

## Evidence for marine influx during the Miocene in southwestern Amazonia, Brazil

### Evidencias de influencia marina durante el Mioceno en el Sudoeste de la Amazonia (Brasil)

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#### Abstract

The possibility of marine incursions into the Amazonia during the Miocene has been the subject of discussion for a long time, while incomplete geological and paleontological data impedes the exact tracing of the proposed marine incursions. However, previous records of marine taxa mixed with transitional and non-marine fossils, including foraminifers, marginal marine mollusks, shark teeth, rays, mangrove pollen, ostracods and barnacles, indicate that marine influence was present, at least episodically, in Amazonia during the Neogene although fluvial and lacustrine environments predominated.

Here we present micropaleontological analyses of core samples (core 1AS - 31-AM) from the southwest of Amazonas State, Brazil of that corroborate marine influence during the Miocene. The samples, from between 170.90 and 174.40 m depth yielded a mixture of marine (mainly based on planktonic foraminifers and bryozoans), transitional and non-marine faunal elements. Some of these organisms are resilient by stress conditions, such as the ostracod *Cyprideis*, some mollusks and agglutinated foraminifers. The radiation of *Cyprideis* and the presence of noded *Cyprideis*-valves below and above the mixed faunal levels point to abrupt paleoenvironmental change related to salinity fluctuations (from marine normal to non-marine). These fossils and the particular morphologic (ecophenotypic traits) features can be associated with a short-lived marine incursion. The presence of planktonic foraminifers indicates that marine influence must have been much more profound than previously reported. The marine influence reached the central part of Amazonia, probably during the Early Middle Miocene age.

**Key-words:** Marine Miocene, Brazilian Amazonia, ostracods, Solimões Formation.

## Resumen

Probables incursiones marinas en la región Amazónica durante el Mioceno han sido objeto de debates durante mucho tiempo. La base de datos general, impide una exacta localización de las ingresiones marinas propuestas. Sin embargo, una mezcla de grupos marinos y de transición o no marinos como foraminíferos, moluscos marinos marginales, dientes de tiburones, rayas, polen de los manglares, ostrácodos y percebes han sido registradas en estudios previos. Esto indica que la influencia marina puede haber jugado, al menos esporádicamente, algún papel en los depósitos neógenos de la Amazonia, a pesar que los ambientes fluviales y lacustres fueron los predominantes. Recientes estudios micropaleontológicos con muestras de testigo (IAS-31-AM, profundidad de 302 m; 05°18'S / 71°02'O; río Ituí) del suroeste del estado Amazonas corroboran esta evidencia marina. Las muestras entre 170,90 y 174,40 metros de profundidad, contienen esporádicamente una mezcla de organismos marinos (principalmente basado en la presencia de foraminíferos y briozoarios), otra fauna de transición y también no marinos (principalmente de foraminíferos y ostrácodos). Aparte de estos elementos de la fauna, también la presencia de *Cyprideis* nodulares por debajo y por encima de los niveles de mezcla de fauna, indican fluctuaciones de los niveles de salinidad y cambios paleoambientales abruptos. Estos microfósiles y las características morfológicas particulares de los fósiles pueden estar relacionados con una ingesión marina de corta duración. Esta influencia marina que llegó a la parte central de la Amazonia, probablemente puede haber ocurrido durante el inicio del Mioceno Medio.

**Palabras clave:** Mioceno marino, Amazonia brasileña, ostrácodos, Formación Solimões.

## INTRODUCTION

Neogene deposits are widespread in Amazonia. In Brazil, these deposits are represented by the Solimões Formation that reflects part of the orogenetic history of Western Amazonia during the Neogene. Considerable environmental changes took place during this period when the uplift of the Andes Mountains and sea-level fluctuations affected the hydrographical, ecological and climate systems of this region (Shephard et al. 2010).

Previous studies recorded the presence of marine, transitional and non-marine fossil taxa in the Solimões Formation and others contemporaneous units, which indicates that marine conditions, at least sporadically, influenced Amazonia during the Neogene (Shepard & Bate 1980; Hoorn 1993, 1994 a, b; Räsänen et al. 1995; Monsch 1998; Muñoz-Torres et al. 1998; Wesselingh et al. 2002, 2006; Gingras et al. 2002; Hovikoski et al. 2010). However, a complex of fluvial and lacustrine environments generally predominated (Wesselingh et al. 2006; Ramos 2006; Lundberg et al. 2010; Hoorn 1996; Hoorn et al. 2010; Latrubesse et al. 2010; Gross et al. 2011), and the biostratigraphical correlation of different localities within the Solimões Formation remains problematic (see Hoorn & Wesselingh 2010).

Most investigations are restricted to only a few localities that cover relatively short stratigraphical range. The availability of core material from petroleum companies is usually difficult due to their policy of restrictive access, and is mostly limited to the western fringe of Amazonia where hydrocarbon resources are being explored. Most of the cores that have been analysed in detail originate from western Brazilian Amazonia where they were collected in the 1970's by the Geological Survey of Brazil (CPRM) to investigate the presence of lignite. The studies on these cores began with Purper (1979, employing ostracods), and was followed by Hoorn (1994a, 1994b, utilising pollen). The recent re-examination of these cores has focused mainly on palynological taxonomy, biostratigraphy and paleoecology (Leite 2006; Silva-Caminha et al. 2010; Latrubesse et al. 2007, 2010). The present paper presents a new micropaleontological analysis of samples from core IAS-31-AM (05°18'S/71°02'W, 302 m depth), located near the Ituí River, southwest of Amazonas state, Brazil (Figura 1). The main aim is to reconstruct the paleoenvironmental evolution of this area during the Miocene and to attempt correlations with previous studies.

