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Modern sedimentation in the Lower Negro River, Amazonas State, Brazil

Elena Franzinelli*, Hailton Igreja

Department of Geociences, University of Amazonas, Manaus, 69077-000 Brazil

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Abstract

The Negro River, which flows through the north central Amazon Basin, is one of the largest tributaries of the Amazon. The name "Negro" comes from the colour of its water, which reflects the large quantity of dissolved humic acids and iron oxides that also gives the water its characteristic acid pH. The river is estimated to have the fifth largest water discharge in the world, about 30,000 m^3/s. The Negro River is characterized by a high dissolved load but a low energy system. Neotectonics and water quality are the principal factors that control the modern sedimentation in the Lower Negro River. The Lower Negro River is controlled largely by a NW–SE tectonic lineament, that is a segment of a major tectonic transcurrent dextral megasystem of the Amazon Basin. Neotectonism in this area is responsible for the depth of the river and for the occurrence of steep "falésias" (cliffs), along some parts of its borders. It also seems that neotectonics have influenced the origin of the Anavilhanas Islands, which are a series of anastomosed, elongated silty clayey channel bars, with internal round or long narrow lakes. The "igapó", which is the forested area flooded during part of the year, appears to have a neotectonic origin as well. Igapós are located on intermediate blocks between the high blocks of the "terra firme" and the low blocks of the channel. The absence of clastic sediments carried in suspension is related to the rare appearance of floodplains, which are limited to very thin layers of fine sediments, located on the abrasion shelfs carved in clastic deposits of the Alter do Chão Formation. Sand bars occur in places along the base of the cliffs and along the edges of the channel system. These sand bars are composed of quartz sand, derived from the reworking of the sand of the Alter do Chão Formation. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Lower Negro River; Amazon Basin; Neotectonism; Black water; Anavilhanas Archipelago

1. Introduction

The Negro River is one of the largest tributaries of the Amazon and the largest on the north side. The size, width and colour of its water caught the attention of the explorers of the Amazon region (von Spix and von Martius, 1823–1831; Bates, 1982; von Humbold, 1829).

Sioli (1954) pioneered scientific studies regarding the water quality, soil, vegetation and ecological problems of Amazonia with a special reference to the Negro River region. However, modern data on the hydrology, climatology, sedimentology and ecology of the Negro River and its basin, are also included in papers that deal with the whole of Amazonia. Sternberg (1950), observing the NW–SE rectilinear direction of the Negro and

* Corresponding author.
E-mail addresses: elena@fua.br, elena@tecnonet.it (E. Franzinelli), hligreja@argo.com.br (H. Igreja).

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other rivers to the east flowing in parallel directions, first speculated on the effect of tectonics on the lower course of the Negro River. Franzinelli (1994) emphasized the great differences between the Negro and the Solimões especially regarding water quality, mineralogical characteristics, rates of transported load and composition and texture of modern deposits.

Franzinelli et al. (1999) showed that the modern neostructural directions that control the fluvial megasystem of the Amazon Basin can be summarized as follows: (1) Solimões River: N60W; (2) Negro River: N45W; (3) Amazon River: N80E; (4) Madeira River: N50E; (5) Tarumã River: N10E. These directions are the result of transcurrent faults affecting parts of the South American Plate under tension caused by the collision of the Nazca Plate to the west and the Caribbean Plate to the north, which began in the Tertiary (Miocene).

The central belt of the Amazon ecosystem has developed on the Amazonian Structural Province (Palaeozoic sedimentary rocks) situated between the Branco River and Tapajós River Structural Provinces, north and south respectively, on Precambrian igneous and metamorphic rocks) (de Almeida, 1977). These provinces have undergone cyclic tectonic reactivation.

The aim of this paper is to discuss the sedimentation that currently occurs in the Negro River, and to demonstrate how the modern deposition and water quality in this river system are controlled by regional neotectonism.

2. Regional setting

The drainage area of the Negro River is about 600,000 km^2, which covers parts of Colombia, Venezuela and Brazil. The Negro River joins the Solimões close to the city of Manaus, forming the Amazon (Fig. 1). Based on its average discharge, the Negro ranks as the fifth largest river in the world (Meade et al., 1991). Its sources are located in the llanos of Colombia where it is called the Guainia. It receives the designation "Negro" after its confluence with the Brazo Cassiquiare, in Venezuela. The Cassiquiare connects the upper course of the Negro River with the Orinoco Basin. It marks the boundary between Colombia and Venezuela until it enters Brazil at about 1000 km from its confluence with the Solimões River. The Upper Negro River drainage basin is on the sedimentary rocks of the Colombian Llanos, a flat savanna region bounded to the west by the Andes Mountains. Most of the upper course of this river, however, is in the Guyana Shield region, a low lying granitic and granulitic Precambrian craton, covered by rainforest (Fig. 1). The region consists of a wide pediplain, between 80 and 160 m above sea level. On this plain there are numerous inselbergs whose tops occur at two levels, about 460 and 700 m. The Negro River and its tributaries are well entrenched into the truncated surface of the Guyana Shield. The majority of rivers and tributaries follow fractures or faults formed by regional tectonism. Most of the tributaries have rapids or falls, which are less than 8-m high.

