies extending from the early to the late Miocene (Cruz, 1984; Hoorn, 1993, 1994b; Silva-Caminha et al., 2010; Silveira and Souza, 2017; Horbe et al., 2019; Kern et al., 2020). Later, biozonation based on mollusks (Wesselingh et al., 2006b) and ostracods attested the same range (Muñoz-Torres et al., 2006; Linhares et al., 2019).

The lithology of the Solimões Formation is made up of dark, greenish-gray mudstone and siltstone, with shades that vary from light to dark brown in their transition to lignite formation; fine to medium clayey sandstone, whitish, greenish gray, yellowish or brown; breccias with sub-angular fragments, with carbonate, gypsum and ferruginous concretions and lignite intercalations; at the top of its sedimentary unit,

occurs poorly consolidated white sandstone, with sub-angular to sub-rounded grains of fine to coarse grain size (Caputo et al., 1971; Maia et al., 1977; Wanderley Filho et al., 2007).

In Brazil, the Solimões Formation occurs in most of the state of Amazonas, extending to the state of Acre (Acre Basin), reaching a thickness of more than 1000 m (Caputo, 1984; Maia et al., 1977; Latrubesse et al., 2010). In Peru, the Solimões Formation is correlated with the Pebas Formation (Maia et al., 1977; Hoorn, 1994a). Such correlations can be identified mainly by chronological, lithostratigraphic, and paleontological aspects, originated from the same geological and paleoenvironmental historical context (Hoorn et al., 2010; Antoine et al., 2016).

Several paleontological studies carried out in the Solimões Formation demonstrate that the lithostratigraphic unit has a very rich and

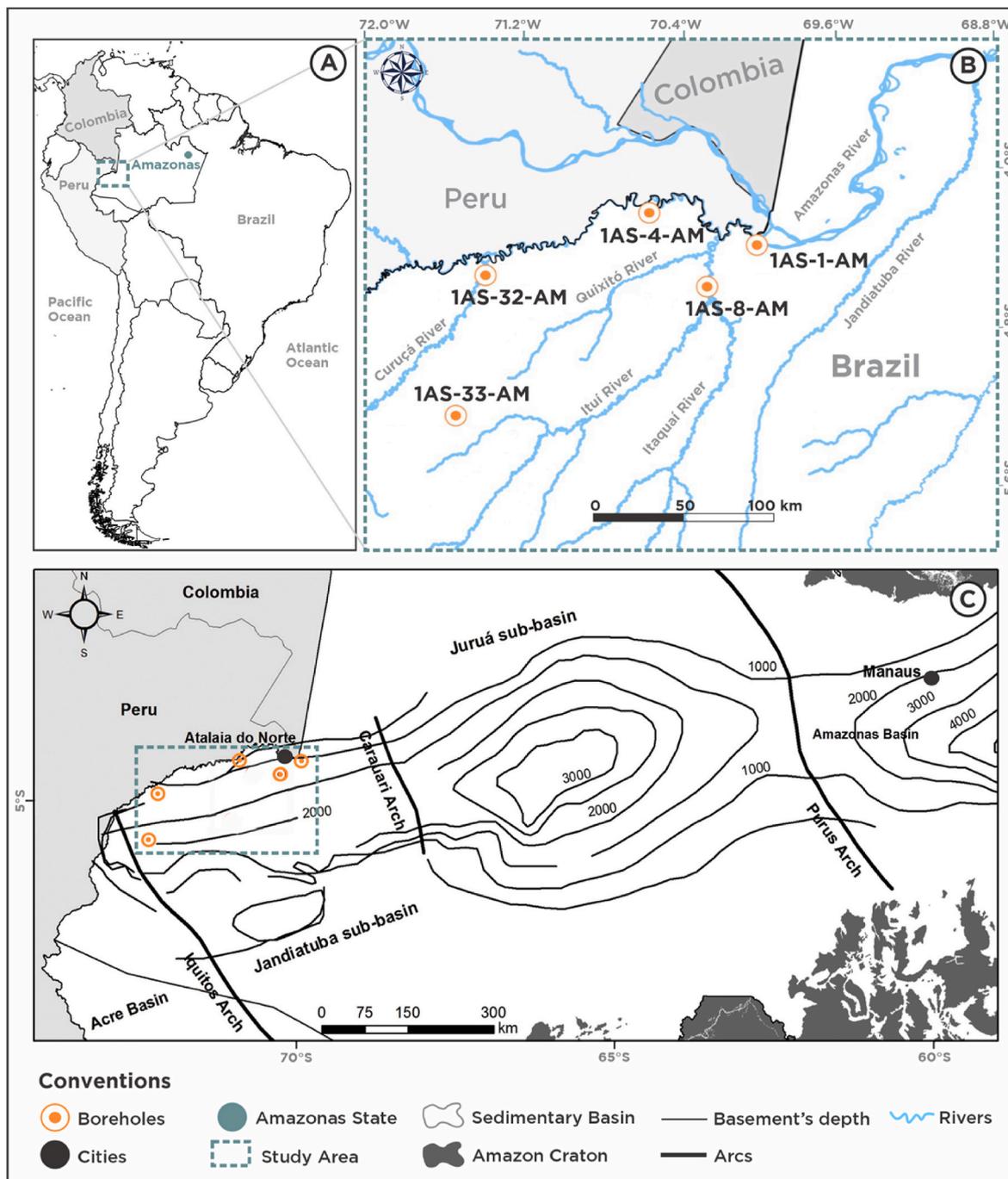


Fig. 1. (A) Location of the study area in South America; (B) details of location of the studied boreholes; (C) overview of Solimões Basin, subdivided into two sub-basins: Juruá (east) and Jandiatuba (west) by the Caraurari Arch. Source: A-B, Authors; C, Linhares and Ramos (2022).

diverse fossil content, including ostracods (Gross et al., 2014; Linhares et al., 2017), mollusks (Wesselingh et al., 2002, 2006a; Wesselingh and Ramos, 2010), foraminifera (Linhares et al., 2011; Leandro et al., 2022), fish, birds (Latrubesse et al., 2010), reptiles (Souza et al., 2016), and wood (Machado et al., 2012).

3. Material and methods

The present study reviewed the ostracod assemblage from five wells (1AS-1-AM, 1AS-4-AM, 1AS-8-AM, 1AS-32-AM and 1AS-33-AM), drilled by the Geological Survey of Brazil (CPRM), near Atalaia do Norte town, in the Amazonas State, northern Brazil, during the project Carvão no Alto Solimões, in the 1970's to investigate the presence of lignite in the area (Maia et al., 1977).

All the material here studied were previously prepared, picked and mounted in specific slides through usual methods study to ostracods (Purper, 1977; Purper and Pinto, 1983, 1985; Purper and Ornellas, 1991; Linhares et al., 2017, 2019).

In the present work the ostracods were reanalyzed taxonomically and the best specimens of each species were picked out with stereoscopic microscope and photographed with scanning electron microscope (SEM) model LEO 1450VP, of the Laboratory of Electronic Microscopy of the Museu Paraense Emílio Goeldi (MPEG).

For comparative study, the type material of Purper (1979) and Purper and Ornellas (1991), housed at UFRGS microfossil collection, and the type material of Linhares et al. (2017, 2019), Gross et al. (2013, 2014), Linhares and Ramos (2022) and Sousa and Ramos (2023) housed in the micropaleontological collection of the Museu Paraense Emílio Goeldi (MPEG), were also consulted. The suprageneric classification follows Liebau (2005).

The type material and figured specimens here studied are all housed in the micropaleontological collection of the MPEG, Pará State, Brazil, under catalogue number MPEG-992-M to MPEG-1097-M.

Morphological abbreviations: LV = left valves; RV = right valves; H = height; L = length.

4. Results

4.1. Qualitative and quantitative analysis of the ostracods from the studied wells

Among the 98 samples analyzed from the five investigated wells (1AS-1-AM, 1AS-4-AM, 1AS-8-AM, 1AS-32-AM and 1AS-33-AM), a total of 9,095 ostracod valves (including carapaces) were counted (Table 2). The samples comprised eight genera: *Cypria*, *Cyprideis*, *Cytheridella*, *Paracypris*, *Pellucistoma*, *Penthesilenula*, *Perissocytheridea*, and *Rhadinocytherura*.

Regarding the genus *Cyprideis*, twenty-two species were identified, in which nineteen were previously recorded besides two new species here described: *Cyprideis goeldiensis* sp. nov., *Cyprideis javariensis* sp. nov.; one other species was maintained with open nomenclature (*Cyprideis* sp. 1) due to poor material recovery.

The quantitative and qualitative analysis of ostracods in the analyzed samples revealed that the genus *Cyprideis* predominates in the study area, represented by 95.05% (Table 1) of the total identified genera.

Table 1

Percentage of genera occurrence in the study area.

Genera	<i>Cyprideis</i>	<i>Perissocytheridea</i>	<i>Penthesilenula</i>	Other genera (<0.5%): <i>Cypria</i> , <i>Cytheridella</i> , <i>Paracypris</i> , <i>Pellucistoma</i> , <i>Rhadinocytherura</i>
Percentage of occurrence	95.05%	2.61%	1.27%	1.07%

In the study area the most abundant species of the genus *Cyprideis* (Table 2) are: *Cyprideis multiradiata*, *Cyprideis caraionae*, *Cyprideis javariensis* sp. nov., *Cyprideis machadoi*, and *Cyprideis sulcosigmoidalis*. The most frequent species are *Cyprideis machadoi*, *Cyprideis ituiaie*, and *Cyprideis sulcosigmoidalis*, occurring in all studied cores.

Regarding the newly described species, *Cyprideis goeldiensis* sp. nov. and *Cyprideis javariensis* sp. nov., co-occur in wells 1AS-1-AM, 1AS-4-AM, 1AS-8-AM, and 1AS-32-AM, although *Cyprideis javariensis* sp. nov. is far more abundant than *Cyprideis goeldiensis* sp. nov.; and among the other genera, *Perissocytheridea* and *Penthesilenula* are predominant, with 244 and 119 valves, respectively. Concerning the rest of the genera, they compose about 1.07% of the identified assemblage (Table 1).

It is also worth to mention that the species *Cyprideis santaelenae* Sousa and Ramos (2023), originally recorded in Iquitos, Peru, was identified for the first time in the Solimões Formation. However, it is restricted to the depth 197 m of the core 1AS-33-AM.

4.2. Systematic paleontology

Class Ostracoda Latreille, 1802

Superorder Podocopomorpha Kozur, 1972

Order Podocopida Sars, 1866.

Superfamily Cytheroidea Baird, 1850.

Family Cytherideidae Sars, 1925

Subfamily Cytherideinae Sars, 1925.

Genus *Cyprideis* Jones, 1857

Type-species: *Candona torosa* Jones (1850). Pleistocene Beds of Newbury Copford, England.

***Cyprideis goeldiensis* sp. nov.**

Fig. 2, 1–34.

2014 *Cyprideis* aff. *graciosa* Purper (1979); Gross et al. (2014): 56, pl. 7, Figs. 1–20.

Etymology: In reference to the researcher Emílio Goeldi.

Holotype: Female, carapace (MPEG-992-M).

Paratypes: Females, valves (MPEG-993-M, MPEG-994-M, MPEG-998-M - MPEG-1001-M); males, carapace (MPEG-995-M) and valves (MPEG-996-M, MPEG-997-M, MPEG-1002-M - MPEG-1005-M).

Type-locality: Borehole 1AS-1-AM (90 m), lat. 04°22'S long. 70°01'W, Javari River.

Diagnosis: Sub-rectangular outline species, with eight spines along the entire anterior margin. Posterior margin truncated. Posteroventral region with three small vestigial spines and an additional well-developed one, closer to the ventral region. Surface with strong reticulation, although it is almost smooth in the anterior region.

Description: Sub-rectangular (female) to subtriangular (male) outline in lateral view. Remarkable inclined cardinal angle, creating a convexity on the dorsal margin. Anterior margin with well-developed flange, with approximately eight thick spines spaced apart and sometimes, smaller spines are associated. Ventral margin of the right valve with slight oral concavity and almost straight in the left valve. Posterior margin truncated, with four posteroventral spines, three of which are almost always vestigial; in addition, a long and developed one closer to the ventral margin.

