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INVITED REVIEW

Eustatic and tectonic change effects in the reversion of the transcontinental Amazon River drainage system

Efeitos de mudanças eustáticas e tectônicas na reversão do sistema de drenagem do Rio Amazonas transcontinental

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ABSTRACT: The development of the transcontinental Amazon River System involved geological events in the Andes Chain; Vaupés, Purus and Gurupá arches; sedimentary basins of the region and sea level changes. The origin and age of this river have been discussed for decades, and many ideas have been proposed, including those pertaining to it having originated in the Holocene, Pleistocene, Pliocene, Late Miocene, or even earlier times. Under this context, the geology of the sedimentary basins of northern Brazil has been analyzed from the Mesozoic time on, and some clarifications are placed on its stratigraphy. Vaupés Arch, in Colombia, was uplifted together with the Andean Mountains in the Middle Miocene time. In the Cenozoic Era, the Purus Arch has not blocked this drainage system westward to marine basins of Western South America or eastward to the Atlantic Ocean. Also the Gurupá Arch remained high up to the end of Middle Miocene, directing this drainage system westward. With the late subsidence and breaching of the Gurupá Arch and a major fall in sea level, at the beginning of the Late Miocene, the Amazon River quickly opened its pathway to the west, from the Marajó Basin, through deep headward erosion, capturing a vast drainage network from cratonic and Andean areas, which had previously been diverted towards the Caribbean Sea. During this time, the large siliciclastic influx to the Amazon Mouth (Foz do Amazonas) Basin and its fan increased, due to erosion of large tracts of South America, linking the Amazon drainage network to that of the Marajó Basin. This extensive exposure originated the Late Miocene (Tortonian) unconformity, which marks the onset of the transcontinental Amazon River flowing into the Atlantic Ocean.

KEYWORDS: Amazon River reversion; Headwater erosion; Tortonian; Gurupá Arch.

RESUMO: *O desenvolvimento do Sistema de drenagem do Rio Amazonas envolveu eventos geológicos nos Andes; arcos de Vaupés, Purus e Gurupá; bacias sedimentares da região, assim como mudanças do nível do mar. A origem e a idade deste rio têm sido discutidas por décadas, e muitas ideias têm sido propostas, incluindo aquelas relacionadas a ele ter se originado no Holoceno, Pleistoceno, Plioceno, Neomioceno, ou mesmo antes. Nesse contexto, a geologia das bacias sedimentares do norte do Brasil foi analisada a partir da era Mesozoica, e alguns esclarecimentos são colocados na sua estratigrafia. O Arco de Gurupá permaneceu elevado até o Mesomioceno, direcionando o sistema de drenagem primeiro para o oeste e posteriormente para norte, sem obstrução do Arco do Purus na Amazônia central. O Arco de Vaupés, na Colômbia, foi soerguido junto com as montanhas dos Andes no Mesomioceno, separando a drenagem do Caribe da do Rio Amazonas. Com a subsidência tardia e o brechamento do Arco do Gurupá e uma grande queda no nível do mar no início do Neomioceno, o Rio Amazonas abriu rapidamente seu caminho, de leste para oeste, a partir da Bacia do Marajó. Isto aconteceu através de erosão remontante profunda, que capturou a vasta rede de drenagem das áreas cratônicas e andinas, que anteriormente se desviara ao mar do Caribe. Durante esse tempo, o grande influxo de siliciclásticos à Bacia da Foz do Amazonas e seu leque aumentou, em razão da erosão em vastas áreas da América do Sul, incorporando a rede de drenagem da Bacia do Marajó à drenagem amazônica. Essa exposição extensiva originou a discordância tortoniana que marca o estabelecimento do Rio Amazonas transcontinental em direção ao Oceano Atlântico.*

PALAVRAS-CHAVE: *Reversão Rio Amazonas; Erosão remontante; Tortoniano; Arco do Gurupá.*

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INTRODUCTION

In Brazilian Amazonia, geological data from wells and geophysical surveys initiated by the National Petroleum Council (*Conselho Nacional de Petróleo* – CNP), in 1939, and by Petrobras, in 1953, revealed three structural arches, which presented diverse ages and origins, while in Peruvian and Colombian Amazonia, other arches were also identified. In Brazil, the Iquitos, Purus and Gurupá arches segmented the sedimentary area in the Upper, Middle and Lower Amazon basins, respectively (Morales 1957, 1959). According to this author, the Iquitos Arch separates the Acre and Andean Foreland basins from the Solimões Basin (formerly denominated Upper Amazon Basin); the Purus Arch separates the Solimões and Amazon basins (designated Middle Amazon Basin); and the Gurupá Arch separates the latter from the Marajó Basin (denominated Lower Amazon Basin) (Schobbenhaus *et al.* 2004).

Gurupá Arch is the shoulder of the Marajó rift that formed in the early phases of the Central Atlantic Ocean opening, in the Early Cretaceous time (Caputo 2012). Purus Arch resulted from a Middle Proterozoic graben in central Brazil, with an approximate north-south direction, which crossed the Amazonian basin area and reversed in the Late Proterozoic, becoming an exposed high up to the Mississippian time (Wanderley Filho 1991).

The Iquitos Arch resulted from a Neogene peripheral isostatic forebulge brought about by the Andean chain overloading on the South-American Plate western edge (Caputo 1985a,b, 1991, 2012, Roddaz *et al.* 2005, Caputo & Silva 1990). This arch, with a NW-SE direction, has remarkable expression in Peru, but is less visible in Brazil, where it has been inferred in several positions, being for this reason difficult to determine its actual location. Nevertheless, this arch does not separate the Acre and Andean foreland basins from the Solimões Basin in Brazil, being this separation accomplished by the Envira Arch, formed by the Late Jurassic Juruá Orogeny (Caputo 2014).

In addition to the mentioned arches, highs are also described in the basins of northern Brazil. The Monte Alegre Dome, with an area of 20 by 30 km, does not segment the Amazon Basin, having local character in the Amazon Basin's Northern Platform, and its genesis is likely related to Mesozoic basic intrusions. The Carauari High subdivides the Solimões Basin in the sub-basins of the Juruá (East) and Jandiatuba (West), and its genesis is related to an isostatic peripheral forebulge of a thick diabase sill (upper sill; Fig. 1). Vaupés Arch, in Colombia, a transversal feature to the Andes, was formed with the Andean uplift in the Middle Miocene (Mora *et al.* 2010), caused by the Nazca and South-American plates collision.

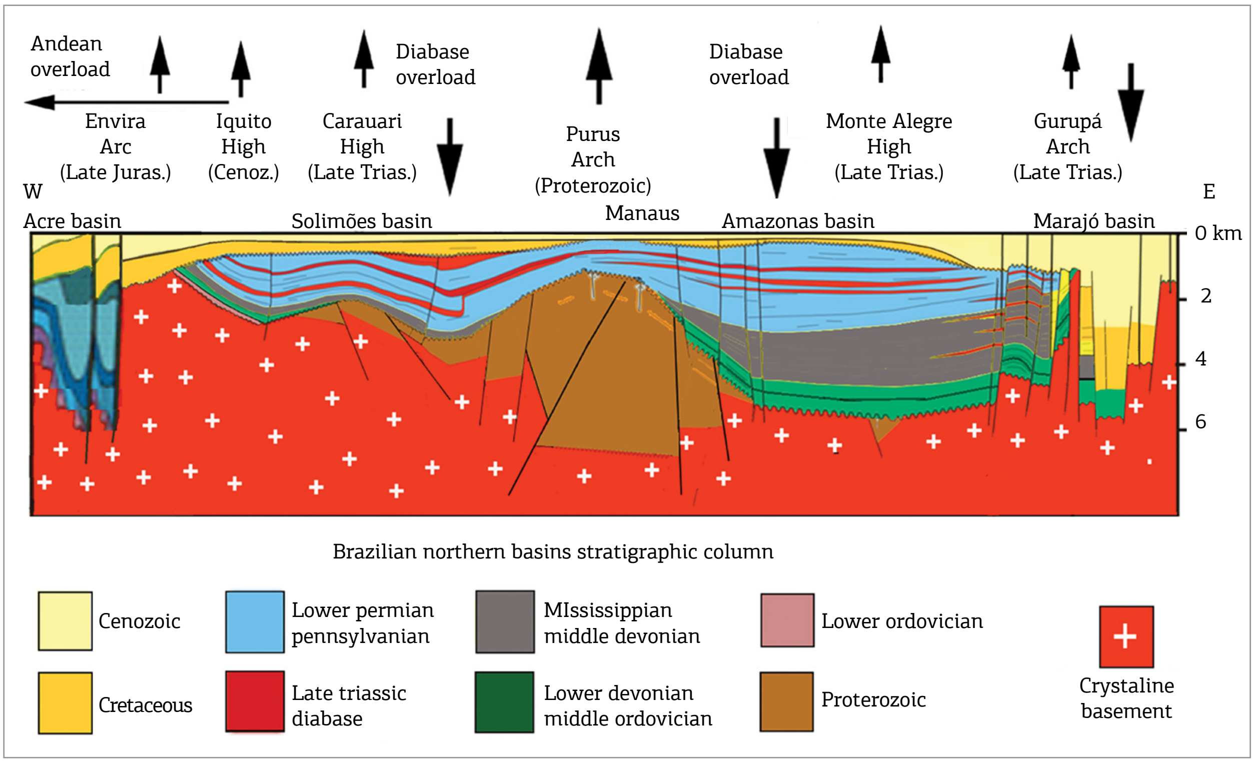

Figure 1. The Schematic longitudinal section of the Acre, Solimões, Amazon and Marajó basins shows structural arches and highs. Modified section of Wanderley Filho and Travassos (2009).

Tectonic activity of structural highs and arches was fundamental in directing the northern South-American drainage network, while sea level changes influenced on sedimentation (continental and marine) and erosion in sedimentary basins.

AMAZONIA STRUCTURAL ARCHES GENESIS AND PALEOGEOGRAPHY GURUPÁ ARCH AND NEIGHBORING AREAS

Paleozoic Amazon and Parnaíba basins were connected between themselves and the Paleozoic basins of northwestern Africa (Taodeni and Accra basins), with marine ingressions originated through that continent. In Accra Basin (Ghana), in onshore and offshore regions, the Paleozoic column presents the same stratigraphy and glacial events as that of the Parnaiba basin, up to the Carboniferous (Caputo 1984a). Gondwana and Laurasia continents amalgamation in the Mississippian time caused the North African Paleozoic basins to uplift and close, bringing about the Amazon Basin's marine sedimentation discontinuity. Only in Pennsylvanian did the sea enter again, coming from the West, through the Solimões Basin and Purus Arch. In the Permian, the sea retreated from the area towards the coastal marine basins of Western South America (Caputo 1984a).

In the Triassic time, an intercontinental drainage system linked the current high Sahara region (Africa) to the western portion of South America, where correlative sediments were deposited. This would be the first intercontinental Amazon River. At the final stage of the Triassic Period, a thermal uplifting, at the junction between these continents (Aires 1985), broke the continuity of that drainage, being that the portion which remained in South America, from the east end of the Amazon Basin, would have kept its course westwards, constituting the first transcontinental Amazonian drainage. The aforementioned uplifting caused widespread erosion and may be connected to a hot spot, since data from gravimetric modeling conducted by Aires (1985) suggested crustal replacement for denser mantle material to have occurred in the Marajó region, when the North Atlantic Ocean rifting took place. The continental crust was thinned and heated, causing it to arch and rise along with the Paleozoic sedimentary package of the Amazon Basin eastern end (Fig. 2). Extensive old NW cratonic fractures were reactivated and filled with diabase during the basic intrusions of Penatecaua Formation, which presented its largest number of fractures in this direction (Fig. 3), according to geological data from the Amapá State cratonic area (Villegas 1994, Costa *et al.* 2002).

Probably, from the Jurassic began to take place the most positive trend of uplift of the Marajó region. Its climax occurred in the

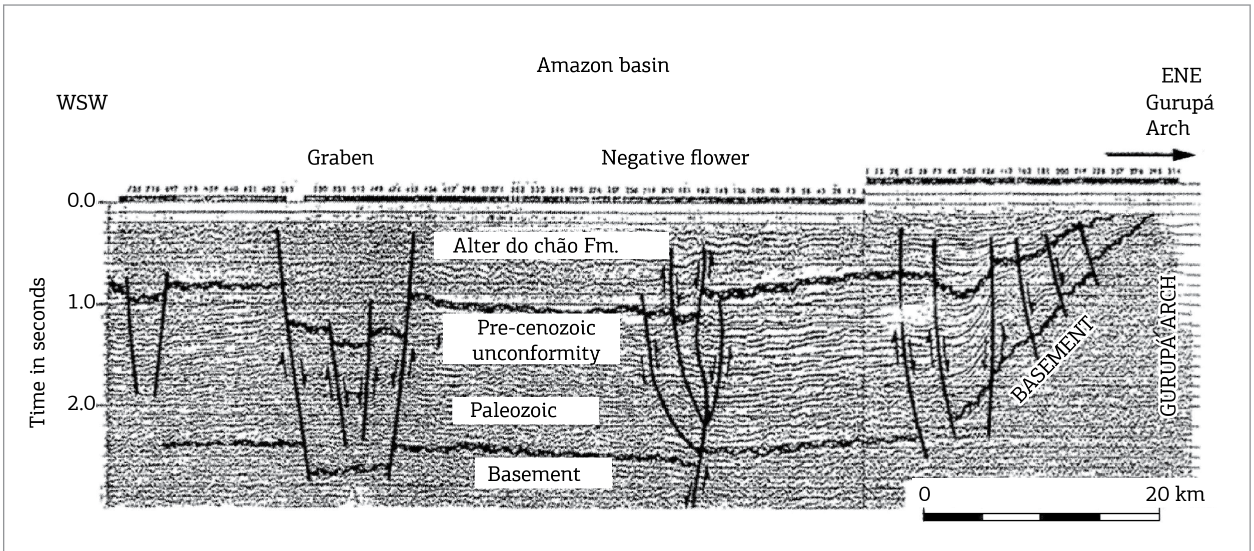

Figure 2. Seismic geological section of Gurupá Arch, where the basement still remains elevated, at the Amazon Basin's eastern end. This high hindered the Amazon and Solimões basin eastward drainage and directed it at first westward and later, with the construction of the Andes, northward toward the Caribbean Sea. The horizontal Cenozoic layers, overlaid the uplifted arch, characterize an angular unconformity, and normal faults also affected the dip of the beds. While there was almost continuous subsidence and deposition of the post-rift section of the Marajó Basin, the Gurupá Arch was being uplifted. This structural feature would only have been buried with the Late Miocene sedimentation in situation of downlap, when there would have been a possibility of draining to the Atlantic Ocean. Modified section of Campos and Teixeira (1988).

Early Cretaceous with the rupture of the Gondwana Continent and the formation of the Central Atlantic Ocean and the Marajó rift, the shoulder of which constituted the Gurupá Arch (Fig. 1), situated near the new ocean coast (Zalán & Matsuda 2007).

