



Anais da Academia Brasileira de Ciências

ISSN: 0001-3765

aabc@abc.org.br

Academia Brasileira de Ciências

Brasil

Lima da Silva, Clauzionor; Morales, Norberto; Crósta, Alvaro P.; Costa, Solange S.; Jiménez-Rueda, Jairo R.

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Anais da Academia Brasileira de Ciências, vol. 79, núm. 4, 2007, pp. 693-711

Academia Brasileira de Ciências

Rio de Janeiro, Brasil

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Analysis of tectonic-controlled fluvial morphology and sedimentary processes of the western Amazon Basin: an approach using satellite images and digital elevation model

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*Manuscript received on March 17, 2006; accepted for publication on February 21, 2007;
presented by ALCIDES N. SIAL*

ABSTRACT

An investigation of the tectonic controls of the fluvial morphology and sedimentary processes of an area located southwest of Manaus in the Amazon Basin was conducted using orbital remote sensing data. In this region, low topographic gradients represent a major obstacle for morphotectonic analysis using conventional methods. The use of remote sensing data can contribute significantly to overcome this limitation. In this instance, remote sensing data comprised digital elevation model (DEM) acquired by the Shuttle Radar Topographic Mission (SRTM) and Landsat Thematic Mapper images. Advanced image processing techniques were employed for enhancing the topographic textures and providing a three-dimensional visualization, hence allowing interpretation of the morphotectonic elements. This led to the recognition of main tectonic compartments and several morphostructural features and landforms related to the neotectonic evolution of this portion of the Amazon Basin. Features such as fault scarps, anomalous drainage patterns, aligned ridges, spurs and valleys, are expressed in the enhanced images as conspicuous lineaments along NE-SW, NW-SE, E-W and N-S directions. These features are associated to the geometry of alternated horst and graben structures, the latter filled by recent sedimentary units. Morphotectonic interpretation using this approach has proven to be efficient and permitted to recognize new tectonic features that were named Asymmetric Ariáú Graben, Rhombohedral Manacapuru Basin and Castanho-Mamori Graben.

Key words: morphotectonics, morphostructural, neotectonics, Amazon Basin.

INTRODUCTION

The use of thematic maps, such as landscape, drainage, hypsometric, morphometric and geomorphologic maps, constitutes the basis of morphotectonic analysis, particularly for investigating Cenozoic tectonics. The production of these maps can be considerably facilitated by em-

ploying digital elevation models (DEMs). This makes the morphotectonic interpretation and the definition of tectonic compartments easier. In addition, the digital nature of DEMs allows the support of computer processing techniques for manipulation, enhancement, fusion and visualization of image data and the interpretation of terrain features. Application of techniques including different angles of observation, vertical exaggeration factors,

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artificial shadowing in different directions and color enhancements allows interpreting the terrain features.

In the Amazon region, morphotectonic analysis is not a simple task due mainly to the lack of altimetric data at adequate scales. Most of this region has only cartographic maps in the scale of 1:250,000, without or only with a few topographic data, mainly due to low topographic gradients. This data constraint occurs mostly along the Amazon River channel, where there are only point altimetric values. More detailed cartography is limited to some charts in the scale of 1:100,000, restricted to the region surrounding the city of Manaus and some neighboring areas. Furthermore, existing topographical surveys were carried out in the 1970s and 1980s, based on small-scale aerial photographs, with altimetric data being estimated on the basis of the height of tree canopies, which sometimes does not express the actual ground heights.

A new remote sensing technology based on radar interferometry (InSAR) is making it possible to acquire high quality altimetric data (Madsen and Zebker 1998). Using this technology, NASA launched the *Shuttle Radar Topography Mission* (SRTM) in 2000, which allowed the acquisition of altimetric data and the generation of DEMs of nearly 80% of the Earth's surface (Rabus et al. 2003). These data were used in the present study in order to overcome the scarcity of information on the topography of the study region and to enable morphotectonic analysis.

In spite of the limitations inherent to the region's thick vegetation coverage, and the available SRTM data with moderate spatial resolution (90 m), DEMs enabled three-dimensional visualization of the region's landscape and contributed significantly to the analysis of the main geomorphologic features. The topographic data contained in these DEMs are more precise than those contained in the previous topographic charts of the area, and permit the extraction of information for the elaboration of several types of thematic maps. Furthermore, the use of three-dimensional (3-D) digital visualization tools, in conjunction with the SRTM data, allows for the recognition of important and previously unknown morphostructural.