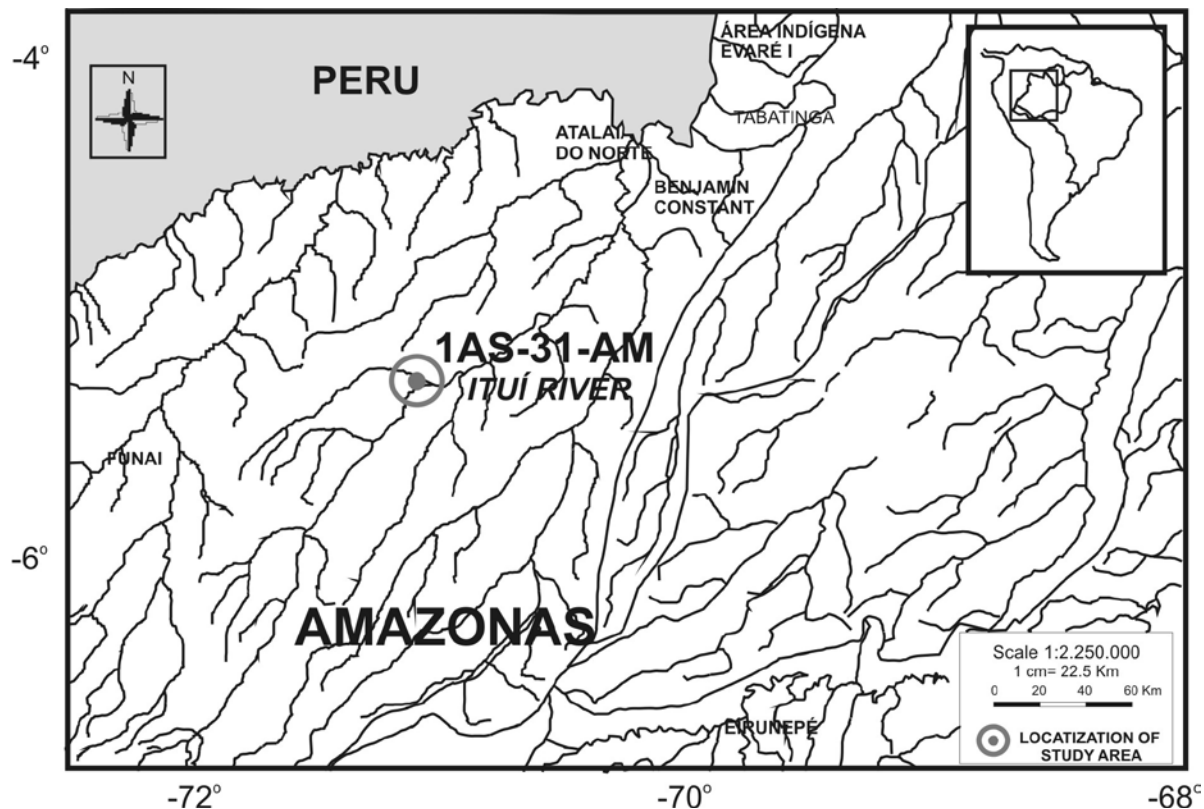


Figure 1. Location map of the study area (modified from RADAMBRASIL, 1977).

Figura 1. Mapa de la localidad estudiada (modificado del RADAMBRASIL, 1977).

