Evolution of the lowest Amazon basin modeled from the integration of geological and SRTM topographic data

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Abstract

Morphologic features obtained from SRTM data, integrated with geologic information, are emphasized in this paper in order to provide the basis for understanding the development of the lowest Amazon drainage basin, focusing on the history of one of the largest Amazonian tributaries, the Tocantins River, and on the origin of the Marajó Island, throughout the Quaternary. This approach led to the recognition of a fan morphology related to the record of a tectonically controlled N/NW–S/SE orientated paleovalley cut down into Miocene and older rocks. The incised valley was fed by a paleo Tocantins River, which deposited its sediment load continuously to the north–northwest, reaching the Marajó Island and producing a deposit with a fan-morphology during the Plio–Pleistocene/Pleistocene. As characterized in the SRTM images, this channel system became abandoned due to capture by NE–SW orientated faults and establishment of the Pará River by W–E strike slip movements. This event, which probably took place in the Mid-Holocene, was responsible for the detachment of the Marajó Island from the mainland.

Keywords: SRTM imagery; Topographic model; Landscape evolution; Quaternary; Amazonian; Geology

1. Introduction

The Amazon fluvial system is extraordinary, having the largest volume discharge (i.e., 175,000 m³/s) in the world, and a length exceeding 6400 km. Although representing a unique system, there is little research dealing with the Amazon drainage basin and, in particular, no efforts have been presented attempting to provide the history neither of the main river nor of its tributaries through time. This type of study is important to help understanding the mode of formation and evolution of this large river system, which can be used as an analog for reconstructing similar fluvial systems in the ancient record.

The lack of detailed studies, the great size and, many times, the inaccessible nature of Amazonia, are aspects favorable for the application of remote sensing as an important tool for the characterization of the physical environments (Moran and Brondizio, 1994). Given that processes involving sediment transport, erosion and weathering are directly imprinted in the land surface, the study of morphological properties is important to help understanding the geological history in this area. In particular, interpretations derived from remote sensing data might be of great help for identifying features of the physical environment developed throughout the Quaternary, as these have a great potential to be still preserved on the modern landscape.

In this paper, a general morphologic characterization of the lowest Amazon drainage basin is provided with basis on the interpretation of data provided by the Shuttle Radar Topographic Mission (SRTM). Application of this resource had the advantage of furnishing digital elevation information with a minimum influence of vegetation and perennial clouds, both...
representing major problems when using other remote sensing imagery (i.e., Landsat) in the Brazilian Amazonia (Asner, 2001). The goal was to combine spatial analysis with geological data available in the literature in order to: 1. create the basis for discussing the geologic history of this area during the Late Tertiary–Quaternary, attempting to reconstruct the evolution of one of the main Amazon tributary in its lower course, the Tocantins River; and 2. understand the origin of the largest fluvial island in the world, the Marajó Island. Herein, it is also discussed how tectonic reactivations have contributed to the geological evolution of this area.

2. Methods

This work was based on the integration of sedimentological and structural information available in the literature with new morphologic and topographic data derived from SRTM-90 data. These were downloaded in August 2003 from USGS Seamless Data Distribution System (http://srtm.usgs.gov/data/obtainingdata.html), in the first version, now known by “unfinished” dataset, in TIFF format. Though seamless in its origin, SRTM data were downloaded in tiles corresponding 1:250,000 quads (Fig. 1) to facilitate storage and avoid overflow. More information about SRTM data is presented by Rabus et al. (2003), as well as an increasing number of papers dealing with it.

SRTM-90 m data were resampled (from 3" to 1") in order to achieve improvements for morphometric derivations, as well as interpretation in detailed scales. This procedure followed a geostatistical approach (Valeriano, 2002a) through kriging, using the following computational programs: ENVI (Research Systems Incorporated, 2002) for failure correction, sampling and ASCII data export; MINITAB® (MINITAB Incorporated, 2000) for trend analysis and calculation of residues; VarioWin (Pannatier, 1996) for geostatistical analysis; and Surfer (Golden Software, 1995) for kriging interpolation. These procedures, depicted in Valeriano et al. (2006), were shown to improve the results of derivative techniques. Consequently, shaded relief presentations (which are essentially a function of the derivatives slope angle and aspect), were also improved, with significant gains for visual interpretation (Fig. 2).