The middle and lower courses of the Negro River developed in the deposits of the Amazon sedimentary basin. This region consists of wide plateaus, upper Pleistocene in age (Projeto Radambrasil, 1978), that are composed of interfluvial tabular areas alternating with hills carved in the clastic deposits of the Amazon Basin. To the north of this area, a narrow strip of white sandstone and yellow siltstone of the Silurian Trombetas Formation. (Caputo et al., 1972) occurs in contact with the granulitic rocks of the Guyana Shield. To the south Cretaceous deposits of the Alter do Chão Formation and Tertiary deposits of the Solimões Formation outcrop. The Cretaceous continental deposits (red clayey sandstones, siltstones and claystones of the Alter do Chão Formation with some silicified beds in the upper portion) cover the older sedimentary rocks of the basin. The Cenozoic fine gray sandstones and claystones of the Solimões Formation cover the Alter do Chão Formation in the western part of the Amazon Basin.

The climate of this region is tropical humid. Rainfall in the Negro River basin varies from 3500 mm/year in the upper basin to 2137 mm/year in the lower basin (Mota, 1996). The average temperature of the region varies from 24 to 32 °C. The vegetation of the region is predominantly tropical forest.

According to the geology of the area, the course of the Negro River can be divided into three parts:

(1) The Upper Negro River, from its sources to the locality of Santa Isabel, where the river leaves the crystalline rocks of the Guyana Shield and flows across the sedimentary deposits of the Amazon Basin. In this reach the channel is straight with slow-flowing sections that alternate with rapids and waterfalls. The maximum depth is about 12 m in the dry season.

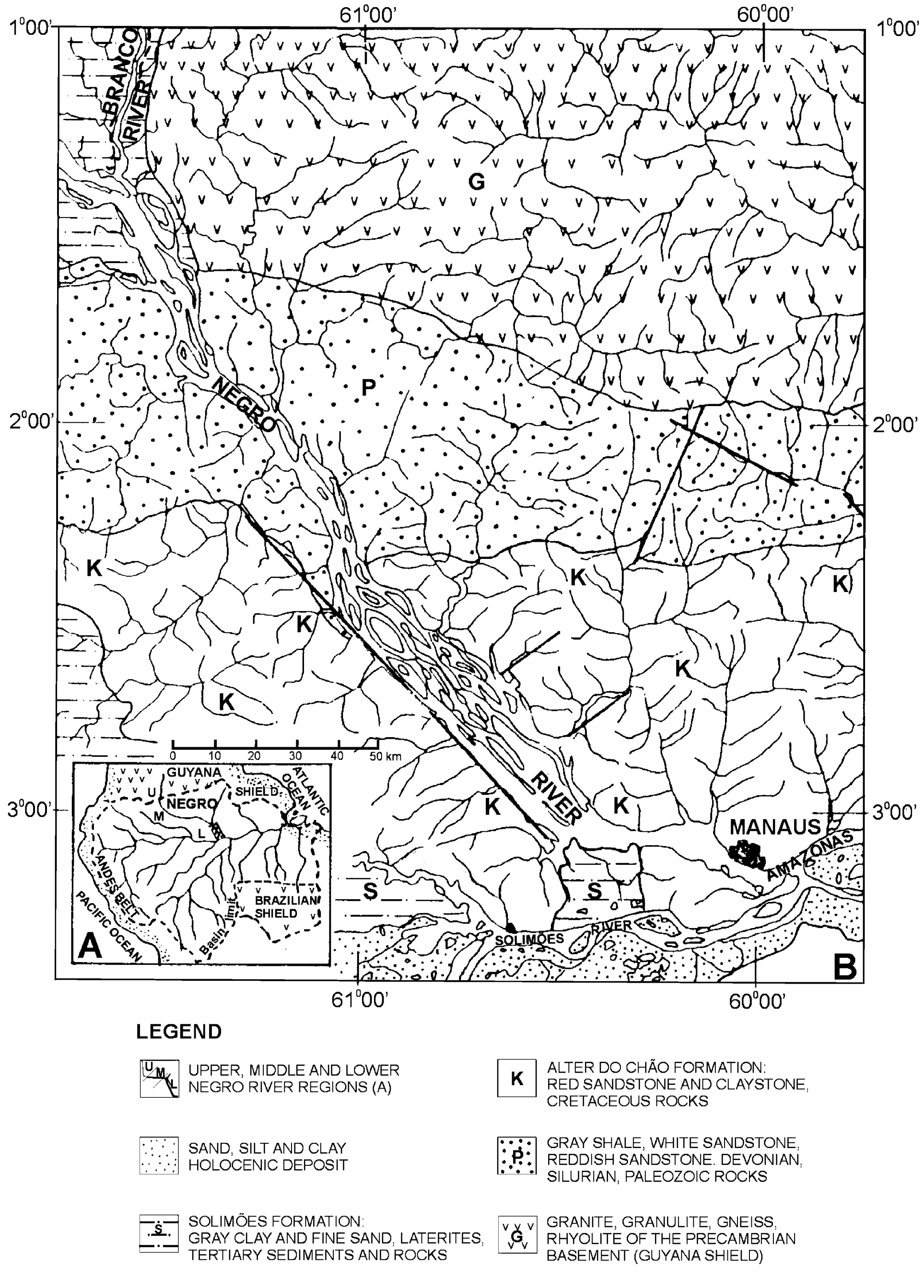


Fig. 1. A—The Amazon Basin and Negro River. B—Geological map of the Lower Negro River Region.

