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THE OSTRACODS FROM SOLIMÕES FORMATION, BRAZIL: AN ALTERNATIVE BIOSTRATIGRAPHIC ZONATION FOR THE NEOGENE OF AMAZONIA

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ABSTRACT – The Solimões Formation is a widespread lithological unit that was deposited during the Neogene throughout northwestern Brazil, southeastern Colombia, eastern Ecuador, northeastern Peru and northwestern Bolivia. As a result of the Brazilian project *Carvão no Alto Solimões*, a drill core was recovered from this formation, of which the 1-AS-33-AM section is evaluated for its ostracod biostratigraphy. Analyses of the material from the municipality of Atalaia do Norte, State of Amazonas, identified 12 ostracod species, most of which were attributed to the genus *Cyprideis*. The stratigraphic distribution of these species led us to propose a biostratigraphic zonation that integrates previous results based on ostracods for the Solimões Formation from Colombia and Peru. Three biozones were identified: the *Cyprideis caraionae* Range Zone; the *Cyprideis multiradiata* Range Zone; and the *Cyprideis sulcosigmoidalis* Latest Occurrence Interval Zone. Stratotypes are defined for each of these zones.

Key words: Solimões Formation, biostratigraphy, ostracods, Miocene.

RESUMO – A Formação Solimões compreende uma ampla unidade litológica depositada durante o Neógeno no noroeste do Brasil, sudeste da Colômbia, leste do Equador, nordeste do Peru e noroeste da Bolívia. O projeto Carvão no Alto Solimões foi responsável por uma extensa campanha de sondagem na porção noroeste da Amazônica Ocidental, próximo à fronteira com a Colômbia. Este projeto culminou na recuperação de dezenas de testemunhos e dentro deste universo amostral, o poço 1-AS-33-AM foi avaliado com ênfase na obtenção de uma bioestratigrafia baseada em ostracodes. Análises do material proveniente do município de Atalaia do Norte, Estado do Amazonas, permitiu a identificação de 12 espécies de ostracodes, sendo a maioria atribuída ao gênero *Cyprideis*. A distribuição estratigráfica dessas espécies levou a uma proposta de zoneamento bioestratigráfico que integra resultados anteriores baseados em ostracodes para a Formação Solimões da Colômbia e do Peru. Três biozonas foram identificadas: *Cyprideis caraionae*, *Cyprideis multiradiata* e *Cyprideis sulcosigmoidalis*. Os estratotipos são definidos para cada uma dessas zonas.

Palavras-chave: Formação Solimões, bioestratigrafia, ostracodes, Mioceno.

INTRODUCTION

The Neogene Solimões Formation is a stratigraphic unit of considerable thickness (up to 200 m at its southwestern portion, Cunha, 2007) and extension (approximately 500,000 km^2, Maia *et al.*, 1977) in Western Amazonia whose paleontological content has been studied for decades. Because of access difficulty, scarcity of good natural outcrop exposures in an enormous, sparsely populated region of South America, studies on the ostracod fauna of the formation are based either on cores or samples collected in exposed outcrops (Purper, 1977, 1979; Shepard & Bate, 1980; Purper & Pinto, 1985; Purper & Ornellas, 1991; Whatley *et al.*, 1998; Muñoz-Torres *et al.*, 1998, 2006; Ramos, 2006; Wesselingh & Ramos, 2010; Linhares *et al.*, 2011; Gross *et al.*, 2013a,b, 2014, 2015).

In the last 40 years, the Brazilian **CPRM** (Companhia de Pesquisa de Recursos Minerais, Geological Survey of Brazil), through its *Carvão no Alto Solimões* project, collected sedimentary samples of the Solimões region (Maia *et al.,* 1977) and made them available for micropaleontological studies. During this project, boreholes were drilled in Western Amazonia for coal-prospecting purposes. The 1-AS-33-AM drill hole is part of this exploratory effort, and was selected for the biostratigraphic distribution of Miocene ostracods of the Solimões Formation. The results obtained from the samples from1-AS-33-AM allowed an alternative ostracod-based biostratigraphic zonation for this formation to be proposed in this study.

The analysis of recovered and properly identified specimens constitutes a major contribution to the ostracod research in Western Amazonia. These are critical to improving our understanding of the paleoenvironmental evolution of Amazonia during the Neogene, which was clearly punctuated by numerous eustatic variations, subsidence in response to the Andean paroxysm and climatic seasonality.

Study area

The Solimões Formation is comprised of cyclic successions of mudstones, calcareous mudstones, siltstones, medium to fine sandstones, gypsum and ferruginous concretions, as well as occasional layers of limestone, lignite and peat (Maia *et al.*, 1977). This succession represents sandbars, channels, and flood plains, formed in response to a distal molassic sedimentation during the Andean Orogeny. Progressing upwards in the section, the sequence becomes more characteristic of fluvial and lacustrine environments (Caputo *et al.*, 1972; Reis *et al.*, 2006; Wanderley Filho *et al.*, 2007). Studies on mollusks (Wesselingh, 1993) and palynomorphs (Hoorn, 1994a) suggest a Miocene age for the formation.

