**UNIVERSIDADE FEDERAL DO PARÁ**
**INSTITUTO DE GEOCIÊNCIAS**
**PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA E GEOQUÍMICA**

---

## TESE DE DOUTORADO Nº 126

# OSTRACOFAUNA DA FORMAÇÃO SOLIMÕES (ATALAIA DO NORTE, AMAZONAS, BRASIL): TAXONOMIA, IMPLICAÇÕES PALEOAMBIENTAIS E BIOESTRATIGRÁFICAS

**Tese apresentada por:**

ANA PAULA LINHARES PEREIRA

Orientador: Prof. Dr. Maria Inês Feijó Ramos (MPEG)

---

**BELÉM**

**2017**

Dados Internacionais de Catalogação de Publicação (CIP)
Biblioteca do Instituto de Geociências/SIBI/UFPA

Pereira, Ana Paula Linhares, 1981-

Ostracofauna da Formação Solimões (Atalaia do Norte, Amazonas, Brasil): taxonomia, implicações paleoambientais e bioestratigráficas / Ana Paula Linhares Pereira. – 2017.

xvii, 101 f. : il. ; 30 cm

Inclui bibliografias

Orientador: Maria Inês Feijó Ramos

Tese (Doutorado) – Universidade Federal do Pará, Instituto de Geociências, Programa de Pós-Graduação em Geologia e Geoquímica, Belém, 2017.

1. Ostracodes – Atalaia do Norte (AM). 2. Formações (Geologia) – Atalaia do Norte (AM). 3. Geologia estratigráfica – Neogeno. 4. Palinologia. 5. Fósseis. I. Título.

CDD 22. ed. 595.33098113

**Universidade Federal do Pará**
**Instituto de Geociências**
**Programa de Pós-Graduação em Geologia e Geoquímica**

# OSTRACOFAUNA DA FORMAÇÃO SOLIMÕES (ATALAIA DO NORTE, AMAZONAS, BRASIL): TAXONOMIA, IMPLICAÇÕES PALEOAMBIENTAIS E BIOESTRATIGRÁFICAS

**TESE APRESENTADA POR:**

## ANA PAULA LINHARES PEREIRA

**Como requisito parcial à obtenção do Grau de Doutor em Ciências na Área de GEOLOGIA**

**Data de Aprovação: 12/ 09 / 2017**

Banca Examinadora:

Prof.ª Dr.ª Maria Inês Feijó Ramos
Orientadora – MPEG

Prof. Dr. Dermeval Aparecido do Carmo
Membro – UNB

Prof. Dr. Gerson Fauth
Membro – UNISINOS

Prof. Dr. Marcelo Cancela Lisboa Cohen
Membro – UFPA

Prof. Dr. Orangel Antonio Aguilera Socorro
Membro – UFF

À minha família: Solange,
Guilherme, Sofia e Paulo, meu
bem mais precioso.

## AGRADECIMENTOS

À Universidade Federal do Pará (UFPA), com referência ao Programa de Pós-graduação em Geologia e Geoquímica (PPGG), pela infraestrutura e apoio fornecido.

À Coordenação de Ciências da Terra e Ecologia (COCTE) do Museu Paraense Emílio Goeldi (MPEG), pela infraestrutura, fundamental para o desenvolvimento da pesquisa, em especial ao Dr. Hilton Tulio Costi, por toda colaboração no laboratório de Microscopia Eletrônica de Varredura (MEV).

Ao Serviço Geológico do Brasil (CPRM)-Manaus e ao 8º. Distrito do Departamento de Produção Mineral (DNPM)-Manaus pela concessão das amostras. Á CPRM-Belém por permitir acesso e uso do MEV, em nome do Dr. Marcelo Vasquez.

Ao Centro de Microscopia Eletrônica da Universidade Federal do Rio Grande do Sul (FRGS). Ao Dr. João Carlos Coimbra, Msc. Natália Luz e Msc. Inaiê Miranda, os quais orgarizaram minhas sessões de fotografia e minha estadia em Porto Alegre.

À minha orientadora Dra. Maria Inês Feijó Ramos por sua orientação e paciência dedicada no processo de construção desse trabalho, e aos membros da banca examinadora que aceitaram o convite de avaliar minha tese.

Aos amigos do MPEG que colaboraram para o meu crescimento acadêmico: Dr. Francisco Berrêdo, Draª Laura Miglio, Msc. Lívia Guimarães, Msc. Sauri Machado e Bruna Antunes. Em especial à Msc. Maria Heloisa Moraes Santos por sua disponibilidade nas dúvidas gramaticais e à Drª Pryscilla Almeida pelo apoio e ajuda na identificação taxonômica das diatomáceas. Aos amigos Msc. Paulo Panarra, Dayane Dantas, Fernanda Menezes e Laylana Almeida que me incentivaram a continuar o trabalho em momentos difíceis.

Ao Msc. Felipe Leite, amigo para todas as horas, sempre me apoiando e ajudando nas problemáticas que surgiram no curso da tese. Ao Msc. Yuri Friaes, grande amigo e colega de trabalho que muito colaborou na palinologia, a qual não avançaria sem seu conhecimento.

Agradeço também imensamente ao meu grande amigo Msc. Valber Gaia, que além de ter colaborado nos artigos, também foi fundamental para que a tese fosse finalizada, talvez muitas coisas não seriam concluídas sem a sua ajuda! Obrigada à minha amiga Sulsiene Machado, que mesmo distante, torceu para que nosso trabalho fosse concluído com sucesso.

À minha família, e em especial à minha mãe Solange, meu marido Paulo e aos meus filhos Guilherme e Sofia, por seu amor e paciência nessa árdua e longa jornada. Amo muito vocês! A todos aqueles, que não tiveram os seus nomes aqui citados, mas que de alguma forma contribuíram para a realização deste trabalho.

"Nem todo ponto de vista vai ser ponto final."

Oswaldo Montenegro

# RESUMO

O estudo de ostracodes provenientes dos testemunhos 1AS-7D-AM, 1AS-8-AM e 1AS-31-AM, perfurados no município de Atalaia do Norte, Amazonas, Brasil, permitiu reconhecer 9 gêneros e 30 espécies; o gênero eurihalino *Cyprideis* é o mais abundante e diverso, com 19 espécies já identificadas e duas novas espécies descritas nesse trabalho: *C. atalaiensis* sp. nov. e *C. dictyon* sp. nov. Outros gêneros marinhos e/ou transicionais (*Paracypris*, *Perissocytheridea*, *Rhadinocytherura*, *Pellucistoma* e *Skopaeocythere*) e não-marinhos (*Cypria*, *Cytheridella* e *Penthesilenula*) foram encontrados, além de outros microfósseis (foraminíferos, peixes, moluscos e palinomorfos) que foram utilizados como elementos auxiliares nas interpretações paleoambientais e bioestratigráficas da Formação Solimões. A análise integrada da distribuição estratigráfica de ostracodes e palinomorfos nos testemunhos 1AS-8-AM e 1AS-7D-AM, permitiu datar a sequência do Eomioceno ao Neomioceno. Foram observadas, através dos fósseis- index, cinco zonas palinológicas já propostas para a Formação Solimões: *Verrutricolporites,* Mioceno Inferior; *Psiladiporites–Crototricolpites,* final do Mioceno Inferior ao início do Mioceno Médio; *Crassoretitriletes*, Mioceno Médio; *Grimsdalea*, final do Mioceno Médio ao início do Mioceno Superior; e *Asteraceae*, Mioceno Superior. A distribuição das espécies de *Cyprideis* permitiu reconhecer cinco zonas equivalentes às zonas palinológicas, das quais quatro já estabelecidas anteriormente, embora seus limites temporais tenham sido alterados nesse estudo: *C. aulakos*, renomeada para *C. sulcosigmoidalis,* final do Mioceno Inferior a início do Mioceno Médio; *C. caraionae*, Mioceno Médio a início do Mioceno Superior; *C. minipunctata,* início do Mioceno Superior; e *C. cyrtoma*, início do Mioceno Superior. Além dessas, é proposta aqui uma nova zona de ostracode: *C. paralela*, do Mioceno Superior. A análise bioestratigráfica integrada (palinologia e ostracodes), bem como o registro da microfauna associada revela uma sequência que inicia no Mioceno Inferior, com influência de ambientes costeiros, atestada pela presença de palinomorfos e foraminíferos tipicamente de manguezal. No Mioceno Médio as condições paleoambientais passam a ser de um ambiente flúvio-lacustre, com influência marinha. Finalmente, no Mioceno Superior, apesar de ainda apresentar intervalos de influência marinha, premomina um ambiente flúvio-lacustre em direção ao topo da sequência estudada.

**Palavras-chave**: Neógeno; Formação Solimões; ostracodes; evolução paleoambiental; incursões marinhas.

# ABSTRACT

The study of the ostracods from the boreholes 1AS-7D-AM, 1AS-8-AM and 1AS-31-AM, drilled at the locality of Atalaia do Norte, in Amazonas State, Brazil, allowed to recognized 9 genera and 30 species; the eurialyne genera *Cyprideis* is the most abundant and diverse, with 19 known species and two new species described herein: *C. atalaiensis* sp. nov. and *C. diction* sp. nov. Other marine and/or transitional (*Paracypris*, *Perissocytheridea*, *Rhadinocytherura*, *Pellucistoma* and *Skopaeocythere*) and non-marine (*Cypria*, *Cytheridella* and *Penthesilenula*) genera have been found, as well as other microfossils (foraminifera, fishs, mollusks and palinomorphs) which have been used for the paleoenvironmental interpretations and biostratigraphy of the Solimões Formation. The integrated stratigraphic analisys of ostracods and palinomorphs in the boreholes 1AS-8-AM and 1AS-7D-AM allowed to date the sequence from Early Miocene to Late Miocene. Through the index fossils, were identified five palinological zones already proposed from the Neogene of western Amazon: *Verrutricolporites,* Early Miocene; *Psiladiporites-Crototricolpites*, Late Early Miocene to Early Middle Miocene; *Crassoretitriletes*, Middle Miocene; *Grimsdalea*, Late Middle Miocene to Early Late Miocene; and *Astaraceae*, Late Miocene. The distribution of the *Cyprideis* species allowed to recognize five zones corresponding to the palynological zones, four of which previously established, although its age limits have been changed in this study: *C. aulakos*, renamed as *C. sulcosigmoidalis*, from late Early Miocene to early Middle Miocene, *C. caraione*, Middle Miocene to early Late Miocene, *C. minipunctata*, late Late Miocene and *C. cyrtoma* Late Miocene. Furthermore, is proposed here a new ostracod zone: *C. paralela*, from Late Miocene. The biostratigraphic analysis, based on palinology and ostracods, as well as other microfossils reveals a sequence which starts at the Early Miocene, with influence of coastal environments attested by the presence of palinomorphs and foraminifera typically from mangrove. At the Middle Miocene, the paleoenvironments are characterized as fluvio-lacustrine with marine influence. Finally, in the Late Miocene although still marked by marine influence, predominate fluvio-lacustrine environment upward to the section.

**Key-words:** Neogene; Solimões Formation; ostracods; paleoenvironmental evolution; marine incursions.

# LISTA DE ILUSTRAÇÕES

## CAPÍTULO 1

## CAPÍTULO 2

**CAPITULO 3**

## CAPÍTULO 4

# LISTA DE TABELAS

## CAPÍTULO 1

## CAPÍTULO 2

## CAPÍTULO 3

# SUMÁRIO

# CAPÍTULO 1

## 1 CONSIDERAÇÕES INICIAIS

A tese de doutorado está organizada em cinco capítulos, sendo três deles em formato de artigos. O capítulo 1 corresponde à parte introdutória que inclui: uma apresentação com o resumo dos tópicos abordados na tese, a localização da área de estudo, os objetivos, os materiais e métodos utilizados, e uma revisão de trabalhos anteriores sobre o contexto geológico, paleontologia, paleoambientes e idade da Formação Solimões. Para evitar repetições, a parte introdutória foi inserida de forma simplificada nos textos dos artigos. O capítulo 2, o primeiro artigo da tese, submetido ao Periódico Zootaxa, trata do estudo taxonômico ostracofauna da Formação Solimões encontrada em testemunhos de três sondagens 1AS-7D-AM, 1AS-8-AM e 1AS-31-AM (Município de Atalaia do Norte, Estado do Amazonas), incluindo discussões sobre a revisão taxonômica de espécies do gênero *Cyprideis*, e a descrição de duas novas espécies.  O capitulo 3, segundo artigo da tese, a ser submetido ao periódico Palaios, trata da análise bioestratigráfica integrada utilizando-se grãos de pólen e ostracodes em 1AS-7D-AM e 1AS-8-AM, com o intuito de identificar as biozonas correspondentes à sequência estudada e consequentemente datar o intervalo da Formação Solimões na área estudada. O terceiro artigo compõe o capítulo 4, o qual foi publicado em Journal of South American Earth Sciences, e aborda a reconstrução paleoambiental da área de estudo, discutindo a influência marinha em depósitos do Neógeno na Amazônia Ocidental no Brasil. O quinto capítulo inclui as considerações finais obtidas a partir dos artigos desenvolvidos, apresentando resumidamente os resultados e conclusões alcançadas.

### 1.1 INTRODUÇÃO

Nas últimas décadas, diversos estudos (principalmente geológicos, paleontológicos e geoquímicos) têm sido sendo desenvolvidos com o intuito de buscar esforços para a reconstrução paleoambiental do Neógeno da Amazônia Ocidental (Hoorn & Wesselingh, 2010a; b). Porém, apesar do estabelecimento de alguns modelos propostos, algumas questões ainda estão em discussão, principalmente no que se refere às evidências sobre a influência marinha e a sequência temporal desses eventos nos limites do Brasil (Kachniasz & Silva-Caminha, 2016). Durante o Neógeno, a região amazônica foi altamente influenciada por eventos tectônicos, como a orogenia andina, que moldaram sua paisagem, e consequentemente levaram à mudanças no ecossistema (Wanderley Filho *et al*., 2010; Mora *et al*., 2010; Roddaz *et al*., 2010; Espurt *et al*., 2010; Hoorn *et al*., 2010a; b).

A micropaleontologia tem sido uma ferramenta fundamental para elucidar a evolução da biota e dos paleoambientes associados. Os palinomorfos, ostracodes e moluscos são os principais grupos que têm contribuído para os estudos bioestratigráficos, paleoecológicos e paleobiogeográficos, devido à sua grande abundância, diversidade, excelente preservação e rápida evolução durante o Neógeno na Amazônia Ocidental (Purper, 1979; Hoorn, 1994a; b; Muñoz-Torres *et al.*, 1998; 2006; Leite, 2006; Ramos, 2006; Wesselingh *et al*., 2006 a; b; c; d; Silva, 2008; Latrubesse *et al.*, 2010; Wesselingh & Ramos, 2010; Linhares *et al.*, 2011; Gross *et al.*, 2013; 2014; 2015; Boonstra *et al.*, 2015; Kachniasz & Silva-Caminha, 2016; Jaramillo *et al*., 2017).

Desde os primeiros estudos paleontológicos (Roxo, 1924; 1935; Maury, 1937), a ocorrência de um assembleia de faunas representadas por grupos marinhos, transicionais e não-marinhos, nos estratos da Formação Solimões, tem dificultado a interpretação da sua evolução paleoambiental, bem como dos sistemas deposicionais. A presença desses elementos tem sido a causa de discussões a respeito das influências marinhas na Amazônia Ocidental (Hoorn, 1993; Linhares *et al.*, 2011; Antoine *et al.*, 2016; Jaramillo *et al*., 2017), uma vez que em geral os estudos sedimentológicos não registram essas influências (Latrubesse *et al.*, 2010; Nogueira *et al.*, 2013; Gross *et al.*, 2014).

Trabalhos mais recentes em afloramentos de diferentes localidades no oeste do Estado do Amazonas, integrando paleontologia e sedimentologia, mesmo de forma localizada e temporalmente limitada, têm contribuído para a interpretação paleoambiental da Formação Solimões, atestando a presença de um sistema deposicional muito semelhante ao atual (Latrubesse *et al*., 2007; 2010; Gross *et al*., 2011; Nogueira *et al*., 2013; Paz *et al*., 2015). Entretanto, evidências de incursões marinhas, primeiramente apontadas por Hoorn (1993), têm sido confirmadas por diversos autores através de estudos micropaleontológicos em testemunhos de sondagem na região oeste da Amazônia no Brasil (Linhares *et al.*, 2011; Leandro, 2012; Kachniasz & Silva-Caminha, 2016; Jaramillo *et al*., 2017).

Assim, o presente estudo teve por objetivo, através da análise micropaleontológica e da bioestratigrafia integrada de ostracodes e palinologia de três testemunhos de sondagem, nas proximidades do Município de Atalaia do Norte, Amazonas, contribuir para a reconstrução da evolução paleoambiental, datação da sequência estudada e correlação desta área com outras localidades já estudadas no Brasil, Peru e Colômbia. Estes testemunhos são de posicionamento estratégico devido à proximidade destes com os outros, onde foram constatados registros de influência marinha (1AS-4A-AM/Hoorn, 1993; 1AS-31-AM/Linhares *et al.*, 2011; Kachniasz & Silva-Caminha, 2016), e por estarem nas proximidades da fronteira com outras áreas já estudadas onde também foram atestadas evidências de incursões marinhas como a Formação Pebas, no Peru e Carbonera, na Colômbia (Boonstra *et al.*, 2015; Antoine *et al.*, 2016; Jaramillo *et al.*, 2017).

## 1.2 OBJETIVOS

### 1.2.1 Objetivo geral

O presente trabalho tem por objetivo geral contribuir para as interpretações da evolução paleoambiental de depósitos do Neógeno da Formação Solimões, Amazônia, Brasil, através do estudo micropaleontológico integrando principalmente ostracodes e palinomorfos de testemunhos de três sondagens, e para a correlação com as demais localidades já estudadas no Brasil e unidades correlatas na Colômbia e Peru.

### 1.2.2 Objetivos específicos

- Realizar o estudo taxonômico dos ostracodes dos testemunhos analisados;
- Avaliar a idade da sequência estudada, através da distribuição estratigráfica dos ostracodes (*Cyprideis*) e grãos de pólen e das espécies guia identificadas.
- Reconstruir a evolução paleoambiental através da distribuição dos ostracodes e palinomorfos, além de outros microfósseis encontrados associados;
- Correlacionar a área estudada com áreas adjacentes no Brasil, Peru e Colômbia.

## 1.3 LOCALIZAÇÃO DA ÁREA DE ESTUDO

A área de estudo (Fig. 1) compreende a porção oeste do Estado do Amazonas, de onde foram obtidas amostras de três testemunhos de sondagem perfurados nas proximidades do Município de Atalaia do Norte, sendo a sondagem 1AS-7D-AM (lat. 04°34’S-long. 70°41´W) próxima ao rio Quixito, enquanto que 1AS-8-AM (lat. 04°36’S-long. 70°16´W) está próximo ao rio Itacuaí, e o 1AS-31-AM próximo ao rio Ituí (lat. 05°18’S-long. 71°02´W).

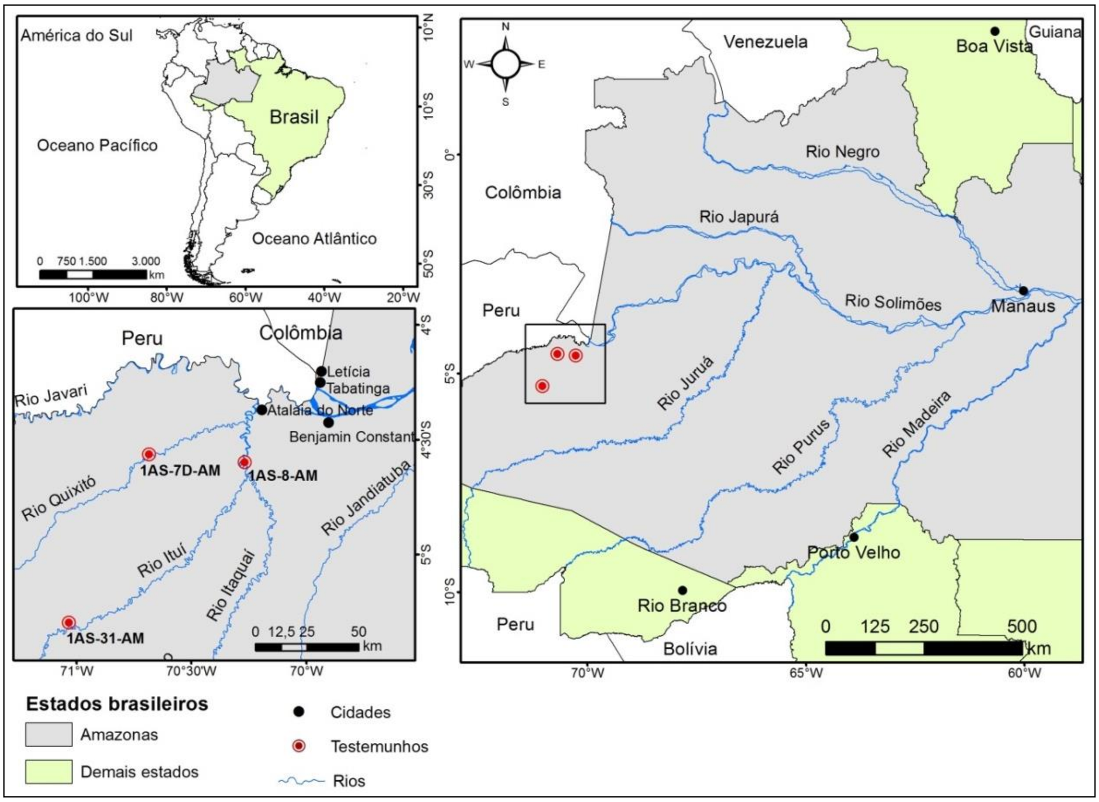


Figura 1 - Área de estudo com a localização dos testemunhos de sondagem analisados.

## 1.4 MATERIAL E MÉTODOS

O material de estudo compreende 304 amostras provenientes de três testemunhos perfurados no escopo do Projeto Carvão no Alto Solimões (Maia *et al*., 1977), e encontram-se armazenados na litoteca do Serviço Geológico do Brasil (CPRM), Manaus, Estado do Amazonas. Dentre estas, 112 amostras procedem do 1AS-7D-AM, 83 amostras do 1AS-8-AM e 109 do 1AS-31-AM. As seções colunares foram feitas com base nas apresentadas no relatório de Maia *et al*. (1977) com o refinamento das litologias conforme ilustradas nas figuras 2 a 4. A amostragem dos testemunhos foi realizada segundo critérios litológicos e aparente conteúdo macrofossilífero.

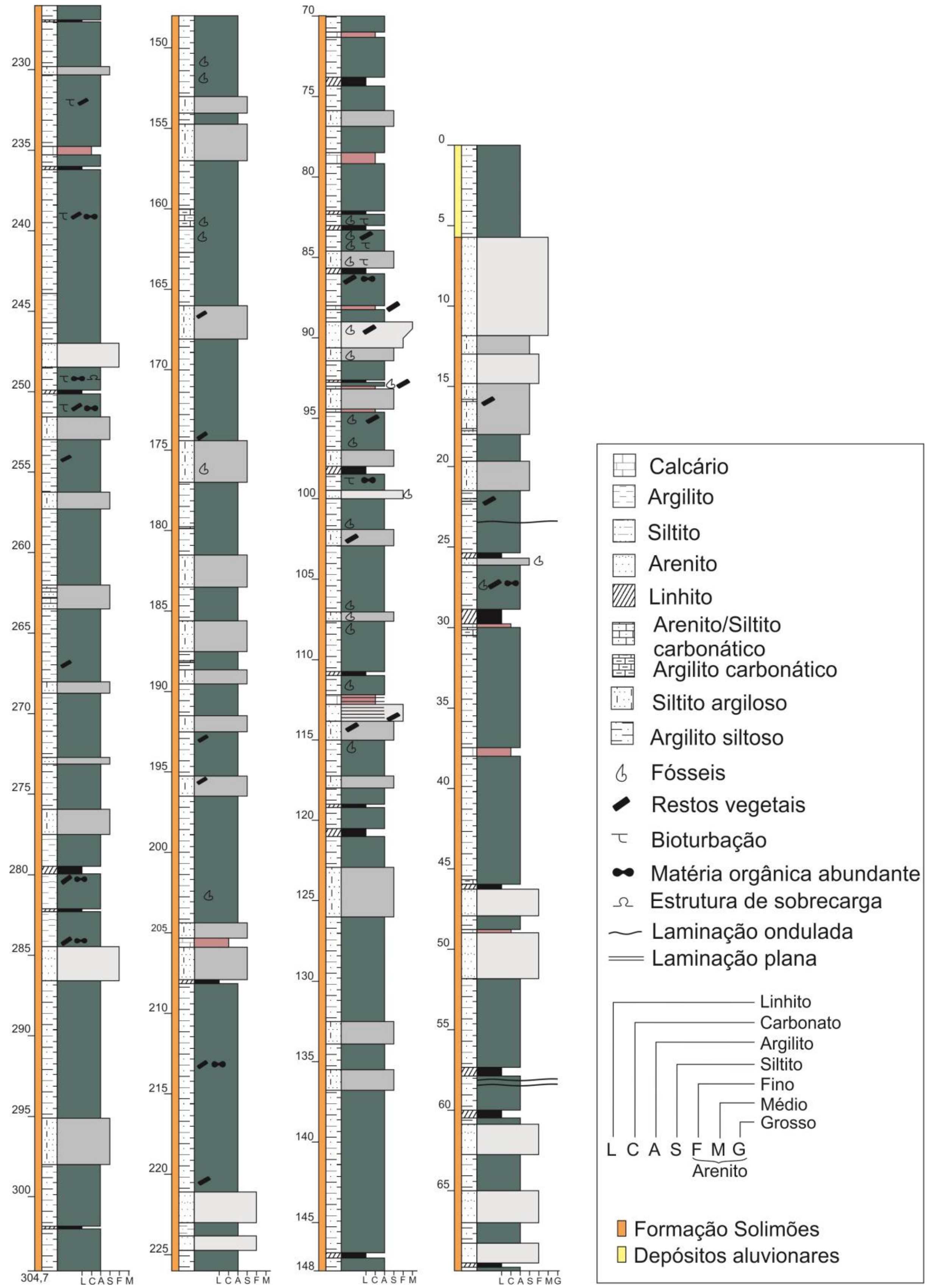


Figura 2 - Perfil litológico do testemunho de sondagem 1AS-7D-AM.

Fonte: Modificado de Maia *et al*. (1977).

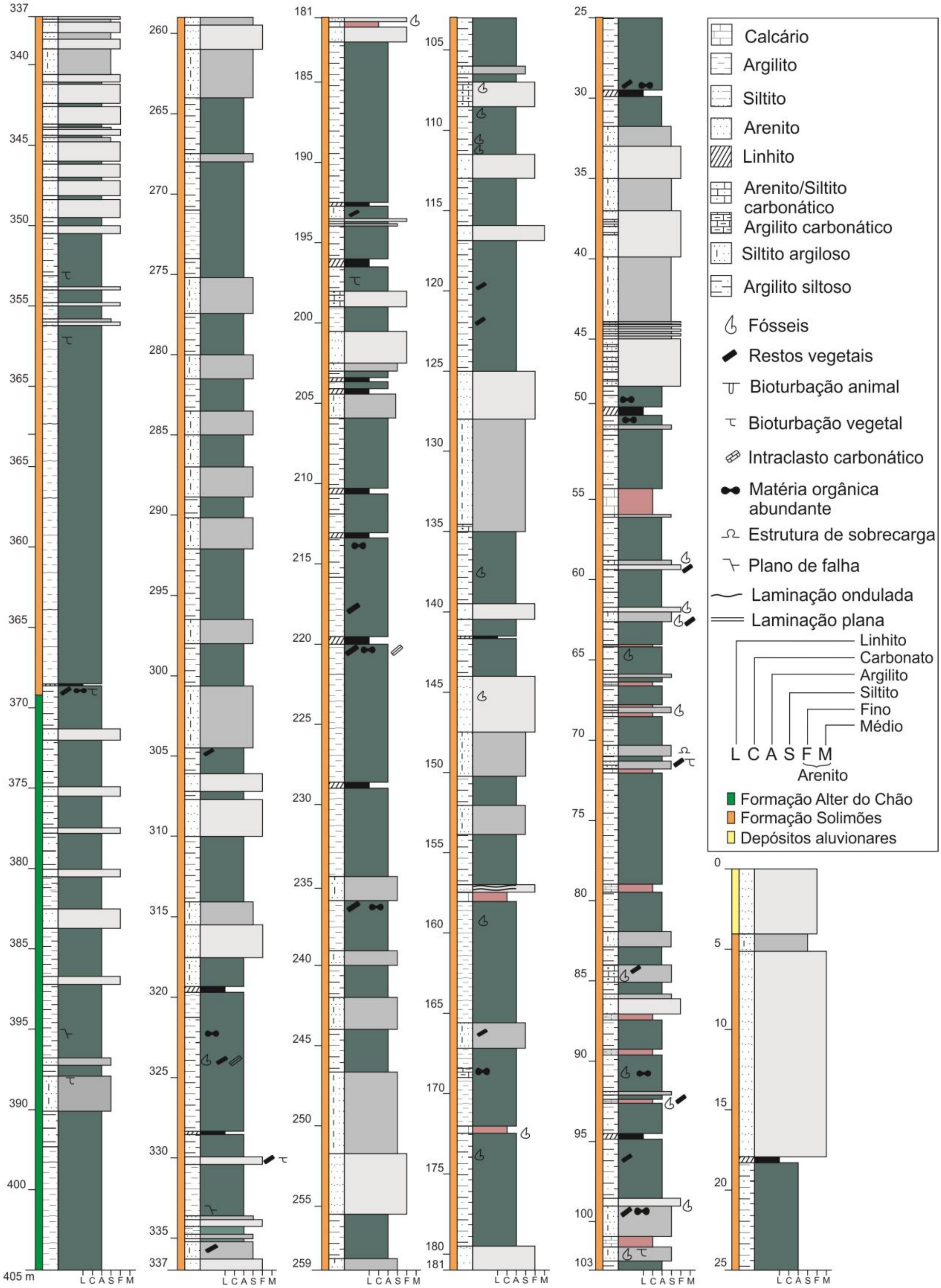


Figura 3 - Perfil litológico do testemunho de sondagem 1AS-8-AM.

Fonte: Modificado de Maia *et al*. (1977).

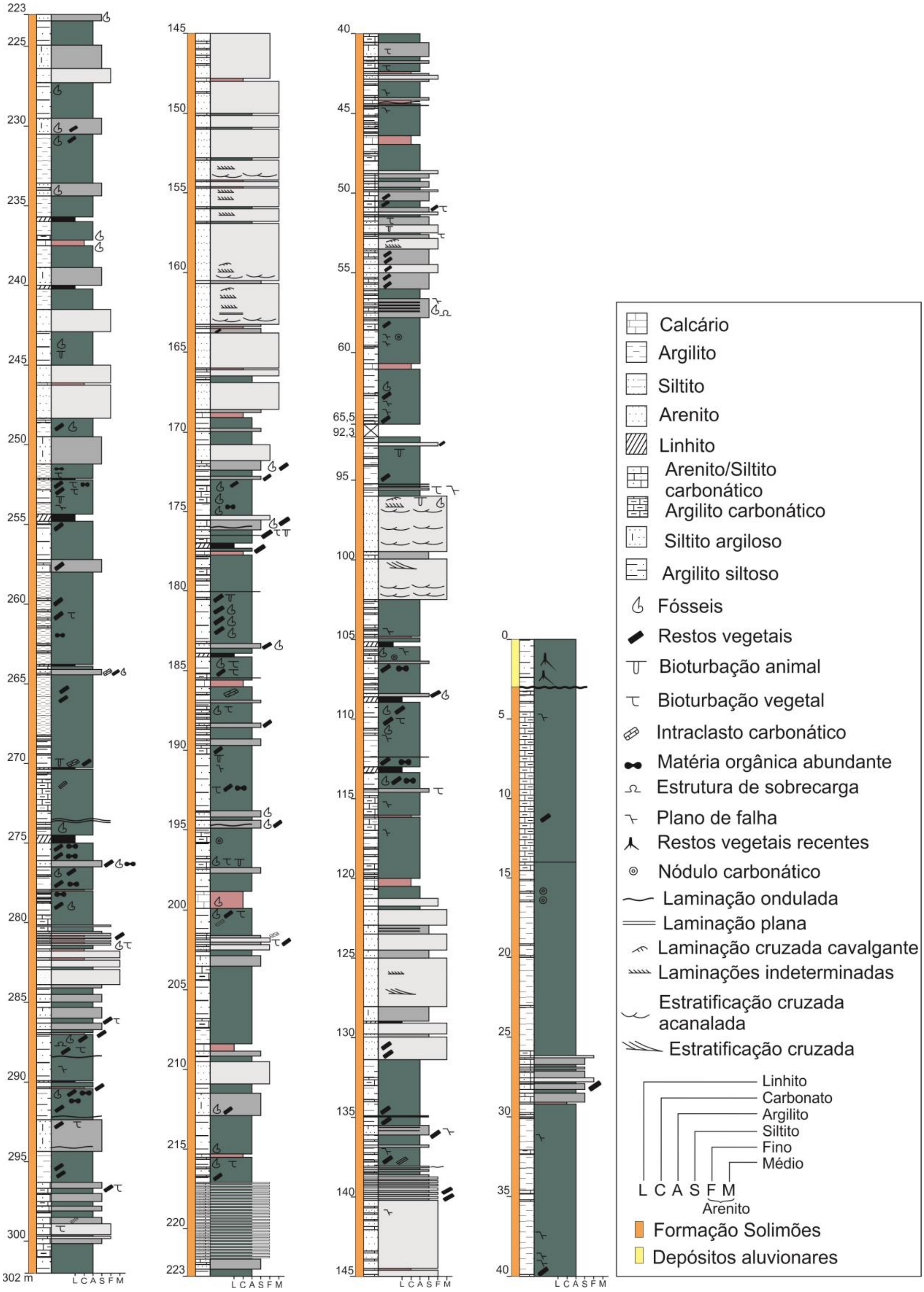


Figura 4 - Perfil litológico do testemunho de sondagem 1AS-31-AM.

### 1.4.1 Análise micropaleontológica

A preparação das amostras para a análise de microfósseis calcários foi realizada no laboratório de Sedimentologia/Polimento da Coordenação de Ciências da Terra e Ecologia (COCTE) do Museu Paraense Emílio Goeldi (MPEG), através da metodologia padrão detalhadamente descrita em Wanderley (2010), a qual segue as seguintes etapas:

**1)** Padronização do peso bruto em aproximadamente 180 gramas;
**2)** desagregação das amostras em béquer com água por um período médio de 24 horas;
**3)** lavagem e peneiramento das amostras utilizando-se malhas de 500, 250, 180 e 125 µm;
**4)** limpeza das peneiras no ultrassom após cada peneiramento, e banho de 15 minutos em água com Azul de Metileno para detectar possível contaminação de uma amostra para outra;
**5)** secagem do material residual em estufa a 50ºC;
**6)** pesagem das amostras em balança de precisão e padronização em 2g de sedimento, de cada fração de peneira, para as análises quantitativas;
**7)** triagem dos microfósseis do sedimento foi realizada com o auxílio de pincéis 00 e de lupa da Zeiss;
**8)** colagem dos microfósseis com cola arábica em lâminas de “Células Flanke”;
**9)** seleção de melhores espécimes para posteriormente limpeza com álcool e água deionizada;
**10)** contagem dos espécimes de cada amostra;
**11)** preparação de “stubs” para a realização das fotografias;
**12)** obtenção de eletromicrografias com o uso de MEV (Laboratório de Microscopia Eletrônica de Varredura, modelo Leo 1450);
**13)** tombamento dos espécimes tipo e figurados na coleção de microfósseis do acervo de Paleontologia do MPEG.

Como suporte para as interpretações paleoambientais, além dos ostracodes, foram também utilizados outros microfósseis recuperados durante a triagem tanto para a análise de microfósseis calcários como para palinomorfos. No testemunho 1AS-7D-AM, 41 amostras apresentaram ostracodes e/ou outros grupos fósseis e 71 são estéreis. Em 1AS-8-AM, 33 apresentaram ostracodes e/ou outros grupos fósseis e 50 são estéreis. O testemunho 1AS-31-AM, previamente estudado por Linhares *et al*. (2011), foi reamostrado, sendo que além das 93 amostras já estudadas, mais 16 foram analisadas, totalizando 109 amostras; destas, 51 contêm ostracodes e/ou contêm outros microfósseis e 58 são estéreis (Tab. 1).

Tabela 1- Ocorrência de ostracodes e outros grupos fósseis encontrados nos testemunhos de sondagem 1AS-7D-AM, 1AS-8-AM e 1AS-31-AM.

| Nº Amostra | **1AS-7D-AM** (profund.) | Ostracodes | Outros grupos | **1AS-8-AM** (profund.) | Ostracodes | Outros grupos | **1AS-31-AM** (profund.) | Ostracodes | Outros grupos |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3,40 m | | | 32,00 m | | | 3,05 m | | |
| 2 | 14,80 m | ● | ● | 35,05 m | | | 6,17 m | | |
| 3 | 15,95 m | | | 38,50 m | | | 9,15 m | | |
| 4 | 17,70 m | | | 44,55 m | | ● | 9,85 m | | |
| 5 | 22,55 m | | | 50,55 m | | | 11,45 m | | |
| 6 | 23,55 m | | | 55,50 m | | | 12,00 m | | |
| 7 | 27,55 m | | | 59,25 m | ● | ● | 15,30 m | | |
| 8 | 27,65 m | | | 61,00 m | | | 20,00 m | ● | |
| 9 | 29,55 m | | | 62,60 m | | ● | 22,00 m | | |
| 10 | 29,90 m | ● | | 70,90 m | | ● | 22,55 m | | |
| 11 | 30,30 m | | | 77,10 m | | | 23,21 m | | |
| 12 | 36,80 m | ● | | 86,00 m | | | 25,75 m | | |
| 13 | 45,95 m | ● | ● | 86,10 m | | | 26,10 m | ● | |
| 14 | 50,00 m | ● | ● | 87,30 m | ● | ● | 26,12 m | ● | |
| 15 | 58,00 m | | | 88,00 m | | | 29,50 m | | |
| 16 | 58,15 m | | | 92,63 m | ● | ● | 29,51 m | | |
| 17 | 68,50 m | | | 93,05 m | ● | ● | 29,88 m | | |
| 18 | 73,60 m | ● | ● | 96,00 m | | | 32,68 m | | |
| 19 | 76,50 m | ● | ● | 99,15 m | ● | ● | 35,58 m | | |
| 20 | 78,50 m | ● | ● | 102,60 m | ● | ● | 37,85 m | | |
| 21 | 84,65 m | | | 103,20 m | ● | ● | 39,55 m | ● | |
| 22 | 88,15 m | ● | | 109,00 m | | | 45,00 m | | |
| 23 | 89,00 m | | | 110,60 m | ● | ● | 45,10 m | | |
| 24 | 90,00 m | | ● | 110,73 m | | | 50,50 m | | |
| 25 | 91,50 m | ● | ● | 110,80 m | ● | ● | 56,50 m | ● | |
| 26 | 93,15 m | ● | ● | 111,50 m | ● | ● | 58,00 m | ● | |
| 27 | 94,50 m | | | 116,90 m | | | 63,00 m | | |
| 28 | 96,00 m | ● | ● | 119,70 m | | | 65,25 m | | |
| 29 | 96,30 m | ● | ● | 121,65 m | | | 89,80 m | | |
| 30 | 97,50 m | ● | ● | 127,35 m | | | 90,15 m | | |
| 31 | 98,90 m | | | 132,45 m | ● | ● | 93,00 m | | |
| 32 | 99,90 m | ● | ● | 135,30 m | ● | ● | 93,20 m | | |
| 33 | 101,90 m | ● | ● | 137,30 m | | ● | 96,25 m | | |
| 34 | 103,20 m | ● | ● | 140,45 m | | ● | 99,30 m | | |
| 35 | 106,00 m | ● | ● | 141,00 m | | | 102,35 m | | |
| 36 | 107,00 m | | ● | 141,50 m | | | 110,60 m | | |
| 37 | 110,00 m | | | 145,00 m | | ● | 122,29 m | | ● |
| 38 | 111,50 m | ● | ● | 150,10 m | | ● | 127,00 m | | |
| 39 | 113,00 m | | | 154,05 m | ● | | 135,90 m | ● | |
| 40 | 114,00 m | | | 159,20 m | ● | ● | 138,20 m | ● | ● |
| 41 | 114,50 m | | ● | 165,00 m | | | 140,85 m | ● | |
| 42 | 115,50 m | ● | ● | 166,00 m | | | 141,00 m | | |
| 43 | 116,20 m | | ● | 168,45 m | | | 148,75 m | ● | ● |
| 44 | 117,20 m | ● | ● | 172,23 m | ● | ● | 153,00 m | | |
| 45 | 117,70 m | ● | ● | 172,30 m | ● | | 157,25 m | ● | |
| 46 | 118,00 m | | | 173,60 m | ● | | 163,00 m | ● | |
| 47 | 119,00 m | | | 173,85 m | ● | ● | 166,40 m | ● | |
| 48 | 120,00 m | | | 179,45 m | | | 168,35 m | | |
| 49 | 121,00 m | ● | | 181,00 m | ● | ● | 170,80 m | ● | ● |
| 50 | 125,00 m | ● | | 193,55 m | ● | ● | 170,90 m | ● | ● |
| 51 | 126,50 m | | ● | 193,85 m | ● | ● | 171,40 m | | ● |
| 52 | 136,20 m | ● | ● | 195,85 m | ● | | 171,80 m | | |
| 53 | 152,00 m | | | 198,10 m | | | 172,40 m | ● | ● |
| 54 | 160,50 m | ● | ● | 199,00 m | | | 172,50 m | ● | |
| 55 | 161,00 m | ● | | 200,60 m | | | 173,60 m | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 56 | 162,00 m | ● | ● | 208,55 m | | | 174,30 m | ● | ● |
| 57 | 163,00 m | | | 214,00 m | | | 174,40 m | ● | ● |
| 58 | 165,20 m | | | 214,70 m | | | 174,55 m | ● | ● |
| 59 | 166,00 m | | | 218,00 m | | | 174,65 m | | ● |
| 60 | 166,70 m | | | 220,00 m | | | 174,70 m | | ● |
| 61 | 168,00 m | | | 225,25 m | | | 174,80 m | ● | |
| 62 | 172,00 m | | | 228,25 m | | | 174,82 m | | ● |
| 63 | 174,40 m | | | 234,50 m | | ● | 174,90 m | | ● |
| 64 | 176,20 m | | ● | 246,76 m | | ● | 175,00 m | ● | ● |
| 65 | 179,20 m | ● | ● | 251,70 m | | | 175,05 m | | ● |
| 66 | 181,50 m | | | 258,30 m | | | 175,30 m | | |
| 67 | 184,00 m | | | 263,35 m | | | 175,50 m | ● | |
| 68 | 188,00 m | | | 271,00 m | | | 176,80 m | | |
| 69 | 193,00 m | ● | | 274,10 m | | | 177,20 m | | |
| 70 | 195,50 m | | | 304,50 m | | | 180,90 m | | |
| 71 | 197,40 m | | ● | 314,15 m | | | 181,00 m | ● | |
| 72 | 199,00 m | | | 315,45 m | | | 181,10 m | | |
| 73 | 202,80 m | ● | ● | 323,40 m | | ● | 181,95 m | | ● |
| 74 | 204,30 m | | | 330,40 m | | | 183,00 m | | |
| 75 | 205,80 m | ● | ● | 336,70 m | | | 186,60 m | | ● |
| 76 | 212,00 m | | | 336,80 m | | | 188,65 m | | |
| 77 | 212,50 m | | | 342,00 m | | | 189,70 m | ● | |
| 78 | 215,50 m | | | 348,95 m | | | 195,00 m | | ● |
| 79 | 219,30 m | | | 357,25 m | | | 199,70 m | | |
| 80 | 220,60 m | | ● | 368,00 m | | ● | 199,90 m | ● | |
| 81 | 221,10 m | | | 368,50 m | | | 216,90 m | ● | ● |
| 82 | 224,90 m | ● | ● | 383,70 m | | | 218,30 m | ● | ● |
| 83 | 225,50 m | | | 403,00 m | | | 219,95 m | ● | ● |
| 84 | 228,20 m | | | | | | 222,80 m | ● | |
| 85 | 230,20 m | | | | | | 227,40 m | ● | ● |
| 86 | 232,70 m | | | | | | 227,41 m | ● | |
| 87 | 236,00 m | | | | | | 230,00 m | ● | ● |
| 88 | 240,30 m | | | | | | 251,90 m | | |
| 89 | 244,45 m | | | | | | 258,80 m | | |
| 90 | 247,00 m | | | | | | 264,00 m | | |
| 91 | 248,85 m | | | | | | 267,00 m | | |
| 92 | 252,20 m | | | | | | 273,05 m | ● | |
| 93 | 254,15 m | | ● | | | | 273,20 m | | |
| 94 | 256,35 m | | | | | | 276,20 m | ● | |
| 95 | 258,50 m | | | | | | 281,10 m | | |
| 96 | 262,15 m | | | | | | 284,90 m | | |
| 97 | 263,65 m | | ● | | | | 285,00 m | | |
| 98 | 266,00 m | | | | | | 287,50 m | | |
| 99 | 267,10 m | | | | | | 288,80 m | | |
| 100 | 268,00 m | | | | | | 292,40 m | | ● |
| 101 | 269,15 m | | | | | | 292,50 m | | |
| 102 | 270,55 m | | | | | | 294,35 m | | |
| 103 | 273,20 m | | | | | | 295,00 m | ● | ● |
| 104 | 279,20 m | | | | | | 296,80 m | ● | |
| 105 | 281,30 m | | | | | | 296,90 m | ● | |
| 105 | 285,35 m | | | | | | 297,50 m | ● | |
| 106 | 288,60 m | | | | | | 299,00 m | | ● |
| 107 | 291,40 m | | | | | | 299,05 m | | ● |
| 108 | 294,30 m | ● | | | | | 299,30 m | | |
| 109 | 296,20 m | | | | | | 301,00 m | | |
| 110 | 301,60 m | | | | | | | | |
| 111 | 304,70 m | | | | | | | | |
| 112 | 387,75 m | | | | | | | | |

### 1.4.2 Análise palinológica

Para as análises palinológicas seguiu-se a metodologia padrão de Uesugui (1979) com algumas adaptações:

**1)** 30 a 50g de cada amostra foram colocadas em béquer e tratadas inicialmente com ácido clorídrico (HCl) a 32% por 2 horas para a eliminação de carbonatos;
**2)** depois do primeiro ataque ácido, as amostras são lavadas com água destilada por três vezes; posteriormente são levadas ao segundo ataque ácido com ácido fluorídrico (HF) a 40%, por um mínimo de 12 horas, para a eliminação de silicatos;
**3)** após esta etapa, as amostras são novamente lavadas com água destilada por três vezes afim de neutralizar a ação dos ácidos;
**4)** após lavagem com ácido clorídrico (HCl) a 10% e água destilada em banho-maria a 60°C por 30 minutos, a amostra permaneceu em Becker por um período de 24 horas para a decantação dos minerais pesados e para a recuperação do material sobrenadante mais leve. Esta metodologia substituiu a centrifugação que causava a destruição dos palinomorfos mais frágeis;
**5)** o material foi lavado novamente com água destilada e peneirado em malha de 200 μm;
**6)** a partir dos resíduos finais foram preparadas três lâminas para contagem de cada amostra que, posteriormente, foram analisadas na objetiva de 40x com auxílio do microscópio óptico da Zeiss e fotografadas com objetiva de 100x na câmera digital Canon PowerShot A640, acoplada ao microscópio;
**7)** em todas as etapas de descarte das amostras em meio ácido foi acrescida solução básica para neutralização da solução ácida.