After resampling, the refined DEM was derived into morphometric maps using the application of a suite of algorithms developed in Idrisi Macro Language (Eastman, 1995). These included aspect (directly from the GIS resources), slope (Valeriano, 2002b), profile curvature (Valeriano, 2003), and plan curvature (Valeriano and Carvalho Júnior, 2003). A derivation specially developed for visual evaluations of DEM (Valeriano, 2002a), here called ADD (Azimuth, Drainage and Divides), presents thalwegs and divides overlaid on aspect angle image, codified as brighter colors for northward directions grading to darker tones for southward slopes, thus rendering a type of hill shading. Slope angle images were calculated through the vector sum of slope orthogonal components, as quantified through moving windows in “x” and “y”
orientation systems, taking the maximum vertical displacement in each windowed direction and the maximum resultants between the orientations. These procedures produced results of higher correlation with controlled estimates (Valeriano, 2002b). The method for mapping profile curvature was based on local 3 × 3 pixel windows designed to perform geometrically the second order derivative through the slope profile. Curvature calculations required the DEM spatial resolution as one of the inputs, so as to calculate a slope change rate per horizontal distance as unit, in degrees per meter (°/m). Because this is calculated towards the eight neighbor pixels of each windowed position, one of the eight results is chosen according to the local slope direction classified in octants. Plan curvature was mapped through a similar application of moving windows, on the slope direction image instead, providing the slope direction change rate per horizontal distance (°/m) as unit.

Though originally developed for quantitative applications, the morphometric maps were promptly observed together with elevation presentations under visual interpretation. Because of the local character of the derived variables and the regional expression of most of the targeted features, a quantitative approach, not developed in this paper, would be convenient only after establishing terrain patches, with further statistics. Segmentation or binning techniques, successfully applied by Kellndorfer et al. (2004) to study canopy effects, may represent digital alternatives for visual classification of terrain units in this task. The crispy appearance of derived maps in detailed excerpts (Fig. 3) indicates their high variability in short distances. Besides terrain features, canopy effect was observed to cause a substantial portion of this variability (Valeriano et al., 2006), particularly noticeable on flat terrain.

Image interpretation of elevation data was made possible by the use of the software Global Mapper (Global Mapper Software LLC). Given the very low topography, the study area had to be visualized accordingly using customized shade schemes and palettes to efficiently highlight the morphologic features of interest to this paper. Color schemes were rearranged to present strong hue transitions near the height of terrain units boundaries, often requiring adjustments from a local to another.

3. Geologic framework

3.1. Regional geology

The main part of the study area is located within the Marajó Graben System. This consists of an elongated area up to 1.5 × 10⁶ km² in the northeast of the State of Pará, which has subsided as a result of the extension related to the opening of the Equatorial South Atlantic Ocean during the late Jurassic/early Cretaceous (Azevedo, 1991; Galvão, 1991; Villegas, 1994). The Marajó Graben System configures a northwest to northeast oriented belt formed by four depocenters (Fig. 4), named Cametá and Mocajuba (southeast), Limoeiro (central) and Mexiana (northeast) sub-basins,

Fig. 3. Excerpt of morphometric maps derived from refined SRTM data, showing the high variability of the topographic variables. Note the canopy effect by observing a forest clear cut at bottom right.
the latter being located entirely on the continental shelf. Seismic data indicate a sediment pile up to 10 km thick, with the upper 5.5 km being represented by Cretaceous syn-rift deposits, including the Breves (Albian to Cenomanian) and the Limoeiro (mostly Upper Cretaceous) formations (Fig. 5), and a much thinner (i.e., 900 m thick) Tertiary post-rift interval (Galvão, 1991), referred as the Marajó (Paleocene–Middle Miocene), Tucunaré and Pirarucu (Late Miocene to Pleistocene) formations.