## METHODOLOGY

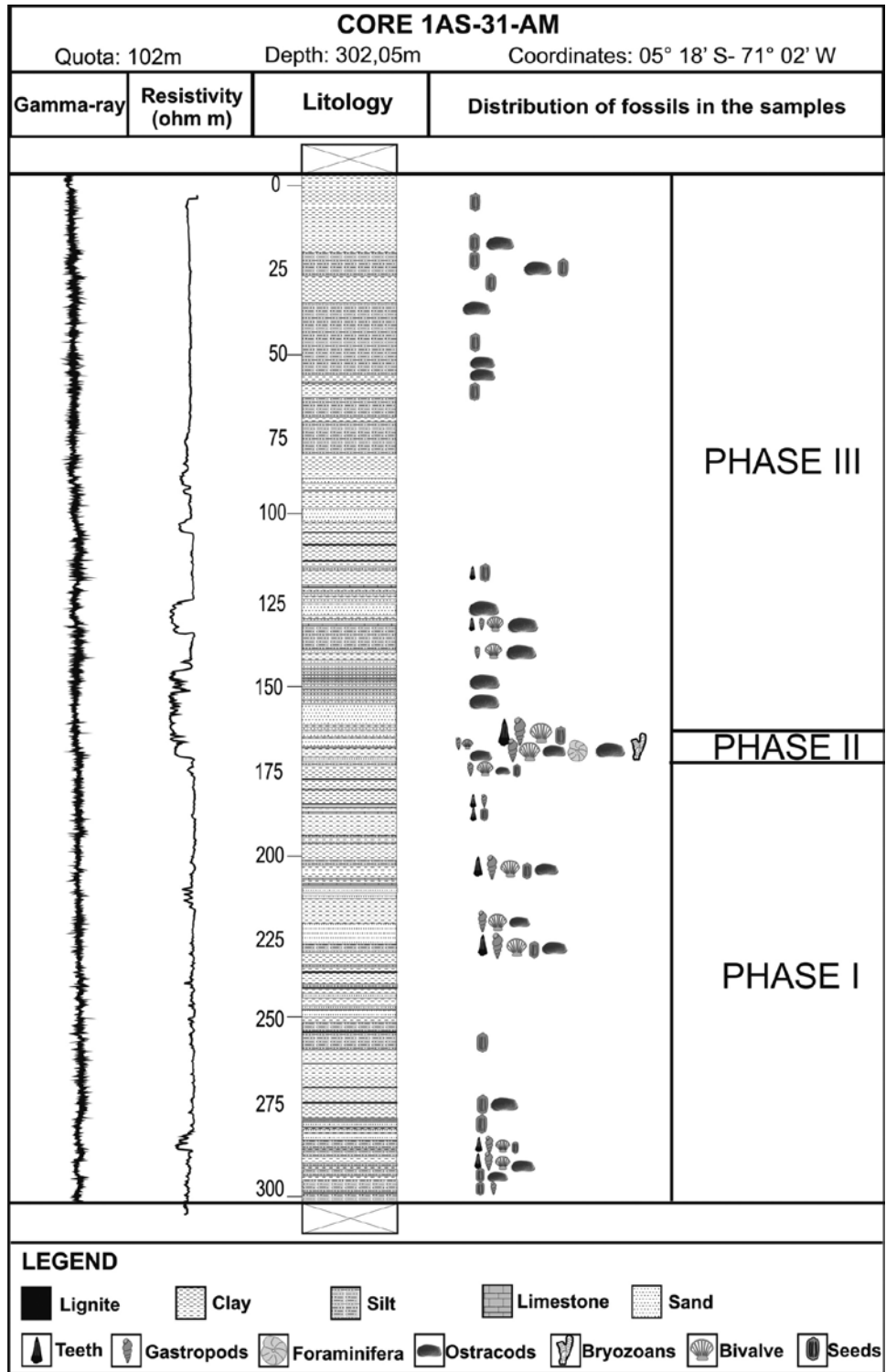
The study material comprise 93 samples from core 1AS-31-AM (Figura 2), drilled on the margin of the Ituí river (Maia et al. 1977). The core reached a depth of 302.05 m; five cm of sediment was taken from each cored sampled interval. Samples were processed following conventional micropaleontological techniques (250g of dry sediment sieved through a  $\geq 250\mu\text{m}$  size fractions). Microfossils were extracted from the sieve residual using a stereo microscope and then identified. Photographs were obtained by using LEO 1450VP SEM (Museu Paraense Emilio Goeldi, Belem, Para). The core samples were loaned by Departamento Nacional de Produção Mineral (8° Distrito, Manaus).

## RESULTS AND DISCUSSIONS

The genus *Cyprideis* comprises 90% of the ostracod fauna from the Solimões Formation with high diversity

and abundance (Muñoz-Torres et al. 1998, 2006). However, it also occurs with few marine, marginal-marine and freshwater taxa (e.g. *Paracypris*, *Pontocypris*, *Perissocytheridea*, *Cytheridella*, *Cypria*, *Darwinula*, *Heterocypris*) at different localities in the Neogene of Amazonia (Purper 1979; Shepard & Bate 1980; Whatley et al. 1998; Ramos 2006; Wesselingh & Ramos 2010). Ecophenotypes of *Cyprideis* can tolerate lower to higher salinities (1.5‰ to 60‰ Athersuch et al. 1989 *vide* Keyser et al. 2004) thriving in environments that can be physiologically stressful such as lagoons and inland ephemeral saltwater lakes (e.g., Whatley et al. 1998; Aladin & Potts 1996).

*Cyprideis* can develop nodes as a response to salinity fluctuation, generally linked to lower (<5‰) saline conditions (Keyser & Aladin 2002; Keyser 2005). According to Keyser (2005) the main cause of the nodding in low salinity waters is a failure in osmoregulation capacities during molting, which also can occurs in



**Figure 2.** Lithologic columns of the core 1AS-31-AM with the distribution of fossils in the respective environmental phases (I, II and III).

**Figura 2.** Columna litológica y distribución de fósiles en el testigo 1AS-31-AM.

others genera like *Heterocypris* (see Keyser & Aladin 2002; Keyser 2005). Although *Cyprideis* is more usually associated with brackish water it also occurs in freshwater, especially the African lakes (Martens et al. 1994; Wouters and Martens 1992, 2001).

The Solimoes and Pannonian Basin of SW Europe are two important examples of adaptive radiations of *Cyprideis* during the Miocene (Whatley et al. 1998; Gross & Piller 2009). According to Whatley et al. (1998) the radiation of *Cyprideis* in Solimões Formation, occurred in a brackish closed hydrological system where extra-basinal species migration was limited. There appears to be no correlation between enhanced evolutionary activity and named extrinsic events.

As with other records, the microfauna of IAS-31-AM is dominated *Cyprideis*, with 18 species, 11 recorded previously from others localities and seven new species to science (Figs. 3, 4 and 5).

*Cyprideis* species occur from 297.50 m to 20.0 m depth. The highest diversity as well as the presence of noded *Cyprideis*-valves are found in samples below and just above of the marine incursion interval (at 175 and 170.80 m respectively, Figura 5). Besides the ostracodes, the microfossil assemblages analyses throughout the core allowed identifying three temporally variable salinity intervals (Figura 2): *Lacustrine Phase* (Interval I); *Transitional to marine Phase* (Interval II); and *Fluvio-lacustrine Phase* (Interval III).