This arch became a watershed between the Amazon and Marajó basins (Fig. 2). The latter basin consists of an assemblage of genetically related taphrogenic sub-basins (Figs. 1 and 3), formed on the Brasiliano-Pan African Araguaia and

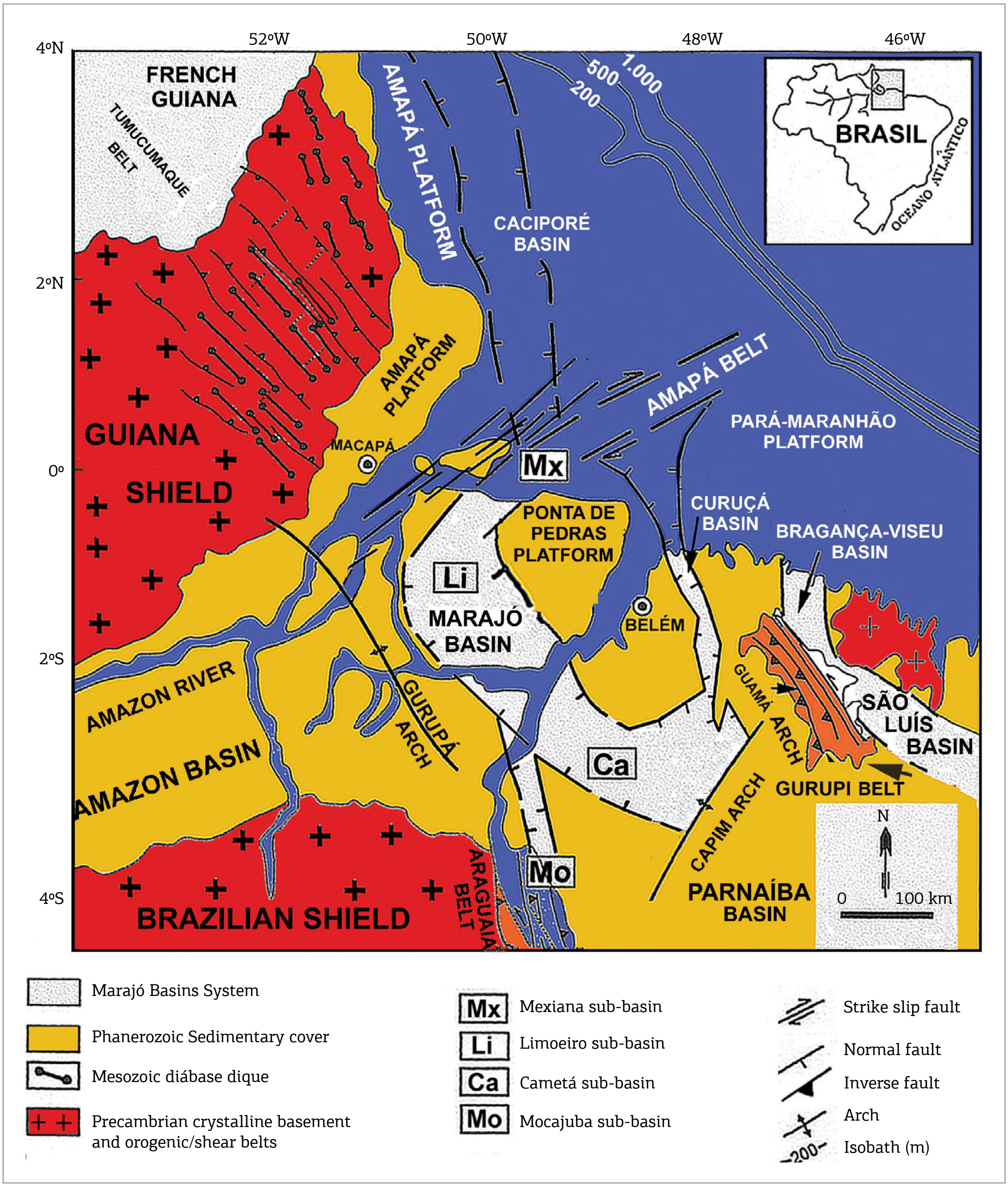

Figure 3. Tectonic framework of the Marajó Basin system, subdivided into four sub-basins and dominated by normal and strike-slip faults, and flanked by Amapá and Ponta de Pedras platforms, as well as Gurupá and Capim arches. The Marajó basin system area encompasses the island regions of Marajó Archipelago and part of continental areas of Pará and Amapá states. Modified of Villegas (1994) and Costa *et al.* (2002).

Gurupi belts (Zalán & Matsuda 2007, Costa *et al.* 2002). The oldest Mesozoic layers drilled in this region show to be as old as Barremian, but seismic sections indicate significant presence of older Mesozoic beds.

The rifting, which gave rise to the Marajó Basin, at the Early Cretaceous, caused independent sedimentation from the Amazon Basin. The Marajó Basin has many affinities and formations common to the Grajaú (Parnaíba Basin) and Foz do Amazonas basins (Zalán & Matsuda 2007, Santos & Rossetti 2006, Rossetti & Valeriano 2007, ANA 2015).

Following the opening of the Amazon Basin (Cuminá Event) in the beginning of the Paleozoic, the Gurupá tectonism was the most expressive tectonic event, since it definitely destroyed the Amazon Basin's physical continuity with the Parnaíba and northwestern Africa basins, and uplifted its eastern Pre-Ordovician basement during the rupture of the Gondwana Continent (Caputo *et al.* 1983, Caputo 1984a, 2012).

The continental crust stretching was not enough to break up the continental plate and form an oceanic crust on the Marajó Basin floor. The Gurupá Arch uplift brought about the erosion of over 5,000 m of Paleozoic strata and diabase sills, as well as Pre-Ordovician rocks of unknown thickness. Remnants from Amazon and Parnaiba basins' Paleozoic strata were preserved on Marajó rift (Caputo 1984a, Zalán & Matsuda 2007), indicating their preterit continuation with the Parnaíba and African basins. On the west edge of this rift, by the Gurupá Arch, occurred sedimentation of fanglomerates (Jacarezinho Formation), resulting from debris flows along a steeped faulted zone, similar to what occurred with the Salvador Formation in the Recôncavo Basin (Bahia State), throughout the rift stage, indicating a high relief on this border. At the end of the Albian, occurred an interruption in the sedimentation that lasted near 3 Ma, with the closing of the rift stage (Zalán & Matsuda 2007). With the return of the sedimentation in the post-rift stage there was an expansion of the depositional site, with sediments overlapping deposits from the rift stage and the basement portion of the adjacent Amapá and Ponta de Pedras platforms (Fig. 3) from the end of the Albian onwards (Galvão 2004, Zalán & Matsuda 2007).

The Gurupá Arch did not apparently subside completely due to the thermal decay that should normally take place 40 Ma following the rifting, because other tectonic forces also began to work in the area. During the subsidence and deposition in the post-rift stage of the Marajó Basin, uplifting in the area of the arch occurred, suggesting a possible tectonic decoupling between the arch and taphrogenic basins, from the Albian onwards. While subsidence and deposition continued in the Marajó Basin up to the Quaternary, with few sedimentation breaks, subsidence ceased for a long time on other Brazilian coast's aborted Cretaceous rifts (Tacutu, Bragança-Vizeu, Araripe, Jatobá, Tucano and Recôncavo). Marajó Basin and Gurupá Arch presented an anomalous behavior as to subsidence when compared with other mentioned rifts.

From the Cretaceous, the Marajó Basin deposition had continuity with the Grajaú Basin (Parnaíba) equivalent formations, represented by Codó, Itapecuru, Ipixuna, Pirabas, Barreiras and Post-Barreiras formations (Santos & Rossetti 2006, Zalán & Matsuda 2007, Figueiredo *et al.* 2007).

Cretaceous and Cenozoic sediments presented a quite significant amount of Braziliano zircon minerals in the Foz do Amazonas Basin (Jorge de Jesus Picanço de Figueiredo, personal communication, 2015), indicating a different source than that of the rocks of the Amazon River Valley.

The presence of abundant Brasiliano-aged and older zircon minerals in the Itapecuru Formation suggests, for Marajó Basin, a major sediment source from tectonostratigraphic terranes of Araguaia and Gurupi Brasiliano belts, and older rocks recycled from Parnaíba Basin, Borborema and Maroni-Itacaúnas Provinces (Fig. 4) (Nascimento 2006).

The greater sedimentary supply on Marajó Basin arose from its East-southeast flexural border, and originated from drainage from Grajaú and Parnaíba basins, as well as the ancestral Tocantins River (Figs. 3 and 4), which currently drains 700,000 km^2 of the Central region of Brazil (Latrubesse *et al.* 2010).

Gurupá Arch stayed exposed from its formation up to the early Late Miocene. The arch's elevation maintenance is also deduced, since an epeirogenesis in the Amazon Basin occurred, from the Albian, evidenced in several apatite fission track studies (Gonzaga *et al.* 2000, Pina *et al.* 2014, among others), and neither presents marine formations, since the end of the Paleozoic (Daemon & Contreiras 1971a, b), conversely to what is seen in Marajó Basin.

Toward the Gurupá Arch apex, in the seismic section (Fig. 2), the latest Cenozoic beds are seen to onlap the Paleozoic sedimentary package. This shows that the region has been high up to the Middle Cenozoic time. Some anomalous dips in the section are due to the presence of normal faults. Nevertheless, the possible Late Miocene-Early Pliocene layers downlap towards Marajó basin is not observed due to the lack of a farther to the east seismic record (Fig. 2). Gurupá Arch was only covered by sediments in the latest Miocene.

In the continental platform of states of Amapá and Pará (Foz do Amazonas Basin), with some clastic sediment interruptions, the accumulation was predominantly constructed of limestone since the Paleocene (Selandian) up to the Middle Miocene (Serravalian) (Figueiredo *et al.* 2007). The Marajó Basin functioned as an intermediary basin decanting coarse clastic sediments. This fact is pointed out by the low amount of clastic contribution to the open sea, through this basin, when the Amazon drainage went westward.

In the beginning of the Late Miocene, due to glaciation in Antarctica, a major sea level drop triggered deep river incision and headward erosion, extending the Amazon River drainage from the Atlantic coast westward up to the Andes and Vaupés foothills, thus configuring a large trans-continental river. This brought a larger sedimentary income, due to the incorporation of the Amazon River drainage into that of the Marajó Basin, and sea-level fall, beyond the shelf edge, causing the destruction of the carbonate platform in the Foz do Amazonas Basin.

At this time, a larger amount of clastics would have been carried out to the open sea, through the Mexiana Sub-basin (Fig. 3), forming valleys in the continental shelf. In the continental slope, a large submarine canyon directed sediments to abyssal regions of the Foz do Amazonas Basin (Castro *et al.* 1978). This is made clear by the presence of coarser clastics in the Foz do Amazonas Basin in the continuation of the Mexiana Sub-basin. Most sedimentation on the Amazonian cone was directed northward from the Amazon River Mouth, in the confrontation with Amapá state, due to sediments dragging and transporting caused by northward marine currents along the north Brazilian coast. With high deposition rates, a section as thick as 8,000 m was deposited at the foot of the continental slope, building the Foz Amazon Basin fan (Silva *et al.* 1999).

Following the Antarctic glaciation, the sea level raised transferring most of the Andean-sourced sedimentation to the continental area with the deposition of the Late Miocene-Pliocene Solimões Formation in northern basins of Brazil.

With the new glaciations in the northern hemisphere, at the end of the Pliocene and Pleistocene (Miller 2011), new erosion on the continental basins increased the sedimentary income on the Foz do Amazonas Basin and on its submarine fan. At this time, deposition of the Tucunaré Formation sandy deposits on the Marajó Basin and upon the Continental Platform (Figueiredo *et al.* 2007), and sedimentation of thin clastics of Pirarucu and Orange formations on the slope and deep regions, respectively, have increased.

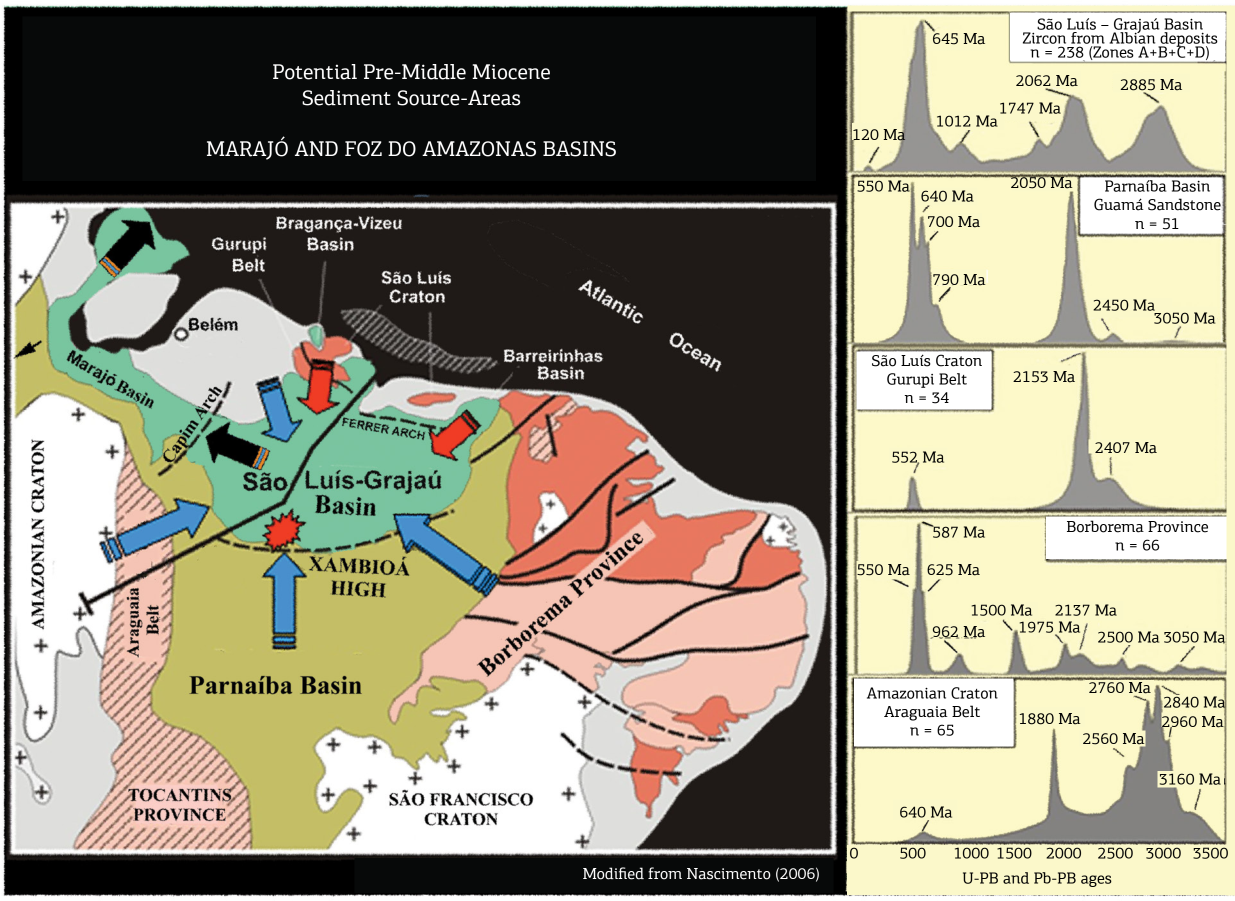

Figure 4. Potential source-areas of the Mesozoic (and Cenozoic) sediments from Marajó and Foz do Amazonas basins and U-Pb age distribution of the various potential source areas. Colored arrows indicate source areas, and black ones were added to the map of Nascimento (2006) to indicate the drainage way. The ancestral Amazon River drainage was directed westwards (small arrow).