### 1.4.3 Identificação taxonômica

A classificação taxonômica supragenérica dos ostracodes seguiu os trabalhos de Liebau (2005); as demais classificações seguem Purper (1977a; b; 1979), Whatley *et al.* (1998), Muñoz-Torres *et al.* (1998), e Gross *et al.* (2014), além do uso das coleções de referência de Purper (1979), Purper & Pinto (1983) e Gross *et al.* (2014). Para a identificação palinológica foram utilizadas principalmente as propostas de Lorente (1986), Hoorn (1993; 1994a; b) e Jaramillo *et al.* (2011). Para as demais identificações foram utilizadas referências diversas citadas ao longo dos artigos.

### 1.4.4 Análise bioestratigráfica

O estudo bioestratigráfico foi feito de maneira integrada, através da análise da distribuição estratigráfica das espécies de ostracodes do gênero *Cyprideis* e grãos de pólen identificados; bem como da identificação dos taxa-index. Para o biozoneamento palinológico utilizou-se os arcabouços estabelecidos para a América do Sul (Lorente, 1986; Hoorn, 1993). Para os ostracodes foi utilizada a proposta de Muñoz-Torres *et al.* (2006) para a Amazônia Ocidental, na qual os limites das biozonas de ostracodes foram definidos pelo primeiro (FAD) e último (LAD) aparecimento, seguindo o Código Internacional de Nomenclatura Estratigráfica. O presente trabalho seguiu os mesmos critérios.

## 1.5 CONTEXTO GEOLÓGICO

### 1.5.1 Tectônica

A Orogenia Andina é o principal evento que influenciou a evolução da paisagem da região amazônica durante o Cenozóico e ocorreu em três fases, sendo a primeira entre o Oligoceno Superior e Mioceno Inferior (~23 Ma), a segunda no Mioceno Superior (~10 Ma) e a terceira no Plioceno Inferior (~4,5 Ma) (Figueiredo *et al.*, 2009; Hoorn *et al*, 2010a; b; Mora *et al.*, 2010).

A primeira fase do soerguimento andino gerou subsidência flexural das áreas a leste da cordilheira oriental, levando a formação das bacias do tipo *foreland* (retroarco) e influenciando a deposição sedimentar nas bacias do Solimões e do Acre, em sistemas de lagos, canais e planícies alagadas (*megawetlands*), onde se depositaram os sedimentos da Formação Solimões (Hoorn *et al.*, 2010a; b; Bezzera & Ribeiro 2015).

No segundo momento, o espessamento crustal formado pelo soerguimento máximo da cordilheira oriental (~10 Ma) foi compensado isostaticamente através de um soerguimento periférico, formando o alto flexural (*forebulge*) de Iquitos na Amazônia central e, por consequência, suas respectivas subsidências adjacentes (*foredeep* e *backbulge*) (Roddaz *et al.*, 2005; Mora *et al.*, 2010; Roddaz *et al.*, 2010; Bezzera & Ribeiro 2015). Esse soerguimento máximo também refletiu no aumento do gradiente do substrato e do suprimento sedimentar nas bacias subandinas, resultando na maior influência fluvial na região e sobrepondo os ambientes de *megawetlands*.

O soerguimento dos Andes desencadeou eventos como o aumento da inclinação do substrato da zona subandina, da precipitação orográfica, da denudação e da sobrecarga sedimentar de origem andina em direção à drenagem amazônica, levando ao início do processo de inversão do sistema de drenagem para leste, em direção ao arco de Purus, com idade provável entre 11 Ma e 9 Ma (Figueiredo *et al.*, 2009; Mora *et al.*, 2010; Hoorn *et al.* 2017).

No Mioceno Superior, o soerguimento do arco de Vaupés Swell e, posteriormente no Plioceno (~4,5 Ma), do arco de Fitzcarrald, desenvolveram importante papel na configuração da bacia amazônica, separando as bacias *foreland* em norte e sul. Consequentemente, houve a separação da drenagem do rio proto-Amazonas, a sul, da do rio proto-Orinoco, a norte, interrompendo o fluxo do rio Amazonas em direção ao Mar do Caribe (Mora *et al*., 2010). No entanto, a idade da inversão e do estabelecimento total desse sistema de drenagem ainda é divergente, sendo atualmente apontada entre o Neomioceno (Figueiredo *et al*., 2009; Hoorn *et al*., 2010a; b; 2017) e o Pleistoceno (Latrubesse *et al*., 2010; Nogueira *et al*., 2013).

O papel dos arcos estruturais na evolução da paisagem amazônica também não é consenso. Para Mora *et al*. (2010) os arcos de Iquitos, Carauari e Purus não se apresentam como barreiras geográficas para o fluxo em direção a leste da drenagem amazônica. No entanto, Nogueira *et al*. (2013) argumenta que no Mioceno Superior o arco de Purus apresentou importante papel na compartimentação da bacia do Solimões, configurando uma barreira geográfica que a separava da bacia do Amazonas. Ainda, para estes autores, até o Plioceno essa região foi submetida a soerguimento e posterior erosão, formando grande discordância na Formação Solimões na porção leste da bacia e que, apenas a partir do Pleistoceno, a área foi submetida a grande subsidência possibilitando a sobreposição do arco de Purus e a deposição dos sedimentos fluviais meandrantes da Formação Içá. De outro modo, Hoorn *et al*. (2017) consideram, que de alguma forma, a drenagem poderia ter contornado o arco de Purus ainda no Mioceno Superior (9.4 Ma a 9 Ma), estabelecendo o fluxo transcontinental do rio Amazonas.

Sabe-se que os efeitos das mudanças tectônicas geradas a partir da Orogenia Andina desencadearam ao longo do Neógeno variações ambientais, especialmente climáticas, e ainda, proporcionaram a formação de barreiras geográficas naturais que geraram eventos de especiação e consequentemente levaram à grande diversidade da biota na região amazônica. Isto pode ser evidenciado amplamente através de estudos biogeográficos e filogenéticos de peixes e ostracodes (Lundberg *et al*., 1998; Albert *et al*., 2006; Whatley *et al*., 2006; Lovejoy *et al*., 2006; 2010; Gross *et al*., 2014; 2015).

### 1.5.2 Bacia do Solimões

A área estudada está posicionada no limite norte da bacia do Solimões, na sub-bacia de Jandiatuba. Esta bacia, instalada no cráton amazônico e situada geograficamente no Estado do Amazonas, apresenta uma área aproximada de 450.000 km$^2$ (Eiras *et al*., 1994; Wanderley Filho *et al*., 2010), a qual está hoje totalmente coberta pela exuberante floresta tropical amazônica. Esta bacia é limitada ao norte pelo escudo das Guianas, ao sul pelo escudo Brasil Central, a leste pelo arco de Purus, que a separa da bacia do Amazonas e a oeste pelo arco de Iquitos (Fig. 5), separando-a da bacia do Acre. O substrato sobre a qual se implantou é constituído por rochas ígneas, metamórficas e sedimentares, estas últimas provenientes dos riftes do Proterozóico (Eiras *et al*., 1998; Lisboa *et al*., 2013).

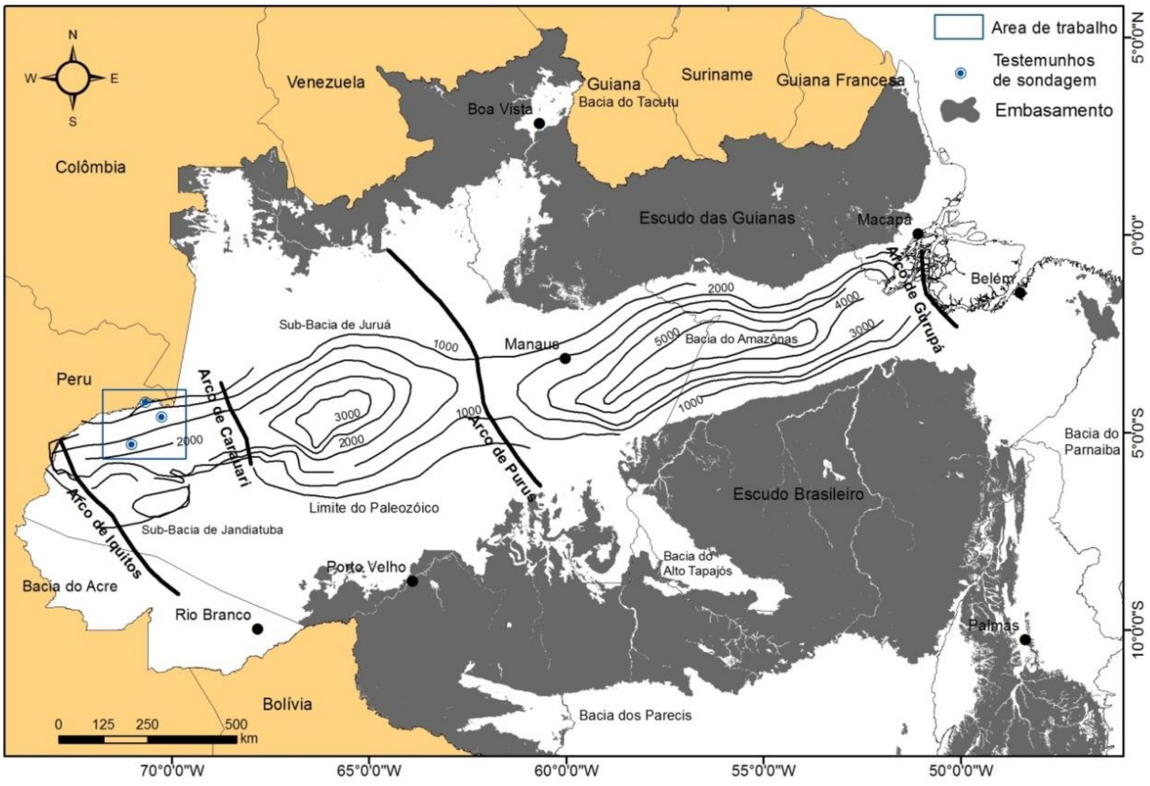


Figura 5 - Mapa de localização geográfica da bacia do Solimões, com suas sub-bacias e seus limites geológicos.

Fonte: modificado de Wanderley Filho *et al*. (2010).

A bacia está subdividida pelo arco de Carauari em duas sub-bacias: Juruá, a leste e Jandiatuba, a oeste; a primeira atinge 3.100 m e a segunda 3.800 m de espessura. O arcabouço estratigráfico Fanerozóico pode ser dividido em duas megassequências: paleozoica, intrudida por diques e soleiras de diabásio, e a mesozoico-cenozoica. As rochas do Paleozoico ocorrem apenas em subsuperfície e estão recobertas pelas extensas sequências de rochas do Cretáceo e cenozóicas, ou seja, ao contrário do que ocorre na bacia do Amazonas, não afloram rochas do Paleozoico nesta bacia (Wanderley Filho *et al*., 2010).

Wanderley Filho *et al*. (2007) divide o arcabouço estratigráfico da bacia do Solimões em cinco sequências deposicionais:

- *Sequência do Ordoviciano*: equivale aos clásticos neríticos da Formação Benjamin Constant, Sub-bacia Jandiatuba, encontrando-se truncados por discordância decorrente de provável soerguimento relacionado à Orogenia Taconiana;

- *Sequência do Siluriano-Devoniano*: equivale aos sedimentos carbonáticos e terrígenos neosilurianos e eodevonianos da Formação Jutaí da Sub-bacia Jandiatuba;

- *Sequência do Devoniano-Carbonífero*: equivale aos terrígenos e depósitos silicosos neríticos e glácio-marinhos neodevonianos e eocarboníferos do Grupo Marimari que ultrapassam os limites do arco Carauari e que também se fazem presentes na bacia Juruá. A discordância decorrente está aparentemente relacionada à Orogenia Eo-Herciniana.

- *Sequência do Carbonífero-Permiano*: equivale aos materiais clásticos, carbonatos e evaporitos marinhos e continentais do Grupo Tefé, encontrados em quase toda a bacia do Solimões. Sobre esta sequência há uma discordância erosiva com hiato da ordem de 170 Ma, decorrente da atuação da Orogenia Tardi-Herciniana e Diastrofismo Juruá.

- *Sequência do Cretáceo*: equivale aos clásticos fluviais da Formação Alter do Chão, preservados em função da subsidência ligada à atividade da Orogenia Andina;

- *Sequência do Neógeno*: equivale aos pelitos e arenitos flúvio-lacustres do Mio-Plioceno da Formação Solimões, também depositados em conexão com a Orogenia Andina.

### 1.5.3 Formação Solimões

A Formação Solimões (Grupo Javari), estende-se por aproximadamente 500.000 $km^2$ (Maia *et al.*, 1977) no oeste da Amazônia do Brasil, recobrindo as bacias do Solimões e do Acre, separadas entre si pelo arco de Iquitos, compreendendo a sequência neógena dessas bacias (Wanderley Filho *et al.*, 2007; 2010). A partir de seu contexto geológico e paleontológico, a Formação Solimões correlaciona-se, em parte, com outras unidades do Neógeno da Amazônia Ocidental, que inclui as formações: Pebas, no Peru (Antoine *et al.*, 2015); Carbonera, na Colômbia (Gomez *et al.*, 2009; Jaramillo *et al.*, 2017); Curaray, no Equador (Wesselingh *et al.*, 2002); e Urumaco, na Venezuela (Lundberg *et al.*, 2010; Riff *et al.*, 2010).

Na bacia do Acre, a formação Solimões sobrepõe-se em discordância angular aos argilitos, siltitos e folhelhos da Formação Ramon (Maia *et al.*, 1977; Latrubesse *et al.*, 2010), enquanto que na bacia do Solimões ela grada lateral e inferiormente para a Formação Alter do Chão, da qual está separada por discordância erosiva. O contato superior está recoberto por uma sequência arenosa apoiada sobre uma discordância erosiva de possível idade pleistocena denominada Formação Içá e por terraços fluviais quaternários mais jovens (Radambrasil, 1977; Maia *et al.*, 1977; Eiras *et al.*, 1994; Valderrama & Marmos, 2000; Wanderley Filho *et al.*, 2007; Latrubesse *et al.*, 2010; Silveira & Souza, 2015; Rossetti *et al.*, 2015).

Formação Solimões foi um termo designado inicialmente por Moraes Rêgo (1930) e revalidado por Caputo *et al*. (1971), os quais descreveram a unidade pela primeira vez, caracterizando-a como um pacote sedimentar do Neógeno ocorrente em toda a porção ocidental da Amazônia do Brasil e estendendo-se para áreas vizinhas na Colômbia e no Peru. Sua litologia constitui-se, sobretudo de argilas vermelhas, cinza e variegadas, além de níveis de siltitos, arenitos, calcários e conglomerados, que representariam fácies de maior energia; as fácies de baixa energia seriam compostas por sedimentos de cor verde a verde-acinzentado e estratificação planar ou estrutura maciça (Caputo *et al*., 1971; Latrubesse *et al*., 1997) .

A unidade caracteriza-se por apresentar frequentes restos vegetais e intercalações de linhito, argilas carbonosas e calcários, sendo os níveis de linhito mais numerosos no terço superior desta sequência (Maia *et al*., 1977). A abundância e a preservação dos fósseis encontrados indicam o predomínio de um ambiente redutor e de baixa energia, evidenciados por abundantes níveis carbonosos e sedimentos finos (Hoorn, 1993).

Estudos em afloramentos, através de dados paleontológicos e análises de fácies, apontam que os níveis mais superiores da Formação Solimões (Mioceno Superior) foram depositados em um ambiente continental, dominado por rios avulsivos associados a um sistema deltaico e rios avulsivos associados a planícies de inundação (pântanos, lagos, deltas internos e crevasse-splay) (Latrubesse *et al.*, 1997; 2010; Gross *et al.*, 2011; 2013). Ainda são registrados ambientes fluviais com lagos perenes, associados a ambientes de energia mista com episódios de inundações (Paz *et al.*, 2015), e um sistema flúvio deltaico com sedimentos finos do prodelta lacustrino fornecido pelos distributários meandrantes em ambientes de frente de delta (Nogueira *et al.*, 2013). Entretanto, os estudos de testemunhos de sondagem já apontam que, apesar desta unidade apresentar predominantemente um contexto deposicional continental, existe evidências de intercalações destes depósitos com estratos de incursões marinhas breves e geograficamente limitadas, pelo menos nos níveis mais basais da formação, baseado principalmente na análise do conteúdo fossilífero (Hoorn, 1996; Wesselingh *et al*., 2002; Vonhof *et al*., 2003; Linhares *et al*., 2011). Recentemente, Antoine *et al*. (2016) revela a presença destas evidências em afloramentos do Peru, o qual, inclusive, correlaciona com os resultados dos estudos do testemunho 1AS-31-AM, apresentados por Linhares *et al*. (2011) e Jaramillo *et al*. (2017), na Colômbia, através da correlação com o testemunho 1AS-105-AM, no Brasil.

## 1.6 PALEONTOLOGIA DO NEÓGENO DA AMAZÔNIA OCIDENTAL

A paleontologia tem sido a principal ferramenta empregada para a reconstrução paleoambiental e datação da sequência do Neógeno da Amazônia Ocidental, devido à abundância e diversidade dos grupos fósseis. Dentre os paleovertebrados, destacam-se os registros de mamíferos (Mones & Toledo, 1989; Souza-Filho *et al*., 1993; Negri *et al.* 2010); aves (Negri *et al.* 2010), répteis (Gaffney *et al.* 1998; Bocquentin & Melo 2006; Meylan *et al.* 2009; Riff *et al.* 2010), e peixes (Lundberg *et al*., 1998; Malabarba *et al*., 1998; Monsch, 1998; Malabarba & Dutra 2002; Lovejoy *et al*., 2006; Lundberg *et al*., 2010). Esses estudos vêm contribuindo com incremento da paleobiodiversidade, e ainda, apontando o registro de taxa essencialmente continentais, com eventuais formas costeiras para o Neógeno da Formação Solimões.

Os paleoinvertebrados são os mais abundantes e diversos na unidade (Wesseling & Ramos, 2010), sendo os principais representantes os ostracodes (e.g. Purper, 1979; Ramos, 2006; Gross *et al*, 2014) e os moluscos (Nuttal, 1990; Wesselingh *et al*., 2002; Anderson *et* *al*., 2006; Kandoorp *et al*., 2006; Wesselingh *et al*., 2006 a; b; c; d), que vêm sendo importantes ferramentas nos estudos paleobiogeográficos, paleoambientais e bioestratigráficos da Formação Solimões e unidades correlatas.

Os trabalhos sobre a paleobotânica incluem principalmente o estudo de grãos de polén e esporos, os quais são empregados na reconstrução de modelos de paleovegetação e datação dos depósitos do Neógeno da Amazônia Ocidental (e.g. Hoorn, 1993; 1994 a; b; Latrubesse *et al*., 2010; Nogueira *et al*., 2013; Silveira & Souza, 2015). Entretanto, serão abordados neste capítulo, principalmente os artigos relacionados aos ostracodes, principal ferramenta empregada no presente estudo.

### 1.6.1 Ostracofauna

As primeiras pesquisas com ostracodes na Formação Solimões iniciaram a partir do século XX. Gardner (1927) e Gold (1967) fazem uma breve citação do registro deste grupo, porém sem uma descrição detalhada dos gêneros e espécies, embora os autores citem a ocorrência do gênero *Cypris*, típico de água doce, associado a moluscos.

Estudos taxonômicos mais aprofundados da unidade tiveram início com os trabalhos de Purper (1977a; b; 1979), onde a autora descreve diversos gêneros e espécies novas provenientes de amostras de sondagens e afloramentos da bacia do Solimões, no Brasil, considerando a fauna endêmica, típica de ambiente mixohalino de águas calmas e de baixa energia, com raras e eventuais formas de água doce. Posteriormente, Purper & Pinto (1983) descrevem dois novos gêneros e quatro novas espécies, referindo também características mixohalinas para ostracofauna.

Paralelamente a estes, Sheppard & Bate (1980) estudando amostras da Colômbia e do Peru, também descrevem novos gêneros e espécies, verificando a associação desta fauna com outras áreas estudadas no Brasil. Isto foi confirmado por Purper & Ornellas (1991), que identificam quatro espécies novas e relatam similaridades do material estudado com ostracodes provenientes dos depósitos do Neógeno da Colômbia e do Peru. As autoras concluem que apesar da fauna ser endêmica, detalhes morfológicos registrados nas carapaças indicam condições mesohalinas para a área estudada.

Posteriormente, Muñoz-Torres *et al*. (1998) e Whatley *et al*. (1998) realizando uma ampla revisão taxonômica da ostracofauna, emendam a diagnose do gênero *Cyprideis* Jones, 1857 e colocam vários gêneros identificados por Purper (1979), Sheppard & Bate (1980) e Purper & Pinto (1983) em sinonímia. Com esta nova proposta, o gênero passa a representar mais de 90% da ostracofauna registrada na Formação Solimões e unidades adjacentes, como a Formação Pebas. Além destes autores, Swain (1998) registram na área de Iquitos, Peru, a ocorrência de seis espécies e subespécies do gênero *Cyprideis* considerando-as duvidosamente do Plioceno e típicas de águas transicionais.

Realizando estudos bioestratigráficos em localidades do Peru, Colômbia e Brasil, Muñoz-Torres *et al.* (2006) estabelecem cinco zonas de ostracodes, correspondentes ao final do Mioceno Inferior ao início do Mioceno Superior; além disto, os autores realizam um estudo evolutivo do gênero *Cyprideis*, onde evidenciam a ocorrência, a partir de características morfológicas, de duas linhagens evolutivas: uma de carapaça lisa e outra de carapaça ornamentada.

Ramos (2006) estudando seções aflorantes da Formação Solimões, na região sudoeste do Amazonas, reconhece diversas espécies endêmicas do Neógeno da Amazônia Ocidental (*Cyprideis lacrimata* Muñoz-Torres *et al*. (1998); *Cyprideis longispina* Purper, 1979; *Cyprideis pebasae* Purper, 1979; *Cyprideis graciosa* Purper, 1979; *Cypria aqualica* Shepard & Bate, 1980 e *Darwinula fragilis* Purper, 1979). O estudo destes afloramentos permitiu verificar a similaridade com depósitos do Mioceno do oeste da Amazônia, sugerindo uma fauna autóctone associada a um sistema deposicional flúvio-lacustre e de baixa energia.

Dando continuidade à análise da ostracofauna em amostras de testemunho da Formação do Solimões, Linhares *et al.* (2011), confirma o predomínio do gênero *Cyprideis* em depósitos da Formação Solimões no Município de Atalaia do Norte, Estado do Amazonas, Brasil, com o registro de 18 espécies. Os autores identificam três fases associadas ao gradiente de salinidade do ambiente: I- Fase lacustre, II- Fase transicional a marinha e III- Fase flúvio-lacustre.

Posteriormente, Gross *et al.* (2013), estudando depósitos de afloramentos do município de Eirunepé (Amazonas), identificam espécies dos gêneros *Cypretta, Cypria*, *Cyprideis*, *Cytheridella*, *Ilyocypris*, *Penthesilenula*, *Physocypria*, *Pseudocandona* e *Perissocytheridea*, realizando um estudo sistemático de descrição e associação de fácies, as relacionam a um grande sistema deposicional flúvio-lacustre.

Gross *et al.* (2014), realizam uma extensiva revisão taxonômica em aproximadamente 70% das espécies do gênero *Cyprideis* no testemunho 1AS-10-AM, já descritas nos trabalhos anteriores, e verificam uma alta variabilidade intraespecífica que pôde ser diagnosticada através de morfologia comparativa e que permitiu organizar as 20 espécies encontradas em grupos e subgrupos. Esses autores ainda revalidam cinco espécies, renomeiam e colocam duas em sinonímia e descrevem duas novas espécies. Mais recentemente, Gross *et al.* (2015) registra a ocorrência de uma nova espécie *Pellucistoma curupira*, sendo este o primeiro registro do gênero, tipicamente encontrado em águas marinhas rasas na América do Norte, Central e do Sul, nos depósitos flúvio-lacustres da Formação Solimões.

## 1.7 PALEOAMBIENTES DO NEÓGENO DA AMAZÔNIA OCIDENTAL

Os trabalhos sobre o Neógeno da Amazônia Ocidental, tanto no Brasil, como também no Peru e na Colômbia, apresentam resultados que divergem nas opiniões em duas linhas: a que aceita a influência e registro marinho; e a que refuta de maneira plena ou parcialmente essa influência na evolução paleoambiental da região.

Com base em estudos paleontológicos em testemunhos de sondagem, diversos autores defendem que a região foi constituída predominantemente por ambientes característicos de planícies de inundação, com conexão com ambientes costeiros, devido a episódios localizados de incursão marinha na região central e oeste da Amazônia durante o Neógeno, com registro de áreas de manguezal, o que pôde ser evidenciado a partir de estudos de microfósseis (Hoorn 1993; 1994 a; b, Linhares *et al.*, 2011; Leandro, 2012; Antoine *et al.*, 2016; Jaramillo *et al.*, 2017). Esses episódios de incursão marinha restrita, possivelmente, foram marcados por progradação rápida, influenciados por maré, com intercalação de sequências de água salobra e de água doce para o Neógeno da Amazônia Ocidental (Räsänen *et al.*, 1995; Hovikoski *et al.*, 2007; 2010; Rebata, 2012).

A hipótese de influência marinha na Amazônia ainda é reforçada através de resultados de assinatura isotópica em moluscos, que demonstram aumento no grau de salinidade, além de da ocorrência de bioturbações de uma associação de icnogêneros característicos de ambientes marinhos marginais; contudo os trabalhos ainda apontam o predomínio de ambientes lacustrinos rasos e pantanosos (Vonhof *et al.*, 1998; 2003; Gingras *et al.*, 2002; Wesselingh *et al.*, 2006c). Já com base no estudo de diversos grupos de peixes e seguindo os critérios de distribuição geográfica das espécies, Lovejoy *et al.* (2006) mostram consistência na hipótese de incursão marinha na Amazônia durante o Mioceno, e que as conexões desempenharam um papel de transição para os habitas de água doce.

A partir da base de dados obtida por trabalhos de caráter paleontológico e sedimentológico, foi possível realizar um levantamento das localidades (Fig. 6) que apresentam elementos que sustentam a hipótese de existência de influência marinha tanto em depósitos da Formação Solimões (Brasil), quanto em depósitos da Formação Pebas (Peru e Colômbia) (Hovikoski *et al*., 2007; 2010).

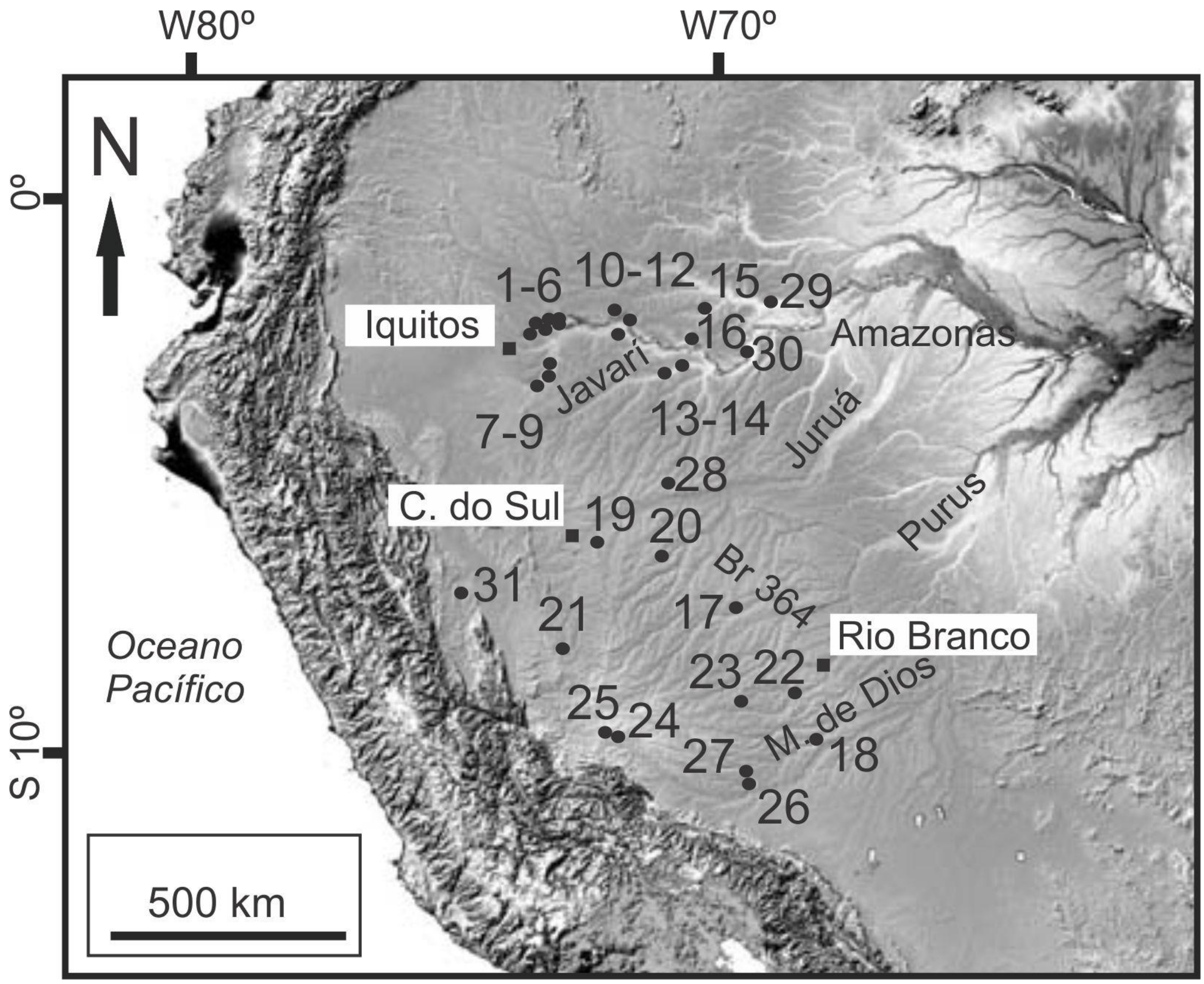


Figura 6 - Localidades com registro de influência marinha no oeste da Amazônia. **1-5**: Indiana (Loreto, Peru); **6**: Santa Teresa, **7**: Tamshiyacu, **8**: San Rafael, **9**: Porvenir, **10**: Ave Maria, **11**: Santa Julia, **12**: Santa Rosa de Pichana, todos em Loreto, Peru; **13 e 14**: Rio Javarí, Amazonas, Brasil; **15:** Buenos Aires; **16**: Los Chorros, ambos na Amazônia, Colômbia; **17**: Purus, Amazonas, Brasil; **18**: Seringal Amapá; **19:** Comunidade Katukina; **20**: Tarauacá; **21**: Volta Grande; **22**: Rio Branco- Bolívia, estrada Rio Branco-Bolívia; **23**: Boca de São Pedro, todos no Acre, Brasil; **24-25**: Cocha Cashu, **26**: Pastora e **27**: Rio de las Piedras, todos em Madre de Dios, Peru. **28**: Cururú, Rio Ituí; **29**: Arapanã, Rio Japurá; **30**: Igarapé Pagão, Rio Içá, todos no Amazonas, Brasil; **31**: Contamana, Perú.

Fonte: modificado de Hovikoski *et al*. (2010).

A segunda linha de interpretação sobre a evolução paleoambiental da Formação Solimões infere que os depósitos da Amazônia atribuídos ao Mioceno foram mal interpretados por diversos autores, tanto no aspecto ambiental como cronológico. Os autores descartam a possibilidade de incursões marinhas, mesmo que breves, e atribuem ao Mioceno Superior da Formação Solimões características de um ambiente continental dominado por rios avulsivos associados a sistemas de megadeltas e planícies de inundação, tais como pântanos, lagos perenes, deltas internos e *crevasse splays*, onde os depósitos anóxicos, ricos em matéria orgânica, apresentariam pouco aporte sedimentar (Latrubesse *et al*., 2010; Gross *et al*., 2011; 2013; Nogueira *et al.*, 2013; Paz *et al.*, 2015).

Entretanto, através de estudos em testemunhos de sondagem, Hoorn *et al*. (2010a) demonstra que ambas propostas podem ser aceitas, contudo em momentos distintos dentro do Neógeno. Assim, os autores propõem que a evolução paleoambiental pode ser definida por três. A fase percussora (~24 a 16 Ma) que é caracterizada por depósitos flúvio-lacustres; a fase Pebas (~16 a 11.3 Ma) representando um amplo sistema de inundação (mega-wetland) com esporádicas incursões marinhas; e por fim a fase Acre (<11.3 a 7 Ma) que seria representada por depósitos de inundação com interferência de marés fluviais. Muitas teorias propostas nos últimos anos ainda são alvos de questionamentos, contudo o incremento de um conjunto de dados paleoambientais multidisciplinares provenientes de vários níveis estratigráficos do Mioceno em diversas localidades da Amazônia possivelmente permite uma melhor compreenção da evolução desses paleoambientes ao longo do Neógeno.

## 1.8 CRONOESTRATIGRAFIA DOS DEPÓSITOS DA AMAZÔNIA OCIDENTAL

As datações estabelecidas para o Neógeno da Amazônia Ocidental tanto no Brasil, Peru como na Colômbia têm sido alvo de muitos questionamentos, devido às divergências nas idades propostas e nos materiais e métodos apresentados pelos diversos autores. Os primeiros trabalhos paleontológicos de afloramentos estabelecem idades distintas que se estendem desde o Neomioceno ao Recente (Roxo, 1924) e do Paleoceno ao Pleistoceno (Caputo *et al*., 1971); ainda, estudos em testemunhos de sondagem no Brasil na Colômbia também divergem e propõem idades entre o Mioceno e o Plioceno (Maia *et al*., 1977; Purper, 1979), e Plio-Pleistoceno (Sheppard & Bate, 1980).

Diante destas divergências, diversos estudos em testemunhos de sondagem procedentes do “Projeto Carvão do Alto Solimões”, principalmente de cunho palinológico, vêm sendo desenvolvidos visando contribuir para o avanço do conhecimento do intervalo estratigráfico da Formação Solimões, foco do presente estudo, e que serão apresentados a seguir, embora ainda divergindo nas idades propostas para essa unidade:

### 1.8.1 Palinologia

As propostas de biozoneamento com base em palinologia indicam um intervalo de idade do Eomioceno até o Pleistoceno, de acordo com os diferentes autores e diferentes testemunhos de sondagem estudados no Brasil (Fig. 7). A primeira proposta foi realizada por Hoorn (1993), com base no estudo de 1AS-4a-AM, localizado no Município de Atalaia do Norte, Amazonas, a qual estabeleceu cinco zonas palinológicas: *Verrutricolporites*, *Retitricolporites* (Mioceno Inferior); *Psiladiporites-Crototricolpites* (final do Mioceno Inferior ao início do Mioceno Médio); *Crassoretitriletes*, (Mioceno Médio) e *Grimsdalea* (final do Mioceno Médio a início do Mioceno Superior). Este biozoneamento foi reforçado por estudos de moluscos e ostracodes (Wesselingh *et al*., 2006b; Muñoz-Torres *et al*., 2006).

Através do estudo do testemunho 1-AS-32-AM e de afloramentos no Estado do Amazonas, Silva (2004) concluiu que a sucessão estudada é equivalente às zonas *Grimsdalea*, final do Mioceno Médio a início do Mioceno Superior, e *Asteracea* do Mioceno Superior. Posteriormente, Leite (2006) analisando amostras do 1AS-33-AM, no sudoeste do Amazonas, identificou três biozonas: 1) *Psiladiporites – Crototricolpites*, final do Mioceno Inferior a início do Mioceno Superior; 2) *Crassoretitriletes*, Mioceno Médio; e 3) *Psilatricolporites caribbiensis*, para o topo da seção estudada, estendendo a unidade para o Plioceno.

Silva (2008) identificou três zonas para os testemunhos de sondagem 1AS-19-AM e 1AS-27-AM, conferindo o intervalo de idade entre o Mesomioceno ao Plioceno através da identificação das seguintes biozonas: 1) *Grimsdalea*, do Mioceno Médio/Superior; 2) *Asteraceae*/*Fenestrites*, do Mioceno Superior; e 3) *Psilatricolporites caribbiensis*, do final do Mioceno Superior ao Plioceno. Silva-Caminha *et al*. (2010) refina as informações desses testemunhos e limita a idade apenas na zona *Psilatricolporites caribbiensis*, que vai do final do Neomioceno ao Plioceno. Latrubesse *et al*. (2010), reavalia os dados palinológicos dos testemunhos 1AS-19-AM, 1AS-27-AM e 1AS-32-AM, e indicam um intervalo de idade do Neomioceno para a Formação Solimões.

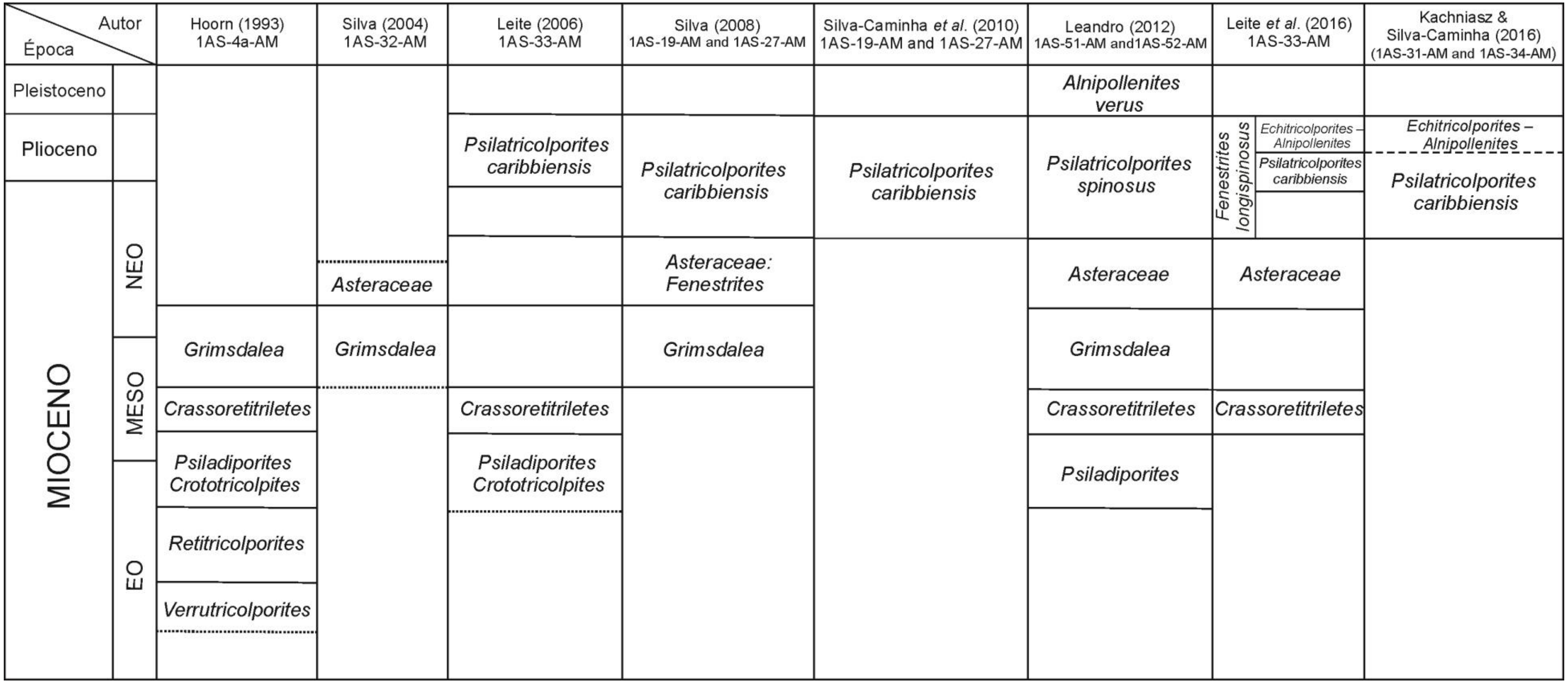
Leandro (2012) analisando amostras dos testemunhos 1AS-51-AM e 1AS-52-AM observou seis biozonas para o intervalo estudado: 1) *Psiladiporites*, do final do Mioceno Inferior a início do Mioceno Médio; 2) *Crassoretitriletes*, do Mioceno Médio; 3) *Grimsdalea*, do final do Mioceno Médio a início do Mioceno Superior; 4) *Asteraceae*, do Mioceno Superior; 5) *Echitricolporites–Alnipollenites*, do Plioceno; e 6) *Alnipollenites verus*, do Pleistoceno.