The hinge is typical of the genus, well developed, with positive elements on the right valve, divided into four elements: the anterior element is the most expressive with nine teeth; crenulated and short anteromedial element; posteromedial element also crenulated, however longer; and posterior element with six teeth. On the left valve, the hinge elements are negative, complementing the ones on the right valve. The internal lamella is well developed, thick and marked on both valves. Groove in the dorsal anteromedian region, slightly marked, and more noticeable on the left valve. This species surface is strongly reticulated and in the anterior region it is almost smooth. Set of muscle scars is also very typical of the genus, where the central scars constitute a vertical row of four adductor impressions and a V-shaped frontal scar; a group of

Table 2
Number of specimens per species recovered in the studied wells.

Studied wells		1AS-1-AM	1AS-4-AM	1AS-8-AM	1AS-32-AM	1AS-33-AM	Total of valves per species
Genus <i>Cyprideis</i> species	<i>Cyprideis amazonica</i>	13	0	10	272	180	475
	<i>Cyprideis caraionae</i>	0	0	0	439	1235	1674
	<i>Cyprideis curucae</i>	5	24	5	7	0	41
	<i>Cyprideis cyrtoma</i>	4	0	20	110	0	134
	<i>Cyprideis inversa</i>	15	43	0	45	4	107
	<i>Cyprideis ituiaie</i>	33	203	26	219	2	483
	<i>Cyprideis longispina</i>	1	0	0	0	0	1
	<i>Cyprideis machadoi</i>	81	119	118	324	162	804
	<i>Cyprideis marginuspinosa</i>	0	0	2	10	0	12
	<i>Cyprideis matorae</i>	1	9	9	0	0	19
	<i>Cyprideis minipunctata</i>	0	13	36	23	0	72
	<i>Cyprideis multiradiata</i>	562	555	364	391	92	1964
	<i>Cyprideis munoztorresi</i>	21	113	98	38	0	270
	<i>Cyprideis olivencai</i>	0	0	0	9	0	9
	<i>Cyprideis paralela</i>	20	9	0	46	17	92
	<i>Cyprideis retrobispinosa</i>	0	0	0	301	0	301
	<i>Cyprideis santaelenae</i>	0	0	0	0	37	37
	<i>Cyprideis anterospinosa</i>	0	0	34	11	0	45
	<i>Cyprideis sulcosigmoidalis</i>	75	160	162	169	64	630
	<i>Cyprideis goeldiensis</i> sp. nov.	12	0	62	7	0	81
<i>Cyprideis javariensis</i> sp. nov.	4	56	18	1307	0	1385	
<i>Cyprideis</i> sp. 1	0	6	0	0	0	6	
Other genera	<i>Cypria</i>	14	0	0	3	7	24
	<i>Cytheridella</i>	1	0	2	2	1	6
	<i>Paracypris</i>	2	5	0	5	1	13
	<i>Pellucistoma</i>	0	20	0	1	0	21
	<i>Penthesilenula</i>	8	57	0	37	17	119
	<i>Perissocytheridea</i>	10	142	12	38	42	244
	<i>Rhadinocytherura</i>	2	18	0	2	4	26

dorsal scars above the central ones; two mandibular scars below, a smaller lower one and a larger upper one.

Strong sexual dimorphism, with females more inflated than males. The males are more elongated and tapered with a subtriangular posterior margin, and an anterior margin with much longer and more developed spines.

Material: 63 valves, 9 carapaces.

Dimensions (mm): MPEG-992-M (holotype), female, LV: L: 0.87, H: 0.47; MPEG-992-M (holotype), female, RV: L: 0.86, H: 0.47; MPEG-993-M (paratype), female, LV: L: 0.85, H: 0.46; MPEG-994-M (paratype), female, RV: L: 0.84, H: 0.45; MPEG-995-M (paratype), male, LV: L: 0.88, H: 0.45; MPEG-995-M (paratype), male, RV: L: 0.93, H: 0.47; MPEG-996-M (paratype), male, LV: L: 0.92, H: 0.46; MPEG-997-M (paratype), male, RV: L: 0.79, H: 0.38; MPEG-998-M (paratype), female, LV: L: 0.86, H: 0.47; MPEG-999-M (paratype), female, RV: L: 0.83, H: 0.44; MPEG-1000-M (paratype), female, LV: L: 0.87, H: 0.47; MPEG-1001-M (paratype), female, RV: L: 0.81, H: 0.43; MPEG-1002-M (paratype), male, LV: L: 0.93, H: 0.46; MPEG-1003-M (paratype), male, RV: L: 0.91, H: 0.45; MPEG-1004-M (paratype), male, LV: L: 0.90, H: 0.43; MPEG-1005-M (paratype), male, RV: L: 0.89, H: 0.43.

Remarks: *Cyprideis goeldiensis* sp. nov. is similar to the species *C. graciosa* Purper (1979), however it differs in outline, where the species described here is more sub-rectangular while *C. graciosa* is more subtriangular, with a posterodorsal margin more inclined towards the posteroventral margin. *C. graciosa* has a more median sulcus. It also differs in ornamentation pattern, which *C. graciosa* has a strongly punctuated ornamentation over its margins, differing from the smooth surface on the *C. goeldiensis* sp. nov. margins. A posteroventral spine occurs on the left valve of *C. graciosa*, which is absent on the species here described, and less developed anterior and posterior spines with a wider posteroventral flange than in *C. goeldiensis* sp. nov.

The strong sexual dimorphism can be observed when females are more inflated than males, and the males which are more elongated and tapered with a subtriangular posterior margin, and an anterior margin with much longer and more developed spines than the ones in the female.

In Gross et al. (2014), the *Cyprideis* aff. *graciosa* group (Plate 6, Figs. 33–44; Plate 7, Figs. 1–20) is referred as a diversity of specimens consider very similar to *C. graciosa* species, but differ in ornamentation pattern, and for that this group stayed in open taxonomic classification. Between the specimens illustrated in Gross et al. (2014) (Plate 6, Figs. 33–44), some specimens differ from the species here described mainly in the more punctuated ornamentation pattern than the strong reticulation present in *C. goeldiensis* sp. nov., in addition to thinner marginal ribs; antero and posteromarginal spines, are more elongated when present. Furthermore, they have a smaller average size than the new species here presented. The other specimens illustrated by Gross et al. (2014) as *C. aff. graciosa* (Pl. 7, Figs. 1–20) are very similar to the species *C. goeldiensis* sp. nov., although they are slightly smaller and, differ only in the posteroventral marginal spines, that are more developed and preserved in Gross et al. (2014), they are here considered to be the same species.

Cyprideis goeldiensis sp. nov. is also quite similar to *Cyprideis indianensis* Sousa and Ramos (2023), described for the Neogene deposits of the Pebas Formation, Iquitos region, in Peru, however it differs in the ornamentation of its margins, which is smooth in *C. goeldiensis* sp. nov., and in the anterior marginal spines that are more elongated, thicker and occurs in greater numbers in *C. goeldiensis* sp. nov., with eight spines, while *C. indianensis* has seven anteromarginal spines. Posterior margin is more truncated and larger in *C. goeldiensis* sp. nov.

Geographic and stratigraphic distribution: in this work: boreholes 1AS-1-AM (90 m, 103.5 m), close to the Amazonas River; 1AS-8-AM (110.6 m, 110.8 m), close to the Ituí River; and 1AS-32-AM (41 m, 50 m), close to the Curuçá River, western of the Amazonas State, Brazil. Solimões Formation, Miocene; in Gross et al. (2014): borehole 1AS-10-AM (130.7 m, 141.2 m) close to Ituí River, western Amazonia, Brazil. Solimões Formation, Miocene.

***Cyprideis javariensis* sp. nov.**

Fig. 3, 1–32.

Etymology: In reference to the Javari River, near the species type-locality, well 1AS-32-AM.

Holotype: Female, carapace (MPEG-1006-M, MPEG-1007-M).

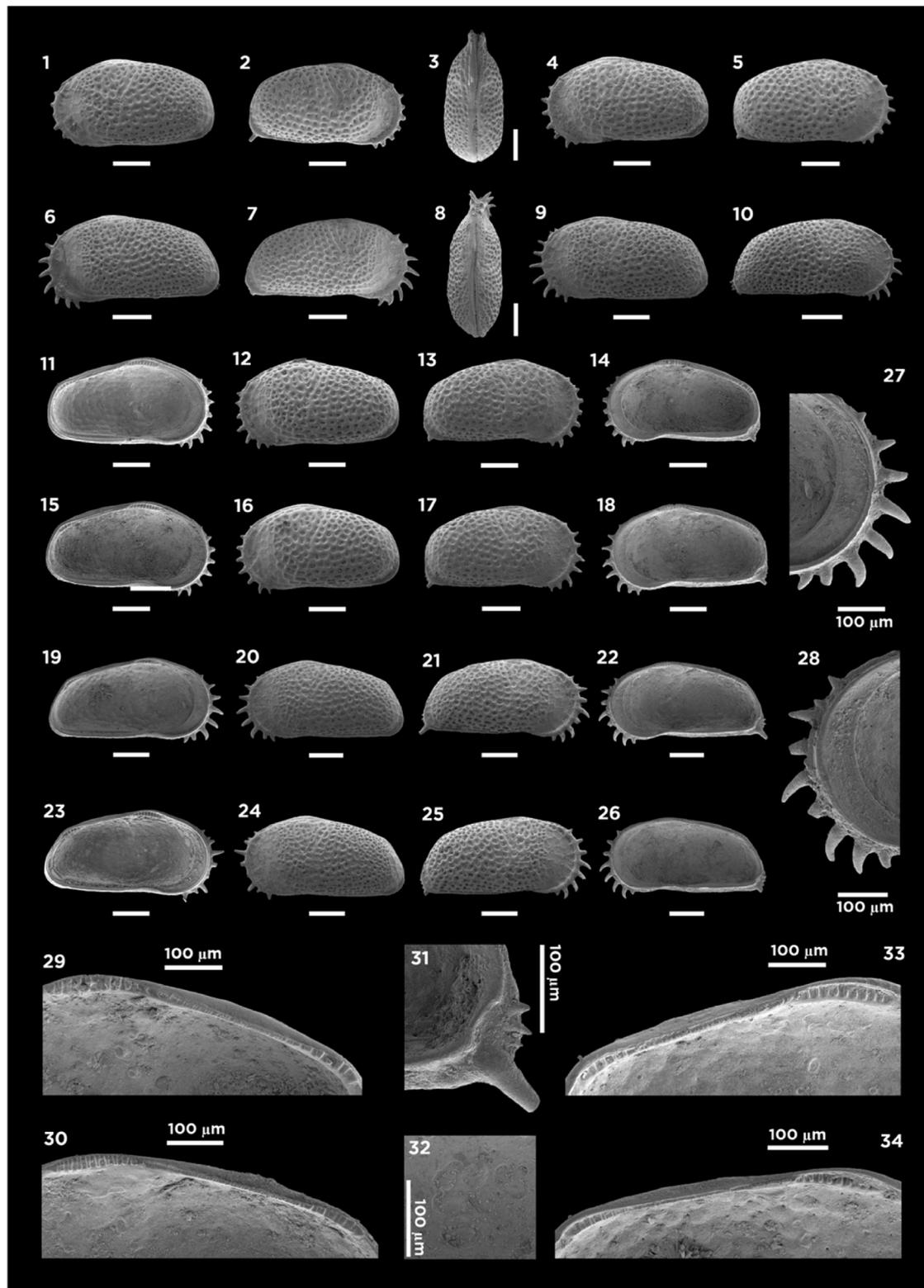


Fig. 2. 1–34, *Cyprideis goeldiensis* sp. nov. 1. (MPEG-992-M), female, LV, external view (holotype); 2. (MPEG-992-M), female, RV, external view (holotype); 3. (MPEG-992-M), female, dorsal view (holotype); 4–26, (paratypes) 4. (MPEG-993-M), female, LV, external view; 5. (MPEG-994-M), female, RV, external view; 6. Paratype (MPEG-995-M), male, LV, external view; 7. Paratype (MPEG-995-M), male, RV, external view; 8. Paratype (MPEG-995-M), male, dorsal view; 9. (MPEG-996-M), male, LV, external view; 10. (MPEG-997-M), male, RV, external view; 11–12. (MPEG-998-M), female, LV, internal and external view; 13–14. (MPEG-999-M), female, RV, external and internal view; 15–16. (MPEG-1000-M), female, LV, internal and external view; 17–18. (MPEG-1001-M), female, RV, external and internal view; 19–20. (MPEG-1002-M), male, LV, internal and external view; 21–22. (MPEG-1003-M), male, RV, internal and external view; 23–24. (MPEG-1004-M), male, LV, internal and external view; 25–26. (MPEG-1005-M), male, RV, external and internal view; 27. (MPEG-1002-M), details of the anteromarginal spines and inner lamella; 28. (MPEG-1003-M), details of the anteromarginal spines and inner lamella; 29. (MPEG-999-M), details of the hinge structure; 30. (MPEG-1003-M), details of the hinge structure; 31. (MPEG-1003-M), details of the posteroventral spines; 32. (MPEG-1002-M), details of the muscle scars; 33. (MPEG-998-M), details of the hinge; 34. (MPEG-1002-M), details of the hinge.