The Barreiras Formation sedimentation (Late Oligocene-Middle Miocene) in the Pará State coastal region and Marajó Basin is related to the worldwide sea-level eustatic rise that had its peak in the Middle Miocene (20 – 12 Ma), in the Burdigalian and Serravallian time (Arai 2006, Rossetti *et al.* 2001). This deposition was independent of that of the Alter do Chão Formation in the Amazon Basin due to the presence of the Gurupá Arch. The Miocene deposition underwent interruption in the early Late Miocene (Tortonian), when there was the remarkable sea level drop, which caused erosion both in the Foz do Amazonas Basin and inland coastal (Arai 2006, Rossetti *et al.* 2001) and continental regions of the Amazon, Solimões, Acre and Andean foreland basins. In the Early Tortonian, sea level fell beyond the contemporary shelf edge over the entire Brazilian coast (Figueiredo *et al.* 2010). That unconformity in the marine region occurs within the NN9 Nanofossil Biozone in the Tortonian, with a break of 0.7 Ma (Figueiredo *et al.* 2009). Furthermore, the lowering of the sea level brought about deposition of thin grained clastics on the Foz do Amazonas Basin submarine fan. Only at the end of the Miocene and the beginning of the Pliocene (Zanclean, 4 – 5 Ma), with new, significant sea-level rise, clastic sediments started to accumulate again in the platform and coastal region (Arai & Shimabukuro 2003, Arai 2006).

The deposited Post-Tortonian sequence, named informally Post-Barreiras 1 and Post-Barreiras 2 or Upper Barreiras Formation, in the coast of Pará, displays a large abundance of reworked, pre-Tortonian and Tortonian fossils (Arai 2006), and it is correlated to the Solimões Formation and Içá formations respectively in the Western Amazon, Solimões and Acre basins. Post-Barreiras sediments, with other names (Tucunaré, Pirarucu, and Orange formations), are very well developed in offshore areas and Foz do Amazonas Basin fan.

At the end of the Pliocene and Pleistocene, sea-level changes degraded and aggraded the continental region many times due to glacial and interglacial phases. In the Holocene, with the general ice melting, a new rise of the sea-level occurred. The Amazonian submarine fan became inactive (Figueiredo *et al.* 2009) and sedimentation started to happen along the continental platform of the Foz do Amazonas Basin, as well as along the river floodplains and valleys of the Amazon drainage.

The Foz do Amazonas Basin submarine fan presents varying deposition rates (Figueiredo *et al.* 2009) due to many modifying factors, such as: sea-level and sea-current changes, growing expansion of the Amazon drainage, reduction and increase in forest area, worldwide and regional continental climate changes that can change weathering, sediment supply, and Amazon River sediment transport. Furthermore, the Caribbean, the Andes and sedimentary basins neotectonics may change the sediment input. One observes currently, with the high sea-level, the Amazonian cone receives just a minute volume of pelagic ooze. After deposition of the Post-Barreiras Formation a flexural uplift occurred along a belt with its crest situated ~300 km from the coastline (Driscoll & Karner 1994), but the Amazon River overcame this high. This flexural bulge, as high as 40 – 50 m, spatially coincident with the Gurupá Arch, was induced by the Amazon fan load and may have affected the fluvial and coastal depositional processes after the Middle Miocene.

PURUS ARCH AND AMAZON BASIN

The Purus Arch and Amazon Basin geological relationship is linked on the distribution of loads between erosion and deposition rates, promoting isostatic balanced vertical movements. The crystalline basement erosion induces its isostatic rise due to load alleviation, while the resulting eroded sedimentary load causes additional subsidence on the basins and vicinities along with a peripheral bulge farther out from them (Banks *et al.* 1977). Up to now, the Guyana and Brazilian shields erosion have released, for filling the Amazon Basin, sediments for building an over 5,000 m thick sedimentary pile, as well as countless amounts of them to other areas. The sedimentary filling promoted isostatic uplifting of cratonic areas and basin flank areas, the outcrops and plateau surfaces of them may be found at over 200 m above sea-level, and higher in basin flank belts.

The Amazon Basin with an area of nearly 500,000 km^2 of Paleozoic layers presents a stratigraphic column mainly comprised by Ordovician to Permian-aged groups and formations (Cunha *et al.* 2007, ANA 2015). In addition, over 1,000 m thick diabase sills intruded into the Paleozoic section at the end of the Triassic time. Above Cretaceous strata capped by Cenozoic layers occur, which enclose the deposition on the Amazon Basin.

The first oil wells in the Amazon Basin, drilled in the 1950s in the localities of Codajás (2-CS-1-AM), Lábrea (2-LA-1-AM), Três Bocas (1-TB-1-AM) and Tupana (2-TN-1-AM), showed the absence of Silurian and Devonian formations, between Pennsylvanian strata and Pre-Silurian basement in the Purus Arch region, west of Manaus. At that time, rocks as old as Ordovician were unknown in those basins (Caputo *et al.* 1971, 1972). Morales (1957, 1959) inferred the Purus Arch uplift to have started in the Devonian, having culminated in the Mississippian, when there would have been erosion of the previously deposited Siluro-Devonian strata. This conception resulted from the alleged existence of a continuous basin from the Lower to the Upper Amazon region. According to that author, in the Pennsylvanian time, during the Monte Alegre, Itaituba and Nova Olinda formations deposition, the Purus Arch would have restricted the connection between the Upper and Middle Amazon basins, creating conditions for the evaporites deposition within the Middle Amazon Basin up to Gurupá Arch. Nevertheless, current data reveal that this eastern arch still had not been formed in the Paleozoic time. Salt accumulation had only come about due to high evaporation rates in a shallow Amazonian sea nourished by the far west ocean.

On wells of the flanks of the Purus Arch, Caputo and Vasconcelos (1971) observed the thinning and pinching out of some basal Paleozoic formations and their onlap by younger stratigraphic units, showing no physical evidence of a typical regional Paleozoic tectonism, such as faults, folds or tilts. Therefore, the geological setting was incompatible with the proposition of a tectonic uplift of that arch, following the Devonian deposition, without physically affecting it and older strata, as proposed by Morales (1957, 1959). This fact leads them to conclude that this arch had been built prior to the Paleozoic sedimentation on Solimões and Amazon basins, serving as a divider between them and originating two independent basins (Caputo & Vasconcelos 1971).

Caputo (1984a) proposed designating the Upper and Middle Amazon basins as Solimões and Amazon, respectively, while the Lower Amazon Basin was already being denominated as Marajó Basin. This geotectonic context was also confirmed in later studies by Silva (1987, 1988) and Quadros (1988) who proved these basins to have been independent up to the Mississippian. As a consequence, the Pre-Pennsylvanian marine transgressions reached the Upper Amazon (Solimões) Basin by the west side of South America and the Middle and Lower Amazon basins by its east side (Caputo & Vasconcelos 1971).

With the aggregation of the Pangea Continent in the Mississippian, the Amazon Basin marine communication with African basins was closed, turning out the marine ingressions coming just from the west, through the Solimões Basin. Such conclusion opposes the Morales interpretation (1957, 1959), which suggested Amazonian Paleozoic basins would have an open marine connection up to the Devonian, with restrictions only in the Permo-Carboniferous.

The Purus Arch, located 240 km west of Manaus, consists of a regional structure originated from the distension in the Mesoproterozoic Era, which resulted in the development of the Cachimbo Graben; this, in turn, consists of a broad depression in Central Brazil containing sedimentary and igneous rocks as thick as 8,000 m (Wanderley Filho 1991, Wanderley Filho & Costa 1991). At the Neoproterozoic time, the Cachimbo Graben was reversed, due to compressive stresses in the region, becoming a structural high (Wanderley Filho 1991). During its development, the northern portion of that graben extended to the area where the Paleozoic sedimentation of the Amazon and Solimões basins, in northern Brazil, was to take place later on. The Purus Arch remained exposed from the Neoproterozoic up to the beginning of the Pennsylvanian and, during its long exposure, it is here interpreted that erosion diminished its weight, bringing about isostatic rise and lowering through erosion, phenomenon common to what takes place in mountains denudation. In a complementary way, it is interpreted that the Paleozoic sedimentation on the sedimentary basins adjacent to the big arch must have also caused a partial rise, as well as erosion, due to peripheral isostatic bulging brought about by the adjoining basin sediments combined burden. The intermittent lowering of this arch must have likewise been caused by the overload and erosion created by glaciers during four glacial phases in Llandoverian, Famennian, Tournaisian and Visean times, recorded in the Amazon, Solimões, Parnaíba and Paraná basins (Caputo *et al.* 2008), which may have contributed to wear the Purus Arch. It is also deduced that sea-level changes would have caused discrete isostatic upward and downward movements of the arch, due to the loading and unloading of sediments and water in the adjacent basins of the region.

The Purus Arch had its apex in Tefé and Coari township area (Solimões Basin, eastern portion), when it held its first Paleozoic sediments. Only in the Early Pennsylvanian the arch, lowered by erosion, was then for the first time surpassed and covered by intermittent marine ingressions coming from the west (Fig. 5 – section A).

The transgressions reached even the Paleozoic Basin of the Parnaíba and, probably, African basins, with generalized evaporitic-carbonate-clastic cyclothemic sedimentation, containing fossils with Andean affinities (Mesner & Wooldridge 1962, 1964). Marine communication between those basins was intermittent, according to what is inferred from the changes of the vertical facies in Pennsylvanian cyclothems of the Paleozoic basins of northern Brazil.

Data from boreholes show the arch have been buried for the first time by the Monte Alegre and Itaituba formations of the Amazon Basin (Fig. 5). The first unit is thin or locally absent on the arch, according to the record on some Petrobras boreholes, indicating the presence of some irregularities in the arch paleorelief, which were gradually covered and leveled by the subsequent Itaituba Formation sedimentation. From the Pennsylvanian to the Permian, it is observed that, under the effect of the ever-growing Paleozoic sedimentary pile overload, a small subsidence occurred in the area of the arch and a larger one in the neighboring sedimentary basins central areas.

In the region of the Purus Arch, Cretaceous layers are absent (Figs. 1 and 5). Early-Middle Miocene sediments

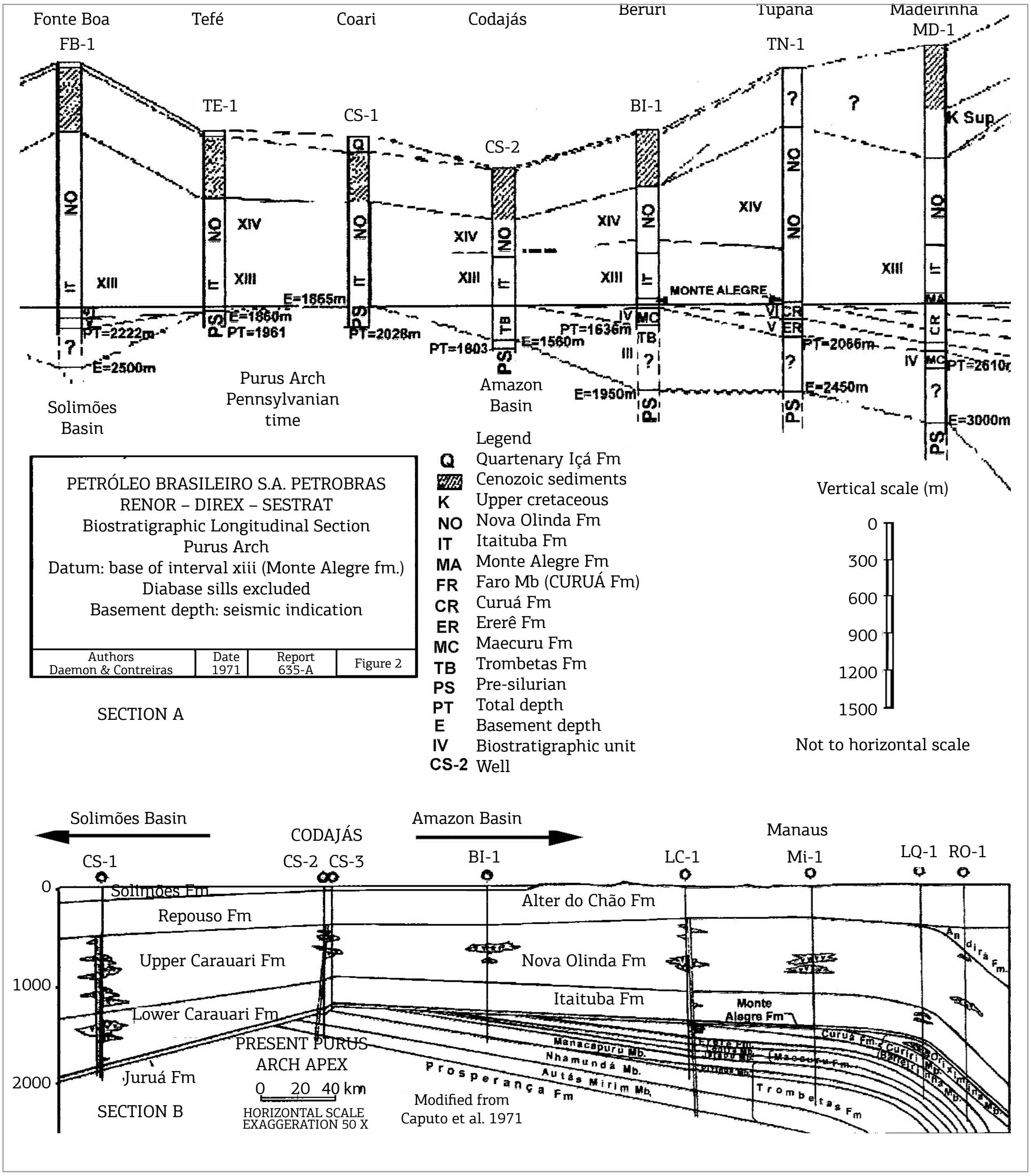

Figure 5. Partial geologic sections of Solimões and Amazon basins and Purus Arch. The datum from stratigraphic section A (Daemon & Contreiras 1971a) is the base of the Monte Alegre Formation, which shows the position of the Purus Arch in the Pennsylvanian (Morrowan) (Becker 2005), when the sea extended into the Amazon Basin from the west for the first time. The structural section B (Caputo et al. 1971) shows the new Purus Arch apex, deformed by additional overload of the upper Penatecaua Diabase sill on the western portion of the arch. In the region of the arch no Cretaceous layers occur. Cenozoic sediments to the east of the arch belong to the Alter do Chão Formation, and to the west they belong to the new Repouso Formation, proposed by ANA (2015) of a more pelitic nature. The Solimões Formation, with an Andean source area, goes beyond the Purus Arch eastward and is younger than the Repouso and Alter do Chão Formations. Içá Formation, not shown, is above Solimões Formation. See also Figure 1.

with Gurupá Arch source area, to the east of the Purus Arch, belong to the Alter do Chão Formation and, to the west, to the new Repouso Formation with a pelitic nature. Sediments of this unit are composed of plastic, laminated or massive dark grey and light green mudstone and siltstone. Fine grained greenish grey sandstone intercalations are often present, and white and grey-green limestone occurs in small proportion.