A remaining part of the study area is in the southeastern edge of the Amazonas Basin, and in the Bragantina and Pará platforms. The Amazonas Basin represents a main E–W and SW–NE orientated rift formed in the Transamazonic Craton during Early Paleozoic intraplate extension. Its filling consists mostly of Paleozoic rocks and Cretaceous deposits of the Alter do Chão Formation. The platforms correspond to shallow areas of relative tectonic stability between the Marajó Graben System and other sedimentary
basins formed during the South American and African split. The lowest Amazon drainage basin is developed in a region strongly affected by NE/SW and E–W strike-slip faults (Szatmari et al., 1987), formed as a consequence of the main rifting during the early Cretaceous. Regardless of its location in a passive margin, these faults remained active up to the present, though moving at lower rates (Azevedo, 1991; Galvão, 1991; Villegas, 1994; Bezerra, 2003). As a result, the study area is dominated by numerous NE/SW, NW/SE–NNW/SSE, and E/W–ENE/WSW faults with offsets of up to several hundreds of meters (Villegas, 1994) that affected not only the Cretaceous, but also the Tertiary and even the Quaternary sedimentation (Costa et al., 1993, 1995; Bemerguy, 1997; Costa and Hasui, 1997; Góes and Rossetti, 2001) and, ultimately, had a great influence on the development of the modern morphology.

3.2. Description of the sedimentary units

The sedimentary units from the lowest Amazon area are of Cretaceous and younger ages. These units, with distinct designations in sub-surface and surface (Fig. 5), are represented in surface by the Itapecuru Group (Cretaceous), Pirabas/Barreiras (late Oligocene/early Miocene) and Post-Barreiras sediments (Plio/Pleistocene/Pleistocene). Cretaceous deposits are mostly represented by the Ipixuna Formation, which consists of kaolinitized, cross-stratified and parallel-laminated sandstones, interbedded with heterolithic deposits, as well as mudstone and intraformational conglomerates. This unit has been also traditionally interpreted as entirely continental in nature (Góes, 1981), but more recent studies have demonstrated that it includes deposits formed chiefly by wave and tidal processes in marginal marine and possibly estuarine settings (Rossetti and Santos, 2003; Santos and Rossetti, 2003; Rossetti, 2004). Exposures of Cretaceous deposits to the west of the Tocantins River are referred to as the Alter do Chão Formation in the Amazonas Basin. The latter deposits are siliciclastic red beds consisting of sandstones and mudstones attributed to continental (e.g., Daemen, 1975) and, more recently, wave-dominated deltaic environments (Rossetti and Netto, 2006).

The Alter do Chão and Ipixuna formations are unconformably overlain by the Pirabas/Barreiras succession, which include carbonates, mudstones and sandstones that are locally highly fossiliferous, allowing determination of a precise late Oligocene/early Miocene age based on micropaleontological data (Arai et al., 1988; Leite et al., 1997). Previous studies emphasizing facies characteristics have led to the recognition of deposits formed in a variety of tidal-influenced depositional environments related to estuarine paleovalley systems (Góes et al., 1990; Rossetti, 2001; Rossetti and Santos, 2004).