*Lacustrine Phase*: Interval I (230.0-175.0 m) is dominated by the *Cyprideis* assemblage that consists of nine species (*C. amazonica*, *C. caraionae*, *C. graciosa*, *C. machadoi*, *C. olivencai*, *C. pebasae*, *C. sulcosigmoidalis*, *C. sp. 6* and *C. sp. 7*) and 93 specimens that reduce abruptly by 180.9 m. Rare mollusks and fish remains occur associated to the ostracods.

The first occurrence of foraminifera (*Amphistegina* sp) is at 181 m. In the end of the Interval I, at 175.0 m, besides noded *Cyprideis*-valves the *Cyprideis* assemblage re-emerges with two new species, and a total of 11 species from 220 specimens. Also, at this depth, an otolith of typical marine fish was found (Aguilera et al. in press). It could indicate the first signals of the marine influence.

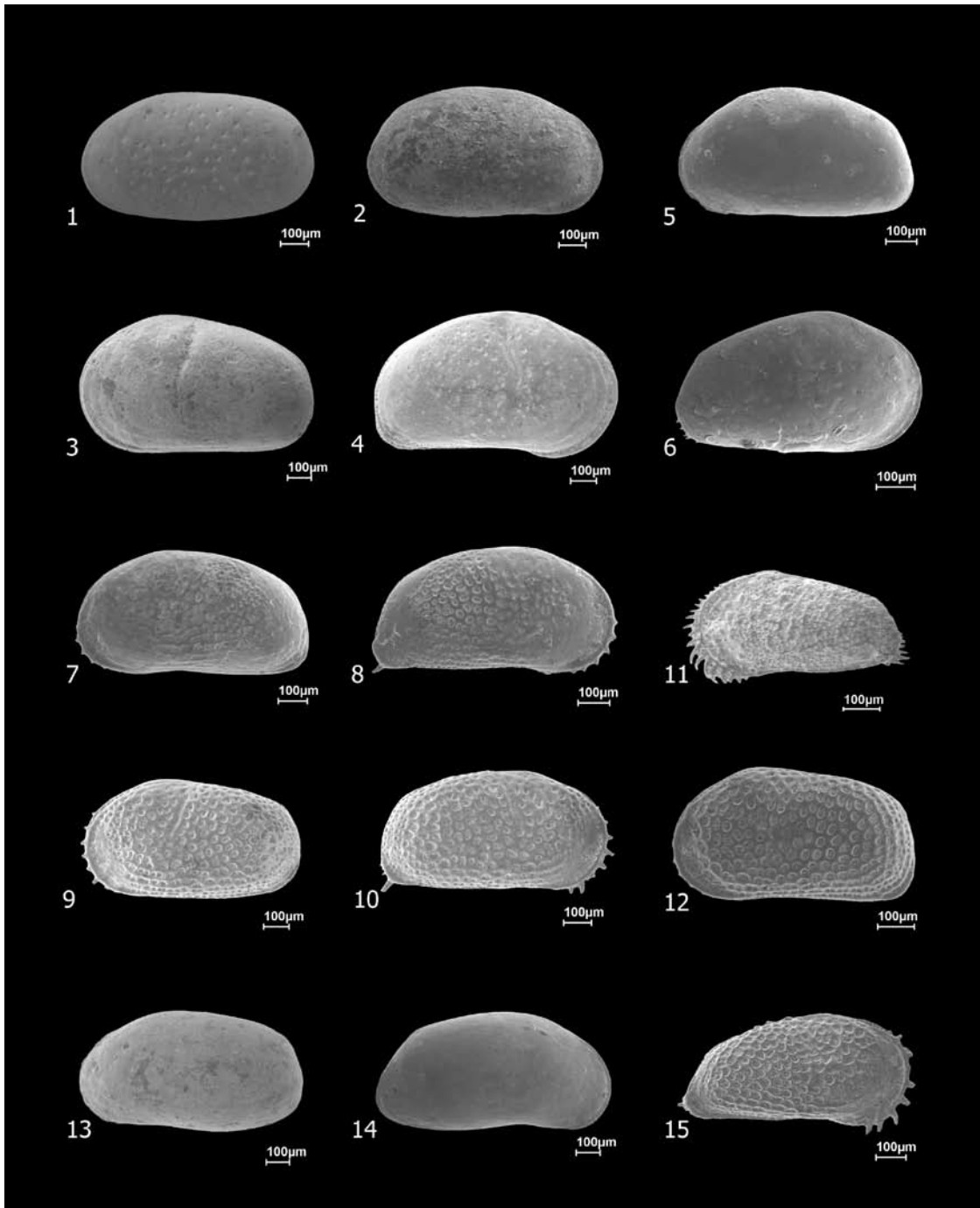
*The Transitional to Marine Phase*: Interval II (174.90-170.90 m) is represented by a mixture of marine, transitional and non-marine taxa. This interval begins with

the presence of marine mollusk *Melongena woodwardii* alongside a lower diversity (five species) and abundance of *Cyprideis* (*C. amazonica*, *C. aulakos*, *C. graciosa*, *C. machadoi* and *C. pebasae*). At 174.65 m and 174.40 m charophyte oogonia were found with a few specimens of *Amphistegina* spp., bryozoans and *Cyprideis* (*C. aulakos*, *C. machadoi* and *C. pebasae*). At 172.40 m, a more diverse assemblage occurs: benthic (*Amphistegina* spp. and *Quinqueloculina*) and agglutinated (*Textularia*) foraminifers, bryozoans, decapods, mollusks, fishes remains, rare non-marine ostracods (*Candona* and *Cytheridella*) and some species of *Cyprideis* (*C. inversa*, *C. Olivencai*, *C. pebasae*, *C. sulcosigmoidalis*, *C. sp. 1*, *C. sp. 3* and *C. sp. 5*).