The Solimões Formation, with an Andean source area, goes beyond the Purus Arch eastward and it is younger than the Repouso and Alter do Chão formations.

Organic geochemical-based modeling studies, carried out by Gonzaga *et al.* (2000) on Paleozoic layers of the Amazon Basin, indicated a 1,800 m thick Paleozoic section to have been eroded, and the basin old borders extended far beyond their present position.

During the Phanerozoic, 16 known erosive unconformities in the Amazon Basin occurred, related mainly to sea-level changes, regional glaciations and, in a smaller extent, to epeirogenesis. Possibly, short duration unconformities were caused by sea-level changes and glaciations (Caputo *et al*. 2006a, b), and longer lasting ones by epeirogenesis.

Following the closing of the Paleozoic deposition in the Permian, a new erosive stage in the Amazonian basins came about, and in the area of the arch a discrete isostatic lowering occurred, due to the decrease of the lateral lithoestatic pressure, on account of the removal of sediments from the neighboring sedimentary basins during the Triassic.

At the end of the Triassic Period (~200 Ma), the Penatecaua tectomagmatism took place in the Amazon and Solimões basins, and adjacent shields, resulting on the intrusion of diabase dikes and sills into Paleozoic stratigraphic units, with over 1,000 m of total sill thickness. This magmatism makes part of the Central Atlantic Magmatic Province (CAMP) defined by around 200 Ma-aged tholeiitic basalts and diabases, cropping out from previously united parts of North America, Europe, Africa and South America (Marzoli *et al.* 1999). The thick intrusions brought about uplifting of the formations of the Paleozoic basins, being more significant in Gurupá and Purus arches, and in the Carauari and Monte Alegre highs, and larger relative subsidence in the central area of the basins due to the weight exerted on those areas by the wider sill thickness (Fig. 1).

Following the basic magmatism, from the latest Triassic onwards, a period of erosion and applanation occurred, lasting for 75 Ma in the Amazon and Solimões basins and structural highs (Carauari, Purus, Monte Alegre and Gurupá). The Permian, Andirá (Amazon Basin) and Fonte Boa (Solimões Basin) formations underwent deep erosion in the basins and were completely removed from the above mentioned structural highs. Likewise, the upper portions of Arari (Amazon) and Taititu (Solimões) formations, corresponding to the biostratigraphic zone XVI of Daemon and Contreiras (1971a, b), were partially eroded. These last mentioned formations, which are also of evaporitic character and unconformable, cap the Carauari (Solimões) and Nova Olinda (Amazon) formations and were recently proposed by ANA (2015).

It has been deduced that, with the higher relief in the eastern part of the Amazon Basin, drainage still headed westward throughout the Jurassic, Cretaceous and most of the Cenozoic time. Subsidence and sedimentation returned in the Cretaceous, from the Aptian to the Late Cenomanian time (Dino *et al.* 2000), with the implementation of continental fluvial environment in the Amazon Basin, the deposits of which have been attributed to the Alter do Chão Formation (Cunha *et al.* 1994, 2007). However, in a recent study based on paleontological evidence, Caputo (2009, 2011) proposed a change of the lithostratigraphy of the post-Paleozoic sedimentary units of the Amazon Basin, through calling them Jazida da Fazendinha (Cretaceous) and Alter do Chão (Cenozoic) formations, respectively. The name Alter do Chão Formation, proposed by (Kistler 1954), has priority and is well established in the geological literature to define the Cenozoic Amazon Basin's sedimentary cover. As a complement, palynostratigraphic studies on outcrops of Central Amazonia, regions of Manaus, Manacapuru, Presidente Figueiredo municipalities and Uatumã River, show the extensive Middle Miocene sedimentary cover which makes up the relief of this portion of the basin (Dino *et al.* 2012, Soares *et al.* 2015).

During the Cretaceous deposition, the Purus Arch presented less subsidence because of the differential sedimentary overload on the Paleozoic sedimentary basins.

Studies on apatite fission tracks indicate that in the eastern region of the Brazilian Shield denudation has occurred between 3 and 7 km, following the Middle Paleozoic, with higher intensity from 130 to 60 Ma ago (Harman *et al.* 1998). Around 110 (Gonzaga *et al.* 2000) or 106 Ma ago (Pina *et al.* 2014), in the Albian, there was cooling (uplifting) in the Amazon Basin's basement and sedimentary area, as observed by fission tracks, indicating a broad exhumation. Fission track data also show a cooling and uplifting of Chapada do Araripe (northeastern Brazil), initiated between 100 and 90 Ma ago (Morais Neto *et al.* 2006). Geomorphologic uplift was also detected in the region between the southeast of the Amazonian Craton, Amazon River Mouth and the Guianas region from Cretaceous onwards, which may have influenced on the watershed between the Amazon and Marajó basins (Zonneveld 1985).

From the Turonian to the Paleocene time, despite higher sea-level stands, erosion has taken place in the Amazon Basin, when the Purus Arch was simultaneously uplifted and worn down. This applanation wholly and partially removed the Cretaceous and upper Pennsylvanian beds from biostratigraphic zones XV and part of the XIV, respectively, as well (Daemon & Contreiras 1971a, b, Fig. 2). In the eastern region of the basin, the erosion was more intense and reached stratigraphically deeper Paleozoic layers, and at the Gurupá Arch apex (Fig. 1), in the eastern extremity of the Amazon Basin, the whole Paleozoic section and part of the basement were removed (Daemon & Contreiras 1971a, b, Fig. 2) (Fig. 1).

During the Cenozoic time salt movement (halokinesis) took place in the Amazon Basin (Costa 2002). From the Eocene time on, the Alter do Chão Formation deposition started in the Amazon Basin, partially covering the Jazida da Fazendinha Formation (Cretaceous), and in the Purus Arch (Fig. 5) covering the Nova Olinda Formation (Late Pennsylvanian) and in Gurupá Arch older Paleozoic formations (Fig. 2).

There are controversies as to the onset of the transcontinental Amazon fluvial System. Castro *et al.* (1978 and Shephard *et al.* (2010) suggested it to have taken place in the Middle Miocene time; Hoorn *et al.* (1995) and Figueiredo *et al.* (2009) in the Late Miocene; Espurt *et al.* (2007) and Roddaz *et al.* (2005) not before the Pliocene; Latrubesse *et al.* (2010), Campbell *et al.* (2006) and Campbell (2010) in the Late Pliocene; and Almeida (1974) in the Pliocene-Early Pleistocene. Bezerra (2003), Rossetti *et al.* (2005) and Bezerra and Ribeiro (2015) inferred the Amazon River to have flowed through the Tacutu Rift, the Essequibo River and the coast of Guyana Republic to the Atlantic Ocean in the Plio-Pleistocene and at the end of the Pleistocene and in the Holocene, being guided to its present valley site, by following neotectonic faults. However, a quite significant clastic deposition should have had taken place in the Plio-Pleistocene, forming a delta and a submarine fan during the alleged permanence of the Amazon River Mouth on the Guyana Republic coast. Moreover, the Plio-Pleistocene-aged Boa Vista formation and Holocene sediments, partly resulting from eolian deposition, which covers the Tacutu Rift, presents an elevation of 100-120 m above sea level throughout its full extension (Eiras and Kinoshita, 2006; Vaz *et al.*, 2007), that is, almost twice that of the Amazon River valley in the Colombia, Peru and Brazil triple border. Echo sounding profiles of shelf off Essequibo River (section DK) show no indication of a Quaternary delta building, but off the Orinoco River mouth (section DH) they present a delta platform (Nota, 1958). The sedimentary record of the neighboring Orinoco River delta occurs in the Maturin Basin of eastern Venezuela at the end of the Miocene, and is particularly evident during the Pliocene and Pleistocene (Díaz de Gamero, 1996).

The Purus Arch movement analysis here performed points out the Solimões Basin to have been exposed at the end of the Oligocene or the beginning of the Early Miocene, when the sea-level was low. In the Amazon Basin it still has not been possible to prove a possible intra-Alter do Chão Late Oligocene fossils-based unconformity.

In the Solimões Basin (Jandiatuba Sub-basin), Early Miocene (or Late-Oligocene) layers occur unconformably over the Cretaceous (Javari Formation). But, from the end of the Oligocene to the beginning of the Late Miocene, both the Purus Arch and sedimentary basins were the focus of subsidence and sedimentation, with the deposition of the upper portion of the Alter do Chão Formation in the Amazon Basin and Repouso Formation in the Solimões Basin. The latter formation is discussed in the Solimões Basin section.

At the Tortonian time, with the subsidence of the Gurupá Arch, wide sea-level fall and simultaneous Vaupés Arch uplifting (Hoorn *et al.* 2010, Mora *et al.* 2010), the whole continental area was exposed to erosion (Ucayali unconformity of Campbell *et al.* 2006). This caused a deep headward valley incision of the fluvial system of the Amazon River from the Marajó Basin, with no obstruction from the Purus Arch, which left the way free for the transcontinental Amazon River to flow into the Atlantic Ocean.

At the end of the Late Miocene and Early Pliocene, due to the sea level rise (Haq *et al.* 1987, 1988), the Solimões Formation deposition took place with fluvial sediments originating from the Andes, in Acre and Solimões basins, and in a small part of the west extremity of the Amazon Basin (Cunha *et al.* 2007, Motta 2008). Fluvial paleocurrents show an eastward flow, and sedimentation was first in deep valley floors of Amazon and Solimões Basin rivers and later along their floodplains.

Most of the Amazon Basin provided no accommodation for the Solimões Formation accumulation, since its relief became too high due to epeirogenic uplifting after the Middle Miocene time (Fig. 6). This uplifted area is the site of numerous Neogene bauxitic and no-bauxitic plateaus, higher in the basin flanks and lower close to the central basin axis area. Large plateau tops reached about 250 m above sea level, according to SRTM 90 m digital elevation model (DEM) from NASA, as opposed to the conclusions of Shephard *et al.* (2010), who stated subsidence lowered central and eastern basins of northern South America driven by mantle convection, from 14 Myr ago to date. Sacek (2014) concluded that the reversal of the Amazon River can be interpreted by the dynamics of surface processes and the flexure of the lithosphere in response to the formation of the Andes instead of regional uplift guided by mantle convection as proposed by Shephard *et al.* (2010), but Sacek's (2014) hypothesis also fails to fully reproduce the area stratigraphic development.

He informs that further investigation is therefore needed in order to understand the dynamic interaction between surface and tectonic processes, and their implications on the development of a megawetland that preceded the reversal of the Amazon River drainage.

In the Pleistocene Epoch, several sea level ups and downs took place due to the northern hemisphere glaciation cycles, with sedimentation of the Içá Formation and several terraces in the Amazon and Solimões basins, along river valleys and floodplains.

The earliest Pleistocene deposits of the Içá Formation were recorded 50 m beneath the Rio Negro valley floor (Soares *et al.*, *in press*), suggesting that at this time aggradation first took place in the deep valley, then along the floodplain. Likewise, the preservation of older sequences in the Foz do Amazonas Basin shows to be in the incised canyon floor rather than along the shelf area (Gorini *et al.* 2013). As the sea level rose over the shelf's edge, some sequences began to be preserved on the continental shelf once again.

There is a general idea asserting the Purus Arch would have been a topographic barrier separating the drainage between Solimões and Amazon basins, prior to the formation of the modern Amazon River (Potter 1997, Figueiredo *et al.* 2009, Nogueira *et al.* 2013, Rossetti *et al.* 2015). Nevertheless, no evidence was found to support this idea, since on the Purus Arch area and westernmost portion of the Amazon Basin, Solimões Formations strata occur, containing Andes-originated palynomorphs and minerals (Cunha *et al.* 2007, Motta 2008, Soares *et al.* 2015), indicating there have been no obstruction of the eastward drainage from the Solimões Basin to the Atlantic Ocean throughout the Negro, Amazon and other river deep valleys.