In Brazil, the Solimões Formation extends along the Acre and Solimões basins, overlapping the Alter do Chão Formation (middle-Upper Cretaceous?–Neogene?), and reaching more than 2,000 m in thickness in its southwestern portion. In the Solimões Basin, the Solimões Formation is discordantly capped by the Pleistocene Içá Formation (Maia *et al.*, 1977; Caputo, 1984; Cunha, 2007). In regional terms, it constitutes a transnational geological unit, comprising a sedimentary wedge that ranges from the Purus arch to the subandine basins. In Peru, the pelitic Neogene deposits of the Pastaza, Marañón and Madre de Dios basins are called, respectively, the Pebas, Ipururo and Nauta formations. In Colombia, in the Amazonas and Putumayo basins are known as the Amazonian Tertiary and La Tagua beds (Hoorn, 1993, 1994a,b; Whatley *et al.*, 1998; Campbell Jr. *et al.*, 2001; Roddaz *et al.*, 2005; Rebata-Hernani *et al.*, 2006a,b).

Considering its expansiveness, nomenclatural questions about this stratigraphic unit have been recurrent throughout the years. Purper (1979) points out that the stratigraphic section for the Solimões Formation was designated in Peru by J.B. Steere (Hartt, 1872) and extended to the Brazilian territory by Brown (1879). Rego (1930) suggested the denomination "series of Solimões" for the sediments corresponding to the Pebas Formation in Brazil. However, the author did not formalize a stratigraphic section, adopting the one proposed for Pebas, in Peru. The Solimões Formation was formally proposed by Caputo *et al.* (1972), who concluded that the lithological characteristics of all layers are regionally indistinguishable, composing a single lithostratigraphic unit.

MATERIAL AND METHODS

Samples were collected from the 1-AS-33-AM drillhole at the Curuçá River (5º15'S, 71º33'W), District of Canamã, Municipality of Atalaia do Norte, Amazonas State, Brazil (Figure 1). The borehole was continuously drilled to 404.15 m as part of a coal exploration campaign conducted by CPRM, in partnership with the **DNPM** (Departamento Nacional de Produção Mineral) that resulted in the drilling of 84 boreholes in Western Amazonia from March 23, 1975 to November 27, 1976. A full description of the well lithology was included in Maia *et al.* (1977) (Figure 2). Initially, a control number under the prefix **MP** (Micropaleontologia) was assigned to each of the 205 collected samples from the well, according to the Collection Catalogue of the **LabMicro-UnB** (Laboratório de Micropaleontologia do Instituto de Geociências da Universidade de Brasília), Brasilia, Brazil.

The methodology used to process these samples was based on Antonietto *et al.* (2015), with the following modifications: 10 g of dried sediment were prepared for disintegration; and they were washed afterwards through 62, 106, 150 and 250 µm sieves. Ostracod specimens were identified under Zeiss SteREO DiscoveryV20 stereomicroscope and grouped in micropaleontological cardboard slides according to their morphological similarity and ontogenetic stages. SEM (scanning electron microscope) images of representative specimens of each species were taken on a JEOL JCM-5000 Neoscope at the LabMicro-UnB. The material illustrated here is housed in the Research Collection of the LabMicro-UnB, under the prefix "**CP**" (Coleção de Pesquisa).