The Interval II, at 170.90m depth, finish with a typical marine microfauna dominated by planktonic (*Globigerinoides*, *Globorotalia* and *Globigerina*) and benthic foraminifers (*Amphistegina*, *Planorbulina* and *Quinqueloculina*), totalizing 21 specimens, as well as bryozoans (Figura 6). The presence of planktonic foraminifers at this depth indicates the peak of marine conditions within this sequence. At this depth, the others taxa (mollusks, fish remains, etc.) mentioned before and the ostracods disappear with only one remaining specimen of *C. aulakos*.

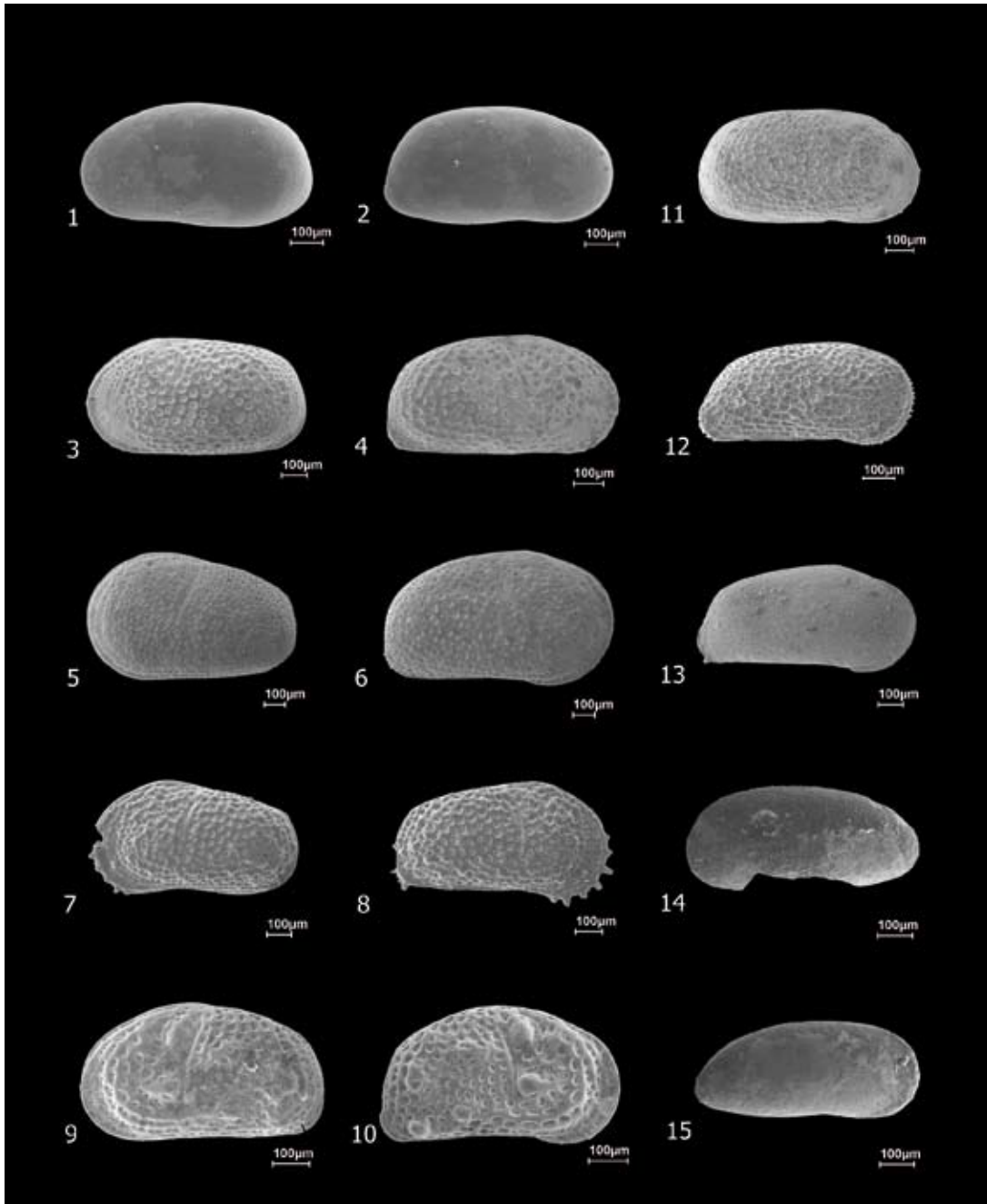
*Fluvio-lacustrine Phase*: Interval III (170.80-20 m) begin with the disappearance of marine taxa and the return of high *Cyprideis* diversity (*C. amazonica*, *C. aulakos*, *C. caraionae*, *C. cyrtoma*, *C. graciosa*, *C. machadoi*, *C. olivencai*, *C. pebasae*, *C. sulcosigmoidales*, *C. sp. 1* and *C. sp. 7*); the presence of noded *Cyprideis* (Figs. 4; 9-10) as well as agglutinated foraminifers and mollusks (e.g. *Neritina roxoi*) which are able to tolerant fluctuating salinities as well as fresh-water fishes remains suggests abrupt decrease of salinity water. From 157.25 m to 138.20 m the diversity of *Cyprideis* reduces and new fresh water ostracodes genera, such as *Cypria* and *Darwinula* arise indicating a freshening of waters. To the uppermost of this interval the ostracodes almost disappear, remaining only few freshwater species (*Cypria aqualica*, *Darwinula fragilis* and *Cytheridella* sp.) and few *Cyprideis* (*C. amazonica*, *C. graciosa* and *C. machadoi*). This fresh water ostracod assemblage (*Cypria*, *Cytheridella* and *Darwinula*) has been recorded in the Late Miocene (Solimões Formation) outcrops around Eirunepé city, in environments associated with a complex *fluvio-lacustrine* environment (Ramos, 2006; Gross et al. 2011). Recently, living *Cypria* and *Cytheridella* has been found in fresh-