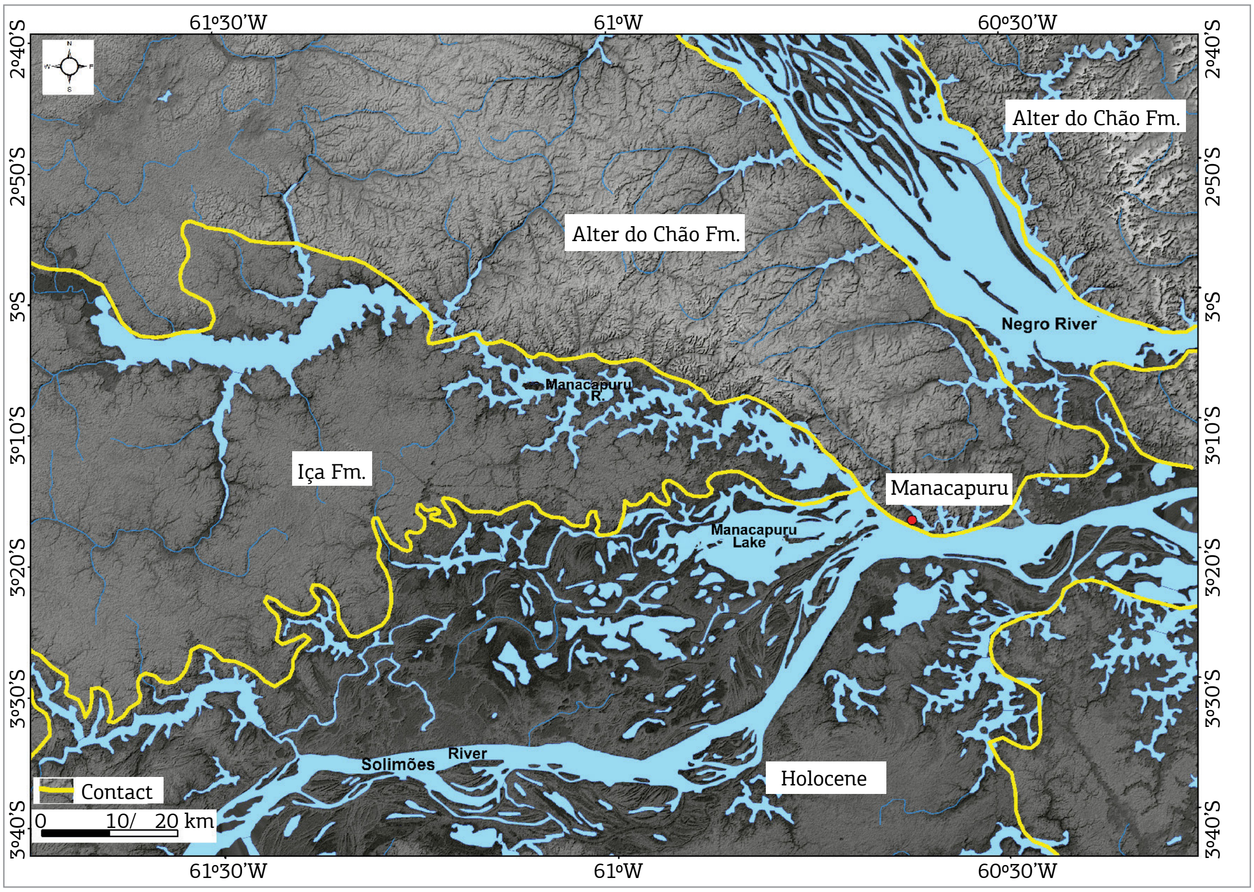

Figure 6. Contact between the Alter do Chão (Eocene-Middle Miocene) and Içá (Pleistocene) formations eastward from the Purus Arch and westward from the Negro River in the Amazon Basin. Içá Formation in the west is characterized by immature, extremely flat and low relief, while in the east Alter do Chão Formation is uplifted in a more advanced dissicated stage with deep valleys and dense drainage. On Içá Formation Pleistocene terraces occur not yet fully delimited. One observes that the area of the Manacapuru town to the North is situated in the grounds of Alter do Chão Formation, which is considered by some authors as the informal Novo Remanso Formation. This contact, considered as Solimões-Alter do Chão had been observed by Santos (1974) in radar semi-controlled mosaic of the SA.20-Z-A sheet. Source: Digital Elevation Model (DEM), SRTM 90m, TOPODATA Project-Geomorphometric database of Brazil.

At least three, between 200,000 and 6,000 years ago, Pleistocene and Holocene fluvial terraces were developed along the Amazon River drainage in the Amazon Basin (Soares *et al.* 2007, Soares *et al.* 2010, Gonçalves 2013). In a recent study, Rossetti *et al.* (2015) describe up to 300,000 years old, Pleistocene fluvial terraces in the Madeira River, pertaining to Içá Formation.

SOLIMÕES AND ACRE BASINS

In Solimões Basin, the Carauari High delimits the Jandiatuba (West) and Juruá (East) sub-basins. Paleozoic formations cover an area of 440,000 km^2 (Wanderley Filho *et al.* 2007), and its Cenozoic isostatic uplift showed to be lower than that of the Amazon Basin due to a thinner Paleozoic sedimentary column, high magmatism at the end of the Triassic and intense tectonism at the end of the Jurassic time followed by erosion. The erosion was more intense in that basin after the latest Triassic Penatecaua tectomagmatism and the Late Jurassic Juruá Orogeny. It is interesting to observe that in the Juruá Sub-basin the differential, thick diabase upper sill (first sill) overload depressed the earth's crust in its central region, preserving part of the Fonte Boa Formation (Permian) of the top of the Paleozoic column (Fig. 1). The broad sill isostatically depressed the crust up to its periphery, including the western part of the Purus Arch and, uplifted the outer region, generating to the west the Carauari High, and, to the east, it raised the eastern portion of the Purus Arch even more, moving its apex eastward, from the Tefé and Coari township zone (Fig. 5 – Section A) to the Codajás township area (Fig. 5 – Section B). The additional Purus Arch uplifting caused erosion and reduction of the Solimões and Amazonas Paleozoic basins wideness in the arch region (Fig. 7).

The sills accompanied the isostatic elevation of Paleozoic beds in the highs (Fig. 1), where the total erosion of Permian beds and partial erosion of Pennsylvanian ones in the northern basins of Brazil took place.

At the end of the Jurassic (Kimmeridgian – 150 Ma), the Juruá Orogeny caused structural inversions, block uplifts, folds and tilts, attributed to compression and shearing along a wide belt of the Solimões Basin (Fig. 7), and massive erosion resulting on strong, subsequent applanation, from the Late Jurassic to the Early Cretaceous time (Caputo 2014).

In the past, the whole Amazon and Solimões basins post Paleozoic section was called Alter do Chão Formation with a probable Cenozoic age. Then, the Solimões Formation was

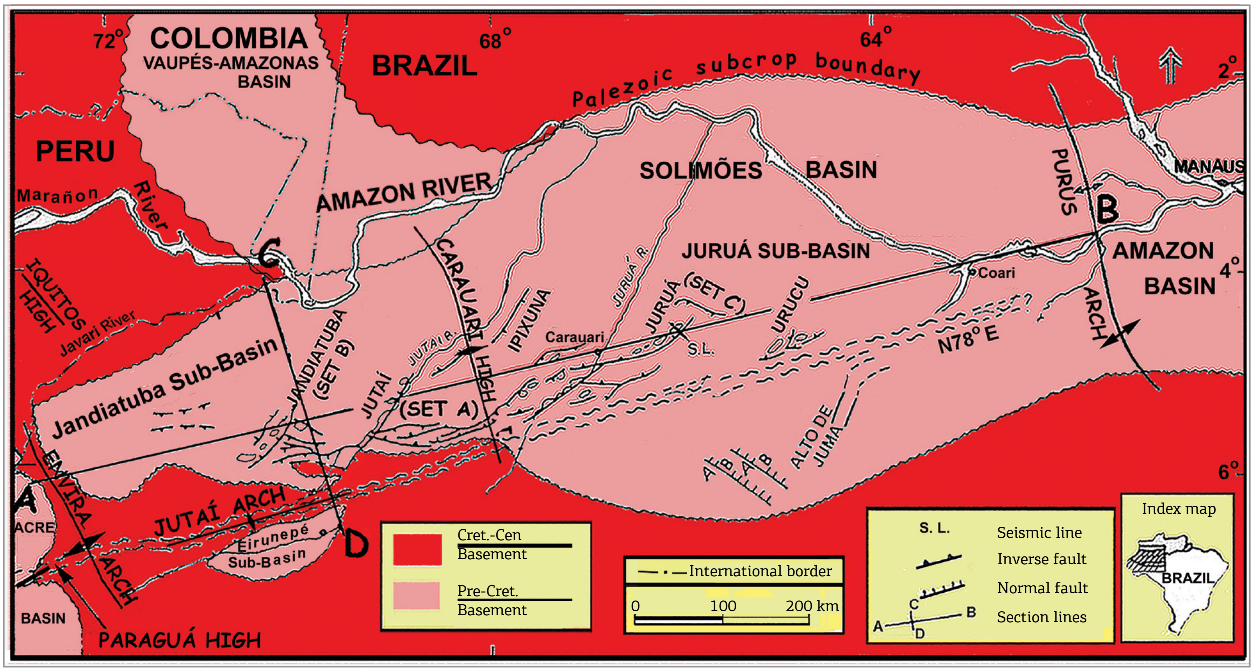

Figure 7. In the Paleozoic time, the Solimões Basin also had continuity with the basins of Vaupés-Amazon of Colombia (Baldis 1988), Marañon and Ucayali of Peru and Madre de Dios of Bolívia. The Juruá Orogeny as old as Late Jurassic (150 Ma) affected, in Brazil, Acre and Solimões basins, causing uplift and erosion on their eastern and western portions, respectively, when vast basement areas were exposed and removed (red color). Eirunepé and Acre basins were disconnected during the Juruá Orogeny from the Solimões Basin by Jutaí and Envira arches, respectively (Caputo 2014, ANA 2015). Exposed Paleozoic Solimões Basin sedimentary strata and diabase sills were covered by the Javari Formation in the Cretaceous time.

revalidated as a Cenozoic upper unit in the Solimões Basin (Caputo *et al.* 1972) to replace the Solimões Series of Rego (1930) due to its general lutaceous character, and partly reducing depositional environment, with the lower sandy section remaining as the Cretaceous-aged Alter do Chão Formation. Eiras *et al.* (1994) created the Javari Group by bringing the two formations together. The Javari Group, comprised by the Solimões and Alter do Chão formations, was undone as a group (ANA 2015), because of the presence of an unconformity between these well distinct units. The new Cretaceous Javari Formation, which before was in the group rank and now in the formation category, was used to replace the Alter do Chão Formation denomination in this stratigraphic section, since this unit proves to be as old as Cenozoic in its type-section in the Amazon Basin (Caputo 2009, 2011a,b, 2014, ANA 2015). The Javari Formation is basically made up by fine and coarse grained sandstones and conglomerates as old as Cretaceous. The type-section of this unit is located in the depth interval between 1,261 to 765 m of the Petrobras borehole 2-RJ-1-AM (Javari River, stratigraphic nº 1, Amazonas State), in the 4º 45' 49" S and 72º 11' 49" W geographical coordinates.

The Cretaceous Javari Formation covers up the whole Paleozoic section, dibase sills and part of the basement (Fig. 7), widening the basin's depositional area. This unit is thicker than the corresponding Amazon Basin's Cretaceous section (Jazida da Fazendinha Formation) and it is not dated yet, but it presents lithic continuity with the Acre Basin's Cretaceous-dated formations (Cunha *et al.* 2007), possibly with distribution from the Aptian to the Maastrichtian (?). It likely may present internal unconformities similar to those which occur in Acre Basin.

Above the Javari Formation a quite pelitic unit, as old as Late Oligocene or Early Miocene to earliest Late Miocene, which was considered to be the Solimões Formation, is present in several works addressing the basin's geology and palynology. However, there is an unconformity that separates it from the Late Miocene-Pliocene-aged Solimões Formation, described on the surface by Rego (1930). This section was denominated as Repouso Formation (ANA 2015), a name derived from a locality in the Atalaia do Norte (AM) municipality, in the Lower Javari River, where the borehole 1AS-4a-AM was drilled in 90 m above sea-level, down to 353 m by the Coal Project in the Javari River (Maia *et al.* 1977). This borehole studied by Hoorn (1993) was proposed as the type-section (04º 23' S and 70º 55' W) for the Repouso Formation in the depth interval between 23.5 and 330 m, where there is a lithologic change (ANA 2015). The 274 to 353 m interval is palynologically sterile, though containing mollusc remains at the 286 and 330 m interval (Hoorn 1993).

The unit consists of gray and variegated shales, fossiliferous siltstones, sandstones and limestone, with many lignite lenses and marine and transitional influence on several stratigraphic levels. Late Oligocene or Early Miocene to earliest Late Miocene is likely to be the age of this unit (Hoorn 1993, Hoorn *et al.* 2010), with it being correlated with the Barreiras Formation on the coast of Brazil, as well as the upper portion of the Amazon Basin's Alter do Chão Formation. The continental, transitional and marine depositional environments distinguish it from the continental lacustrine and fluvial character of the Alter do Chão Formation.

Outcrops of this unit are not delimited, currently taking place only in the Acre Basin and the westernmost part of the Solimões Basin. Paleontological analysis, based on ichthyolites (Pinto & Puper 1984) of several Coal Project wells (Maia *et al.* 1977), shows that possibly the Iquitos Arch goes through the region of the lower Javari River drainage. Wells 1AS-32-AM, 1AS-4-AM, 1AS-4a-AM and 1AS-1-AM contain an older uplifted Miocene section (Repouso Formation), since the well 1AS-33-AM to the west studied by Leite (2006) and the wells to the east 1AS-19-AM and 1AS-27-AM studied by Silva (2004) and Silva-Caminha *et al.* (2010), respectively, present a younger section (Late Miocene-Early Pliocene), known as the Solimões Formation.

Cruz (1984), who zoned the Solimões Basin's Cenozoic section, based on sporomorphs found in several Coal Project wells, placed the herein discussed Repouso section in the Zone A (Miocene). As this unit is still little known, more thorough stratigraphic studies are needed. The unit's upper disconformable contact with the Solimões Formation was established in the field by Campbell (2006), being named the Ucayali unconformity in the Acre River.

In the subsurface, horizons of this unit located between 170.90 and 174.40 m deep in well 1AS-31-AM of the Coal Project (Maia *et al.* 1977) in the Upper Solimões River show evidence of marine and transitional environment, based on planktonic and benthic foraminifera, nodular ostracods, bryozoans, rays, shark's teeth, crustaceans (barnacles), marine fish otoliths and marginal marine molluscs dated from the Middle Miocene (Ramos *et al.* 2011, Linhares *et al.* 2011). Mangrove plant pollens, in the well 1AS-4a-AM, studied by Hoorn (1993), probably indicate a coastal environment nearby, in different levels of this formation, during sea level high stands. Repouso Formation correlates with the Peruvian Marañon Basin's Pebas Formation and Ucayali Basin's Chambira Formation.

Above it, there is the Solimões Formation, which overlaps the Repouso Formation and part of the crystalline basement on some parts of basin edges. The Solimões Formation type-section is located in the valley of the Upper Solimões River, including the Benjamim Constant, Tabatinga and

São Paulo de Olivença municipalities, close to Brazil, Peru and Colombia triple border (Rego 1930). It consists of gray, green and variegated shales and siltstones, sometimes with scattered and in veined gypsum minerals, as well as white and red sandstones, with limestone nodules and vertebrate and invertebrate fossils, characteristic of fluvial, fluvio-lacustrine and lacustrine palaeoenvironments.

Following the drainage reorganization at the beginning of Late Miocene, the Late Miocene-Early Pliocene-aged Solimões Formation (Cruz, Zone B, 1984, Silva 2004, Latrubesse *et al.* 2007, 2010 and others) represents the Amazon River sedimentation towards the Atlantic Ocean, when the sea level rose again, since it exhibits Andean palynomorphs (Nogueira *et al.* 2013, Motta 2008) and minerals (Mapes 2009), in the east of the Purus Arch, as well.

Conglomerates above the unconformity often contain the Huayquerian mammal fossil fauna (SALMA – South American Land Mammals Age) and other fossil groups, indicating Late Miocene age between 9 and 6.5 Ma for fauna and sediments associated with the lower Solimões Formation, which unit was well detailed by Latrubesse *et al.* (2007, 2010) and Gross *et al.* (2011).

The Içá formation was proposed by Maia *et al.* (1977) to designate an unconformable section above the Solimões Formation along the Içá River, consisting mainly of friable, reddish-yellow, ranging from fine sand to conglomeratic clasts, with silty and argillaceous sandstone intercalations, and gray and variegated conglomerates, siltstones and shales, deposited in continental fluvial and fluvio-lacustrine environments. The conglomerate existing in the basal section, generally lenticular and little lithified, are formed by rounded hyaline or smoky quartz clasts, chalcedony, flint and rock fragments, with clay-sandy matrix. Conglomerates exhibit millimetric to centimetric, up to nearly 60 cm diameter-sized soft clay balls (*clay galls*) (Maia *et al.* 1977), which seem to originate from the Solimões Formation.