Analisando o testemunho 1AS-33-AM, Município de Atalaia do Norte, Estado do Amazonas, Leite *et al*. (2016) identificaram as seguintes zonas: 1) *Crassoretitriletes*, Mioceno Médio; 2) *Asteraceae*, Mioceno Superior; e as subzonas *Psilatricolporites caribbiensis*, final do Mioceno Superior ao Plioceno e *Echitricolporites–Alnipollenites*, Plioceno. Paralelamente, Kachniasz & Silva-Caminha (2016) analisando os testemunhos 1AS-31-AM e 1AS-34-AM, perfurados na mesma região, identificaram duas zonas: *Psilatricolporites caribbiensis* e *Echitricolporites–Alnipollenites*, limitando o intervalo de idade entre o final do Neomioceno e o Plioceno.

Além das propostas de biozoneamento para testemunhos de sondagem, alguns estudos com amostras de afloramentos próximos às localidades dos municípios de Manacapuru, Iranduba, Coari, Tabatinga e Atalaia do Norte, Estado do Amazonas (Dino *et al*., 2012; Nogueira *et al*., 2013; Silveira & Souza, 2015), vêm apontando idades entre o Mesomioceno e o Plioceno. Recentemente, estudos no Peru (Antoine *et al*., 2016), Brasil e Colômbia (Jaramillo *et al*., 2017) dataram os depósitos da Formação Solimões, e da correlata Formação Pebas, indicando a idade do Eomioceno ao Neomioceno.

### 1.8.2 Ostracodes

Muñoz-Torres *et al*. (2006), usando como base o arcabouço palinoestratigráfico de Hoorn (1993) e da ostracofauna caribeana de águas transicionais (Bold, 1988), definiram cinco biozonas de ostracodes para o Neógeno no Brasil, no Peru e na Colômbia (Fig. 8). A partir das espécies do gênero *Cyprideis*, foram propostas as zonas *Cyprideis aulakos* (final do Mioceno Inferior a início do Mioceno Médio), *C. caraionae* (Mioceno Médio), *C. minipunctata* (Mioceno Médio), *C. obliquosulcata* (Mioceno Médio) e *C. cyrtoma* (final do Mioceno Médio a início do Mioceno Superior).



| Época \ Autor | | Hoorn (1993)<br>1AS-4a-AM | Silva (2004)<br>1AS-32-AM | Leite (2006)<br>1AS-33-AM | Silva (2008)<br>1AS-19-AM and 1AS-27-AM | Silva-Caminha *et al.* (2010)<br>1AS-19-AM and 1AS-27-AM | Leandro (2012)<br>1AS-51-AM and1AS-52-AM | Leite *et al.* (2016)<br>1AS-33-AM | Kachniasz & Silva-Caminha (2016)<br>(1AS-31-AM and 1AS-34-AM) |
|---|---|---|---|---|---|---|---|---|---|
| Pleistoceno | | | | | | | *Alnipollenites verus* | | |
| Plioceno | | | | *Psilatricolporites caribbiensis* | *Psilatricolporites caribbiensis* | *Psilatricolporites caribbiensis* | *Psilatricolporites spinosus* | *Fenestrites longispinosus*: *Echitricolporites – Alnipollenites*<br>*Psilatricolporites caribbiensis* | *Echitricolporites – Alnipollenites*<br>*Psilatricolporites caribbiensis* |
| MIOCENO | NEO | | *Asteraceae* | | *Asteraceae: Fenestrites* | | *Asteraceae* | *Asteraceae* | |
| | MESO | *Grimsdalea*<br>*Crassoretitriletes* | *Grimsdalea* | *Crassoretitriletes* | *Grimsdalea* | | *Grimsdalea*<br>*Crassoretitriletes* | *Crassoretitriletes* | |
| | EO | *Psiladiporites Crototricolpites*<br>*Retitricolporites*<br>*Verrutricolporites* | | *Psiladiporites Crototricolpites* | | | *Psiladiporites* | | |

Figura 7- Biozoneamentos propostos para a Formação Solimões com base nos estudos palinológico em testemunhos de sondagem.

Fonte: modificado de Silva (2008).

No estudo de Linhares (2011) foi realizada uma tentativa de biozoneamento com amostras provenientes do testemunho de sondagem 1AS-31-AM, perfurado na porção sudoeste da bacia do Solimões, onde a distribuição estratigráfica das espécies de *Cyprideis*, conforme Muñoz-Torres *et al*. (2006), permitiu identificar três biozonas denominadas OS1, OS2 e OS3, as quais correspondem respectivamente às idades do final do Eomioceno a início do Mesomioceno, Mesomioceno e final do Mesomioceno a início do Neomioceno.

Estudos em afloramentos no Município de Eirunepé, Estado do Amazonas, Brasil, (Gross *et al*., 2011; 2013) estabelecem a idade do Neomioceno, atestando que os afloramentos são mais recentes que a sequência estudada nos testemunhos. Mais recentemente, Gross *et al*. (2014), estabelece que a sessão do testemunho de sondagem 1AS-10-AM, noroeste do Estado do Amazonas, corresponde às biozonas *Cyprideis minipunctata* e *Cyprideis cyrtoma*, equivalentes, com intervalo de idade que vai do Meso ao Neomioceno.

### 1.8.3 Moluscos

Wesselingh *et al*., (2006b) com base em moluscos encontrados no testemunho 1AS-4a-AM, propôs 12 biozonas, com idade entre o Eomioceno e Neomioceno (Fig. 8): MZ1- *Aylacostoma ava* Zona de amplitude; MZ2- *Dyris denticulatus* Zona de amplitude; MZ3- ?Zona indeterminada; MZ4- *Toxosoma carinatum* Zona de amplitude; MZ5- *Diplodon indianensis* Zona de amplitude; MZ6- *Onobops*? *iquitensis* - *Onobops communis* Zona de intervalo; MZ7- *Dyris pebasensis* Zona de amplitude; MZ8- *Dyris lanceolatus* Zona de amplitude; MZ9- *Pachydon trigonalis*- *Dyris tricarinatus* Zona de concorrência; MZ10: *Dyris mattii*- *Tryonia minuscula* Zona de intervalo; MZ11: *Pachydon obliquus*- *Dyris megacarinata* Zona de concorrência; MZ12: *Dyris bicarinatus sofianensis* Zona de amplitude.

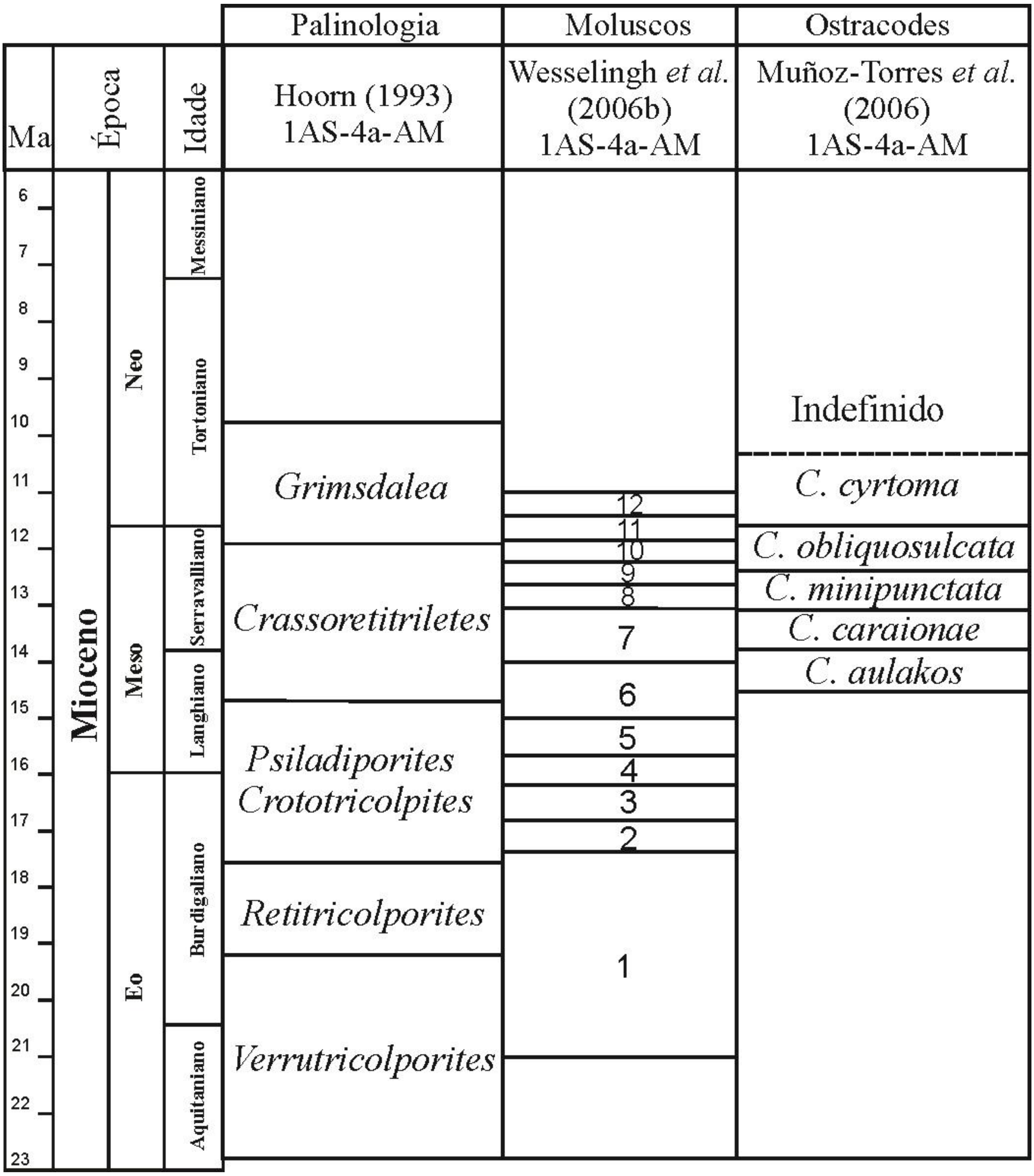


Figura 8- Biozoneamento do testemunho 1AS-4a-AM proposto por Muñoz-Torres *et al*. (2006) com base no estudo de ostracodes, de palinologia por Hoorn (1993) e de moluscos por Wesselingh *et al*. (2006b).

Fonte: modificado de Muñoz-Torres *et al*. (2006).

# CAPÍTULO 2

## 2 NEW CONTRIBUTIONS TO THE OSTRACODS TAXONOMY OF THE SOLIMÕES FORMATION (ATALAIA DO NORTE, AMAZONAS STATE, BRAZIL), WITH THE DESCRIPTION OF TWO NEW SPECIES*

Ana Paula Linhares[1,2] & Maria Inês Feijó Ramos[1]

[1] *Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia. Av. Presidente Tancredo Neves 1901, Belém, PA, Brazil (alinhares@museu-goeldi.br; mramos@museu-goeldi.br)*

[2] *Programa de Pós-Graduação em Geologia e Geoquímica, Instituto de Geociências, Universidade Federal do Pará, Rua Augusto Corrêa s/n, Belém-PA, Brazil, (alinhares@museu-goeldi.br)*

* Submmited to Zootaxa

### Abstract

The analysis of 304 samples from three boreholes 1AS-7D-AM, 1AS-8-AM and 1AS-31-AM (Atalaia do Norte Municipality, Amazonas State, Brazil) resulted in the recognition of nine genera and 30 species, which the genus *Cyprideis* is the most abundant and diverse, represented by 19 species already identified for Solimões Formation, and two new species *C. atalaiensis* sp. nov. and *C. dictyon* sp. nov., described herein. The species *C. atalaiensis* sp. nov. occurs in the 1AS-7D-AM and 1AS-31-AM boreholes, while *C. diction* sp. nov. is restricted to 1AS-31-AM. The genus *Cyprideis* presents a high intra and interspecific variability, due to its fast adaptive evolution, as response paleoenvironmental changes, as the salinity gradient, mainly related to the marine incursions during the Neogene, evidencing its ecophenotypic plasticity.

**Key words:** Ostracoda, new species, morphological variation, Solimões Formation.

## Introduction

The Neogene deposits of Solimões Formation present great fossiliferous diversity, represented mainly by mollusks, fishes, palynomorphs, foraminifera and ostracoda (Hoorn 1993; Monsch, 1998; Wesselingh 2006; Linhares *et al*. 2011; Gross *et al*. 2014). Previous studies, based on the taxonomy of ostracods, have showned an endemic and particular assemblage for the Neogene of Western Amazonia, which presents high morphological variation, hindering the generic and specific identification, mainly of the genus *Cyprideis*, and consequently the phylogeny, biostratigraphy, palaeoecology and palaeogeography (Purper 1979; Muñoz-Torres *et al*. 1998; 2006; Gross *et al.* 2013; 2014).

The amazing intra and interspecific morphological variation of *Cyprideis* is due to the rapid adptative evolution of the genus, as response to the physico-chemistry changes through the time, mainly regarding the salinity gradient, as a consequence of the cyclical marine ingressions (Linhares *et al*. 2011; 2017), evidencing the ecophenotypic plasticity of the genus *Cyprideis*. Several works point that the combination of high morphological variability and genetic alteration has triggered a problematic and confused taxonomy and that the ecophenotypic variation is a response to environmental change, well represented by the genus *Cyprideis* (Sandberg 1964; Ruiz *et al*. 2013).

Until now, approximately 30 species of this genus have been recorded to the Neogene of Western Amazonia (Muñoz-Torres *et al*. 1998; Wesselingh & Ramos 2010; Gross *et al*. 2014). Nevertheless, this is not a real number, and the generic and specific classification still needs to be revised. Therefore, this work bring new contributions to the taxonomy of the ostracods recovered from three cores (1AS-7D-AM, 1AS-8-AM and 1AS-31-AM) drilled in the Atalaia do Norte Municipality, Amazonas State, Brazil, as well as identifies two new species, contributing to increment of the specific diversity of the studied area and consequently to the evolutionary, paleoenvironmental and biostratigraphical studies.

## Material and methods

304 samples of the three cores were investigate for microfossils, 112 are from the core 1AS-7D-AM (lat. 04°34’S - long. 70°41´W), 109 from the core 1AS-31-AM (lat. 05°18’S - long. 71°02´W) and 83 from 1AS-8-AM (lat. 04°36’S - long. 70°16´W) (Fig. 1). The cores were drilled by the Geological Survey of Brazil (CPRM), in the Atalaia do Norte Municipality,

Amazonas State, northern Brazil, during the Project Carvão no Alto Solimões, which aimed the lignites exploration (Maia *et al.* 1977). The core 1AS-7D-AM reaches a total depth of 304.70 m, 1AS-8-AM, reaches the depth of 405 m, and AS-31-AM, reaches 302.05 m-depth.

The material was processed following the usual procedures for calcareous microfossils of Wanderley (2010), which consist in the disaggregation of the samples and washing through standard sieves (63/125/250/500 μm). Wet sieve residuals were dried at 60 °C and then residuals ≥63 μm were picked out completely for microfossils analysis using a stereo microscope, for subsequent identification. Photographs were taken with a eletronic scanning microscope (SEM) from Museu Paraense Emílio Goeldi (LEO 1450VP) and Centro de Microscopia Eletrônica at Universidade Federal do Rio Grande do Sul (JEOL JSM 6060), Brazil; to the taxonomic identification, the type material of Purper (1979), Purper & Pinto (1983), Purper & Ornellas (1991) and Gross *et al*. (2013; 2014) were used to the comparative studies.

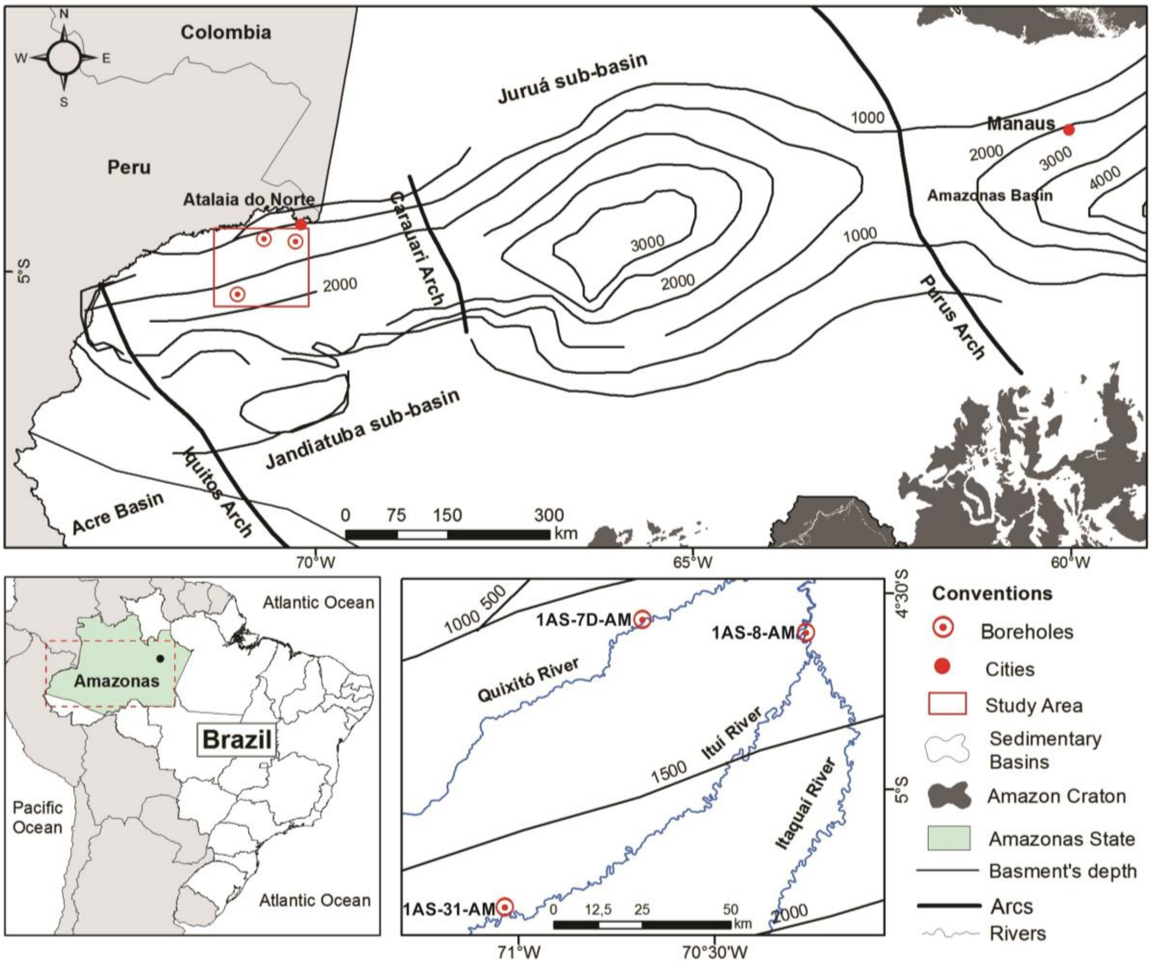


**Figure 1.** Location of the study area, with tectonic compartmentation of the Solimões Basin, subdivided by the Carauari Arch into the Jurua and Jandiatuba sub-basins, and the location of the studied boreholes. Source: Wanderley Filho *et al*. (2010).

## Results

The analysis of the ostracods resulted in the recovery of nine genera and 30 species, completing 2.351 specimens (Figs. 2, 3 and 4). *Cyprideis* is the most diverse and abundant genus, presenting 21 species already, of which 19 identified to others localities (Figs. 5 and 6): *C. amazonica* Purper (1979), *C. caraionae* Purper & Pinto (1985), *C. cyrtoma* Muñoz-Torres *et al*. (1998), *C. curucae* Gross *et al*. (2014), *C. inversa* (Purper & Pinto 1983), *C. ituiae* Gross *et al*. (2014), *C. kotzianae* (Purper & Ornellas 1991), *C. machadoi* (Purper 1979), *C. matorae* Gross *et al*., 2014; *C. multiradiata* (Purper 1979), *C. munoztorresi* Gross *et al*. (2014), *C. minipunctata* Purper & Ornellas (1991), *C. olivencai* (Purper 1979), *C. paralela* (Purper 1979), *C. reticulopunctata* (Purper 1979), *C. schedogymnos* Muñoz-Torres *et al*. (1998), *C. retrobispinosa* Purper & Pinto (1983), *C. simplex* (Shepard & Bate 1980) and *C. sulcosigmoidalis* (Purper 1979) (Figs. 5 and 6); and two new species *C. atalaiensis* and *C.*

*dictyon*, described herein (Figs. 8 and 9). Other genera and species were identified, as follow: *Cypria aqualica* Shepard & Bate (1980), *Cytheridella danielopoli* Purper (1979), *Paracypris* sp., *Penthesilenula olivencae* (Purper 1979), *Perissocytheridea acuminata* (Purper 1979), *Perissocytheridea ornellasae* (Purper 1979), *Rhadinocytherura amazonensis* Shepard & Bate (1980), *Skopaeocythere tetrakanthos* Whatley *et al*. (2000) and *Pellucistoma curupira* Gross *et al*. (2015) (Fig. 6).

## Taxonomic discussions

In Brazil, ostracods were initially studied by Purper (1977a; b; 1979; Purper & Pinto 1983; 1985; Purper & Ornellas 1991), which analyzed samples of several boreholes and outcrops in Amazonas State, proposing a serie of new genera and species to the Solimões Formation and characterizing the ostracofauna as highly endemic. The authors described new species to the genera *Cytheridea* Bosquet 1852, *Cyprideis* Jones 1857, *Cypria* Zenker 1845, *Cytheridella* 1905, *Hulingsina* Puri 1958, *Paracytheridea* Muller 1894, and, moreover, described new genera: *Amazonacytheridea*, *Chlamydocytheridea*, *Pseudoparakrithella*, *Proparacytheridea*, *Leptocytheromorpha*, *Paulacoutoia*, *Sohnicythere* and *Nealecythere*, which were posteriorly reviewed by Muñoz-Torres *et al*. (1998); the authors included the most of the new genera identified by Purper (1979) as synonymy of *Cyprideis* (Tab.1), except to *Nealecythere* and *Pseudoparakrithella*.

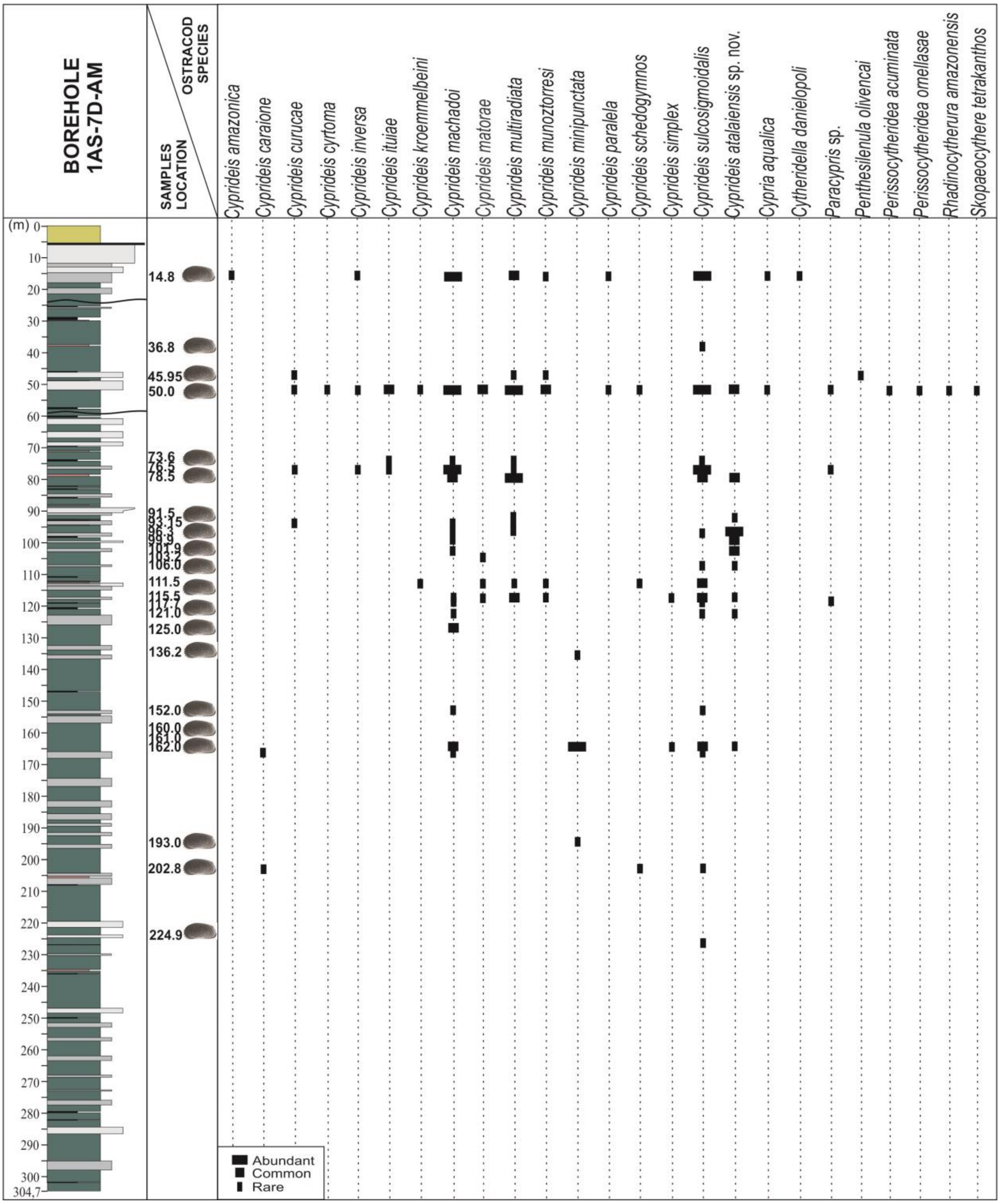


**Figure 2.** Section of the well 1AS-7D-AM (based on nonpublished CPRM reports) and stratigraphical distribution and abundance of the ostracod species.

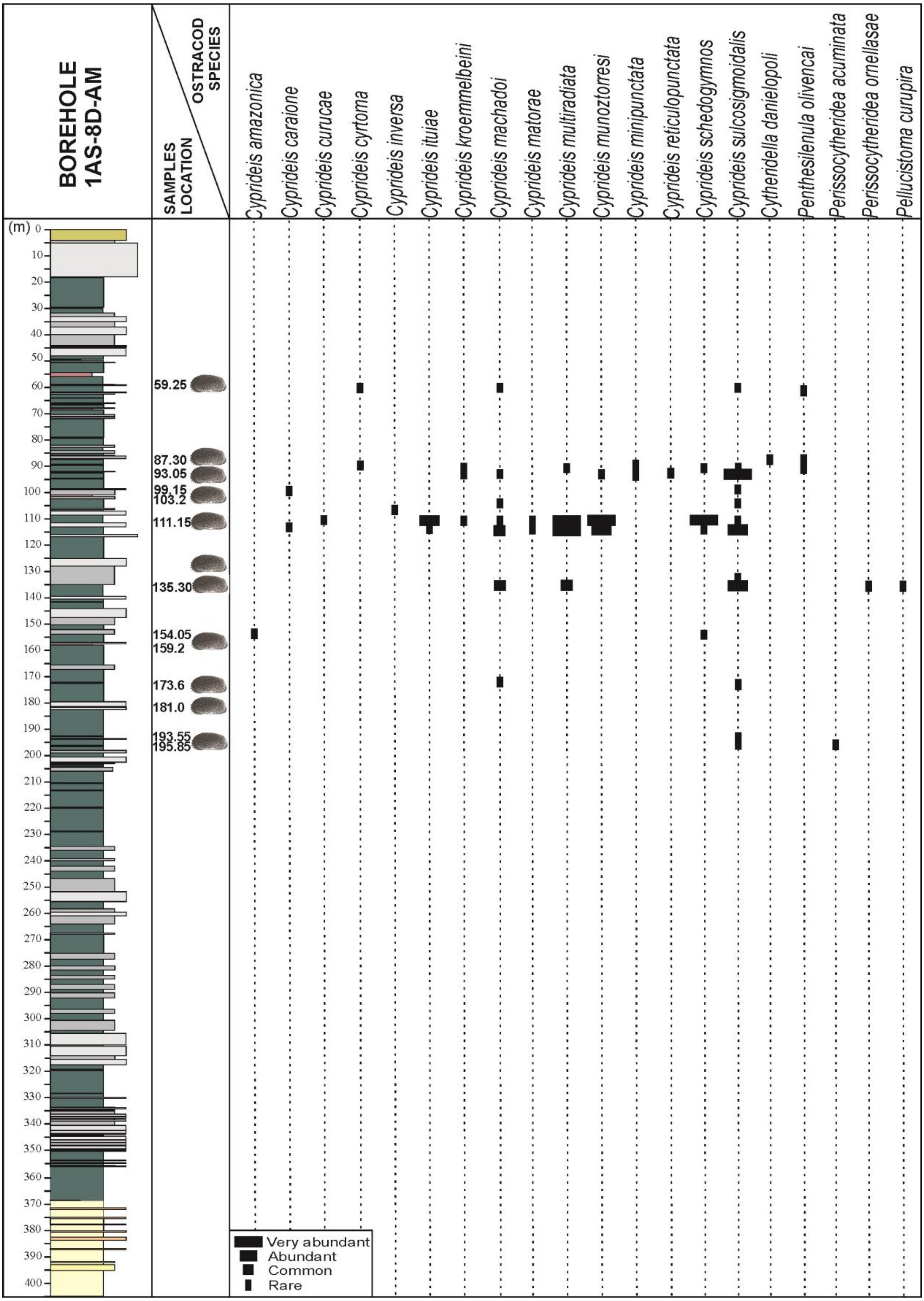


**Figure 3.** Section of the well 1AS-8-AM (based on nonpublished CPRM reports) and stratigraphical distribution and abundance of the ostracod species.

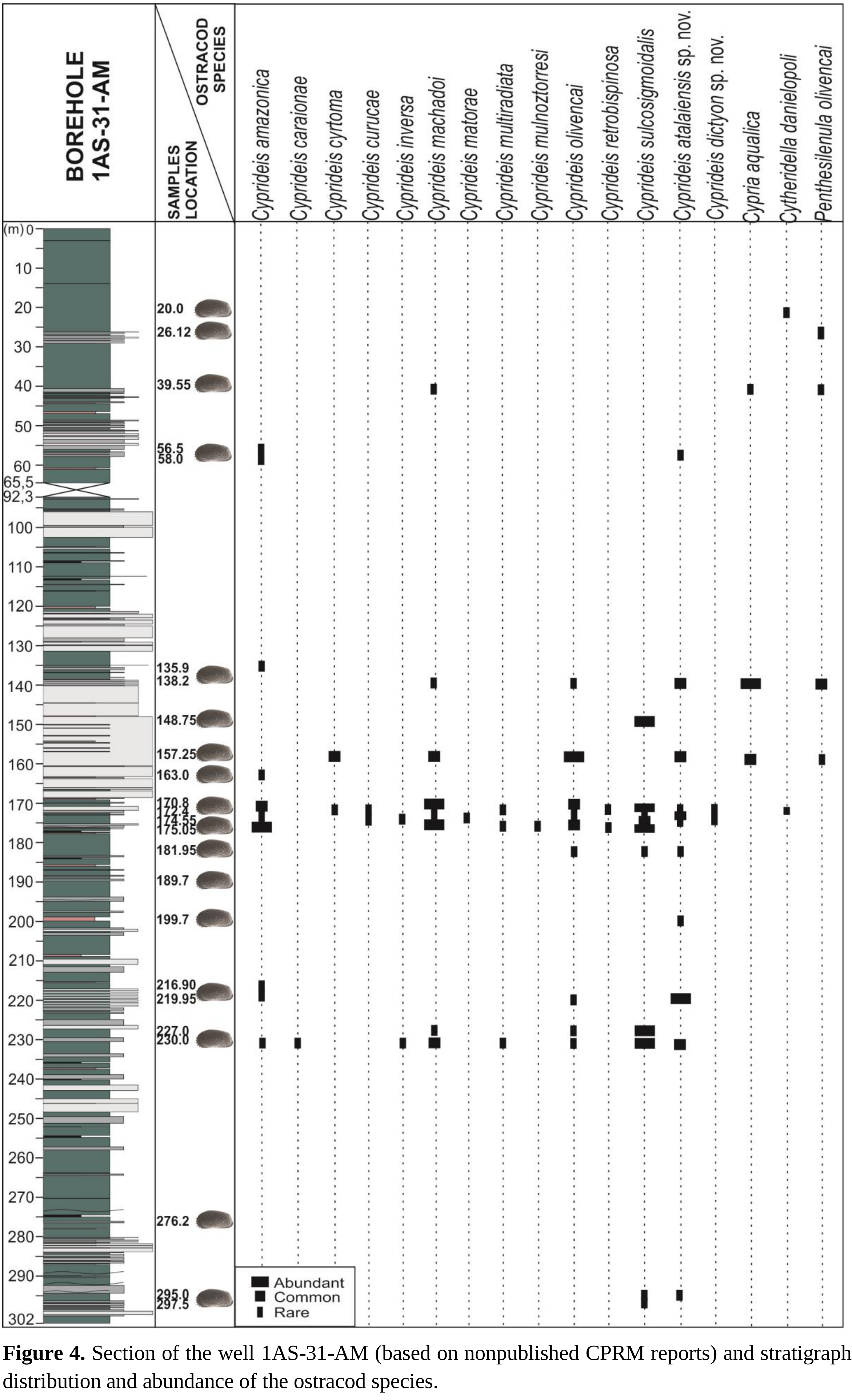


**Figure 4.** Section of the well 1AS-31-AM (based on nonpublished CPRM reports) and stratigraphical distribution and abundance of the ostracod species.

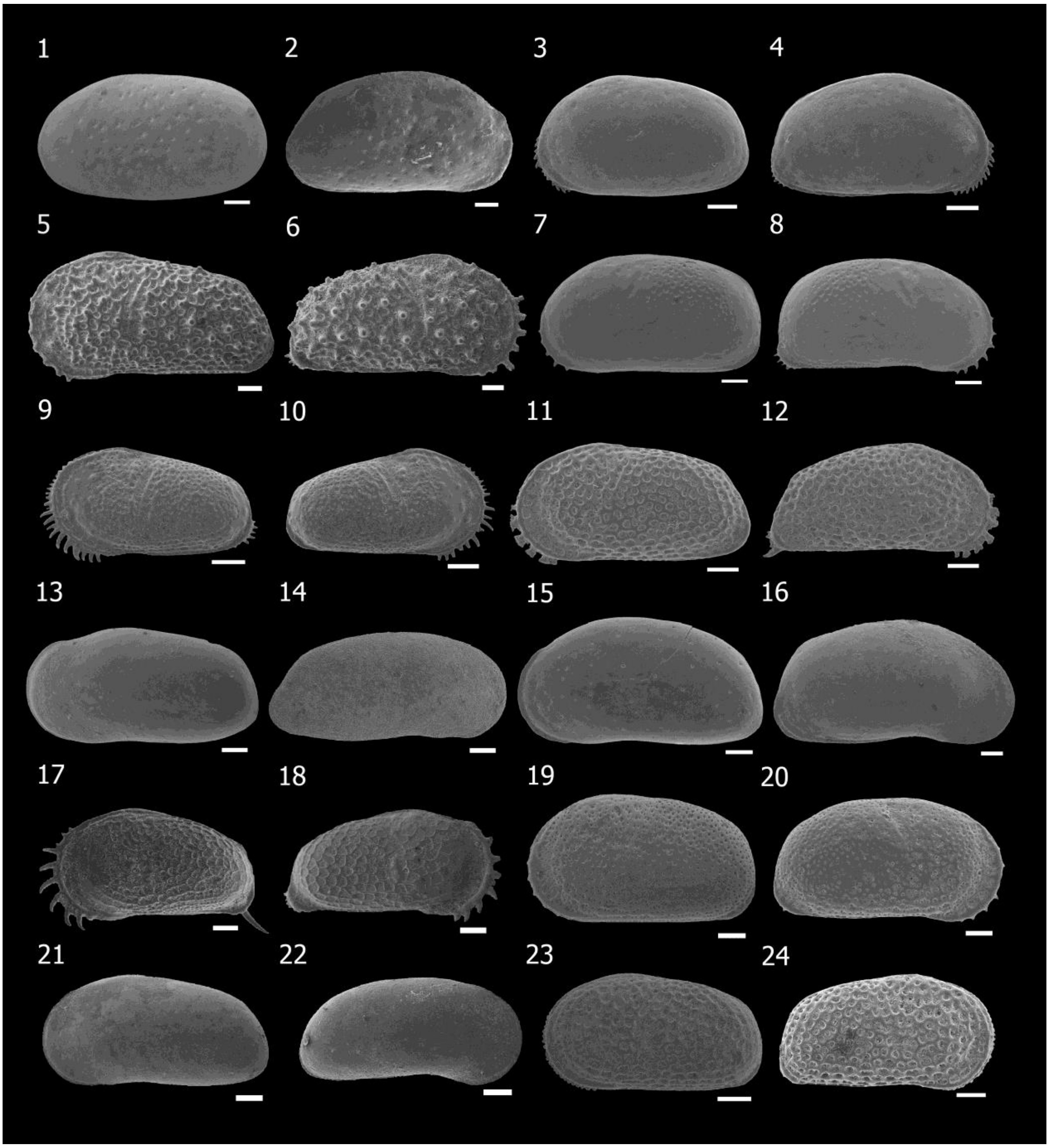


**Figure 5.** *Cyprideis amazonica*: 1. LV, female (MPEG-549-M), 2. RV, female (MPEG-550-M); *C. caraionae*: 3. LV, female (MPEG-551-M), 4. RV, female (MPEG-552-M); *C. curucae*: 5. LV, male (MPEG-553-M), 6. RV, female (MPEG-554-M); *C. cyrtoma*: 7. LV, female (MPEG-555-M), 8. RV, female (MPEG-556-M); *C. inversa*: 9. LV, female (MPEG-557-M), 10. RV, female (MPEG-558-M); *C. ituiae*: 11. LV, male (MPEG-559-M), 12. RV, male (MPEG-560-M); *C. kotzianae*: 13. LV, female (MPEG-561-M), 14. RV, female (MPEG-562-M); *C. machadoi*: 15. LV, female (MPEG-563-M), 16. RV, female (MPEG-564-M); *C. matorae*: 17. LV, female (MPEG-565-M), 18. RV, female (MPEG-566-M); *C. minipunctata*: 19. LV, female (MPEG-567-M), 20. RV, female (MPEG-568-M); *C. multiradiata*: 21. LV, female (MPEG-569-M), 22. RV, female (MPEG-570-M); *C. munoztorresi*: 23. LV, female (MPEG-571-M), 24 RV, female (MPEG-572-M). Scale bar = 100 µm.

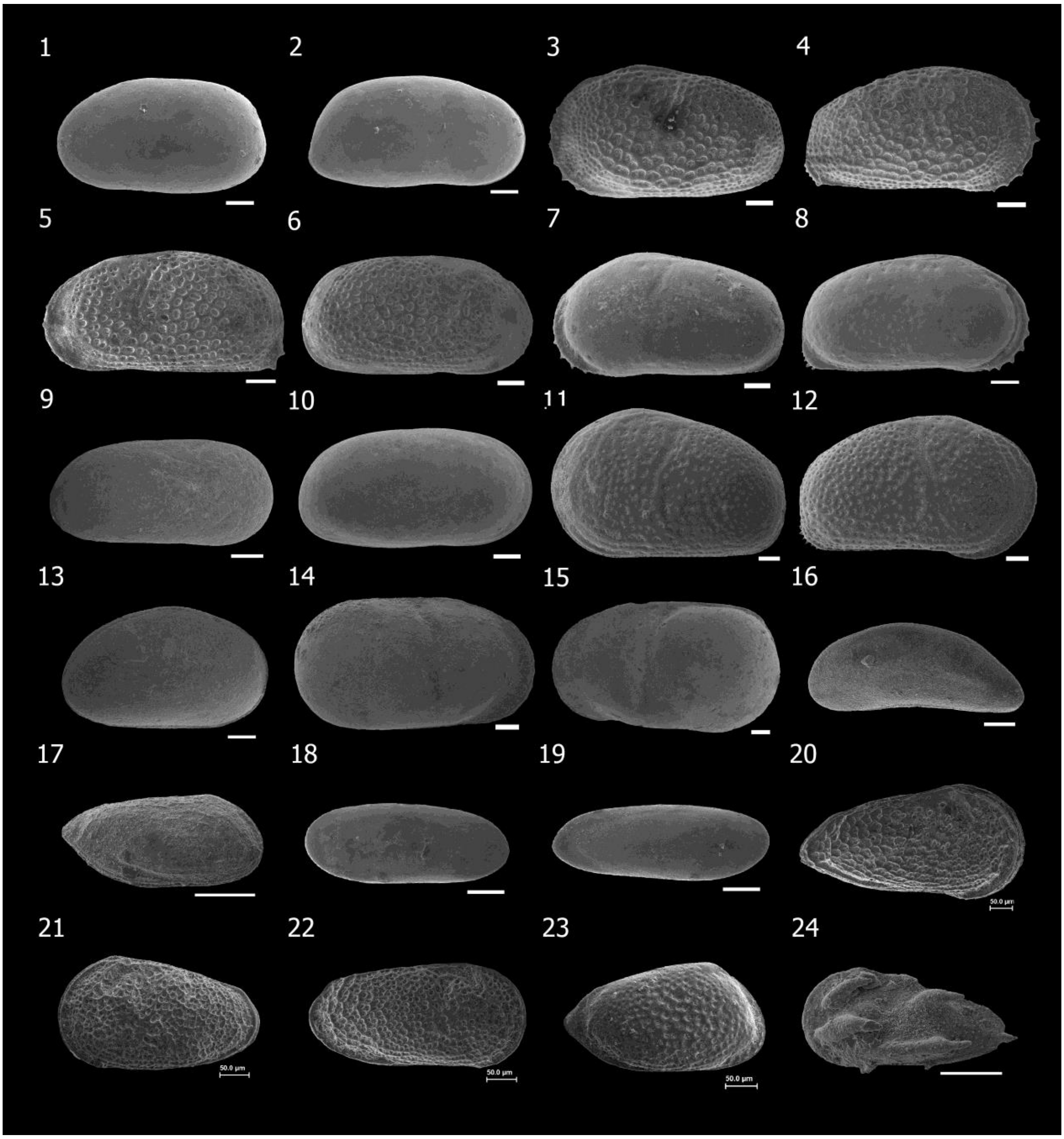


**Figure 6.** *Cyprideis olivencai*: 1. LV, female (MPEG-573-M), 2. RV, female (MPEG-574-M); *C. reticulopunctata*: 3. LV, juvenile, female (MPEG-575-M), 4. RV, juvenile, female (MPEG-576-M); *C. retrobispinosa*: 5. LV, female (MPEG-577-M), 6. RV, female (MPEG-578-M); *C. schedogymnos*: 7. LV, female (MPEG-579-M), 8. RV, female (MPEG-580-M); *C. paralela*: 9. RV, male (MPEG-581-M); *C. simplex*: 10. RV, female (MPEG-582-M); *C. sulcosigmoidalis*: 11. LV, female (MPEG-583-M), 12. RV, female (MPEG-584-M); *Cypria aqualica*: 13. RV, ♀ (MPEG-585-M); *Cytheridella danielopoli*: 14. LV, ♀ (MPEG-586-M), 15. RV, female (MPEG-587-M), *Paracypris* sp.: 16. LV, female (MPEG-588-M); *Pellucistoma curupira*: 17. RV, female (MPEG-589-M); *Penthesilenula olivencai*: 18. LV, female (MPEG-590-M), 19. RV, female (MPEG-591-M); *Perissocytheridea acuminata*: 20. RV, male (MPEG-592-M); *Perissocytheridea ornellasae*: 21. LV, female (MPEG-593-M), 22. RV, male (MPEG-594-M); *Rhadinocytherura amazonensis*: 23. RV, female (MPEG-595-M); *Skopaeocythere tetrakanthos*: 24. LV, male (MPEG-596-M). Scale bar = 100 µm.