**Figure 3.** Diversity of *Cyprideis* species: 1-2. *Cyprideis amazonica*; 3-4. *C. aulakos*; 5-6. *C. caraionae*; 7-8. *C. cyrtoma*; 9-10. *C. graciosa*; 11. *C. inversa*; 12. *C. lacrimata*; 13-14. *C. machadoi*; 15. *Cyprideis* sp.3.

**Figura 3.** Diversidad de las especies de *Cyprideis*: 1-2. *Cyprideis amazonica*; 3-4. *C. aulakos*; 5-6. *C. caraionae*; 7-8. *C. cyrtoma*; 9-10. *C. graciosa*; 11. *C. inversa*; 12. *C. lacrimata*; 13-14. *C. machadoi*; 15. *Cyprideis* sp.3.



**Figure 4.** Diversity of *Cyprideis* species: 1-2. *Cyprideis olivencai*; 3-4. *C. pebasae*; 5-6. *C. sulcosigmoidalis*; 7-8. *Cyprideis* sp. 1; 9-10. *Cyprideis* sp. 5 with nodes; 11. *Cyprideis* sp. 2; 12. *Cyprideis* sp.4; 13. *Cyprideis* sp. 6; 14-15. *Cyprideis* sp. 7.

**Figura 4.** Diversidad de las especies de *Cyprideis*: *Cyprideis olivencai*; 3-4. *C. pebasae*; 5-6. *C. sulcosigmoidalis*; 7-8. *Cyprideis* sp. 1; 9-10. *Cyprideis* sp. 5 with nodes; 11. *Cyprideis* sp. 2; 12. *Cyprideis* sp.4; 13. *Cyprideis* sp. 6; 14-15. *Cyprideis* sp. 7.