Paratypes: Females, valves (MPEG-1008-M, MPEG-1009-M, MPEG-1014-M - MPEG-1019-M); males, valves (MPEG-1010-M - MPEG-1013-M).

Type-locality: Borehole 1AS-32-AM (41 m), lat. 04°32'S long. 71°24'W, Curuçá River.

Diagnosis: Sub-rectangular outline species. Anterior margin rounded with about nine curved spines in both valves. Posterior margin of the right valve with three to four vestigial spines and a long, very well-developed one in the lower region. Pointed reticulation, more frequent in the marginal regions and smoother in the anterior region.

Description: sub-rectangular outline in lateral view. Dorsal margin slightly concave in the median region, followed by a discreet cardinal angle, truncated towards the anterior region. Rounded anterior margin with marked ribs with about nine spaced and curved medium size spines. Ventral margin is almost straight, being discreetly sinuous where the oral concavity occurs. The posterior margin is truncated and more rounded on the left valve; the posteroventral flange is short, with three to four inconspicuous spines, in addition to a more developed and long one in the lower portion. Pointed reticulation, becoming more frequent towards the marginal regions and almost smooth in the anterior region. Moderately marked groove, located in the dorsal anteromedian region, inclined towards the anterior portion. Strong sexual dimorphism, with shorter females, generally more inflated and with a sub-oval outline, while males are longer, tapering in the posterior region.

Material: 1335 valves, 25 carapaces.

Dimensions (mm): MPEG-1006-M (holotype), female, LV: L: 0.88, H: 0.50; MPEG-1007-M (paratype), female, RV: L: 0.84, H: 0.48; MPEG-1008-M (paratype), female, LV: L: 0.91, H: 0.52; MPEG-1009-M (paratype), female, RV: L: 0.84, H: 0.46; MPEG-1010-M (paratype), male, LV: L: 0.98, H: 0.49; MPEG-1011-M (paratype), male, RV: L: 0.99, H: 0.46; MPEG-1012-M (paratype), male, LV: L: 0.97, H: 0.48; MPEG-1013-M (paratype), male, RV: L: 0.98, H: 0.48; MPEG-1014-M (paratype), female, LV: L: 0.91, H: 0.52; MPEG-1015-M (paratype), female, RV: L: 0.86, H: 0.46; MPEG-1016-M (paratype), female, LV: L: 0.84, H: 0.48; MPEG-1017-M (paratype), female, RV: L: 0.81, H: 0.44; MPEG-1018-M (paratype), female, LV: L: 0.83, H: 0.40; MPEG-1019-M (paratype), female, RV: L: 0.83, H: 0.46.

Remarks: *Cyprideis javariensis* sp. nov. is similar to *Cyprideis marginuspinosa* Purper and Ornellas (1991) and *Cyprideis indianensis* Sousa and Ramos (2023) species. Therefore, those species were individually compared here in more details.

a) *Cyprideis javariensis* sp. nov. x *Cyprideis marginuspinosa* Purper and Ornellas (1991)

Females: The females of both mentioned species can be well differentiated in terms of outline, in which *C. marginuspinosa* is less oval and inflated. The reticulation patterns are also different. The punctuation in *C. javariensis* sp. nov. much more spaced and coarser; and in *C. marginuspinosa*, is more delicate and frequent. Finally, they also differ in the spine occurrences, those are thicker and more curved in *C. javariensis* sp. nov than the ones in *C. marginuspinosa*.

Males: The outline in male valves of both species are very similar, they differ mainly in terms of ornamentation, which like in the females, tends to be a more delicate and frequent pattern of punctuation in *Cyprideis marginuspinosa*.

The marginal ribs are more evident in *C. javariensis* sp. nov., and its anterior margin flange is thicker. Furthermore, the dorsal outline is slightly concave, which gives a more subtriangular outline to the *C. marginuspinosa* species, while in *C. javariensis* sp. nov. that outline is straight. In the ventral region of *C. marginuspinosa* there is a sinuosity close to the oral concavity, differing from *C. javariensis* sp. nov. that has a straight ventral margin.

b) *Cyprideis javariensis* sp. nov. x *Cyprideis indianensis* Sousa and Ramos (2023)

Females: In outline, *C. indianensis* has a more sub-rectangular and elongated shape, and even though *C. javariensis* sp. nov. also has a sub-rectangular shape, it tends to be more rounded. Both species can also be differed by their anterior spines, which are longer and curved in *C. javariensis* sp. nov. than the shorter and straighter ones in *C. indianensis*.

Males: The males of both species are very distinct. In outline, *C. indianensis* appears to have a tapered sub-rectangular shape, with a much more pronounced posterior margin. While *C. javariensis* is more sub-rectangular, with almost parallel dorsal and ventral margins.

They also differ in size, where *C. javariensis* is bigger than *C. indianensis*. In addition, the anteromarginal spines in *C. indianensis* are short and almost straight, and in *C. javariensis* they are longer and curved.

Geographic and stratigraphic distribution: Boreholes 1AS-1-AM (90 m), close to Amazonas River, and 1AS-32-AM (41 m, 50 m, 70 m, 107 m), Curuçá River, western of the Amazonas State. Brazil. Solimões Formation, Miocene.

Cyprideis sp. 1 (Fig. 4, 1–16)

Figured specimens: MPEG-1020-M, female, RV: L: 0.82, H: 0.43; MPEG-1021-M, female, RV: L: 0.82, H: 0.44; MPEG-1022-M, male, RV: L: 0.83, H: 0.41; MPEG-1023-M, male, RV: L: 0.94, H: 0.45; MPEG-1024-M, male, RV: L: 0.84, H: 0.42; MPEG-1025-M, male, RV: L: 0.82, H: 0.41.

Material: Six valves.

Description: *Cyprideis* sp. 1 has a very peculiar morphology, right valve with a sub-oval (female) to subtriangular (male) outline in lateral view. The dorsal margin is slightly convex, with a very discreet cardinal angle in the female, and more pronounced in the male, truncated towards the anterior region. It has a rounded anterior margin, with approximately eight long, spaced and very curved spines, which may occur associated with other straight and short spines. The posterior margin has a sub-oval outline, where there is a very pronounced flange in the posteroventral region, with a group of four short spines and in the male, there is a larger spine in the lower portion. Straight ventral margin with very discreet oral concavity. Strongly punctuated reticulation, with a robust appearance, that tends to be smooth in the anterior region. Discreetly marked groove in diagonal position, located in the middle of the dorsal line and is inclined towards the anterior region. Strong sexual dimorphism, with more inflated females and thinner males with more expressive spines in the posteroventral region.

Remarks: Only right valves were recovered of this species. The only species that has similar morphological features to *Cyprideis* sp. 1 is the species *Cyprideis curucae*, as both have coarse, strongly punctuated reticulation and long, curved marginal spines. However, both differ greatly in outline, since *C. curucae* is more sub-rectangular, does not have sinuosity on the ventral margin, nor have a pronounced posterior flange with well-developed spines, as occurs in *C. sp. 1*. Furthermore, *Cyprideis curucae* has very strong reticulation throughout its valves, and in *Cyprideis* sp. 1, the surface is almost smooth in the anterior region.

During this study, only two valves which were assumed to be from the female and four valves from the male of *Cyprideis* sp. 1 were found. Thus, due to the unavailability of sufficient material for a more precise and appropriate definition and description of a new species, it was maintained in open nomenclature.

Geographic and stratigraphic distribution: Borehole 1AS-4-AM (39 m), close to Javari River, western of the Amazonas State. Brazil. Solimões Formation, Miocene.

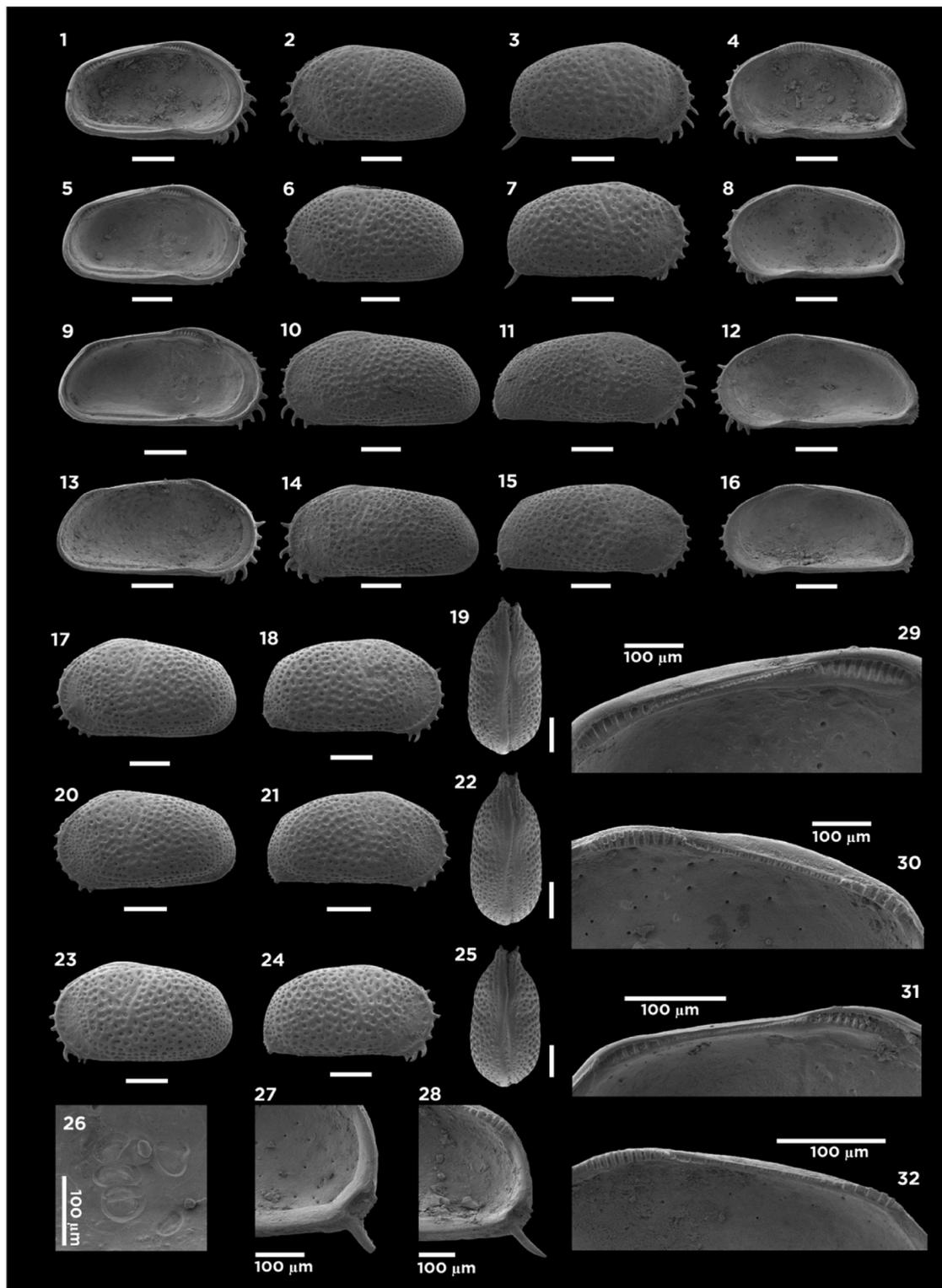


Fig. 3. 1–32, *Cyprideis javariensis* sp. nov., 1–2. (MPEG-1006-M), female, LV, internal and external view (holotype); 3–4. (MPEG-1007-M), female, RV, valve, external and internal view (holotype); (5–25, paratypes) 5–6. (MPEG-1008-M), female, LV, internal and external view; 7–8. (MPEG-1009-M), female, RV, external and internal view; 9–10. (MPEG-1010-M), male, LV, internal and external view; 11–12. (MPEG-1011-M), male, RV, external and internal view; 13–14. (MPEG-1012-M), male, LV, view internal and external; 15–16. (MPEG-1013-M), male, RV, external and internal view; 17. (MPEG-1014-M), female, LV, external view; 18. (MPEG-1015-M), female, right valve, external view; 19. (MPEG-1014-M, MPEG-1015-M), female, dorsal view; 20. (MPEG-1016-M), female, LV, external view; 21. (MPEG-1017-M), female, RV, external view; 22. (MPEG-1016-M, MPEG-1017-M), female, dorsal view; 23. (MPEG-1018-M), female, LV, external view; 24. (MPEG-1019-M), female, right valve, external view; 25. (MPEG-1018-M, MPEG-1019-M), female, dorsal view; 26. (MPEG-1008-M), details of the muscle scars; 27. (MPEG-1009-M), details of the posteroventral spine; 28. (MPEG-1007-M) Details of the posteroventral spine; 29. (MPEG-1008-M), details of the hinge; 30. (MPEG-1009-M), details of the hinge; 31. (MPEG-10010-M), details of the hinge; 32. (MPEG-1011-M), details of the hinge.

