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Late Miocene continental sedimentation in southwestern Amazonia and its regional significance: Biotic and geological evidence

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Abstract

Fossil content (vertebrate paleofauna and palynology) indicates that the sediments of the Solimões Formation in Acre (SW Brazilian Amazonia) are continental, having been deposited by avulsive fluvial belts in a floodbasin–floodplain environment. The main source area was the Andes chain. Widespread lacustrine swampy deposits, stacked channel deposits, and paleosoils are typical elements that characterize the Solimões Formation sediments that outcrop in southwestern Brazilian Amazonia. New data on fossil vertebrate assemblages and palynology corroborate the Late Miocene age suggested previously and assign the fossils to the Huayquerian mammalian biozone, spanning 9–6.5 Ma. These geological and paleontological data show that the existence of an intracontinental seaway through SW Amazonia during the Late Miocene (11–10 Ma), connecting the Caribbean Sea with the Parana Basin as previously proposed is unsustainable, because the sediments used by previous authors to propose the seaway were deposited in a continental environment and are younger than 11–10 Ma.

Keywords: Solimões formation; Amazon; Paleogeography; Paleoecology; Late Miocene

1. Introduction

The Amazon, the world's largest fluvial system, is of fundamental importance for understanding Late Cenozoic environmental change. However, much of Amazonia is inaccessible and has not been studied in detail, and the limited investigations to date have resulted in many controversies. Brazilian researchers (including the authors) have been working since the 1990s on the Neogene record of southwestern Brazilian Amazonia. Part of Amazonia, consisting of the Brazilian state of Acre and neighboring parts of Amazonas and Rondonia, were visited by an IGCP 449 field excursion organized by E.M. Latrubesse and J.C. Stevaux in 2003 (e.g., Westaway, 2006), when some of these controversies were discussed at length and the results obtained were discussed with specialists from several countries. This article presents new evidence and synthesizes our results in relation to these issues.

During recent decades, preliminary data sets pertaining to the Cenozoic sediments of SW Amazônia have been generated (Radambrasil, 1976, 1978; Latrubesse, 1992; Latrubesse et al., 1997). One of the best known publications, by Räsänen et al. (1995), proposed the existence of an intracontinental seaway through western Amazonia, linking the western Caribbean with the Rio de la Plata estuary via western Amazonia and the modern Parana drainage basin (Fig. 1).

This proposal been received favorably by some researchers, mainly paleontologists and biogeographers who regard it as a new paleogeographic alternative to understanding biogeographic patterns in South America (Webb, 1996; Lovejoy et al., 1998, 2006; Albert et al., 2006). However, this seaway model has received some criticism (Hoorn, 1996; Marshall and Lundberg, 1996; Praxton et al.,

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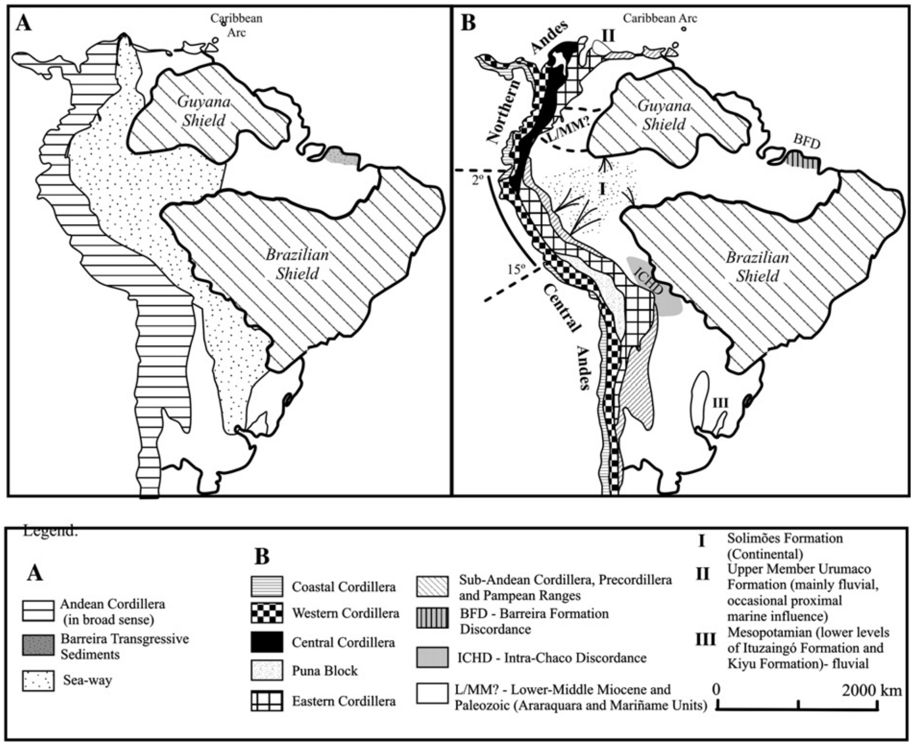

Fig. 1. (A) Inset showing the seaway inferred to have existed during the Late Miocene by Räsänen et al. (1995), connecting the Caribbean Sea with the south Atlantic through the Venezuelan/Colombian Llanos Basin, western Amazonia, the Beni-Chaco plain, and the Parana Basin in Argentina. (B) Late Miocene model proposed herein. The position of the flat slab of the central Andes at 2–15°S is indicated. The Late Miocene deposits of the Mesopotamian (lowermost levels of the Ituzaingo Formation) and the Kiyú Formation in the La Plata Basin, the Urumaco Formation in Venezuela, and the continental sedimentation of the Solimões Formation is recorded. The occurrence of Late Miocene discordance in the coastal Barreiras Formation (BFD) sediments and the intra-Chaco discordance in Bolivia (ICHD) is indicated. In the sub-Andean Chaco area of south central Bolivia, the Tariquia Formation should be recorded at this time. Hoorn (1994a) did not record Late Miocene sediments in the northernmost outcrops of the lowlands of southeastern Colombia but in the Paleozoic rocks of the Araraquara Formation and the outcrops of the lower–middle Miocene sediments Mariñame unit (L/MM?), which should be an obstacle for marine ingressions in the early Late Miocene coming from the Caribbean Sea (Hoorn, 1993).

1996), but only circumstantial evidence against it was presented. For this reason, geologists working in the Parana–Chaco Basin were tempted to correlate data from the Chaco Basin with sediments outcropping in Acre, speculating on marine connections and ingressions from both basins in the Bolivian Chaco during the Late Miocene (Hernandez et al., 2005; Hulka et al., 2006). A new publication by Rebata et al. (2006) on the Pastaza–Marañon Basin continues to postulate marine incursions in southwestern Amazonia during the Late Miocene. We show that the existence of such an intracontinental seaway is unsustainable in the middle–later part of the Late Miocene, in light of the geological and paleontological evidence presently available in SW Brazilian Amazonia (the same source area of Räsänen et al., 1995). We also suggest that the proposal derived from misunderstandings by Räsänen et al. (1995) of the stratigraphy and fossil fauna, which led those authors incorrectly to correlate sediments of the Amazon and Parana basins.

2. Geological interpretation

Räsänen et al. (1995) describe outcrops on the Purus and Acre rivers, as well as along BR-364 road from Rio Branco to Sena Madureira city, in SW Amazonia, interpreting them as deposited within tidal flats and estuarine environments. We are familiar with these and many other outcrops but interpret the same deposits differently. Late Cenozoic sediments, mainly sandstones, siltstones, and claystones, cover most of western Amazonia and have been interpreted independently as deposited in a continental fluvial/lacustrine environment (Radambrasil, 1976, 1978; Latrubesse, 1992). These sediments were included in a single lithostratigraphic unit named the Solimoes Formation (Caputo et al., 1971), which reaches thicknesses of up to 1800 m (borehole I Nst-1-AM; Radambrasil, 1978); in Acre state, these Cenozoic sediments are up to 800 m thick (Fig. 2). Westaway (2006) has suggested that in view of its vast extent and considerable thickness, this sedimentary unit could deserve at least the stratigraphic status of a group, not a formation.

Acre state is characterized by a dissected fluvial landscape caused by incision into the uppermost part of the Solimoes Formation deposits (Fig. 3). The outcrops analyzed by Räsänen et al. (1995), and investigated by us, are along river banks and roads. The relief in this region, between the highest parts of the landscape and valley floor levels, is nowhere more than approximately 80 m. Therefore, we

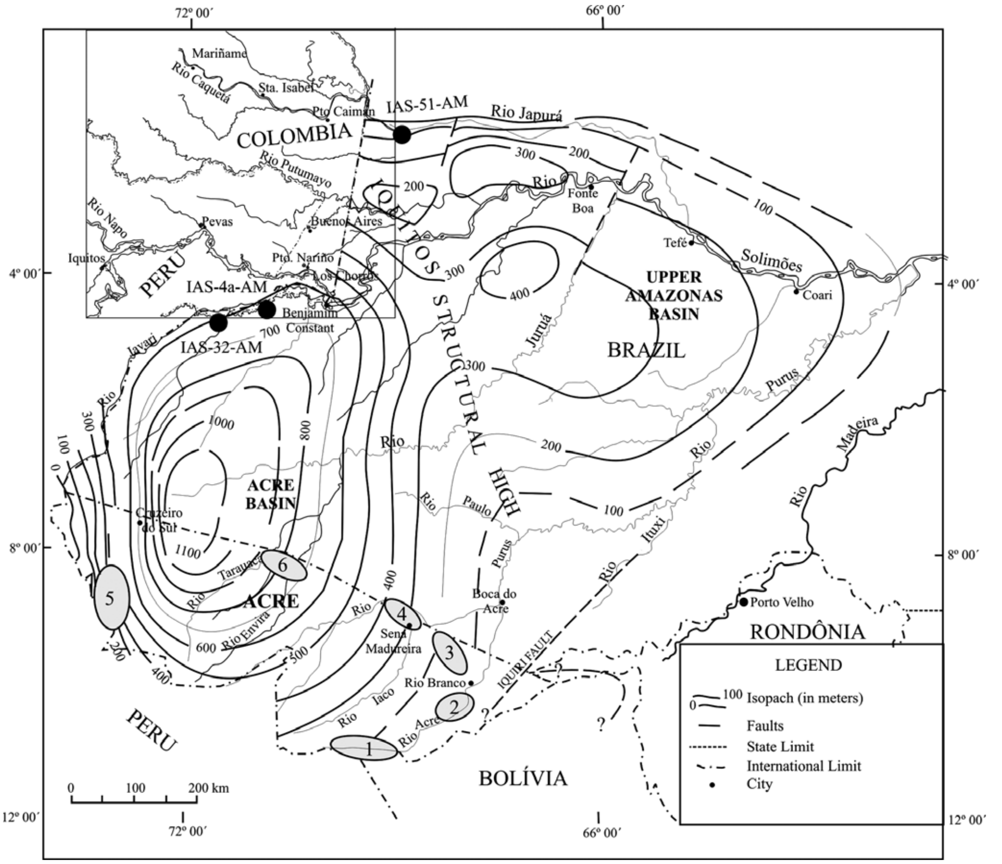

Fig. 2. Isopach map of the Solimões Formation (from Maia et al., 1977). Numbered circular areas indicate main areas with Late Miocene fossiliferous, palynological, and/or geological data. 1, Upper Acre River; 2, Acre River upstream of Rio Branco (also studied by Räsänen et al., 1995); 3, BR 364 from Rio Branco to Sena Madureira; 4, BR 364 from Sena Madureira to Manuel Urbano and outcrops along the Iaco and Purus rivers; 5, Upper Jurua. Square in the northwestern corner indicates the area studied by Hoorn (1993, 1994a,b).