The Tertiary deposits, mostly exposed in the platform areas, include the Pirabas/Barreiras formations and the Post-Barreiras Sediments. The Pirabas Formation (late Oligocene–early Miocene) consists of limestones interbedded with black, gray and greenish laminated mudstones and, subordinately, calciferous sandstones (Petri, 1957; Ferreira, 1966; Góes et al., 1990). Fossils are abundant throughout this unit, attributed to inner shelf, lagoon and mangrove depositional environments (Ferreira, 1977; Góes et al., 1990) formed in the late Oligocene/early Miocene (Arai et al., 1988; Toledo, 1989; Araí, 1997; Leite et al., 1997). The Barreiras Formation (latest early Miocene/middle Miocene) consists of variegated, non-fossiliferous, siliciclastic deposits (conglomerate, sandstone and claystone) overlying the Pirabas Formation (Andrade, 1955; Matoso and Robertson, 1959). This unit has been traditionally considered as continental in origin (e.g., Góes, 1981); however, studies emphasizing facies analysis revealed a variety of sedimentary features related to tidal processes acting within NW/SE trending estuarine systems (Rossetti et al., 1989, 1990; Rossetti, 2004; Rossetti and Santos, 2004).

The Barreiras Formation is unconformably overlain by the Post-Barreiras sediments, a geographically extensive, but still poorly studied, massive to incipiently stratified unit that consists of light red, moderately to poorly sorted, fine to coarse-grained sands, and locally highly bioturbated massive mudstones (Rossetti, 2001). The sands are mostly monocrystalline, sub-angular to sub-rounded quartz grains. A Plio-Pleistocene/Pleistocene age has been estimated for these deposits through stratigraphic relationships, as they overlie the Upper Miocene Barreiras Formation, the latter overlap, in turn, by an unconformity formed by a latest Miocene drop in relative sea level (Rossetti, 2004). Additionally, the Post-Barreiras sediments are overlain by various Holocene deposits (Simões, 1981; Costa et al., 1997; Behling and Costa, 2000; Behling et al., 2001).
4. Morphologic characterization

Extensive previous fieldwork, as summarized above, combined with analysis of the available geological maps, reveal that deposits of Pleistocene, and possibly also Plio-Pleistocene ages, referred generically as the Post-Barreiras Sediments, prevail in the study area. These strata define a NNW/SSE elongated belt that starts southward at the locality of Tucuruí, and spreads out continuously northward from the mainland, reaching the southwestern and central parts of the Marajó Island (Fig. 4). Because in plain view these deposits display a triangular shape that defines a morphology resembling a fan, this term will be used throughout the text for descriptive purpose only. The use of this term herein does not imply the presence of alluvial fans in the study area, as the deposits in this instance were formed mostly in fluvial systems within incised paleovalleys, as discussed below. The fan-like deposits are fringed by Holocene deposits, which are particularly widespread in the eastern and northwestern part of this island.

Analyses of radar data revealed the main morphological aspects of the Post-Barreiras Sediments and of the associated deposits, to be described herein according to their occurrence in the southern, mid and northern sectors of the fan. If in one hand the processed SRTM data did not add much to define the overall fan-like deposits, they were crucial to characterize each fan sector described below, allowing a much better description of their morphological aspects, recorded by paleochannels of various sizes.

4.1. Southern fan sector

The southernmost and narrower tip of the fan-like deposits is elongated, defining a funnel shape up to 140 km long and ranging from 2–3 km wide upstream in the locality of Tucuruí to 25 km and 52 km wide in the middle and upper reaches, respectively (Fig. 4). Fieldwork revealed that this sector (Fig. 6A) is dominated by the Post-Barreiras Sediments, which correspond to flat sandy terrains with elevation averaging 30 m and a main northward-orientated, low...
density drainage. A few NNW/SSE orientated paleochannels up to 2 km wide were recognized in the Post-Barreiras Sediments located in the extreme western portion of this sector, paralleling the basement (Fig. 6B). Holocene deposits occur only northward in this sector, where a rapid enlargement is observed. In that area, the Holocene deposits are distinguished by sediments located at altitudes of 12 m and lower and which are morphologically characterized by abundant abandoned meandering channels and flooded areas. These deposits are intersected by the Tocantins River, which reaches the eastern edge of the sector from this point, running through it.