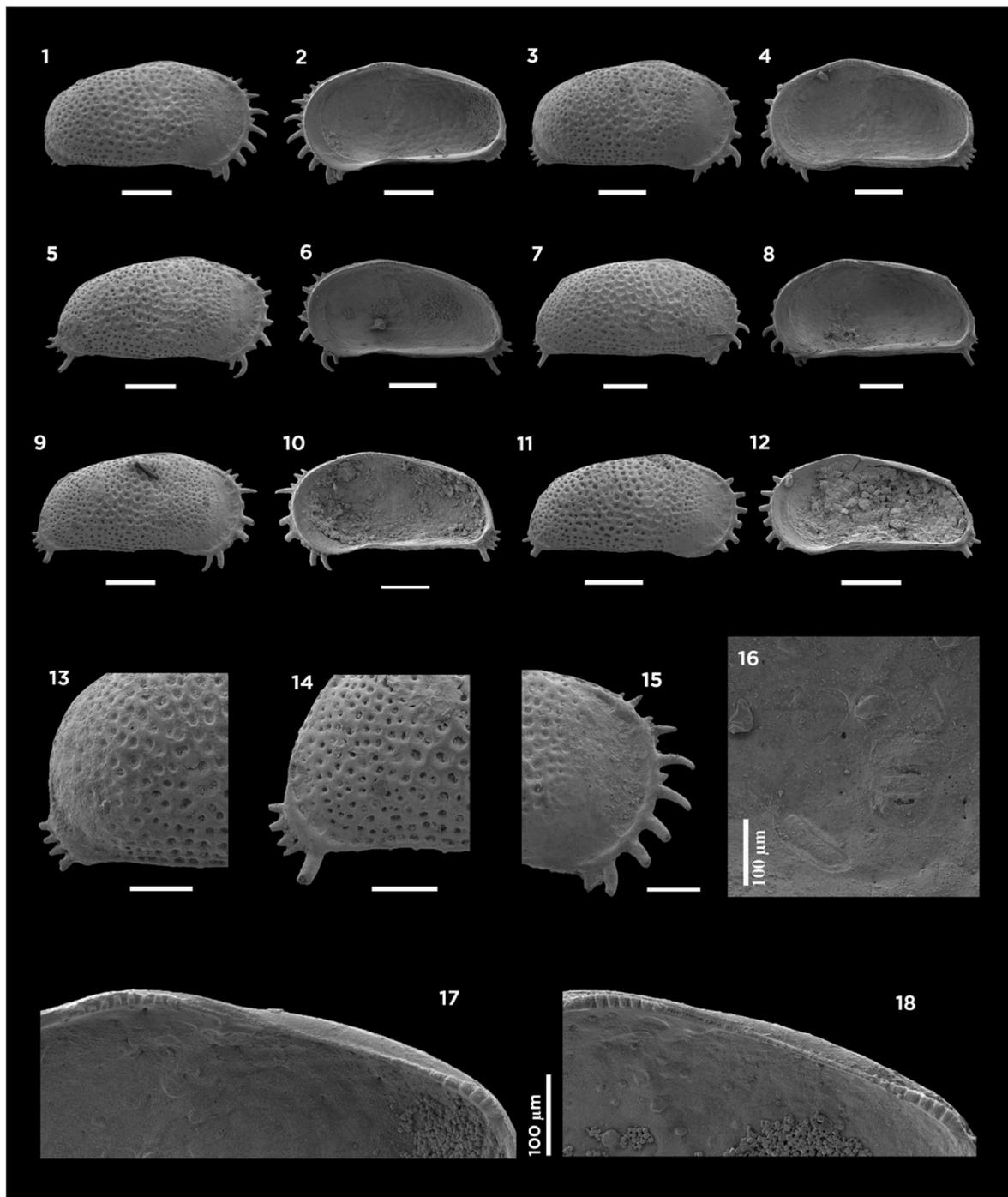


Fig. 4. 1–16, *Cyprideis* sp. 1. 1–2. (MPEG-1020-M), female, RV, external and internal view (0.82; 0.43); 3–4. (MPEG-1021-M), female, RV, external and internal view (0.82; 0.44); 5–6. (MPEG-1022-M), male, RV, view external and internal (0.83; 0.41); 7–8. (MPEG-1023-M), male, RV, external and internal view (0.94; 0.45); 9–10. (MPEG-1024-M), male, RV, external and internal view (0.84; 0.42); 11–12. (MPEG-1025-M), male, RV, external and internal view (0.82; 0.41); 13. (MPEG-1021-M), details of the posteroventral spines; 14. (MPEG-1024-M), details of the posteroventral spines; 15. (MPEG-1020-M), details of the anterior marginal spines; 16. (MPEG-1020-M), details of muscle scars; 17. (MPEG-1020-M), details of the hinge; 18. (MPEG-1022-M), details of the hinge.

4.3. Additional remarks

Between the nineteen *Cyprideis* species already described in the literature and recognized in the studied samples two of them are worth to mention, due to intra-specific morphologic variation here observed.

Cyprideis matorae Gross et al. (2014) (Fig. 5, 1–16)

To the present date, in general, the internal and external taxonomic features of all the specimens of *Cyprideis matorae* already identified are very similar (Linhares et al., 2011; Gross et al., 2014; Linhares and

Ramos, 2022). However, in the present study some morphological variations were noted in specimens here identified; it was possible to observe that the polygonal-shaped reticulation in the external surface appears to be stronger and thicker walls. In addition, the occurrence of one or two larger posteroventral spines on the left valve of the female and three very evident spines on the right valves of both male and female, were not yet observed in specimens illustrated in previous studies (in Linhares et al., 2011: Fig. 3/15; in Gross et al., 2014: Fig. 6l-m, Pl. 12, Figs. 1–14; and in Linhares and Ramos, 2022: Fig. 5Q, R). Therefore,

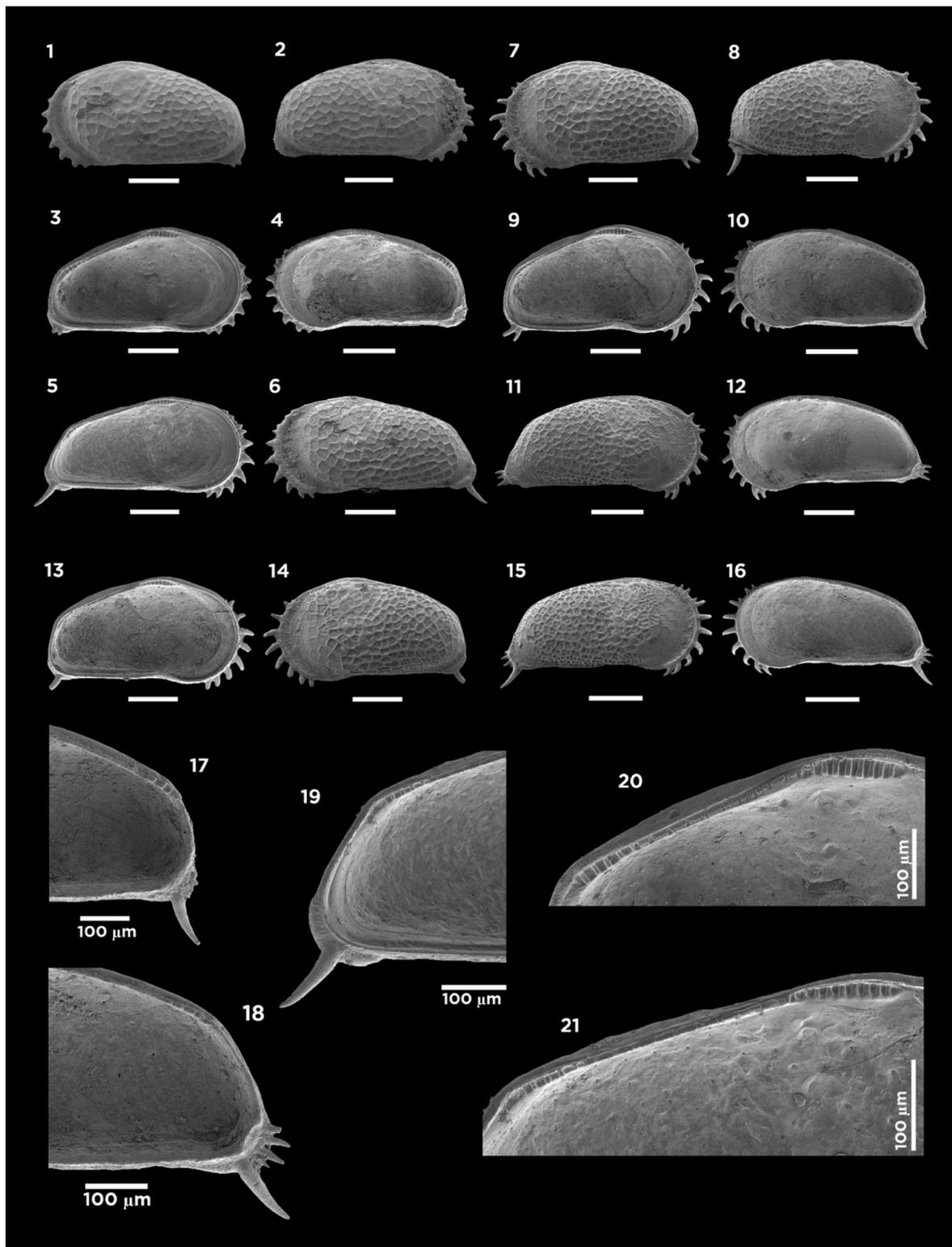


Fig. 5. 1–21, *Cyprideis matorae* Gross et al., (2014). 1, 3. (MPEG-1026-M), female, LV, external and internal view (0.78; 0.41); 2, 4. (MPEG-1027-M), female, RV, external and internal view (0.77; 0.41); 5, 6. (MPEG-1030-M), male, LV, internal and external view (0.80; 0.38); 7, 9. (MPEG-102-8M), female, LV, external and internal view (0.77; 0.43); 8, 10. (MPEG-1029-M), female, RV, external and internal view (0.73; 0.38); 11–12. (MPEG-1031-M), male, RV, external and internal view (0.74; 0.36); 13–14. (MPEG-1032-M), female, LV, internal and external view (0.75; 0.40); 15–16. (MPEG-1033-M), male, RV, external and internal view (0.75; 0.35); 17. (MPEG-1029-M), details of the posteroventral spines, internal view; 18. (MPEG-1033-M), details of the posteroventral spines, internal view; 19. (MPEG-1030-M), details of the posteroventral spines, internal view; 20. (MPEG-1026-M), details of the hinge; 21. (MPEG-1030-M), details of the hinge.