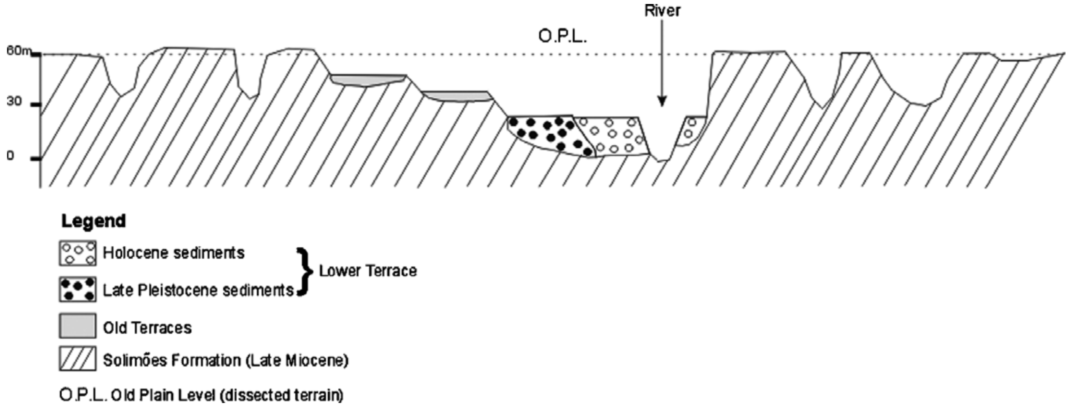

Fig. 3. Schematic section showing the main elements of the landscape in SW Brazilian Amazonia (lowlands). Tertiary sediments of the Solimões Formation outcrop along the banks of main rivers and along the watershed areas, mainly exposed on road cuts.

can discuss, at most, the uppermost 80 m of a deposit that reaches 800 m thick. Our surveys along the banks of the Acre, Iaco, Purus, Jurua, and Moa rivers and in road cuts lead us to identify two main facies assemblages: a channel-dominated assemblage and a floodplain–lacustrine low-energy assemblage.

The channel assemblage is typically composed of red–brown to brown sand, silty and clayey sand, and intraformational mud ball beds. It is dominated by lateral accretion structures and abandoned channels and shows characteristic major trough cross-bedding structures and ripples (Figs. 4 and 5). The predominant low-energy assemblage is composed mainly of green to grey–green clay and silty clay and interpreted as deposited in a floodplain/lacustrine/paludal environment (Fig. 6). These sediments show mainly massive structure and lamination in some cases. Paleosols are marked by the presence of nodular horizons, rhizolits, root casts, mudcracks, and mottled

Fig. 4. Amapa outcrops in the Acre River, upstream of Rio Branco, described by Räsänen et al. (1995) as a point bar generated below tidal influence generated by the seaway (location, area 2 of Fig. 2). We interpret the deposits as formed by lateral accretion structures. Note the decrease in bed thickness from 1 to 2 and floodplain-dominating deposits in the uppermost part of the profile (3) indicated in (B). The channel macroform is mainly formed by large, 20–80 cm thick sets of inclined fine-sand point bar ripple drift lamination, predominantly B type with top sets (A) and between thin beds of fine sediments (B). (C) Details of ripple drift lamination.

structures (Fig. 6). In some more lacustrine sediments, convolute structures are also found. Differences in color, varying from green or grey–green to pale red, can be attributed to differences in water depth and oxygenation. Lignite beds are scarce in the swampy lacustrine sediments that crop out in Acre. However, in some localities, such as the upper Acre River, it is possible to find fossilized wood and other organic matter or pyrite associated with woody fragments or organic beds.

In both facies assemblages, fossil bones, gypsum veins, and calcareous concretions occur. The sediments are rich in the bones of autochthonous and para-utochthonous vertebrates and bones and shells of invertebrates such as bivalves and gastropods. Abundant crocodilian coprolites have also been recorded in some outcrops.

The channel assemblage can be interpreted in terms of active and unstable channels with sequences of fining-upward sediments and cycles of cut and fill. Point-bar accretion surfaces are formed by fine-grained sediment (fine sand, silt, mud), with ripple structures predominant in the bedsets of these lateral accretion deposits. A good example of fine, dominated point bar deposits are those described by Räsänen et al. (1995) at Seringal Amapa, in the Acre River, as a point bar that formed under the influence of tidal conditions. We posit that the outcrop repre-

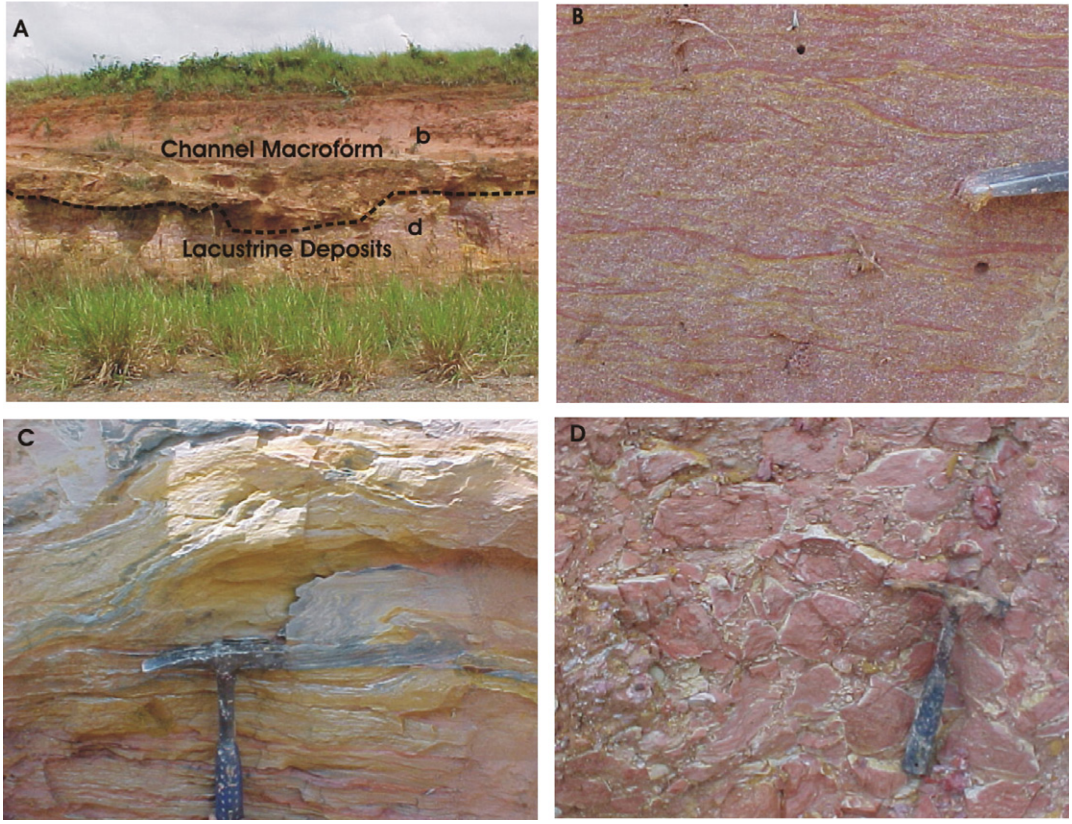

Fig. 5. (A) Channel macroform related to crevasse splay or small delta in water-saturated environment, road cut, BR 364 from Rio Branco to Sena Madureira (9°26′58.97 S, 68°23′29.97 W, area 3 of Fig. 2). (B) Channel cuts and enters lacustrine/marshy deposits. Road cuts BR 364 from Rio Branco to Sena Madureira. (B–D) Relate to this kind of deposit in outcrops along the same area. (B) Sandy sets of the channel environment with B-type ripples; (C) convolute beds in fine lacustrine deposits; (D) intraformational conglomerate indicating flash entrance and/or reactivation of a channel in a splay/delta. Sediments indicate channel erosion in a depositional plain. Mudballs are the coarser fraction, transported very short distances, by the suspended load fluvial systems of the Solimões Formation.

sents a fluvial point-bar deposit with rapid fine sedimentation. This channel macroform is mainly formed by 20–80 cm thick, inclined, fine-sand point-bar ripple drift lamination, predominantly B type with topsets (Fig. 4A and B).

Bottomsets (total ~5 cm thick) indicate high sedimentation rates. The 10–20 cm thick, intercalated, massive, muddy beds suggest backwater ponding, as interpreted by Westaway (2006). Thus, these kinds of deposits indicate highly seasonal behavior, with peaks of suspended sediment transport (producing sand laminations) alternating with rapid falls in water level or slackwater effects (producing mud laminations). Such deposits are widespread throughout the Solimões Formation.

Other important sedimentological aspects in the channel assemblages include the presence of nonrepetitive scroll structures and abruptly abandoned channels, typically without oxbow-lacustrine deposits. Thus, avulsion was an important mechanism of channel adjustment. Associated with paleochannel features, abundant finely laminated to massive fine sediment plugs can be found, which indicate that channels were filled quickly by fine-grained sediments. Coarse sediments are represented and restricted to intraformational mudballs (Fig. 5). Mudballs are typical channel lithofacies that represent channel reactivation inside an aggradational fluvial system with a tendency toward subsidence, which erode/run on a muddy river bed cutting floodplain or lake deposits. Mudballs are eroded and shortly transported by several processes, such as erosion in a muddy bottom channel; the entrance of a channel in muddy sediments, mainly in a saturated floodplain/lake; the generation of a new fluvial belt by avulsion that cut the fine-grained sediments of the floodplain again; and mass movements along the banks that introduced sediments into the channel. All these mechanisms are recorded in the sediments of the Solimões Formation.

Large channel macroforms are clearly associated with floodplain deposits and lateral and vertical relations between channel macroforms, and floodplain deposits can be identified in the field (Fig. 5). These fluvial systems typically transported fine-grained suspended sediments.