Simultaneously at Colombia and Peru, Sheppard & Bate (1980) studied the ostracods from Pebas Formation, describing three new genera (*Otarocyprideis*, *Botulocyprideis* and *Rhadinocytherura*) and recording the presence of *Cypria* Zenker 1845, *Cyprideis* Jones 1857, *Cytheridella* Daday 1905, *Perissocytheridea* Stephenson 1938, and *Ambocythere* Bold 1958, attesting its similarity with the ostracofauna of Solimões Formation, in Brazil. However, the new genera *Otarocyprideis* and *Botulocyprideis* were also placed into synonymy of *Cyprideis* by Muñoz-Torres *et al*. (1998) (Tab.1).

Thereby, the genus *Cyprideis* became the most representative, with 90% of the ostracofauna registered in the Solimões Formation and adjacent units, like Pebas Formation (Muñoz-Torres *et al*. 2006). Nevertheless, Gross *et al.* (2014) studying the borehole 1AS-10-AM and the genus *Cyprideis*, particularly the smooth and vestibulate species, formerly attributed to *Amazonacytheridea*, *Chlamydocytheridea*, *Paulacoutoia* and *Pseudoparakrithella* by Purper (1979) (with the possible synonyms *Botulocyprideis* and *Nealecythere*), mentioned that they diverge significantly of the *Cyprideis* defined by earlier authors (e.g. Kollmann 1960; Benson *et al*. 1961; Van Morkhoven 1963; Sandberg 1964) and, maintain as *Cyprideis* with some reservation (Tab.1). The authors attested the high intraspecific variability through comparative morphology, and grouped the 20 species identified into groups and subgroups. Furthermore, the authors revalidated five species (*Cyprideis kroemmelbeini*, *Cyprideis kotzianae*, *Cyprideis paralela*, *Cyprideis reticulopunctata* and *Cyprideis simplex*), renamed others two (*Cyprideis curucae* and *Cyprideis munoztorresi*), placed into synonymy (*Cyprideis aulakos* to *Cyprideis sulcosigmoidalis* and *Cyprideis lacrimata* to *Cyprideis pebasae*), and described two new species (*Cyprideis ituiae* and *Cyprideis matorae*).

Although most of *Cyprideis* species were identified to specific level without problems, the taxonomic study of the ostracods brought the same morphological problematic in the tentative to identify some species. During the identification of the new species *C. atalaiensis*, based on a number of SEM photography and in the comparative study with the type material of Purper (1979), Purper & Pinto (1983), Purper & Ornellas (1991), and Gross *et al*. (2013; 2014) we got some conclusions, as presented below.

The holotype of *C. graciosa* figured by Purper, 1979 (p. 271, pl. 3, figs. 1–2, from boreholes CPCAN II and III, Amazonas State, Brazil) is a juvenile, probably A-2, while the adults of this species were figured in outcrops from Eirunepé, southwestern Amazonas State, Brazil (Ramos 2006: p. 93, figs. 7.d, f; Gross *et al*. 2013: p. 224, pl. 4, figs. 1–2, 5–6, 9–17), and in the boherole 1AS-1-AM, northwestern Amazonas State, Brazil ( Purper & Ornellas 1991: p. 27, pl. 1, figs. 10–15). This mistake induced to erroneous classification of some specimens in *C. graciosa* by some authors (Muñoz-Torres *et al*. 1998: p. 97, pl. 3, figs. 1–3; Whatley *et al*. 1998: p. 241, pl.1, figs. 11–15; Linhares *et al*. 2011: p. 96–97, figs.3.9–10, 4.3–4). Some of them are here include in the synonymy of the new species *C. atalaiensis* (Figs. 9.1–12).

The species *C. longispina* (Purper 1979) and *C. pebasae* (Purper 1979) are also well represented in the outcrops from Eirunepé (Ramos 2006: p. 91, figs. 6.o–y, p. 93, figs. 7.i–n; Gross *et al*. 2013: p. 224, pl. 4, figs. 18–34, p. 226, pl. 5, figs. 1–17), those where it is registered *C. graciosa*, dated as Late Miocene and corresponding to the uppermost portion of the Solimões Formation. They are also rare in the cores (mainly in the lowermost layers that represent the Early Miocene to early Late Miocene). *C. longispina* and *C. pebasae* can exceptionally occur in the uppermost samples of the borehole (e.g. Purper 1979: p. 269, pl. 2, figs. 11–23, boreholes CPCAN I and II; p. 271, pl. 3, figs. 10–21, borehole CPCAN I); which are dated as Late Miocene/Pliocene (Hoorn 1993; Kachniasz & Silva-Caminha 2016) and are correlated to the outcrops of Eirunepé. The specimens figured by Muñoz-Torres *et al*. (1998) as *C. longispina* (p. 97, pl. 3; figs. 12–14) and *C. pebasae* (p. 99, pl. 4, figs. 8–10) differ of the type material of Purper (1979) and shoud not be considered to these species. Until now these species are restricted to Brazil (Tab. 2).

Regarding to the species *Cyprideis curucae* (*Sohnicythere tuberculata* Purper & Pinto 1983), renamed by Gross *et al*. (2014), the analysis of 30 specimens, including the type series (Purper & Pinto 1983), allowed to verify different patterns in the ornamentation of this species that previously induced to identify it as a new species, being in open nomenclature (Muñoz-Torres *et al*. 1998; Whatley *et al*. 1998; Linhares *et al*. 2011). However, with the present study we note that all the specimens observed belong to the same species *C. curacae*, representing three morphotypes: (1) with tubercles (Figs. 8.a–b); (2) partially with tubercles (Figs. 8.c–d); and (3) without tubercles (Figs. 8.e–f), in agree with Gross *et al*. (2014).

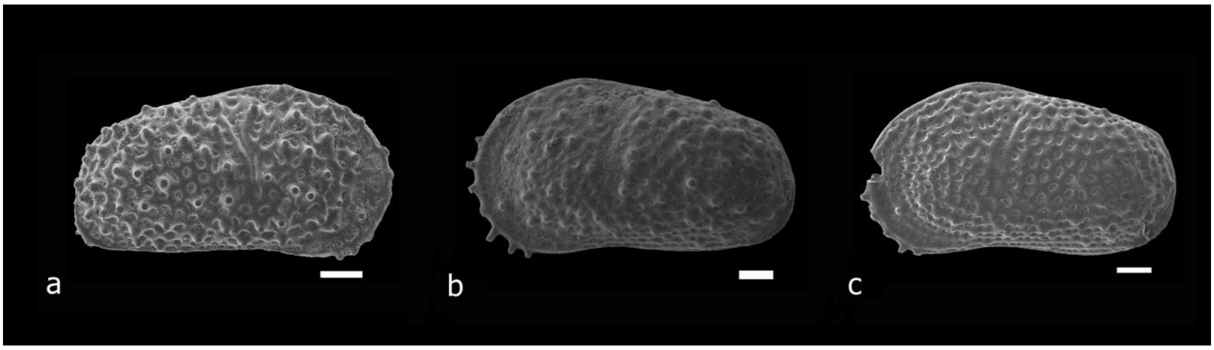


**Figure 7.** Morphotype of *Cyprideis curucae*: a: morphotype with tubercles (borehole 1AS-31-AM at depth 230.0 m); b: morphotype partially with tubercles (borehole 1AS-8-AM at depth 110.60 m); c: morphotype without tubercles (borehole 1AS-31-AM at depth 172.40 m). Scale bar= 100 µm.

**Table 1. Taxonomic classification of genera and species of ostracods from Neogene of Western Amazon.**

| Purper 1979 | Shepard & Bate 1980 | Purper & Pinto 1983 | Purper & Ornellas 1991 | Muñoz-Torres *et al*. 1998 | Gross *et al*. 2014 |
|---|---|---|---|---|---|
| *Amazonacytheridea multiradiata* | | | | *Cyprideis olivencai* | *Cyprideis multiradiata* |
| | *Botulocyprideis simplex* | | | | *Cyprideis simplex* |
| | *Cyprideis purperi purperi* | | *Cytheridea minipunctata* | *Cyprideis minipunctata* | |
| *Cytheridea graciosa* | | | | *Cyprideis graciosa* | |
| *Cytheridea longispina* | | | | *Cyprideis longispina* | |
| *Cytheridea pebasae* | | | | *Cyprideis pebasae* | |
| | | | *Chlamydocytheridea kotzianae* | *Cyprideis machadoi* | *Cyprideis kotziane* |
| *Chlamydocytheridea machadoi* | *Otarocyprideis machadoi* | | | *Cyprideis machadoi* | |
| *Cytheridea reticulopunctata* | | | | | *Cyprideis reticulopunctata* |
| *Hulingsina?* | | | | *Cyprideis* sp. 1 | *Cyprideis pebasae* |
| *Leptocytheromorpha ornellasae* | *Perissocytheridea? elongata* | | | *Perissocytheridea ornellasae* | |
| *Paulacoutoia kroemmelbeini* | | | | *Cyprideis machadoi* | *Cyprideis kroemmelbeini* |
| *Paulacoutoia olivencai* | *Botulocyprideis simplex* | | | *Cyprideis olivencai* | |
| *Pseudoparakrithella paralela* | | | | | *Cyprideis paralela* |
| *Proparacytheridea acuminata* | | | | *Perissocytheridea acuminata* | |
| | | *Sohnicythere inversa* | | *Cyprideis inversa* | |
| | | *Sohnicythere tuberculata* | | *Cypridei* sp. 1 | *Cyprideis curucae* |

**Table 2. Occurrence of the species *C. graciosa*, *C. longispina* and *C. pebasae* in the wells and outcrops from Western Amazon.**

| **Species** | **References** | **Occurrences** |
|---|---|---|
| *Cyprideis graciosa* | Purper (1979); Purper & Ornellas (1991); Ramos (2006); Gross *et al*. (2013). | Wells: CPCAM-III- São Paulo de Olivença- at depth 19.50–20.78m, CPCAN-II- Porerê-at depth 154.05–156.36 m, and 1AS-1-AM- at depth 15.40m. Outcrops: Torre da Lua, Remanso, Morada Nova, Pau D'Alho, Torre da Lua, Barro Branco, Amazonas State (Brazil). |
| *Cyprideis longispina* | Purper (1979); Ramos (2006); Gross *et al*., 2013. | Well: CPCAN-I- Tamanduá- at depth 211.86–214.96 m, Amazonas State Amazonas State (Brazil). Outcrops: Torre da Lua, Aquidabã, Morada Nova and Barro Branco (Amazonas State, Brazil). |
| *Cyprideis pebasae* | Purper (1979); Ramos (2006); Gross *et al*. (2013); Gross *et al*. (2014) | Wells: CPCAM-III- São Paulo de Olivença- at depth 19.50–20.78m, CPCAN-I- Tamanduá- at depth 211.86–214.96 m, and 1AS-10-AM- at depth 3m, 19m, 23m, 27m and 42m. Outcrops: Torre da Lua, Remanso, Aquidabã, Morada Nova, Pau D'Alho, Barro Branco and others outcrops at Atalaia do Norte Municipality, Amazonas State (Brazil). |

The great variation in ornamentation pattern of *Cyprideis sulcosigmoidalis* were also observed during the comparative study with the type material of Purper (1979), which description present the ornate pattern. The occurrence of a slightly punctuated to smooth pattern in the samples studied by Muñoz-Torres *et al*. (1998), caused the misconception on identification of the new species *Cyprideis aulakos*. The analysis of our material showed distinct morphotypes, as demonstrated by Gross *et al*. (2014, fig. 7; pl. 9, figs. 20–34), besides one morphotype presenting denticles in the posterior and anterior regions, in both valves. Then, we agree with the considerations of Gross *et al*. (2014), keeping all morphotypes in *C. sulcosigmoidalis*. Thus, tubercles, spines and other ornamentation patterns of the *Cyprideis* in Solimões Formation should be carefully taken into account in the identification of the species, since these characters are more ecological than genetic factors (Ruiz *et al*. 2013; Fürstenberg *et al*. 2015). Therefore, it needs more attention to future studies, to avoid mistakes in the taxonomical classification and in the settlement of new species.

## Systematic Taxonomy

Suprageneric classification follows Liebau (2005), and completely of the proposals of Purper (1979), Sheppard & Bate (1980), Muñoz-Torres *et al*. (1998), Whatley *et al*. (1998), Ramos (2006), Gross *et al*. (2013, 2014).

The type material, as well as the figured specimens (Figs. 5, 6, 8 and 9), are housed in the Micropaleontology Collection of the Museu Paraense Emílio Goeldi, Pará, Brazil, under the numbers MPEG-549-M to MPEG-605-M. The dimensions of the specimens are in millimeters. Abbreviations: LV = left valve, RV = right valve.

Class OSTRACODA Latreille, 1802

Order PODOCOPIDA Sars, 1866

Suborder PODOCOPINA Sars, 1866

Superfamily CYTHEROIDEA Baird, 1850

Family CYTHERIDEIDAE Sars, 1925

Subfamily CYTHERIDEINAE Sars, 1925

Genus *Cyprideis* Jones, 1857

Type species: *Candona torosa* Jones, 1850

***Cyprideis atalaiensis*** **sp. nov.**

Fig. 8: 1–12

1998 *Cyprideis graciosa* (Purper 1979). Whatley *et al*., p. 234, est. 1, figs. 11–15.

1998 *Cyprideis graciosa* (Purper 1979). Muñoz-Torres *et al*., p. 96, est. 3, figs. 1–3.

2011 *Cyprideis graciosa* (Purper 1979). Linhares *et al*., p. 100, fig. **3**.9–10.

2011 *Cyprideis pebasae* (Purper 1979). Linhares *et al*., p. 101, fig. **4**.3–4.

2014 *Cyprideis* aff. *graciosa* (Purper 1979). Gross *et al*., p. 54, pl. 6, fig. 38.

**Type material.** Holotype. Carapace (MPEG-597-M): female; RV, length 0.85 mm; height: 0.46 mm; LV, length 0.48 mm; height: 0.88 mm.

**Paratypes**. MPEG- 598-M, female, RV, length 0.85 mm; height: 0.45 mm. Carapace (MPEG-599-M): LV, length 1.02 mm; height: 0.50 mm; RV, length 0.99 mm; height: 0.49 mm.

**Additional material.** 116 specimens.

**Type locality.** Borehole 1AS-31-AM at Cururu close to Rio Ituí (lat. 05°18’S - long. 71°02´W); Atalaia do Norte Municipality, Amazonas State, Brazil.

**Type horizon.** 1AS-31-AM/174.55 m.

**Derivation of name.** Atalaia do Norte, Municipality of Amazonas State where borehole 1AS-31-AM was drilled.

**Diagnosis.** Large. Subrectangular. Moderately reticulated, fossae with relatively deep, tending to smooth or punctuated in the anterior region.

**Description.** Medium sized. Relatively thick-shelled. In lateral view, subrectangular and elongate. The dorsal and ventral margins are nearly parallel. The left valve is larger than the right valve. The median dorsal margin is slightly arched, maximum height at anterior cardinal angle. The ventral margin nearly straight in the left valve, and gently sinuous in the right valve, with apparent oral curvature. Anterior margin well rounded with seven to eight shorts spines; posterior margin slightly truncate with a short caudal process in the female, more acute in the male; discrete posteroventral flange and small marginal spine in the posteroventral region of the right valve. Surface with moderated pitted reticulation, varying to smooth, to the anterior margin. Sinuous sulcus extending to median part of shell. Dorsal view: elliptic and slightly inflated in the posterior region, with parallel sides. Internal view: entomodont hinge, inner lamella in a regular contour, wide anteriorly, narrow ventrally and posteriorly muscle scars typical of the genus. Evident sexual dimorphism, males more elongated and less inflated than females.

**Remarks.** *Cyprideis atalaiensis* sp. nov. resembles to *Cyprideis graciosa* (Purper 1979) in the reticulated ornamentation, but differ: in the size, which is bigger than the last species; in the shape, which is more subrectangular and less subtriangular; the new species presents only one spine in the right valve compared to four posteroventral spines typical of *C. graciosa*; in dorsal view is less inflated, and do not presents the evident constriction in the median portion. *Cyprideis* aff. *graciosa* identified by Gross *et al*. (2014) (plate 6, figs. 34–40) is partially similar in shape with *Cyprideis atalaiensis* sp. nov., but the ventral portion is more sinuous, the female left valve is more elongated, and presents larger spines.

**Occurrence and distribution.** In this study, this species occurs in the northwestern Amazonas State, Brazil (Fig. 1), borehole 1AS-31-AM (coordinates: lat. 05°18’S - long. 71°02´W), at 56.50 m; 58.00 m; 138.20 m; 157.25 m; 170.80 m; 174.30 m; 174.55 m; 174.65 m; 174.70 m; 174.80 m; 174.82 m; 174.90 m; 175.00 m; 175.05 m; 181.10 m; 199.70 m; 216.90 m; 218.30 m; 219.95 m; 230.00 m and 295.00 m. **Borehole 1AS-7D-AM (**coordinates: lat. 04°14’S - long. 70°41´W); at depth 50.00 m; 76.50 m; 91.50 m; 96.00 m; 96.30 m; 101.90 m; 106.00 m; 115.50 m; 121.00 m and 160.50 m. **Others occurrences.** Is widely distributed in the Colombia localities, and rare in the Peru localities (Pebas Formation).

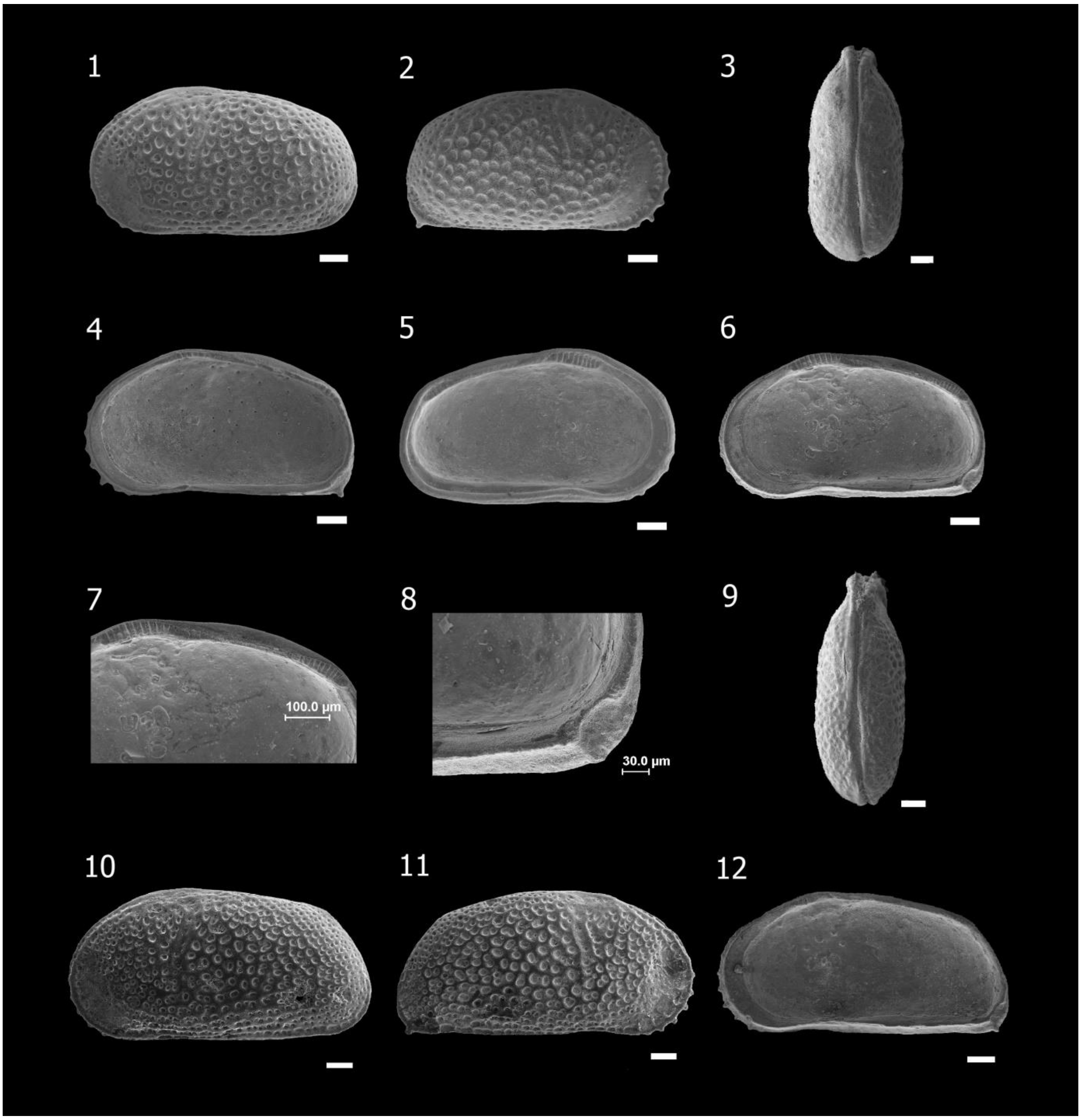


**Figure 8.** 1–12. *Cyprideis atalaiensis* sp. nov.: 1–5 (Holotype, female carapace, MPEG-597-M); 1- LV, external view; 2- RV, external view; 3- dorsal view; 4- RV, internal view; 5- LV, internal view; 6–8 (Paratype, MPEG-598-M); 6- RV, female, internal view; 7- RV, female; detail of the hinge; 8- RV, female; detail of the flange; 9–12 (Paratype, male carapace, MPEG-599-M); 9- dorsal view; 10- LV, external view; 11- RV, external view; 12- RV, internal view. Scale bar = 100 µm.

***Cyprideis dictyon* sp. nov.**

Fig. 9: 1–15

2011 *Cyprideis* sp. 5. Linhares *et al.*, p. 97, figs. 4 9–10.

**Type material. Holotype**. MPEG-600-M, female, RV, length 0.65 mm; height: 0.35 mm.

**Paratypes**. MPEG-601-M, female, LV, length 0.67 mm; height: 0.37 mm. MPEG-602-M, female, LV, length 0.67 mm; height: 0.38 mm. MPEG-603-M, female, RV, length 0.62 mm; height: 0.36 mm. MPEG-604-M, male, LV, length 0.69 mm; height: 0.37 mm. MPEG-605-M, male, LV, length 0.71 mm; height: 0.40 mm.

**Additional material.** 10 specimens.

**Type locality.** Borehole 1AS-31-AM at Cururu, close to Ituí river (lat. 05°18’S - long. 71°02´W); Atalaia do Norte Municipality, Amazonas State, Brazil.

**Type horizon.** 1AS-31-AM/170.80 m.

**Derivation of name.** From Grego δικτυωτή. With reference to its well-developed reticulate ornamentation.

**Diagnosis.** Middle-sized *Cyprideis*. Female subrectangular to subquadrate in lateral view. Male elongated, subrectangular in shape. Posterior margin of the right valve truncate to almost straight, with a short posteroventral caudal process extended by the flange. In the female, dorsal margin strongly arched in the median region. Ornament with well-developed reticulation.

**Description.** Middle-sized. Relatively thick-shelled, subrectangular to subquadrate in lateral view. The dorsal and ventral margins are almost parallel. Dorsal margin strongly arched in the median region, greatest height just mid-length. The ventral margin almost straight, but with a well-defined oral incurvature, mainly in the right valve; left valve with straighter ventral margin than right valve; anterior margin well rounded extending to the middle of anteroventral region. Posterior margin almost straight in the right valve with a short and prominent caudal process extended by the posteroventral flange, in the right valve. Surface with well-developed reticulation. Three ribs parallel running to the anterior margin, extending through the ventral one. Deep sulcus extending from subcentral dorsal region to ¾ of the carapace, bifurcated at the ⅓ of the carapace. Dorsal view: elliptical and slightly inflated in the posterior region, with parallel sides. Internal view: entomodont hinge, inner lamella in a regular contour, wide anteriorly, narrow ventrally and posteriorly; muscle scars typical to the genus. Evident sexual dimorphism, males more elongated and less inflated than females.

**Remarks.** *Cypdrideis dictyon* sp. nov. resembles to *Cyprideis lacrimata* (Muñoz-Torres *et al*. 1998, plate 3; figs. 7–9) in the reticulated ornamentation pattern, but differ in the size, which is smaller, in the shape that is less subrectangular and besides, present sulcus. *Cyprideis sulcosigmoidalis* (Purper 1979) is also similar in the shape to *Cyprideis diction* sp. nov., but *C. sulcosigmoidalis* is more subtrapezoidal in lateral view and differs in the ornamentation, that is more punctuated than reticulated. Some valves of *C. diction* sp. nov. present nodes (Figs. 10. 4–5; 7–8). However, the presence of nodes in some specimens is not a diagnostic character but a ecophenotypic variation in response to environmental changes as discussed already to the other species.

**Occurrence and distribution.** In this study, this species occurs in the northwestern of Amazonas State, Brazil, (Fig. 1), borehole 1AS-31-AM (coordinates: lat. 05°18’S - long. 71°02´W), at depths of 170.80 m, 174.65 m, 174.80 m and 175.00 m.

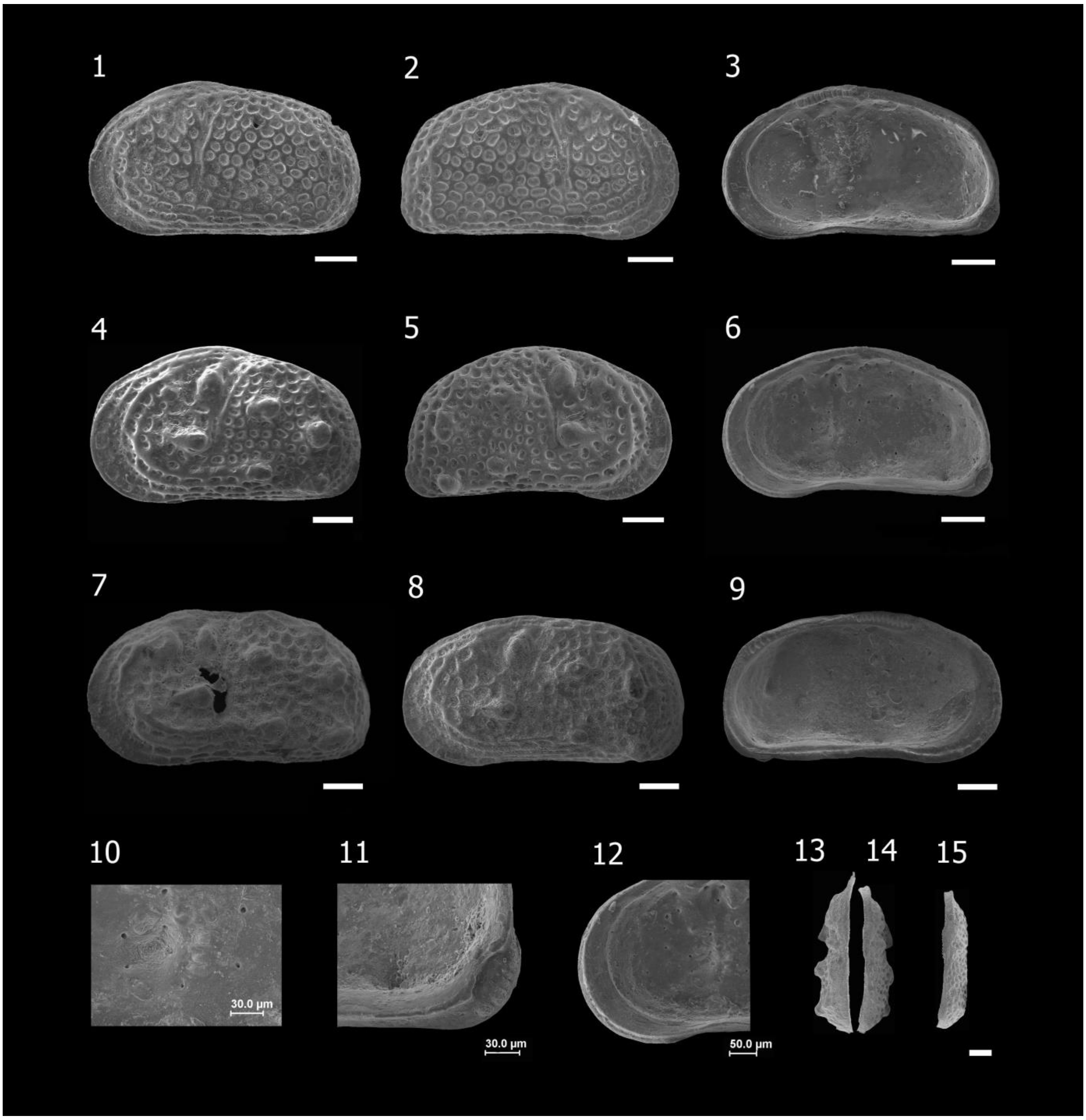


**Figure 9.** 1–15. *Cyprideis dictyon* sp. nov.: 1- (Paratype, MPEG-601-M), LV, female; external view; 2–3 (Holotype, female, MPEG-600-M); 2- RV, external view; 3- RV, internal view; 4- (Paratype, MPEG-602-M); LV, female, external view; 5–6 (Paratype, female, MPEG-603-M); RV, external view; 6- RV, internal view; 7- (Paratype, MPEG-604-M), LV, male; 8–9 (Paratype, male, MPEG-605-M); 8- RV, external view; 9- LV, internal view; 10–11 (Paratype, female, MPEG-603-M); 10- muscle scar; 11- detail of the flange; 12- detail of the anterior margin in internal view; 13- (Paratype, MPEG-602-M), LV, female, dorsal view; 14- (Paratype, MPEG-603-M), RV, female, dorsal view; 15- (Paratype, MPEG-600-M), RV, female, dorsal view. Scale bar = 100 µm.

## Conclusions

The study of the ostracods of the boreholes 1AS-7D-AM, 1AS-8-AM and 1AS-31-AM allowed identify nine genera and 30 species. The great morphological diversity of *Cyprideis*, attest a high intraspecific variability propably triggered by paleoenvironmental changes in the Neogene of the Solimões Formation, evidencing its ecophenotypic plasticity. Besides, we increase the specific diversity proposing two new species to the Neogene of Western Amazonia.

## Acknowledgments

The authors thank the Brazilian Departamento Nacional de Produção Mineral (DNPM) and the Serviço Geológico do Brasil (CPRM), for permission to access and use the core samples. The Museu Paraense Emilio Goeldi (MPEG) supported this study. The Federal University of Pará (UFPA) supported this research through the Programa de Pós-Graduação em Geologia e Geoquímica (PPGG). The Centro de Microscopia Eletrônica at Universidade Federal do Rio Grande do Sul (URGS) provided facilities for SEM photography.

## References

Benson, R.H., Berdan, J.M., Bold, W.A., Hanai, T., Hessland, I., Howe, H.V., Kensling, R.V., Levinson, S.A., Reyment, R.A., Moore, R.C., Scott, H.W., Shaver, R.H., Sohn, I.G., Stover, L.E., Swain, F.M., Sylvester-Bradley, P.C. & Wainwright, J. (1961) Systematic descriptions. *In*: Moore, R. & Pitrat, C. W. (Eds), *Treatise on Invertebrate Paleontology, Pt. Q. Arthropoda 3, Crustacea, Ostracoda*. Geological Society of America and University of Kansas Press, Lawrence, pp. 99–421.

Fürstenberg, S., Frenzel, P., Peng, P., Henkel, K. & Wrozyna, C. (2015) Phenotypical variation in Leucocytherella sinensis Huang, 1982 (Ostracoda): a new proxy for palaeosalinity in Tibetan lakes. *Hydrobiologia*, 751, 55–72.

Gross M., Ramos M. I., Caporaletti M. & Piller W. E. (2013) Ostracods (Crustacea) and their paleoenvironmental implication for the Solimões Formation (Late Miocene; Western Amazonia/Brazil). *Journal of South American Earth Sciences,* 42, 216–241.

Gross, M., Ramos, M.I. & Piller, W.E. (2014) On the Miocene Cyprideis species flock (Ostracoda; Crustacea) of Western Amazonia (Solimões Formation): Refining taxonomy on species level. *Zootaxa*, 3899 (1), 001–069.

Gross, M., Ramos, M.I.F. & Piller, W.E. (2015) A minute ostracode (Crustacea: Cytheromatidae) from the Miocene Solimões Formation (western Amazonia, Brazil): evidence for marine incursions?. *Journal of Systematic Palaeontology*, 14(7), 581–602.

Hoorn, C. (1993) Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study**.** *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 105, 267–309.

Kachniasz, K.E. & Silva-Caminha, S.A.F. (2016) Palinoestratigrafia da Formação Solimões: comparação entre bioestratigrafia tradicional e o método de associações unitárias. *Revista Brasileira de Paleontologia*, 19(3), 481–490.

Kollmann, K. (1960) Cytherideinae und Schulerideinae n. subfam. (Ostracoda) aus dem Neogen des ostlichen Oester- reich. *Mitteilungen der Geologischen Gesellschaft in Wien*, Vienna, 51, 89–195.

Liebau, A. (2005) A revised classification of higher taxa of the Ostracoda (Crustacea). *Hydrobiologia*, 538, 115–137.

Linhares A.P., Ramos M.I., Gross M. & Piller W.E. (2011) Evidence for marine influx during the Miocene in southwestern Amazonia, Brazil. *Geología Colombiana*, 36 (1), 91–104.

Linhares, A.P., Gaia, V.C.S., Ramos, M.I.F. (2017) The significance of marine microfossils for paleoenvironmental reconstruction of the Solimões Formation (Miocene), Western Amazonia, Brazil. *Journal of South American Earth Sciences*, 79, 57–66.

Maia, R.G.N., Godoy, H.O., Yamaguti, H.S., Moura, P.A., Costa, F.S.F., Holanda, M.A. & Costa, J.A. (1977) *Projeto Carvão no Alto Solimões*; Relatório Final. Manaus: CPRM; DNPM, 142 pp.

Martens, K., Savatenalinton, S. (2011) A subjective checklist of the Recent, free-living, non-marine Ostracoda (Crustacea). *Zootaxa*, 2855, 1–79.

Meisch C. (2000) Freshwater Ostracoda of Western and Central Europe. *In*: J. Schwoerbel & P. Zwick (eds), Süßwasserfauna von Mitteleuropa 8/3. *Spektrum Akademischer Verlag*, Heidelberg, pp. 522.

Monsch, K.A. (1998) Miocene fish faunas from the northwestern Amazonia Basin (Colombia, Peru, Brazil) with evidence of marine incursions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 143, 31–50.

Muñoz-Torres, F., Whatley, R.C. & Van Harten, D. (1998) The endemic Non-marine Miocene ostracod fauna of the upper Amazon Basin**.** *Revista Española de Micropaleontologia*, 30 (3), 89–105.

Muñoz-Torres, F., Whatley, R. & Van Harten, D. (2006) Miocene ostracod (Crustacea) bioestratigraphy of the upper Amazon Basin and evolution of the genus *Cyprideis*. *Journal of South American Earth Sciences*, 21, 75–86.

Purper, I. (1977a) Some Ostracodes from the Upper Amazon Basin, Brazil. Environment and age. *In*: Loffler, H. Danielopol, D. (Eds), Aspects of Ecology and Zoogeography of Recent and Fossil Ostracoda. *Sixth International Ostracods Symposium*, *Saalfelden*, pp. 353–367.

Purper, I. (1977b) Ostracodes cenozóicos da Amazônia Ocidental. Instituto de Geociências, *Universidade Federal do Rio Grande do Sul*, Rio Grande do Sul, Tese de Doutorado, 131 pp.

Purper, I. (1979) Cenozoic Ostracodes of the Upper Amazon Basin, Brazil. *Pesquisas*, 12, 209–281.

Purper, I. & Pinto, I.D. (1983) New genera and species of ostracodes of the Upper Amazon Basin. *Pesquisas*, 15, 113–126.

Purper, I. & Pinto, I.D. (1985) New data and new ostracods from Pebas Formation—Upper Amazon Basin. *8° Congresso Brasileiro de Paleontologia*, Rio de Janeiro, 1985, Seria Geologia, Paleontologia/Estratigrafia, DNPM 27, 427–441.

Purper, I. & Ornellas, L. (1991) New ostracodes of endemic fauna of the Pebas Formation, Upper Amazon Basin Brasil. *Pesquisas*, 18**,** 25–38.

Ramos, M.I.F. (2006) Ostracods from the Neogene Solimões Formation (Amazonas, Brazil). *Journal of South American Earth Sciences*, 21, 87–95.

Ruiz, F., Abad, M., Bodergat, A.M. Carbonel, P., Rodríguez-Lázaro, J., González-Regalado, M.L., Toscano, A., García, E.X. & Prenda, J. (2013) Freshwater ostracods as environmental tracers. *International Journal of Environmental Science and Technology*, 10, 1115–1128.

Sandberg, P.A. (1964) *The ostracod Genus Cyprideis in the Americas*. Acta Universitatis Stockholmiensis, Stockholm, 178 pp.

Shepard, L. & Bate, R. (1980) Plio-Pleistocene ostracods from the Upper Amazon of Colombia and Peru. *Palaeontology*, 23(1), 97–124.

Van Morkhoven, F.P.C.M. (1963) *Post-Palaeozoic Ostracoda: Their Morphology, Taxonomy and Economic Use. Vol. II Generic descriptions*. Elsevier, New York, 478 pp.

Wanderley, M. (2010) Técnicas de preparação de microfósseis. *In*: Carvalho, I. S. (Eds), *Paleontologia: Microfósseis, paleoinvertebrados*. Interciência, Rio de Janeiro, pp. 65–80.

Wanderley Filho, J.R., Eiras, J.F., Cunha, P.R.C., van der Ven, P.H. (2010) The Paleozoic Solimões and Amazonas basins and the Acre foreland basin of Brazil. *In*: Hoorn, C., Wesselingh, F.P. (Eds.) *Amazonia: Landscape and species evolution, a look into the past*, Wiley-Blackwell publications, Chichester, pp. 29–37.

Wesselingh, F.P. (2006) Molluscs from the Miocene Pebas Formation of Peruvian and Colombian Amazonia. *Scripta Geologica*, 133, 19–290.

Wesselingh, F.P. & Ramos M.I.F. (2010) Amazonian aquatic invertebrate faunas (Mollusca, Ostracoda) and their development over the past 30 million years. *In*: Hoorn C. & Wesselingh F.P. (Eds). *Amazonia: Lanscape and species evolution, a look into the past*, Wiley-Blackwell publications, Chichester, pp. 302–316.

Whatley, R.C., Muñoz-Torres, F. & Van Harten, D. (1998) The Ostracoda of isolated Neogene saline lake in the western Amazon Basin. *In*: Crasquin-Soleau, S.; Braccini, E. & Lethiers, F. (Eds), *What about Ostracoda! Actes du 3$^{o}$ Congrès Européen des Ostracodologistes*. Bulletin du Centre de recherches Elf exploration production. Mémoire 20, pp. 231–245.

# CAPÍTULO 3

## 3 INTEGRATED BIOSTRATIGRAPHY BASED ON PALYNOLOGY AND OSTRACODS FROM SOLIMÕES FORMATION (ATALAIA DO NORTE, AMAZONAS, BRAZIL)*

Ana Paula Linhares[1,2], Maria Inês Feijó Ramos[1], Valber do Carmo de Souza Gaia[3], Yuri Souza Friaes[3].

[1]*Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia. Av. Presidente Tancredo Neves 1901, Belém, PA, Brazil (alinhares@museu-goeldi.br; mramos@museu-goeldi.br)*

[2]*Programa de Pós-Graduação em Geologia e Geoquímica, Instituto de Geociências, Universidade Federal do Pará, Rua Augusto Corrêa s/n, Belém-PA, Brazil, (alinhares@museu-goeldi.br)*

[3]*Programa de Capacitação Institucional, Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia. Av. Presidente Tancredo Neves 1910, Belém, PA, Brazil (valbergaia@museu-goeldi.br; yurifriaes@hotmail.com)*

* To be submmited to Palaios.

**ABSTRACT**: The integrated study of palynology and ostracods from the boreholes 1AS-8-AM and 1AS-7D-AM, Atalaia do Norte Municipality, Amazonas State, Brazil (western Amazon), allowed to date the studied sequences from Early Miocene to Late Miocene. Five palynological zones previously proposed for the Solimões Formation were identified: *Verrutricolporites*, Early Miocene (1AS-8-AM), *Psiladiporites–Crototricolpites*, late Early Miocene to early Middle Miocene (1AS-7D-AM); *Crassoretitriletes*, Middle Miocene (1AS-7D-AM); *Grimsdalea*, late Middle Miocene to Late Miocene (both boreholes) and *Asteraceae*, Late Miocene (1AS-7D-AM). At the same time, stratigraphical distribution of the *Cyprideis* species allowed to recognize five zones corresponding to the palynological zones, four ostracod zones already established were observed, although its limits have been changed here: *C. aulakos* renamed to *C. sulcosigmoidalis*, (late Early – early Middle Miocene), *C. caraionae* (late Middle Miocene to early Late Miocene, *C. minipunctata* (late Middle Miocene to Late Miocene) and *C. cyrtoma* (early Late Miocene). The guide species of the *C.*

*obliquosulcata* zone do not occurs in this work. Besides, we propose a new zone, *Cyprideis paralela* (Late Miocene) (in the borehole 1AS-7D-AM).

**Key words**: Solimões Formation; biostratigraphy; palynology; ostracods.

## INTRODUCTION

Biostratigraphy is fundamental to determinate the age of the layers in a studied sequence and consequently to understand the paleoenvironmental evolution and the bioevents associated (Tantawy *et al*., 2001; Beiranvand *et al*., 2014). Since the first paleontological record of the Neogene deposits of western Amazonia (Conrad, 1871; Woodward, 1871; Etheridge, 1879), a precise age and/or stratigraphycal range of the studied sequence is tentatively proposed (Brown, 1879; Roxo, 1937; Simpson, 1961). These deposits inferred to be part of the Pebas and Solimões Formations, both correlated units and with similar paleontological contents (Purper, 1979; Hoorn, 1994a; b; Antoine *et al*., 2016).

A more consistent age (late Early to early Late Miocene) to these sequences was attributed based on integrated information using sedimentology, stratigraphy and palynological biozonation from outcrops and in a borehole drilled in the division between Peru/Colômbia and Brazil by Hoorn (1993, 1994a; b; c), allowing an advance in the future discussions about the stratigraphical range of the Solimões Formation and to the understanding the evolution of the biota and the related paleoenvironments of the Neogene of Western Amazonia (Hoorn *et al*., 2010 a; b).

The fast evolution of the biota and high endemism, as the example of the mollusks and ostracods, allowed to propose a regional biostratigraphy by Wesselingh *et al*. (2006), Muñoz-Torres *et al*. (2006). It was made in a tentative to correlate the similar sequences in Colombia, Peru and Brazil, and to verify the stratigraphical and geographical range using as a base the palynological biozonation of Hoorn (1993), as major bioevents should be recognizable as datum planes over wide areas (Muñoz-Torres *et al*., 2006).