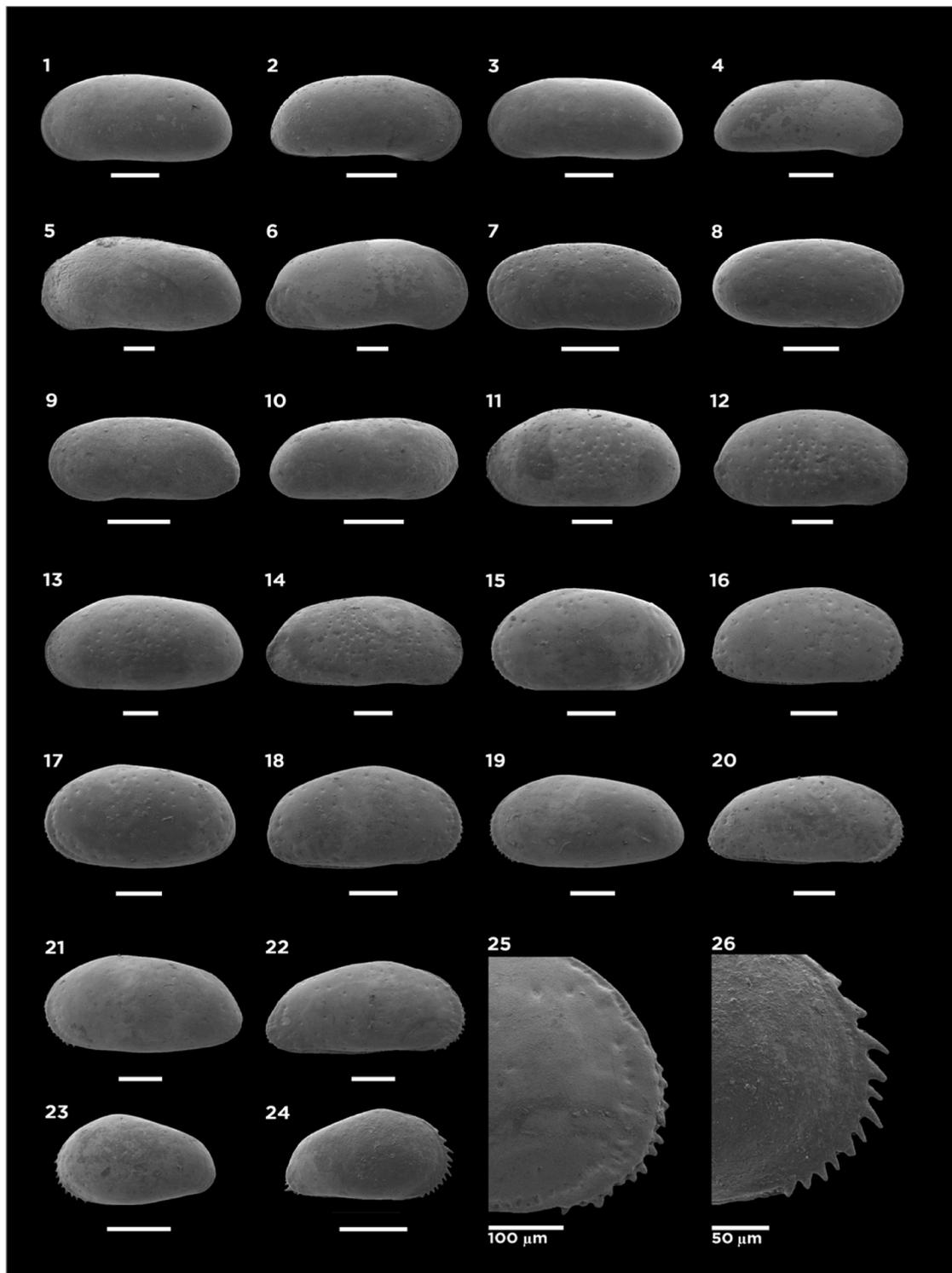


Fig. 6. 1–26, *Cyprideis* species of smooth surface, 1–4. *C. multiradiata* Purper (1979), 1. (MPEG-1034-M), female, LV, external view (0.81; 0.39); 2. (MPEG-1035-M), female, RV, external view (0.78; 0.38); 3. (MPEG-1036-M), male, LV, external view (0.83; 0.39); 4. (MPEG-1037-M), male, RV, external view (0.85; 0.37); 5–6. *C. machadoi* Purper (1979), 5. (MPEG-1038-M), female, LV, external view (1.32; 0.65); 6. (MPEG-1039-M), female, RV, external view (1.31; 0.63); 7–10. *C. paralela* Purper (1979), 7. (MPEG-1040-M), female, LV, external view (0.69; 0.33); 8. (MPEG-1041-M), female, RV, external view (0.70; 0.35); 9. (MPEG-1042-M), male, RV, external view (0.61; 0.29); 10. (MPEG-1043-M), male, RV, external view (0.63; 0.29); 11–14. *C. amazonica* Purper (1979), 11. (MPEG-1044-M), female, LV, external view (0.96; 0.53); 12. (MPEG-1045-M), female, RV, external view (0.98; 0.54); 13. (MPEG-1046-M), male, LV, external view (1.11; 0.57); 14. (MPEG-1047-M), male, RV, external view (1.07; 0.53); 15–26. *C. caraionae* Purper and Pinto (1983), 15. (MPEG-1048-M), female, LV, external view (0.83; 0.48); 16. (MPEG-1049-M), female, RV, external view (0.81; 0.44); 17. (MPEG-1050-M), female, LV, external view (0.86; 0.50); 18. (MPEG-1051-M), female, RV, external view (0.79; 0.45); 19. (MPEG-1052-M), male, LV, external view (0.88; 0.46); 20. (MPEG-1053-M), male, RV, external view (0.94; 0.46); 21. (MPEG-1054-M), male, LV, external view (0.92; 0.49); 22. (MPEG-1055-M), female, RV, external view (0.90; 0.46); 23. (MPEG-1056-M), juvenile, LV, external view (0.49; 0.30); 24. (MPEG-1057-M), juvenile, RV, external view (0.47; 0.28); 25. (MPEG-1055-M), details of the anterior marginal spines; 26. (MPEG-1057-M), details of the anterior marginal spines.

considering all morphological peculiarities presented, a new variation of the *Cyprideis matorae* species is here proposed.

Geographic and stratigraphic distribution: in this work: boreholes 1AS-4-AM (57.0 m), and 1AS-8-AM (110.6 m), western of the Amazonas State. Brazil. Solimões Formation, Miocene. In [Linhares et al. \(2011\)](#): borehole 1AS-31-AM (172.4 m); in [Gross et al. \(2014\)](#): borehole 1AS-10-AM (118.0 m and 141.2 m); in [Kern et al. \(2020\)](#): borehole 1AS-14-AM (109.0 m); in [Linhares and Ramos \(2022\)](#): borehole 1AS-7D-AM (50.0 m, 103.7 m, 111.5 m and 115.5 m), 1AS-8-AM (110.6 m) and 1AS-31-AM (174.55 m), western of the Amazonas State. Brazil. Solimões Formation, Miocene.

***Cyprideis santaelenae* Sousa and Ramos (2023) (Fig. 7, 5–8)**

The specimens of *Cyprideis santaelenae* [Sousa and Ramos \(2023\)](#) identified in this study are highly compatible with the type species recently described, in sedimentary material from the Pebas Formation (Peru), however it is possible to observe some variations.

The left valves of the female are quite similar when compared in lateral view, however they differ in some morphological structures in the right valves: the specimens from the Pebas Formation appear to be more inflated, with a more sub-rectangular anterior outline and the occurrence of a group of small spines, together with a larger one in the posteroventral region; the valves studied here have more marked marginal ribs and the group of posteroventral spines on the right valve is always vestigial and the larger spine is always absent.

As for the valves of the male, the specimens from the Pebas Formation have a more subtriangular outline, stronger reticulation and better developed anterior and posteroventral spines. Specimens from the Solimões Formation have shorter anterior spines and more discreet vestigial posteroventral ones, and as in the female valves of Solimões Formation, the larger spine is always absent.

Despite the morphological divergences mentioned, these are not sufficient to separate the specimens of *Cyprideis santaelenae* from Pebas and Solimões formations in two different species. Therefore, here is present the first record of the *Cyprideis santaelenae* species in the Solimões Formation strata.

Geographic and stratigraphic distribution: In this work: Boreholes 1AS-33-AM (197 m), close to the Negro River, western of the Amazonas State. Brazil. Solimões Formation, Miocene. In [Sousa and Ramos \(2023\)](#): outcrop Santa Elena (T488), bank of the Amazonas River, Quito. Peru. Pebas Formation, Miocene.

5. Discussion

5.1. Age and correlation of the study area

Among the boreholes studied here (wells 1AS-1-AM, 1AS-4-AM, 1AS-8-AM, 1AS-33-AM and 1AS-32-AM), most of them has been dated based on the palynomorphs, ostracods and mollusks, besides others not studied here ([Table 3](#)).

The strata of the Solimões Formation were initially dated based on palynomorphs, mollusks and ostracods mostly attributing an Aquitanian to Tortonian interval ([Hoorn, 1993](#); [Wesselingh et al., 2006b](#); [Muñoz-Torres et al., 2006](#)). Subsequent studies diverge in part of this range extending to the Pliocene ([Table 3](#)). Absolute dating, including zircon dating, established ages from the late middle to upper Miocene and investigate ages to the Pliocene, based on cores 1AS-33-AM ([Horbe et al., 2019](#)) and 1AS-14-AM ([Kern et al., 2020](#)).

[Leite et al. \(2021\)](#), reviewed the palynological content of core 1AS-33-AM, as well as material from 1AS to 37-AM, and observed that their age interval extends from the middle to upper Miocene, corresponding to palynozones T14 (~16–14.2 Ma), T15 (14.2–12.7 Ma) and T16 (12.7–7.1 Ma) sensu [Jaramillo et al. \(2010\)](#), and no longer to the Pliocene.

Regarding ostracods, the first biozonation in the western Amazonia was made by [Muñoz-Torres et al. \(2006\)](#), who analyzed the same sample cores (1AS-4a-AM) studied by [Hoorn \(1993\)](#), for palynomorphs, and

[Wesselingh \(2006d,e\)](#) to mollusks, including 26 other localities in the Pebas and Solimões formations. In this study, [Muñoz-Torres et al. \(2006\)](#) identified five biozones: *Cyprideis aulakos* (Burdigalian – Langhian), *Cyprideis caraionae* (Langhian), *Cyprideis minipunctata* and *Cyprideis obliquosulcata* (Serravallian) and *Cyprideis cyrtoma* (Serravallian – Tortonian).

[Gross et al. \(2014\)](#), studied the ostracods from core 1AS-10-AM and identified two biozones: the *Cyprideis minipunctata* Zone and the *Cyprideis cyrtoma* Zone, sensu [Muñoz-Torres et al. \(2006\)](#), both ostracod zones correspond to the *Grimsdalea* palynozones, establishing the Serravallian-Tortonian interval for this borehole.

However, [Linhares et al. \(2019\)](#), analyzed the palynological and ostracod content of cores 1AS-8-AM and 1AS-7D-AM and concluded that the age ranges attributed to the ostracod biozones proposed by [Muñoz-Torres et al. \(2006\)](#) were mistaken, regarding the ages assigned by the palynozones. In this way, the authors corrected the age of the ostracod zones, and in addition, proposed new zones. Of those, five palynozones identified: *Verrutricolporites* (Aquitanian – Burdigalian), *Psiladiporites-Crototricolporites* (Burdigalian – Langhian), *Crassorettriletes* (Langhian – Serravallian), *Grimsdalea* (Serravallian – Tortonian) and *Asteraceae* (Tortonian). And five ostracod zones: the *Cyprideis aulakos* Zone (= *sulcosigmoidalis*), previously attributed to the Burdigalian – Serravallian interval, equivalent to the *Crassorettriletes* palynozones, and now restricted to the Langhian – Serravallian; the *Cyprideis caraionae* Zone had its extension adjusted to the Serravallian – Tortonian interval, corresponding to the *Crassorettriletes* and *Grimsdalea* palynozones; the *Cyprideis minipunctata* Zone had its limit extended to the Tortonian and is associated with the *Grimsdalea* palynozones; the *Cyprideis cyrtoma* Zone entered the Tortonian, and is also associated with the *Grimsdalea* palynozones and the upper part of the *Asteraceae* Zone.