The association of sedimentary environments, such as widespread shallow lacustrine swampy deposits, paleosols, and stacked channel deposits, with abundant terrestrial and aquatic vertebrate remains indicates the existence of a large floodbasin, exhibiting floodplain surfaces with

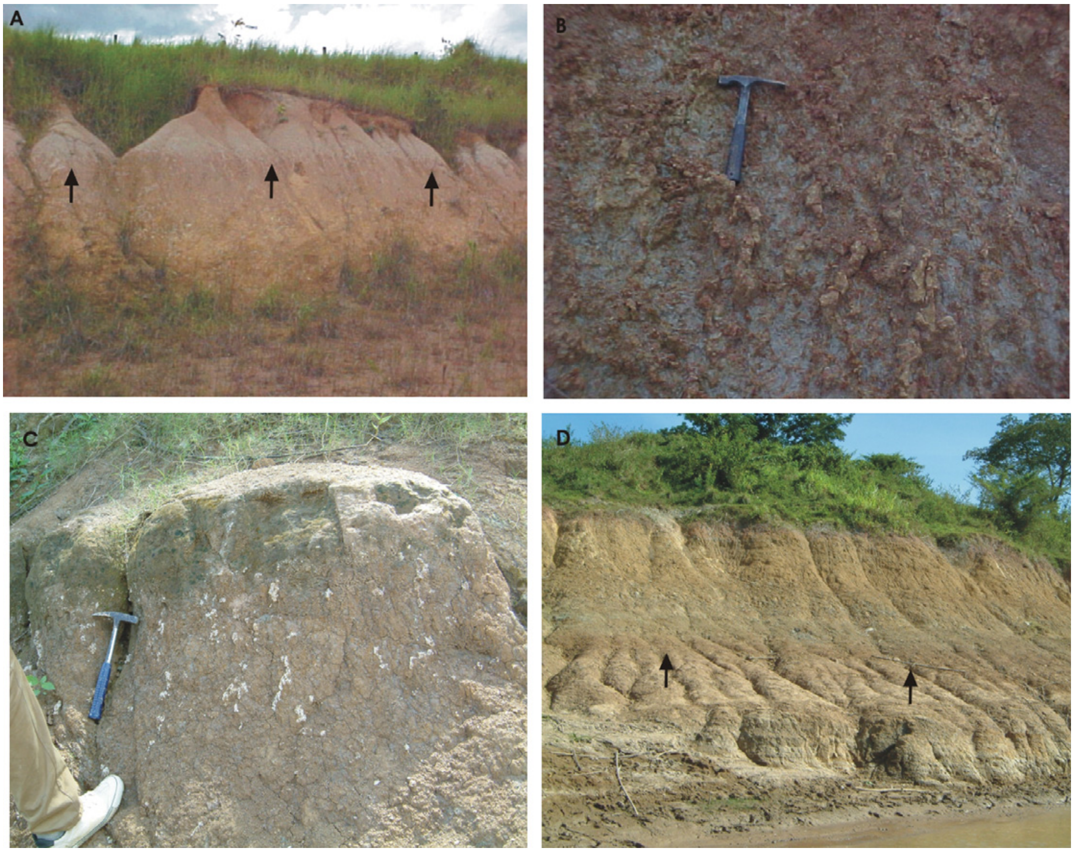

Fig. 6. (A) Pedogenic features in floodplain deposits (massive silty/clayey sediments) in road outcrops of BR 364, location 9°37′17.25 S, 68°14′12W, area 3 of Fig. 2. (B) Paleosoils characterized by blocky peds, mottles, root casts, and rhizoliths. Floodplain paleosoils are covered by "wetter" floodplain deposits with less pronounced pedogenetic features (above arrows). (C) Paleosoil in a Acre River bank outcrop upstream of profile described by Räsänen et al. (1995), in Amapa (area 2, Fig. 2). The outcrops extend from 10°02′1.74″S, 67°52′29.09W to some hundreds of meters upstream on the left banks of the Acre River. The paleosoil is found in a fine sediment-dominated sequence of floodplain deposits. Vertebrates and freshwater bivalves occur in floodplain deposits, such as *Pachydon* sp., *Castalia* sp., *Prisodon* sp., *Diplodon* sp., and *Mycetopoda* sp. (material identified by María Inês Feijó Ramos, Museu Paraense Emilio Goeldi, Belém, Brazil). (D) Floodplain deposits in Preventorio, left bank of the Acre River, Rio Branco urban area. Arrows indicate vertebrate fossiliferous levels. Remains of Late Miocene vertebrates stored in the Laboratório of Paleontological Research of the Federal University of Acre; the most spectacular piece is a jaw of the giant crocodile *Purusaurus brassiliensis*.

paleosols, avulsive channel systems, crevasse splays, and deltaic environments.

Several other Late Cenozoic sedimentological systems are closely analogous to the Solimões Formation, as discussed at the field conference Amazon 2003-IGCP 449 (Westaway, 2006). Large depositional megafans are characteristic of tropical systems. In active orogenic belts and foreland settings, some of the world's largest megafans, extending over thousands of square kilometers, have developed, such as the Kosi and Gandak megafans in the Gangetic plains of India and the Parapetí, Pilcomayo, and Bermejo fans in the Chaco plains of South America (Latrubesse et al., 2005). It is widely recognized that large sediment loads, frequent avulsion, low longitudinal gradients, and highly variable flow regimes are major factors controlling the development of such fans.

An approximately similar modern analogue environment to the Solimões Formation deposits cropping out in Acre is suggested by the Quaternary Chaco system. With an area of >800,000 km^2, the Chaco plain spreads across Bolivia, Paraguay, and northern Argentina. The climate is wet/dry tropical, with annual precipitation decreasing from 1000 to 2500 mm in the sub-Andean zone to 1200 mm in the Oriental Chaco and 400 mm in the Occidental Chaco. Sedimentation in the Chaco consists of large Quaternary alluvial fans formed by hyperavulsive rivers, which represent the largest fluvial-like system of coalescing fans in the world. These fans are formed from north to south by the Grande, Parapetí, Pílcomayo, Bermejo, and Salado rivers (Iriondo, 1993; Wilkinson et al., 2006). In the Upper Paraguay Basin, a large wetland/floodbasin area, the Pantanal, formed of extensive megafans (São Lourenço, Taquarí, etc.) is fed by the Brazilian highlands close to the megadepositional fans system to the east. These megafans are formed by well-delimited alluvial belts created during humid periods and smaller and less stable paleochannels active during dry periods as a response to the climatic changes of the Late Quaternary. Avulsion is the main mechanism producing abandoned alluvial belts, with fine sediments predominant in the plains (Assine, 2005).

Swampy areas are widespread, with more than 125,000 km^2 of the Bermejo and Pilcomayo fans flooded (Iriondo, 1993). Parts of the Chaco and Pantanal are hyposaline.

Sediments deposited by hyperavulsive systems in a foreland basin are also recorded in some units of the Lower and Middle Siwalik deposits and their modern analogues in the Gangetic plain (Jain and Sinha, 2003). These fluvial sequences are characterized by a predominance of stacked sandstones and overbank mudstones, paleosols, and abundant fossil content (e.g., Beherensmeyer, 1987; Beherensmeyer and Tauxe, 1982; Willis and Behrensmeyer, 1994; Bhatia, 2003; Kumar et al., 2003).

The Chaco, Indogangetic plain, and Solimões Formation deposits indicate broadly similar processes of sedimentation. The most important difference is that deposition was more distal and conditions were wetter in the Amazon during the Upper Miocene than in the Quaternary of the Chaco and the Late Miocene Siwaliks, as indicated by the tropical fauna and vegetation recorded in the Solimões Formation. Aeolian deposits, common in Chaco, and thick calcrete paleosoils, found in the Indogangetic plain, have not been recorded in the Solimões Formation. Conversely, permanent water bodies (swamps, shallow lakes) were widespread during deposition of the Solimoes Formation, indicating that southwestern Amazonia acted as a floodbasin similar to the present-day Pantanal system but fed from the Andes.

3. Fossil vertebrates and their interpretation

Land mammal assemblages are the most used biostratigraphic evidence to correlate Tertiary continental deposits in South America (Flynn and Swisher, 1995). As a consequence of isolation during most of the Cenozoic, because of the absence of a land bridge linking South and North America, South America has a distinct Cenozoic fauna. This uniqueness has long been recognized, notably as a result of work on mammalian biostratigraphy by the Argentinean paleontologist Florentino Ameghino in the late nineteenth and early twentieth centuries.

Originally, Latrubesse (1992) and Latrubesse et al. (1997) proposed that the fossil fauna of Acre state belongs to the Huayquerian mammal age, possibly extending to the Montehermosan age. They also proposed a correlation of the Solimões Formation fossil assemblage with the Mesopotamiense from Argentina and the Urumaco in Venezuela. Given the current evidence and the stratigraphic advances reached in Argentina and Venezuela, the fossil vertebrates of Acre are now attributable to the Huayquerian–Mesopotamian South America Land Mammal Age (SALMA) (9–6.5 Ma), defined mainly for Mesopotamian fauna (Cione et al., 2001).

Fossils were first recorded in Acre by the Chandless expedition in 1866. Fundamental reviews of these vertebrates have been written by Rancy (1985, 1991) and Webb and Rancy (1996). The vertebrate fauna of Acre is one of the most complete and complex in the Late Miocene of South America, comprising 51 genera. The fossils were collected along river banks and from the uppermost levels cropping out on the hills of the lowland dissected plain (Fig. 3). Most species can be found in the Laboratorio de Pesquisas Paleontológicas of the Federal University of Acre in Rio Branco. Fossils have been mainly found in situ in both facies assemblages, but the floodplain/lacustrine/paludal assemblage has yielded more complete assemblages with better preservation because of the low-energy depositional environment (Fig. 7).

Fig. 7. Fossiliferous outcrop of the Solimões Formation in the Acre River upstream of Brasileia, Calvalcante locality (10°55′42″S, 69°49′53″W, area 1 of Fig. 2). The remains belong to a Late Miocene Toxodontidae found in the low-energy facies assemblage.

We reviewed the fossil record of vertebrates from the Solimões Formation in SW Brazilian Amazonia, the Urumaco Formation in Venezuela, and the Mesopotamian of Argentina (Table 1). The data from Acre were taken from previous publications, mainly Campbell et al. (2000), Latrubesse et al. (1997), and from the collections of the Laboratório de Pesquisas Paleontológicas and our own data. Faunal data for the Mesopotamian are from Cione et al. (2001), the collections of La Plata Museum of Natural Sciences (La Plata city), and the Argentinean Museum of Natural Sciences "Bernardino Rivadavia" (Buenos Aires) in Argentina, as well as our own data. Data from the Venezuelan localities are from Marshall et al. (1993), Sánchez-Villagra et al. (2003), and Linares (2004).

Twenty genera found in Acre are also present in the Mesopotamian fauna of Argentina, with 11 species in common between both assemblages, including the rodents *Potamarchus murinus*, *Neoepiblema horridula*, *Phoberomys burmeisteri*, and *Kiyutherium orientalis*, as well as other amniote groups. A list of the fossil amniotes from the Mesopotamia (Argentina), Solimões Formation (Brazil), and Urumaco (Venezuela) appears in Table 1. Several taxa shared with the Mesopotamian fauna are also found in Urumaco fauna from northern Venezuela, such as the toxodontid *Grynodon* and the rodents *Kiyutherium* and *Phoberomys*. The Acre faunal assemblage preceded the Great American Biotic Interchange (GABI), as indicated by the

Table 1
List of the Late Miocene (Huayquerian–Mesopotamian SALMA) amniotes (mammals, reptiles, and birds) from the Solimões Formation in SW Brazilian Amazonia, Urumaco Formation in Venezuela, and the Mesopotamian (lowermost levels of Ituzaingó Formation) in Argentina

	"Mesopotamian"	Acre	Urumaco
Rodentia			
Brianomys	X		
Carlesia	X		
Diaphoromys	X		
Doellomys	X		
Eumegamysops	X		
Isostylomys	X		
Paranamys	X		
Pentastylodon	X		
Pentastylomys	X		
Pseusygmodus	X		
Tetrastylomys	X		
Protomegamys	X		
Neoepiblema	X	X	X
Phoberomys	X	X	X
Kiyutherium	X	X	X
Cardiatherium	X		X
Potamarchus	X	X	X
Tetrastylus	X	X	X
Gyriabrus	X	X	
Eumegamys	X	X	X
Telicomys		X	X
Simplimus		X	
"*Scleromys*"		X	
Lagostomopsys	X		
Perimys	X		
Protabrocoma	X		
Eumysops	X		
Haplostropha	X		
Paradoxomys	X		
Steiromys	X		
Microsteiromys	X		
Cardiomys	X		
Caviodon	X		
Paleocavia	X		
Paradimys	X		
Pliodolichotis	X		
Anastochoerus	X		
Anchimys	X		
Anchimisops	X		
Contracavia	X		
Plexochoerus	X		
Procardiatherium	X		
Protohydrochoerus	X		
Colpostemus	X		
Myocastor	X		
Xenarthra			
Pliomegatherium	X		
Promegatherium	X		
Pyramiodontotherium	X		
Pronothrotherium	X		X
Neohapalops	X		
Pliomophus	X		
Menilau?	X		
Torrellia	X		
Paranabradys	X		
Orthotherium	X		
Amphiocnus	X		
Promegalonyx	X		
Megalonychops	X		
Promylodon	X		
Prolestodon	X		
Megabradys	X		
Strabassodon	X		
Sphenotherium	X		
Octomylodon	X		
Diedomus	X		
Octodontobradys		X	
Urumacotherium		X	X
Acretherium		X	
Pseudoprepotherium		X	
Prepotherium			X
Ranculus	X	X	
Plohophorus	X	X	
Paraglyptodon	X	X	
Berthawyleria	X		
Hoplophorus	X		
Trachycalyptus	X		