(2) The Middle Negro River flows on the Tertiary sedimentary deposits, in a general NW–SE direction. This reach has a very large channel, with numerous bars, especially near its southern end at the confluence with the Branco River, where the crystalline rocks of the basement outcrop in a small area and force the river

into a narrow channel. In the reach upstream from the Branco River, where it reaches a width of 20 km and more, and a maximum depth of 18 m in the dry season, it resembles an active sedimentation basin, with the crystalline rocks at the mouth of the Branco River forming a barrier causing an upstream accumulation of sediments (Franzinelli and Latrubesse, 1998).

(3) The lower course of the Negro River (Fig. 1B), between 62°W and its confluence with the Solimões (60°W), displays tectonic control. According to Franzinelli and Igreja (1990), this region is a structural lineament trending NW–SE, confining the river. The lineament belongs to a larger transcurrent system of geological features (faults, folds and rhombochasms) that occur in the whole Amazon Basin (Fig. 2). In this section the river is up to 20-km wide and it is bordered by discontinuous cliffs (falésia), formed by the Alter do Chão deposits.

3. Neotectonism

A neotectonic model for this region has been proposed based on remote sensing and verification of neotectonic features (Fig. 2) in the field (Franzinelli and Igreja, 1990).

The Lower Negro River region is governed by two distinct neostructural domains that control its physiography: (1) normal fault domain and (2) dextral fault domain. The normal domain, located on the left side of the river, maintains and directs the flow of the major tributaries (NE–SW) from the east towards the west, and the smaller NW–SE oriented tributaries, which flow southwest as well as towards the southeast. The dextral fault domain, consisting of dextral transcurrent faults N45W and secondary faults arranged en echelon in the direction N70E, promotes the fluvial flow predominantly from west to east.

These two principal domains, which have formed a half graben, have been altered by the younger third set of faults in a general west–east orientation, resulting in a transtensional basin (rhombochasm). This third set is difficult to identify on radar and satellite images in the north part of the area, but is fairly easy to observe in the field. It is essentially a set of dextral transcurrent faults and governs the southern part of the region, where it restricts the channels of both the Negro and Solimões rivers. Very wide reaches of the river, which are the result of the third set of faults, together with the first and second sets forming a NE–SW distension and a NW–SE oblique transtension confining the Negro valley, influence the inflow/evaporation balance of the river. The formation of these wide lake-like features involved the inclination and rototranslation of blocks, which tended to form wide depressions along the main faults that are concentrated along the riverbed. These dextral transtensional processes resulted in negative flower structures (a flower structure is similar in form to a flower with various-sized overlapping blocks (petals) radiating outward and upward from a central fault (stem)), from meters to kilometers in size, the petals of which form many collapsed structures, which are prominent at the entrance of the Solimões River Basin (Igreja, 1999).

The tectonosedimentary evolution of the Lower Negro River with an auto-cycling tendency is similar to the processes of politaxitic and oligotaxitic alternation observed in some Cenozoic basins around the world (Fischer and Arthur, 1977; Miall, 1990) that have an accelerated subsidence and an alternation of a population explosion and high biodiversity during the rainy season, and decimation and low biodiversity during the dry season.

4. Hydrology

The name “Negro” comes from the colour of its water, caused by the large quantity of dissolved humic acids and iron oxides, which also give the water its characteristic acidic pH. According to Bringel et al. (1999), the pH value of the Negro River varies from 4.2 for the water of the central channel to 5.8 for the water close to the confluence with the Branco River. The humic acids come from organic material, such as roots, leaves and wood that decay slowly in the water. The headwaters of the numerous small tributaries generally drain wide, shallow swamps situated on the acid rocks of the Guyana Shield or on sandy sheets derived from the weathering of these rocks. According to Sioli (1991), the origin of black water is largely related to the podzolic soil of the headwater area. In this type of soil, the organic material rapidly undergoes decomposition to humus, which is easily dissolved by the percolating rain water and transported to the water table, finally emerging on the surface as small streams.