Içá Formation, located in the upper portion of the Cenozoic stratigraphic column, was estimated to be of Pleistocene age by Maia *et al.* (1977). It displays a sand and minor clay distribution of more than 600,000 km^2 in area and a thickness of tens of meters up to 140 m in the well 2-FG-1-AM according to Maia *et al.* (1977), but this wide distribution and thickness may be exaggerated.

Therefore, in the Solimões Basin, the Mesozoic and Cenozoic stratigraphic section consist of the Javari (Aptian-Maastrichtian?), Repouso (Late Oligocene or Early Miocene to the beginning of Late Miocene), Solimões (end of Late Miocene to Early Pliocene) and Içá (Pleistocene) formations. However, there is non-dated Cenozoic stratigraphic section below the Repouso Formation. Other younger Quaternary sediments occur under the form of Pleistocene terraces with distribution along the large rivers of Amazonia and some river islands. Holocene terraces also occur on flood plains and river islands along the river valleys.

The Acre Basin Cenozoic section holds several nameless older units, and Repouso, Solimões, Içá formations, terraces and alluvial sediments, even so, the Cenozoic stratigraphic section is more complete than in the Solimões Basin and still requires further elaboration in its lower section.

ANDES TECTONIC ACTIVITY

There is evidence of tectonic pulses in the Andes since the Mesozoic, but the Andean Orogeny affected the development of the sub-Andean sedimentary basins more significantly during the Cenozoic (Hoorn *et al.* 2010). In the Early Miocene the Andes uplifted farther, blocking and redirecting the East drainage towards the Caribbean region (Almeida 1974, Hoorn 1993, 1994, Hoorn & Wesselingh 2010). Some drainage restrictions created conditions for the formation of lacustrine and swampy environments with deposition of lignite lenses at several horizons, with episodic marine influences eastward from the sub-Andean basins from Colombia to Bolivia, including Solimões and Acre basins of Brazil. Sedimentation of Early Miocene to early Late Miocene, predominantly of fluvial-lacustrine, fluvio-deltaic, estuarine and marine origin, constitutes the Pebas Formation in the Marañon Basin in Peru, and Repouso Formation in Acre and Solimões basins in Brazil.

In the Middle Miocene time, new and vigorous Andean uplift started to fill the Andean foreland basins with thick molasses pile, resulting from the fast erosion of the Eastern Andean Cordillera, pushing the eastern drainage toward the Caribbean. The uplift of the Vaupés transversal Arch or Swell in Colombia (Mora *et al.* 2010) retained the sediments and elevated the lands to the south of this feature. The sedimentary supply in the area showed to be higher than the subsidence.

Using thermochronology of six sites of the Peruvian Andes, based on U-Th/He both of apatite and zircon, Michalak (2013) found that between latitudes 5 and 12° S a significant cooling of the rocks is registered, which indicates an acceleration of exhumation of Andean rocks from 0.04 to 0.25 mm/y in the Late Miocene. That quick exhumation may have been reflected in the high Eastern Andean range, where the glacier-covered mountains started to prevent the movement of clouds to the west Andean side, where, currently, there are deserts (Mora *et al.* 2010). This came to greatly accelerate the mechanical and chemical weathering and erosion on the eastern Andean slopes that released abundant molasse deposits for Andean foreland, Acre and Solimões basins.

AMAZON RIVER

The Amazon River and its tributaries traverse the States of Acre, Amazonas, Pará and Amapá; from the west to the east and upriver from its confluence with the Negro River, in Manaus, it is called the Solimões River, and in Peru it gets the name of Marañon River.

Zircon minerals from the Amazon Basin cratonic area, from Geochronologic Maroni-Itacaiúnas and Central Amazon provinces (Tassinari & Macambira 2004), collected in Middle Miocene sandstones of Alter do Chão Formation, near the town of Óbidos (Pará), located 1,100 km from Belém by waterway, with isotopic ages of 2 and 2.3 Ga and 2,088 ± 7 Ma and a mineral with an isotopic age of 1,648 ± 77 Ma, indicate a provenance from the eastern side of the basin (Mapes *et al.* 2006, Mapes 2009). The 1,648 ± 77 Ma-aged mineral may have been derived from post-orogenic igneous rocks present in the Maroni-Itacaiúnas Province, as emphasized by Tassinari *et al.* (2000).

Zircon minerals collected from Alter do Chão Formation, locally known as Novo Remanso Formation, in the Manacapuru Municipality, not far westward from Manaus (Fig. 6), provided U-Pb ages between 1,904 ± 7 and 1,910 ± 7 Ma originated from the Geochronologic Ventuari-Tapajós Province, and younger minerals indicated ages between 1,465 ± 51 and 1,346 ± 49 Ma (Mapes *et al.* 2006). The latter mineral ones, characteristic of Rondonian-San Ignacio Province, may have been carried by the Tapajós and Madeira rivers that cut through that province in the central portion of Brazil and flowed into the ancestral Amazon River, below Manaus, when this large river still flowed westwards.

Moreover, as was also to be expected, the direction of the ancestral Amazon River flowed westward until the early Late Miocene, and no Andean mineral or palynomorph was found in Alter do Chão or its equivalent Novo Remanso Formation. However, the lack of Andean-sourced palinomorphs and minerals in the Middle Miocene Alter do Chão Formation led to concluding incorrectly the Purus Arch would have functioned as a geographical barrier, preventing deposition of any material coming from the Andes, up to the Pliocene (Mapes 2006, Dino *et al.* 2012, Nogueira *et al.* 2013). In Solimões Basin, Repouso Formation sandstone zircons, from the well 31MT-0003-AM, located in the town of Tefé (Amazonas State), dated by Russel W. Mapes, indicated U-Pb Archean ages. Russel datings were presented in a table by Abinader (2008, p. 15) in his master's dissertation. This indicates the continuation of the fluvial transport, in the Middle Miocene, of clastics from the Archean-aged Amazon Basin's Central Amazonia Geochronological Province to the Solimões Basin.

Solimões Formation surface samples, still in the Township of Tefé, collected by Mapes (2009), present several populations made up by ages younger than 1.5 Ga, being a prominent group with U-Pb ages close to 210 Ma, consistent with an Andean derivation. Samples still contain zircon minerals with ages of 550 Ma (Brasiliano), 1,110 Ma (Sunsás) and 1,400 Ma (Rondonian-San Ignácio). Those zircon mineral datings are similar to those pertaining to the ages of the zircon minerals presently found in the sands of the Solimões River valley, in that same locality, obtained by Mapes (2009). In that region, Solimões Formation is capped by Içá Formation as old as Pleistocene and younger sediments.

Data presented by Figueiredo *et al.* (2009) relative to Sm-Nd dating of Foz do Amazonas Basin strata show that the Early Miocene and Early Pliocene layers have model ages, typical to Maroni-Itacaiunas Province (1.95 to 2.2 Ga), corresponding to the coastal lands of the State of Amapá which are joined with the Foz do Amazonas Basin. Middle-Miocene samples from Foz do Amazonas Basin provide Sm-Nd model ages that correlate with the ages (1.8 – 1.55 Ga) of the Rio Negro-Juruena Province, a region close to the western boundaries of Brazil.

It is interesting to note that ages of zircon minerals from Central Amazonia and Ventuari-Tapajós provinces, which now occupy over 50% of the area traversed by the Amazon River, were not found in the earliest Late Miocene sediments of Foz do Amazonas Basin. Latrubesse *et al.* (2010) raised this inquiry to the model presented by Figueiredo *et al.* (2009). On the other hand, the rather abundant presence of zircon minerals dated as Brasiliano in the earliest Late Miocene sediments of Foz do Amazonas Basin (personal communication from Jorge de Jesus Picanço de Figueiredo 2015) indicates a source different from the one of the cratonic areas crossed by the Amazon River, keeping in mind that the ancestral Amazon River drainage flowed westward up to the earliest Late Miocene. Therefore, a more plausible source for these earliest Late Miocene and older sediments would be the Grajaú Basin (Parnaíba Basin) and the Tocantins River and surrounding areas (Fig. 4), through the Marajó Basin, as can be inferred from the work of Nascimento (2006).

The Amazon River water is presently flowing at 2 to 2.5 m/Sec in the low water season with a gradient of <1 cm/km (Sioli 1967) downriver from Manaus. Naturally, with the steep sea-level fall in the Tortonian, the gradient increased, providing this major river with higher erosive action and carrying capacity. The rise of Vaupés Arch in Colombia (Mora *et al.* 2010) began to hinder the drainage to the Caribbean, providing the formation of lakes and swamplands in the region. During the sea-level lowering in the Tortonian, the Colombian Vaupés Arch also prevented the headward erosion of the rivers southward from that structural feature.

The Amazon River floodplain has an average breadth of 40 km in the axis of the basin with a very low elevation. Nowadays, in Santarém municipality, the Amazon River, about 850 km from its mouth, reached the quota of minimum water depth of 5.5 m above sea level in the 1997 low-water season, and the Alter do Chão Formation top of the hill of its type-section (Serra Piroca and well 1-AC-1-PA, Pará) reached about 130 m (Caputo 2011a,b). Altitude of other plateaus reaches higher elevations in other nearby areas.

In Manaus, nearly 1,400 km from the sea, the minimum Amazon River level reached 13.63 m in the low water period in 2010, according to Manaus Harbor Data (2014). This value represents a lower than 1 cm/km gradient and the elevation of the Alter do Chão Formation top reaches, in average, over 100 m in the vicinity.

In the town of Tabatinga, sited on the triple border between Brazil, Colombia and Peru, and 3,128 km away from the sea, the level of the Solimões River reaches about 60 m, with a gradient close to 3 cm/km in the stretch to Manaus, and the mean altitude of the nearby hills is of about 80 and 100 m. In the current high sea-level conditions, sediments from the Andes still get to the sea, mainly those being held in suspension. According to Mapes (2009), 80% of the zircon minerals collected at the Amazon River mouth originates from the Andes, 5% from cratonic areas and 15% from lowland sedimentary rocks.

Acre Basin holds a higher relief than Solimões and Amazon basins and an increasingly thickening Cenozoic sedimentary pile towards the Andes, from where it received a large contribution of its sediments, since the Andes uplifting up to now.

The Negro River bottom, near its confluence with the Amazon river, has lately been measured to reach 103 m deep, at a narrow canyon-shaped profile; and, in many other places, it and its tributaries show to be around 80 – 90 m deep (Sioli 1967). These depths could be the effect of neotectonics, current erosion on account of local hydrodynamics in the rivers, or due to the sea-level lowering in the Pleistocene. The latter assumption may be admitted, since the Pleistocene lasted from about 2,588,000 to 11,700 years ago (International Commission on Stratigraphy), when sea level began to rise. The last sea level rise reduced erosion rate leading to sedimentation along the valleys, floodplains and banks of the Amazon River and its tributaries, but the current bottom load on this river consists of sand (fine and coarse) associated with the load in suspension (Sioli 1967). Many of the Amazon River tributaries are drowned, with their valleys disproportionately large in relation to the river's current discharge. Those rivers are being called "rivers-lakes" (Sioli 1967), yet technically they are interior rias or fluvial rias. Many of these rivers do confluence with the Amazon River and other major rivers, and are in filling process, where sedimentation at their mouths consists of muddy materials (clay and silt), like at the mouths of the Tapajós, Negro, Coari, Tefé rivers and others. Some rias occur away from the current large river floodplains and develop on the boundaries of the oldest fluvial terraces, during the migration of the channels (Soares 2007). Lake Manacapuru is an inner ria whose damming by the Amazon River sedimentation is causing its filling, mainly in the boundary of the Amazon River floodplain (Fig. 6). This morphology can not have been elaborated by those rivers current draining conditions, with their almost stagnant waters and broad valleys. This river drowning may be attributed to the sea level rising in the Holocene (Sioli 1967).

With the subsidence of the Gurupá Arch in the Tortonian, the Amazon River headward erosion and captures opened a pathway from Marajó Basin to the basins in the west of South America up to the Andes. It is deduced that, at this time, a rather deep incision of the Amazon River drainage occurred, as a consequence of the steep sea level drop. The deep incision on the valleys impeded deposition on floodplains, lakes, point bars and fluvial deltas, which no longer existed. At that time, swamps started to be drained and destroyed, and the steep river valley slopes were broadened by erosion due to the less resistance to erosion of the beds of Alter do Chão and Repouso formations. This must have brought about environmental changes and the extinction of many terrestrial and aquatic species living in those habitats. Therefore, during the early Late Miocene (Tortonian), the superficial regolith was transported through the deep valleys to the sea in the east, with no deposition and erosion occurring in the entire continent.

With the deglaciation and consequent sea-level rising, at the end of the Late Miocene (Messinian) and early Pliocene, the valleys, before under an erosion regime, came at some point to be filled, that is, the Solimões Formation sedimentation started to prevail where there was room for its accommodation and then spread over part of the Repouso Formation top plains.

In Latest Miocene, even with the high sea level, the gradient of rivers on the slopes of the Andes and Subandean areas was high, eroding and transporting enormous amount of material. The relief of the Amazon Basin, constituted by Alter do Chão Formation, from the western region of the Negro River towards the east, was high, being seemingly an insurmountable barrier. Yet, the Andes and Subandean erosion products (Solimões Formation) were deposited in Acre, Solimões and western tip of the Amazonas Basin, as well as carried through deep incised channels of the Negro, Amazon and other major rivers (Fig. 6) to the Atlantic Ocean for building the Foz do Amazonas Basin fan. Westward from Negro River a subsidence process took place with deposition of the Solimões Formation, while the Amazon Basin uplifting was present, there occurred erosion.

At the close of the Pliocene and Pleistocene, sea level oscillations (Miller *et al.* 2011), due to glaciations in the northern hemisphere, including the Andes (McDaniel *et al.* 1997), deepened the drainage several times, eroding most of the material previously deposited in the valleys and floodplains. Since several glacial and interglacial stages occurred, with consequent droppings and risings of sea level, several differently-aged fluvial terraces were built up along the rivers of Brazilian Amazon and other neighboring countries (Franzinelli & Ori 1988, Rossetti *et al.* 2005, Gonçalves Junior 2013, Carlotto *et al.* 2008, Soares *et al.* 2010a). In the Central Amazon area, the oldest terrace is probably represented by the Içá Formation, other known, ancient fluvial terraces of the Solimões River, informally denominated as Upper Terrace, present ages of approximately 200,000 years Before Present (BP) and are continuous and parallel to the major rivers (Soares *et al.* 2010a, b, Gonçalves 2013), being only interrupted by tributaries like the Purus and Madeira rivers. During the Pleistocene, occurred new extinction processes because of the environmental changes deriving from several droppings and risings of sea level.