Line missing

Paleohoplophorus	X		

Table 1 (*continued*)

	"Mesopotamian"	Acre	Urumaco
Protoglyptodon	X		
Parahoplophorus	X		
Uratherium	X		
Pseudoeuryurus	X		
Comaphorus	X		
Eleuterocercus	X		
Chlamyphractus	X		
Dasypus	X		
Chasicotatus	X		
Macroeuphractus	X		
Proeuphractus	X		
Zaedius(?)	X		
Kraglievichia	X	X	
Scirrotherium	X		
Asterotemma		X	
Neoglyptatelus	X	X	
Notoungulata			
Adinotherium	X		
Bernia	X		
Xotodon	X		
Eutomodus	X		
Stenotephanus	X		
Haplodontotherium	X		
Pachynodon	X		
Dilobodon	X		
Dinotoxodon	X		
Eutypotherium	X		
Munizia	X		
Protypotherium	X		X
Abrothrodon		X	
Gyrinodon		X	X
Trigonodops		X	
Trigodon		X	
Plesiotoxodon		X	
Toxodontherium	X	X	
Neotrigodon		X	
Neotoxodon		X	
Mesenodon		X	
Mesotoxodon		X	
Minitixodon		X	
Paleotoxodon	X		X
Oneotherium			X
Litopterna			
Protherotherium	X	X	
Epitherium	X		
Brachytherium	X		
Licaphrium	X		X
Thoatherium	X		
Carlosoma(name?)	X		
Scalabrinitherium	X		
Oxyodontotherium	X		
Mesorhinus	X		
Paranauchenia	X		
Promacrauchenia	X		
Culinia		X	
Sirenia			
Ribodon	X	X	X
Cetacea			
Ischyrorhynchus	X	X	X
Saurocetes	X	X	X
Chiroptera			
Noctilio		X	
Proboscidea			
Amahuacatherium		X	
Primates			
Acrecebus		X	
Stirtonia		X	
Solimoea		X	
Carnivora			
Cyonasua	X		
Marsupialia			
Didelphis		X	
Zygolestes	X		
Notictis	X		

Line missing

Stylocynus	X		X
Achlysictys	X		

Table 1 (*continued*)

	"Mesopotamian"	Acre	Urumaco
Pelecaniformes			
Anhinga	X	X	
Macranhinga	X	X	
Gruiformes			
Onactornis	X		
Andalgalornis	X		
Charadriiformes			
Maegapaelus	X		
Crocodylia			
Charactosuchus		X	X
Caiman	X	X	X
Purusaurus		X	X
Melansuchus			X
Mourasuchus	X	X	X
Gryposuchus	X	X	X
Hesperogavialis		X	X
Ikanogavialis			X
Chelonia			
Stupendemys		X	X
Podocnemys		X	X
Chelus		X	X
Phrynops	X		
Chelonoidis		X	
Lacertilia			
Tupinambis	X		

The data from Acre were taken from the collections of the Laboratório de Pesquisas Paleontológicas and our own data, as well as from Campbell et al. (2000) and Latrubesse et al. (1997). Data from the Mesopotamian come from the collections of La Plata Museum of Natural Sciences (La

absence of immigrant mammals like Sigmodontine rodents. Nevertheless, some elements suggest that a low rate exchange already had been initiated at the time of connection between the Americas (Campbell et al., 2000, 2001; Cione et al., 2001).

The fossil vertebrates do not support the hypothesis of a marine environment, even though the richest faunal groups are aquatic: crocodilians, turtles, and fish. Giant alligatorids such as *Purussaurus* (largest Cenozoic terrestrial predator, ~15 m long) (Fig. 8) and other alligatorids, gavials, crocodilids, and the extinct endemic family Netosuchidae indicate a greater diversity of crocodilians in this region than any other region, past or present. The river turtle family Pelomedusidae, endemic to South America, is a good indicator of stable water bodies with abundant vegetation and a tropical to subtropical climate. Bony and cartilaginous fish, reptiles, cetaceans, and sirenians (manatees) indicate a large flooded basin with shallow lakes and swamps, crossed by fluvial belts. Some fishes such as *Arapaima*, *Hoplias*, *Colosoma*, and other genera continue to be found today in the fluvial systems of Amazon Basin. Lungfish (Lepidosirenidae) are represented by the giant extinct *Lepidosiren megalos*, similar to the smaller living *L. paradoxa*. Siluriformes (catfish) are the most abundant and diverse group of fish and are good indicators of freshwater environments. Cartilaginous fish are represented by the endemic Potamotrygonidae (freshwater stingrays), the anfibiotic shark genera *Carcharhinus*, and *Pristis*.

Fig. 8. Skull of *Purusaurus brasiliensis*, the largest alligatorid recorded in the Solimões Formation and one of the largest predators, reaching up to 15 m in length. For comparison, see the head of an Amazon living black caiman *Melanosuchus niger* that reached 3.5 m in length. This cast of the *Purussaurus* skull is on exhibit at the Museum of Paleontology of the Federal University of Acre, Rio Branco, Acre, Brazil.

Mammals are also a highly significant aspect of the vertebrate assemblage. Rodents are well represented and can be used as environmental indicators. The rodent *Kiyutherium orientalis* (Hydrochoeridae, Cardiatheriinae), a typical Huayquerian rodent recorded in the Solimões Formation as well as in Venezuela, Argentina, and Uruguay, inhabited areas near bodies of water like the present capivaras. Proterotheres (Liptoterna), astrapotheres, glyptodons, pampatheres (Xenarthra, Cingulata), and ground sloths (Mylodontidae and Megatheriidae) indicate more terrestrial habits in both browsing and grazing forms (Latrubesse et al., 1997). The presence of Platyrrhini primates of the families Cebidae and Atelidae indicate the existence of gallery forests along the rivers.

4. Palynology of the Solimões Formation

The first palynological data of Cenozoic age from the Amazonas Basin were published by Daemon and Contreiras (1971), who suggested a Paleocene–Miocene age for the sediments. Cruz (1984) established three palynological zones corresponding tentatively to the Miocene, Miocene/Pliocene, and Pliocene in cores from the CPRM/DNPM boreholes.

Hoorn (1993) analyzes samples from boreholes 1AS-4a-AM and 1AS-51-AM in Amazonas state near the border with Peru, as well as bank outcrops (Figs. 2 and 9), and identifies five pollen biozones for the Miocene (Fig. 10): the *Verrutricolporites* and *Retitricolporites* zones (Early Miocene), the *Psiladiporites–Crototricolpites* zone (Early/Middle Miocene), the *Crassoretitriletes* zone (Middle Miocene), and the *Grimsdalea* zone (Middle/Late Miocene).

We studied core samples from CPRM/DNPM borehole 1AS-32-AM (Figs. 2 and 9), located approximately

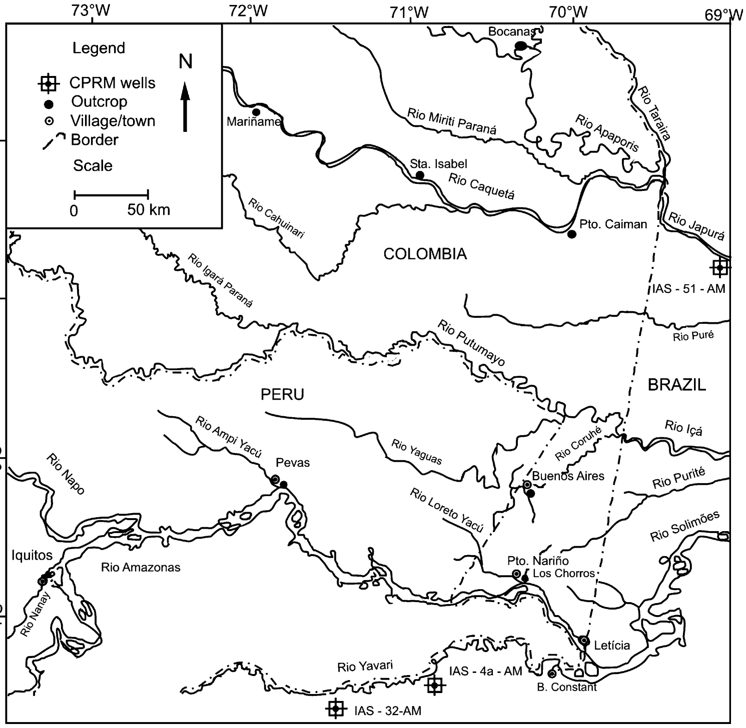

Fig. 9. Area studied by Hoorn (1993, 1994a,b), as indicated with a square in Fig. 2. Borehole IAS 32-AM is also indicated.

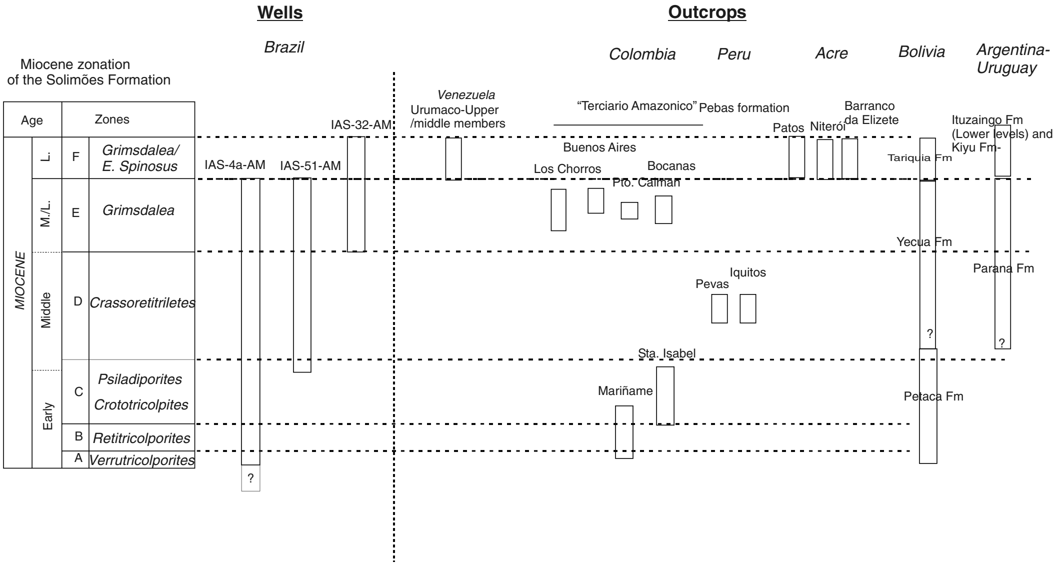

Fig. 10. Correlation of wells IAS-4a AM and IAS-51-AM with outcropping sediments in Brazilian and Colombian Amazonia, according to Hoorn (1993, 1994a,b) and data herein on Acre outcrops and well IAS 32-AM. Note random correlation of Miocene deposits along the outcrops, as proposed by Hoorn. Why small temporal differences might exist among Los Chorros, Puerto Caiman, Bocanas, and Buenos Ares inside the early Late Miocene was not explained by Hoorn, nor are they sustained by the pollen content. The correlation of the Solimões Formation with the Mesopotamian of Argentina and Uruguay (lowermost levels of Ituzaingo and Kiyu formations) and the Falcon Basin in Venezuela and Tariquia Formation in Bolivia is shown.