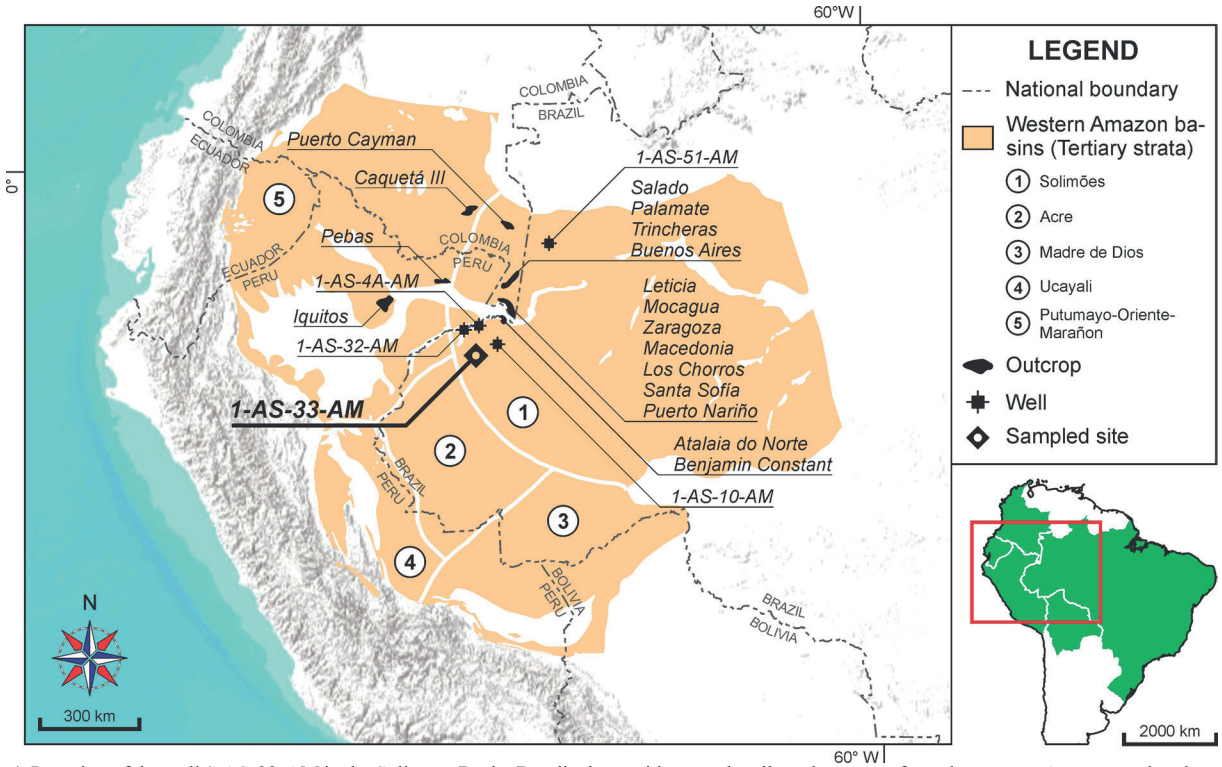

Figure 1. Location of the well 1-AS-33-AM in the Solimões Basin, Brazil, along with several wells and outcrops from the western Amazon region that yielded ostracods in previous studies (Muñoz-Torres *et al.*, 2006; Gross *et al.*, 2014, 2015).

RESULTS

The present analysis resulted in the identification of 12 ostracod species, nine of them, after the most recent review by Gross *et al.* (2014), belonging to the genus *Cyprideis* Jones, 1857: *Cyprideis* aff. *C. amazonica* Purper, 1979, *Cyprideis caraionae* Purper & Pinto, 1985, *Cyprideis* aff. *C. graciosa* (Purper, 1979), *Cyprideis inversa* (Purper & Pinto, 1983), *Cyprideis machadoi* (Purper, 1979), *Cyprideis multiradiata* (Purper, 1979), *Cyprideis pebasae* (Purper, 1979), *Cyprideis simplex* (Sheppard & Bate, 1980), and *Cyprideis sulcosigmoidalis* (Purper, 1979). Other species found were *Alicenula olivencae* (Purper, 1984); *Rhadinocytherura amazonensis* Sheppard & Bate, 1980 and *Perissocytheridea* sp. A *sensu* Purper, 1977 (Figure 3).

The species identified were grouped according to their stratigraphic distribution throughout the core obtained from the 1-AS-33-AM site, which is the basis of our new chronobiostratigraphic framework (Figure 4). The current zonation is based on Muñoz-Torres *et al.* (2006); however, because some of the species identified in that study are absent from the 1-AS-33-AM fossiliferous succession, changes to the zonation were made to accommodate sections from both works. The age interpretations for the present stratigraphical framework follow Wesselingh *et al.* (2006) for mollusks and Hoorn (1994c) for palynomorphs, despite more recent, contradictory results of the latter group from Jaramillo *et al.* (2011) and Leite *et al.* (2017), which will be further discussed herein.

In accordance to the *Código Brasileiro de Nomenclatura Estratigráfica* (CENE/SBG. 1986) and the International Stratigraphic Guide (Murphy & Salvador, 1999), a code for previous and newly created biozones is proposed using **ABC** (initials for "Amazonia Biostratigraphy based on *Cyprideis*"). The summarization of the modifications include the following: (i) the *Cyprideis caraionae* Range Zone is codified as ABC-1 and a stratotype is based on it; (ii) the *Cyprideis minipunctata* Latest Occurrence Interval Zone, an intrazonal depletion interval, and the *Cypridei sobliquosulcata* Range Zone are grouped into the newly created *Cyprideis multiradiata* Latest Occurrence Interval Zone (ABC-2), with *Cyprideis multiradiata*as as its index, and a stratotype based on it; and (iii) the *Cyprideis cyrtoma* Latest Occurrence Interval Zone is converted into the *Cyprideis sulcosigmoidalis* Latest Occurrence Interval Zone (ABC-3), with *Cyprideis sulcosigmoidalis* as its index, and a stratotype based on it.

Cyprideis caraionae Range Zone (ABC-1)

Definition. The delimitation of this taxon range zone is based on the range of the *Cyprideis caraionae* in the studied section. Its base and top correspond respectively to the first and last appearances of *Cyprideis caraionae*.