CENOZOIC FORMATIONS AGE, ENVIRONMENT AND UNCONFORMITIES

In a recent study, Guimarães *et al.* (2015) erroneously redated the upper layers of Novo Remanso Formation (Alter do Chão) in the township of Manacapuru (Fig. 6), not far from Manaus, which had already been dated and set in the Middle Miocene by Dino *et al.* (2012). They proposed a very broad age, Middle Miocene-Pliocene, based on the presence of *Grimsdalea magnaclavata* defined by Lourens *et al.* (2004), as indicative of Middle Miocene up to the Pliocene and of other species bearing wide stratigraphic amplitude. These authors did not discuss the absence of younger guide forms, specific markers of Late Miocene and early Pliocene, such as *Cyatheacidites annulatus, Echitricolporites mcneillyi etc*. Therefore, the present study only accepts the earliest Late Miocene age, excluding the Late Miocene-Pliocene, corroborating the studies by Dino *et al.* (2012) and Soares *et al*. (2015) for the top of the Miocene unit (Alter do Chão Formation) in the regions of Manacapuru and Presidente Figueiredo municipalities (Uatumã River). Guimarães *et al.* (2015) still suggest that the existence of some reworked Cretaceous palinomorphs would indicate the presence of Cretaceous outcrops nearby. Probably, those reworked, elaterated Cretaceous forms (*Elaterosporites klaszii*) came from distant areas like the Parecis Basin located on the Xingu and Tapajós river headwaters, in Central Brazil, between the Upper Tapajós and Paraná basin areas.

In the region of the well 1AS-4a-AM, in the Javari River (Solimões Basin), of the Coal Project (Maia *et al.* 1977), Hoorn (1993) dated the new Repouso Formation as Early Miocene to the beginning of the Late Miocene age, but the basal layers were not dated and might reach the Late Oligocene (Hoorn *et al.* 2010). These locations are close to Pebas in Peru on the Marañon River (Solimões River), whose section exhibits the same age and fossiliferous content as Repouso Formation does, according to several researchers, who used other fossil groups in addition to palinomorphs (Hoorn *et al.* 2010).

The absence of Early Miocene beds, verified by Hoorn (1993), on the studied second well (1AS-51-AM) is due to its marginal position in the northern part of the Solimões Basin, onlapping the ramp of the crystalline basement.

Hoorn *et al.* (1995) inform that in the Magdalena River valley (Colombia), following a short period of erosion and no deposition between 11.5 and 10.1 Ma, a fluvial-originated conglomerate and other clastics sediments were accumulated from 10.1 Ma onwards. The unit containing the Late Miocene-aged conglomerate with Andean originated pebbles (flint, lithic fragments and quartz) would have been the result from one more Andean tectonic pulse. In the region denominated Northwest Amazon Basin, in the rain forest between Colombia and Peru, an unconformity occurs between the initial and final Late Miocene (Hoorn *et al.* 1995). This discontinuity is also observed by Hoorn *et al*. (1995, p. 238) in the Llanos Basin (Colombia).

Campbell *et al.* (2006) discuss that unconformity, named Ucayali, with further detail in the Andean Countries (Ecuador, Peru and Bolivia), being it more attributed to tectonic processes in the Andes than to the sea-level fall. Since the Tortonian unconformity (10.1 Ma) displays a wide continental distribution, away from the Andes, it is possible the drop of sea level in the Tortonian would have contributed much more significantly to its generation. Reworked cretaceous palinomorphs found in the thin organic fraction of the Cenozoic section indicate an Andean origin in regions studied by Hoorn (1993), because many Mesozoic and Paleozoic formations were uplifted, and partially exposed to erosion on the Andes in the Neogene.

Hoorn (1993, 1996) demonstrates that the origin of the cratonic sedimentation on the Andean Foreland basins in eastern Colombia has given rise to Andean sedimentation contribution already in the Middle Miocene. This indicates that the drainage from the Amazon craton toward the western coastal basins, still in the early Middle Miocene, was hindered by the rising of the Andes in Middle Miocene.

In latest Serravalian and Tortonian, in addition to another great Andean tectonic pulse, a steep drop in sea level occurred, due to glaciations taking place at this time in Antarctica, southern tip of South America and the Andes. This brought about the end of Repouso Formation sedimentation between 10.55 and 9.69 Ma, according to the international zoning based on Lourens *et al.* (2004), Raffi *et al.* (2006) and recognized by Figueiredo *et al.* (2010) as well.

Many authors have interpreted plain or tenuous marine influence on outcrops and wells in the Solimões Formation (Hoorn 1993, Räsänen *et al.* 1995, Webb 1996, Arai *et al.* 2003, Nogueira *et al.* 2003, Hovikoski *et al.* 2003, 2005, Monsch 1998, among others), but some discard this possibility (Latrubesse *et al.* 1997, 2007, 2010, Marshall & Lundberg 1996, Praxton *et al.* 1996, Dino *et al.* 2012, Riff *et al.* 2010, Gross *et al.* 2011). The problem is that Repouso and Solimões Formations identification is misunderstood, and the sedimentary environments also depend on the stratigraphic level analyzed in environmental interpretation.

In fact, the Solimões Formation, observed on the surface in Solimões and Acre basins, features continental paludal, lacustrine, fluvial-lacustrine, fluvial and fluvio-deltaic environment. Repouso Formation holds many levels with many transitional and marine fossils. On the horizons between 170.90 and 174.40m deep of the well 1AS-31-AM of the Coal Project (Maia *et al.* 1977), there is evidence of marine and transitional environment, based on planktonic and benthic foraminifers, bryozoans, nodded ostracods, rays, shark's teeth, crustaceans (barnacles), marine fish otoliths, marine marginal molluscs dating from the early Middle Miocene (Ramos *et al.* 2011, Linhares *et al.* 2011). Mangrove plant pollens found in well 1AS-4a-AM may indicate, in the neighborhood, marine environment at different stratigraphic levels of Repouso Formation when sea level was high (Hoorn 1993).

According to Del´Arco *et al.* (1977), in his historical retrospect of the geology of Juruá sheet (RADAM Project), several paleontologists, referenced since the XIXth century, put the invertebrate and vertebrate fossils, found in outcrops of the Solimões Formation, in the Late-Miocene and Pliocene, as well as the now recognized Içá Formation in the Pleistocene.

The Madre de Dios Formation, in Peru, holds three members, with the two lower ones both corresponding to Solimões Formation in Brazil (Campbell *et al.* 2006) and Ipururo Formation in Ucayali Basin in Peru (Carlotto *et al.* 2008). The Upper member is Middle Pliocene-aged and corresponds to Madre de Dios Formation itself (Carlotto *et al.* 2008). Conglomerates of the base of the lower member (Ipururo Formation) often contain the *Huayquerian* fauna of mammal fossils (SALMA - South American Land Mammals Age), indicating Late Miocene age between 9 and 6.5 Ma for the associated fauna and sediments of Solimões Formation, very well detailed by Latrubesse *et al.* (2007, 2010). In the area of Eirunepé, eastward from the Envira Arch, the Solimões Formation with *Huayquerian* fauna was described in further detail by Gross *et al.* (2011).

Campbell *et al.* (2006) dated initially in Peru two levels of volcanic ashes from the alleged Madre de Dios Formation, by the Ar^{40}/Ar^{39} method, obtaining ages of 3.23 ± 0.3 and 9.01 ± 0.28 Ma, the latter in a section 4 m above the base of the lower member, constituted by an often fossiliferous, regional conglomerate, denominated by these authors as Acre Conglomerate. Below this conglomerate, there is a sedimentary discontinuity that received the name of Ucayali unconformity (Campbell *et al.* op. cit.).

The erosion that formed the Ucayali unconformity of Ipururo/Solimões Formation may have lasted for approximately 1.0 My, which matches well with the beginning of the correlative about 10 Ma-aged sedimentation on the Ceará Rise in the Atlantic Ocean, proceeding from the Andes (Dobson *et al.* 2001, Harris & Mix 2002, Figueiredo *et al.* 2010). The age of Solimões Formation is late Late Miocene, when the sea level started to rise again, up to Early Pliocene (Zanclean Stage).

Carlotto *al.* (2008), based on the second Ar^{40}/Ar^{39} (3.23 ± 0.3 Ma) dating, estimate the top of Ipururo Formation (Solimões Formation) would be around 4 to 5 Ma old (Zanclean), and the base of Madre de Dios Formation itself Late Pliocene-aged, which indicates this Peruvian unit may partly correlate with Içá Formation. Içá Formation basal unconformity was better detected in Brazil along the Içá River (Maia *et al.* 1977).

The unconformity, below the Ipururo/Solimões Formation, has not been recognized by a few researchers (Räsänen *et al.* 1995, Cozzuol *et al.* 2006, Rebata 2006 a, b, Silva 2001), yet it is widely recognized. It was mapped in various continental (Maia *et al.* 1977), coastal (Rossetti *et al.* 2001, Arai 2006) and marine (Figueiredo *et al.* 2009, 2010) areas of Brazil. Figueiredo *et al.* (2009) inform there is an interval of 0.7 Ma in the Amazon River fan corresponding to that discontinuity. The unconformity was observed in Bolivia, Peru, Ecuador (Campbell *et al.* 2006, Carlotto *et al.* 2008) and Colombia (Hoorn *et al.* 1995) as well.

DISCUSSION

Price (1960) was the first to quote Cretaceous age to the Amazon Basin's Post-Paleozoic section, named Alter do Chão Formation, based on a tooth of a dinosaur of class Theropoda, found in the 193 – 196 m interval in well 1-NO-1-AM of Petrobras, in the region of Nova Olinda (Amazonas State). In his work, Price informed the comment by Setembrino Petri that in the same well a less consolidated, undated, 175 m thick top section occurs, which might be Cenozoic in age. Daemon and Contreiras (1971a, b) palynologically studied several wells in the Acre, Upper, Middle and Lower Amazon (Marajó) basins, along a W-E longitudinal section, where they identified a Cretaceous-aged and other Eocene-Quaternary-aged Post-Paleozoic sedimentary section, without studying the type well 1-AC-1-PA (Alter do Chão stratigraphic well nº 1).

Daemon (1975) later studied the section of well 1-AC-1PA-1, where he verified Cretaceous age only in the core 23 of that well, at the depth of 502 m; other upper cores were barren. In addition, Daemon and Contreiras (1971a,b) and Daemon (1975) extrapolated the Cretaceous age to the surface in that well, as they had done in other wells in the central part of the basin. The base of the Cenozoic section they considered as old as Paleocene (table page 82) or Eocene (page 83), with the top section placed in the Holocene, on stratigraphic interval XVIII. The lithostratigraphic column prepared by Caputo *et al.* (1971, 1972) at that time was based on the ages obtained on the above-mentioned palynological studies.

Middle Miocene strata, dated in Central Amazon outcrops, in the vicinity of Manaus, was informally designated as Novo Remanso Formation (Rozo 2004, Rozo *et al.* 2005, Dino 2006 a, b, Soares 2007, Soares *et al.* 2010a,b, Dino *et al.* 2012, Soares *et al.* 2015), on the assumption that Alter do Chão Formation was as old as the Cretaceous, justifying a new Cenozoic stratigraphic unit in the basin. This Cenozoic unit supports the high relief of the regions of Manacapuru, Manaus, Itacoatiara, Itapiranga and São Sebastião do Uatumã localities (Fig. 6), for 300 km, and is partially covered by Quaternary deposits (Abinader 2008, Andrade & Soares 2009, Soares *et al.* 2015). The above-mentioned surface layers are still considered as old as Cretaceous by some authors.

Caputo (2009, 2011a,b), based on a well cuttings study of the type-well 1-AC-1-PA conducted by the palynologist Eglemar Conde Lima, divulged there is a thick Cenozoic-aged sedimentary column in most of the type-section of the Alter do Chão Formation, attributed to the Cretaceous by Daemon and Contreiras (1971a,b) and Daemon (1975). Caputo (2011a,b) maintained the Alter do Chão Formation name, already consolidated in the geological literature, for the Cenozoic outcrops of Serra Piroca and most of the section in well 1-AC-1-PA, totalizing 537 m in thickness. He still created a new unit, Jazida da Fazendinha Formation, to harbor the nearly 120 m thick, unconformable Cretaceous basal section in the considered well, which was dated as Aptian-Albian to Late Cenomanian-aged by Dino *et al.* (1999, 2000) in several other wells of the basin. Daemon and Contreiras (1971a, b) (Fig. 2) only recognized Cenozoic layers on the surface and subsurface in the Amazon Basin's western and eastern portions.

The surface sedimentary cover of other areas of the Amazon Basin is yet to be directly dated. Nevertheless, data recognized up to now, including seismic surveys, point out that, apart from the Paleozoic outcrop belts and Monte Alegre Dome, the whole Amazon Basin displays a Middle Miocene sedimentary cover. On a small portion of the western region of the Amazon Basin (Fig. 5), the cover is made by Late Miocene-Pliocene Solimões and Pleistocene Içá formations and younger sediments. Gurupá Arch cover is inferred to be Late Miocene-Pliocene and Pleistocene-aged.

In Serra de Paituna, in the region of the Monte Alegre Dome, where post-Middle Miocene neotectonism had taken place, near the mouth of the Tapajós River and well 1-AC-1-PA, Eocene fossil leaves (Duarte 1987) occur in outcrops near the base of Alter do Chão Formation.

According to palynological determinations of Daemon and Contreiras (1971a,b) and Daemon (1975), Cunha *et al.* (1994, 2007) denominated the Cenozoic section of the western portion surface of the Amazon Basin of the Solimões Formation and in its eastern portion of the Marajó Formation, maintaining the Cretaceous allegedly cropping out on the central region of the basin. Other researchers overlooked these dated Cenozoic layers, considering the whole Amazon Basin's cover as old as Cretaceous. Current data indicate the Cretaceous unit just to be present in the more central and deeper areas of the Amazon and Solimões basins (Caputo 2009, 2011a,b, ANA 2015). The Mesozoic formations in question are separated in the subsurface by the Purus Arch, where they are absent (Fig. 1 and 5). It is worth adding that, in northern Brazil, Cretaceous units only crop out on Parnaíba Basin, as well as Acre Basin and Andean region, due to the uplifting brought about by the Andean Orogeny.

Solimões Basin sedimentary cover is mainly represented by Içá Formation (Pleistocene), with alluvial Holocene, but their area is still to be well defined, being much smaller than what the Amazon State CPRM geological map shows (Ferreira *et al.* 2006). On the Solimões Basin's western part, along deep valleys and some interfluves, Solimões and Repouso formations sediments occur on the surface.

Nogueira *et al.* (2003) identified, initially in the area of Coari, 360 km west of Manaus, in Solimões Basin, two unconformable sedimentary units in the Solimões Formation. The lower one would be characteristic to a paleoenvironment composed of tide-influenced estuarine bay and meandering fluvial channel deposits; and the upper one would contain tidal and fluvial channels deposits. The tidal sedimentary structures would be indicative of the marine influence on these deposits. The strongest marine evidence was based on a single dinoflagellate cyst (*Diphyes?* sp.), identified by Arai *et al.* (2003), which could have been reworked Repouso Formation material from the uplifted Amazon drainage system headwaters in the Andes and its foreland region.