53.5 km SW of borehole 1AS-4a-AM studied by Hoorn (1993). We studied 13 samples in borehole 1AS-32-AM, between 132 and 12 m depth below ground level, at intervals of around 10 m, and identify two zones (Grimsdalea and Asteraceae zones).

Samples for pollen analysis were also collected from outcrops of the Solimões Formation sediments along the Acre River banks in the Brazil/Peru/Bolivia border area (Figs. 2 and 11). Sediment samples were treated according to the methodology of Uesugui (1979). The preparation involved grinding of the samples, followed by reaction with 32% HCl and 40% HF, then separation using $ZnCl_2$. A total of 300 pollen types were counted. In addition to presenting new palynological data, we reassess some stratigraphic and paleoenvironmental inferences proposed previously. Notably, our analysis of the sediments along the Acre River reveals no evidence of marine (or brackish-water) indicators, such as dinoflagellate cysts, foraminiferal linings, or mangrove assemblages, which is detrimental for the seaway model proposed by Räsänen et al. (1995).

4.1. Samples from borehole 1AS 32-AM

As we already noted, the upper 132 m of borehole 1AS-32-AM were sampled, which corresponds to the *Grimsdalea* interval zone (*sensu* Lorente, 1986), with the uppermost part of the borehole section corresponding to the Asteraceae interval zone (*sensu* Lorente, 1986).

Three distinct intervals can be recognized. In the lower part, 132—48 m, the lithology consists at the base of a lignite clay layer, followed by silt, sand, and lignite inclusions (1.65–0.40 cm thick). Limestone, pyrite nodules, and plant debris are abundant at around 55 m depth. This interval is characterized by *Grimsdalea magnaclavata* (first occurrence defines the base of the zone), with abundant *C. vanraadshoovenii* and *P. pokornyi*, plus *Mauritiidites franciscoi*, *Monoporopollenites annulatus*, and *D. adriennis*. Other species such as *Cicatricosisporites* sp., *M. grandiosus*, *Retitricolpites lorentae*, *Bombacacidites baculatus*, *Bombacacidites bellus*, *B. muinaerum*, *Corsinipollenites oculusnoctis*, *Verrucatosporites usmensis*, *Verrumonoletes* sp., *Verrutriletes* sp., *Psilamonoletes tibui*, *Psilatriletes* sp., *Echitriletes muellerii*, *Matonisporites* sp., and *Polypodiaceiosporites* sp., are also present in small quantities. Lorente (1986) defines the base of the Grimsdalea zone by the first occurrence of this species and the top as just below the first occurrence of *Echitricolpites spinosus*. *Retitricolpites lorentae* has its first occurrence in this zone, and *Bombacacidites bellus* also occurs (Hoorn, 1993), which confirms the presence of the Grimsdalea zone in this interval.

In the middle part of the borehole section, 48–25 m, the lithology is characterized by beds of clay intercalated with limestone. Lignite, remains of calcareous fragments, and fossils with pyrite nodules are also found. The presence of *G. magnaclavata* and the absence of *C. vanraadshoovenii* suggest that this section belong to the upper *Grimsdalea* zone (*sensu* Lorente, 1986) but above the uppermost levels of Hoorn (1993). *Grimsdalea* sp1., *E. maristellae*, *Proxapertites tertiaria*, *Crototricolpites annemariae*, *E. estelae*, and *Syncolporites anibalii* also are present. However, a gap exists between 48 and 25 m, where *C. vanraadshoovenii* is absent and *E. spinosus* has not appeared, possibly due to problems in the record.

Finally, the upper part occurs between 25 and 12.1 m. This interval is characterized by clay, limestone, and sand beds. Its top is defined by carbonaceous clay. The first appearance of *Echitricolporites spinosus*, which occurs at 25 m depth, characterizes the base of Asteraceae zone, but it is not very frequently observed (<2%). This section is instead dominated by *G. magnaclavata*, *D. adriennis*, *P. pokornyi*, *Azolla* sp., *Magnastriatites grandiosus*, *E. maristellae*, and *Proxapertites tertiaria*. In addition, *Grimsdalea* sp1., *V. usmensis*, *Clavatriletes* sp., *R. lorentae*, *B. bellus*, *B. baculatus*, *B. muinaerum*, *Echitricolpites* sp.,

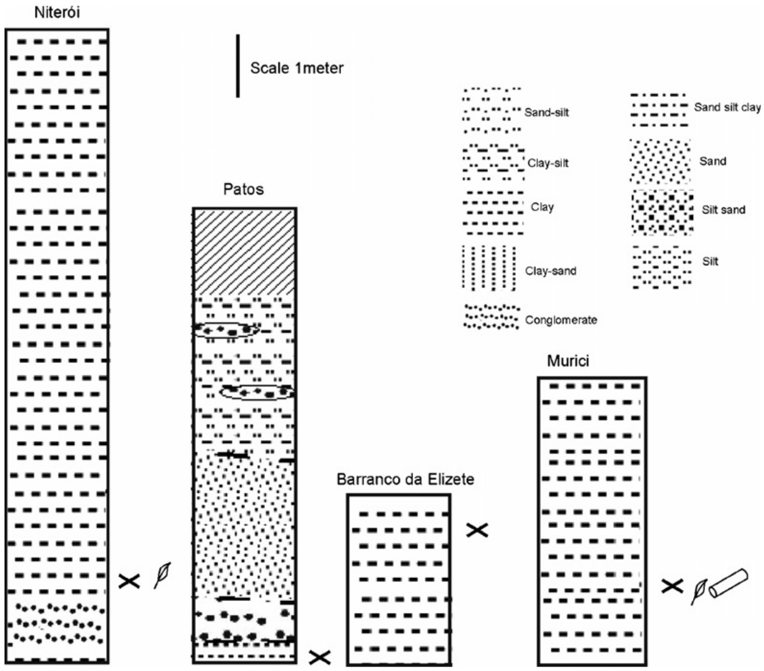

Fig. 11. Riverbank outcrops with palynologic data from the Acre River. Outcrops located in area 1 of Fig. 2.

Matonisporites sp., *M. annulatus*, *Psilatriletes* sp., *C. columbianus*, *M. vanderhamenii*, and *P. tibui* are found in low quantities. Hoorn (1993) and Leite (2004) record the appearance of *E. spinosus* from the Middle Miocene (Crassoretitriletes zone), though Germeraad et al. (1968), Lorente (1986), and Muller et al. (1987) record *E. spinosus* from the upper Miocene, considering it a good stratigraphic marker. Other species characteristic of the Late Miocene, such as *Cyathecidites annulatus*, *Pachydermites diederixi*, and *Bombacacidites ciriloensis*, were not recorded in our study. Cruz (1984) records *Cyathecidites annulatus*, *Pachydermites diederixi*, *Echitricolporites spinosus*, *Polypodiaceiosporites potonei*, *Fenestrites spinosus*, *Magnastriatites howardi*, and *Striasyncolpites zwardi* in samples from the Solimões Formation, considering them characteristic of the Late Miocene.

4.2. Samples from the banks of the Acre River

As we have noted, four localities on the Acre were investigated using palynological data (Fig. 11). At Patos and Niterói, pollen samples and vertebrates were collected from the same stratigraphic level. At Murici and Barranco da Elizete, the sediments provided pollen but no vertebrate fossils. The lithological sections of the surface localities are represented in Fig. 11 and described next. Palynological diagrams appear in Fig. 12.

Murici is on the right bank of the Upper Acre River, close to the town of Assis Brasil on the Brazil–Bolivia border. The sediments from which the samples were collected are clays rich in organic material including lignite, approximately 3 m above the low-stage water level. The outcrop is characterized by an abundance of *G. magnaclavata* and the absence of *C. vanraadshoovenii* and *E. spinosus*. In order of abundance, the following taxa are present at Murici: *G. magnaclavata*, *D. adriennis*, *Verrucatosporites usmensis*, *Psilatriletes* sp., *Monoporopollenites annulatus, Perisyncolpites pokornyi*, *Verrutriletes* sp., *Psilatriletes* sp3., and *M. grandiosus*. Frequencies of up to 2% are observed for *Mauritiidites franciscoi*, *Azolla* sp., *Bombacacidites* sp3., *Retitricolporites* sp2., *R. porispectus*, *R. lorentae*, *Psilatricolporites minimus*, *Retimonocolpites* sp., and *P. tertiaria*. Frequencies of <1% are found for *Bombacacidites* sp1., *Retimonocolpites* sp2., *Chomotriletes minor*, *C. columbianus*, *E. maristellae*, *Echiperiporites* sp1., *Psilatriletes* sp3., and *Retitricolpites* sp1.

The Barranco da Elizete locality is on the left bank of the Upper Acre River. The sample, of a dark clay lens, was taken at the low-water level during the dry season (southern hemisphere winter). The presence of *E. spinosus* and *Fenestrites* sp. could indicate a Late Miocene age. The assemblage is composed of *Psilatriletes* sp., *Verrutriletes* sp., *Verrumonoletes* sp., *Concavisporites* sp., *Echitricolporites spinosus*, *Psilatriletes* sp2., *Echitricolporites maristellae*, Echiperiporites sp., *Bacutriletes* sp. *Cicatricosisporites* sp., *Echitriletes* sp., *Matonisporites* sp., *Kuylisporites waterbolkii*, *Illexpollenites* sp., *Polypodiaceoisporites* sp. *Retitricolpites* sp., *Echipollenites* sp., and *E. estelae*.