Characterization. *Cyprideis caraionae* is the only species of *Cyprideis* recovered up to 290.05 m deep, occurring in remarkable abundance from the depth of 350.50 m to below. A total of 103 specimens were found in this interval. The extinction of *Cyprideis caraionae* and the appearance of six other ostracod species (*Cyprideis* aff. *C. amazonica*, *Cyprideis*

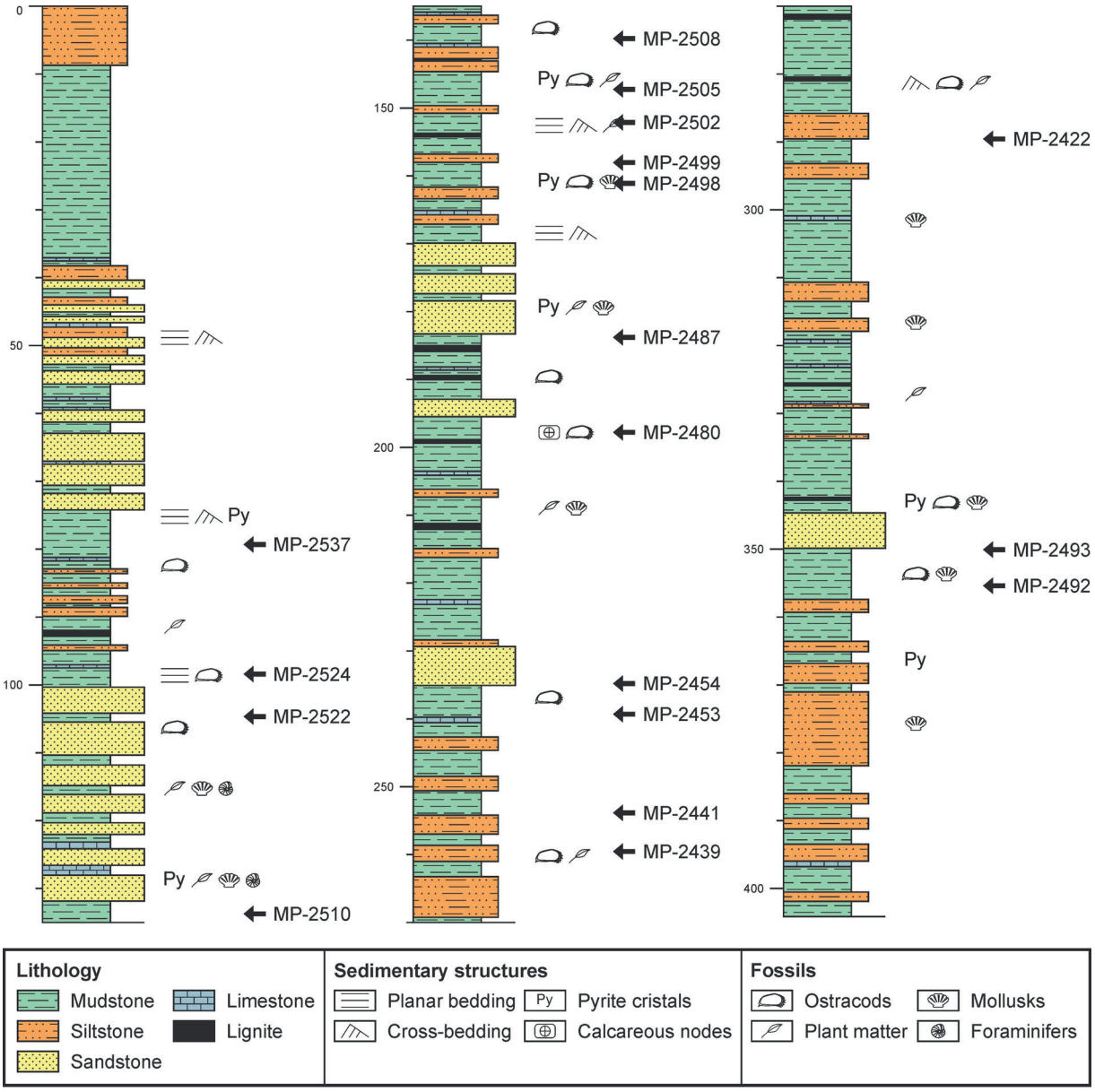

Figure 2. Lithology of the 1-AS-33-AM well, Atalaia do Norte, Brazil. Sampled levels are indicated by Black arrows, accompanied by the cataloguing codes of the Laboratório de Micropaleontologia, Instituto de Geociências. Universidade de Brasília, Brasilia, Brazil.

machadoi, *Cyprideis simplex*, *Cyprideis sulcosigmoidalis* and *Perissocytheridea* sp. A mark the upper limit of ABC-1.
Stratotype. 1-AS-33-AM well, 351.40-290.05 m deep. District of Canamã, Municipality of Atalaia do Norte, Amazonas State, Brazil.
Chronostratigraphy. middle Serravalian.
Discussion. Based on the chronobiostratigraphic correlation in Wesselingh & Ramos (2010) and palynological zonation by Leite *et al.* (2017) for the 1-AS-33-AM drillboring, the *Cyprideis caraionae* Range Zone is inserted into the *Crassoretitriletes* palinozone, lower Serravallian, middle Miocene. Muñoz-Torres *et al.* (2006) erected *Cyprideis caraionae* as a concurrent range zone for the middle Serravalian Stage, and this interpretation is followed herein to encompass the amplitude of the *Cyprideis caraionae* in the 1-AS-33-AM drillcore.