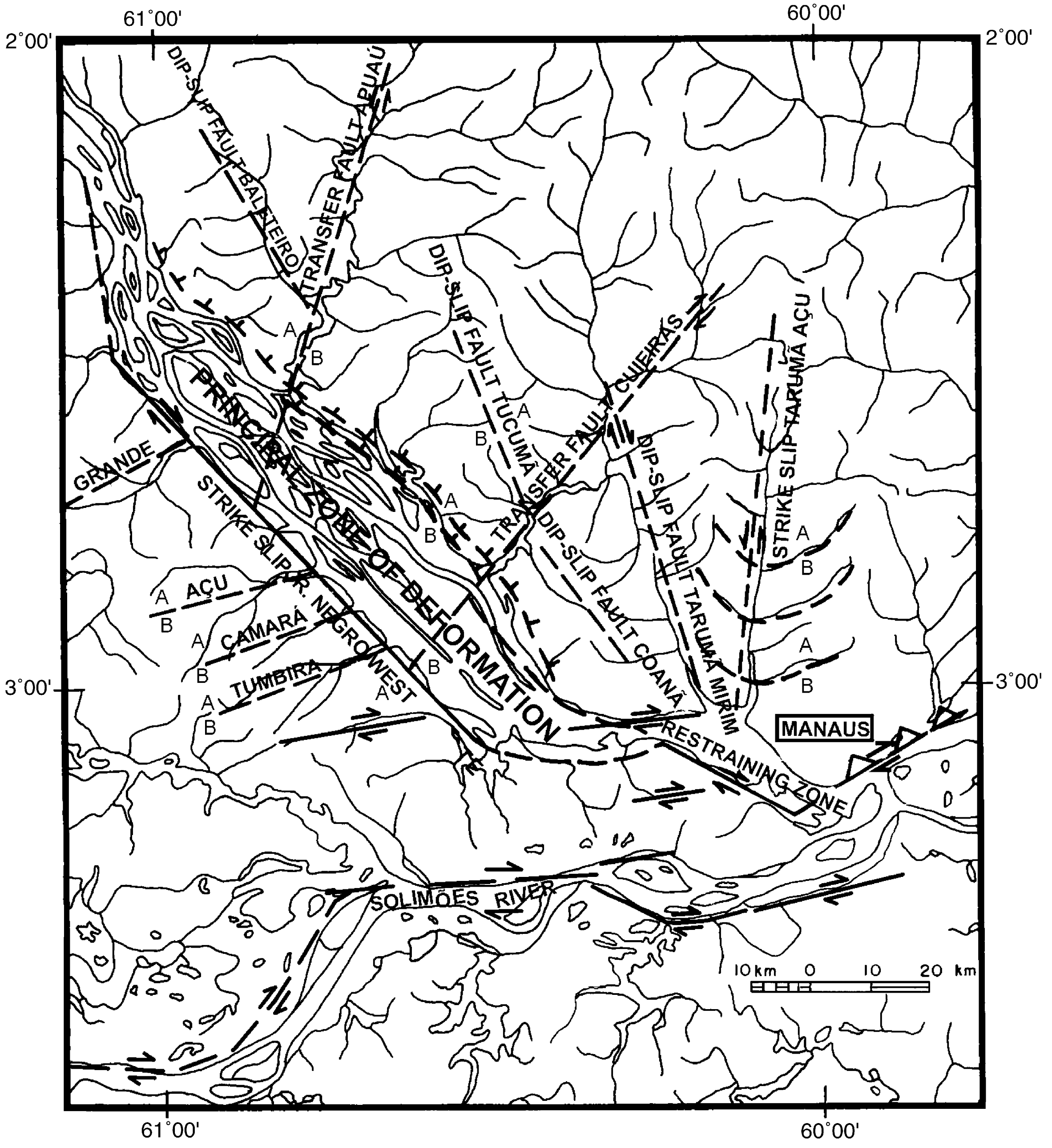


Fig. 2. Neotectonic model of Lower Negro River, principal structural lineaments: A = High Block, B = Low Block; ⇅ Strike-slip movements; ▽▽▽ Significant reverse component; ⊥⊥⊥ Significant normal component (from Franzinelli and Igreja, 1990). This region is a smalll subsystem of the transcurrent Amazon mega-system.

The mean annual discharge of the Negro is about 30,000 m^3/s (Meade et al., 1991). The maximum annual fluctuation in river level measured at the port of Manaus is about 14 m (Trisciuzzi, 1979). The height of the water during the maximum annual flood reaches about 28 m above sea level at the port of Manaus. According to Sternberg (1998), the maximum fluctuation of this century occurred in 1953, when the level of the water reached 29.50 m above sea level. During the rainy season the high water level facilitates the development of a high amount of biodiversity. During the dry season the low water level results in a decrease of biodiversity due to hydrogeochemical factors.

Sediment load transported by the Negro River is mostly dissolved load. According to Martinelli et al. (1988), the Negro River supplies an annual total load of 0.057×10^8 t. The annual total load at Obidos for the Amazon River was estimated to be 2.46×10^8 t. According to Dunne et al. (1998), 7% of the mean annual load is made up of sand, and 93% of silt and clay. The Negro River carries very little sedimentary load to the Amazon.

5. Geomorphology

Cross sections from different sites along the Negro River have been plotted in Fig. 3. The sections illustrate the control of bedrock and tectonics on channel morphology. Such features are floodplain, sand bars, Anavilhanas Islands, and igapó.