Some studies indicate similarities of the microfossil assemblage from the Pebas Formation (Peru) with the Solimões Formation (Brazil), correlating the areas, and considering the marine interval as the relevant marker for correlation between the intra-basins from Peru, Brazil and Colombia (Antoine *et al*., 2016; Jaramillo *et al*., 2017; Linhares *et al*., 2017).

More recent palynological studies in different cores drilled in western Amazonia (Brazil) also contributed to established the stratigraphical range of the Solimões Formation, although extending the top to the Pliocene (Silva-Caminha *et al.*, 2010; Kachniasz & Silva-Caminha, 2016; Leite *et al.*, 2016). Therefore, due the difference of the limits obtained untill now to the stratigraphical range of the Solimões Formation and the need of more integrated biostratigraphical studies to reach a more precise age and a better understanding of the paleoenvironmental evolution, we propose here a biostratigraphical analysis using ostracods and palynology from two boreholes located in the Atalaia do Norte Municipality, northwestern Solimões basin, Brazil.

## GEOLOGY/ STUDY AREA

The study area is located in the intracratonic Solimões Basin, Amazonas State (Fig. 1), covering an area of approximately 450,000 km$^2$. It is limited northwards by the Guiana Shield, southwards by the Brazilian Shield, to the east by the Purus Arch, and to the west by the Iquitos Arch. The Basin is subdivided by the Carauari Arch: to the east into the Jurua sub-basin and to the west into the Jandiatuba sub-basin. The sedimentary fill can be divided into five sequences: Ordovician, Upper Silurian – Early Devonian, Middle Devonian – Lower Mississippian, Upper Mississippian – Lower Permian Upper Cretaceous – Cenozoic (Wanderlei Filho *et al.*, 2007). The last sequence comprises the Cretaceous Alter do Chão Formation and the Miocene Solimões Formation separated by the Neocretaceous regional unconformity (Eiras *et al.*, 1994; Wanderley Filho *et al.*, 2007).

The Solimões Formation is represented by siliciclastic deposits (mainly pelites and sandstones), presenting organic matter, fossil and its distinguished feature, the levels of lignite. The deposits are typically fluvio-lacustrine, interlayed by marine ingressions during the Miocene (Hoorn 1993; Boonstra *et al.*, 2015; Linhares *et al.*, 2011; 2017; Jaramillo *et al.*, 2017).

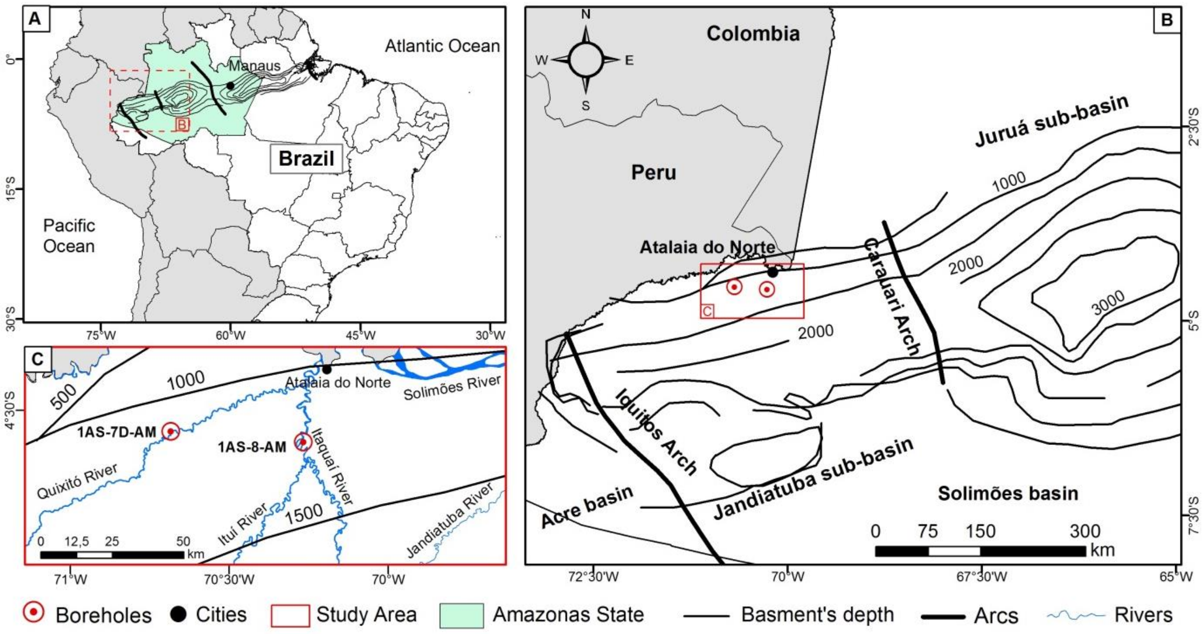


Figure 1 - A) Location of the study area, with tectonic compartmentation of the Solimões Basin. B) Subdivision of Solimões basin by the Carauari Arch into the Jurua and Jandiatuba sub-basins. C) Location of the studied boreholes. Source: Wanderley Filho *et al*. (2010).

## MATERIAL AND METHODS

A total of 196 samples was collected from the borehole 1AS-7D-AM (lat. 04°34’S - long. 70°41´W) (112 samples), near Quixito river, and from the borehole 1AS-8-AM (lat. 05°18’S - long. 71°02´W) (84 samples), near Itacuaí river, Amazonas State, Brazil. The boreholes were drilled by the Geological Survey of Brazil (CPRM) to investigate the presence of lignite (Maia *et al*., 1970). The core 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, when it is overlaid by quaternary sediments; the borehole 1AS-8-AM reaches the 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.

The ostracods were recovered following the standard methodology for calcareous microfossils of Wanderley (2010), which 180 g of dry sediment were washed through sieves 0.5 mm; 0.250 mm; 0.180 mm and 0.125 mm, and dried in an oven at 60◦C. Palynomorph extraction followed the procedure of Uesugui (1979) in which samples of 50 g of dry sediment were submitted first to hydrochloric acid (32%) for two hours and then to hydrofluoric acid (40%) for 12 hours; the material was washed with distilled water and sieved in 200 µm mesh, followed by extraction of light residue which was spread on palynological thin sections to be studied; at least three slides of the each sample were scanned and until approximately 200 specimens were identified and photographed under an optical microscope at 100x magnification. The palynostratigraphic analysis was based on previous palinological stratigraphic framework already established for South American (Hoorn, 1993; Lorente, 1986). To the biostratigraphy of the ostracods, the proposal of Muñoz-Torres *et al*. (2006) was used to definy the biozones of *Cyprideis*. To the correlation, others biostratigraphical framework proposal based on palynology, ostracods and mollusks from Neogene of Western Amazonia, were used (Wesselingh *et al*., 2006; Silva-Caminha *et al*., 2010; Jaramillo *et al*., 2010; Wesselingh & Ramos, 2010; Linhares *et al*., 2011; Gross *et a*l., 2014; Leite *et al*., 2016).

## BIOESTRATIGRAPHY

The present integrated biozonation is based in data of the palynology and ostracods. It was proposed to better link both biozones and to date the interval studied with more reliability. This This methodology was already applied to other basins with satisfactory results (Tantawy *et al*., 2001; Beiranvand *et al*., 2014; Lehrmann *et al*., 2016), mainly related to bioevents. Thus, we combined the distribution of index fossils of ostracods and pollens in the 1AS-7D-AM and 1AS-8-AM to atribute the age to the stratigraphic range of the studied seccions.

### *Stratigraphycal considerations and cronostratigraphycal framework*

The main biostratigraphical framework of the South American include the work of the Lorente (1986), which studied the cenozoic portion of the three basins from Venezuela, and proposed a palynostratigraphic zonation adjusted to the of planktonic foraminifera and calcareous nanofossils biozones, established by Muller *et al*. (1987). This proposal grounded some biozonations of the Neogene of western Amazon (Hoorn, 1993; Silva-Caminha *et al*. 2010; Leite *et al*., 2016; Kachniasz & Silva-Caminha, 2016). Besides, the proposal of Jaramillo *et al*. (2011) is also widely considered and correlates the age of approximately 70 sections located in Colombia with marine and terrestrial fossils, carbon isotopes (δ13CTOM) and magnetostratigraphy.

Hoorn (1993), using this biozonation, analyzed samples of the borehole 1AS-4a-AM, in the Atalaia do Norte Municipality (Amazonas, Brazil) and established five biozones (Fig. 2): *Verrutricolporites*, *Retitricolporites* (Lower Miocene); *Psiladiporites–Crototricolpites* (late Lower Miocene – Middle Miocene); *Crassoretitriletes* (Middle Miocene) and *Grimsdalea* (late Middle Miocene – early Late Miocene). This biozonation was corroborated by others authors studying mollusks (Wesselingh *et al*., 2006b) and ostracods (Muñoz-Torres *et al*., 2006), studied in the same borehole. However, the presence of the zone *Psilatricolporites caribbiensis*, from late Late Miocene to Pliocene, on the boreholes 1AS-19-AM and 1AS-27-AM (Silva-Caminha *et al*., 2010) indicate an earlier age to the top of the Solimões Formation than previously proposed.

Concordantly, Leite *et al*. (2016) studying the borehole 1AS-33-AM, Atalaia do Norte Municipality, Amazonas State, recognised the zones: *Crassoretitriletes*, Middle Miocene; *Asteraceae*, Late Miocene; and the subzones *Psilatricolporites caribbiensis*, from late Middle Miocene to Pliocene and *Echitricolporites–Alnipollenites*, Pliocene. In parallel, Kachniasz & Silva-Caminha (2016) based on samples of 1AS-31-AM and 1AS-34-AM, drilled in the same region, identified two zones: *Psilatricolporites caribbiensis* and *Echitricolporites–Alnipollenites*, also limiting the top of the section to the Pliocene (Fig. 2).

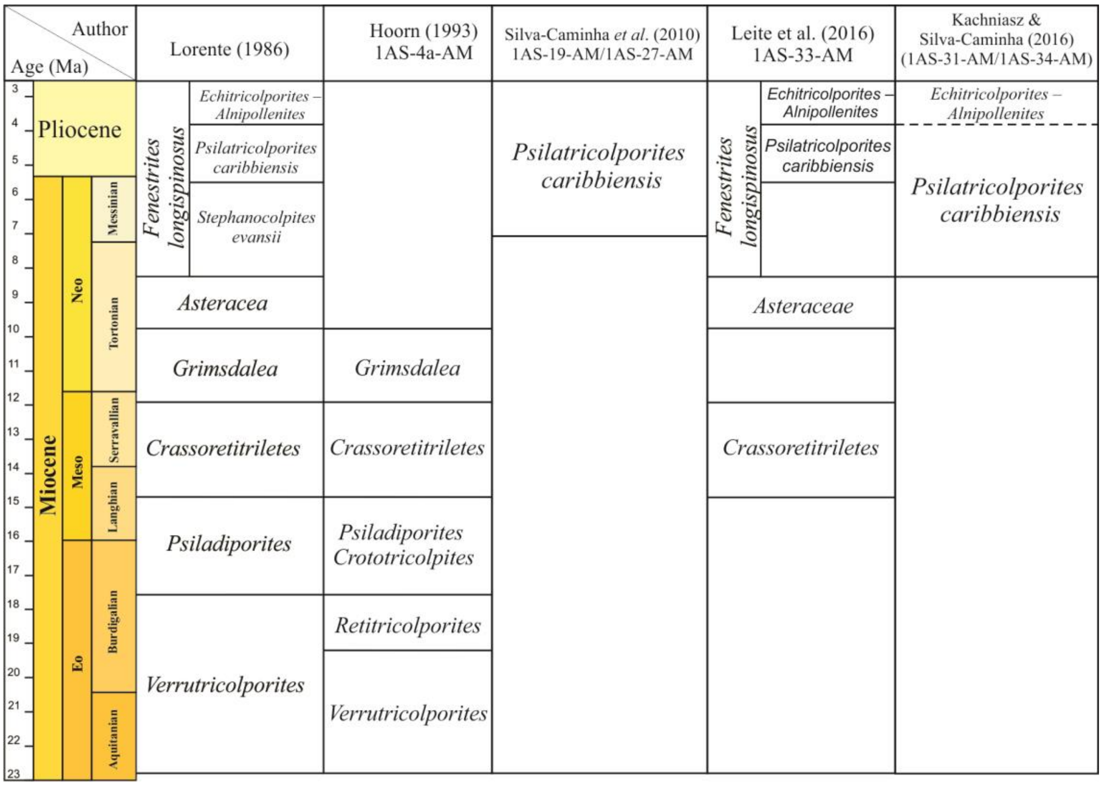


Figure 2 - Biozonation proposals for Neogene of the South American, based on palynology of boreholes drilled in Western Amazon, and the correlation with Lorente (1986).

The first proposed of ostracods biozonation was presented in Muñoz-Torres *et al*. (2006), which on the basis of the palinozones of Hoorn (1993) and in the tentative to correlate with the caribbean ostracod fauna from transitional waters (Bold, 1988), they settled five zones to the Neogene deposits of Brazil, Peru and Colombia (Fig. 3): *Cyprideis aulakos* (late Early Miocene to early Middle Miocene); *C. caraionae* (Middle Miocene); *C. minipunctata* (Middle Miocene); *C. obliquosulcata* (Middle Miocene) and *C. cyrtoma* (late Middle Miocene to early Late Miocene).

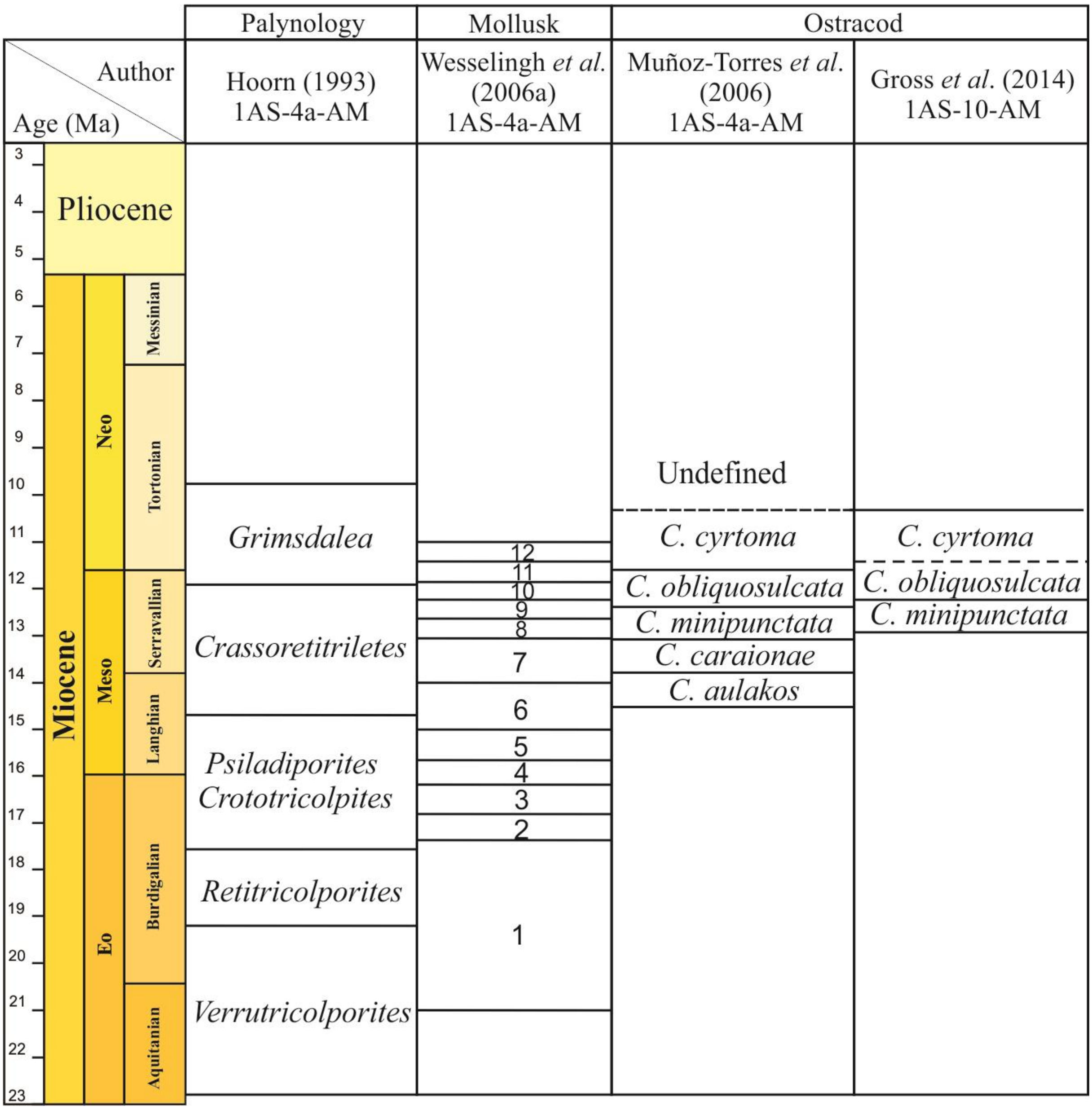


Figure 3 - Biozonation proposals for the borehole 1AS-4a-AM, including palynology, mollusk and ostracod zones, and correlation with the borehole 1AS-10-AM.

Linhares (2011) studying the borehole 1AS-31-AM (at Atalaia do Norte Municipality) and following the proposal of Muñoz-Torres *et al*. (2006) carried out a biostratigraphic analysis, identifying three biozones: *C. aulakos*, *C. caraionae* and *C. cyrtoma*, dating the interval as late Early Miocene to Late Miocene. More recently, Gross *et al*. (2014) studying samples of the core 1AS-10-AM (at Atalaia do Norte Municipality) and based in the distribution of the index species of *Cyprideis* (Muñoz-Torres *et al*., 2006), identified also three biozones: *C. minipuncta*, *C. obliquosulcata* and *C. cyrtoma*, dating the studied interval as Middle Miocene to Late Miocene.

Besides ostracods and palynological zonations, mollusks zones were proposed by Wesselingh *et al*. (2006b). The authors used the borehole 1AS4a-AM, the same studied by Hoorn (1993), determining 12 biozones, dated from Early Miocene to Late Miocene: MZ1- *Aylacostoma ava* amplitude zone; MZ2- *Dyris denticulatus* amplitude zone; MZ3- ? undeterminade zone; MZ4- *Toxosoma carinatum* amplitude zone; MZ5- *Diplodon indianensis* amplitude zone; MZ6- *Onobops*? *iquitensis* - *Onobops communis* interval zone; MZ7- *Dyris pebasensis* amplitude zone; MZ8- *Dyris lanceolatus* amplitude zone; MZ9- *Pachydon trigonalis*- *Dyris tricarinatus* taxon-range zone; MZ10: *Dyris mattii*- *Tryonia minuscula* interval zone; MZ11: *Pachydon obliquus*- *Dyris megacarinata* taxon-range zone; MZ12: *Dyris bicarinatus sofianensis* amplitude zone (Fig. 3).

### ***Palinologycal zones in this study***

The palynological zones herein identified were based mainly in the palynological zonation proposed for the South American tropics by Lorente (1986) and the proposal to the Solimões Formation of the Hoorn (1993). In the present work we observed the distribution and abundance of the index taxa in the boreholes (Figs. 4 and 5) used in the zonations, allowing the recognition of five biozones (Fig. 8): *Verrutricolporites*, Early Miocene (1AS-8-AM), *Psiladiporites–Crototricolpites*, late Early Miocene to Middle Miocene (1AS-7D-AM); *Crassoretitriletes*, Middle Miocene (1AS-7D-AM); *Grimsdalea*, late Middle Miocene to Late Miocene (both boreholes) and *Asteraceae* (1AS-7D-AM).

## Zones of the 1AS-8-AM

### *Verrutricolporites* Acme zone *sensu* Lorente (1986) (368–323.40 mm)

The V*errutricolporites* zone is defined by the presence of the *Verrutricolporites rotundiporus* and the absence of *Psiladiporites minimus*. The upper limit is marked by the reduction of *V. rotundiporus*. In the present study the lower limit is characterized by the occurrence *Mauritiidites franciscoi*, *Psilamonocolpites amazonicus*, *P. nanus*, *Zonocostites ramonae* and *Deltoidospora adriennis*. Throughout the zone, there is the reduction of these species and an increase of *Heterocolpites incomptus*, *H. rotundus*, *Retricolporites guianensis*, *Magnastriatites grandiosus*, *Psilatricolporites varius*, *P. operculatus*, *Echiperiporites akanthos*, *Verrucatosporites usmensis* and *Psilamonoletes tibui*. At 323.40 m there is the occurrence of marine palynomorphs represented by microforaminifera.

### *Crassoretitriletes* interval zone *sensu* Lorente (1986) (246.76–141 m)

The lower limit is determined by the first appearance of *Crassoretitriletes vanraadshoovenii*, and the upper limit is placed by the first appearance of *Grimsdalea magnaclavata*. In this zone we also have the first occurrence of *Bombacacidites baculatus*, *Ilexpollenites* sp. and *Perisyncolporites pokornyi*. Between 220 m and 199.0 m depth occur *Mauritiidites franciscoi*, *Ilexpollenites* sp., *Psilastephanocolporites scheneideri*, *Psilatricolporites crassoexinatus*, *psilatricolporites operculatus*, *psilatricolporites varius*, *Retimonocolpites maximus*, *Retitricolporites irregulares* and *bombacacidites baculatus*. In the 220 m depth there is a decrease the curve of *Crassoretitriletes vanraadshoovenii*, *Bombacacidites baculatus*, *Perisyncolporites pokornyi*, *Rtimonocolpites maximus*, *Monoporites annulatus*; and between 199 m and 141 m occur *Retricolpites simplex*, *Crototricolpites* sp., *Psilatricolporites crassoexinatus* and *Magnastriatites grandiosus*. The interval is marked by moderate values of *Verrucatoporites umensis* and *Psilamonoletes tibui.* At 165.20 m there is the occurrence of marine palynomorphs represented by microforaminifera.

### *Grimsdalea* interval zone *sensu* Lorente (1986) (141–32 m)

The lower limit this biozone is defined by the first appearance of *Grimsdalea magnaclavata*, besides of the abundance of *Psilatricolporites crassoexinatus*, *Magnastriatites* *grandiousus* and *Bombacacidites muinaneorum*. Upper section there is decrease of *Grimsdalea magnaclavata* and the predominance of *Heterocolpites incomptus*, *Monoporites annulatus*, *inaperturopollenites solimoensis* and *Magnastriatites grandiousus.* There is high fluctuation of *Psilamonoletes tibui* and moderate values of *Verrucatosporites usmensis*.

### Zones of the 1AS-7D-AM

#### ***Psiladiporites–Crototricolpites*** **range zone *sensu* Hoorn (1993)** (296–184 m)

The lower limit is defined by the first occurrence of *Crototricolpites annemariae* and *Retitricolporites guianensis.* Besides, occur the species *Psilastephanoporites herngreenii*, *Psilatricolporites magniporatus*, *Echiperiporites* sp. and *Polypodiaceoisporites potoniei.* The upper limit is characterized by the first occurrence of *Crassoretitriletes vanraadshoovenni*. This interval is dominated by abundance of *Mauritiidites franciscoi*, *Psilamonocolpites nanus*, *Zonocostites Ramonae*, *Retricolpites simplex*, *Magnastriatites grandiousus*, *Perisyncolporites pokornyi* and *Verrucatosporites usmensis*. *Psilamonoletes tibui* occurs moderately. At 268 m there is the occurrence of marine palynomorphs represented by microforaminifera.

#### ***Grimsdalea*** **interval zone *sensu* Lorente (1986)** (184–125m)

The zone is defined by the presence of *Grimsdalea magnaclavata* and the absence of elements of the *Asteracea* zone. The lower interval is marked by the abundance of *G. magnaclavata*; this interval is dominated by *Retitricolporites irregulares*, *Magnastriatites grandiousus*, *Mauritiidites franciscoi* and *Heterocolpites incomptus*.

#### ***Asteraceae*** **Zone - Interval zone *sensu* Lorente (1986)** (125–6 m)

The subzone is characterized by the appearance of *Echitricolporites spinosus*. In this interval the subzone *Fenestrites* by Lorente (1986) do not occur. This subzone is characterized by presence of *Podocarpidites* sp., *Fenestrites garciae*, *Malvacipollis spinulosa*, *Polyadopollenites mariae*, *Psilatricolporites maculosus*, *Striatricolpites catatumbus*, and abundance of *Verrucatosporites usmensis*. In the upper section *Grimsdalea magnaclavata* decreases.

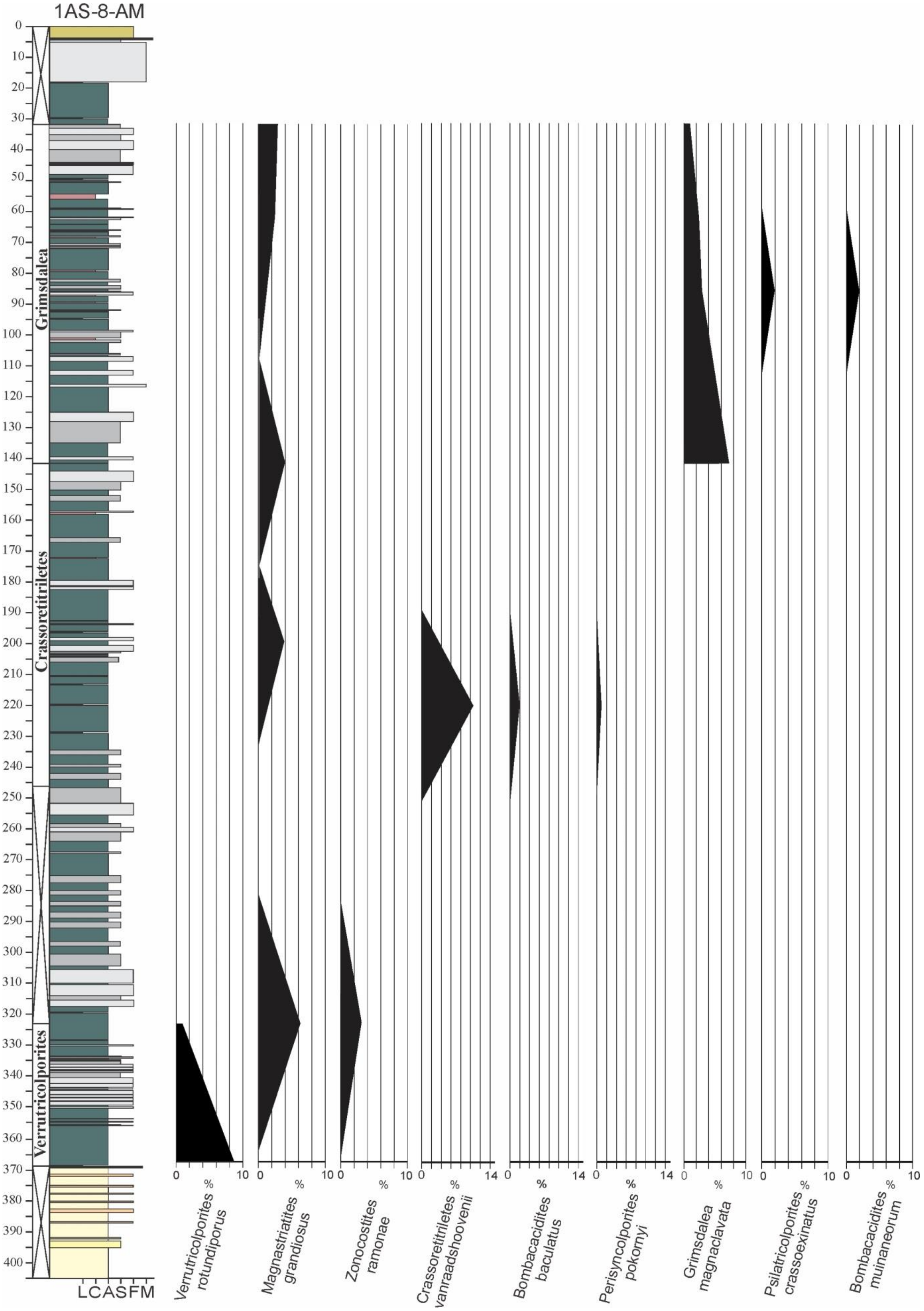


Figure 4 - Distribution and relative abundance of the main index taxa of the palynological zones in the borehole 1AS-8-AM

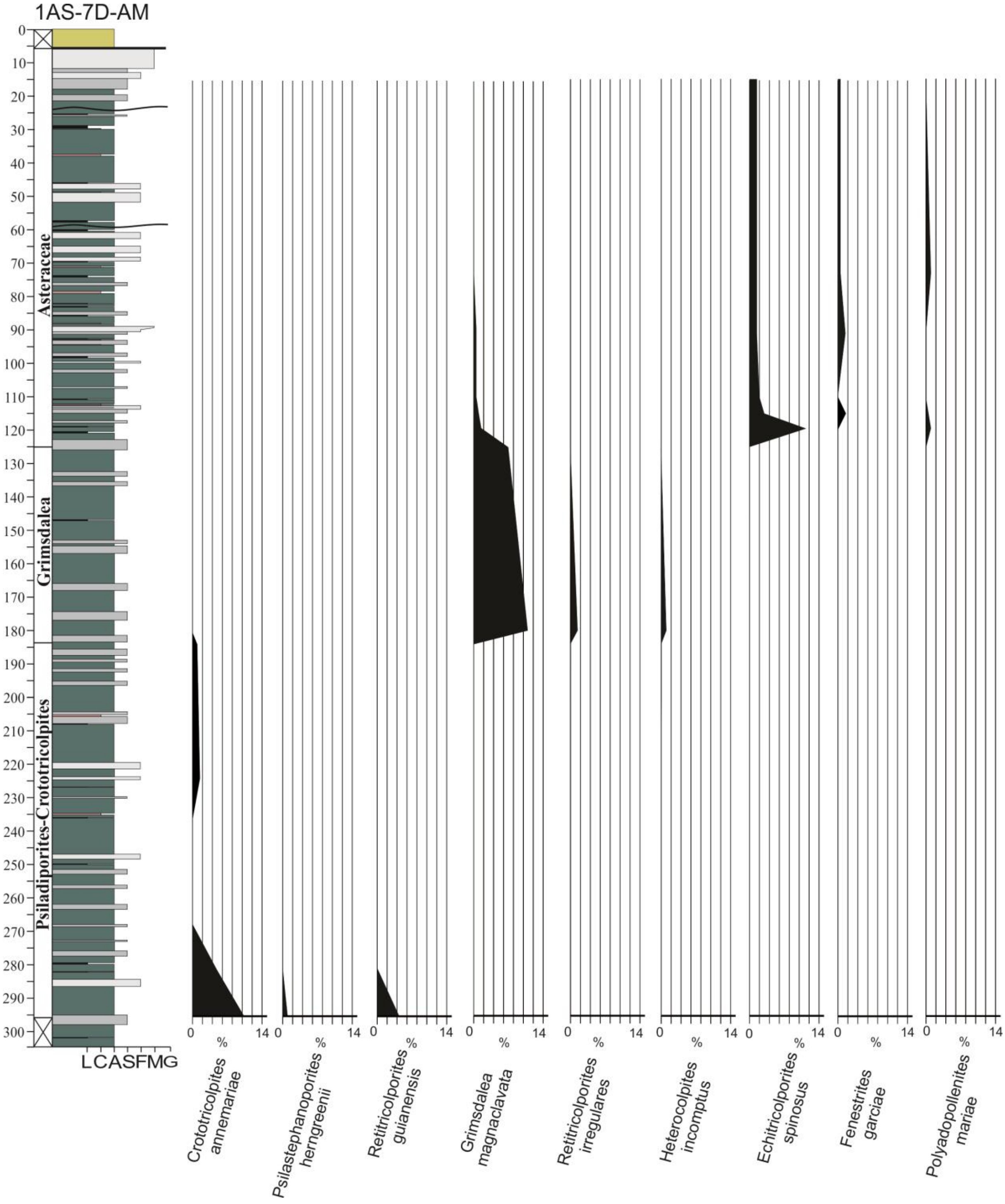


Figure 5 - Distribution and relative abundance of the main index taxa of the palynological zones in the borehole 1AS-7D-AM

### *Ostracods zones in this study*

The proposed biostratigraphy is based on the stratigraphical position of the studied samples and in the distribution of the ostracods that they contain, following the ostracod-based zonation proposal of Muñoz-Torres *et al.* (2006). The zone definition was based on the first appearance (FAD) and last appearance (LAD) of the species.

The distribution of *Cyprideis* species in the 1AS-8-AM (Fig. 6) and 1AS-7D-AM (Fig. 7) allowed recognizing five zones (Tabs. 1 and 2, Fig. 8), which four zones already established by Muñoz-Torres *et al.* (2006), although its limits have been changed here: *C. sulcosigmoidalis= C. aulakos, C. caraionae, C. minipunctata* and *C. cyrtoma* (both boreholes). The guide species of the *C. obliquosulcata* zone do not occur in this work. Besides, we propose a new zone, *Cyprideis paralela* (in the borehole 1AS-7D-AM).

The *C. aulakos* zone is here renamed to *C. sulcosigmoidalis* zone, due the first species was unvalidated and placed in synonymy of *Cyprideis sulcosigmoidalis* by Gross *et al.* (2014). The great variation in the ornamentation pattern of *C. sulcosigmoidalis*, including the occurrence of a slightly punctuated to smooth pattern in the samples studied by Muñoz-Torres *et al.* (1998), caused the mistake on identification of the new species *C. aulakos* as also attested in Linhares & Ramos (submitted).

Another question is the misconception in the correlation of this ostracod zone in relation to the palynologycal zone and the position of the *Crassoretitriletes* zone also by Muñoz-Torres *et al.* (2006), which place this zone belonging to the end of the Burdigalian and part of Serravallian referencing Hoorn (1994c); this mistake induced the misconception about the age of the ostracod zone *C. aulakos* by some authors (Wesselingh & Ramos, 2010; Linhares *et al.*, 2011; Gross *et al.*, 2014). Thus, we elucidate here that *C. sulcosigmoidalis* zone comprises to the palynological zone *Pisiladiporites–Crototricolpites* and extending to the base of *Crassoretritiletes* zone (*sensu* Hoorn, 1993), ranging from late Early Miocene to late Middle Miocene.

The zone *C. caraionae* has herein extended its amplitude (both lower and upper limits) then previously proposed. Muñoz-Torres *et al.* (2006) indicated that this zone is restricted to Middle Miocene and exclusively correspondent to *Crassoretitriletes* zone, but in present study it reaches the age interval between the early Middle Miocene and early Late Miocene, equivalent to part of the *Pisiladiporites–Crototricolpites* and *Crassoretitriletes* zones.

Besides, they indicated that *C. minipunctata* biozone is equivalent to *Crassoretitriletes* by Hoorn (1994c), dated from the late Early Miocene to early Middle Miocene, but we identified here that this is equivalent to *Grimsdalea* (Tab. 1), dated from late Middle Miocene to early Late Miocene, extending the upper limit of this biozone.

Related to *C. cyrtoma* zone we have extended it to earlier age then proposed before, to part of the *Grimsdalea* and *Asteraceae* zones (Tab. 2). Muñoz-Torres *et al*. (2006) limited this zone only to the palynological zone corresponding *Grimsdalea*. Furthermore, the authors mentioned that the occurrence of the *Skopaeocythere tetrakanthos* Whatley *et al*. (2000) is restricted to the *C. obliquosulcata* zone not recorded here. However, we observed that this species has been also found in *C. cyrtoma* zone (1AS-7D-AM at 50 m depth). *S. tetrakanthos* is also associated with foraminifera of the genus *Ammonia*.

The new zone proposed herein *C. paralela*, occurs exclusively in the upper portion of the borehole 1AS-7D-AM and is equivalent to palynologinal zone *Asteraceae*, from Late Miocene. The zone is defined by the last appearance of *C. cyrtoma* (lower limit) and last appearance of *C. paralela* (upper limit) (Tab. 2).

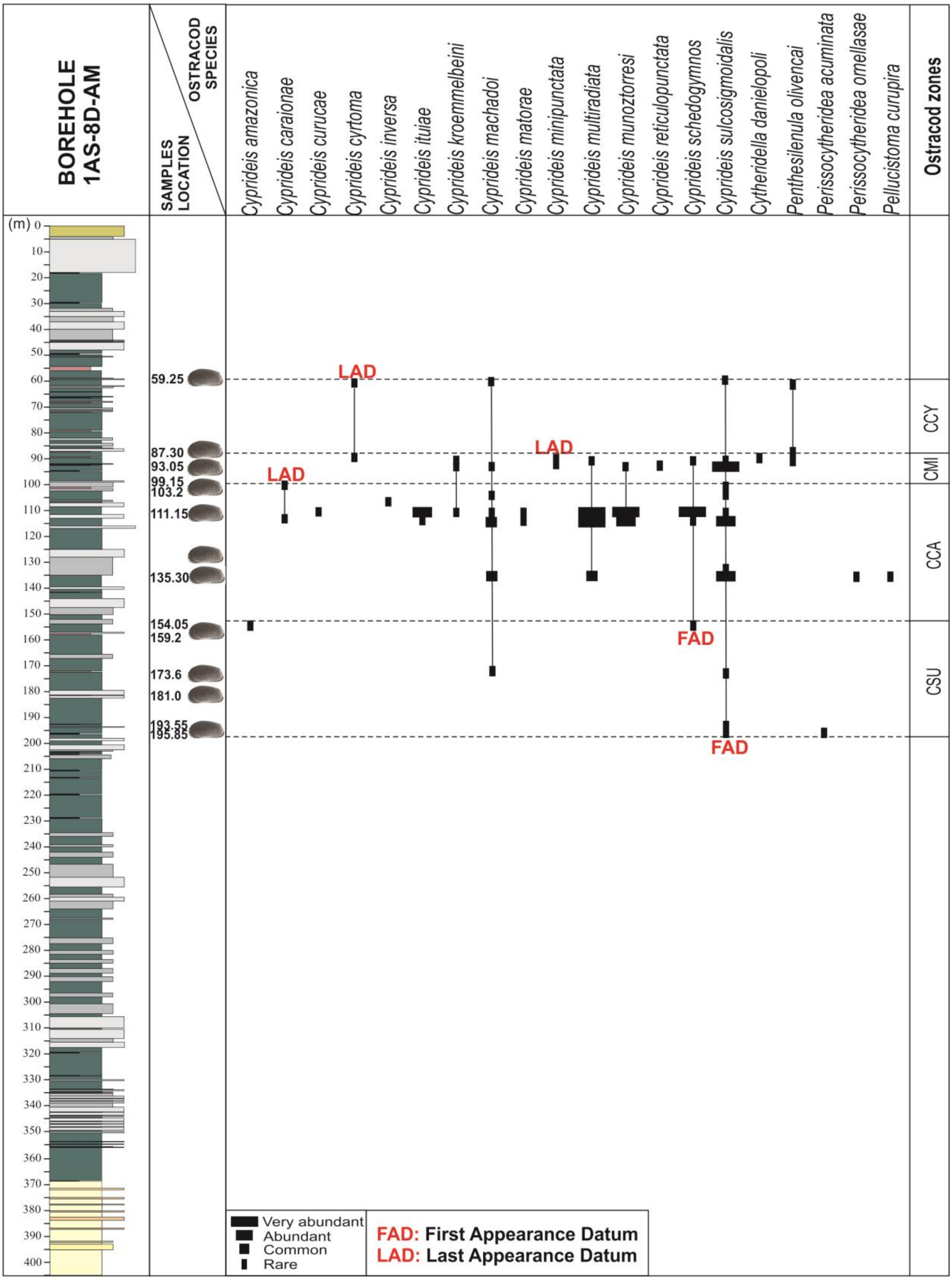


Figure 6 - Stratigraphical distribution of ostracods species in the borehole 1AS-8-AM. and ostracod zones. CSU: *C. sulcosigmoidalis*, CCA: *C. caraionae*, CMI: *C. minipunctata*, CCY: *C. cyrtoma*.

Table 1 - Ostracods biozones found in borehole 1AS-8-AM.

| | |
|---|---|
| *Cyprideis sulcosigmoidalis* interval zone (first appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
| **Interval** | 195.85–154.05 m |
| **Characteristics** | Lower limit marked by first appearance of *Cyprideis aulakos*= *Cyprideis sulcosigmoidalis* (Purper, 1979). Upper limit is defined by the first appearance of *Cyprideis schedogymnos* Muñoz-Torres *et al*. (1998). |
| **Associated species** | *Cyprideis machadoi* (Purper, 1979) and *Perissocytheridea acuminata* (Purper, 1979). |
| **Palynological zone** | *Crassoretitriletes* zone *sensu* Lorente (1986). |
| **Age** | Middle Miocene. |
| *Cyprideis caraionae* interval zone (first and last appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
| **Interval** | 195.85–99.15 m |
| **Characteristics** | Lower limit marked by first appearance of *C. schedogymnos*. Upper limit is defined by the last appearance of *Cyprideis caraionae* Muñoz-Torres *et al*. (1998).<br>In this interval the species *Cyprideis curucae* (Purper, 1979), *Cyprideis inversa* (Purper and Pinto, 1983), *Cyprideis ituiae* Gross *et al*. (2014), *Cyprideis matorae* Gross *et al*. (2014), *Perissocytheridea ornellasae* (Purper, 1979) and *Pellucystoma curupira* Gross *et al*. (2015) have its first and last appearance. |
| **Associated species** | *Cyprideis kotzianae* (Purper and Ornellas, 1991), *C. machadoi*, *Cyprideis multiradiata* (Purper, 1979), *Cyprideis munoztorresi* (Muñoz-Torres *et al*., 1998) and *C. sulcosigmoidalis.* |
| **Palynological zone** | Part of *Crassoretitriletes* and of the *Grimsdalea* zone *sensu* Lorente (1986). |
| **Age** | Middle Miocene to early Late Miocene. |
| *Cyprideis minipunctata* interval zone (last appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
| **Interval** | 99.15–87.3 m |
| **Characteristics** | Lower limit marked by last appearance of *C. caraionae*. Upper limit is defined by the last appearance of *Cyprideis minipunctata* Purper and Ornellas (1991). *Cyprideis reticulopuncta* (Purper, 1979) is rare and has its first and last appearance in this interval. |
| **Associated species** | *C. kotzianae*, *C. machadoi*, *C. multiradiata*, *C. munoztorresi*, *C. schedogymnos*, *C. sulcosigmoidalis*, *Cytheridella danielopoli* Purper (1979) and *Penthesilenula olivencai* (Purper, 1979). |
| **Palynological zone** | *Grimsdalea sensu* zone Lorente (1986). |
| **Age** | early Late Miocene. |
| *Cyprideis cyrtoma* interval zone (last appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
| **Interval** | 87.3–59.25 m |
| **Characteristics** | Lower limit marked by last appearance of *C. minipunctata*. Upper limit is defined by last appearance of *Cyprideis cyrtoma* Muñoz-Torres *et al*. (1998). *Cyprideis reticulopunctata* (Purper, 1979) is rare and has its first and last appearance in this interval. |
| **Associated species** | *C. kotzianae*, *C. machadoi*, *C. multiradiata*, *C. munoztorresi*, *C. schedogymnos*, *C. sulcosigmoidalis*, *Cytheridella danielopoli* Purper (1979) and *Penthesilenula olivencai* (Purper, 1979). |
| **Palynological zone** | *Grimsdalea sensu* Lorente (1986). |
| **Age** | early Late Miocene. |

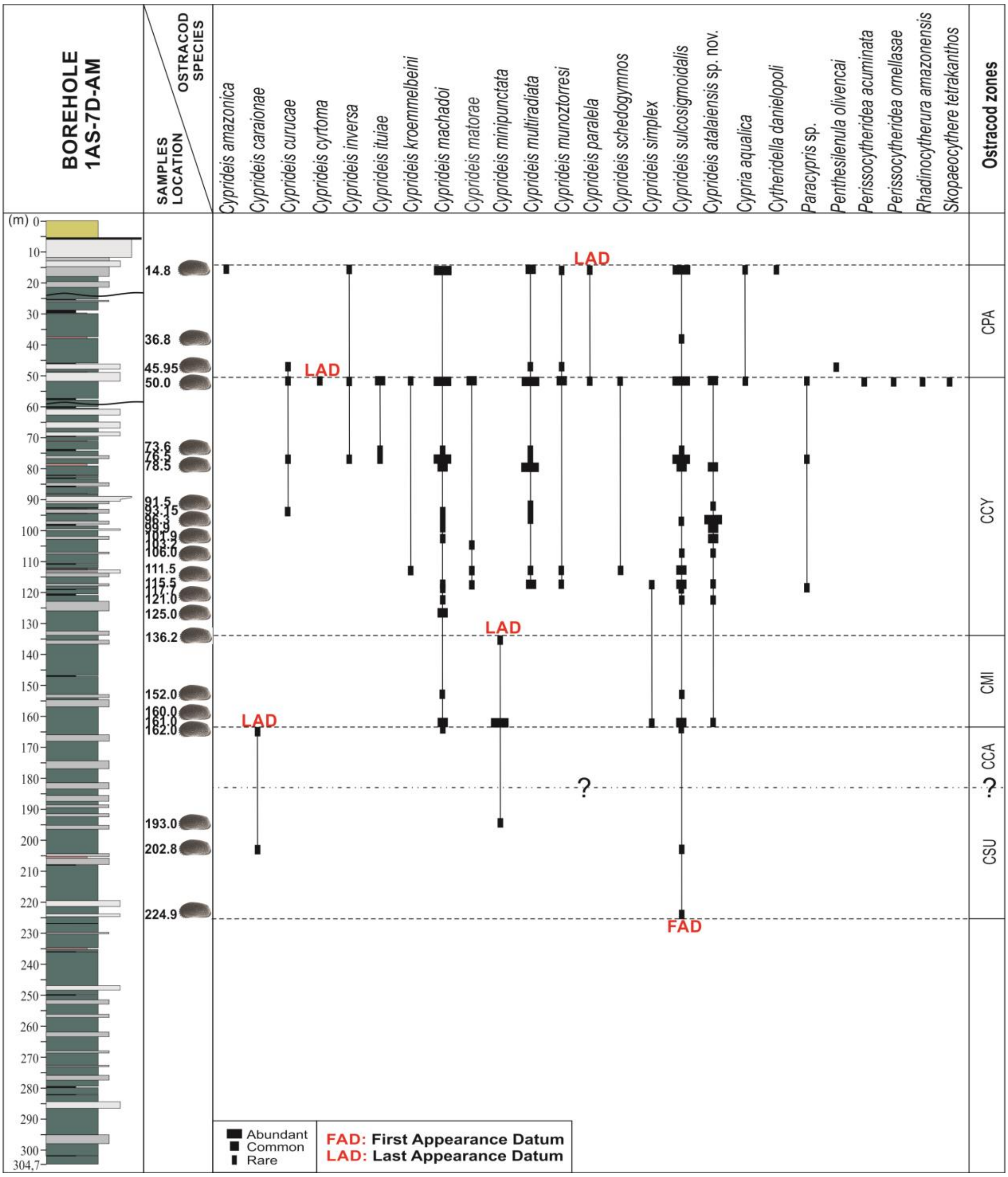


Figure 7 - Stratigraphical distribution of ostracods species in the borehole 1AS-7D-AM and ostracod zones. CSU: *C. sulcosigmoidalis*, CCA: *C. caraionae*, CMI: *C. minipunctata*, CCY: *C. cyrtoma*, CPA: *C. paralela*.