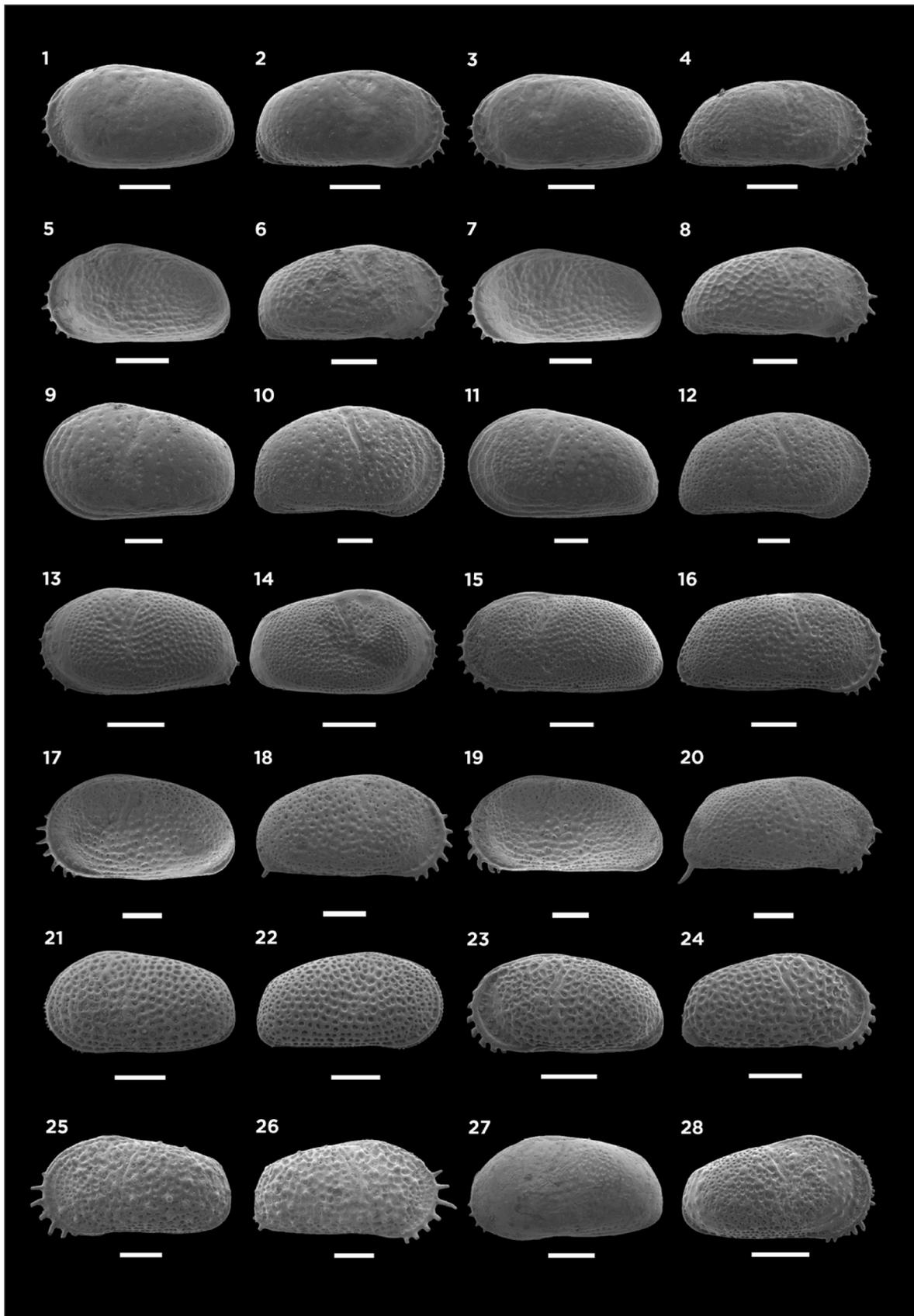
[Linhares et al. \(2019\)](#) also proposed a new ostracod zone, the *Cyprideis paralela* Zone, which corresponds with the *Asteraceae* palynozones, of Tortonian age. For the core 1AS-8-AM, the Aquitanian to Tortonian age range was previously assigned based on the study of ostracods and palynomorphs, as it was for the core 1AS-7D-AM, with Burdigalian to Tortonian age range.

[Kern et al. \(2020\)](#) studied the palynological and ostracod assemblages in the borehole 1AS-14-AM, from Solimões Formation, for a better understanding about the biotic changes in Amazonia. The authors also compared the biostratigraphic information with maximum deposition ages indicates by U/Pb measurements on detrital zircon grains. The zircon populations showed a maximum deposition age in the Tortonian (late Miocene) for the top of the Solimões Formation (~95 m). The palynological stratigraphy showed two biozones: the *Grimsdalea magnaclavata* Zone (to the depth of 181.8 m) and the *Psiladiporites caribbiensis* Zone (from 181.8 m to the top), dating the late middle Miocene – late Miocene and the late Miocene – Pliocene, respectively. The ostracod content indicates biozones: the *Cyprideis minipunctata* Zone, from the late middle Miocene – late Miocene, and the *Cyprideis cyrtoma* Zone from the late Miocene (see [Fig. 8](#)).

5.2. Ostracod zones in borehole 1AS-32-AM

The borehole 1AS-32-AM was previously assigned with a late Miocene age by [Latrubesse et al. \(2010\)](#) with study based on palynomorphs. Here we present a biozonation of ostracods for the first time following the ostracod biozonation by [Linhares et al. \(2019\)](#); four zones can be identified: *Cyprideis caraionae* Zone (220.5 m–198.0 m), *Cyprideis minipunctata* Zone (198.0 m–117.0 m), *Cyprideis cyrtoma* Zone (117.0 m–54.0 m), and *Cyprideis paralela* Zone (54.0 m–33.0 m) ([Figs. 9 and 10](#)).

According to [Linhares et al. \(2019\)](#), after [Muñoz-Torres et al. \(2006\)](#) the *Cyprideis caraionae* Zone has the lower limit defined by the last occurrence of the species *Cyprideis schedogygnos* and the upper limit defined by the uppermost appearance of *Cyprideis caraionae*, extending from the Serravallian to the Tortonian.



(caption on next page)

Fig. 7. 1–28, *Cyprideis* species of ornate surface, 1–4. *C. anterospinosa* Purper and Ornellas (1991), 1. (MPEG-1058-M), female, LV, external view (0.76; 0.42); 2. (MPEG-1059-M), female, RV, external view (0.81; 0.41); 3. (MPEG-1060-M), male, LV, external view (0.93; 0.47); 4. (MPEG-1061-M), male, RV, external view (0.89; 0.42); 5–8. *C. santaelenae* Sousa and Ramos (2023), 5. (MPEG-1062-M), female, LV, external view (0.79; 0.43); 6. (MPEG-1063-M), female, RV, external view (0.81; 0.41); 7. (MPEG-1064-M), male, LV, external view (0.91; 0.45); 8. (MPEG-1065-M), male, RV, external view (0.87; 0.42); 9–12. *C. sulcosigmoidalis* Purper (1979), 9. (MPEG-1066-M), female, LV, external view (1.04; 0.63); 10. (MPEG-1067-M), female, RV, external view (1.10; 0.64); 11. (MPEG-1068-M), male, LV, external view (1.20; 0.69); 12. (MPEG-1069-M), female, RV, external view (1.23; 0.66); 13–14. *C. retrobispinosa* Purper and Pinto (1983), 13. (MPEG-1070-M), female, LV, external view (0.69; 0.37); 14. (MPEG-1071-M), female, RV, external view (0.71; 0.40); 15–16. *C. minipunctata* Purper and Ornellas (1991), 15. (MPEG-1072-M), male, LV, external view (0.93; 0.47); 16. (MPEG-1073-M), male, RV, external view (0.93; 0.45); 17–20. *C. marginuspinosa* Purper and Ornellas (1991), 17. (MPEG-1074-M), female, LV, external view (0.97; 0.54); 18. (MPEG-1075-M), female, RV, external view (0.91; 0.41); 19. (MPEG-1076-M), male, LV, external view (1.03; 0.51); 20. (MPEG-1077-M), male, RV, external view (0.97; 0.47); 21–24. *C. munoztorresi* Gross, Ramos and Van Harten, 2014, 21. (MPEG-1078-M), female, LV, external view (0.75; 0.40); 22. (MPEG-1079-M), female, RV, external view (0.76; 0.39); 23–24. *C. ituiaie*, 23. (MPEG-1080-M), female, LV, external view (0.69; 0.35); 24. (MPEG-1081-M), female, RV, external view (0.71; 0.35); 25–26. *C. curucae* Gross, Ramos and Piller, 2014, 25. (MPEG-1082-M), female, LV, external view (0.90; 0.47); 26. (MPEG-1083-M), female, RV, external view (0.96; 0.51); 27. *C. longispina* Purper (1979), (MPEG-1084-M), female, LV, external view (0.83; 0.45); 28. *C. inversa* Purper and Pinto (1983), (MPEG-1085-M), female, RV, external view (0.67; 0.36).