5.1. Floodplains

Floodplains are very poorly developed along the banks of the Negro River because (1) the river is confined in a channel (Fig. 4) formed by faulting (Franzinelli and Igreja, 1990), and (2) the river transports little suspended sediment load. Floodplains are developed above abrasion terraces that are the result of erosional activities on the red claystone or silicified sandstone of the Alter do Chão Formation. Thin fine sandy beds cover these terraces that are completely flooded during the rainy season (Fig. 5). The small areas of floodplain are generally limited by cliffs (Fig. 6) that can reach 20 m in height and are the edge of the "terra firme" or high terrains that are never inundated during floods. The cliffs were originated by faults that emphasize the confinement of the river. These small areas of floodplain are more common on the south side of the Negro due to the regional tilting of the neotectonic blocks. One of these blocks contains the Ariau River (Figs. 4 and 7), a tributary on the south side whose upper drainage area is in the floodplain of the Solimões River. The direction of flow of this tributary depends on the timing of the Solimões or Negro River floods. For example, when the Negro River is in flood stage and its water level is higher than the Solimões, the direction of flow is from the Negro to the Solimões. When the Solimões is in flood stage, the flow is reversed. When the Ariau drains into the Negro River the sediments that the river transports are deposited at its mouth, forming an elongate delta (Fig. 7). X-ray analysis of the delta sediments (Franzinelli et al., 1996) confirmed their origin from the Solimões floodplain.

5.2. Sand bars

Modern sand bars result from the deposition of quartz sand along the banks of the river. These are lateral bars; other types of bars are very rare. Sand bars are more prominent on the south side of the river due to the dominant winds that blow from the northeast generating waves on the river, which promote accumulation of the sand along the edges of the tectonic blocks. These sand bars are typically situated at the foot of the cliffs (falésias) (Fig. 7) or are isolated along the shores where the cliffs have been completely destroyed by erosion forming the natural levees of the river. A long, flat sand bar occurs on the right bank downstream from the confluence with the Branco River. The mean grain size of its white sand is 0.23 mm, the sand is very well sorted, and the quartz grains show good roundness. This bar is situated in an area of Paleozoic sandy rocks and reflects the similar textural characteristics of the source rocks. The best developed sand bars, also called "beaches", are located at Ponta Negra where these are about 2-km long, situated on the north side of the river, 15 km upstream from downtown Manaus and at Praia Grande, where the bars are about 12-km long, 200-m wide and 16-m high, on the south side, 70 km upstream from Manaus (Figs. 4 and 7). Grain size, sorting and roundness analysis indicate that these bars were derived from local reworking of sand beds of the Alter do Chão Formation (Brito et al., 1994a,b; Brito, 1996). From a mineralogical point of view, these sands are very pure quartz sand (Potter and Franzinelli, 1985).

5.3. Anavilhanas Islands

The archipelago of the Anavilhanas Islands (Figs. 4, 7 and 8) is a prominent feature of the Lower Negro