Table 2 - Ostracods biozones found in borehole 1AS-7D-AM.

| *Cyprideis sulcosigmoidalis* interval zone (first appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
|---|---|
| **Interval** | 224.9~184 m |
| **Characteristics** | Lower limit marked by first appearance of *C. sulcosigmoidalis*. The upper limit is not defined, due the absence of *C. schedogymnos* in this interval. |
| **Associated species** | *C. caraionae*, *C. machadoi* and *C. minipunctata*. |
| **Palynological zone** | *Psiladiporites–Crototricolpites sensu* Hoorn (1993). |
| **Age** | late Early Miocene to early Middle Miocene. |

| *Cyprideis caraionae* interval zone (first and last appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
|---|---|
| **Interval** | ~184–162 m |
| **Characteristics** | Upper limit is defined by last appearance of *C. caraionae*. The lower limit is not defined, due the absence of *C. schedogymnos* in this interval. |
| **Associated species** | *C. machadoi* and *C. sulcosigmoidalis*. |
| **Palynological zone** | Part of the *Grimsdalea sensu* Lorente (1986). |
| **Age** | late Middle Miocene to early Late Miocene. |

| *Cyprideis minipunctata* interval zone (last appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
|---|---|
| **Interval** | 162.00–136.20 m |
| **Characteristics** | Lower limit marked by last appearance of *C. caraionae*. Upper limit is defined by last appearance of *C. minipunctata*. |
| **Associated species** | *C. atalaiensis* sp. nov. Linhares & Ramos, *C. machadoi*, *C. minipunctata*, *C. schedogymnos*, *Cyprideis simplex* (Shepard and Bate, 1980) and *C. sulcosigmoidalis*. |
| **Palynological zone** | *Grimsdalea sensu* Lorente (1986). |
| **Age** | early Late Miocene. |

| *Cyprideis cyrtoma* interval zone (last appearance zone) *sensu* Muñoz-Torres *et al*. (2006) | |
|---|---|
| **Interval** | 136.20–50m |
| **Characteristics** | Lower limit marked by last appearance of *C. minipunctata*. Upper limit is defined by last appearance of *C. cyrtoma*. |
| **Associated species** | *Cyprideis atalaiensis* sp. nov., *C. curucae*, *C. inversa*,*C. ituiae*, *C. kotzianae*, *C. machadoi*, *C. matorae*, *C. multiradiata*, *C. munoztorresi*, *C. schedogymnos*, *C. sulcosigmoidalis*, *C. simplex*, *Cypria aqualica* Shepard and Bate (1980), *Paracypris* sp., *Perissocytheridea acuminata*, *Perissocytheridea ornellasae* (Purper 1979), *Rhadinocytherura amazonensis* Shepard & Bate (1980) and *Skopaeocythere tetrakanthos* Whatley *et al.* (2000). |
| **Palynological zone** | Part of the *Grimsdalea* and of the *Asteraceae sensu* Lorente (1986). |
| **Age** | early Late Miocene. |

| *Cyprideis paralela* interval zone (last appearance zone) This Study | |
|---|---|
| **Interval** | 50–14.8 m |
| **Characteristics** | Lower limit marked by the last appearance of *C. cyrtoma*. Upper limit is defined by the last appearance of *Cyprideis paralela* (Purper 1979). |
| **Associated species** | *C. amazonica*, *C. inversa*, *C. machadoi*, *C. multiradiata*, *C. munoztorresi*, *C. sulcosigmoidalis*, *C. aqualica* and *Cytheridella danieolopoli* Purper (1979). |
| **Palynological zone** | *Asteraceae sensu* Lorente (1986). |
| **Age** | Late Miocene. |

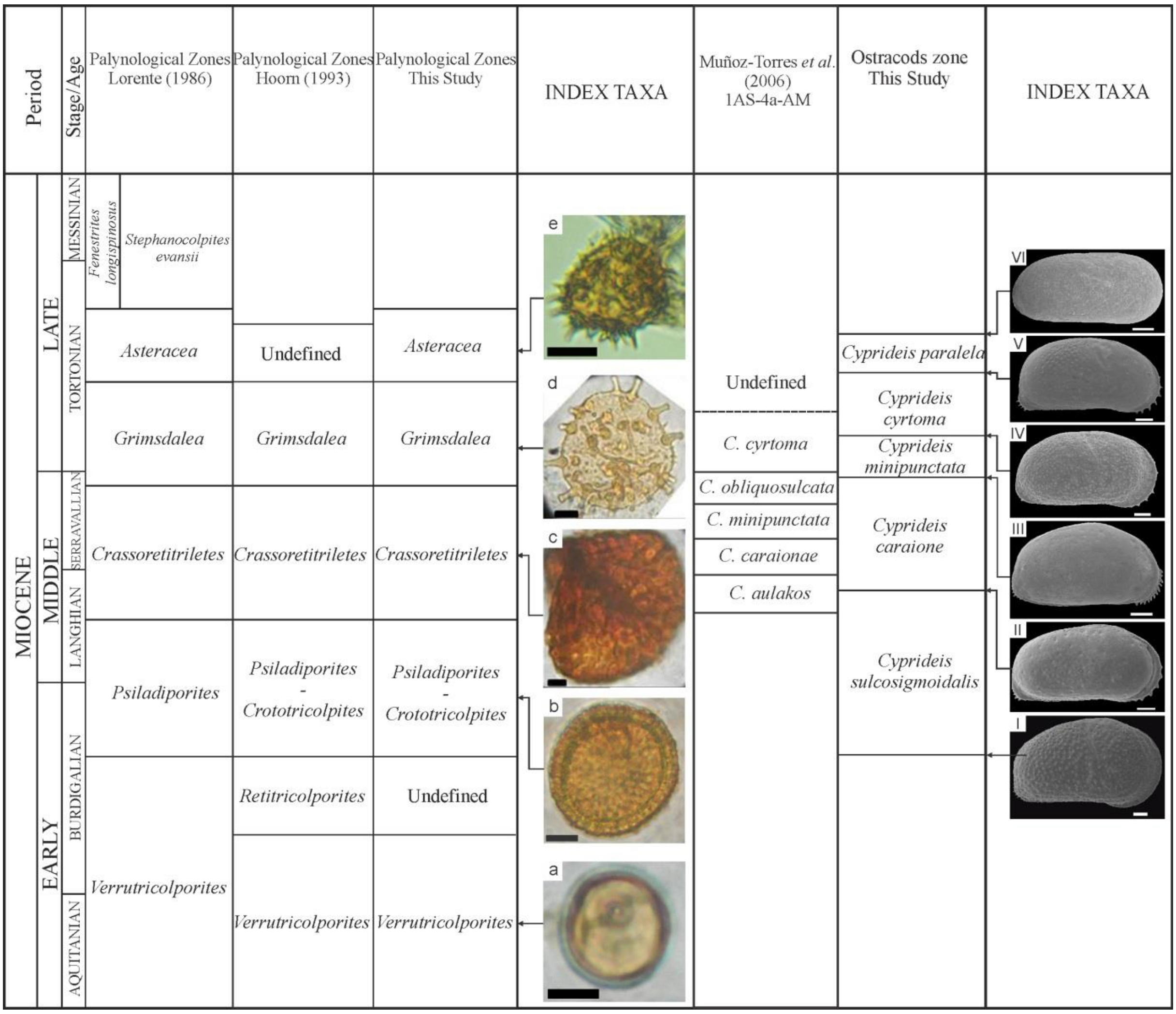


Figure 8 - Correlation of the palynological and ostracod biozonation proposed in this study whith the palynological zones of Lorente (1986), Hoorn (1993) and the ostracod zones proposed by Muñoz-Torres *et al*. (2006).

## DISCUSSIONS

The presented results from two boreholes show that the interval studied reaches the age from Early Miocene do Late Miocene in the Atalaia do Norte Municipality. In 1AS-8-AM, the strata correspondent to Solimões Formation is dated to Early Miocene extending to early Late Miocene, while the 1AS-7D-AM cover the late Early Miocene to Late Miocene. This sequence is very similar to the range proposed by Hoorn (1993) and Muñoz-Torres *et al*. (2006) in the borehole 1AS-4a-AM, mainly in the more basal portion of 1AS-8-AM (*Verrutricolporites* zone), although the borehole 1AS-4a-AM do not reach the *Asteraceae* palynological zone and *Cyprideis paralela* ostracod zone found in the upper part of 1AS-7D-AM. Therefore, the study area covers a wider extension of the Solimões Formation.

Silva-Caminha *et al*. (2010) and Kachniasz & Silva-Caminha (2016) report the presence of the *Psilatricolporites caribbiensis* zone in the boreholes 1AS-19-AM, 1AS-27-AM, 1AS-31-AM and 1AS-34-AM. The last authors still indicate the zone *Echitricolporites–Alnipollenites* for 1AS-31-AM. Silveira & Souza (2015) also evidence the presence of this zone in outcrop samples from localities of the counties Coari, Tabatinga and Atalaia do Norte (Amazonas State, Brazil), dating the Solimões Formation as late Late Miocene to Pliocene.

Leite *et al*. (2016) registered for 1AS-33-AM the oldest interval than the authors cited above, dated between Middle Miocene and the Pliocene, which includes the zones *Crassoretitriletes*, *Asteraceae*, *Plilatricolporites caribbiensis* and *Echitricolporites–Alnipollenites*. This borehole is partly equivalent to the 1AS-7D-AM, mainly in the basal and median portion.

As mentioned by Leite *et al*. (2016), we considered the irregularity of the basement and topography the cause for the different limits (base and top) or diferences in the total range atributed to the Solimões Formation. This is could be related to the paleogeography of the basement, probably affected by the peripheral effects of the Andean orogeny (DeCelles, 2012), given the different thickness of Solimões Formation, sometimes covering the cretaceous deposits and sometimes expanding the previous basin's limits, covering the basement (Maia *et al*., 1977).

## CONCLUSIONS

The integrated study using ostracods and palynology allowed to date the sequence of the Solimões Formation, in the Atalaia do Norte Municipality, as from Early Miocene to Late Miocene. This data are supported by the occurrence of five palynological zones: *Verrutricolporites*, *Psiladiporites–Crototricolpites*, *Crassoretitriletes*, *Grimsdalea*, and *Asteraceae*. Were also recognize five ostracod zones, which four already previously, although the limits have been changed here: *Cyprideis aulakos*= renamed for *C. sulcosigmoidalis*, *C. caraionae*, *C. minipunctata* and *C. cyrtoma*). Besides, we proposed one new ostracod zone, *C. paralela*.

## ACKNOWLEDGMENTS

The authors thank the Brazilian Departamento Nacional de Produção Mineral (DNPM) and the Serviço Geológico do Brasil (CPRM-AM), for permission to access and use the core samples (SUREG-AM) and provided facilities for SEM photography (CPRM-PA). The Museu Paraense Emilio Goeldi (MPEG) supported this study and provided facilities for SEM photography. The Federal University of Pará (UFPA) supported this research through the Programa de Pós-Graduação em Geologia e Geoquímica (PPGG).

## REFERENCES

Antoine, P., Abello, M.A., Adnet, S., Altamirano Sierra, A.J., Baby, P., Billet, G., Boivin, M., Calderon, Y., Candela, A., Chabain, J., Corfu, F., Croft, D.A., GanerØd, M., Jaramillo, C., Klaus, S., Marivaux, L., Navarrete, R.E., Orliac, M.J., Parra, F., Perez, M.E., Pujos, F., Rage, J., Ravel, A., Robinet, C., Roddaz, M., Tejada-Lara, J.V., Velez-Juarbe, J., Wesselingh, F.P., Salas-Gismondi, R. 2016. A 60-million-year Cenozoic history of western Amazonian ecosystems in Contamana, eastern Peru. *Gondwana Research*, **31**: 30–59.

Beiranvand, B., Zaghbib-Turki, D., Ghasemi-Nejad, E. 2014. Integrated biostratigraphy based on planktonic foraminifera and dinoflagellates across the Cretaceous/Paleogene (K/Pg) transition at the Izeh section (SW Iran). *Comptes Rendus Palevol*, **13**: 235–258.

Bold van den, W.A. 1988. Neogene Paleontology in the northern Dominican Republic 7. The Subclass Ostracoda (Arthropoda:Crustacea). *Bull. Am. Paleontol*, **94**: 1–105.

Boonstra, M., Troelstra, S.R., Lammertsma, E.I., Ramos, M.I.F., Antoine, P.-O., Hoorn, C. 2015. Marine connections of Amazonia: evidence from foraminifera and dinoflagellate cysts (early to middle Miocene, Colombia/Peru). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **417**: 176–194.

Brown, C.B. 1879. On the Tertiary deposits on the Solimões and Javary rivers, in Brazil. *Quaterly Journal of the Geological Society of London*, London, **35**: 76–81.

Conrad, T.A. 1871. Descriptions of new fossil shells of the Upper Amazon. American Journal of the Upper Amazon. *American Journal of Conchology*, **6**(3): 192–8.

DeCelles, P.G. 2011. Foreland basin systems revisited: Variations in response to tectonic settings. *In*: Tectonics of Sedimentary Basins. Recent Advances. Wiley–Blackwell, Oxford, p. 405–426.

Eiras, J.F., Becker, C.R., Souza, E.M., Gonzaga, F.G., Silva, G.F., Daniel, M.L.F., Matsuda, N.S, Feijó, F.J. 1994. Bacia do Solimões. *Boletim Geociências Petrobrás*, Rio de Janeiro, **8**(1): 17–49.

Etheridge, R. 1879. Notes on the Mollusca colected by C. Barrington Brown from the Tertiary deposits of Solimões and Javary Rivers, Brazil. *Quaterly Journal of the Geological Society of London,* **35**: 82–88.

Gross, M., Ramos, M.I., Piller, W.E. 2014. On the Miocene Cyprideis species flock (Ostracoda; Crustacea) of Western Amazonia (Solimões Formation): Refining taxonomy on species level. *Zootaxa*, **3899**(1): 1–69.

Hoorn, C. 1993. Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **105**: 267–309.

Hoorn, C. 1994a. Fluvial palaeoenvironments in the intracratonic Amazonas Basin (Early Miocene-early Middle Miocene, Colombia). *Palaeogeography, Palaeoclimatology, Palaeoecology,* **109**: 1–54.

Hoorn, C. 1994b. An environmental reconstruction of the palaeo-Amazon River system (Middle-Late Miocene, NW Amazonia). *Palaeogeography, Palaeoclimatology, Palaeoecology,* **112**: 187–238.

Hoorn, C. 1994c. Miocene palynostratigraphy and paleoenvironments of Northwestern Amazonia: evidence for marine incursions and the influences of the Andean. PhD thesis, University of Amsterdam, 156 p.

Hoorn, C., Wesselingh, F.P., Hovikoski, J., Guerrero, J. 2010a. The development of the Amazonian mega-wetland (Miocene; Brazil, Colombia, Peru, Bolivia). *In*: Hoorn, C., Wesselingh, F.P. (Eds). Amazonia: Lanscape and species evolution, a look into the past. Wiley-Blackwell, p. 123–142.

Hoorn, C., Wesselingh, F.P., ter Steege, H., Bermudez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramilho, C., Riff, D., Negri, F.R. Hooghiemstra, H., Stadler, T., Särkinen, T., Antonelli, A. 2010b.

Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science*, **330**: 927–931.

Jaramillo, C., Rueda, M., Torres, V. 2011. A palynological zonation for the Cenozoic of the Llanos and Llanos Foothills of Colombia. *Palynology*, **35**: 46–84.

Jaramillo, C., Romero, I., D'Apolito, C., Bayona, G., Duarte, E., Louwye, S., Escobar, J., Luque, J., Carrillo-Briceño, J.D., Zapata, V., Mora, A., Schouten, S., Zavada, Z., Harrington, G., Ortiz, J., Wesselingh, F.P. 2017. Miocene flooding events of western Amazonia. *Science Advances*, **3**(5): 1–11.

Kachniasz, K.E., Silva-Caminha, S.A.F. 2016. Palinoestratigrafia da Formação Solimões: comparação entre bioestratigrafia tradicional e o método de associações unitárias. *Revista Brasileira de Paleontologia*, **19**(3): 481–490.

Lehrmann, D.J., Stepchinski, L., Altiner, D., Orchard, M.J. Montgomery, P., Enos, P., Ellwood, B.B., Bowring, S.A., Ramezani, J., Wang, H., Wei, J., Yu, M., Griffiths, J.D., Minzoni, M., Schaal, E.K., Li. X, Meyer, K.M., Payne, J.L. 2015. An integrated biostratigraphy (conodonts and foraminifers) and chronostratigraphy (paleomagnetic reversals, magnetic susceptibility, elemental chemistry, carbon isotopes and geochronology) for the Permian–Upper Triassic strata of Guandao section, Nanpanjiang Basin, south China. *Journal of Asian Earth Sciences*, **108**: 117–135.

Leite, F.P.R., Paz, J.D., Carmo, D.A., Silva-Caminha, S.A.F. 2016. The effects of the inception of Amazonian transcontinental drainage during the Neogene on the landscape and vegetation of the Solimões Basin, Brazil. *Palynology*, 1–11.

Linhares A.P., Ramos M.I., Gross M., Piller W.E. 2011. Evidence for marine influx during the Miocene in southwestern Amazonia, Brazil. *Geología Colombiana*, **36**(1): 91–104.

Linhares, A.P., Gaia, V.C.S., Ramos, M.I.F. 2017. The significance of marine microfossils for paleoenvironmental reconstruction of the Solimões Formation (Miocene), Western Amazonia, Brazil. *Journal of South American Earth Sciences*, **79**: 57–66.

Linhares, A.P. and Ramos, M.I.F. New contributions to the ostracods taxonomy of the Solimões Formation (Atalaia do Norte, Amazonas State, Brazil), with the description of two new species. Submitted.

Lorente, M.A. 1986. Palynology and palynofacies of the Upper Tertiary in Venezuela. *Dissertationes Botanicae*, 222 p.

Maia, R.G.N., Godoy, H.O., Yamaguti, H.S., Moura, P.A., Costa, F.S.F., Holanda, M.A., Costa, J.A. 1977. Projeto Carvão no Alto Solimões; *Relatório Final*. Manaus: CPRM; DNPM, **1**: 142 p.

Muller, J., Di Giacomo, E., Van Erve, A.W. 1987. A palynological zonation for the Cretaceous, Tertiary, and Quaternary of northern South America. *AASP Contribution Series*, **19**:7–76.

Muñoz-Torres, F., Whatley, R., Van Harten, D. 2006. Miocene ostracod (Crustacea) bioestratigraphy of the upper Amazon Basin and evolution of the genus Cyprideis. *Journal of South American Earth Sciences*, **21**: 75–86.

Purper, I. 1979. Cenozoic Ostracods of the Upper Amazon Basin, Brazil. *Pesquisas*, **12**: 209-281.

Roxo, M.G.O. 1937. Fósseis Pliocênicos do Rio Juruá, Estado do Amazonas, Brasil. *Notas preliminares e Estudos do Serviço Geológico e Mineralógico do Brasil*. Rio de Janeiro.

Silva-Caminha, S.A.F., Jaramillo, C.A., Absy, M.L. 2010. Neogene palynology of the Solimões Basin, Brazilian Amazonia. *Palaeontographica B*, **284**: 13–79.

Silveira, R.R., Souza, P.A. 2015. Palinologia (grãos de pólen de angiospermas) das Formações Solimões e Içá (Bacia do Solimões), nas regiões de Coari e Alto Solimões, Amazonas. *Revista Brasileira de Paleontologia*, **18**(3): 455–474.

Simpson, G.G. 1961. The supposed Pliocene Pebas Beds of the Upper Juruá River, Brazil. *Journal of Palaeontology*, **35**(3): 620–624.

Tantawy, A.A., Keller, G., Adatte, T., Stinnesbeck, W., Kassab, A., Schulte, P. 2001. Maastrichtian to Paleocene (Dakhla Formation) depositional environment of the Western Desert in Egypt: sedimentology, mineralogy and integrated micro-and macrofossil biostratigraphies. *Cretaceous Research*, **22**: 795–827.

Uesugui, N. 1979. Palinologia: técnicas de tratamento de amostras. *Boletim Técnico da Petrobrás*, **22**(4): 229–240.

Wanderley Filho, J.R.W., Eiras, J.F., Vaz, P.T. 2007. Bacia do Solimões. *Boletim de Geociências. Petrobras*, Rio de Janeiro, **15**(2): 217–225.

Wanderley Filho, J.R., Eiras, J.F., Cunha, P.R.C., van der Ven, P.H. 2010. The Paleozoic Solimões and Amazonas basins and the Acre foreland basin of Brazil. *In*: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, p. 29–37.

Wanderley, M.D. 2010. Técnicas de preparação de microfósseis. *In*: Carvalho, I.S. (Ed.), Paleontologia: microfósseis, paleoinvertebrados. *Interciência*, Rio de Janeiro, p. 65–80.

Wesselingh, F.P., Hoorn, M.C., Guerrero, J., Räsänen, M.E., Romero Pittmann, L., Salo, J. 2006. Stratigraphy of Miocene Amazonian deposits. *Scripta Geologica*, **133**: 291–322.

Wesselingh, F.P. and Ramos, M.I.F. 2010. Amazonian aquatic invertebrate faunas (Mollusca, Ostracoda) and their development over the past 30 million years. *In*: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, p. 302–316.

Woodward, H. 1871. The Tertiary shells of the Amazon Valley- *Annals and Magazine of Natural History*, New York, **4**(7): 59–64.

# CAPÍTULO 4

## 4 THE SIGNIFICANCE OF MARINE MICROFOSSILS FOR PALEOENVIRONMENTAL RECONSTRUCTION OF THE SOLIMÕES FORMATION (MIOCENE), WESTERN AMAZONIA, BRAZIL*

Ana Paula Linhares[1, 2], Valber do Carmo de Souza Gaia[3], Maria Inês Feijó Ramos[1]

*[1]Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia. Av. Presidente Tancredo Neves 1901, Belém, PA, Brazil (alinhares@museu-goeldi.br; mramos@museu-goeldi.br)*

*[2]Programa de Pós-Graduação em Geologia e Geoquímica, Instituto de Geociências, Universidade Federal do Pará, Rua Augusto Corrêa s/n, Belém-PA, Brazil, (alinhares@museu-goeldi.br)*

*[3]Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia. Av. Presidente Tancredo Neves 1910, Belém, PA, Brazil (valbergaia@museu-goeldi.br)*

** Publicated in Journal of South American Earth Sciences*

Journal of South American Earth Sciences 79 (2017) 57–66

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

# The significance of marine microfossils for paleoenvironmental reconstruction of the Solimões Formation (Miocene), western Amazonia, Brazil

Ana Paula Linhares [a, b, *], Valber do Carmo de Souza Gaia [c], Maria Inês Feijó Ramos [a, b]

[a] Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia, Av. Presidente Tancredo Neves 1901, Belém, PA, Brazil
[b] Programa de Pós-Graduação Em Geologia e Geoquímica, Instituto de Geociências, Universidade Federal Do Pará, Rua Augusto Corrêa s/n, Belém, PA, Brazil
[c] Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia, Av. Presidente Tancredo Neves 1910, Belém, PA, Brazil

ARTICLE INFO

*Article history:*
Received 16 May 2017
Received in revised form
13 July 2017
Accepted 18 July 2017
Available online 20 July 2017

*Keywords:*
Solimões Formation
Western Amazonia
Marine incursion
Microfossils

ABSTRACT

Micropalaeontological studies of borehole cores 1AS-7D-AM and 1AS-8-AM, from Atalaia do Norte, Amazonas state, Brazil, support previous evidence for Miocene marine ingressions in Western Amazonia. Three marine incursion events are recorded: the first in the Early/early Middle Miocene (in both cores), the second in the late Middle/early Late Miocene (1AS-8-AM), and the third in the Late Miocene (1AS-7D-AM). The first event is characterized by exclusively mangrove taxa, and the last two present a mixture of marine, fresh, and brackish water taxa. However, at the end of the third event an increase of fluvial influence is demonstrated by the predominance of freshwater taxa. These marine incursions reached the study area through narrow and geographically limited connections, controlled by the tectonic setting, at a time between the Early/early Middle Miocene and late Middle/Late Miocene. Thereafter, fluvial conditions were reestablished before Pliocene times.

## 1. Introduction

Several works have indicated marine incursions in the Neogene of western Amazonia, including in the Solimões Formation, Amazonas, Brazil. These occurrences are predominantly associated with floodplain deposits, connected to coastal environments and mangrove areas, as evidenced by microfossil studies (Hoorn, 1993; Linhares et al., 2011; Boonstra et al., 2015; Kachniasz and Silva-Caminha, 2016; Jaramillo et al., 2017).

The episodic marine ingressions from the western Amazon were possibly marked by rapid progradation, with thin interbedding of marginal marine and continental strata (Hovikoski et al., 2007; Rebata, 2012). These connections played an important role in the adaptation of the marine biota to freshwater environments, as well as in the speciation and radiation of many groups such as commonly observed in fishes, mollusks, and ostracods (Monsch, 1998; Lundberg et al., 1998; Whatley et al., 1998; Malabarba and Dutra, 2002; Wesselingh and Salo, 2006; Wesselingh and Ramos, 2010; Lovejoy et al., 2006; Albert and Reis, 2011; Gross et al., 2015).

Other investigations point to a predominantly fluvial influence during the Neogene, when the uplift of the Andean Cordilleras provided conditions for aquatic habitats in plateaus, while foreland subsidence propitiated the development of certain species in a lacustrine system (Lundberg et al., 1998; Ramos, 2006; Wesselingh, 2006). Other authors dismiss the possibility of marine incursions, even brief ones. They treat the marine incursion hypothesis as a complete misinterpretation, attributing the system to a continental environment dominated by avulsive rivers associated with mega-deltas and floodplain systems, such as marshes, perennial lakes, inner deltas, and *splays*, whose anoxic organic matter-rich deposits, would present low sediment input (Latrubesse et al., 1997; Gross et al., 2011, 2013; Nogueira et al., 2013; Paz et al., 2015).

In this context, although with distinct conclusions, all proposals are important and complementary to the comprehension of the paleoenvironmental evolution of the Amazonian Neogene. Considering these debates, we use here paleontological data from two wells in western Amazonia, Brazil, aiming to contribute to a better understanding of the Neogene paleoenvironmental evolution, as regards the complex issue of marine incursions. The studied boreholes (Fig. 1) are located in northwestern Amazonas state,

---

[*] Corresponding author. Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia, Av. Presidente Tancredo Neves 1901, Belém, PA, Brazil.

*E-mail addresses:* alinhares@museu-goeldi.br (A.P. Linhares), valbergaia@museu-goeldi.br (V.C.S. Gaia), mramos@museu-goeldi.br (M.I.F. Ramos).

http://dx.doi.org/10.1016/j.jsames.2017.07.007
0895-9811/

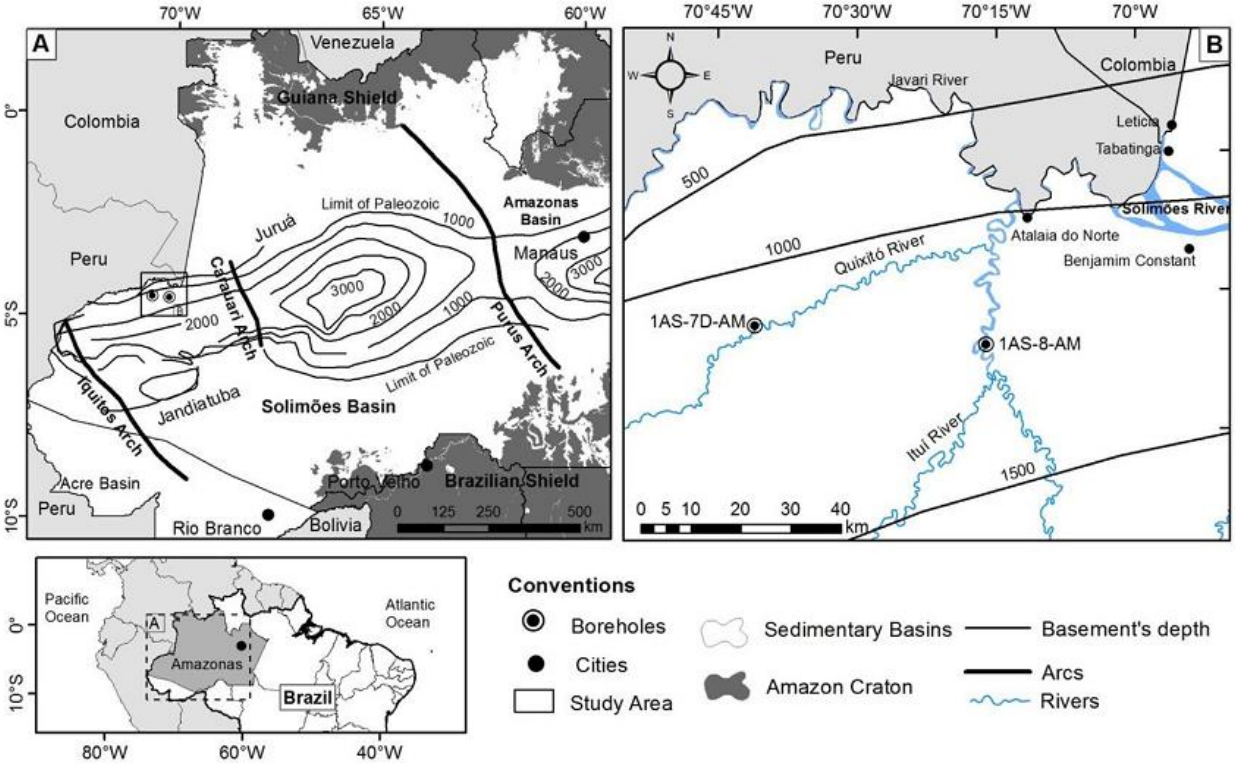


**Fig. 1.** Location and geologic map of the study area. A) Tectonic compartmentalization of the Solimões Basin, subdivided by the Carauari Arch into the Jurua and Jandiatuba sub-basins and limited by the Purus and Iquitos arches. B) Study area, showing boreholes near the Quixito and Itui rivers, north of the Jandiatuba sub-basin. Source: Lisboa et al. (2013).

Brazil, municipality of Atalaia do Norte. Borehole 1AS-7D-AM was drilled close to the Quixito River, and reached 304.7 m depth (04°34′S 70°41′W), and borehole 1AS-8-AM near the Itacuaí River reached 405 m depth (04°36′S 70°16′W).

## 2. Geological settings

The intracratonic Solimões Basin is located in Amazonas state, covering an area of about 450,000 km$^2$. It is limited northwards by the Guiana Shield, southwards by the Brazilian Shield, to the east by the Purus Arch, and to the west by the Iquitos Arch. The Basin is subdivided by the Carauari Arch: to the east into the Jurua sub-basin and to the west into the Jandiatuba sub-basin. The sedimentary fill was initially Paleozoic (Ordovician-Permian), followed by Triassic Penatecaua magmatism (Fig. 1A). The sedimentary input resumes in the Cretaceous with deposition of the Alter do Chão Formation, and during the Miocene with the Solimões Formation (Caputo, 1991; Eiras et al., 1994; Wanderley Filho et al., 2010).

During the Cenozoic, the Solimões Basin showed environmental changes and sedimentary filling, reflecting the influence of the Andean Orogeny, which transformed the entire Amazonian landscape, as well as its fauna and flora (Hoorn et al., 2010a, b). The Andean uplift generated a flexural subsidence in the eastern areas from the Eastern Cordillera, forming foreland basins (backarch system), and consequently generating accommodation space for the deposition of the Solimões Formation in a system of long-lived lakes, channels, and floodplains, in both the Solimões and Acre basins (Hoorn et al., 2010a; Roddaz et al., 2010; Shephard et al., 2010; Bezerra and Ribeiro, 2015).

At a second moment, crustal thickening formed by the extreme uplift of the Eastern Cordillera (~10 Mya) was isostatically compensated by a peripheral elevation, forming the Iquitos forebulge in central Amazonia (Mora et al., 2010; Roddaz et al., 2010), increasing the substrate gradient and fluvial influence, consequently changing the drainage system and sedimentary supply of the Amazon region.

Subsequently, the elevations of the Vaupés Swell Arch during the Late Miocene, and later the Fitzcarrald Arch during the Pliocene (~4.5 Mya) played an important role in the Amazon basin scenario, separating the foreland basins into north and south and limiting possible connections of the Amazon River drainage with the Orinoco River and the Caribbean (Mora et al., 2010; Hoorn et al., 2017), as well as reducing the chances of new marine ingressions (Jaramillo et al., 2017).

## 3. Paleoenvironments and the age of the Solimões Formation

The first sedimentological studies by the Geological Survey of Brazil in the 19th century inferred an exclusively continental origin of the Solimões Formation, characterizing it as mainly lacustrine with fluvial influences including channels, floodplains, sandbars, and other overbank deposits (Caputo et al., 1971; Maia et al., 1977; Radambrasil, 1977). However, since the first paleontological studies, brackish water environments have been inferred due to the presence of a mixture of marine and non-marine groups, which puzzled researchers trying to the comprehend the paleoenvironmental evolution of the basin (Conrad, 1874; Roxo, 1924; Purper, 1977a; b, 1979).

Paleontological and sedimentological studies from outcrops of the Solimões Formation in Amazonas state have indicated that the upper strata of that Formation, dated as Late Miocene, were deposited in a continental environment, dominated by avulsive rivers associated with a delta system and overbank environments (swamps, lakes, inner deltas, and crevasse-splay) (Latrubesse et al., 1997, 2010; Gross et al., 2011, 2013; Paz et al., 2015; Nogueira et al., 2013).

However, despite these studies from outcrops that showed a predominantly continental depositional context, micropalaeontological studies from boreholes, which exhibit a greater chronostratigraphic range, attest to marine influences in the earliest strata (Early and Middle Miocene) of the Solimões Formation, shown by the presence of marine-to-transitional taxa (Hoorn, 1993; Wesselingh et al., 2002; Vonhof et al., 2003; Linhares et al., 2011; Boonstra et al., 2015).

Over the years, marine influences have been questioned or even rejected by many authors. Nevertheless, these have been successively confirmed in more recent studies from boreholes of this area and others of correlated ages in Peru and Colombia (Hoorn, 1993; Linhares et al., 2011; Boonstra et al., 2015; Antoine et al., 2016; Kachniasz and Silva-Caminha, 2016; Jaramillo et al., 2017).

Marine influences in western Amazonia have been differently interpreted according to the literature. Some authors have suggested that this influence was relatively long-lived, with a wide geographic distribution (Räsänen et al., 1995; Gingras et al., 2002). Others infer that the floodplain systems were predominant, with localized episodes of marine incursion in central and western Amazonia, based on microfossil studies (Hoorn, 1993, 1994a; b; Linhares et al., 2011; Antoine et al., 2016). The hypothesis of marine influence is further reinforced by isotope signatures in mollusk fossils, which point to a high salinity range, as well as by bioturbated strata which are represented by ichnogenera characteristic of marginal marine environments (Vonhof et al., 1998, 2003; Gingras et al., 2002). According to Hovikoski et al. (2007, 2010) and Antoine et al. (2016), these restricted episodes of marine incursion in the western Amazonian Neogene were possibly marked by fast progradation and tidal influence with intercalation of brackish and freshwater sequences. However, studies with mollusks point to the predominance of shallow and fluvio-lacustrine scenarios (Wesselingh et al., 2002, 2006a).

Hoorn et al. (2010a), in a review of the main features of the latest Oligocene to Miocene depositional environments concerning the Pebas and Solimões Formations from exploration wells and outcrops data, proposed a model of paleoenvironmental evolution for the wetlands of Neogene Amazonia, subdividing it in three distinct phases: a) a fluvio-lacustrine precursor phase (~24–16 Mya); b) the Pebas phase (~16–11.3 Mya), represented by a wide floodplain system (mega-wetland) with episodic marine influence; and c) the Acre phase (<11.3 to 7 Mya) represented by fluvial-tidal-dominated wetlands.

As is common to the controversial paleoenvironmental reconstruction, the chronostratigraphic range of the Solimões Formation is also as yet not well defined, and it represents another uncertain datum since it is difficult to establish its limits and its vertical distribution by studying only the outcrops. Various studies using micropaleontology have speculated on the age of the unit. Although the first studies on deposits of the Solimões Formation inferred an age from the Paleocene to the Pleistocene (Roxo, 1924; Daemon and Contreiras, 1971; Caputo et al., 1971; Shepard and Bate, 1980), other studies from core samples attested to a more precise age, from Miocene to Pliocene times (Maia et al., 1977; Purper, 1979). Advances in this subject were reached through biostratigraphical studies mainly employing palinology (Hoorn, 1993; Leite, 2006; Silva-Caminha et al., 2010).

Previous studies based on palynology and ostracods (Hoorn, 1993; Muñoz-Torres et al., 2006) were performed on cores from the borehole 1AS-4a-AM, located close to the wells studied herein, and supported five biozones: *Verrutricolporites* and *Retitricolporites* (Early Miocene), *Psiladiporites-Crototricolites* (Late to early Middle Miocene), *Crassoretitriletes* (Middle Miocene), and *Grimsdalea* (Middle Miocene to early Late Miocene). Five biozones were proposed with ostracods of the genus *Cyprideis* as follow: *C. aulakos* (late Early Miocene to early Middle Miocene), *C. caraionae* (Middle Miocene/Langhian), *C. minipunctata* (Middle Miocene/Langhian-Serravallian), *C. obliquosulcata* (Middle Miocene/Serravallian), and *C. cyrtoma* (Middle Miocene to early Late Miocene).

Recently, other palynological studies in the same area (cores 1AS-32-AM, 1AS-33-AM, and 1AS-34-AM) have recorded a more recent age than the previous proposal of Hoorn (1993), limiting the base of the Solimões Formation to the Middle/Late Miocene and extending the top to the Pliocene (Silva-Caminha et al., 2010; Silveira and Souza, 2015; Kachniasz and Silva-Caminha, 2016; Leite et al., 2016).

In the present study, the age attributed to the studied sequences, in relation to the Solimões Formation, was also based on palynological analysis from the cores using index fossil (Fig. 4e–l) (Linhares et al., in prep.), enabling the identification of the following biozones: *Verrutricolporites* (368–323.4 m), Early Miocene; *Crassoretitriletes* (246,76–141 m), Middle Miocene; and *Grimsdalea* (141–32 m), from the Middle to Late Miocene for the borehole 1AS-8-AM; for the borehole 1AS-7D-AM, the biozones *Psiladiporites-Crototricolpites* (296–184 m), from the Early to Middle Miocene; *Grimsdalea* (184–125 m), and *Asteraceae* (125–6 m), Late Miocene were identified. These data support the previous dated age for the core 1AS-4a-AM (Hoorn, 1993), pointing to Early Miocene at the base of the Solimões Formation. The top of the unit is marked here as Late Miocene. The youngest Pliocene age inferred for the top of the cores 1AS-31-AM (Kachniasz and Silva-Caminha, 2016) and 1AS-33-AM (Leite et al., 2016) was not identified here, but it is probably due to the geographical position of the cores and its relation with isopachs and other tectonic settings (Wesselingh et al., 2006a; b).

## 4. Material and methods

This study utilized 192 samples from wells 1AS-7D-AM (112 samples) and 1AS-8-AM (83 samples), drilled by the Geological Survey of Brazil (CPRM) in the 1970's, to investigate the presence of lignite. Micropaleontological analyses were carried out in two procedures: 1) calcareous microfossils were extracted following the methodology of Wanderley (2010) in which 180 g of dry sediment were washed through standard sieves (0.5 mm; 0.250 mm; 0.180 mm; 0.125 mm). Wet sieve residue was dried at 60 °C and microfossils then were picked out using a stereo microscope, for subsequent identification. Photographs were taken with a LEO 1450VP SEM (Scanning Electron Microscopy) at the Museu Paraense Emílio Goeldi, Belém, Pará); 2) Palynomorph extraction followed the procedure of Uesugui (1979) in which samples of 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 200 μm mesh, followed by extraction of light residue which was spread on palynological thin sections to be studied and photographed under an optical microscope at 100x magnification.

Sedimentological data were obtained for both cores by lithological description and confection of tabular sections following Miall (1996) and Tucker (2011). Stratigraphic surfaces (S1 and S2) were identified by limiting the lithostratigraphic units (Catuneanu et al., 2009).