The Post-Barreiras and Holocene deposits in this southern fan sector are sharply entrenched into rocks that vary northward from Paleozoic to Cretaceous, and then Miocene ages. The Quaternary deposits display edges configuring slope profiles that are smooth in the western side and abrupt in the eastern side. In the latter, the margin stands almost vertically, reaching an altitude of 80 m (Fig. 6C). Several straight segments displaying NNW–SSE orientation characterize the funnel margins along this sector (Fig. 6A). A north/south elongated relic of Miocene deposits (see white arrows in Fig. 6A) circa 3 km wide and 30 km long occurs in the right margin of the Tocantins River, extending to the southern part of the mid fan sector.

4.2. Mid fan sector

This sector, which represents the point where the fan-like deposits become the widest, includes a central area located between the Tocantins and the Jacundá rivers, and two lateral wings (Fig. 4). The central sector extends for 90 km in the north/south direction, and 170 km in the east/west direction. The wing located to the west of the Jacundá River extends throughout almost 90 km northwestward, reaching the Caxiuana Bay. It has an overall rhombic shape formed by three land masses defined mostly by the courses of the Anapu, Pacajá and the Jacundá rivers. These rivers display segments deflected in a similar pattern from NNW to WNW, and then NNW, discharging in the WNW and W–E orientated Pará River at the northern end of the mid fan sector. The modern channels in this area run mostly to NW or NE. The
wing to the east of the Tocantins River forms a NE/SW elongated belt that is 165 km long and up to 50 km wide, and displays few channels running mostly to NNE.

The Post-Barreiras sediments are the prevailing deposits in all sectors, occurring at altitudes of up to 35 m, with an average of 25 m. In both wings, the Post-Barreiras Sediments do not show paleochannels. However, paleochannels mapped in the southern fan sector continue throughout this area (Fig. 7A), where they show the same orientation and magnitude, though they are more abundant and become branched into several lateral channels. Noteworthy is the eastward inflexion of a main channel at the transition of the southern and the mid fan sectors (white arrow in Fig. 7A), a pattern that is followed by the Tocantins River, which turns to east through a distance of almost 20 km at this same position.

Except for modern alluvial sediments, geological maps do not show any significant Holocene deposits in the mid fan sector. Analyses of radar images, however, revealed volume-trically significant Holocene deposits in the northeastern side of the central area, with two large, and in part seasonally flooded, areas up to 25 km long and around 15 km wide (Fig. 7B). Other occurrences of Holocene sediments are recorded in the southern part of the eastern wing, and in the eastern block of the western wing. In all these places, the Holocene deposits occur at altitudes of only 4 to 8 m (Fig. 7C).

### 4.3. Northern fan sector

The northern fan sector is the largest one, encompassing the Marajó Island, as well as several other islands located in the northwest of the study area. A great part of this sector is characterized by Post-Barreiras sediments. This unit extends throughout the Marajó Island, forming a continuous sedimentary succession that extends from the mid fan to this sector. The Post-Barreiras sediments disappear northward, where they are replaced by Holocene deposits (Fig. 8A). These are also present in the eastern side of the Marajó Island, where large, periodically flooded areas are abundant. A narrow, but elongated belt up to 100 km long and averaging 10 km wide in the eastern part of this island contains elevated areas, consisting of deposits representing

![Fig. 8. SRTM data illustrating the northern fan sector. A) Contrast between the western and eastern sides of the Marajó Island, represented by Post-Barreiras and Holocene deposits, respectively. A narrow belt in the extreme eastern margin of this island is also represented by Post-Barreiras sediments. Note the complex of abandoned channels in the western side of the island, some of them ending abruptly in the contact with the Holocene sediments (arrows). (The three boxes locate figures C, E and F, and the segment A–A' locates the topographic profile shown in figure B). B) Topographic profile from segment A–A' shown in figure A, illustrating that lower relief of the area with Holocene sediments relative to adjacent areas with Post-Barreiras sediments.](image-url)
the Barreiras Formation and the Post-Barreiras sediments (Fig. 8A).