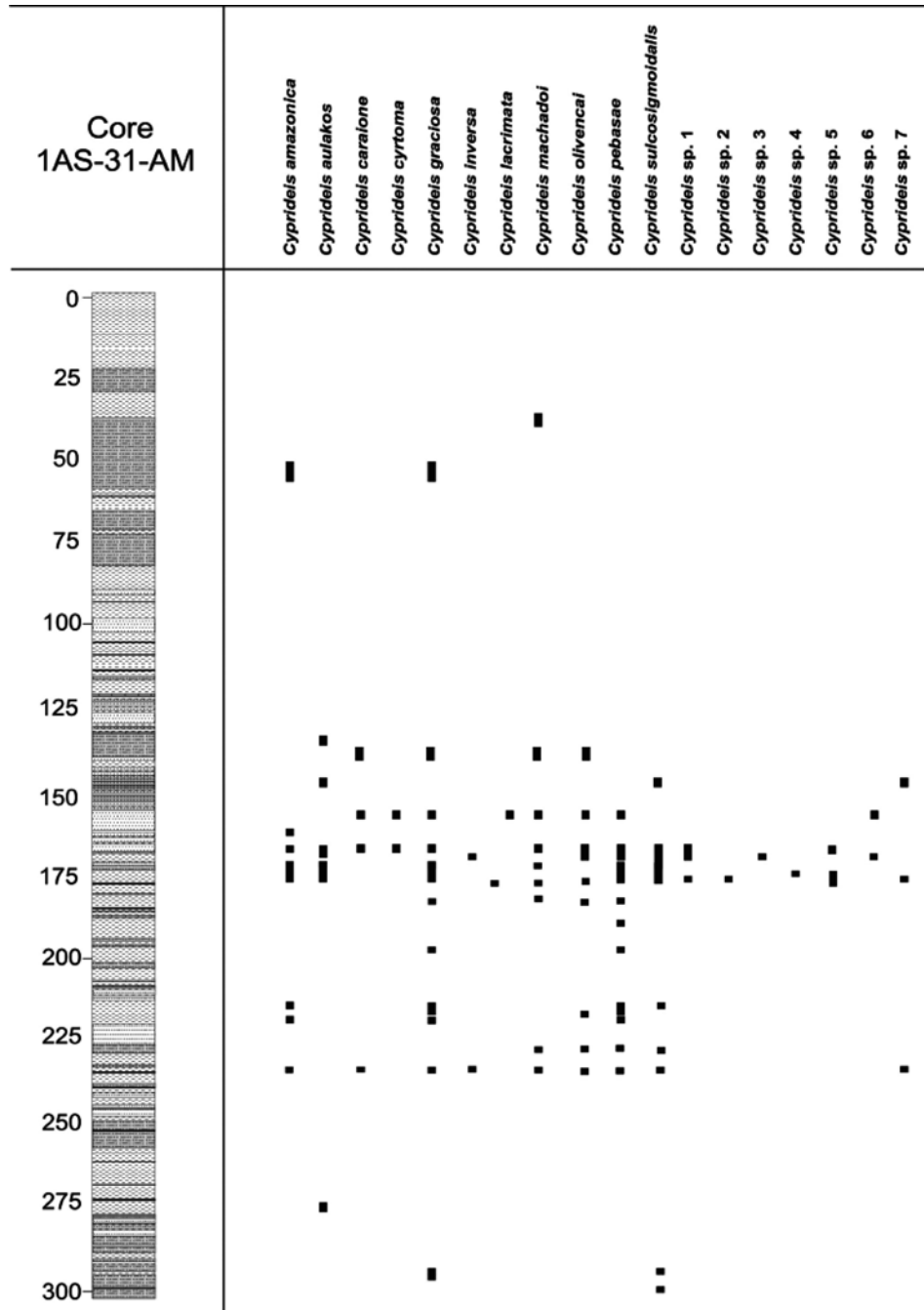
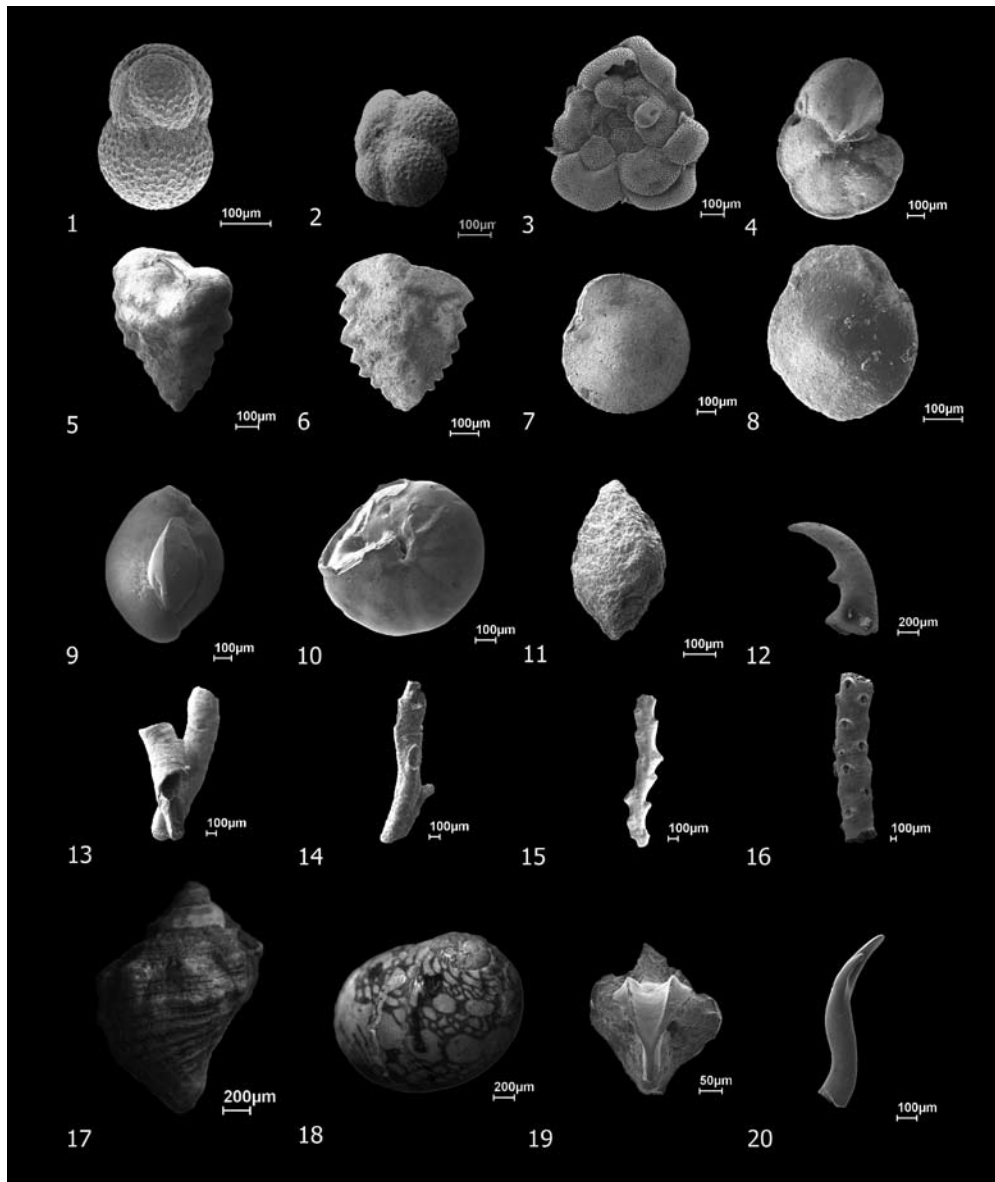


Figure 5. Stratigraphical distribution of the *Cyprideis* species in the studied core.

Figura 5. Distribución estratigráfica de las especies de *Cyprideis* en la sección estudiada.





**Figure 6.** Microfossils representing the mixed assemblage: 1-11. Foraminifers: 1. *Globigerinoides* sp.; 2. *Globigerina* sp.; 3. *Planorbulina* sp.; 4. *Globorotalia* sp.; 5. *Textularia* sp.1; 6. *Textularia* sp.2; 7. *Amphistegina* sp. 1; 8. *Amphistegina* sp. 2; 9. *Quinqueloculina* sp.; 10. gen. indet.1; 11. gen . indet. 2; 12. decapod claw; 13-16. Unidentified bryozoan remains; 17. *Melongena woodwardi*; 18. *Neritina roxoi*; 19-20. Unidentified fish remains.