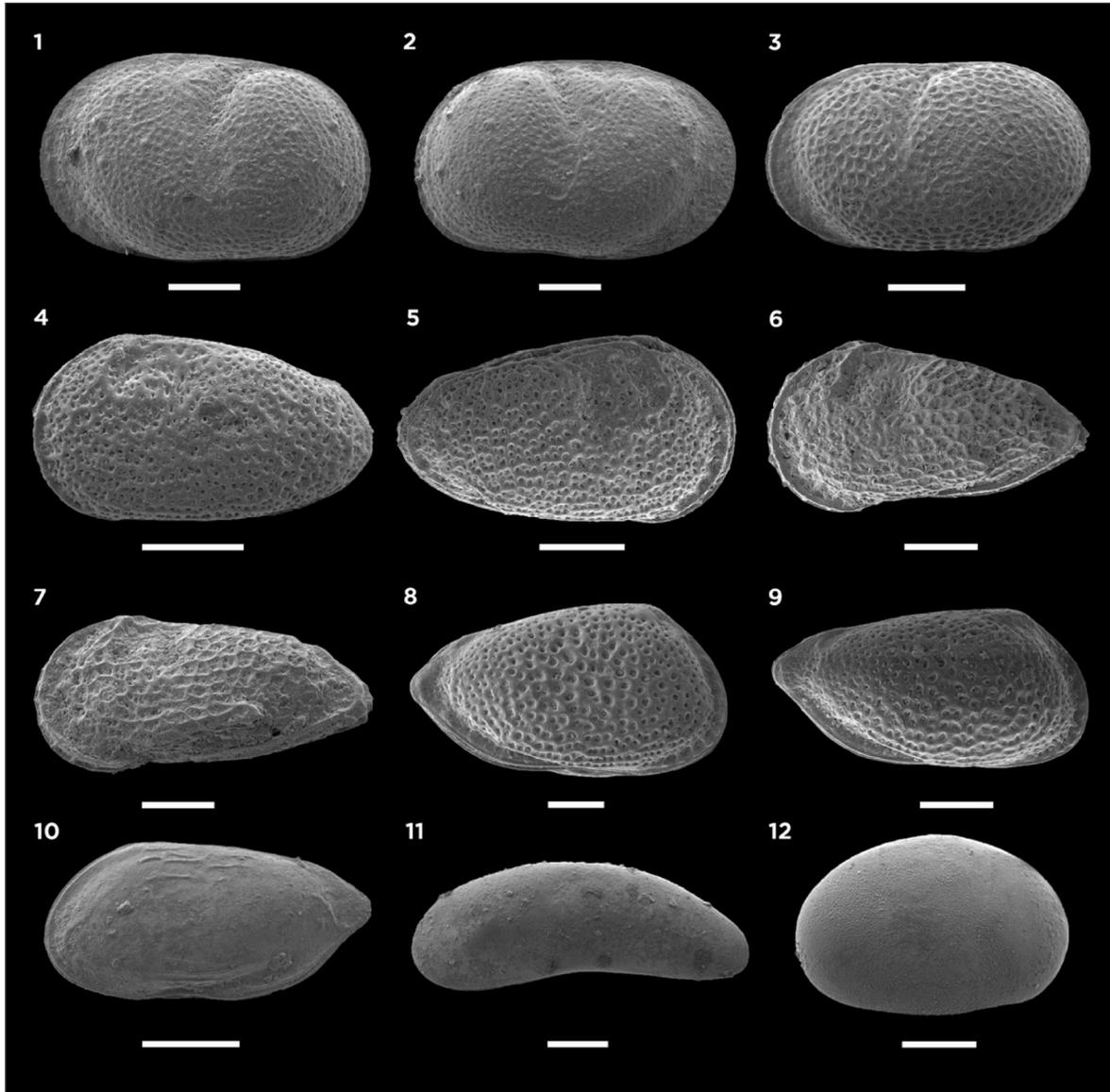


Fig. 8. 1–12, Genera diversity in the study boreholes, 1. (MPEG-1086-M), *Cytheridella* sp. 1 Purper (1979), LV, external view (0.47; 0.28); 2. (MPEG-1087-M), *C. sp. 1*, RV, external view (0.45; 0.28); 3. (MPEG-1088-M), *C. sp. 2*, LV, external view (0.88; 0.51); 4. (MPEG-1089-M), *Perissocytheridea ornellasae* Purper (1979), LV, external view (0.33; 0.18); 5. (MPEG-1090-M), *P. ornellasae*, RV, external view (0.32; 0.17); 6. (MPEG-1091-M), *P. acuminata* Purper (1979), female, LV, external view (0.44; 0.24); 7. (MPEG-1092-M), *P. acuminata*, male, LV, external view (0.47; 0.22); 8. (MPEG-1093-M), *Rhadinocytherura amazonensis* Sheppard and Bate 1980, female, RV, external view (0.28; 0.15); 9. (MPEG-1094-M), *R. amazonensis*, male, RV, vista externa (0.26; 0.13); 10. (MPEG-1095-M), *Pellucistoma curupira* Gross et al. 2015, LV external view (0.33; 0.16); 11. (MPEG-1096-M), ?*Paracypris* sp., LV, external view (0.57; 0.22); 12. (MPEG-1097-M), *Cypria aqualica*, RV, external view (0.40; 0.26).

Table 3
Data about previously studied boreholes from western Amazonia.

Boreholes	Authors	Tool	Age
1AS-4a-AM	Hoorn (1993, 1994a)	Palynology	early Miocene – late Miocene
	Muñoz-Torres et al. (2006)	Ostracods	middle Miocene – early late Miocene
	Wesselingh et al. (2006b)	Mollusks	middle Miocene – early late Miocene
1AS-5-AM	Friaes et al. (2022)	Palynology	middle Miocene – late Miocene
1AS-7D-AM	Linhares et al. (2017, 2019), Friaes et al. (2022), Linhares and Ramos (2022), Leandro et al. (2022)	Palynology and ostracods	late early Miocene – late Miocene
1AS-8-AM	Linhares et al. (2017, 2019), Friaes et al. (2022), Linhares and Ramos (2022), Leandro et al. (2022)	Palynology and ostracods	early Miocene – late Miocene
1AS-10-AM	Gross et al. (2014)	Ostracods	middle Miocene – late Miocene
1AS-14-AM	Kern et al. (2020)	Palynology, ostracods and zircon grains	late middle Miocene – late Miocene/Pliocene?
1AS-15-AM	Gomes et al. (2021)	Palynology	middle Miocene – late Miocene
1AS-19-AM	Silva-Caminha et al. (2010)	Palynology	late Miocene – Pliocene
1AS-27-AM	Silva-Caminha et al. (2010)	Palynology	late Miocene – Pliocene
1AS-31-AM	Linhares et al. (2011), Linhares and Ramos (2022)	Ostracods	early middle Miocene – late Miocene
	Kachniasz and Silva-Caminha (2016)	Palynology	late Miocene – Pliocene
1AS-32-AM	Latrubesse et al. (2010)	Palynology	late Miocene – Pliocene
1AS-34-AM	Kachniasz and Silva-Caminha (2016)	Palynology	late Miocene – Pliocene
1AS-33-AM	Medeiros et al. (2019)	Ostracods	early Miocene – middle Miocene
	Leite et al. (2017, 2021)	Palynology	early middle Miocene – late Miocene
1AS-37-AM	Leite et al. (2021)	Palynology	latest Miocene – Pliocene?
1AS-51-AM	Leandro et al. (2022)	TOC/TN ratio	early Miocene – Pliocene
1AS-52-AM	Leandro et al. (2022)	Palynology and S/TOC	early Miocene - Pliocene
1AS-105-AM	Jaramillo et al. (2017)	Palynology	early Miocene – late Miocene
	Leandro et al. (2022)	Palynology and Bulk sediment CaCO ₃	early Miocene - Pliocene

In this way, the *Cyprideis caraionae* Zone was delimited here based on the lowest and uppermost occurrence of the species that gives name to the ostracod zone, which occur at 220.5 m and 198.0m, respectively, corresponding to the Tortonian age.

The *Cyprideis minipunctata* Zone lower limit is marked by the last appearance of *Cyprideis caraionae* (198.0 m) and the upper limit is marked by the last appearance of the species *Cyprideis minipunctata* (117.0 m), that occurs occasionally in the core. According to Linhares et al. (2019), this ostracod zone corresponds to the *Grimsdalea* palynozone (Hoorn, 1993), both associated with the Tortonian.

In addition to the index species, *Cyprideis caraionae* and *Cyprideis minipunctata*, the species *Cyprideis amazonica*, *Cyprideis cyrtoma*, *Cyprideis machadoi*, *Cyprideis multiradiata*, *Cyprideis paralela*, *Cyprideis schedogymnos*, *Cyprideis sulcosigmoidalis*, *Perissocytheridea ornellae*, *Penthesilenula olivencai* and *Cypria aqualica* also occur in this interval.

The species *Cyprideis marginuspinosa* is also part of the assemblage and is recorded for the first time in the *C. minipunctata* Zone.

The *Cyprideis cyrtoma* Zone has its lower limit marked by the last appearance of *Cyprideis minipunctata* (117.0 m) and its upper limit marked by the last appearance of *Cyprideis cyrtoma* (50.0 m). Linhares et al. (2019) also associated this zone with the *Grimsdalea* palynozone (Hoorn, 1993) of Tortonian age.

The species that also occur in *Cyprideis cyrtoma* Zone are *Cyprideis amazonica*, *Cyprideis curucae*, *Cyprideis inversa*, *Cyprideis ituiaie*, *Cyprideis machadoi*, *Cyprideis marginuspinosa*, *Cyprideis multiradiata*, *Cyprideis munoztorresi*, *Cyprideis olivencai*, *Cyprideis paralela*, *Cyprideis schedogymnos*, *Cyprideis sulcosigmoidalis*, *Perissocytheridea ornellae*, *Penthesilenula olivencai*, *Pellucistoma curupira*, *Rhadinocytherura amazonensis*, ? *Paracypris* and *Cypria aqualica*. Furthermore, the new species *Cyprideis javariensis* sp. nov. also occur in three intervals of the biozone (107.0 m, 84.0 m and 70.0 m), composing this fauna association for the first time.

The *Cyprideis paralela* Zone (Linhares et al., 2019), has the lower limit marked by the last occurrence of *Cyprideis cyrtoma* and the upper limit by the last occurrence of *Cyprideis paralela*. This biozone corresponds to part of the *Asteraceae* palynozone, of Tortonian age. In addition to the index species, the other associated taxa are *Cyprideis amazonica*, *Cyprideis inversa*, *Cyprideis ituiaie*, *Cyprideis machadoi*, *Cyprideis marginuspinosa*, *Cyprideis multiradiata*, *Cyprideis munoztorresi*, *Cyprideis sulcosigmoidalis*, *Perissocytheridea acuminata*, *Penthesilenula olivencai*, ?*Paracypris*, *Cypria aqualica* and *Cytheridella* sp. 1 and *Cytheridella* sp. 2.

It is also possible to observe that the upper limit of the *Cyprideis cyrtoma* Zone and the lower limit of the *Cyprideis paralela* Zone mark the peak of ostracod diversity and abundance present in core 1AS-32-AM as well as in other boreholes already studied (1AS-7D-AM, 1AS-14-AM, part of the 1AS-10-AM). Both ranges have a total of twelve co-occurring species, and are attributed to Tortonian age, established based on ostracods, and matches the palynostratigraphy, being correlated with the transition of *Grimsdalea* and *Asteraceae* zones.

According to Muñoz-Torres et al. (1998), the greatest radiation occurred in the middle Miocene, however, in this study the authors do not have the most species recorded posteriorly to that study.

Linhares et al. (2011) studied samples from the borehole 1AS-31-AM and identified the greatest *Cyprideis* diversity from sample 175 to 170.80 m, in the “*Transitional to Marine Phase*”. According with the authors, this interval is “not younger than early middle Miocene”, based on the biostratigraphic distribution of *C. caraionae* (Muñoz-Torres et al., 2006).

To the core 1AS-10-AM, Gross et al. (2014) identified the interval from depth 141.2 m–116.4 m as the peak of species diversity. The interval corresponds with *C. obliquosulcata* biozone, dated to the late middle Miocene (Muñoz-Torres et al., 2006).

Linhares et al. (2017, 2019) studied samples from core 1AS-8-AM and 1AS-7D-AM. The biostratigraphic distribution of the borehole 1AS-8-AM showed that eleven *Cyprideis* species marked the peak of abundance and diversity, corresponding with the biozone *C. caraionae*, from the middle to late Miocene; and in the borehole 1AS-7D-AM, the peak of diversity is marked by the co-occurrence of twelve *Cyprideis* species in the *C. cyrtoma* biozone, from the late Miocene.

Medeiros et al. (2019) identified the greatest diversity of *Cyprideis* species, corresponding with the biozones *C. obliquosulcata* and *C. cyrtoma*, from the middle to late Miocene, respectively (Muñoz-Torres et al., 2006).

The biostratigraphic distribution of the borehole 1AS-14-AM studied by Kern et al. (2020) registered great *Cyprideis* diversity, composed by fourteen species, in the *C. cyrtoma* biozone, dated in the late Miocene according to Muñoz-Torres et al. (2006) and Linhares et al. (2019).

Then, the correlation of the studied boreholes with the others mentioned above, allowed to infer that the peak of radiation of the *Cyprideis* species occurred during the transition from the end of the middle Miocene to the beginning of the upper Miocene, subsequent to the event of the MMCO. This demonstrates that the radiation was caused