## 5. Results

### 5.1. Sedimentology

Sedimentological analysis of the borehole cores allows easy identification of the Solimões Formation by the presence of lignite, fossil contents, and mainly a typically fine sedimentation with green to grey and less commonly brown and black colors, as a result of high concentrations of organic matter. The upper limit was not well defined, as to whether it belongs to the Içá Formation or to Quaternary deposits, but the original well logging of Maia et al. (1977) identified Quaternary alluvial deposits over the Solimões Formation at well 1AS-8-AM. In addition, at well 1AS-7D-AM, at the top of the sequence, the overlap of plastic clay is probably related to alluvial deposits as well, featuring a bounding surface (S2). This information is confirmed by the nearby well 1AS-31-AM (not included in this work) which presents recent vegetal debris in the last few meters (Fig. 2A). The lower limit is registered only in 1AS-8-AM, below 368 m-depth, on contact with white and mottled pelites and sandstones, usually kaolinitic, without bioturbation, fossil, and organic matter, which clearly represents another lithostratigraphic unit, thus setting the S1. Some authors (Caputo, 1991; Eiras et al., 1994; Wanderley Filho et al., 2010) identified the underlying unit below the Solimões Formation as the Alter do Chão Formation, and Mendes et al. (2012) identified this feature in the Alter do Chão Formation in the Amazonas Basin, describing whitish kaolinitic sandstones and pelites in the upper layers. Therefore, we propose in this paper to attribute the base of 1AS-8-AM to the Alter do Chão Formation.

Sedimentological analysis of the cores demonstrates predominantly fine sedimentation (shale and silty shale), marked by association with vegetal debris, organic matter, fossils, and bioturbation, interbedded with thin layers of lignite and limestones, besides thicker beds of sandstones and siltstones, in coarsening upward trend. This succession is well described by several authors (Latrubesse et al., 2010; Gross et al., 2011; Nogueira et al., 2013), setting this pattern as overbank deposits, such as: floodplains, crevasse splays, lakes, and ponds. This sedimentary pattern is observed throughout the studied boreholes; nonetheless it is locally interrupted by another succession (Fig. 3) which comprises thick layers of fine to medium sandstones (<3 m) with cross stratification and climbing ripple cross laminations that could represent channel sandstone bodies, crevasse channels, or delta-front sandstone bodies associated with the alluvial system.

### *5.2. Micropaleontology of borehole 1AS-8-AM*

Borehole 1AS-8-AM (405 m) presented low fossil abundance and diversity, mainly in its basal and median portions, becoming more fossiliferous from 110.6 m. However, it presents important elements for the interpretation of paleoenvironmental evolution, mainly because it shows the most basal part of the Solimões Formation which reveals the limit with the Alter do Chão Formation at depths from 405 to 368 m.

The strata at the base of the borehole 1AS-8-AM (368–323.4 m), corresponding to the base of the Solimoes Formation, dated as Early Miocene (Linhares et al., in prep.), are characterized by an organic-wall microfossil assemblage containing microforaminiferal linings (Fig. 4a–c) and palynomorphs *Zonocostites ramonae* and *Verrutricolporites rotundiporus* which have an affinity with the respective mangrove species *Rhizophora mangle* and *Pelliciera rhizophorae* (Fig. 4e–f), and agglutinated foraminifera (*Miliammina fusca*) (Fig. 5g–h). This association is sporadically registered along the interval 368.0–323.4 m, where the carbonate-wall microfossils are absent. In the interval from 323.4 to 246.76 m both calcareous and palynomorph microfossils are absent, so it was neither possible to characterize the paleoenvironment nor to date it.

The overlying range (246.76–141 m), corresponding to Middle Miocene (Linhares et al., in prep.), still exhibits a low abundance and diversity of microfossils. The mollusks are represented by *Tryonia*, *Dyris* (Gastropoda), and *Pachydon* (Bivalvia) that are associated with lacustrine environments (Wesselingh and Ramos, 2010). The ostracod assemblage is composed of species of the genus *Cyprideis* (Fig. 6a–i), a euryhaline genus (Van Harten, 2000), representing here 99% of the recovered specimens, and *Penthesilenula* (Fig. 6l) associated with freshwater environments (Rossetti and Martens, 1998). Moreover, the microfossil assemblage also contains teeth, spines, and fish vertebra.

At the upper section of this core (141–32 m), corresponding to the Middle to Late Miocene (Linhares et al., in prep.), the diversity and abundance increased. The ostracod assemblage is represented, besides *Cyprideis*, by *Perissocytheridea* (Fig. 5m–o), a typical marine/transitional genus and by the marine genus *Pellucistoma* (Gross et al., 2015) at 135.3 m (Fig. 5p). This interval is characterized also by the occurrence of crab fragments, ray teeth (Dasyatidae indet.), selachian dermal denticles, and catfish otoliths (*Genidens*) (Fig. 5b–f).

These transitional/marine ichthyolites also occur at 93.05 m, associated with charophyte gyrogonites (Fig. 6p), freshwater *Penthesilenula*, and euryhaline *Cyprideis* ostracods. Furthermore, *Cytheridella* (Fig. 6j), a lacustrine genus (Colin et al., 1997) occurs with charophyte gyrogonites at 87.3 m and 59.25 m, as well. The charophytes occur in continental or brackish environments, such as lakes with high alkalinity and high concentrations of calcium carbonate (Feitosa et al., 2003). The mollusks assemblage is predominantly composed of *Dyris*, *Littoridinops*, *Cochliopina*, and *Pachydon*, with *Toxosoma* and *Pyrgophorus*, genera typically found in freshwater/brackish environments (Wesselingh, 2006).

### *5.3. Micropaleontology of borehole 1AS-7D-AM*

The base of borehole 1AS-7D-AM (296–184.0 m), corresponding to Early Miocene to early Middle Miocene (Linhares et al., in prep.),

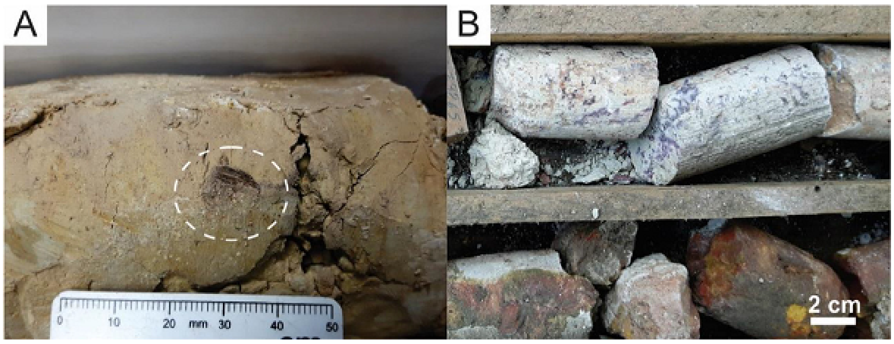


**Fig. 2.** A) Alluvial deposit that overlies the Solimoes Formation, presenting recent vegetal debris (dashed circle) at 1AS-31-AM. B) Underlying Alter do Chão Formation unit (1AS-8-AM) consisting of white to mottled kaolinitic pelite and mottled sandstones.

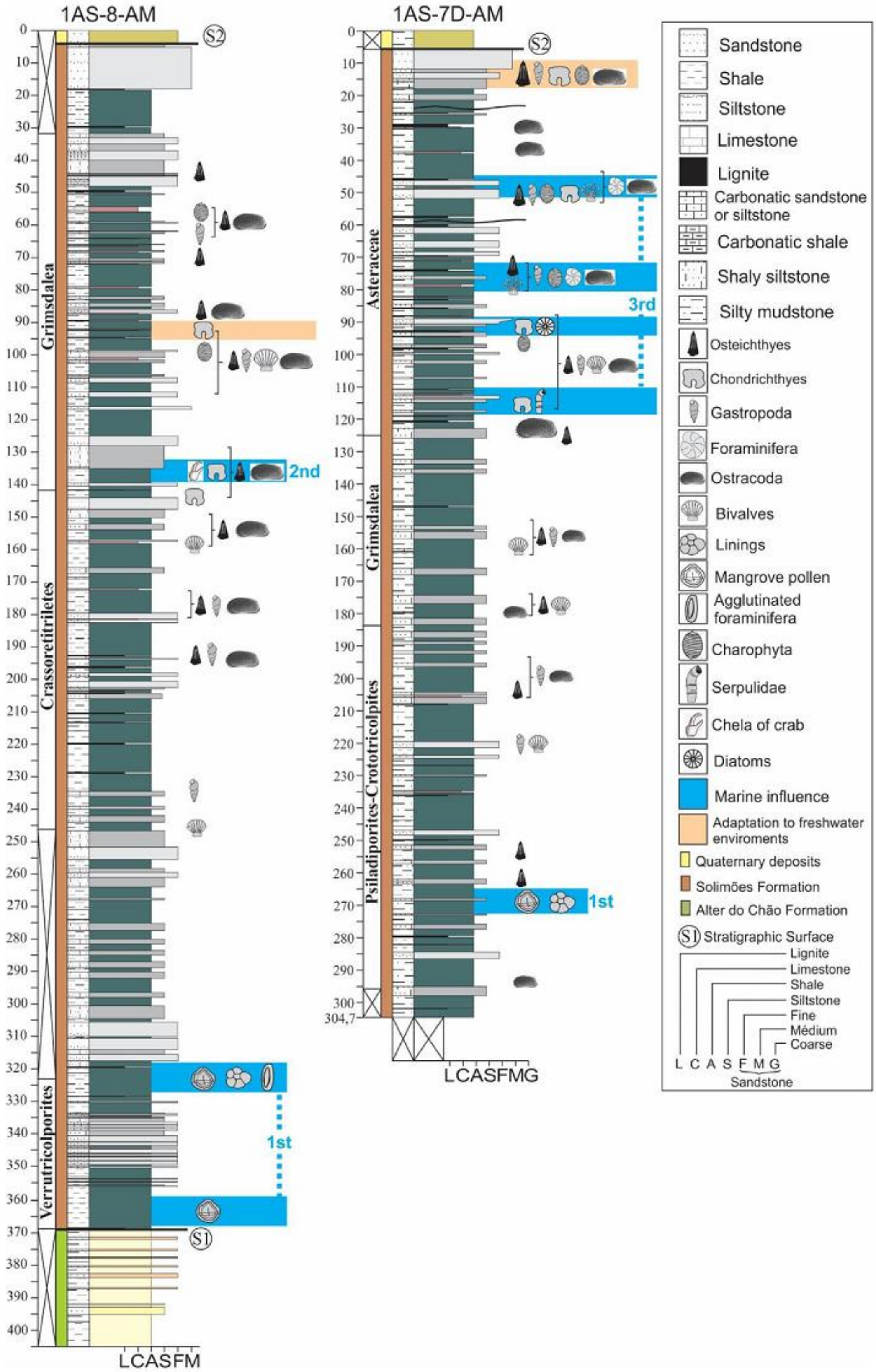


**Fig. 3.** Lithologic sections of cores 1AS-7D-AM and 1AS-8-AM, with the distribution of microfossils and palynological biozonation, according to Linhares et al., (in prep.).

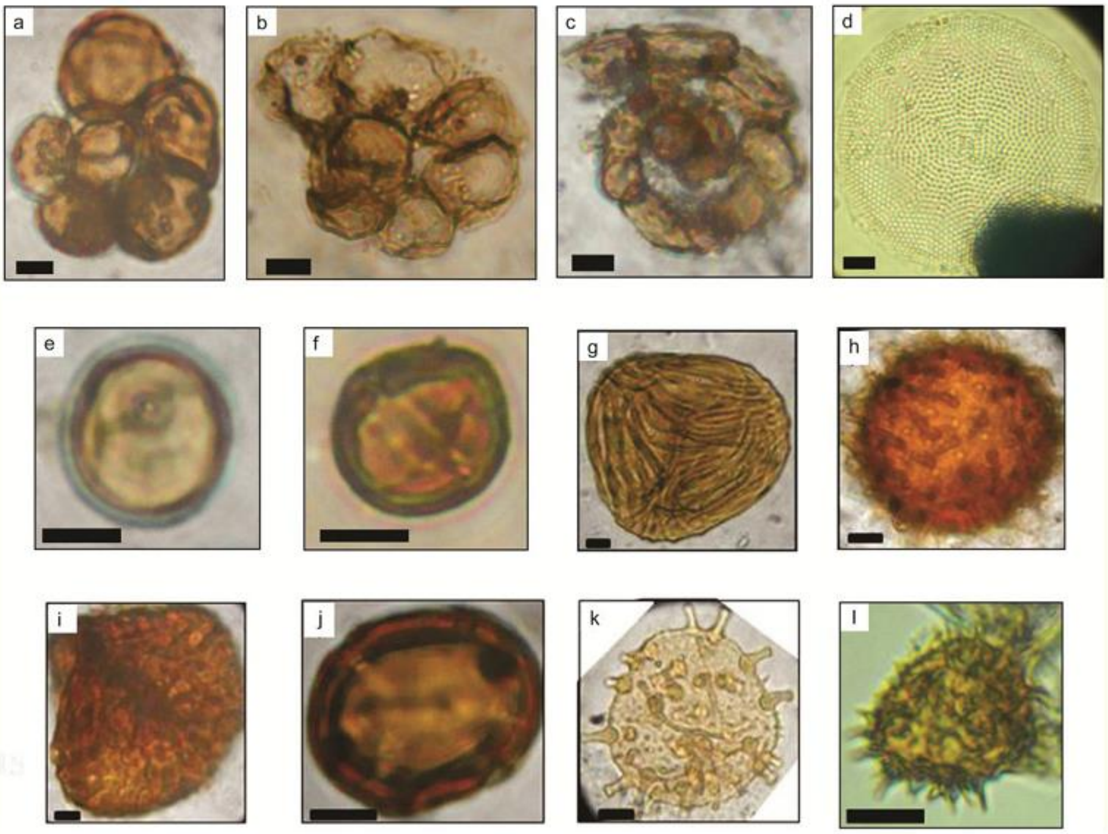


**Fig. 4.** Mangrove/estuarine palynomorph assemblage: a-c. microforaminiferal linings (1AS-8-AM, at 323 m and 1AS-7D-AM, at 268 m); d. Diatom: *Coscinodiscus rothii* (1AS-7D-AM, at 91.5 m); Palynological markers; e. *Verrutricolporites rotundiporus*; f. *Zonocostites ramonae*; g. *Magnastriates grandiosus*; h. *Echiperiporites* sp.; i. *Crassoretitriletes vanraadshoovenii*; j. (1AS-8-AM at 368 m-323 m); *Perisyncolporites pokornyi*; k. *Grimsdalea magnaclavata*; l. *Echitricolporites spinosus*. Positions: 1AS-7D-AM at 296 m: h; at 268 m: c; at 224 m: j; at 91.5 m: d. 1AS-8-AM at 323.4 m: a-b, e-g; at 214 m: i; at 141 m: k; at 125 m: l. Scale bar = 20 μm.

is characterized by low abundance and diversity of fossils. In the sample from 268 m, there are *Zonocostites ramonae* and microforaminiferal linings. This sample resembles the lower portion of borehole 1AS-8-AM; thus, in the following samples (202.8–193 m) a more expressive assemblage of carbonate microfossils occurs represented by ostracods (*Cyprideis*), unidentified mollusks, and a few ichthyolites.

At interval 184–125 m, equivalent to late Middle to early Late Miocene (Linhares et al., in prep.), microfossils are still poorly diverse and abundant, composed of a very small number of mollusks (gastropods and bivalves), some unidentified ichthyolites, and an ostracofauna that is a little more abundant than in the layers below and is represented exclusively by *Cyprideis*.

In the upper intervals (125–6 m), corresponding to Late Miocene (Linhares et al., in prep.), there is a variable pattern of occurrence and distribution of microfossils, with the register of brackish/marine (Fig. 5) and freshwater (Fig. 6j–p) taxa frequently occurring together at some levels. However, from 117.7 to 50 m the marine elements are more abundant, while non-marine taxa predominate only in the last 45 m as discussed below.

Up to this section, the interval between 117.7 and 91.5 m is characterized by marine/transitional elements such as serpulides tubes (Fig. 5a), shark scales, ray teeth (Dasyatidae indet.), and marine ostracods (*Paracypris* and *Perissocytheridea*), although there also occur resilient fluvial-lacustrine taxa of mollusks (*Dyris* and *Tryonia*), euryhaline ostracods (*Cyprideis*), and rare charophyte gyrogonites. In the sample from 91.5 m, there is the first register of marine diatoms within Solimões Formation deposits. The species *Coscinodiscus rothii* (Fig. 4d) occurs from the Miocene to present-day seas, commonly found also in estuaries and rarely in freshwater environments (Andrews, 1976).

Between 78.5 and 50 m, samples present a mixture of marine, freshwater, and brackish water taxa, including the mollusks *Dyris*, *Pachydon*, *Onobops*, and *Neritina*, and ostracods like *Cyprideis*, *Paracypris*, and *Perissocytheridea*, foraminifera *Ammonia* (Fig. 5i–l), stingray dasyatid, shark scales, besides the exclusively freshwater ostracods *Cypria*, *Penthesilenula*, and charophyte gyrogonites. Furthermore, the ostracod *Skopaeocythere tetrakanthos* (Fig. 5r) is recorded at 50 m; this species, according to Whatley et al. (2000), probably occurs in restricted paleoenvironments, possibly of brackish waters, since it occurs mainly associated with species of the genera *Perissocytheridea* and *Cyprideis*, besides the foraminifera *Elphidium* in samples from Los Chorros (Colombia). Gross et al. (2014) also mentioned that this species occurs in association with dwarf elphidiid foraminifers, typical of marginal marine environments, in core 1AS-10-AM, AM, Brazil.

Exclusively freshwater groups occur at 45.5 m and 14.8 m, indicating the predominance of these taxa to the top of the Solimões Formation. Nonetheless, at 14.8 m rare brackish and/or marine ichthyolites (catfish otoliths and ray teeth) are still observed, along with predominantly freshwater taxa such as charophyte gyrogonites, ichthyolites of Characidae (Fig. 6m–o), and ostracods like *Penthesilenula*, *Cytheridella* (Fig. 6j), *Cypria* (Fig. 6k), and *Candona*, besides euryhaline *Cyprideis* at a lower proportion.

## 6. Discussion

The microfossil data from pollen and foraminifera indicate

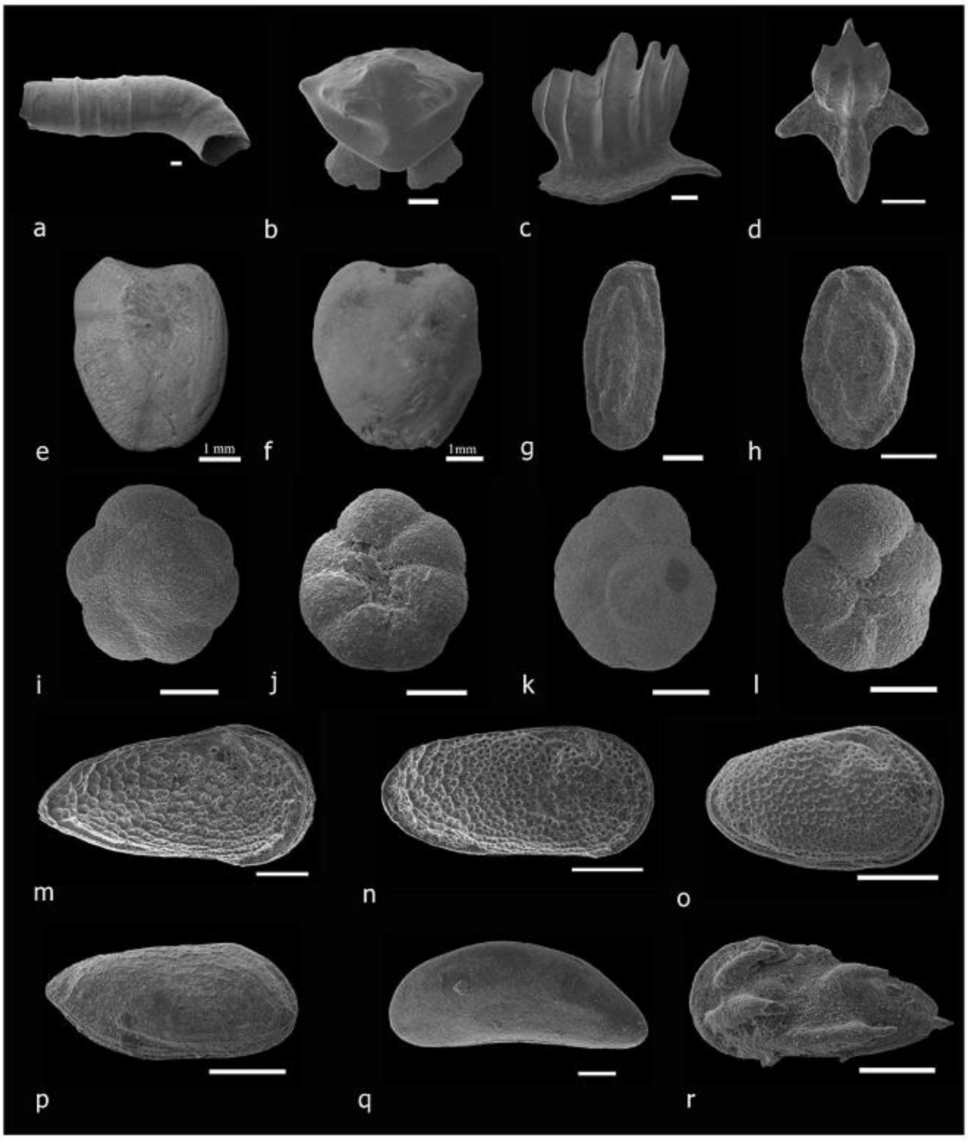


**Fig. 5.** Microfossils representing the brackish and marine assemblage. a. Polychaeta: Serpulidae; b. Stingray: *Dasyatidae* indet.; c-d. Selachian dermal denticles; e-f. Otoliths: *Genidens* sp.; Foraminifers: g-h. *Miliammina fusca*; i-l. Different morphotypes *Ammonia tepida*; Ostracods: m. *Perissocytheridea acuminata*; n-o. *Perissocytheridea ornellase*; p. *Pellucystoma* sp.; q. *Paracypris* sp.; r. *Skopaeocythere tetrakanthos*. Positions: 1AS-7D-AM at 91.5 m: a-f; at 76.5 m: q; at 50 m: i-l and r. 1AS-8-AM at 323 m: g-h; at 135.3 m: p; at 110.6 m: m-o. Scale bar = 100 μm.

typical mangrove conditions at the base of the Solimões Formation (boreholes 1AS-7D-AM and 1AS-8-AM), dated as Early and early Middle Miocene, confirming previous reports (Cruz, 1984; Hoorn, 1993, 1994a; b; 2006). Mangrove pollen and organic-wall foraminifera normally occur in conditions of low pH, reduced oxygen, and high availability of organic matter, which normally would prevent the proliferation of calcareous microorganisms. This association is recognized in mesohaline environments, typically mangroves and swamps, but can also occur in estuarine and oligohaline environments (Murray, 1991a; b; Tyszka, 1997). Therefore, mangrove presence at the base of the Solimões Formation represents here the first marine ingression into the study area.

During the late Middle to Late Miocene, two others events of marine influence were identified. The second in 1AS-8-AM (135.3 m) is dated as Middle Miocene/Late Miocene, while the third event in 1AS-7D-AM (represented by four peaks from 117.7 to 50 m) is dated as Late Miocene. This last event could be correlated with the one observed by Linhares et al. (2011) in borehole 1AS-31-AM (Atalaia do Norte, Amazonas) that presented a thinner interval (4.2 m-thick) than the present one. This interval, called the “Transitional to Marine Phase” (Interval II), presents a mixed assemblage similar to the one observed in 1AS-7D-AM (this study).

The vertical extent of marine events has been discussed in some studies (Hovikoski et al., 2007, 2010) and suggests several ingressions reaching the Western Amazon during the Miocene. However, this is contrary to the theory that marine ingressions shaped the area punctually in the late Middle–early Late Miocene (Shepard and Bate, 1980; Hoorn, 1993, 1994a; b; Räsänen et al., 1995; Monsch, 1998; Muñoz-Torres et al., 1998; Wesselingh et al., 2002, 2006a; b).

The three marine incursions identified in the present study are consistent with the results of Boonstra et al. (2015) and Antoine et al. (2016). The latter study indicates similarities of the microfossil assemblage from the Pebas Formation (Peru) with core 1AS-

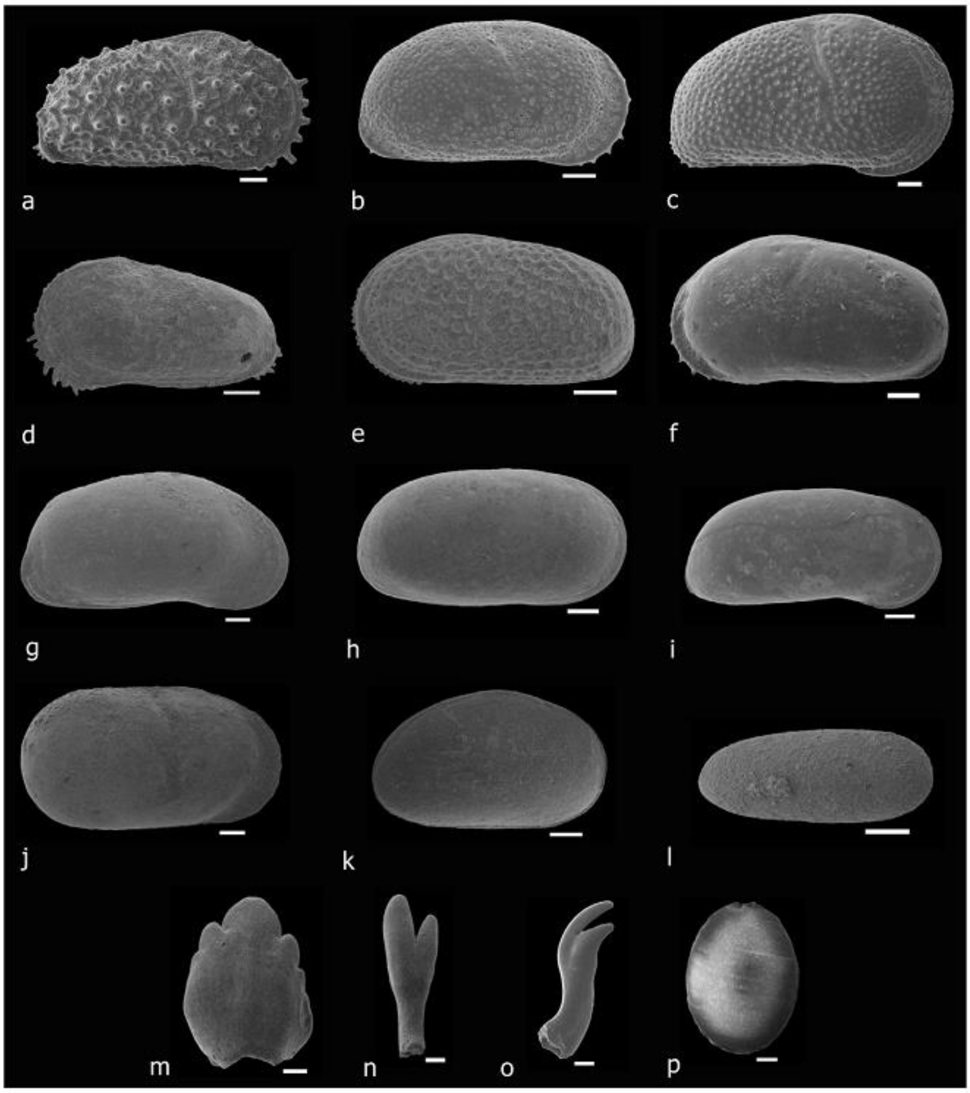


**Fig. 6.** Diversity of *Cyprideis* species and associated taxa: a. *Cyprideis curucae*; b. *C. minipunctata*; c. *C. sulcosigmoidalis*; d. *C. inversa*; e. *C. munoztorresi*; f. *C. schedogymnos*; g. *C. machadoi*; h. *C. paralela*; i. *C. multiradiata*; Freshwater assemblage: Ostracods: j. *Cytheridella danielopoli*; k. *Cypria* sp.; l. *Penthesilenula olivencai*; m. Tooth Characidae indet.; n-o. Palatine teeth Loricariidae indet.; p. Charophyte gyrogonites. Positions: 1AS-7D-AM at 161 m: b, h; at 121 m: g; at 111.5 m: i; at 106 m: m; at 99.9 m: n-o; at 76.5 m: l; at 50 m: d-f, h, k; at 14.8 m: j, p. 1AS-8-AM at 110.6 m: a, c. Scale bar = 100 μm.

31-AM, correlating them to the marine interval of Linhares et al. (2011), and considers this interval as the relevant marker for correlation between the intra-basins from Peru, Brazil, Colombia, Ecuador, and Bolivia (Antoine et al., 2016). More recently, Jaramillo et al. (2017) registered two short-lived marine events between the Early and Middle Miocene in Brazil and Colombia, but they do not dismiss a third marine event in Late Miocene.

Until early Late Miocene, typically fluvial taxa are rare, while transitional/marine taxa are more abundant in the studied cores than in other eastern sections of the Solimões basin, indicating a mostly marine influence on that area. However, in the Late Miocene, although some marine elements still remain, the freshwater taxa predominate over them. These marine fossils probably arrived from previous marine incursions and posteriorly adapted to new conditions. The predominance of euryhaline taxa as ostracods (*Cyprideis*), as well as foraminifera (*Ammonia*) and other tolerant taxa (fishes, mollusks, etc.) in several intervals of both cores attest to the existence of stressful conditions in the wetlands of the western Amazonia. As the example of ostracods shows, the presence of the nodes, changing the ornamentation pattern in some species of *Cyprideis* and reduced size as in the marine *Pellucistoma*, also indicated stressful conditions related to salinity changes (Linhares et al., 2011; Gross et al., 2014, 2015).

These resilient groups are widely known for their ecophenotypic plasticity in response to wide variation in environmental conditions such as temperature, salinity, oxygen, and nutrients availability (Jorissen, 1988; Ruiz et al., 2013; Fürstenberg et al., 2015; Boonstra et al., 2015), and they have adapted to the new physical-chemical conditions of the fluvio-lacustrine system, originating the radiation and endemism of the biota now common in the region (Muñoz-Torres et al., 1998; Wesselingh et al., 2002; Albert and Reis, 2011; Gross et al., 2014). Their occurrence in other cores and outcrops has been the key to indicate salinity changes during the Amazonian Neogene (Hoorn, 1993; Räsänen et al., 1995; Monsch, 1998; Linhares et al., 2011; Gross et al., 2015; Boonstra et al., 2015; Leite et al., 2016; Kachniasz and Silva-Caminha, 2016).

Therefore, we believe that marine groups could have reached

Amazonia through geographically limited connections at some time between the Early to early Middle Miocene and late Middle/Late Miocene, similar to the model proposed by Boonstra et al. (2015), Antoine et al. (2016), and Jaramillo et al. (2017). Afterwards, a few originally marine groups adapted to the fluvio-lacustrine environment, as demonstrated in previous works (Lundberg et al., 1998; Wesselingh and Salo, 2006; Lovejoy et al., 2006; Albert and Reis, 2011; Gross et al., 2015). The upper strata (Late Miocene) indicate a more significant fluvial influence than the lower strata, yielding a more abundant freshwater fauna. This condition is confirmed by several works from outcrops in Brazil (Ramos, 2006; Latrubesse et al., 2010; Gross et al., 2011, 2013, 2014; Nogueira et al., 2013), showing that the Late Miocene strata were already characterized by fluvio-lacustrine deposits without marine influence.

## 7. Conclusions

We consider herein three possible events of marine incursions into the studied area: the first recorded in the Early Miocene to early Middle Miocene (in both cores), the second in the late Middle Miocene to early Late Miocene (1AS-8-AM), and the third in the Late Miocene (1AS-7D-AM). The data indicate that these incursions modified the Amazonian landscape, when typical coastal environments may have become established, including mangroves, estuaries, and lagoons. At the end of the Solimões Formation, these conditions disappeared and were replaced by a fluvio-lacustrine system similar to the modern landscape. As a consequence, the effects of the Andean Orogeny, beyond the marine influence in the deposits of the Western Amazon, triggered environmental variations throughout the Neogene, which consequently fostered the great biodiversity at that time in the Amazon region.

## Acknowledgments

The authors thank the Brazilian Departamento Nacional de Produção Mineral (DNPM) and the Serviço Geológico do Brasil (CPRM), for permission to access and use the core samples. The Museu Paraense Emilio Goeldi (MPEG) supported this study and provided facilities for SEM photography. The Federal University of Pará (UFPA) supported this research through the Programa de Pós-Graduação em Geologia e Geoquímica (PPGG). To Pierre-Olivier Antoine and the other anonymous reviewer for critical contributions that improved the final manuscript. Dr. William Overal (MPEG) helped with the English review.

## References

Albert, J.S., Reis, R.E. (Eds.), 2011. Historical Biogeography of Neotropical Freshwater Fishes. University of California. Press, Berkeley, p. 388. ISBN 0-520-26868-5.

Andrews, G.W., 1976. Miocene marine diatoms from the choptank formation, calvert county, Maryland. U. S. Geol. Surv. Prof. Pap. 910, 1–26.

Antoine, P., Abello, M.A., Adnet, S., Altamirano Sierra, A.J., Baby, P., Billet, G., Boivin, M., Calderón, Y., Candela, A., Chabain, J., Corfu, F., Croft, D.A., GanerØd, M., Jaramilho, C., Klaus, S., Marivaux, L., Navarrete, R.E., Orliac, M.J., Parra, F., Pérez, M.E., Pujos, F., Rage, J., Ravel, A., Robinet, C., Roddaz, M., Tejada-Lara, J.V., Vélez-Juarbe, J., Wesselingh, F.P., Salas-Gismondi, R., 2016. A 60-million-year Cenozoic history of western Amazonian ecosystems in Contamana, eastern Peru. Gondwana Res. 31, 30–59.

Bezerra, P.E.L., Ribeiro, D.T., 2015. Evolução tectônica cenozoica da Amazônia Ocidental. In: Gorayeb, P.S.S., Lima, A.M.M. (Eds.), Contribuições à geologia da Amazônia, Sociedade Brasileira de Geologia, vol. 9, pp. 139–155. Núcleo Norte.

Boonstra, M., Troelstra, S.R., Lammertsma, E.I., Ramos, M.I.F., Antoine, P.-O., Hoorn, C., 2015. Marine connections of Amazonia: evidence from foraminifera and dinoflagellate cysts (early to middle Miocene, Colombia/Peru). Palaeogeogr. Palaeoclimatol. Palaeoecol. 417, 176–194. http://dx.doi.org/10.1016/j.palaeo.2014.10.032.

Caputo, M.V., Rodrigues, R., Vasconcelos, D.N.N., 1971. Relatório Técnico Interno. Litoestratigrafia da Bacia do Rio Amazonas, 641-A, pp. 35–46. Petrobrás- Renor, Belém.

Caputo, M., 1991. Solimões megashear: intraplate tectonics in northwestern Brazil. Geology 19, 246–249.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.S.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Rev. 92, 1–33. http://dx.doi.org/10.1016/j.earscirev.2008.10.003.

Colin, J.-P., Tambareau, Y., Krasheninnikov, V.A., 1997. An early record of the genus Cytheridella daday, 1905 (ostracoda, limnocytheridae, timiriaseviinae) from the upper cretaceous of Mali, West Africa: palaeobiogeographical and palaeoecological considerations. J. Micropalaeontology 16, 91–95.

Conrad, T.A., 1874. Remarks on the Tertiary clay of the Upper Amazon, with descriptions of new shells. Proc. Acad. Nat. Sci. Phila. 26, 25–32.

Cruz, N.M.C., 1984. Palinologia do linhito do Solimões, estado do Amazonas. In: II Simpósio de Geologia da Amazônia. Resumos expandidos. DNPM, Manaus, pp. 473–480.

Daemon, F.R., Contreiras, J.A.C., 1971. In: Zoneamento Palinológico da Bacia do Amazonas. Congresso Brasileiro de Geologia, São Paulo, pp. 79–88. Anais 25.

Eiras, J.F., Becker, C.R., Souza, E.M., Gonzaga, F.G., Silva, G.F., Daniel, M.L.F., Matsuda, N.S., Feijó, F.J., 1994. Bacia do Solimões. Bol. Geociências Petrobrás 8 (1), 17–49. Rio de Janeiro.

Feitosa, A.A.S., Gobbo-Rodrigues, S.R., Kellner, A.W.A., 2003. Partes vegetativas de Carófitas fossilizadas no Membro Romualdo (Albiano, Formação Santana), Bacia do Araripe, nordeste brasileiro, vol. 70. Boletim do Museu Nacional, pp. 1–8. Nova série Geologia, Rio de Janeiro.

Fürstenberg, S., Frenzel, P., Peng, P., Henkel, K., Wrozyna, C., 2015. Phenotypical variation in Leucocytherella sinensis Huang, 1982 (Ostracoda): a new proxy for palaeosalinity in Tibetan lakes. Hydrobiologia 751, 55–72.

Gingras, M.K., Rasanen, M., Pemberton, G.S., Romero, L.P., 2002. Ichnology and sedimentology reveal depositional characteristics of bay-margin parasequenses in the Miocene Amazonian foreland Basin. J. Sediment. Res. 72 (6), 871–883.

Gross, M., Piller, W.E., Ramos, M.I., da Silva Paz, J.D., 2011. Late Miocene sedimentary environments in south-western Amazonia (Solimões Formation; Brazil). J. S. Am. Earth Sci. 32 (2), 169–181. http://dx.doi.org/10.1016/j.jsames.2011.05.004.

Gross, M., Ramos, M.I., Caporaletti, M., Piller, W.E., 2013. Ostracods (Crustacea) and their paleoenvironmental implication for the Solimões Formation (late Miocene; Western Amazonia/Brazil). J. S. Am. Earth Sci. 42, 216–241. http://dx.doi.org/10.1016/j.jsames.2012.10.002.

Gross, M., Ramos, M.I., Piller, W.E., 2014. On the Miocene Cyprideis species flock (ostracoda; Crustacea) of Western Amazonia (Solimões Formation): refining taxonomy on species level. Zootaxa 3899 (1), 1–69.

Gross, M., Ramos, M.I.F., Piller, W.E., 2015. A minute ostracode (Crustacea: cytheromatidae) from the Miocene Solimões Formation (western Amazonia, Brazil): evidence for marine incursions? J. Syst. Palaeontol. 14 (7), 581–602.

Hoorn, C., 1993. Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study. Palaeogeogr. Palaeoclimatol. Palaeoecol. 105, 267–309.

Hoorn, C., 1994a. Fluvial palaeoenvironments in the intracratonic Amazonas Basin (early miocene-early middle Miocene, Colombia). Palaeogeogr. Palaeoclimatol. Palaeoecol. 109, 1–54.

Hoorn, C., 1994b. An environmental reconstruction of the palaeo-Amazon River system (Middle-Late Miocene, NW Amazonia). Palaeogeogr. Palaeoclimatol. Palaeoecol. 112, 187–238.

Hoorn, C., 2006. Mangrove forests and marine incursions in Neogene Amazonia (lower apaporis river, Colombia). Palaios 21, 197–209. http://dx.doi.org/10.2110/palo.2005.p05-131.

Hoorn, C., Wesselingh, F.P., Hovikoski, J., Guerrero, J., 2010a. The development of the Amazonian mega-wetland (Miocene; Brazil, Colombia, Peru, Bolivia). In: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Lanscape and Species Evolution, a Look into the Past. Wiley-Blackwell, pp. 123–142.

Hoorn, C., Wesselingh, F.P., ter Steege, H., Bermudez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramilho, C., Riff, D., Negri, F.R., Hooghiemstra, H., Stadler, T., Särkinen, T., Antonelli, A., 2010b. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. Science 330, 927–931.

Hoorn, C., Bogotá-A, G.R., Romero-Baez, M., Lammertsma, E.I., Flantua, S.G.A., Dantas, E.L., Dino, R., do Carmo, D.A., Chemale Jr., F., 2017. The Amazon at sea: onset and stages of the Amazon River from a marine record, with special reference to Neogene plant turnover in the drainage basin. Glob. Planet Change 153, 51–65.

Hovikoski, J., Räsänen, M., Gingras, M.K., Lopez, S., Ranzi, A., Melo, J., 2007. Palaeogeographical implications of the Miocene Quendeque formation (Bolivia) and tidally-influenced strata in southwestern Amazonia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 243, 23–41. http://dx.doi.org/10.1016/j.palaeo.2006.07.013.

Hovikoski, J., Wesselingh, F.P., Räsänen, M.E., Gingras, M.K., Vonhof, H.B., 2010. Marine influence in Amazonia: evidence from the geological record. In: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Lanscape and Species Evolution, a Look into the Past. Wiley-Blackwell, pp. 143–161.

Jaramillo, C., Romero, I., D'Apolito, C., Bayona, G., Duarte, E., Louwye, S., Escobar, J., Luque, J., Carrillo-Briceño, J.D., Zapata, V., Mora, A., Schouten, S., Zavada, Z., Harrington, G., Ortiz, J., Wesselingh, F.P., 2017. Miocene flooding events of

Western Amazonia. Sci. Adv. 3 (5), 1–11 e1601693.

Jorissen, F.J., 1988. Benthic foraminifera from the Adriatic Sea; principles of phenotypic variation. Utrecht Micropaleontol. Bull. 37, 1–176.

Kachniasz, K.E., Silva-Caminha, S.A.F., 2016. Palinoestratigrafia da Formação Solimões: comparação entre bioestratigrafia tradicional e o método de associações unitárias. Rev. Bras. Paleontol. 19 (3), 481–490. http://dx.doi.org/10.4072/rbp.2016.3.12.

Latrubesse, E.M., Bocquentin, J., Santos, J.C.R., Ramonell, C.G., 1997. Paleoenvironmental model for the Late Cenozoic of southwestern Amazonia: paleontology and geology. Acta Amaz. 27 (2), 103–118.

Latrubesse, E.M., Cozzuol, M., Silva-Caminha, S.A.F., Rigsby, C.A., Absy, M.L., Jaramillo, C.A., 2010. The late Miocene paleogeography of the Amazon basin and the evolution of the Amazon River system. Earth-Science Rev. 99, 99–124. http://dx.doi.org/10.1016/j.earscirev.2010.02.005.

Leite, F.P.R., 2006. Palinologia da Formação Solimões, Neógeno da Bacia do Solimões, Estado do Amazonas: Implicações paleoambientais e bioestratigráfias. Instituto de Geociências, Universidade de Brasília, p. 128. Tese de Doutorado.

Leite, F.P.R., Paz, J.D., Carmo, D.A., Silva-Caminha, S.A.F., 2016. The effects of the inception of Amazonian transcontinental drainage during the Neogene on the landscape and vegetation of the Solimões Basin, Brazil. Palynology 1–11. http://dx.doi.org/10.1080/01916122.2016.1236043.

Linhares, A.P., Ramos, M.I.F., Gross, M., Piller, W.E., 2011. Evidence for marine influx during the Miocene in southwestern Amazonia, Brazil. Geol. Colomb. 36 (1), 91–104.

Lisboa, L.G.S., Wanderley Filho, J.R., Travassos, W.A.S., 2013. Bacia do Solimões-Arco ou Rampa de Carauari? Anais do 13º Simpósio de Geologia da Amazônia 1, pp. 89–91.

Lovejoy, N.R., Albert, J.S., Crampton, W.G.R., 2006. Miocene marine incursions and marine/freshwater transitions: evidence from Neotropical fishes. J. S. Am. Earth Sci. 21, 5–13. http://dx.doi.org/10.1016/j.jsames.2005.07.009.

Lundberg, J.G., Marshall, L.G., Guerrero, J., Horton, B., Malabarba, M.C.S.L., Wesselingh, F.P., 1998. The stage for Neotropical fish diversification: a history of tropical South American rivers. In: Malabarba, L.R., Reis, R.E., Vari, R.P., Lucena, Z.M., Lucena, C.A.S. (Eds.), Phylogeny and Classification of Neotropical Fishes, pp. 13–48. Porto Alegre, Edipucrs.