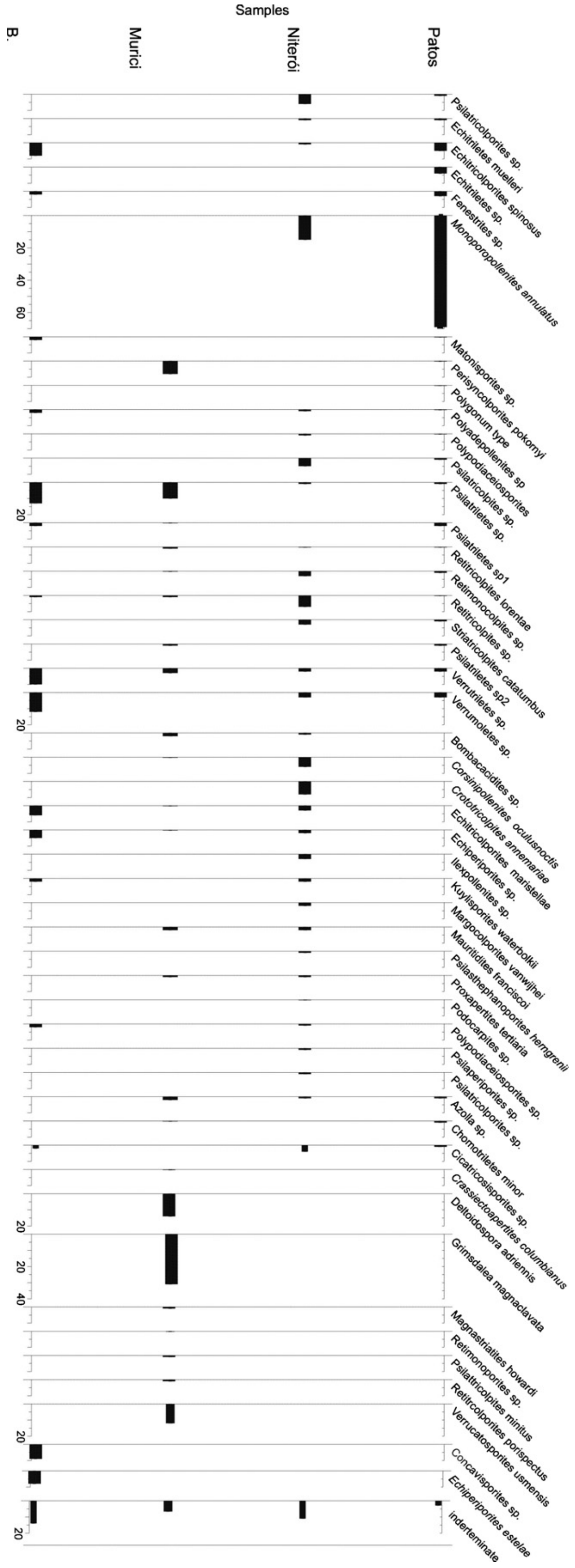

Fig. 12. Palynological diagram of the outcrops samples of the Acre River.

The sample from Patos, also on the Upper Acre River, was collected from the base of an intraformational conglomerate consisting of clay balls and silt, approximately 0.5 m above the water level. This conglomerate is rich in fossil vertebrates of Huayquerian–Mesopotamian SALMA age; Patos is a well-known mammal locality. The palynological assemblage is composed mainly of *M. annulatus* (almost 70%), followed by *E. spinosus*, *Echitriletes* sp., *Fenestrites* sp., *Verrumonoletes* sp., *Verrutriletes* sp., *Psilatriletes* sp., *M. grandiosus*, *Azolla* sp., *Chomotriletes minor*, *Cicatricosisporites* sp., *Psilatricolporites* sp., *Psilatriletes* sp2., *Psilatriletes* sp3., *Retimonocolpites* sp., *S. catatumbus*, and *Echitriletes muellerii*. At frequencies of <1%, we find *Retitricolpites* sp., *R. lorentae*, *Polypodiaceiosporites* sp., *Polyadopollenites* sp., *P. pokornyi*, *Podocarpidites* sp., and *Matonisporites* sp. In this same locality, we collected in situ seeds of Myrtaceae and Euphorbiaceae (genus *Piranhea*), indicating a typical floodplain ("várzea") environment.

Niterói, another well-known mammal locality, is located on the right bank of the Lower Acre River, near the town of Senador Guiomard in Acre. The lithology is dominated by massive green to grey–green clayey sediments. About 90 cm from the low-water level is an intraformational conglomeratic clay, almost 40 cm thick, with mudballs and fish, crocodile, and turtle remains. About 2.4 m above the low-water level is a rich fossiliferous bed. Gypsum crystals are disseminated in the clayey sediments and fill fractures and fossil bones. Lignite and leaves are common in this site. Palynological samples were collected approximately 1 m above the low-water level. *E. spinosus* forms <1% of the pollen count. The assemblage includes *M. annulatus*, *Crototricolpites annemariae*, *Corsinipollenites oculusnoctis*, *Psilatriletes* sp., *Psilatricolpites* sp., *Retitricolporites* sp., *Cicatricosisporites* sp., *Illexpollenites* sp., *E. maristellae*, *Verrumonoletes* sp., *Retimonocolpites* sp., *Striatricolpites catatumbus*, *Mauritiidites franciscoi*, *Verrutriletes* sp., *Retitriletes* sp., *Retitricolporites* sp., *Margocolporites venwijhei*, *K. waterbolkii*, *Polypodiaceoisporites* sp., *Echiperiporites* sp., *Azolla* sp., *Bombacacidites* sp., *Echitriletes muellerii*, *P. herngrenii*, *P. tertiaria*, *Psilaperiporites* sp., *Psilatriletes* sp2., *Psilatricolporites* sp., *Podocarpidites* sp., and *R. lorentae*.

4.3. Palynology and biostratigraphical context

The palynomorphs at different sites can be used to indicate rough absolute ages (Fig. 13) and provide tentative correlations of surface localities and boreholes (Fig. 10). Patos, Barranco da Elizete, and Niterói all represent the same time interval in the Late Miocene according to the presence of *Echitricolporites spinosus* that characterizes the base of the Asteraceae zone and the absence of pollen species that indicate Pliocene and Pleistocene ages, such as *Stephanocolpites evansii*, *Echitricolporites mcneillyi*, and *Alnipollenites verus*. This age estimate is consistent with that from the vertebrate assemblage in the same area.

Regarding borehole IAS-32-AM, despite its proximity to the core studied by Hoorn (1993), we observe paleoenvironmental and biostratigraphical differences. First, *Zonocostites ramonae* (*Rhizophora*), which according to Hoorn (1993) is abundant in samples from the *Grimsdalea* zone, is not found in borehole IAS-342-AM. The association of this species with *Deltoidospora adriennis* was interpreted by Hoorn (1993) as characterizing a costal plain environment (related to Serravallian global sea level rise, see Hoorn, 1993, 1994a,b; Haq et al., 1987). The absence of *Zonocostites ramonae* and the presence of *D. adriennis* suggest a freshwater paleoenvironment in the Grimsdalea zone (Collinson, 2002). In Hoorn's (1993) fig. 9, the *Grimsdalea* zone persists only up to the Middle–Late Miocene boundary, but we recorded *E. spinosus* in the upper section of borehole 1AS-32-AM as well as in outcrops of the Rio Acre in the Late Miocene. Therefore, a younger age than that proposed by Hoorn (1993) applies to well 1AS-4a-AM.

Second, we do not find *C. vanraadshoovenii* in any samples at depths shallower than 48 m and find *E. spinosus* above 25 m. Our observations seem to agree with those of Germeraad et al. (1968) and Muller et al. (1987) (Fig. 13), who note the disappearance of *Crassoretitriletes vanraadshoovenii* at the base of or a little before the Asteraceae zone in the Caribbean. This pollen species extends to the top of the Pleistocene in Borneo and Nigeria. Lorente (1986) shows that *C. vanradshoovenii* is still alive in some parts of the tropics.

Third, Hoorn (1993) concludes that there is no palynological evidence of Late Miocene or Pliocene ages but mentions the presence of *E. spinosus* in the *Crassoretitriletes* zone. Similarly, we associate *E. spinosus* and *Crassoretitriles* with *Fenestrites*, which has been reported to appear only in the Late Miocene and Pliocene (Germeraad et al., 1968; Muller et al., 1987). Our observations seem to agree with the disappearance of *Crassoretitriletes vanraadshoovenii* at the base or a little before the Asteraceae zone.

The biozones established by Hoorn (1993) for western Amazonia, notably the *Crassoretitriletes* (assigned to the Middle Miocene) and *Grimsdalea* (Middle–Late Miocene), thus should be used with some caution, because the biochron of the main biostratigraphic markers seems, on the basis of the inconsistency between different reports in different regions, to be temporally transgressional (Fig. 13). For example, if we use the palynological biozone criteria of abundance/scarcity, we might conclude that some of the Acre River outcrops are of different ages because *E. spinosus* occurrences vary from a representative 8% at Barranco da Elizete to a scarce 1% at Niteroi and none at Murici. *E. spinosus* should be abundant in the Late Miocene (consistent with a Late Miocene age for Barranco da Elizete), and its scarcity or absence would suggest an older or younger age for Murici or Niteroi. However, Niteroi and Patos are the most representative and important localities for Huayquerian (Late Miocene) mammals. Forcing

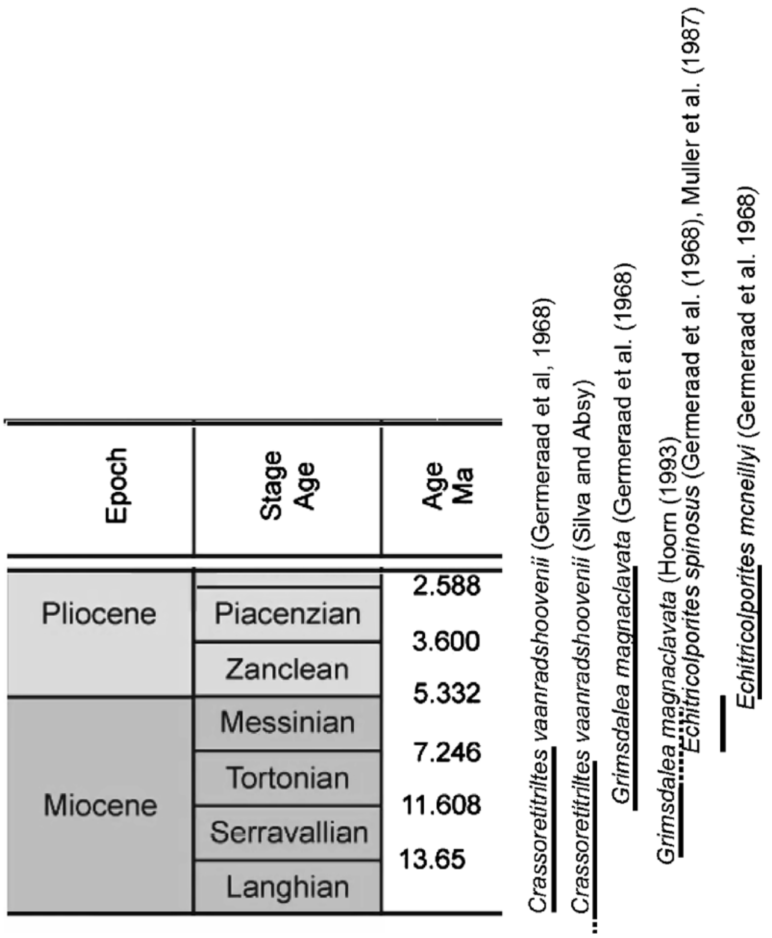

Fig. 13. Biochron of main palynologic biostratigraphic markers used in northern South America for the Middle and Late Miocene. Note the temporal overlap/differences that vary among authors. Note also the different ages proposed for the Grismdalea biozone, though *E. Spinosus* seems characteristic of the Upper Miocene. Sources of information: (1) Germeraad et al. (1968); (2) Silva (2002); (3) Hoorn (1993); and (4) Muller et al. (1987). Germeraad et al. (1968) investigated the Caribbean; Lorente (1986) and Muller et al. (1987) worked in Venezuela. These localities, which are rather distant from the present study region, provide some points of comparison. Hoorn's (1993) work was in western Amazonia.

different ages for these outcrops using the absence, presence, or scarcity of *E. spinosus* or *Grimsdalea* would thus lead to error. Although pollen biozones have been important for recognizing the Miocene ages of the sediments in Amazonia, we need to improve their definitions and calibrations, because their current definitions do not have sufficient stratigraphic sensitivity and thus cannot be used as precise tools for separating spans of time within the Miocene. Instead, they can lead to incorrect age assignments within the Miocene and, thus, miscorrelations of the outcrops and borehole evidence.