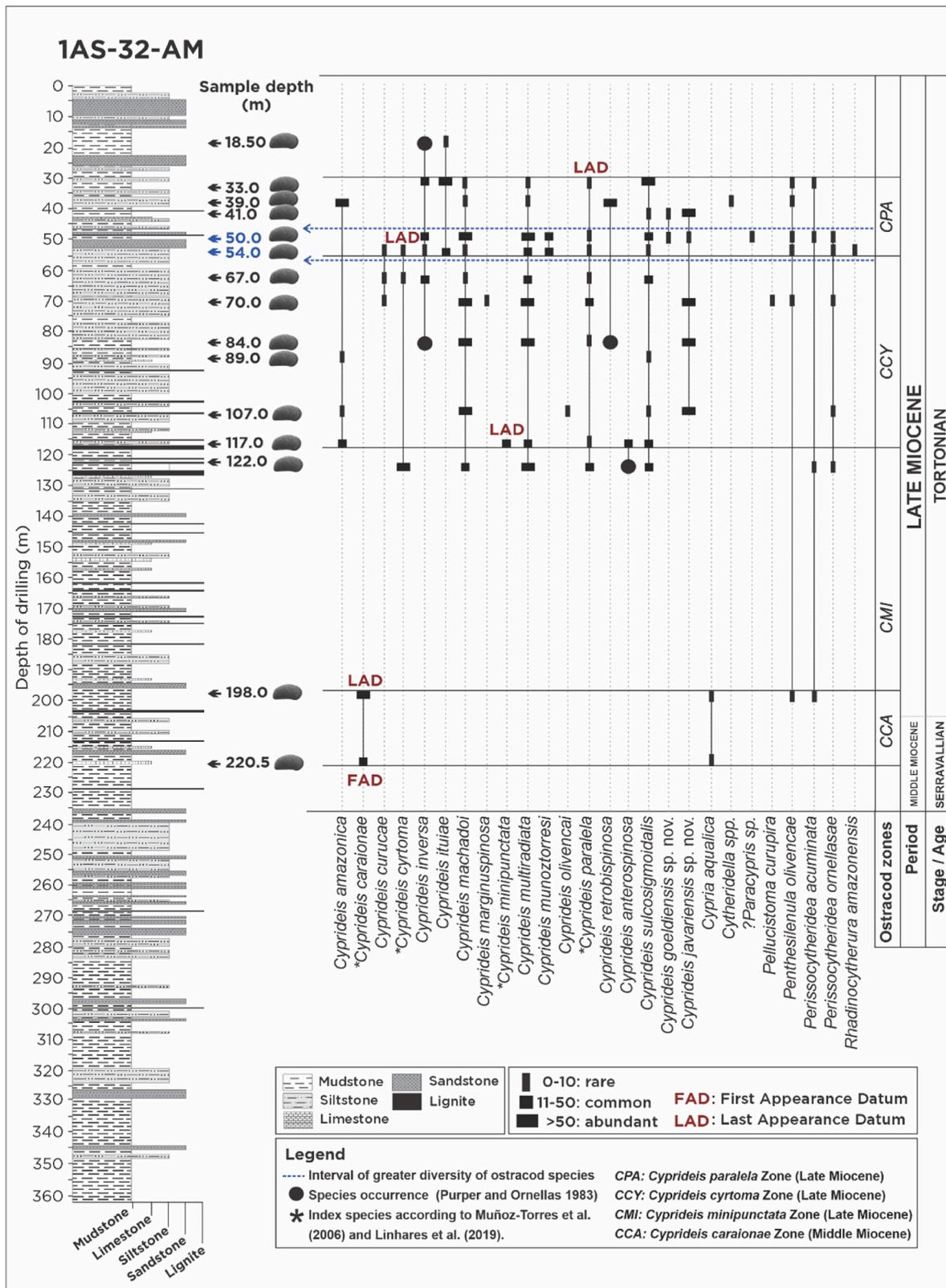


Fig. 9. Stratigraphical distribution of ostracod species in borehole 1AS-32-AM and ostracod zones identified.

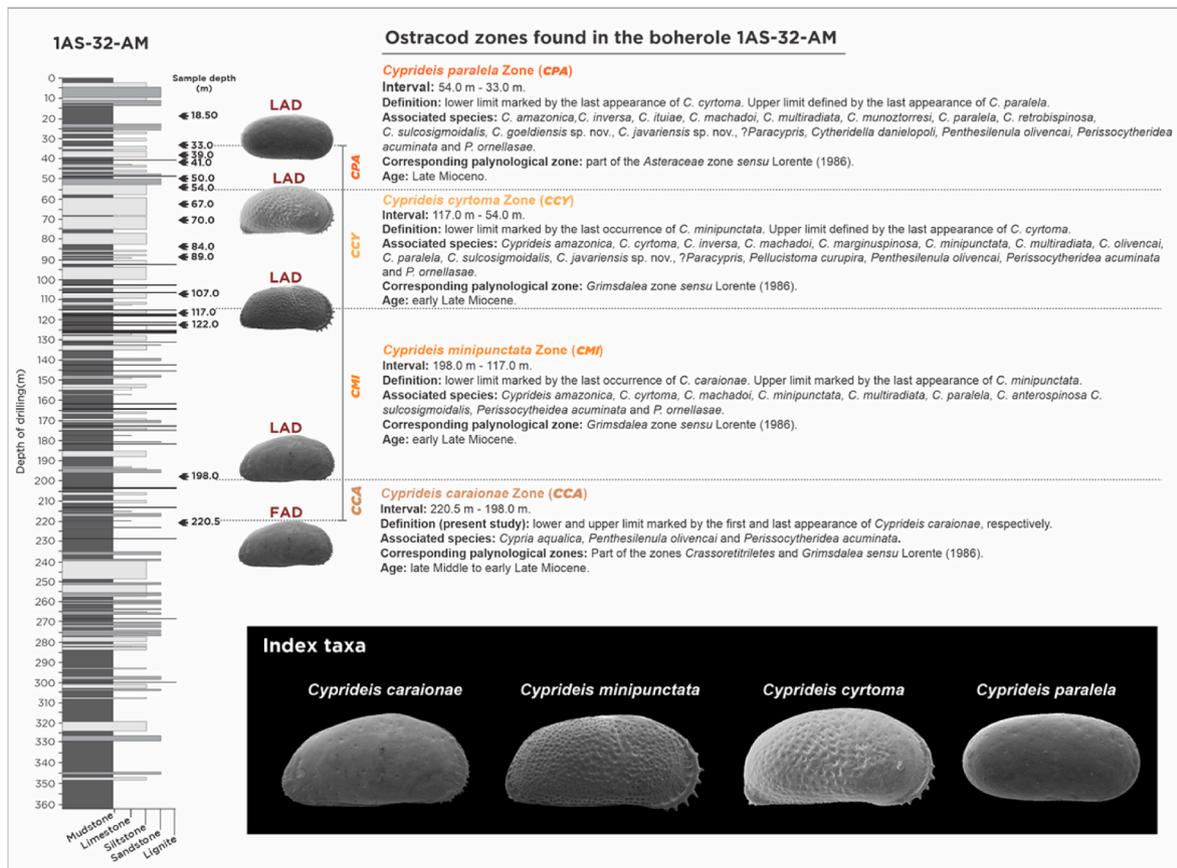


Fig. 10. Ostracod zones in borehole 1AS-32-AM. Other abbreviations see Fig. 9.

by the delayed reflection of climate change related to the MMCO.

5.3. Paleoenvironmental interpretation

The paleoenvironmental evolution “Pebas Mega-Wetland” during the Neogene has been the subject of several studies for a few decades (Hoorn, 1993; Wesselingh et al., 2006a; Leandro et al., 2022). This great system of freshwater lakes and temporary pools took place in most part of the western Amazonia and suffered sporadic marine influence, attested by the fossil record such as pollen, foraminifera, mollusks and mainly ostracods (Hoorn, 1994b; Wesselingh et al., 2006a; Linhares et al., 2011, 2017, 2019; Leandro et al., 2022).

Hoorn et al. (2022) characterized the Pebas System as a permeable biogeographical system that during the Middle Miocene Climactic Optimum (MMCO) (17–15 Ma) reached its maximum extend and was episodically connected to the Caribbean Sea, and because of its inconstant connections, the Andes and eastern Amazonia permitted a two-way migration, causing a massive biotic exchange, and forcing the adaptation of many groups present into the Pebas System, creating an environmental with conditions that made the Miocene Amazonian wetland system one of the most complex species-diverse systems in the world.

This hypothesis is sustained by geological records from the mid-Miocene mega-wetland, pointing that the sediment deposition was cyclic and triggered by orbital forcing and sea-level changes, with constant environmental alteration. In that context, the landscape conditions promoted “biotic exchange at the interface of (1) aquatic and terrestrial, (2) brackish and freshwater and (3) eutrophic to oligotrophic conditions” (Hoorn et al., 2022).

Those bioevents are directly linked to the geological settings of the western Amazonia, resulting from the uplift and the peak of maximum elevation of the Andean Mountain during the Miocene, that caused abrupt changes and brought great environmental and climate stress,

which triggered the quickly thrive of a taxon of high ecophenotypic plasticity such as the genus *Cyprideis*, in that region (Gross et al., 2013, 2014, Purper, 1977, 1979; Linhares and Ramos, 2022).

This genus has osmoregulation control and is capable of withstanding extreme salinity levels (<5 to >35); it is commonly found in diverse environments such as estuaries, lakes and lagoons, with different salinity gradients, and easily adapts to salinity variations caused by seasonal cycles (van Harten, 2000; Sousa and Ramos, 2023).

Thus, this genus never had a so quick and intense radiation as during the deposition of the Neogene Pebas system, in the western Amazonia, not yet recorded in any other lacustrine sedimentary basin in the world. This radiation has so far led to the record of 35 endemic species, in a relatively short period of time, from the Burdigalian to the Tortonian, with a maximum radiation event during the upper Miocene (Tortonian) (Muñoz-Torres et al., 2006; Linhares et al., 2019).

In the studied boreholes, as well as in the others of the project Carvão no Alto Solimões, this scenario is also reflected in the euryhaline genus *Cyprideis*, which had a flake of radiation during the Neogene (Muñoz-Torres et al., 1998; Gross et al., 2014).

The high intraspecific morphological variability of ostracods of the genus *Cyprideis* from the Solimões Formation can be here interpreted as a result of these bioevents that occurred in the Neogene as the MMCO.

In this way, the environmental particularities also prevented competition with other genera, since the salinity level of the water was not appropriated for neither marine nor freshwater genera. Besides the *Cyprideis*, the genus *Perissocytheridea* is the second common genus in the boreholes (2.61% of study valves = 244 valves), which is known to occur in mesohaline environments and has a marginal marine feature, very typical of brackish waters, but can also be found in slightly saline continental lakes (Muñoz-Torres et al., 2006; Nogueira and Ramos, 2016; Gross et al., 2013; Gross and Piller, 2020).

Also, it is worth to mention that in boreholes studied by other

authors (1AS-31-AM: Linhares et al., 2011; 1AS-7D-AM: Linhares et al., 2017, 2019; 1AS-10-AM: Gross et al., 2014; 1AS-14-AM: Kern et al., 2020), the peak of *Perissocytheridea* always corresponds with the interval and age that marks the highest species diversity of *Cyprideis*.

Freshwater genera are rare in the studied boreholes and, their valves are fragile and poorly preserved (*Cytheridella* sp. 1, *Cytheridella* sp. 2 *Cypria aquatica* and *Penthesilenula olivencae*), as well as marine genera (*Rhadinocytherura amazonensis*, *Pellucistoma curupira* and *Paracypris* sp.) indicating be reworked or non-adaptation to the environmental conditions imposed.

6. Conclusion

The taxonomic review of the Neogene ostracods from five boreholes located in the western Amazonas State, from Solimões Basin, allowed to identify eight genera and thirty ostracod species. From that assemblage, twenty-two species belong to the genus *Cyprideis* with two new species properly described (*Cyprideis goeldiensis* sp. nov. and *Cyprideis javariensis* sp. nov.), and one remains with open nomenclature (*Cyprideis* sp. 1). The genus *Perissocytheridea* is the second more abundant while a diverse generic but scarce assemblage (*Cypria*, *Cytheridella*, *Paracypris*, *Pellucistoma*, *Penthesilenula* and *Rhadinocytherura*) occur rarely associated.

With the analysis of the ostracod assemblage of the 1AS-32-AM core and the identification of index *Cyprideis* species, it was possible to identify four ostracod zones (*Cyprideis caraionae* Zone, *Cyprideis minipunctata* Zone, *Cyprideis cyrtoma* Zone and *Cyprideis paralela* Zone) and infer a Serravallian to Tortonian range age to this well.

Finally, the correlation between the cores studied herein with additional cores from Solimões Formation, allowed to attest that the predominance and the larger speciation of the genus *Cyprideis*, occurred in the transition of the Serravallian to the Tortonian, in the limit of the ostracod zones *C. cyrtoma* and *C. paralela* and palynozones *Grimsdalea magnaclavata* and *Asteraceae* corresponding to a late response to the climate changes that occurred during the MMCO event.

Furthermore, based on the taxonomic study of ostracods and a vast bibliographic survey of the paleoenvironmental interpretations from western Amazonia, it is possible to reiterate that the large radiation of the genus *Cyprideis*, and the rare occurrence of freshwater and marine genera, represent a semi-confined lake environment, typically mesohaline with episodic marine influences.

CRediT authorship contribution statement

Renato Rafael Martins Ferreira: Writing – original draft, Writing – review & editing, Visualization, Supervision, Methodology, Data curation, Conceptualization. **Maria Inês Feijó Ramos:** Writing – original draft, Writing – review & editing, Supervision, Methodology, Data curation, 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.

Data availability

The data that has been used is confidential.

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