A 3-D model has been generated for the region southwest of Manaus along the Solimões River, between

the towns of Iranduba and Manacapuru, encompassing about 23,850 km² (Fig. 1), for the purpose of morphotectonic analysis. The area comprises an important segment of the Amazon Basin affected by Cenozoic tectonics and has the availability of topographic maps at 1:100,000 scale to compare results from different applied methods. Analyses of the drainage network, landscape features and geological information were spatially integrated to support the morphostructural interpretation, the field checking of structural features and the spatial analysis of the Cenozoic cover. Important structural features, such as tectonically uplifted and lowered areas, fault scarps, aligned ridges and spurs, and anomalous patterns in the drainage, were determined. Such features were used to interpret the morphotectonic framework of the study area and to compare it to the regional neotectonic model proposed by Hasui (1990) and Costa and Hasui (1997).

MATERIALS AND METHODS

The materials used for the morphotectonic analysis include: a) topographic maps of Manaus and Manacapuru at 1:100,000 scale (Manacapuru SA.20-Z-D-II and Manaus SA.20-Z-D-III); b) geological map of Brazil at 1:2,500,000 in digital format, prepared by the Geological Survey of Brazil – CPRM (Bizzi et al. 2001); c) Landsat Enhanced Thematic Mapper (ETM+) multispectral image (path 231/row 62, acquired on 07.10.2001); and d) digital elevation model from the Shuttle Radar Topographic Mission (NASA).

Drainage elements and topographic contours of the available topographic maps were manually drawn using a digitizing table and vector-data capture software, for qualitative comparison with SRTM data. Data obtained from the geological map of Brazil were superimposed on the DEM with the use of geographic information system (GIS) software for integrated analysis.

The Landsat ETM+ image was submitted to geometrical correction based on known ground control points (GCPs). The assessment of positional errors was carried out through root mean square (RMS) analysis, which resulted in a maximum error of 50 meters, compatible with the working scale. The geometrical correction of the image was performed with a warping technique. The final image was converted into UTM projection,

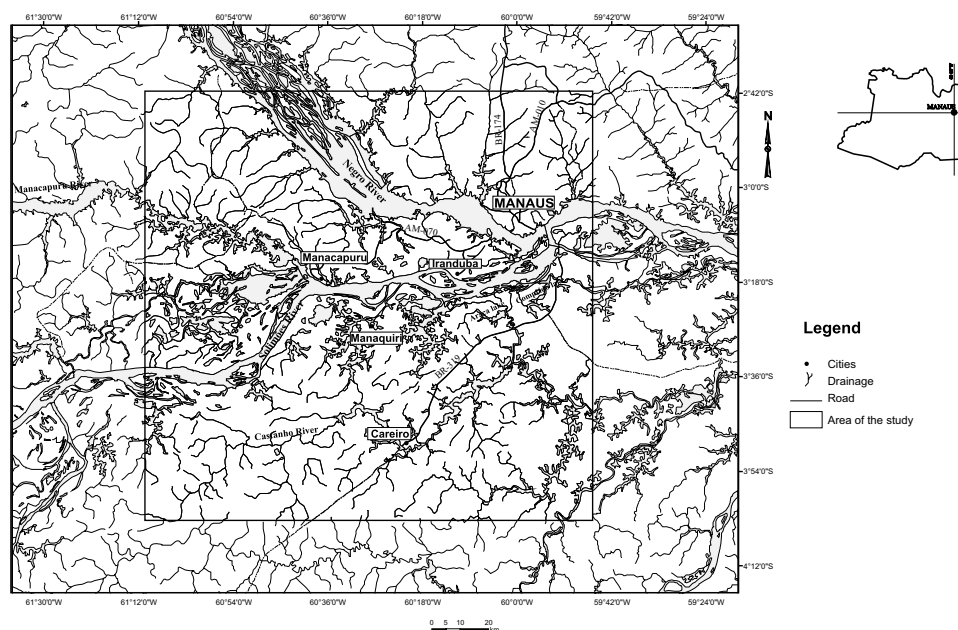


Fig. 1 – Map of the location of the study area (southwest of the city of Manaus).

zone 20. Lineament extraction and landscape/drainage interpretation were made from the geometrically corrected image, using a RGB (red, green and blue) color composition of bands 3, 4 and 5, and also individual bands 5 and 7.

SRTM data were obtained through NASA's website (<http://www.jpl.nasa.gov/srtm/index.html>). SRTM used two different radar systems: C band and X band. In the present study the C band data were used.