4.4. Paleoenvironmental inferences

According to Lorente (1986), sporomorph assemblages that are rich in specimens but poor in species are characteristic of alluvial plains. This combination of characteristics is observed in several borehole and outcrop samples. For instance, dominance by pollen of Gramineae, as observed at Patos, suggests an alluvial plain depositional environment.

The pollen association recorded in the upper levels of borehole IAS-32-AM is dominated by *Grimsdalea magnaclavata*. This is not a living species; Germeraad et al. (1968) infer it is a palm with a marked adaptability to different habitats. In the fossil record, this species is restricted to the Caribbean, Venezuela, Colombia, and Brazil. A high abundance of its pollen probably characterizes the margins of shallow floodbasin lakes (Hoorn, 1994a) or forest elements (Wijninga, 1996). In addition, a high abundance of *P. pokornyi* (Malpighiaceae), recorded in association with *Grimsdalea magnaclavata*, also suggests a forest environment near the area of deposition.

In the lowermost intervals of borehole IAS-32-AM, *Crassoretitriletes vanraadshoovenii* is dominant. This species has botanical affinities with *Lygodium microphylum* (synonymous with *L. scandens*), a climber fern with living representatives in Guyana (botanical samples deposited in the herbarium of the Missouri Botanical Garden) and Brazil (herbarium of the INPA-National Institute of Amazonian Research, Manaus, Brazil, where material collected in São Paulo state is stored). However, some claim this species now lives only in West Africa and southeast Asia (Lorente, 1986).

Swamps are indicated by the presence of *C. vanraadshoovenii* (Schizaceae), and aquatic or wet environments are suggested by *Magnastriatites grandiosus* (Pteridaceae), *V. usmensis* (Polypodiaceae), *Psilamonoletes tibui*, *Deltoidospora adriennis* (Pteridaceae), *Chomotriletes minor*, *Bombacacidites baculatus* (*Pachira aquatica*), and *Azolla* sp. (Hoorn, 1993; Collinson, 2002).

Returning to the pollen collected from the outcrops along the Acre River, Patos shows a predominance of *Monoporopollenites annulatus* (70%), which appears less abundant at Niterói (15%), indicating aquatic vegetation (grassland in floodplains and/or floating meadows; Hoorn, 1994b).

In all four localities, spores (e.g., *Echitriletes muellerii* (Sellaginellaceae?), *Azolla* sp., *K. waterbolkii* (Cyatheacea), *Psilatriletes* sp., *Verrumonoletes* sp., *Cicatricosisporites* sp.) are abundant and indicate a wet or aquatic environment. *Corsinipollenites oculusnoctis* (Onagraceae) and *Chomotriletes minor* are also present, mainly at Niterói, suggesting an aquatic environment. In addition, forest elements are represented by *P. pokornyi*, *Illexpollenites* sp. (Aquifoliaceae), and *Multimarginites vanderhammenii* (Acanthaceae) (Germeraad et al., 1968; Hoorn, 1993; Collinson, 2002).

Overall, the predominance of both spores and pollen indicates an aquatic environment consisting of freshwater lakes and swamps. This inferred abundance of freshwater lake and swamp elements supports deductions made from the fauna. The environment inferred in Acre state and southern Amazonas from both vertebrates and pollen content of the sediments of the Solimões Group implies grassland and gallery forests along rivers, swamps, and shallow lakes, subjected to fluctuating water levels in a tropical to wet–dry tropical seasonal climate.

5. Correlation problems

5.1. Northern Amazonia

The outcrops in Acre were correlated by Räsänen et al. (1995) with the sediments of NW Amazonia described by Hoorn (1993, 1994a,b). As we have noted, it appears that the chronology proposed by Hoorn (1994b), based on palynological studies of boreholes and outcrops, contains some inconsistencies in the correlation of some outcrops with the core sequences. Hoorn's (1994b) five palynological zones cover the time span between the Early Miocene and Middle–Late Miocene (~23 to ~10 Ma). Notably, she correlated the outcrop at Mariñame/Santa Isabel area in the Caquetá River (Fig. 9) with the lowermost levels of borehole 1AS-4a AM (263.5–181.8 m depth; assigned to the *Retitricolporites* and *Psiladiporites–Crototricolpites* zones; Early Miocene), located approximately 300 km to the south. However, the Early Miocene was not recorded in borehole IAS-51-AM, nearly 150 km to the east from the typical outcrops of Mariñame/Santa Isabel area in the Caquetá River (Figs. 9 and 10). Because the Solimões Formation is subhorizontally or horizontally bedded, and no paleorelief or strong vertical displacement of faulting has been described in this area, the topographic difference of 250 m separating the outcrop of Early Miocene sediments at Mariñame and the inferred correlative deposits in well IAS-4a AM, buried around 200 m deep, demand justification (Fig. 14). The outcrops at Puerto Caiman and Buenos Aires in the Caquetá and Cotuhé rivers, as well as those along the Colombian part of the Amazon, near Mariñame, have been correlated with the *Grimsdalea* zone (Middle–Late Miocene; Hoorn, 1993) (Figs. 9 and 10). Given the absence of concrete field evidence of paleorelief, differential subsidence, or faulting, the lateral correlation between the older Early Miocene sediments at Mariñame and the Middle–Late Miocene sediments cropping out at other localities nearby is a problem. As we noted, Hoorn (1993) did not identify Early Miocene deposits in borehole 1AS-51-AM (Figs. 9, 10, and 14). In this borehole, the basement was reached 167 m below the surface, and a middle Miocene age was assigned to the lowermost levels. If the Early Miocene is not recorded in this well, as reported by Hoorn (1993), it either was never deposited or eroded before deposition of the Middle Miocene sequence.

The more feasible explanation is that the Early Miocene is not recorded in well IAS-51-AM because it is located on the Iquitos arch. The Early Miocene sediments should rest subhorizontally, like a plateau, and deepen generally to the southwest, growing more deep in the direction of the depocenter of the basin (wells IAS 4a–AM) and outcrop laterally in the border/margin of the basin to the northeast in Colombian territory (Mariñame-Santa Isabel area). If this proposition is correct, the Iquitos arch was an active structural barrier during the Early Miocene in the Amazon Basin, probably acting as a forebulge or area in which we might expect thin deposits or no deposition to that time.

However, the situation is more complex for the Late Miocene. Why did depositions continue in NW Brazilian Amazonia but not in SW Colombia? After the deposition of the Mariñame Early Miocene sediments, part of Colombian Amazonia may have acted as a positive relief during the Middle–Late Miocene, but subsidence continued in Brazilian Amazonia and southernmost Colombian Amazonia. This scenario could account for the different ages of the sediments but would exclude the possibility of marine transgressions reaching western Amazonia from the Caribbean Sea, through the Colombian Llanos, in the Middle or Late Miocene (cf. Hoorn, 1993, 1994b), because the northernmost part of the Colombian Amazon lowlands would suffer uplift during the Middle–early Late Miocene. So what happened with the Iquitos arch at this time? Apparently, the arch was overlapped by tertiary sediments during the Middle Miocene–Late Miocene (150 m of Middle–Late Miocene deposits in wells IAS-51-AM); in this case, the forebulge area suffered drastic position and behavior changes, suffered subsidence in the area of the Iquitos arch,

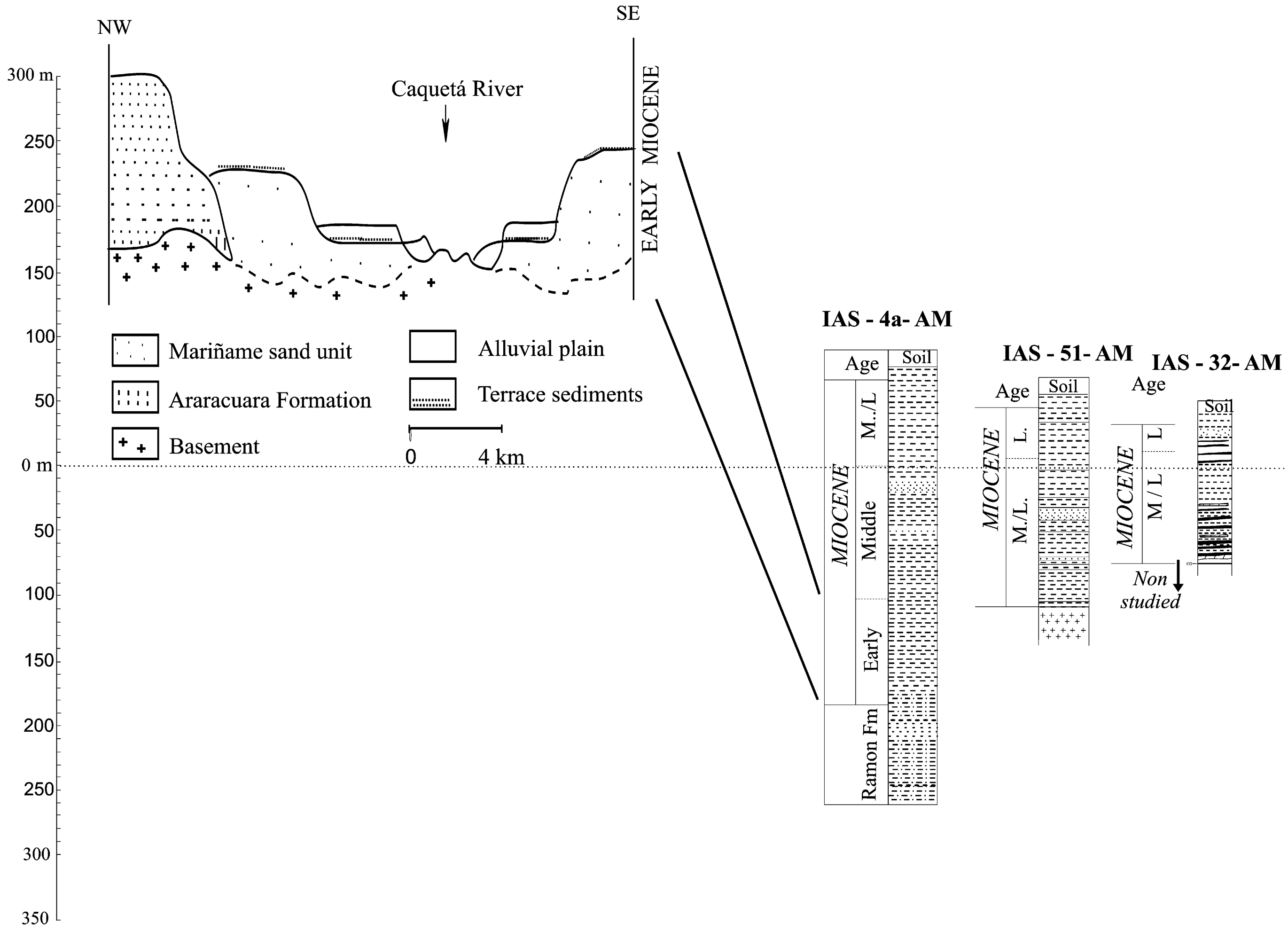

Fig. 14. Another view of sediment positions and correlation in the terrain related to the sea level. The correlation between the Mariñame unit and the early Miocene deposits of the IAS-4a represent a difference of more than 200 m, almost equal to the well depth. Note the absence of Early Miocene sediments in well IAS-51-AM, indicating a hiatus or no deposition period in the section at around 10 Ma.

and migrated east. At present, these remain hypotheses; we need more data to draft a more concrete structural scenario, particularly for the area east of the Iquitos arch.