***Cyprideis multiradiata* Range Zone (ABC-2)**
Definition. The delimitation of this taxon range zone is based on the range of the *Cyprideis multiradiata* in the studied section. Its base and top correspond respectively to the first and last appearances of *Cyprideis multiradiata.*
Characterization. The base of this zone is marked by the first occurrence of *Cyprideis multiradiata*, the disappearance of *Cyprideis caraionae* and the appearance of five other ostracod species: *Cyprideis* aff. *C. amazonica*, *Cyprideis machadoi*, *Cyprideis simplex*, *Cyprideis sulcosigmoidalis* and *Perissocytheridea* sp. A. These species occur concomitantly with *Cyprideis* aff. *graciosa*, *Alicenula olivencae*, *Rhadinocytherura amazonensis*, and a level of foraminifera characterizing the framework of this zone. The extinction of *Cyprideis multiradiata* marks the upper limit of this range zone.

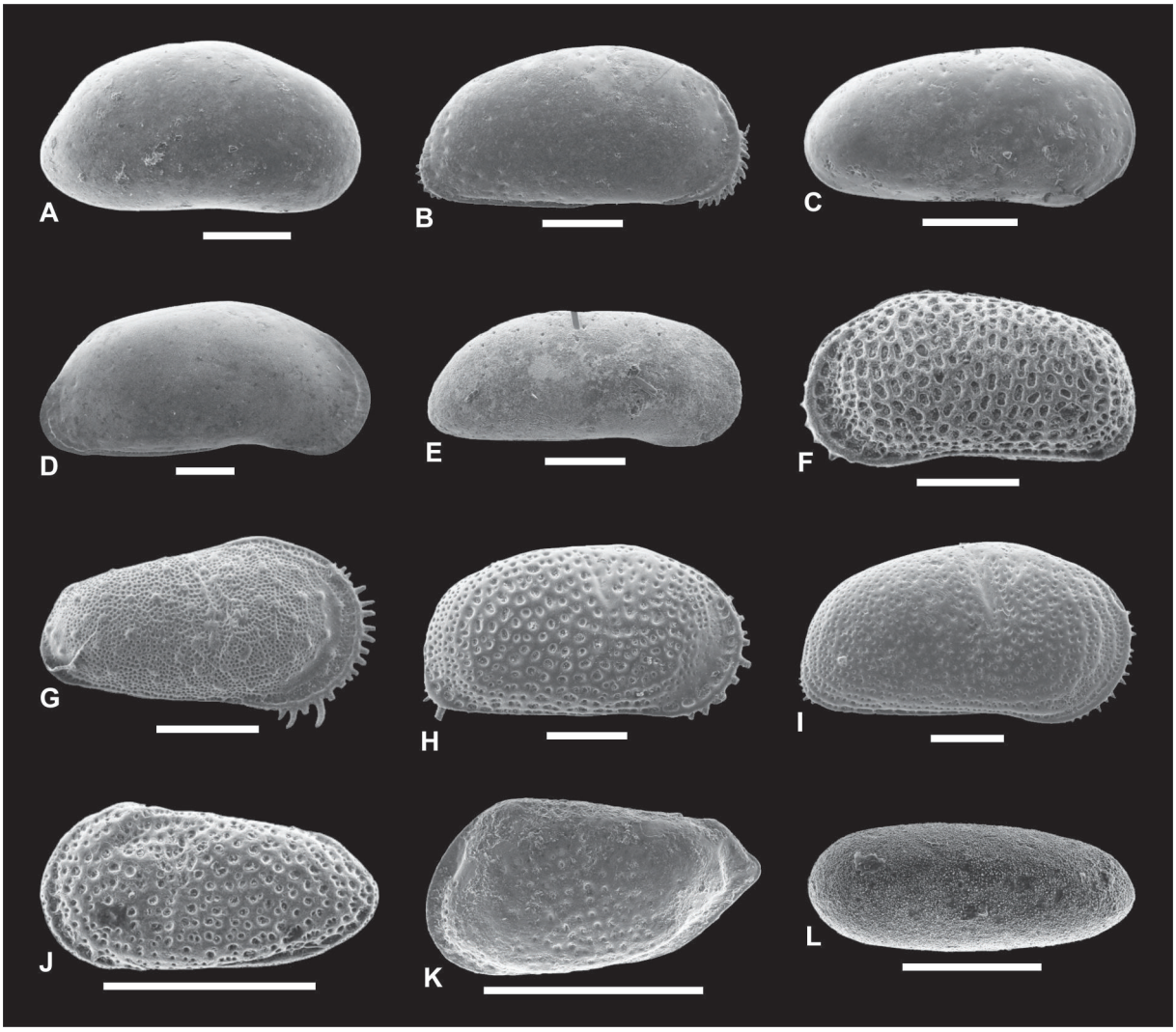

Figure 3. Ostracodes from the middle Serravalian –Tortonian of the Solimões Formation recovered at the 1-AS-33-AM well, Atalaia do Norte, Brazil. **A**, *Cyprideis* aff. *C. amazonica* Purper, 1979, CP-837, right valve. **B**, *Cyprideis caraionae* Purper & Pinto, 1984, CP-820, right valve. **C**, *Cyprideis simplex* (Sheppard & Bate, 1980), CP-823, right valve. **D**, *Cyprideis machadoi* (Purper, 1979), CP-819, right valve. **E**, *Cyprideis multiradiata* (Purper, 1979), CP-827, right valve. **F**, *Cyprideis pebasae* (Purper, 1979), CP-842, left valve. **G**, *Cyprideis inversa* (Purper & Pinto, 1983), CP-829, right valve. **H**, *Cyprideis* aff. *C. graciosa* (Purper, 1979), CP-828, right valve. **I**, *Cyprideis sulcosigmoidalis* (Purper, 1979), CP-818, right valve. **J**, *Perissocytheridea* sp. A *sensu* Purper, 1977, CP-836, leftvalve. **K**, *Rhadinocytherura amazonensis* Sheppard & Bate, 1980, CP-825, left valve. **L**, *Alicenula olivencae* (Purper, 1984), CP-841, right valve. Scale bars = 200 µm.