Nogueira *et al.* (2013) later reinterpreted the same Coari outcrops as having been deposited in a lacustrine environment associated to meandering rivers, with no marine influence, and concluded the lower sequence to correspond to Late Miocene-Pliocene-aged Solimões Formation and the upper one to Pleistocene-aged Içá Formation. Both sequences indicate eastward directed paleocurrents.

The presence of reworked older Cenozoic, Cretaceous and Paleozoic Andean palinomorphs, and the eastward paleocurrents direction of the Solimões Formation (Nogueira *et al.* 2013) points out the drainage to have come from the West, conversely to Alter do Chão and Repouso formations drainage coming from the East.

Içá Formation was deposited on the continental fluvial environment, holding floodplains and associated lakes, with no marine influence as many investigators have suggested, since the Amazon River flowed into the Atlantic Ocean and the sea itself would not be able to reach the Upper Solimões Basin and the Andean foreland basins of northern Brazil in the Pleistocene Epoch.

Nogueira *et al.* (2013 – Fig. 8C) inferred that in the Coari section the reworked and well preserved Devonian palynomorphs came from northwestern Amazon Basin Devonian grounds, uplifted by large faults and eroded from a higher than the Purus Arch level. Correlative sediments and palynomorphs were deposited on a lacustrine setting, adjacent to the Purus Arch in Solimões Basin.

The question is: where both, the huge volume of water that would have converged from the Solimões Basin and the Andes, and the small one from the northwest of the Amazon Basin to the lake barred by the alleged obstacle brought about by the arch, would be? In this case, the enormous volume of water would not be able to exit and would have to evaporate in a large scale and accumulate evaporites, which were never found. Furthermore, the Coari lower section, corresponding to Solimões Formation, holds eastbound paleocurrents in the sections studied by Nogueira *et al.* (2013).

Since Solimões and Içá Formations occur on Purus Arch and the western edge of the Amazon Basin (Cunha *et al.* 2007, Motta 2008), the presence of Andean palynomorphs indicates that have been no alleged obstruction, according to what was postulated by some authors.

Another interpretive problem would be the physical presence of huge faults exposing the Late Devonian, adjacent to the arch. These large faults were not detected in the area by Petrobras surface or subsurface mapping or seismic, gravimetric and magnetometric geophysical surveys. The neotectonic faults observed in the region hold no major throws. In the wide region of the Purus Arch, there are no subsurface Cretaceous and pre-Pennsylvanian deposits either (Daemon & Contreiras 1971a,b, Daemon 1975), since they occur farther away from the arch on the deeper portions of the Amazon and Solimões basins (Fig. 5).

The Late-Devonian units occur in subsurface only on the slopes of the Purus Arch, one of them located close to the Manaus Meridian (Daemon & Contreiras 1971a, b – Fig. 2, Caputo 2011a,b – Fig. 2), 150 km away from the apex of this arch. This geographical position has been known since Morales (1957, 1959), just by keeping in mind that the wide arch has barred sedimentation from Ordovician to Mississippian in both its slopes. Nogueira *et al.* (*op. cit.*) did not discuss Cretaceous palynomorphs in the section of Coari (these were informed by palynologist Rosemery Silveira, co-author of the work of Nogueira *et al. op. cit.*), considering that in the Solimões and Amazon basins the Cretaceous section shows to be thoroughly overlaid by Cenozoic layers from Repouso and Alter do Chão formations, respectively. Cretaceous strata fail to be found along the Purus Arch.

Also for justifying the alleged eastbound drainage blockage, exerted by the Purus Arch, Nogueira *et al.* (2012, 2013) state that the Cretaceous is currently exposed in the Amazon Basin, whereas in the Solimões Basin it is found 600 – 500 m deep, under the Solimões Formation base, suggesting a significant, Neogene differential subsidence in the Solimões Basin near the arch, according to Caputo *et al.* (1972). Actually, the authors quoted by Nogueira *et al. (op. cit.)* just recognized Cenozoic sediments on the surface of the basin in 1972. Currently, it is considered that the sedimentary cover throughout the Amazon Basin is constituted by the Alter do Chão Formation, Middle Miocene-aged, except for the Monte Alegre Dome area and Paleozoic outcrop belts region.

The thickness of Cenozoic-aged Alter do Chão Formation (537 m) in type-well 1-AC-1-PA (Caputo 2011a,b) is of the same order of magnitude (600 – 500 m) as the one mentioned by Nogueira *et al.* (2012, 2013) for Solimões Formation in Solimões Basin. Outcrops of Cretaceous strata do not occur in the Amazon Basin, neither the significant 600 m differential subsidence of the Solimões Formation in Solimões Basin. The very moderate differential subsidence in the Solimões Basin occurred with the deposition of Solimões (Late Miocene-Pliocene) and Içá (Pleistocene) Formations, when the Amazon River started to flow towards the Atlantic. The Alter do Chão Formation features a relief that would be able to block the eastbound drainage in the western region of the Negro River (Fig. 5), but the Amazon River accomplished a headward erosion from Marajó Basin through a central and a deep valley, when sea level was lowered and Gurupá Arch was lowered and breached. The Amazon River drainage would lie nearly 90 m beneath the current sea level. There was only the capture of the drainage coming from cratonic and Andean Foreland areas, which flowed toward the Caribbean (Hoorn 1993). The uplifting of the Vaupés Arch, along with the rising of the Andes in Colombia (Mora *et al*. 2010), started to prevent the Solimões Basin's drainage from flowing towards the Caribbean, as well as to hinder a headward erosion southward from that arch in the Tortonian.

Nogueira *et al*. (2013) state that the unconformity on top of the Late Miocene-Pliocene Solimões Formation, observed for tens of kilometers, would indicate a local Purus Arch and neighboring areas uplifting and erosion, which could have lasted up to the Pliocene, and that the subsidence in the arch allowing the Amazon River to come through would just have taken place in the Pleistocene. However, unconformities between Alter do Chão and Solimões formations, as well as Solimões and Içá Formations, are present in the entire Solimões Basin. These authors did not consider the sea level drops in the beginning of the late Miocene and the Pleistocene to be responsible for erosions and unconformities. Actually, the removal of the sediments from the Amazon and Solimões basins by the continental Tortonian erosion depressed the Purus Arch region. Solimões Formation holds fluvial, lacustrine, floodplain lakes, fluvial channel environments and a plethora of paleosoils throughout its extension (Gross *et al*. 2011), and the lake close to the Purus Arch is a normal feature in the Solimões Formation, not related to an alleged Purus Arch dam.

Leguisamon-Vega *et al*. (2006) and Vega *et al.* (2006) used and described the same 12 m thick Solimões Formation section of Coari, interpreting it as an endorheic drainage with a lacustrine system fed by prograding, meandering rivers coming from the west, which was supposed to have been blocked by the Purus Arch. This feature would prevent the Solimões Basin's drainage from flowing to the Amazon Basin, at least until the Pliocene. However, evidence indicate the transcontinental Amazon River to have had already established itself in the beginning of the Late Miocene (Tortonian) with drainage to the Atlantic Ocean (Dobson *et al*. 2001, Figueiredo *et al*. 2009, 2010, Harris & Mix 2002) prior to the Solimões and Içá formations deposition.

The presence of sandstones bearing detritus zircon minerals of the extensive Geochronological Ventuari-Tapajós Province, with angular and roughly selected grains in the Novo Remanso (Alter do Chão) Formation in Manacapuru Municipality, east of the Purus Arch, led Mapes *et al.* (2006) and Nogueira *et al.* (2012, 2013) to state that the zircon minerals originated from the Purus Arch, located westward and from adjacent cratonic areas. Nevertheless, since the arch is covered by Paleozoic formations, consisting of Pennsylvanian limestones, shales, fine sandstones and evaporites overlain by 300 m thick Neogene layers (Fig. 6), it could not have been the detritus source for the Solimões Formation, in a second sedimentary cycle in the Mid-Miocene. The angular and poorly sorted clastics were more likely to have had originated mainly from adjacent cratons in the first sedimentary cycle, exempting the Purus Arch area from providing the cited minerals. Besides, the drainage at that time (Middle Miocene) flowed freely westward and would hardly have received material from the Purus Arch, which was sited farther west downriver from the Manacapuru outcrops. Therefore, this is not a proof that the alleged Purus Arch high relief area was the source of this material, and blocked the drainage in the Miocene and Pliocene time.

It is interesting to note that in Manacapuru area (Amazon Basin), Dino *et al.* (2012) found typical Southern South American *Araucaricites* genus specimens in the Novo Remanso (Alter do Chão) Formation. This finding may indicate the genus to have expanded from Southern to Northern Brazil, due to a cold climate that has developed and expanded in the Tortonian time. These palynomorphs were transported to the Amazon River by winds and tributaries of the Amazon River bathing Central Brazil region.

Another intriguing point is the presence of few Albian-Cenomanian reworked elaterated forms (*Elaterosporites klaszii*), detected in the Novo Remanso (Alter do Chão) Formation samples studied by Guimarães *et al.* (2015), which could result from the erosion of the Cretaceous-aged Parecis Formation, of the Parecis Basin, central region of Brazil, in the headwaters of the major Tapajós and Madeira Rivers that flow into the Amazon River.

The age of 9.01 ± 0.28 Ma (Middle Tortonian) for the base of the Solimões Formation, corresponding to the Ipururo Formation in Peru, and 3.12 ± 0.02 Ma (Campbell *et al*. 2006) for the basal unconformity of the Madre de Dios Formation (Peru and Bolivia) indicates that the Solimões Formation may have ended sedimentation before 5 Ma due to erosion at its top between 5 and 4 Ma, as suggested by Carlotto *et al.* (2008).

This stratigraphic relationship indicates that Hoorn (1993) dated Repouso Formation sediments in Coal Project well 1AS-4a-AM (Maia *et al.* 1977), and Latrubesse *et al.* (2007, 2010) and Campbell *et al.* (2006) also worked on the Solimões Formation in Acre State and Peru, as well as rivers and dividers of the Acrean and Peruvian rainforests.

CONCLUSION

Currently, the Amazon River bed profile altitude increases gradually from its mouth to the Andes mountain range, as opposed to what occurred prior to the subsidence of the barring of the Gurupá Arch. The late subsidence of the Gurupá Arch in the beginning of the Late Miocene had the greatest importance on reversing the Amazon River drainage, which started to flow toward the Atlantic Ocean. The rise of the Andes in several stages barred the westbound drainage coming from Gurupá Arch to the Paleopacific Ocean and redirected it to the Caribbean Sea in the Mid Miocene (Almeida 1974, Hoorn 1993, 1996). On the other hand, the immense contribution of molasse sediments coming from the Andes pile up on and raised the level of the grounds adjacent to the Andean chain in the Andean Foreland basins (Michalak 2013), pushing the Andean drainage eastward before taking its northward course toward the Caribbean. The high sea level contributed to the retention of sediments during the intermittent marine incursions into the Andean foreland basins, as well as the Solimões Basin from Early to Mid Miocene (Aquitanian-Langhian-Serravallian-Hoorn 1996), creating vast marshy, swampy and lacustrine areas with accumulation of gray shale and several lignite horizons according to Maia *et al.* (1997). The northbound drainage became rather restricted with the uplifting of the transversal Vaupés Arch next to the Andes in Colombia (Mora *et al*. 2010) at the end of the Mid-Miocene (Serravallian), and less restricted eastward with the subsidence of the Gurupá Arch on the western Marajó Basin boundary, reaching the Atlantic seacoast. Thus, the Amazon River headwaters initiated their advance from the Gurupá Arch by relatively quickly, westbound headward erosion, capturing the drainage from cratonic areas and intercepting the northbound drainage coming from the Andes of Bolivia, Peru, Ecuador and Colombia.

The new vigorous drainage dug and deepened rapidly old valleys and adapted to the new river course, managing to impose itself, taking advantage of relatively little consolidated lands. The reversal of the drainage flowing impetuously toward the Atlantic Ocean was not impeded due to its nearly tenfold increased (10 cm/km) new gradient when compared to the current one (<1 cm/km) from Manaus down to its mouth. The Tortonian unconformity marks the time of the establishment of the deeply embedded transcontinental Amazon River. Since the unconformity seems to be of relatively greater extension and short duration, for the reorganization of the Amazon drainage, inside of Bolivia, Peru, Ecuador, Colombia and Brazil, and in marine and coastal regions, the drainage reversal process showed to be relatively very fast.

The Purus Arch region neither stopped the ancestral Amazon River course to the West nor that of the current one to the East.

The Gurupá Arch was breached and isostatically lowered during the erosion of the Tortonian, allowing the transfer of a large bulk of sediments from the Andes, cratonic areas and adjacent Brazilian basins to the marine regions of the Foz do Amazonas Basin.

With a new rising of sea level, the rivers coming from the Andes and Subandean basins initiated the Solimões Formation deposition, at the Late Miocene and Early Pliocene on the Andean foreland, Acre and Solimões basins and western tip of the Amazon Basin.

The general relief of the Amazon Basin was relatively high (>100 m), but it did not stop the Amazon River from flowing eastward, due to the digging of a deep central valley, with minimum unleveling of over 200 m, between the top of the Alter do Chão and the bottom of the Amazon River Valley (Fig. 6). The fact of abundant, Andean zircon minerals being easily found from the Tortonian onwards on the Amazonian cone (Figueiredo *et al.* 2009, 2010) and Ceará Rise sediments (Dobson *et al.* 2001, Harris & Mix 2002) indicates the drainage from the Andes found, as far back as the Tortonian, its pathway into the ocean with no obstructions.

The mentioned unconformity between the Amapá and Pirarucu Formations, as well as the partial unconformity between the deep-water Orange and Travosas Formations in the Foz do Amazonas Basin in the early Late Miocene (Figueiredo *et al.* 2007), points out a new sedimentary regime that ended the deposition of limestones on carbonate platform, overflowed and started to build up the thick clastic submarine fan of the Foz do Amazonas Basin. The incorporation of the huge Amazonian drainage from the Andes and Paleozoic basins to the one from the Marajó Basin greatly multiplied the volume of sediments carried out into the sea with remarkable prograding clasts in Foz do Amazonas Basin.

A corollary of this study is that bauxites and kaolins from Alter do Chão Formation show to be Post-Middle

Miocene-aged. Another question is: Why are there no bauxites from the West of the Amazon Basin till the Acre Basin? In Acre and Solimões basins and western tip of the Amazon Basin, following the short-lived Ucayali unconformity, the Solimões Formation sedimentation occurred practically covering the layers of the mentioned areas, opposed to what took place in the rest of the Amazon Basin, where the layers of the upper portion of Alter do Chão Formation kept themselves exposed on the plateaus from the Mid Miocene up to date.

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