Topographic profiles obtained from SRTM images revealed that areas in the Marajó Island with Holocene sedimentation is located only 2–5 m above present sea level, while areas with Barreiras and Post-Barreiras sediments might be up to 40 m (Fig. 8B). The altitude of the latter deposits is enhanced due to influence of canopy, as they are covered by ombrophyla forests, as opposed to Holocene sediments with prevailing cerrados. Regardless of vegetation influence, topographic data reveal a dominance of altitudes averaging 15 m where the Barreiras and Post-Barreiras deposits are present, with a maximum of 20 m at the locality of Cachoeira do Arari.

A typical feature of the northern fan sector is the abundance of paleochannels, which are particularly well developed in the western side of the Marajó Island (Fig. 9A–D). Some large channels from the southwestern margin of the Marajó Island are in continuity with the NNW–SSE orientated channels described in the southern and mid fan sectors. Features of interest concerning to these paleochannels include: a) the subtle disappearance (see arrows in Fig. 8A), and sometimes the opening forming a funnel shape (Fig. 9C) as they cross into the eastern side of the island where Holocene sedimentation dominates; and b) the frequent dislocation where they are cut by straight structural lineaments (Fig. 9D).

5. Geological history

Given the complex nature, the scarcity of detailed studies, and the great size, many further cooperative efforts remain to be undertaken before the latest geological events that promoted the development of the modern Amazon drainage basin can be depicted in a robust model. The overall morphological characterization of the lowest Amazon drainage basin presented herein, when linked to the available geological data, can serve for launching this process, allowing a first discussion on the main mechanisms that have influenced the evolution of the lower reaches of this fluvial system with the largest discharge in the world, as well as of its associated complex of islands.

A key point in this discussion is the primary recognition that the Plio-Pleistocene/Pleistocene deposits, corresponding to the Post-Barreiras sediments, rather than having a random distribution, configure an elongated, fan-shaped body confined by Miocene and older rocks. Taking into account the relatively young geologic age of these deposits, it is reasonable to consider that such morphology is most likely a reflection of the original geometry of the depositional system.

It is proposed herein that the studied fan-like deposits formed within a large NNW orientated incised paleovalley (Fig. 4). The several NNW–SSE orientated straight segments of the valley margins in the southern fan sector are taken as evidence that the Plio-Pleistocene/Pleistocene paleovalley resulted from faulting, an interpretation that is consistent with the several structural lineaments displaying
this orientation in the study area. As previously summarized, the underlying Miocene deposits were also formed within a paleovalley with similar orientation. An earlier work has stated that such disposition for the Miocene paleovalley, which also runs parallel to the main fault zones, has a tectonic control (Rossetti and Santos, 2004).

The evolution of the Plio-Pleistocene/Pleistocene paleovalley and of the Tocantins River, which runs paralleling the eastern paleovalley margin, seems to be closely related. The rapid changes in the course of this river, as reported earlier, coincide with the location of main E–W, NNW–SSE and NE–SW strike-slip fault zones. These faults were recurrent through time since, at least, the Late Tertiary, but the details of their evolution remain to be better discussed (Costa et al., 1996, 2001). The NNW segment of the Tocantins River ends exactly at the head of the fan, promptly leading to the argument that the paleovalley was established along the same fault zone responsible for the deviation of this river from its E–W course. Furthermore, the fan geometry of the Post-Barreiras sediments, with spreading to NNW, implies in a southeast clastic supply. This morphological characteristics, taken together, readily lead to invoke a time when an ancient Tocantins River would have discharged into the Equatorial South Atlantic Ocean through a NNW course (Fig. 10A), as opposed to its modern NE drainage, feeding the paleovalley with sediments brought from the southeast, and accumulating the succession recorded by the Post-Barreiras sediments.