Maia, R.G.N., Godoy, H.O., Yamaguti, H.S., Moura, P.A., Costa, F.S.F., Holanda, M.A., Costa, J.A., 1977. Projeto Carvão No Alto Solimões; Relatório Final, vol. 1. CPRM; DNPM, Manaus, p. 142.

Malabarba, M.C., Dutra, M.F.A., 2002. Fossil fish remains from the Solimões Formation (Miocene) of the state of Amazonas, Brazil. Acta Geol. Leopoldensia 54, 11–19.

Mendes, A.C., Truckenbrod, W., Nogueira, A.C.R., 2012. Análise faciológica da Formação Alter do Chão (Cretáceo, Bacia do Amazonas), próximo à cidade de Óbidos, Pará, Brasil. Rev. Bras. Geociências 42 (1), 39–57.

Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer, Berlin, p. 582.

Monsch, K.A., 1998. Miocene fish faunas from the northwestern Amazonia Basin (Colombia, Peru, Brazil) with evidence of marine incursions. Palaeogeogr. Palaeoclimatol. Palaeoecol. 143, 31–50. http://dx.doi.org/10.1016/S0031-0182(98)00064-9.

Mora, A., Baby, P., Roddaz, M., Parra, M., Brusset, S., Hermoza, W., Espurt, N., 2010. Tectonic history of the Andes and sub-Andean zones: implications for the development of the Amazon drainage basin. In: Hoorn, C., Wesselingh, E.P. (Eds.), Amazonia: Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, pp. 38–60.

Muñoz-Torres, F., Whatley, R., Van Harten, D., 1998. The endemic non-marine Miocene ostracod fauna of the upper Amazon Basin. Rev. Española Micropaleontol. 30 (3), 89–105.

Muñoz-Torres, F., Whatley, R., Van Harten, D., 2006. Miocene ostracod (Crustacea) bioestratigraphy of the upper Amazon Basin and evolution of the genus Cyprideis. J. S. Am. Earth Sci. 21, 75–86. http://dx.doi.org/10.1016/j.jsames.2005.08.005.

Murray, J.W., 1991a. Ecology and Paleoecology of Benthic Foraminifera. Longman Scientific & Technical, New York, ISBN 0470216867, p. 397.

Murray, J.W., 1991b. Ecology and distribution of benthic foraminifera. In: Lee, J.L., Anderson, R. (Eds.), Biology of Foraminifera. Academic Press, New York, pp. 221–253.

Nogueira, A.C.R., Silveira, R., Guimarães, J.T.F., 2013. Neogene–Quaternary sedimentary and paleovegetation history of the eastern Solimões Basin, central Amazon region. J. S. Am. Earth Sci. 46, 89–99. http://dx.doi.org/10.1016/j.jsames.2013.05.004.

Paz, J.D.S., Ramos, M.I.F., Moraes-Santos, H.M., Silva-Caminha, S.A., 2015. Depósitos fluviais e deltaicos da Formação Solimões, Bacia do Solimões, Eirunepé (AM), Brasil. In: Gorayeb, P.S.S., Lima, A.M.M. (Eds.), Contribuições à geologia da Amazônia, Sociedade Brasileira de Geologia, vol. 9, pp. 81–92. Núcleo Norte.

Purper, I., 1977a. Some ostracodes from the upper Amazon basin, Brazil. Environment and age. In: Loffler, H., Danielopol, D. (Eds.), Aspects of Ecology and Zoogeography of Recent and Fossil Ostracoda, pp. 353–367. Sixth International Ostracods Symposium, Saalfelden.

Purper, I., 1977b. Ostracodes cenozóicos da Amazônia Ocidental. Tese de doutorado. Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Rio Grande do Sul, p. 131.

Purper, I., 1979. Cenozoic ostracods of the upper Amazon basin, Brazil. Pesquisas 12, 209–281.

Radambrasil, 1977. Folha SB.19 Juruá: geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. DNPM, Brasil, p. 436.

Ramos, M.I.F., 2006. Ostracods from the Neogene Solimões Formation (Amazonas, Brazil). J. S. Am. Earth Sci. 21, 87–95. http://dx.doi.org/10.1016/j.jsames.2005.08.001.

Räsänen, M.E., Linna, A.M., Santos, J.C.R., Negri, F.R., 1995. Late Miocene tidal deposits in the Amazonian foreland basin. Science 269, 386–390.

Rebata, L.A., 2012. Peru. Doctoral thesis. The Sedimentology, Ichnology and Hydrogeochemistry of the Late Miocene, Marginal Marine, Upper Pebas and Nauta Formations, Amazonian Foreland Basin, vol. 275. University of Turku, Annales Universitatis Turkuensis, ISBN 978-951-29-5217-5, pp. 1–45.

Roddaz, M., Hermoza, W., Mora, A., Baby, P., Parra, M., Christophoul, F., Brusset, S., Espurt, N., 2010. Cenozoic sedimentary evolution of the Amazonian foreland basin system. In: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia, Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, pp. 61–88.

Rossetti, G., Martens, K., 1998. Taxonomic revision of the Recent and Holocene representatives of the family Darwinulidae (Crustacea, Ostracoda), with a description of three new genera. Bull. l'Institut R. Sci. Nat. Belg. 68, 55–110.

Roxo, M.G.O., 1924. Breve notícia sobre os fósseis Terciários do Alto Amazonas. Bol. do Serviço Geol. Miner. do Bras. 11, 41–52.

Ruiz, F., Abad, M., Bodergat, A.M., Carbonel, P., Rodríguez-Lázaro, J., González-Regalado, M.L., Toscano, A., García, E.X., Prenda, J., 2013. Freshwater ostracods as environmental tracers. Int. J. Environ. Sci. Technol. 10, 1115–1128.

Shepard, L., Bate, R., 1980. Plio-pleistocene ostracods from the upper Amazon of Colombia and Peru. Palaeontology 23 (1), 97–124.

Shephard, G.E., Müller, R.D., Gurnis, M., 2010. Miocene drainage reversal of the Amazon River driven by plate-mantle interaction. Nat. Geosci. 3 (12), 870–875. http://dx.doi.org/10.1038/ngeo1020.

Silva-Caminha, S.A.F., Jaramillo, C.A., Absy, M.L., 2010. Neogene palynology of the Solimões basin, Brazilian Amazonia. Palaeontogr. B 284, 13–79.

Silveira, R.R., Souza, P.A., 2015. Palinologia (grãos de pólen de angiospermas) das Formações Solimões e Içá (Bacia do Solimões), nas regiões de Coari e Alto Solimões. Amazon. Rev. Bras. Paleontol. 18 (3), 455–474.

Tucker, M., 2011. Sedimentary Rocks in the Field: a Practical Guide, fourth ed. Wiley-Blackwell, Chichester, ISBN 978-0-470-68916-5, p. 288.

Tyszka, J., 1997. Miliammina gerochi n.sp. - a Middle Jurassic Rzehakinid (Foraminiferida) from quasi-anaerobic biofacies. Ann. Soc. Geol. Pol. 67, 355–364.

Uesugui, N., 1979. Palinologia: técnicas de tratamento de amostras. Bol. Técnico Petrobras 22 (4), 229–240.

Van Harten, D., 2000. Variable noding in Cyprideis torosa (Ostracoda, Crustacea): an overview, experimental results and a model from Catastrophe Theory. In: Horne, D.J., Martens, K. (Eds.), Evolutionary Biology and Ecology of Ostracoda. Springer, Dordrecht, pp. 131–139. http://dx.doi.org/10.1007/978-94-017-1508-9_10 (Developments in Hydrobiology. vol. 148).

Vonhof, H.B., Wesselingh, F.P., Gringas, G.K., 1998. Reconstruction of the Miocene western Amazonian aquatic system using molluscan isotopic signatures. Palaeogeogr. Palaeoclimatol. Palaeoecol. 141, 85–93.

Vonhof, H.B., Wesselingh, F.P., Kaandorp, R.J.G., Davies, G.R., van Hinte, J.E., Guerrero, J., 2003. Paleogeography of Miocene western Amazonia: isotopic composition of molluscan shells constrains the influence of marine incursions. Geol. Soc. Am. Bull. 115, 983–993, 10.1130/B25058.1.

Wanderley, M.D., 2010. Técnicas de preparação de microfósseis. In: Carvalho, I.S. (Ed.), Paleontologia: Microfósseis, Paleoinvertebrados, pp. 65–80. Interciência, Rio de Janeiro.

Wanderley Filho, J.R., Eiras, J.F., Cunha, P.R.C., van der Ven, P.H., 2010. The paleozoic Solimões and Amazonas basins and the Acre foreland basin of Brazil. In: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, pp. 29–37.

Wesselingh, F.P., Ramos, M.I.F., 2010. Amazonian aquatic invertebrate faunas (Mollusca, Ostracoda) and their development over the past 30 million years. In: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, pp. 302–316.

Wesselingh, F.P., Salo, J., 2006. A Miocene perspective on the evolution of Amazonian biota. Scr. Geol. 133, 439–458.

Wesselingh, F.P., Guerrero, J., Räsänen, M.E., Romero Pitmann, L., Vonhof, H.B., 2006a. Landscape evolution and depositional processes in the Miocene Amazonian Pebas lake/wetland system: evidence from exploratory boreholes in northeastern Peru. Scr. Geol. 133, 323–381.

Wesselingh, F.P., Hoorn, M.C., Guerrero, J., Räsänen, M.E., Romero Pittmann, L., Salo, J., 2006b. The stratigraphy and regional structure of Miocene deposits in western Amazonia (Peru, Colombia and Brazil), with implications for Late Neogene landscape evolution. Scr. Geol. 133, 291–322.

Wesselingh, F.P., Räsänen, M.E., Irion, G., Vonhof, H.B., Kaandorp, R.J.G., Renema, W., Romero-Pittman, L., Gingras, M.K., 2002. Lake Pebas: a palaeoecologial reconstruction of a Miocene, long-lived lake complex in western Amazonia. Cainozoic Res. 1, 35–81.

Wesselingh, F.P., 2006. Molluscs from the Miocene Pebas Formation of peruvian and colombian Amazonia. Scr. Geol. 133, 19–290.

Whatley, R.C., Muñoz-Torres, F., Van Harten, D., 1998. The Ostracoda of isolated Neogene saline lake in the western Amazon Basin. In: Crasquin-Soleau, S., Braccini, E., Lethiers, F. (Eds.), What about Ostracoda! Actes du 3º Congrès Européen des Ostracodologistes, vol. 20. Bulletin du Centre de recherches Elf exploration production, pp. 231–245. Mémoire.

Whatley, R.C., Muñoz-Torres, F., Harten, D.Van, 2000. Skopaeocythere: a minute new limnocytherid (Crustacea, ostracoda) from the Neogene of the Amazon basin. Ameghiniana 37 (2), 163–167.

# CAPÍTULO 5

## 5 CONSIDERAÇÕES FINAIS

### 5.1 NOVAS CONTRIBUIÇÕES PARA A TAXONOMIA DE OSTRACODES DA FORMAÇÃO SOLIMÕES NA REGIÃO DE ATALAIA DO NORTE, AMAZONAS BRASIL, COM A DESCRIÇÃO DE NOVAS ESPÉCIES

O estudo de ostracodes provenientes dos testemunhos 1AS-7D-AM, 1AS-8-AM e 1AS-31-AM, vem a contribuir com novos dados sobre a interpretação da evolução paleoambiental e da idade da Formação Solimões. Além da ostracofauna, outros microfósseis como foraminíferos, ictiólitos e moluscos, além dos palinomorfos, foram utilizados como ferramenta auxiliar para as interpretações. A ostracofauna é representada por 9 gêneros e 30 espécies, sendo ogênero eurihalino *Cyprideis* o mais abundante e diverso, com o registro de 16 espécies já identificadas e duas novas espécies descritas neste trabalho: *C. atalaiensis* sp. nov. e *C. dictyon* sp. nov. A grande diversidade morfológica desse gênero confirma a alta variabilidade intraespecífica relacionada as mudanças paleoambientais, as quais foram desencadeadas por incursões marinhas que atingiram o Neógeno da Formação Solimões, evidenciando sua plasticidade ecofenotípica. Outros gêneros de origem marinha e/ou transicional (*Paracypris*, *Perissocytheridea*, *Rhadinocytherura*, *Pellucistoma* e *Skopaeocythere*) e não-marinha (*Cypria*, *Cytheridella* e *Penthesilenula*) também foram encontrados.

### 5.2 BIOESTRATIGRAFIA INTEGRADA COM BASE EM PALINOLOGIA E OSTRACODES DA FORMAÇÃO (ATALAIA DO NORTE, AMAZONAS, BRASIL)

O estudo integrado de amostras contendo ostracodes e palinomorfos nos testemunhos 1AS-8-AM e 1AS-7D-AM, permitiu datar a sequência estudada do Mioceno Inferior ao Mioceno Superior. Foram observadas, através dos fósseis- index, cinco zonas palinológicas já propostas para o Neógeno da Amazônia Ocidental: *Verrutricolporites*, Mioceno Inferior (1AS-8-AM), *Psiladiporites–Crototricolpites*, final do Mioceno Inferior ao início do Mioceno Médio (1AS-7D-AM); *Crassoretitriletes*, Mioceno Médio (1AS-7D-AM); *Grimsdalea*, final do Mioceno Médio ao início do Mioceno Superior (ambos testemunhos) e *Asteraceae*, Mioceno Superior (1AS-7D-AM). A distribuição das espécies de *Cyprideis* permitiu reconhecer cinco zonas correspondentes às zonas palinológicas, das quais quatro zonas já estabelecidas anteriormente, embora seus limites temporais tenham sido alterados nesse estudo (ambos os testemunhos): *C. aulakos*, renomeada para *C. sulcosigmoidalis*, final do Mioceno Inferior a início do Mioceno Médio; *C. caraionae*, Mioceno Médio a início do Mioceno Superior; *C. minipunctata*, início do Mioceno Superior; e *C. cyrtoma*, início do Mioceno Superior. Além disso, nós propomos uma nova zona de ostracode, *Cyprideis paralela*, datada para o Mioceno Superior (1AS-7D-AM).

## 5.3 O SIGNIFICADO DA PRESENÇA DE MICROFÓSSEIS MARINHOS NA RECONSTRUÇÃO PALEOAMBIENTAL DO NEÓGENO DA FORMAÇÃO SOLIMÕES, AMAZÔNIA OCIDENTAL, BRASIL.

A ocorrência de microfósseis de origem marinha à estuariana nos testemunhos de sondagem 1AS-7D-AM e 1AS-8-AM (Município de Atalaia do Norte, Estado do Amazonas), indica três possíveis eventos de incursão marinha na Formação Solimões: o primeiro registrado no Mioceno Inferior ao Mioceno Médio (em ambos testemunhos), o segundo no final do Mioceno Médio a início do Mioceno Superior (1AS-8-AM), e o terceiro no Mioceno Superior (1AS-7D-AM). Os dados demonstram que essas incursões modificaram a paisagem amazônica, demonstrando proximidade com ambientes tipicamente costeiros, como manguezais, estuários e/ou lagunas. Na porção mais superior da Formação Solimões, essas condições desaparecem e são substituídas por um sistema flúvio-lacustre semelhante à paisagem moderna. Como consequência, o efeitos da Orogenia Andina, além da influência do mar nos depósitos da Amazônia Ocidental, desencadearam variações ambientais durante o Neógeno, o que, consequentemente, promoveu a grande biodiversidade existente na região.

## REFERÊNCIAS

Anderson, L.C., Hartman, J.H., Wesselingh, F.P. 2006. Close evolutionary affinities between freshwater corbulid bivalvesfrom the Neogene of western Amazonia and Paleogene of the northern Great Plains, USA. *Journal of South American Earth Sciences*, **21**: 28–48.

Albert, J.S. & Reis, R.E. (Eds.). 2011. Historical Biogeography of Neotropical Freshwater Fishes. University of California. Press, Berkeley, p. 388.

Antoine, P., Abello, M.A., Adnet, S., Altamirano Sierra, A.J., Baby, P., Billet, G., Boivin, M., Calderon, Y., Candela, A., Chabain, J., Corfu, F., Croft, D.A., GanerØd, M., Jaramillo, C., Klaus, S., Marivaux, L., Navarrete, R.E., Orliac, M.J., Parra, F., Perez, M.E., Pujos, F., Rage, J., Ravel, A., Robinet, C., Roddaz, M., Tejada-Lara, J.V., Velez-Juarbe, J., Wesselingh, F.P., Salas-Gismondi, R. 2016. A 60-million-year Cenozoic history of western Amazonian ecosystems in Contamana, eastern Peru. *Gondwana Research*, **31**:30–59.

Bocquentin, J. & Melo, J., 2006. Stupendemys souzai sp. Nov. (Pleurodira, Podocnemididae) fromthe Miocene-Pliocene of The Solimões Formation, Brazil. *Revista brasileira de paleontologia*, **9**(2): 187–192.

Boonstra, M., Troelstra, S.R., Lammertsma, E.I., Ramos, M.I.F., Antoine, P.-O., Hoorn, C. 2015. Marine connections of Amazonia: evidence from foraminifera and dinoflagellate cysts (early to middle Miocene, Colombia/Peru). *Palaeogeography, Palaeoclimatology, Palaeoecology,* **417**: 176–194.

Bezerra, P.E.L. & Ribeiro, D.T. 2015. Evoluçao tectônica cenozoica da Amazônia Ocidental. *In*: Gorayeb, P.S.S., Lima, A.M.M. (Eds.), Contribuições à geologia da Amazonia, Sociedade Brasileira de Geologia, Núcleo Norte, **9**: 139–155.

Bold van den, W.A. 1988. Neogene Paleontology in the northern Dominican Republic 7. The Subclass Ostracoda (Arthropoda:Crustacea). *Bull. Am. Paleontol.*, **94**(329): 1–105.

Caputo, M.V., Rodrigues, R., Vasconcelos, D.N.N. 1971. Litoestratigrafia da Bacia do Rio Amazonas. *Relatório Técnico Interno. 641-A.* Petrobrás- Renor, Belém, p. 35–46.

Eiras, J.F., Becker, C.R., Souza, E.M., Gonzaga, F.G., Silva, G.F., Daniel, M.L.F., Matsuda, N.S, Feijó, F.J. 1994. Bacia do Solimões. *Boletim Geociências Petrobrás*, Rio de Janeiro, **8**(1) : 17–49.

Eiras, J.F. 1998. Tectônica, Sedimentação e Sistemas Petrolíferos da Bacia do Solimões, Estado do Amazonas *In*: *Searching for Oil and Gas in the Land of Giants*. *The Search Magazine*, Edição Especial sobre o Brasil. Schlumberger, Argentina S.A.

Espurt, N., Baby, P., Brusset, S., Roddaz, M., Hermoza, W., Barbarand, J. 2010. The Nazca ridge and uplift of the Fitzcarrald arch: implications for regional geology in northern South America. *In*: Hoorn, C.; Wesselingh, F. (Eds.). Amazonia, landscape and species evolution: a look into the past. Wiley-Blackwell, p. 89–100.

Figueiredo, J., Hoorn, C., van der Ven, P., Soares, E. 2009. Late Miocene onset of the Amazon River and the Amazon deep-sea fan: Evidence from the Foz do Amazonas Basin. *Geology,* **37**: 619–622.

Gaffney, E.S., Campbell, K.E., Wood, R.C. 1998. Pelomedusoid side-necked turtles from late Miocene sediments in southwestern Amazonia. *American Museum Novitates*, **3245**(5): 1–11.

Gardner, J. 1927. A recent collection of late Pliocene invertebrates from the head-waters of the Amazon. *Journal of the Washington Academy of Science*, Washington, **17**(20): 505–509.

Gingras, M.K., Räsänen, M., Pemberton, G.S., Romero L.P. 2002. Ichnology and sedimentology reveal depositional characteristics of bay-margin parasequenses in the Miocene Amazonian foreland Basin. *Journal of Sedimentary Research*, **72**(6): 871–883.

Gold, O. 1967. Pesquisa Preliminar de Carvão ou Lignito na Bacia Terciária do Alto Amazonas. Comissão do Plano do Carvão Nacional, *Relatório Final*. Rio de Janeiro.

Gomez, A., Jaramillo, C., Parra, M., Mora, A. 2009. Huesser horizon: A lake and a marine incursion in Northwestern South America during early Miocene. *Palaios*, **24**: 199–210.

Gross, M., Piller, W.E., Ramos, M.I., Paz, J.D.S. 2011. Late Miocene sedimentary environments in south-western Amazonia (Solimões Formation; Brazil). *Journal of South American Earth Sciences*, **32**: 169–181.

Gross, M., Ramos, M. I., Caporaletti, M., Piller, W.E. 2013. Ostracods (Crustacea) and their paleoenvironmental implication for the Solimões Formation (Late Miocene; Western Amazonia/Brazil). *Journal of South American Earth Sciences,* **42**: 216–241.

Gross, M., Ramos, M.I., Piller, W.E. 2014. On the Miocene Cyprideis species flock (Ostracoda; Crustacea) of Western Amazonia (Solimões Formation): Refining taxonomy on species level. *Zootaxa*, **3899**(1): 1–69.

Gross, M., Ramos, M.I.F., Piller, W.E. 2015. A minute ostracode (Crustacea: Cytheromatidae) from the Miocene Solimões Formation (western Amazonia, Brazil): evidence for marine incursions?. *Journal of Systematic Palaeontology*, **14**(7): 581–602.

Hoorn, C. 1993. Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **105**: 267–309.

Hoorn, C. 1994a. Fluvial palaeoenvironments in the intracratonic Amazonas Basin (Early Miocene-early Middle Miocene, Colombia). *Palaeogeography, Palaeoclimatology, Palaeoecology,* **109**:1–54.

Hoorn, C. 1994b. An environmental reconstruction of the palaeo-Amazon River system (Middle-Late Miocene, NW Amazonia). *Palaeogeography, Palaeoclimatology, Palaeoecology,* **112**:187–238.

Hoorn, C. 1996. Miocene Deposits in the Amazonian Foreland Basin. *Science,* **273**: 122–123.

Hoorn, C., Wesselingh, F.P., Hovikoski, J., Guerrero, J. 2010a. The development of the Amazonian mega-wetland (Miocene; Brazil, Colombia, Peru, Bolivia). *In*: Hoorn, C., Wesselingh, F.P. (Eds). Amazonia: Lanscape and species evolution, a look into the past. Wiley-Blackwell, p. 123–142.

Hoorn, C., Wesselingh, F.P., ter Steege, H., Bermudez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramilho, C., Riff, D., Negri, F.R. Hooghiemstra, H., Stadler, T., Särkinen, T., Antonelli, A. 2010b. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science,* **330**: 927–931.

Hoorn, C., Bogota-A, G.R., Romero-Baez, M., Lammertsma, E.I., Flantua, S.G.A., Dantas, E.L., Dino, R., do Carmo, D.A., Chemale Jr., F. 2017. The Amazon at sea: onset and stages of the Amazon River from a marine record, with special reference to Neogene plant turnover in the drainage basin. *Global Planet Change*, **153**: 51–65.

Hovikoski, J., Räsänen, M., Gingras, M.K., Lopez, S. Ranzi, A., Melo, J. 2007. Palaeogeographical implications of the Miocene Quendeque Formation (Bolívia) and tidally-influenced strata in the southwestern Amazonia *Palaeogeography, Palaeoclimatology, Palaeoecology,* **243:** 23–41.

Hovikoski, J., Wesselingh, F.P., Räsänen, M.E., Gingras, M.K., Vonhof, H.B. 2010. Marine influence in Amazonia: evidence from the geological record. *In*: Hoorn, C., Wesselingh, F.P. (Eds) Amazonia: Lanscape and species evolution, a look into the past, Wiley-Blackwell, p. 143–161.

Jaramillo, C., Rueda, M., Torres, V. 2011. A Palynological Zonation for the Cenozoic of the Llanos Foothills of Colombia. *Palynology,* **35**: 46–84.

Jaramillo, C., Romero, I., D'Apolito, C., Bayona, G., Duarte, E., Louwye, S., Escobar, J., Luque, J., Carrillo-Briceño, J.D., Zapata, V., Mora, A., Schouten, S., Zavada, Z., Harrington, G., Ortiz, J., Wesselingh, F.P. 2017. Miocene flooding events of western Amazonia. *Science Advances,* **3**(5): 1–11.

Jones T.R. 1857. A monograph of the Tertiary Entomostraca of England. *Monograph of the Palaeontographical Society of London,* **9**: 1–55.

Kachniasz, K.E. & Silva-Caminha, S.A.F. 2016. Palinoestratigrafia da Formação Solimões: comparação entre bioestratigrafia tradicional e o método de associações unitárias. *Revista Brasileira de Paleontologia,* **19**(3): 481–490.

Kaandorp, R.J.G., Wesselingh, F.P. Vonhof, H.B. 2006. Ecological implications from geochemical records of Miocene Western Amazonian bivalves. *Journal of South American Earth Sciences,* **21**: 24–74.

Latrubesse, E.M., Bocquentin, J., Santos, J.C.R., Ramonell, C.G. 1997. Paleoenvironmental model for the Late Cenozoic of southwestern Amazonia: paleontology and geology. *Acta Amazonica,* **27**(2): 103–118.

Latrubesse, E.M., Silva, S.A.F., Cozzuol, M., Absy, M.L. 2007. Late Miocene continental sedimentation in southwestern Amazonia and its regional signifiance: Biotic and geological evidence. *Journal of South American Earth Sciences,* **23**: 61–80.

Latrubesse, E.M., Cozzuol, M., Silva-Caminha, S.A.F., Rigsby, C.A., Absy, M.L., Jaramillo, C.A. 2010. The Late Miocene paleogeography of the Amazon Basin and the evolution of the Amazon River system. *Earth-Science Reviews,* **99**: 99–124.

Leandro, L.M. 2012. Análises palinoestratigráficas da Formação Solimões na porção noroeste do Alto Solimões, Amazonas, Brasil. Instituto Tecnológico de Micropaleontologia, Dissertação de Mestrado, Universidade do Vale do Rio dos Sinos, 108 p.

Leite, F.P.R. 2006. Palinologia da Formação Solimões, Neógeno da Bacia do Solimões, Estado do Amazonas: Implicações paleoambientais e bioestratigráfias. Instituto de Geociências, Universidade de Brasília, Tese de Doutorado, 128 p.

Leite, F.P.R., Paz, J.D., Carmo, D.A., Silva-Caminha, S.A.F. 2016. The effects of the inception of Amazonian transcontinental drainage during the Neogene on the landscape and vegetation of the Solimões Basin, Brazil. *Palynology,* 1–11.

Linhares, A.P.P. 2011. Ostracodes da Formação Solimões, Neógeno do Estado do Amazonas, Brasil: taxonomia, paleoecologia e bioestratigrafia. Programa de pós-Graduação em Geologia e Geoquímica, Universidade Federal do Pará, Dissertação de Mestrado, 112 p.

Linhares, A.P., Ramos, M.I.F., Gross, M., Piller, W.E. 2011. Evidence for marine influx during the Miocene in southwestern Amazonia, Brazil. *Geología Colombiana*, **36**(1): 91–104.

Lisboa, L.G.S., Wanderley Filho, J.R., Travassos, W.A.S. 2013. Bacia do Solimões-arco ou Rampa de Carauari? *Anais do 13º Simposio de Geologia da Amazônia*, **1**: 89–91.

Lorente, M.A. 1986. Palynology and palynofacies of the Upper Tertiary of Venezuela. Dissertationes Botanicae, 222 p.

Lovejoy, N.R., Albert, J.S., Crampton, W.G.R. 2006. Miocene marine incursions and marine/freshwater transitions: Evidence from Neotropical fishes. *Journal of South American Earth Sciences,* **21**: 5–13.

Lovejoy, N.R., Willis, S. C., Albert, J.S. 2010. Molecular signatures of Neogene biogeographical events in the. *In*: Hoorn, C., Wesselingh, F.P. (Eds) Amazonia: Lanscape and species evolution, a look into the past, Wiley-Blackwell, p. 405–417.

Lundberg, J.G., Marshall, L.G., Guerrero, J., Horton, B., Malabarba, M.C.S.L., Wesselingh, F.P. 1998. The Stage for Neotropical fish diversification: a history of tropical South American Rivers. *In*: Malabarba L.R., Reis R.E., Vari R.P., Lucena Z.M., Lucena C.A.S (Eds). *Phylogeny and Classification of Neotropical Fishes*. Porto Alegre, Edipucrs, p. 13–48.

Lundberg, J.G., Pérez, M.H.S., Dahdul, W.M., Aguilera, O.A. (2010): The Amazonian Neogene fish fauna. *In*: Hoorn, C., Wesselingh, E.P. (Eds.) Amazonia: Landscape and species evolution, a look into the past. Wiley-Blackwell, p. 38–60.

Maia, R.G.N., Godoy, H.O., Yamaguti, H.S., Moura, P.A., Costa, F.S.F., Holanda, M.A., Costa, J.A. 1977. *Projeto Carvao No Alto Solimões*; Relatório Final, vol. 1. CPRM; DNPM, Manaus, p. 142.

Maury, C.J. 1937. Argillas fossilíferas do Plioceno do Território do Acre. *Boletim do Serviço Geológico e Mineralógico do Brasil*, DNPM, Rio de Janeiro, **77**: 1–29.

Malabarba, M.C.S.L. and Dutra, M.F. 2002. Fossil fish remains from the Solimões Formation (Miocene) of the State of Amazonas, Brazil. *Acta Geologica Leopoldensia*, **25**(54): 11–19.

Malabarba, M.C.S.L., Oliveira, M.M., Cunha, L.F. 1998. Some Callichthyidae fossil remains (Ostariophysi: Siluriformes) from the Solimões Formation, Acre State, northern Brazil. *Comunicações do Museu de Ciências e Tecnologia da PUCRS. Série Zoologia*, Porto Alegre, **11**: 99–107.

Meylan, P.A., Gaffney, E.G., Campos, D.A. 2009. Caninemys, a New Side-Necked Turtle (Pelomedusoides: Podocnemididae) from the Miocene of Brazil, *American Museum Novitates*, **3639**: 1–26.

Mones, A. & Toledo P.M. 1989. Primer hallazgo de Euphilus Ameghino, 1889 (Mammalia:Rodentia:Neoepible midae) em el Neogeno del Estado do Acre, Brasil. *Contribuciones Paleontologicas Museu Historia Natural de Montevideo*, **21**: 1–15.

Monsch, K.A. 1998. Miocene fish faunas from the northwestern Amazonia Basin (Colombia, Peru, Brazil) with evidence of marine incursions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **143**: 31–50.

Mora, A., Baby, P., Roddaz, M., Parra, M., Brusset, S., Hermoza, W., Espurt, N. 2010. Tectonic history of the Andes and sub-Andean zones: implications for the development of the Amazon drainage basin. *In*: Hoorn, C., Wesselingh, E.P. (Eds.) Amazonia: Landscape and species evolution, a look into the past. Wiley-Blackwell, p. 38–60.

Moraes Rêgo, L.F. 1930. Notas sobre a Geologia do território do Acre e da Bacia do Javari. Cezar & Cavalcante, Manaus, 45 p.

Muñoz-Torres, F., Whatley, R., Van Harten, D. 1998. The endemic non-marine Miocene ostracod fauna of the upper Amazon Basin. *Revista Española de Micropaleontología*, **30**(3): 89–105.

Muñoz-Torres, F., Whatley, R., Van Harten, D. 2006. Miocene ostracod (Crustacea) bioestratigraphy of the upper Amazon Basin and evolution of the genus *Cyprideis*. *Journal of South American Earth Sciences*, **21**: 75–86.

Negri, F.R., Bocquentin-Villanueva, J., Ferigolo, J., Antoine, P. 2010. A review of the Tertiary mammal faunas and birds from western Amazonia *In*: Hoorn C. & Wesselingh F.P.

(eds). Amazonia: Lanscape and species evolution, a look into the past, Wiley-Blackwell publications, p. 245–258.

Nogueira, A.C.R., Silveira, R., Guimarães, J.T.F. 2013. Neogene–Quaternary sedimentary and paleovegetation history of the eastern Solimões Basin, central Amazon region. *Journal of South American Earth Sciences*, **46**: 89–99.

Nuttall, C.P. 1990. A review of the Tertiary non-marine molluscan faunas of the Pebasian and other inland basins of north-western South America. *Bulletin of the British Museum of Natural History (Geology series)*, **45**: 165–371.

Paz, J.D.S., Ramos, M.I.F., Moraes-Santos, H.M., Silva-Caminha, S.A. 2015. Depositos fluviais e deltaicos da Formaçao Solimões, Bacia do Solimões, Eirunepé (AM), Brasil. *In*: Gorayeb, P.S.S., Lima, A.M.M. (Eds.), Contribuições à geologia da Amazonia, Sociedade Brasileira de Geologia, Núcleo Norte, **9**: 81–92.

Purper, I. 1977a. Some Ostracodes from the Upper Amazon Basin, Brazil. Environment and age. *In*: Loffler, H. Danielopol, D. (Eds), Aspects of Ecology and Zoogeography of Recent and Fossil Ostracoda. *Sixth International Ostracods Symposium, Saalfelden*, p. 353–367.

Purper, I. 1977b. Ostracodes cenozóicos da Amazônia Ocidental. Instituto de Geociências, *Universidade Federal do Rio Grande do Sul*, Rio Grande do Sul, Tese de Doutorado, 131 p.

Purper, I. 1979. Cenozoic Ostracods of the Upper Amazon Basin, Brazil. *Pesquisas*, **12**: 209–281.

Purper I. & Pinto I.D. 1983. New genera and species of ostracodes of the Upper Amazon Basin, Brasil. *Pesquisas*, **15**: 113–126.

Purper I. & Ornellas L.P. 1991. New Ostracodes of the Endemic Fauna of the Pebas Formation, Upper Amazon Basin, Brazil. *Pesquisas*, **18**: 25–30.

Ramos, M.I.F. 2006. Ostracods from the Neogene Solimões Formation (Amazonas, Brazil). *Journal of South American Earth Sciences*, **21**: 87–95.

Räsänen, M.E., Linna, A.M., Santos, J.C.R., Negri, F.R. 1995. Late Miocene tidal deposits in the Amazonian foreland basin. *Science*, **269**: 386–390.

Rebata, L.A. 2012. The sedimentology, ichnology and hydrogeochemistry of the late Miocene, Marginal Marine, Upper Pebas and Nauta formations, Amazonian Foreland Basin, Peru. Doctoral thesis. University of Turku, Annales Universitatis Turkuensis, 45 p.

Riff, D., Romano, P.S.R., Oliveira, G.R., Aguilera, O. 2010. Neogene crocodile and turtle fauna in northern South America. *In*: Hoorn C. & Wesselingh F.P. (eds). Amazonia: Lanscape and species evolution, a look into the past, Wiley-Blackwell publications, p. 259–280.

Roddaz, M., Baby, P., Brusset, S., Hermoza, W., Darrozes, J.M. 2005. Forebulge dynamics and environmental control in Western Amazonia: The case study of the Arch of Iquitos (Peru). *Tectonophysics*, **399**: 87–108.

Roddaz, M., Hermoza, W., Mora, A., Baby, P., Parra, M., Christophoul, F., Brusset, S., Espurt, N. 2010. Cenozoic sedimentary evolution of the Amazonian foreland basin system. *In*: Hoorn, C., Wesselingh, F.P. (Eds.) Amazonia, Landscape and species evolution, a look into the past. Wiley-Blackwell, p. 61–88.

Rossetti D.F., Cohen M.C.L., Tatumi S.H., Sawakuchi A.O., Cremon E.H., Mittani J.C.R., Bertani T.C., Munita C.J.A.S., Tudela D.R.G., Yee M, Moya G. 2015. Mid-Late Pleistocene OSL chronology in western Amazonia and implications for the transcontinental Amazon pathway, *Sedimentary Geology*, **330**:1–15.

Roxo, M.G.O. 1924. Breve notícia sobre os fósseis Terciários do Alto Amazonas. *Boletim do Serviço Geológico e Mineralógico do Brasil*, **11**: 41–52.

Roxo, M.G.O. 1935. Considerações sobre a Geologia e Paleontologia do Alto Amazonas. *Anais da Academia Brasileira de Ciências*, **7**(1): 62–68.

Roddaz, M., Hermoza, W., Mora, A., Baby, P., Parra, M., Christophoul, F., Brusset, S., Espurt, N. 2010. Cenozoic sedimentary evolution of the Amazonian foreland basin system. *In*: Hoorn, C., Wesselingh, F.P. (Eds.) Amazonia, Landscape and species evolution, a look into the past. Wiley-Blackwell, p. 61–88.

Shepard, L. & Bate, R. 1980. Plio-Pleistocene ostracods from the Upper Amazon of Colombia and Peru. *Palaeontology*, **23**(1), 97–124.

Silva, S.A.F. 2004. Palinologia do Neógeno da Amazônia Sul Ocidental, Brasil. Dissertação de mestrado. *Instituto Nacional de Pesquisa da Amazônia, Universidade Federal do Amazonas, Manaus*, 107 p.

Silva, S.A.F. 2008. Palinologia do Neógeno da Bacia do Alto Solimões, Amazônia Ocidental, Brasil: aspectos sistemáticos, bioestratigráficos e paleoecológicos. Tese de doutorado.

Programa de pós-graduação em Biologia Tropical e Recursos Humanos, *Universidade Federal do Amazonas*, *Manaus*, 169 p.

Silva-Caminha, S.A.F., Jaramillo, C.A., Absy, M.L. 2010. Neogene palynology of the Solimões Basin, Brazilian Amazonia. *Palaeontographica B*, **284**: 13–79.

Silveira, R.R. & Souza, P.A. 2015. Palinologia (grãos de pólen de angiospermas) das Formações Solimões e Içá (Bacia do Solimões), nas regiões de Coari e Alto Solimões, Amazonas. *Revista Brasileira de Paleontologia*, **18**(3): 455–474.

Souza Filho, J.P., Bocquentin, J.C., Negri, F.R. 1993. Um crânio de Hesperogavialis sp. (Crocodylia, Alligatoridae) do Mioceno Superior-Plioceno do Estado do Acre, Acre-Brasil. *Ameghiniana*, **30**: 321–356.

Uesugui, N. 1979. Palinologia: técnicas de tratamento de amostras. *Boletim Técnico Petrobrás*, **22**(4): 229–240.

Vonhof, H.B., Wesselingh, F.P., Gringas, G.K. 1998. Reconstruction of the Miocene western Amazonian aquatic system using molluscan isotopic signatures. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **141**: 85–93.

Vonhof, H.B., Wesselingh, F.P., Kaandorp, R.J.G., Davies, G.R., van Hinte, J.E., Guerrero, J. 2003. Paleogeography of Miocene western Amazonia: isotopic composition of molluscan shells constrains the influence of marine incursions. *Geological Society of America Bulletin*, **115**: 983–993.

Wanderley Filho, J.R.W., Eiras, J.F., Vaz, P.T. 2007. Bacia do Solimões. *Boletim de Geociências, Petrobras*, Rio de Janeiro, **15**(2): 217–225.

Wanderley Filho, J.R., Eiras, J.F., Cunha, P.R.C.; van der Ven, P.H. 2010. The Paleozoic Solimões and Amazonas basins and the Acre foreland basin of Brazil. *In*: Hoorn, C., Wesselingh, F.P. (Eds.) Amazonia: Landscape and species evolution, a look into the past. Wiley-Blackwell, p. 29–37.

Wanderley, M. 2010. Técnicas de preparação de microfósseis. *In*: Carvalho, I.S. (Eds), *Paleontologia*: *Microfósseis, paleoinvertebrados*. Interciência, Rio de Janeiro, p. 65–80.

Wesselingh, F.P., Räsänen, M.E., Irion, G., Vonhof, H.B., Kaandorp, R.J.G., Renema, W., Romero-Pittman, L., Gingras, M.K. 2002. Lake Pebas: a palaeoecologial reconstruction of a Miocene, long-lived lake complex in western Amazonia. *Cainozoic Research*, **1**: 35–81.

Wesselingh, F.P., Guerrero, J., Räsänen, M.E., Romero Pitmann, L., Vonhof, H.B. 2006a. Landscape evolution and depositional processes in the Miocene Amazonian Pebas lake/wetland system: evidence from exploratory boreholes in northeastern Peru. *Scripta Geologica*, **133**: 323–361.

Wesselingh, F.P., Hoorn, M.C., Guerrero, J., Räsänen, M.E., Romero Pittmann, L., Salo, J. 2006b. The stratigraphy and regional structure of Miocene deposits in western Amazonia (Peru, Colombia and Brazil), with implications for Late Neogene landscape evolution. *Scripta Geologica*, **133**: 291–322.

Wesselingh, F.P., Kaandorp, R.J.G., Vonhof, H.B., Räsänen, M.E., Renema, W. 2006c. The nature of aquatic landscapes in the Miocene of western Amazonia: an integrated palaeontological and geochemical approach. *Scripta Geologica*, **133**: 363–393.

Wesselingh, F.P., Ranzi, A., Räsänen, M.E. 2006d. Miocene freshwater Mollusca from western Brazilian Amazonia. *Scripta Geologica*, **133**: 419–437.

Wesselingh, F.P. & Ramos, M.I.F. 2010. Amazonian aquatic invertebrate faunas (Mollusca, Ostracoda) and their development over the past 30 million years. *In*: Hoorn, C., Wesselingh, F.P. (Eds.), Amazonia: Landscape and Species Evolution, a Look into the Past. Wiley-Blackwell, p. 302–316.

Whatley, R.C., Muñoz-Torres, F., Van Harten, D. 1998. The Ostracoda of isolated Neogene saline lake in the western Amazon Basin. In: Crasquin-Soleau, S., Braccini, E., Lethiers, F. (Eds.), What about Ostracoda! Actes du 3° Congrès Europeen des Ostracodologistes. *Bulletin du Centre de recherches Elf exploration production*, Memoire, **20**: 231–245.

UNIVERSIDADE FEDERAL DO PARÁ
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA E GEOQUÍMICA

## PARECER

## SOBRE A DEFESA PÚBLICA DE TESE DE DOUTORADO DE ANA PAULA LINHARES PEREIRA

A banca examinadora da tese de doutorado de **ANA PAULA LINHARES PEREIRA** orientada pela Prof.ª Dr.ª Maria Inês Feijó Ramos (MPEG), composta pelos professores doutores Dermeval Aparecido do Carmo (UnB), Gerson Fauth (UNISINOS), Orangel Antonio Aguilera Socorro (UFF) e Marcelo Cancela Lisboa Cohen (UFPA), após apresentação de sua tese intitulada "**OSTRACOFAUNA DA FORMAÇÃO SOLIMÕES (ATALAIA DO NORTE, AMAZONAS, BRASIL): TAXONOMIA, IMPLICAÇÕES PALEOAMBIENTAIS E BIOESTRATIGRÁFICAS**" emite o seguinte parecer:

A candidata realizou a sua apresentação de forma clara, organizada e segura em tempo hábil de 60 minutos. Durante a arguição demonstrou domínio da temática abordada e respondeu com segurança as perguntas que lhe foram formuladas pela banca. A tese foi apresentada na forma de três manuscritos, estando um em preparação, um submetido e outro já publicado em periódico internacional. Vale destacar a contribuição desta tese para a ampliação do conhecimento quanto a diversidade e paleobiologia de Ostracoda provenientes da Formação Solimões, bem como a utilização destes em estudos bioestratigráficos e de caracterização paleoambiental. Tais condições atendem plenamente às exigências para a obtenção do título de doutor. Portanto, a banca examinadora decidiu por unanimidade aprovar a tese de doutorado de Ana Paula Linhares Pereira.

Belém, 12 de setembro de 2017.

Maria Inês Feijó Ramos - Orientadora (MPEG)

Dermeval Aparecido do Carmo – Membro (UnB)

Gerson Fauth – Membro (UNISINOS)

Orangel Antonio Aguilera Socorro – Membro (UFF)

Marcelo Cancela Lisboa Cohen – Membro (UFPA)