**Figura 6.** Asociación mixta de los microfósiles: 1-11. Foraminifera: 1. *Globigerinoides* sp.; 2. *Globigerina* sp.; 3. *Planorbulina* sp.; 4. *Globorotalia* sp.; 5. *Textularia* sp.1; 6. *Textularia* sp. 2; 7. *Amphistegina* sp. 1; 8. *Amphistegina* sp. 2; 9. *Quinqueloculina* sp.; 10. gen. indet.1; 11. gen . indet. 2; 12. quela de decapoda; 13-16. briozoarios indet.; 17. *Melongena woodwardi*; 18. *Neritina roxoi*; 19-20. restos de peces.

water natural floodplain lake (abandoned channels fill) in the Amazonia, closed to Eirunepé city (M.I.F.R. pers. comun.). Probably the endemic *Cyprideis* assemblage from Solimões Fm. was extinct at the end of Late Miocene.

The radiation of *Cyprideis* in this study is an excellent biological marker for abrupt salinity change. The number of *Cyprideis* species increase before and after the *Transitional to Marine Phase* (Interval II). When marine waters invade the lacustrine environment for the first time (at 174.90 m), the adaptation of *Cyprideis* begin rapidly resulting carapace nodding. Nodding of *Cyprideis* also occurred during the offstage, as region reverted to continental conditions. Whatley et al. (1998) suggest that the high diversity of *Cyprideis*, throughout the Miocene in Amazonia, occurred within a stable, isolated body of saline water; however, in the study core, radiation is directly associated with the salinities change caused by marine incursions. It represents that the radiation of *Cyprideis* do not occurred in a closed system.

Similar to the *Cyprideis* signature, Wesselingh et al. (2010) show an important mollusk turnover linked to marine incursions in Peru and Colombia. At the time the endemic bivalve *Pachydon obliquus* became replaced by *P. trigonalis* as the dominant bivalve species. Furthermore, several previously common gastropod species, such as *Dyris tricarinatus* disappeared and various novel species appeared. It is thus possible that the marine incursion played an important role in reshaping the invertebrate fauna of Amazonian lakes and wetlands.

Until recently, most authors suggested only marginal marine influence in the Miocene of western Amazonia (e.g., Hoorn 1995; Vohnhof et al. 1998; Vermeij & Wesselingh 2002; Gingras et al. 2002; Wesselingh & Ramos 2010). Geochemical and faunal paleosalinities were estimated at most 5 psu (Vohnhof et al. 1998, 2003). Hovikoski et al. (2007, 2010) recorded within the Pebas Formation a low-gradient depositional system, influenced by recurring, shallow and restricted marine incursions.

The presence of planktonic foraminifera shows, however, that episodically paleosalinities must have been near normal marine and that the (probably short-lived) marine peak influx in Amazonia may have been much more profound than previously recognized.

The *Transicional to Marine Phase* (Interval II) is not younger than Early Middle Miocene based on the

stratigraphical distribution of the *C. caraione*. According to the ostracod biozonation by Muñoz-Torres et al. (2006), the *C. caraione* occur since the *Cyprideis aulakos* zone (Late Early to Early Middle Miocene) to *C. caraione* zone (Early Middle Miocene) in the Langhian.

Although marine incursions was previously attributed to Late Middle Miocene (*Grimsdalea* zone of Hoorn, 1995) based on the occurrence of marine mollusks (including *Melongena woodwardi*), barnacles and bryozoans in samples in localities Buenos Aires, Porvenir, Nuevo Horizonte from Colombia and Peru (Wesselingh et al. 2010; Vohnhof et al. 1998), the estimated Early Middle Miocene age (~ 16 to 11.3 Ma) to the marine incursion in the present study is in agreement with the “Pebas Phase” by Hoorn et al. (2010).

This palaeoenvironmental reconstruction offers new insight into the evolution of the Amazonia depositional system. Micro and macro-faunal evidence clearly indicates a transition from continental (lacustrine) environments at the base to a short duration marine influenced and the re-establishment of fluvial conditions at the top of the sequence. The effect of this environmental change, mainly the abrupt marine incursion is probably related to tectonic activity and/or sea level rise rate change. Probably events of great magnitude that could allow the sea water reach so long distance into the continent. The radiation of *Cyprideis* is most likely triggered by these sudden environmental changes (mainly related to salinity change). These fossils and the particular morphologic (ecophenotypic traits) features infer that a short-lived marine incursions reached the central part of Amazonia, probably in the Early Middle Miocene.

The origin of the marine incursion has a good chance to be from Caribbean region, based on the fossil content, although a more detailed taxonomic study of taxa, is necessary in subsequent publications.

## CONCLUSIONS

The microfossils from 93 samples of the 1-AS-31-AM core (southwestern Amazonas state, Brazil) allowed the reconstruction of paleoenvironmental conditions in southwestern Amazonia, Brazil during the Miocene. Three temporally variable salinity intervals are recognized: *Lacustrine Phase* (Interval I); *Transicional to marine Phase* (Interval II); and *Fluvio-lacustrine Phase* (Interval III). The succession began with

lacustrine environments and graded into a short- live marine incursion and ending with the establishment of a fluviolacustrine system. The peak of the marine incursions at 170.90 m is evidenced by the occurrence of planktonic foraminifers, and the disappearance of brackish and non-marine taxa. The extent of the marine influence is much more profound than previously assumed. The short-lived marine incursion caused rapid changes in water salinities resulting in the radiation of the ostracod genus *Cyprideis*. The presence of nodes in *Cyprideis* valves as well as the presence of eurytopic microfossils is related to abrupt salinity change. This brief but profound marine

incursion was probably caused by tectonic events of great magnitude that most likely took place during the Early Middle Miocene.

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