The NNW fault zone that promoted the development of the paleovalley discussed herein must have been active during the Pliocene. This is revealed by the fact that the paleovalley truncates deposits of Miocene and older ages and is filled mostly by Plio-Pleistocene/Pleistocene sediments. Thus, after deposition of the underlying mid-Miocene Barreiras Formation within an estuarine incised paleovalley formed along a main NW/SE fault zone, there was a prolonged quiescence in the late Miocene, as recorded by an unconformity with a well developed lateritic paleosol that is correlatable throughout the northern Brazilian basins (Costa et al., 1996; Rossetti, 2001, 2004). A subsequent instability took place, with tectonic reactivation and sediment accumulation along the new accommodation space promoted by fault displacement.

Evidence for a paleo Tocantins River discharging northeastward into the Atlantic are the large, NNW oriented paleochannels preserved in the Post-Barreiras sediments, as recognized in all fan sectors. The continuity of both the paleochannels and the fan morphology developed on the Post-Barreiras succession into the Marajó Island demonstrates that this island was still connected to the mainland in the Plio-Pleistocene. The Pará River, then, could not have existed yet.

The fact that the root of the main paleochannels is located right where the modern Tocantins River is inflected to the NE is evidence that they were part of a same river system. NE–SW orientated faults (Costa et al., 1996) were responsible for the capture of the Tocantins River to its modern course, with the consequent abandonment of the NNW orientated channels (Fig. 10B). This process must have taken place in times not older than the Pleistocene, since this channel cuts through the
Post-Barreiras sediments. Previous authors have proposed that this tectonic event took place during the Würm glaciation in the late Pleistocene (Costa et al., 2002). This fault system might have also led to the origin of the Caxiuanã bay, located in the western margin of the paleovalley. Radiocarbon dating from that area revealed maximum ages of around 8000 14C yr B.P. (Costa et al., 1997; Behling and Costa, 2000), which conform to a proposed late Pleistocene age for the NE–SW tectonic event. The north–south elongated remains of Miocene deposits in the southern parts of the mid fan sectors are probably a record of the previous eastern margin of the paleovalley. As the NE–SW faults developed and the Tocatins River migrated to the east, the Miocene was further cut down, resulting in the paleovalley enlargement.

The detachment of the Marajó Island from the mainland is proposed to be as young as the latest Pleistocene to Holocene (Fig. 10C). As mentioned above, the origin of this island is related to migration of the Tocantins River to east, and establishment of the Pará River to the south. The course of the Pará River consists of several WNW–ESE and ENE–WSW orientated segments located along a main E–W strike-slip fault zone attributed to the Holocene (Costa et al., 1996, 1997, 2001). Good evidence that the main E–W fault system is younger than the NE–SW one are: 1. the deflection of the NE orientated course of the Tocantins River to ENE throughout one of these segments; and 2. the deviation of several NE–SW orientated rivers to E in the western wing of the fan. The rhombic shape of this fan sector, which is typical of areas that have undergone strike-slip motions, is further evidence attesting the existence of these two fault zones.

The several straight segments that define the northern edge of the Marajó Island parallel another main E–W fault system that also displays a strike-slip nature (Costa et al., 1996). The interception of the several paleochannels of the Post-Barreiras sediments by these faults attests to its young, late Pleistocene or even post-Pleistocene age. This fault system might have, thus, developed in association with the fault that gave rise to the Pará River in the eastern edge of the Marajó Island. The several narrow ENE–WSW orientated paleochannels mapped inside this island might have been triggered by stress caused by the development of these fault systems. The fact that these channels intercept the larger, main NNW running fluvial drainage is a proof of their younger age, thus being consistent with their attribution to the E–W Holocene faulting.