The original spatial resolution of SRTM data is 1 arcsecond, equivalent to 30 m on the ground. However, for strategic reasons (the mission was funded by the National Imagery and Mapping Agency, North-American military cartographical agency), SRTM data made available to the public for areas outside North America have a moderate spatial resolution of 3 arcseconds, equivalent to about 90 m. Even so, the quality of data is sufficient to generate 3-D models compatible to scales around 1:100,000, with horizontal and vertical accuracies of about 50 m and 12 m, respectively. This repre-

sents a significant advance for areas with limited altimetric data, such as the Amazon.

There are some limitations of InSAR technology for topographic surveys of vegetation-covered areas that must be taken into consideration. The main limitation is the ability of radar waves to penetrate into vegetation. For C band, radar penetration is only partial when the vegetation is dense. It must, therefore, be expected that the DEMs used in this work may not represent with fidelity the true ground surface topography of the study area, yet they may contain topographic values which are intermediate between the plant canopy's topography and that of the ground.

DEM processing included converting its cartographic projection, performing contrast enhancement by histogram adjustments and applying synthetic shading and 3-D visualization techniques. The altimetric contour lines were extracted from the DEM and compared with the available topographic maps. For the integration of the Landsat ETM+ image with the SRTM DEM,

the RGB+Intensity display technique was used, in which the DEM is allocated to the intensity channel whereas three spectral bands of the Landsat ETM+ image are allocated to the red, green and blue channels of the visualization display. In this way, the topography, given by the DEM image, modulates the pixel color intensity of each of the Landsat ETM+ bands used in the RGB color composite, producing an image in which the information from the DEM and the Landsat bands is fully merged.

The geomorphologic analysis comprised the identification and characterization of landscape elements indicative of modern tectonic deformations, such as linear features, fault scarps, formation of asymmetric terraces, low (modern deposition sites) and high (sites prone to erosion) blocks. Maps of lineaments and relief forms were generated to provide support for the interpretation. The principles of the relief analysis used in this study are based on Cooke (1990), Summerfield (1993), Stewart and Hancock (1994) and Keller and Pinter (1996). Analysis of the drainage network was based on recognition of drainage patterns associated with structural elements (weaving, parallel, rectangular, in chandelier patterns, among others), channel anomalies (anomalous meandering, rectilinear channels, etc.), formation of lakes and rivers with drowned valleys and drainage lineaments, associated to the Cenozoic tectonics. The drainage map was used for the interpretation of these features and for the extraction of drainage lineaments. Drainage analysis was based on Howard (1967), Ouchi (1985), Schumm (1986), Deffontaines (1989), Summerfield (1993) and Stewart and Hancock (1994), among others.

The maps obtained from the analysis of lineaments, relief forms and drainage network were integrated with SRTM DEM and Landsat ETM+ images used as a basis for field checking of the main interpreted features. The final results were integrated as a morphotectonic map, showing the tectonic compartments of the study region.

DATA ANALYSIS AND PROCESSING

In order to evaluate the precision of SRTM topographic data, a comparison was made with elevation contours obtained from the topographic maps Manaus SA.20-Z-D-III and Manacapuru SA.20-Z-D-II (Fig. 2). Most of the topographic contours on the existing maps corre-

spond to the 50 m level, being restricted to limited areas reaching up to 100 m in altitude (Fig. 2A). To the south of the Solimões River, there are only a few areas exhibiting 50 m contour lines, since the level of the Amazonian plain is generally lower than 30 m.

It is possible to generate topographic contour lines using SRTM data at any intervals, bearing in mind that these data have a theoretical error of about 12 m in height. However, a large number of contour lines would hinder the comparative analysis. Therefore, contour lines were generated at levels 35, 50 and 70 m (Fig. 2B), which are representative of the relief of the region and are within the theoretical error of the data. The 100 m level was excluded, since its occurrence is rare and does not represent any broad or significant surface. The generation of the contour lines relative to these levels was performed through automatic extraction and tracing using digital image processing software.

The comparison between map and SRTM elevations was done qualitatively, and the results showed that they were quite similar. Furthermore, the 30 m contour closely follows point values with this height shown on the maps. Therefore, the SRTM data were considered to be satisfactory and appropriate for performing the morphostructural analysis in the study region.

A synthetic directional shading filter was applied to the SRTM model represented in pseudo-color, for the purpose of enhancing the topography and landscape features (Fig. 3A). The azimuth and elevation values used in this synthetic shading may be varied interactively, enabling the selection of optimal combinations of azimuth and elevation values to enhance the desired morphological features. The best combination was found to be an azimuth of 62° and elevation of 53°, as shown in Figure 3B. This filtered image was used as the basis for the interpretation of the relief compartments and, from this interpretation, to infer the main brittle structures (fractures and faults) present.