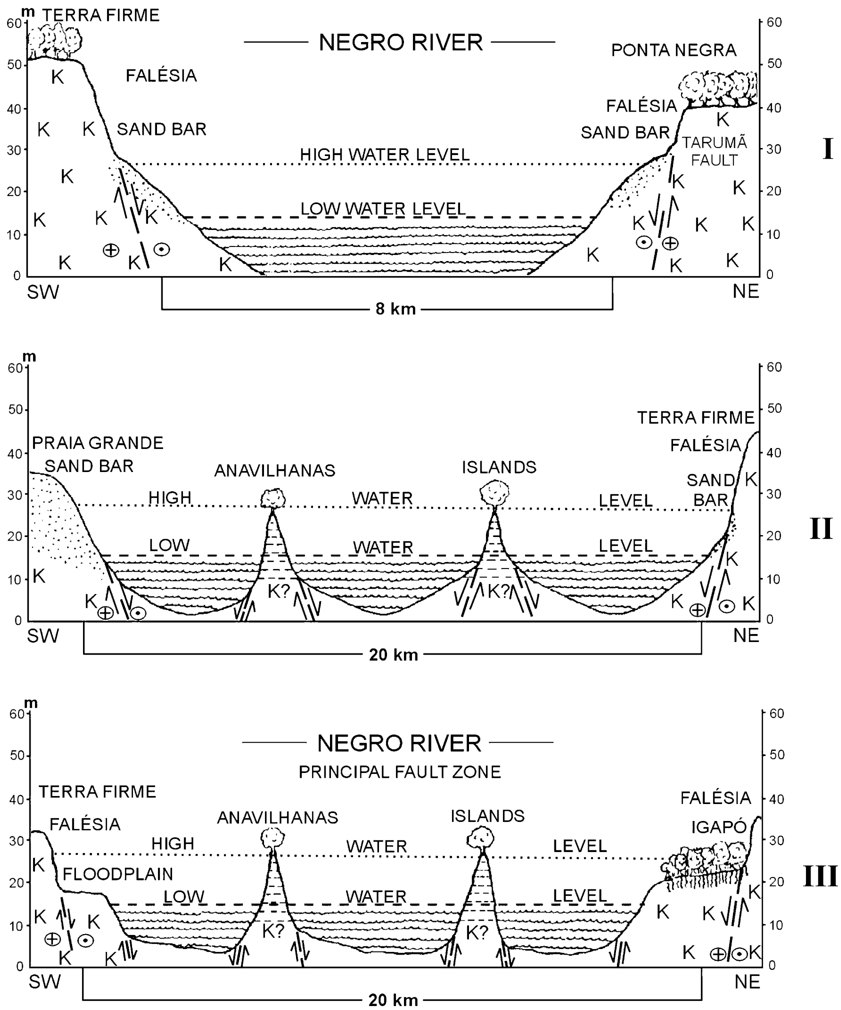
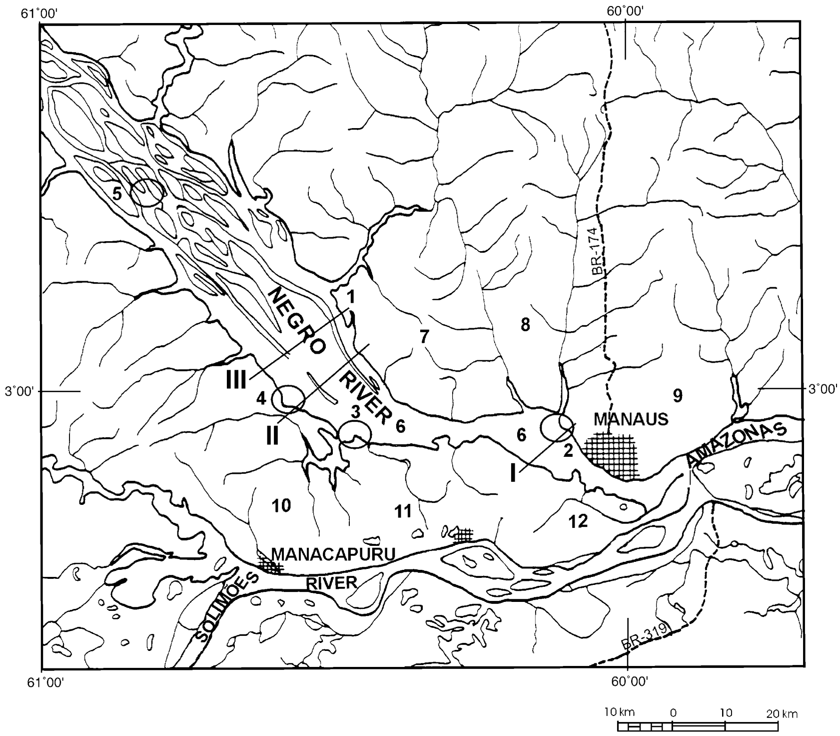


Fig. 3. Schematic cross-sections in the Lower Negro River Region. Data from Projeto Radambrasil (1978) and from measurements during fieldwork. Location of the cross sections I, II, and III shown in Fig. 4. K-Cretaceous, Transtensional Fault (Dextral).

River region. It is a complex of numerous silty clayey channel bars each with a core or upstream head that is generally occupied by a lake, and a very long and narrow downstream tail. The Anavilhana Island, for example, is 40-km long and 130-m wide, probably demarcating a fault line of the same dimensions. In the dry season it is possible to see upstream the lateral banks, which are very steep. Downstream the banks of the islands can be steep, but generally they terminate gradually. The vegetation zonation is marked by a decreasing height and a transition from igapó (periodically inundated forest) to mangrove type vegetation, at the extreme end of the islands. The internal lakes in the cores of the islands have less steep edges than the island banks. A section across the tail of the islands displays a sinusoidal topography with crests and lows of the islands parallel to the flow. These islands are completely flooded during the rainy season. The islands are built with yellow-gray clay and silt, and very rarely contain finely laminated, reddish mottled fine sand. The lithology of these islands shows that their origin is not compatible with the actual dynamic conditions of the river, which in its present state hardly transports any material in suspension. Three elements were essential



1 - CUIEIRAS RIVER MOUTH
2 - PONTA NEGRA SAND BAR
3 - ARIAÚ RIVER DELTA
4 - PRAIA GRANDE SAND BAR
5 - ANAVILHANAS ISLAND.
6 - LARGE INLETS
7 - COANÃ BLOCK
8 - TARUMÃ BLOCK
9 - MANAUS BLOCK
10 - MANACAPURU BLOCK
11 - ARIAÚ BLOCK
12 - CACAU PIREIRA BLOCK

Fig. 4. Location map of the cross sections and of the principal modern sedimentary deposits (○) and neotectonic blocks.

for their formation: (1) a sufficient amount of clay and silt, (2) a very low energy environment, and (3) the linear accommodation space. According to Sioli (1991), these very long bars originated by the deposition of the fine sediments that the Branco River supplies to the Negro River. Bringel et al. (1999) showed some significant textural and mineralogical differences between (1) the bottom sediments of several small lakes that receive water from the Branco River and (2) that of the lakes along the Negro River far from the influence of the Branco. For example, the composition of the bottom sediments of the lakes under the influence of the water of the Branco River is more sandy (53%) than of those downstream in the Negro River. The Anavilhanas Islands present the same clayey content as of all tributaries and not only of the Branco River. These new data indicate that the sediment that forms the islands did not come from the Branco, but from the tributaries that flow into the depression (rhombochasm).