Stratotype. 1-AS-33-AM well, 290.05-136.35 m deep. District of Canamã, Municipality of Atalaia do Norte, Amazonas State, Brazil.

Chronostratigraphy. Upper Serravalian–lower Tortonian.

Discussion. Both the *Cyprideis multiradiata* Range Zone, erected herein, and the *Cyprideis minipunctata* Successive Last Appearance Zone defined by Muñoz-Torres *et al.* (2006) have the last occurrence of *Cyprideis caraionae* in their base. However, the latter has its top marked by the last occurrence of *Cyprideis minipunctata* (Purper & Ornellas, 1991), which was not recorded in this study. Additionally, we did not observe *Cyprideis obliquosulcata* in the 1-AS-33-AM drillcore. Therefore, we have erected *Cyprideis multiradiata* as the index fossil of this zone instead, as it can be found in both sections from the present work and those in Munõz-Torres *et al.* (2006). At the basal section of ABC-2, specimens of the smallish *Rhadinocytherura amazonensis* occur that could be used to determine another zone; however, due to its size and shape, it is possible that it has been mistaken for *Perissocytheridea*, instead of the correct identification present in other stratigraphic works of the Solimões Formation, which impedes any correlation between sections.

Cyprideis sulcosigmoidalis Latest Occurrence Interval Zone (ABC-3)

Definition. The base of this interval zone is defined by the last occurrence of *Cyprideis multiradiata* and the top by the last occurrence of *Cyprideis sulcosigmoidalis*.

Characterization. The base of this zone is defined by the extinction of *Cyprideis multiradiata* and the disappearance of the foraminifera, along with the appearance of *Cyprideis pebasae*, *Cyprideis inversa* and *Cyprideis machadoi*.