However, it is important to note that our palynological data from borehole IAS-32-AM near the area described by Hoorn (1993) suggests that Late Miocene deposition occurred in northern Amazonia, west of the Iquitos arch and in Acre state. The difficulties previously noted prevent the correlation of the deposits of the Solimões Formation throughout Amazonia, particularly when trying to differentiate units within the Miocene. To strengthen such temporal calibrations, a combined stratigraphic approach using vertebrate paleontology is desirable.

5.2. Southwestern Amazonia

In trying to justify an intracontinental seaway, Räsänen et al. (1995) correlate the outcrop of the Solimões Formation in Acre with the marine incursions proposed by Hoorn (1993, 1994b) in northwestern Amazonia and others in the Chaco Basin (Marshall and Sempere, 1993; Marshall et al., 1993) (Fig. 1A). Rasanen et al. also forced a Late Miocene age (Serravalian–Tortonian) on the hypothetical seaway. However, the deposits in Acre yield a Late Miocene fossil assemblage (Latrubesse, 1992; Latrubesse et al., 1997), indicating Huayquerian SALMA dating of 9–6.5 Ma (Flynn and Swisher, 1995; Cione et al., 2001). In contrast, the marine incursions postulated for the sediments of the Pebas Formation in NW Amazonia are dated to the Middle Miocene or early Late Miocene (older than 11 Ma; Hoorn, 1993), indicating they are at least 2.5 Ma older than the Acre sediments. This correlation, suggested by Räsänen et al., appears incorrect, despite the difficulties noted regarding Hoorn's pollen ages (1993, 1994a,b).

Räsänen et al. (1995) suggest that the mammalian fauna in Acre state is not reliably dated and may be Middle Miocene, not Late Miocene. On the contrary, our contemporaneous and subsequent work has significantly strengthened the basis for placing this fauna within the Late Miocene. Notably, support for a Late Miocene age is strengthened by the pollen content of the key vertebrate sites of Patos and Niteroi, which contain *Echitricolpites spinosus*, consistent with the Huayquerian age established for the macrofossils collected from the area (Fig. 10). On the basis of the faunal assemblage, the sediments in Acre can be correlated with the Urumaco Formation in Venezuela, which was deposited in a marginal environment and also is considered Huayquerian because of its fossil vertebrate content and its temporal correlation with the foraminifera zonation of the Caribbean zone (Dias de Gamero, 1996; Linares, 2004) (Fig. 10, Table 1).

A further difficulty regarding the connection with the South Atlantic across Bolivia and the Parana Basin proposed by Räsänen et al. (1995) is that this proposal correlates the Acre sediments with the Yecua Formation. The Yecua Formation in the southern Bolivian plains indicates the northernmost limit of the Middle Miocene transgression within the Parana Basin (Entrerrian transgression; Marshall et al., 1993). This unit has fossil mammals from the Chasicoan mammal age, which is Middle Miocene (>10 Ma) (Marshall and Sempere, 1993; Marshall et al., 1993). None of the fossil vertebrates recorded in the Yecua Formation has been recorded in the Solimoes Formation in SW Amazonia. However, largely correlative with the Yecua Formation are the sediments of the Entrerrian transgression, recorded across much of southern South America as the Paraná Formation in NE Argentina and extending into southern Brazil (as the Mioceno de Pelotas), Uruguay (Camacho Formation), and Patagonia (Puerto Madryn and correlated units). Abundant and spectacular fossils, including bivalves, gastropods, and marine mammals, clearly indicate the marine nature of these sediments (Cozzuol, 1993; Martinez and del Rio, 2002). The minimum age obtained from the marine outcrops in Patagonia was determined as approximately 10 Ma on the basis of ^{86}Sr/^{87}Sr 87 analysis on mollusks (Scasso et al., 2001) and should be around 7Ma in the Chaco–Parana Basin (Hernandez et al., 2005). Nevertheless, new discussions remain open about the age and nature of the marine deposits in southern Bolivia.

The subsequent regression phase is marked in the southern Paraná Basin by the deposition of fluvial sediments of the Ituzaingó Formation, possibly as a response to a fall in sea level at the Serravalian–Tortonian boundary.

The Ituzaingó Formation occurs along the Paraná River in Entre Rios Province, Argentina, and the correlative Kiyú Formation in Uruguay bears a vertebrate assemblage with strong affinities with the Acre fauna (Cione et al., 2001; Perea et al., 1994), clearly dating from the Huayquerian SALMA (Fig. 10, Table 1). During the Late Miocene, the Tariquia Formation was deposited in Bolivia, which should correlate with the deposits described herein and by Räsänen et al. (1995) in Acre. The Tariquia Formation was deposited in a fluvial continental environment between 8 and 6 Ma (Moretti et al., 1996).

This Acre fauna thus postdates the Chasicoan mammals found in deposits dating from the time of the marine transgression, or the Middle Miocene–early Late Miocene in the case of the Yecua Formation record. A synchronous chronological record and posttransgression environment between the fossiliferous levels of the Solimões Formation in SW Amazonia and the fluvial sediments of the Ituzaingó/Kiyú formations in the Paraná–La Plata Basin is thus postulated (Cozzuol, 1993; Cione et al., 2001). The sediments of the Solimões Formation described by Räsänen et al. (1995) and us in Acre thus correlate with the Late Miocene posttrangression sediments represented by the Ituzaingó Formation in the Paraná Basin and the Urumaco Formation in Venezuela, not with the end of Middle Miocene transgression (Fig. 1B).

In conclusion, the Early and the Middle–early Late Miocene are not recorded outcropping in SW Brazilian Amazonia, so we cannot discuss an imaginary paleoscenario to this time in the region. Additional information from wells of the old Coal Project of CPRM and from the Ramón Formation, a unit of probable older tertiary age on the border of Brazil and Peru, eventually may shed some new light on older tertiary records in SW Brazilian Amazonia.

6. Southwestern Amazonia during the Late Miocene

In light of the available evidence, we propose a new paleoenvironmental reconstruction for SW Amazonia during the Late Miocene (Fig. 1B). As we have discussed, much of the evidence of marine influences during the Miocene comes from NW Amazonia. Several authors have proposed that occasional Early–Middle Miocene marine incursions from the Caribbean reached as far south as 2°S (Hoorn, 1993; Vonhof et al., 1998). Stable isotope studies could indicate that the marine incursions, if they existed at all, were weak, with the seawater component diluted by freshwater (Vonhof et al., 1998). Wesselingh et al. (2002) report mainly freshwater molluscs in the Pebas Formation, the part attributed by palynology to the Middle Miocene of the Solimoes Formation in this region. Also, in a more recent study by Kaandorp et al. (2006) only freshwater mollusks were recorded in outcrops of the upper Solimões Basin, including some localities described by Hoorn (1994a). Ostracods in the upper Solimões area could indicate a brackish environment (Muñoz-Torres et al., 2006). However, ostracods found in outcrops of the Tarauacá River, near the border of Amazonas and Acre states, indicate freshwater environments in the area too (Feijó Ramos, 2006). Atypical marine fossil associations (vertebrates or invertebrates) previously were recorded in the Amazon, but no evidence of marine transgressions has been reported in NW Amazonia during the Late Miocene. However, we recognize that some inconsistencies remain unresolved regarding the published pollen ages for this region (Hoorn, 1993, 1994a,b), and some Miocene ages may be subject to future adjustment once an overall regional correlation scheme has been established (Figs. 10 and 13).

To establish the regional conditions during deposition of the Solimões Formation, it is necessary to consider the evolution of the northern and central Andes (Fig. 1A). The first influence of a rising Eastern Cordillera in Colombia appears at around 12 Ma (Guerrero, 1997). Sediments derived from the northern Andes, with the rich fossil fauna of La Venta (∼13–11 Ma), were deposited across the Magdalena Basin (La Honda Formation; Kay et al., 1997).

The evolution of SW Amazonia reflects the evolution of the central Andes, where the Eastern Cordillera likely experienced uplift and erosion between 27 and 5 Ma (Late Oligocene–end of the Miocene) (Nobret et al., 1996), resulting in an influx of sediments to the Amazon foreland basin, which led to the deposition of the lower part (not exposed in Acre) of the Solimões Group. The cratonic areas east of the foreland basin also acted as a sediment source (Hoorn, 1993). The fastest uplift and deformation in the central Andes occurred in the late Miocene (e.g., Coudert et al., 1995; Jordan et al., 1983; Sebrier et al., 1988). After 10 Ma, debris accumulated in the foreland basin, and the sub-Andean fold-and-thrust belt developed (Gubbels et al., 1993). We infer that the sedimentary response to these events was the development in SW Amazonia during the Huayquerian/Mesopotamian SALMA, marking the late Tortonian and early Messinian stages, of a complex terrestrial sedimentary system. At this time, SW Brazilian Amazonia was connected directly to the Andes, and a megadepositional system, formed by avulsive fluvial belts entering and crossing a large floodbasin, deposited at least the uppermost levels of the Solimões Formation (Fig. 1B). Large depositional systems, formed by river-like megafans (similar to but in a wetter environment than the modern Chaco and Indogangetic depositional systems) sourced from the Andes, spread onto the subsiding plain formed by shallow lakes, swamps, and fluvial belts abandoned by avulsion. At this time, the modern Ucayali and Marañon–Huallaga basins did not exist, and the predominant drainage thus was eastward from the Andes. The Divisor ranges seem to have formed a low, positive relief but were unable to act as an effective drainage divide, transected as they were by the fluvial systems and surrounded but not covered by the Late Miocene sediments (Latrubesse and Rancy, 2000).

The climate during the Late Miocene was wet tropical with a dry season. Some lakes were probably slightly saline, as indicated by stable isotopic analyses of molluscs (Vonhof et al., 1998). However, aridity was weak and insufficient to produce calcareous soils (calcretes) or evaporites. An abundant fauna, including fish, turtles, crocodiles, and mammals, inhabited the associated rivers, swamps, lakes, and gallery forests. The vegetation was dominated by a palynological association indicating the presence of freshwater lakes and tropical swamps.

7. Conclusions

New pollen data from established mammal sites in the Brazilian states of Acre and Amazonas and the uppermost levels of well IAS-AM-32 indicate a Late Miocene age for the sediments cropping out in this region, consistent with the age (Huayquerian–Mesopotamian SALMA, 9–6.5 Ma) previously deduced for the vertebrate fauna in these sediments. A terrestrial wetland environment is indicated (Fig. 1B), represented by marshes, shallow lakes, and canopy forest along fluvial channels, consistent with the sedimentary facies present. The water and sediment supplies for this system came from the Andes, forming a vast, highly unstable, hyperavulsive river system or megafan system similar to the Quaternary Chaco environment and the Neogene fluvial systems in the Ganges plain of northern India.

The uppermost levels of the Solimões Formation have been stratigraphically correlated with the Mesopotamian beds of Argentina (lowermost levels of the Ituzaingó Formation) and Uruguay (Kiyu Formation), as well as with the fossiliferous Urumaco Formation from Venezuela. A prior suggestion (Räsänen et al., 1995) that these sediments were deposited in a tidal marine or estuarine environment is strongly refuted, because of the inconsistencies in the seaway environmental interpretation and stratigraphic mistakes committed by those authors when they temporally correlate the Solimões sediments outcropping in southwestern Brazilian Amazonia with sedimentary units in the Parana Basin and northern Amazonia.

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