5.4. Igapós

Igapós are another distinctive depositional feature of the Negro River (Fig. 9). An igapó is a periodically inundated forest, according to Prance (in Sioli, 1984), inundated by regular annual flood cycles of black water rivers. Igapó regions are believed to derive from low dry land areas (“terra firme”), which developed

Fig. 5. Lower Negro River, south bank upstream from Praia Grande Beach bar. Sandy floodplain during flooding. Note the water mixed with sand on the shore due to wave agitation. In the distance, the thin white line is a sandy lateral bar below the terrace of the Alter do Chão deposits.

during the Pleistocene or even the Tertiary (Irion et al. in Sioli, 1984). Igapó deposits normally consist of clay, silt, rare fine sand, and a large quantity of organic material derived from the decay of the vegetation that grows in these areas. Based on intensive studies of igapó areas by remote sensing and verification of geological and structural features in the field, Igreja et al. (1998) concluded that the develop-

Fig. 6. Lower Negro River, south bank. Sandy floodplain upstream from Praia Grande Beach bar, distal view. In the background is a cliff carved in the Alter do Chão deposits.

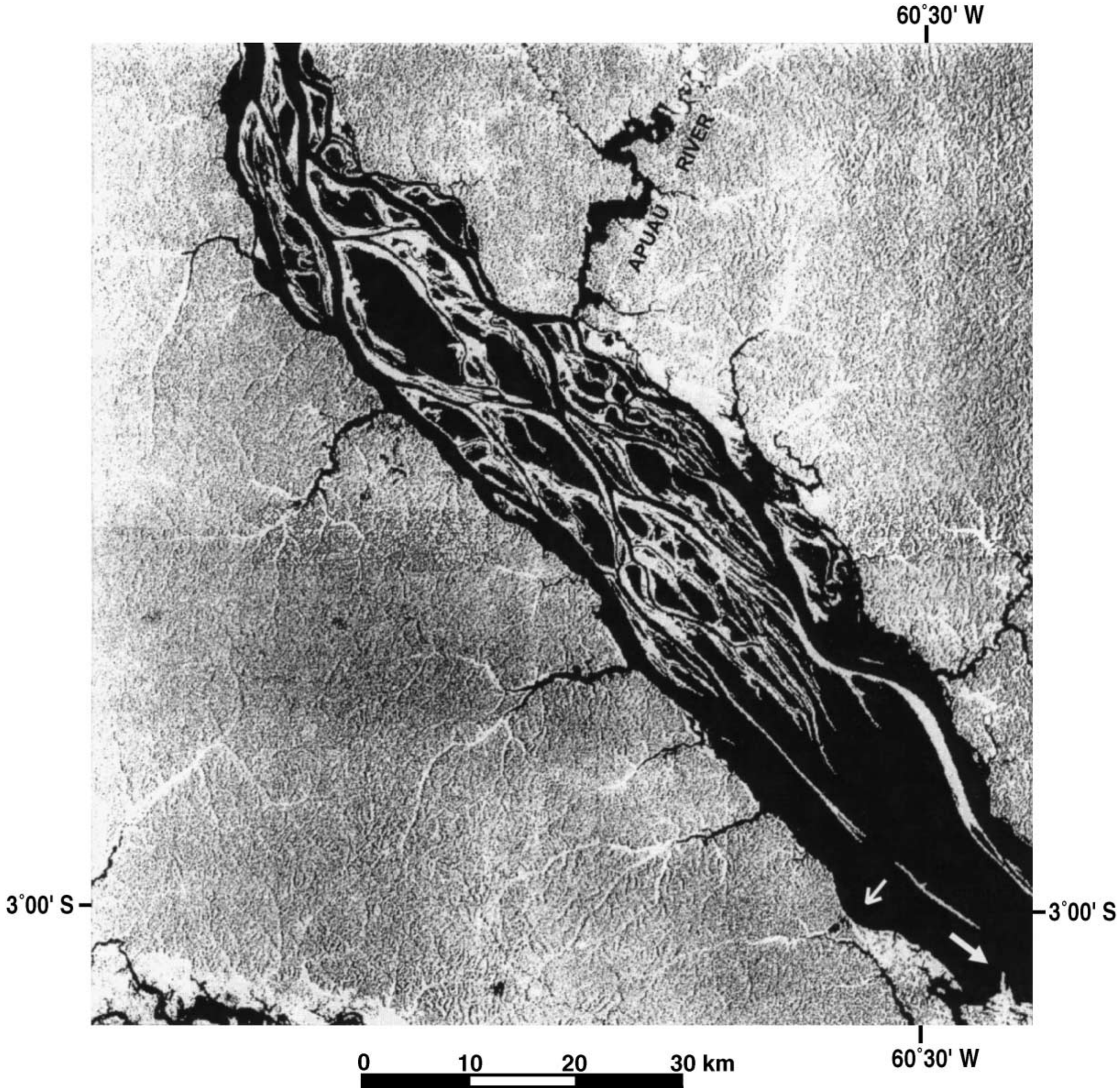


Fig. 7. Anavilhanas Islands in the central part of the Lower Negro River. One can note the lakes, channels and anastomosing islands. Downstream, where the islands form a long tail, the pattern turns deltaic. In the lower right-hand of the figure, on the right bank of the Negro River, the elongate delta of the Ariau River is visible (↘), and upstream, on the same bank, the half-moon shaped ‘‘Praia Grande’’ beach is located (↙). The tributaries of the right bank have wide mouths as they enter the Negro River, which is a consequence of the control by dextral transcurrent faults. On the left bank, to the north, the Apuau River also indicates the influence of neotectonism in its channel, with a widening in the orthogonal course. (Modified from Folha SA. 20-Z-B, Projeto Radambrasil, 1978).