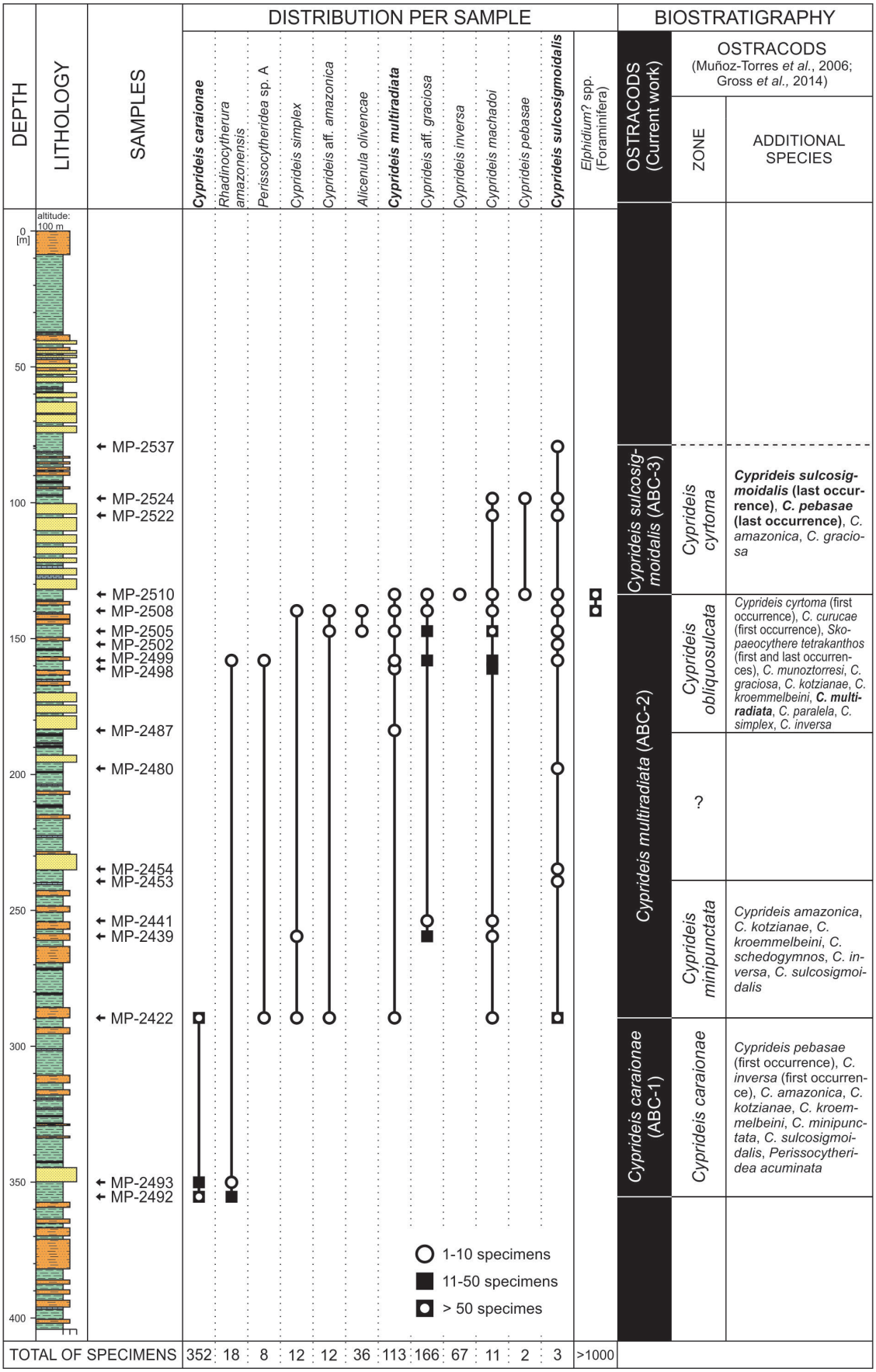

Figure 4. Distribution of ostracod species and zonation of the 1-AS-33-AM well, Atalaia do Norte, Brazil (in black), in comparison to Muñoz-Torres *et al.* (2006).

The top is marked by the last occurrence of *Cyprideis sulcosigmoidalis*, which is the only species of ostracod to be recovered above 99.80 m in the drillcore.

Stratotype. 1-AS-33-AM well, from 136.35 m to 89.3 m deep. District of Canamã, Municipality of Atalaia do Norte, Amazonas State, Brazil.

Chronostratigraphy. Upper Tortonian.

Discussion. Based on the stratigraphic arrangement of the specimens of *Cyprideis sulcosigmoidalis* compared to the species range of *Cyprideis cyrtoma* Successive Last Appearance Zone (Muñoz-Torres *et al.*, 2006), it is possible to correlate these two zones. *Cyprideis cyrtoma* was not recorded at the 1-AS-33-AM site; therefore, we opted to erect *Cyprideis sulcosigmoidalis* as the index fossil of this zone, because it can be found in both the present section and those from Muñoz-Torres *et al.* (2006).

DISCUSSION

As in Gross *et al.* (2014), the zones proposed herein present better correlation with those conceived by Wesselingh *et al.* (2006) and Wesselingh & Ramos (2010). Regarding chronostratigraphic positioning of the 1-AS-33-AM drillcore based on the palynological data by Leite *et al.* (2017), a divergence is clearly observable. From the correlation of these results with other palynozone schemes proposed for the region (Germeraad *et al.*, 1968; Muller *et al.*, 1987; Lorente, 1986; Jaramillo *et al.,* 2011), the upper portion of the drill site would exceed the Miocene–Pliocene boundary. This radically differs from the biostratigraphic correlations established by Wesselingh *et al.* (2006) and Wesselingh & Ramos (2010), which limit their biozones to the upper Miocene (Tortonian).

Because no palynomorphs were recovered from the present samples, we opt to follow results from Hoorn (1994c) (Figure 5), as did (fully or partially) previous works on ostracods of the Solimões Formation, such as Whatley *et al.* (1998), Muñoz-Torres *et al.* (1998, 2006), Ramos (2006), Linhares *et al.* (2011) and Gross *et al.* (2013a,b, 2014, 2015). However, due to the undeniable contradictions with Leite *et al.* (2017), we find it important to reinforce the necessity of future integrated reviews of the several fossil groups from wells and outcrops of the Solimões Formation, to clarify the relations between palynozones and zones from mollusks and ostracods throughout its extension. It is possible that such results would lead to an integration of the Solimões with coeval units in nearby basins, such as the Acre (Brazil), Madre de Diós (Bolivia/Brazil/Peru), Ucayali (Brazil/Peru), Putumayo-Oriente-Marañón (Brazil/Colombia/Ecuador/Peru) and Llanos (Colombia/Venezuela).