Furthermore, it is claimed herein that, before or even simultaneous to detachment, the eastern side of the Marajó Island probably underwent a slight subsidence (Fig. 10C). This hypothesis, though contrary to tectonic models that have proposed an uplift of the eastern Marajó Island since the Pleistocene (Vital, 1988; Costa and Hasui, 1997), is based on the following evidences: 1. this part of the island is mantled by sediments that are younger (i.e., mostly late Holocene) than those occurring in its western side; 2. sandy deposits around the Arari Lake, probably derived from the mainland (Vital, 1988), show ages that are as young as 6000 years B.P.; 3. although the whole area is flat (usually below 15 m altitude), there is a slight depression in its eastern side where cerrado vegetation dominates and flooded areas become abundant; 4. the sharp disappearance of paleochannels when crossing into this area, suggesting that they once ran through it, but fault dislocation and further Holocene sedimentation contributed to bury them; and 5. the opening of some channels when crossing into this area, forming a funnel shape suggesting an estuarine morphology left behind due to a change in paleocoast position. In addition, bouger maps show negative anomalies in this part of the Marajó Island, indicating the presence of a major sedimentary depocenter having a NNW–ESE, and then NE–SW, orientation, which is linked to the Mexiana Sub-basin of the Marajó rift system (Azevedo, 1991). Taking this overall depocenter orientation, it is concluded that both the NNW–ESE and the NE–SW fault systems recorded in the study area, and the Holocene subsidence of the eastern side of the Marajó Island, might attest to tectonic reactivations of the Mexiana rift. The bouger map also indicates important positive anomalies in the extreme eastern edge of this island, revealing that it was not affected by subsidence. This could explain why the morphological characteristics of this area resemble those from the middle and western parts of the island, where the Post-Barreiras sediments dominate, and flooded areas are in general either scarce or absent.

It seems that the subsidence in the eastern Marajó Island was also accompanied by subsidence of several terrains located in the eastern and, mostly, northeastern, of the mid-fan sector, which is also characterized by relatively lower altitudes and flooded areas.

6. Final remarks

The details related to the evolution of the lowest Amazon area remain to be reconstructed, but a preliminary model can already be proposed, which shows that tectonic activity was the main factor controlling the distribution of the sedimentary units and the development of the modern morphology. The model presented herein considers the existence of a paleo Tocantins River discharging its flow to the NNW into the Atlantic Ocean, as opposed to its modern NE discharge. This would have resulted in deposition of a sedimentary succession displaying a fan morphology related to the infill of a paleovalley developed in the Pleistocene/Pleistocene due to NNW–S fault reactivation. During that time, the Marajó Island, and probably also most of the many islands that characterize the lowest Amazon drainage area, was still connected to the mainland. This morphological feature was only formed after the capture of the Tocantins River by NE–SW orientated faults, and the later establishment of the Pará River by W–E strike slip movements. Therefore, a very young, most likely latest Pleistocene or even Holocene age, seems more likely.

The present geomorphological characterization based on SRTM data was crucial for recognizing the incised paleovalley in the study area. Application of this method might
contribute to substantially increase the geological knowledge in similar areas with difficult access, and characterized by an overall lack of information. The great advantage of this procedure is to provide overall models that can serve as the basis to optimize fieldwork aiming to reconstruct the evolution of depositional systems that still keep relics of their past physical environment imprinted on the modern landscape. When combined with regional geological information, the interpretation of geomorphological features using SRTM data was of great contribution for reconstructing the geological history of the lowest Amazon drainage basin. Based on this work, it could be demonstrated, for the first time, that one of the largest Amazon tributaries, the Tocantins River, had a complex evolution, changing its position according to tectonic reactivations, which might have taken place even during the Holocene. In addition, the data presented herein served to approach the origin of the Marajó Island, the largest fluvial island in the world, allowing discussions of the mechanism that would have promoted its detachment from the mainland. These issues, not emphasized in detail in previous publications, are of wide relevance for studies focusing on the Quaternary tectono-sedimentary history of the North Equatorial Brazilian Margin. This work serves also to suggest that the Amazon drainage basin, as presented in the modern landscape, might be a relatively recent scenario. Many possible changes in the river positions due to tectonics might have taken place in past times. These results are important for studies focusing on the distribution of the Amazon biodiversity (e.g., see Rossetti and Toledo, 2006 for a discussion related to this issue).

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