ment of the igapós of the Negro River region was a consequence of neotectonics. Specifically, igapós are formed by the deposition of sediments and organic material above low blocks, sometimes tilted, separated by high blocks of the ‘‘terra firme’’. On these low blocks the vegetation of the ‘‘terra firme’’ adapted itself to the aquatic environment. The different elevations of the tectonic blocks along the Lower Negro River suggest different stages of neotectonic movement and, in consequence, different stages of adaptative

Fig. 8. Anavilhanas Islands in the central part of the Lower Negro River. Note the linear arrangement of the bars and the long internal lakes. The flow is right to left (photo by Antonio Iaccovazo).

evolution of the "terra firme" species composition into igapó species.

6. Sedimentation in the Lower Negro

The description of the neotectonic and geomorphological features and sedimentological and hydrological aspects confirm that the Negro is an unusual tropical river. The Negro can be divided into three sections (Fig. 1A). First, downstream of the confluence with the Branco River, it runs straight in the NW–SE direction in a narrow channel 5–8-km wide. Second, when the river enters the Cretaceous deposits the width of the channel first increases to 20 km for about 100 km then it narrows downstream in the restraining zone (Fig. 2). Neotectonics deeply influence this portion of the river, forming a half-graben rift, located in the clastic friable deposits of the Alter do Chão Formation. In the wide section, the main channel bifurcates, the two new channels flowing along the banks of the river, between 18- and 22-m deep, surrounding the Anavilhanas Islands. The major islands appear to follow faults in the river bed along the principal zone of deformation. (Fig. 2). In these islands or channel bars, sedimentation occurs by lateral accretion in linear deposits. It seems that the deposition of the sediments starts upstream and forms two bars, which act as levees and in some places deflect the flow of water to form secondary channels. Very fine material in suspension is deposited in the middle in the internal lakes. Third, downstream, in the direction towards the restraining zone the bars no longer have any internal lakes. They taper towards the end, giving to the set an aspect of deltaic configuration.

Presently, the provenance of the sediments of the bars cannot be explained, nor the chronological date of their formation. The Negro River does not have a high sedimentary load due to the nature of weathering of the rocks and the geomorphic aspects of the catchment area (Stallard and Edmond, 1983; Stallard, 1985). The amount of sedimentary material that the Branco River contributes to the Negro in the rainy season is not sufficient to explain the formation of the Anavilhanas Islands.

Considering the enlargement of the river on entering the friable deposits of the Alter do Chão Formation and the confinement of the river, it seems reasonable to suppose that these bars were formed by the reworking of the previous sediments in the rift, along with the material coming from the Branco River and other tributaries. However, textural evidence indicates that the

Fig. 9. Cuieiras River, close to its confluence with the Negro River. The white trunks are those of igapó trees that have died due to the subsidence of the low block.

lateral bars in this reach were formed by local sand deposited in an aquatic environment and the exposed sand underwent aeolian transport (Brito et al., 1996). In contrast, the igapós seem to have a tectonic origin, and their sedimentological, depositional and vegetational aspects are characteristic and different from those of the floodplain. In spite of its large discharge, the Negro is a low energy river. Erosion rarely happens. The occurrence of ‘‘terras caídas’’, bank failures due to the interaction of the river water and groundwater, very frequent in the Solimões (Sternberg, 1960), is uncommon. Remarkably, in some periods of the year, generally at the beginning of the rainy season, due to the nonsynchronous arival of high water (Meade et al., 1991), the Solimões River water blocks the Negro River exit, damming its water. The Negro is a very unusual river on many accounts.

7. Conclusion

Studies of the current sedimentation in the Lower Negro River indicate that its hydrology, geomorphology and evolution are strongly controlled by neotectonic elements. Floodplains, sand bars, islands and igapó forests may be considered as concurrent features inherent in the geodynamics of a transtensional basin, which is a part of the Amazonian megasystem. The Amazonian megasystem is in turn a part of a complex transcurrent dextral fault system that covers all of the territory of the Amazon Basin. This transcurrent dextral fault system is a result of the collision of the northern part of the South American Plate with the Nazca Plate to the west and the Caribbean Plate to the north.

Depositional, morphostructural, and hydrochemical processes make the Negro River unusual, with uncommon characteristics associated with a confined tectonic basin environment. Similar valleys, on a smaller scale, may be predicted to occur in other areas with the same neotectonics orientation within the Amazon ecosystem.

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