Near the boundary of the ABC-2 and ABC-3 zones, a sudden paleoenvironmental change is observed between the depths of 139.40 m and 136.35 m. This is marked by an anomalous stratigraphic level foreseeing the establishment of a characteristic association of foraminifera, mollusks, bryozoans, and coral fragments, as well as the disappearance of six ostracod species. In the lithological section, this transition shows an increased calcite content, evidenced by the deposition of thin layers of microsparitic limestone that indicates a change in the depositional environment. The correlation of lithological, petrographic, and fossiliferous data

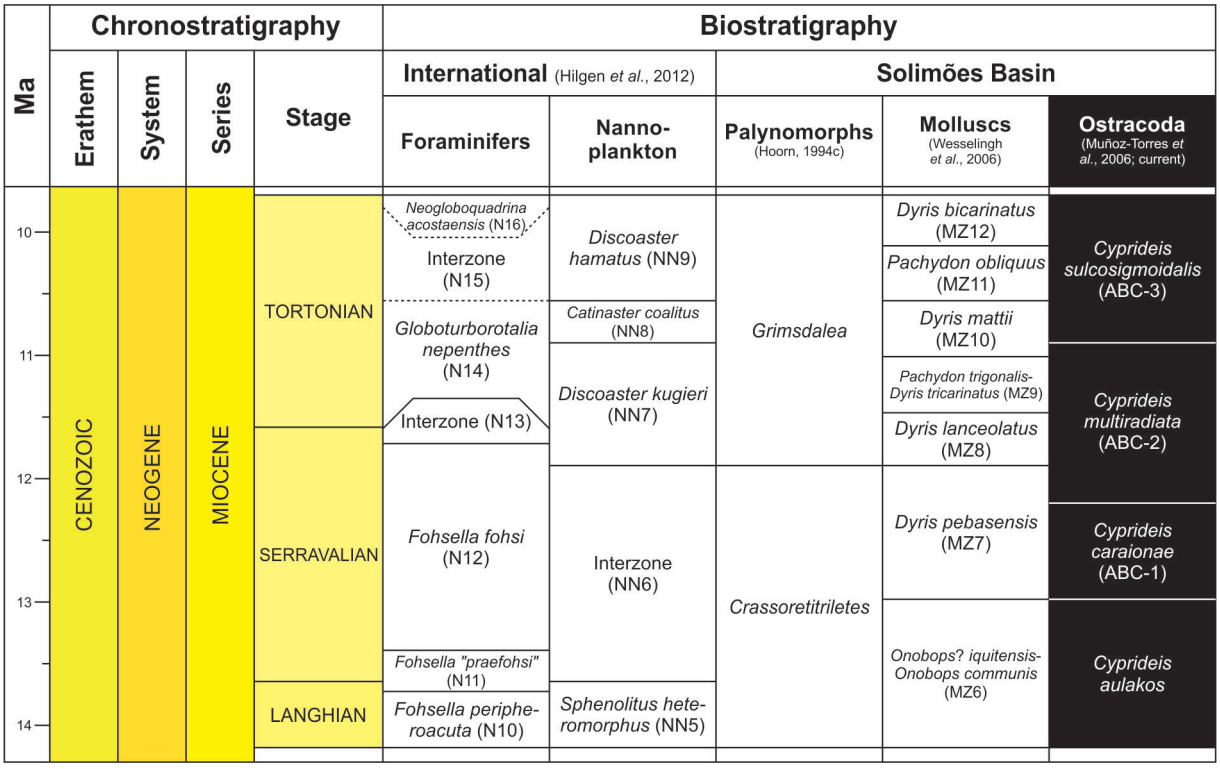

Figure 5. Chronobiostratigraphic correlation of the currently proposed ostracod zonation (in black) with local (Hoorn, 1994c, Wesselingh *et al.*, 2006) and international ones (Hilgen *et al.*, 2012).

permitted the identification of a late Miocene environmental event at the Solimões Formation, apparently caused by a marine incursion at the end of the middle Miocene.

CONCLUSIONS

Species recovered in the present work – *Cyprideis* aff. *C. amazonica* Purper, 1979, *Cyprideis caraionae* Purper & Pinto, 1985, *Cyprideis* aff. *graciosa* (Purper, 1979), *Cyprideis inversa* (Purper & Pinto, 1983), *Cyprideis machadoi* (Purper, 1979), *Cyprideis multiradiata* (Purper, 1979), *Cyprideis pebasae* (Purper, 1979), *Cyprideis simplex* (Sheppard & Bate, 1980), *Cyprideis sulcosigmoidalis* (Purper, 1979), *Alicenula olivencae* (Purper, 1984); *Rhadinocytherura amazonensis* Sheppard & Bate, 1980 and *Perissocytheridea* sp. A *sensu* Purper, 1977 – were used in the proposition of an ostracod zonation based on their stratigraphic amplitude and relative abundance in core samples of the 1-AS-33-AM well. Three biostratigraphic zones were reviewed or created: *Cyprideis caraionae* Range Zone, or ABC-1, *Cyprideis multiradiata* Range Zone, or ABC-2, and *Cyprideis sulcosigmoidalis* Latest Occurrence Interval Zone, or ABC-3.

The ostracod based zonation restricts the 1-AS-33-AM lithological succession to middle Miocene (middle Serravalian–Tortonian). However, the contrast with palynological data extends the deposition of this sedimentary interval to the Pliocene. Future work can help to resolve this issue, through either obtaining new data or re-evaluating the currently available ones. Analyses of recovered foraminifera also should be of interest for future investigations into an integrated view of paleoenvironmental changes on Amazonia. Using newly obtained fossiliferous and biostratigraphic information, the present work identifies a regional, middle Miocene (middle Tortonian) event in Western Amazonia.

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