GEOLOGIC AND TECTONIC CONTEXT

The study area is located along the Solimões-Amazon River system (Fig. 4), in the Amazon Palaeozoic Basin, where the following lithostratigraphic units crop out: Alter do Chão Formation (Cretaceous), Içá Formation or upper member of the Solimões Formation (Neogene),

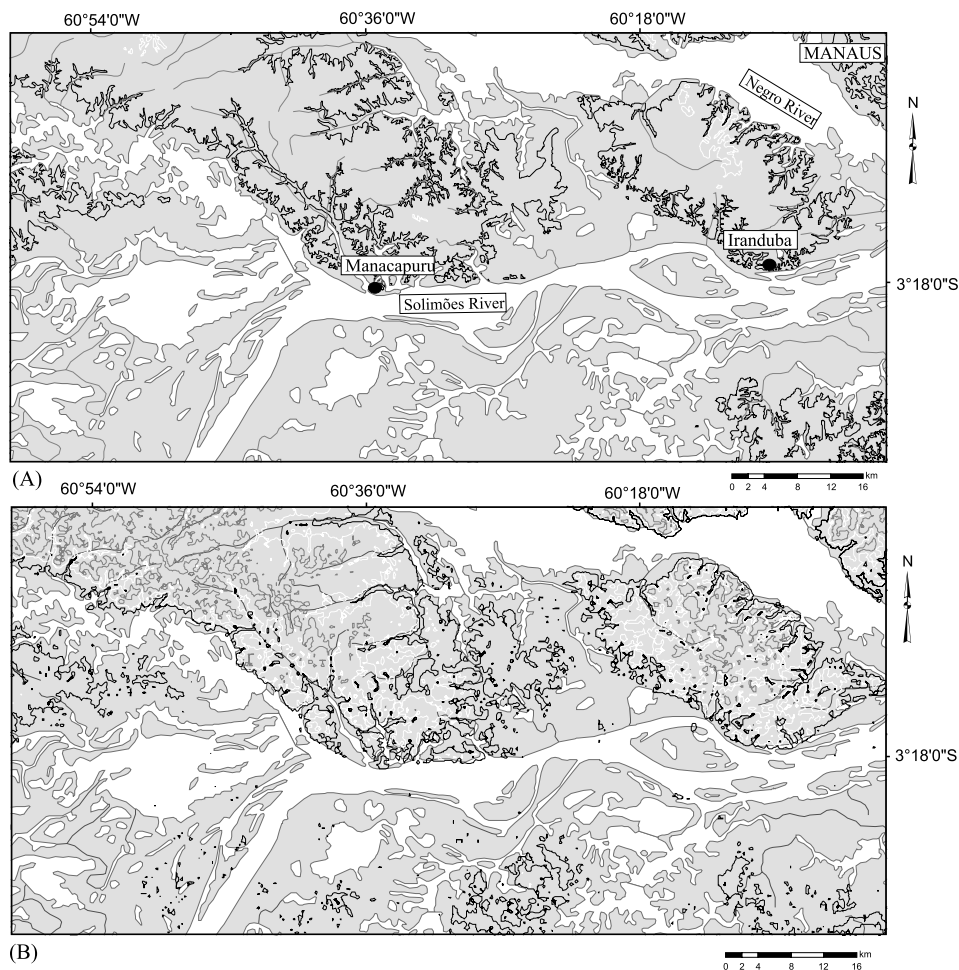
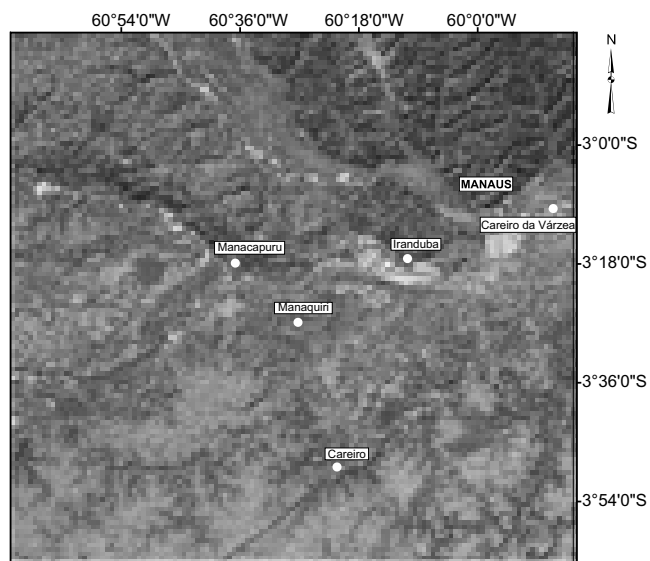


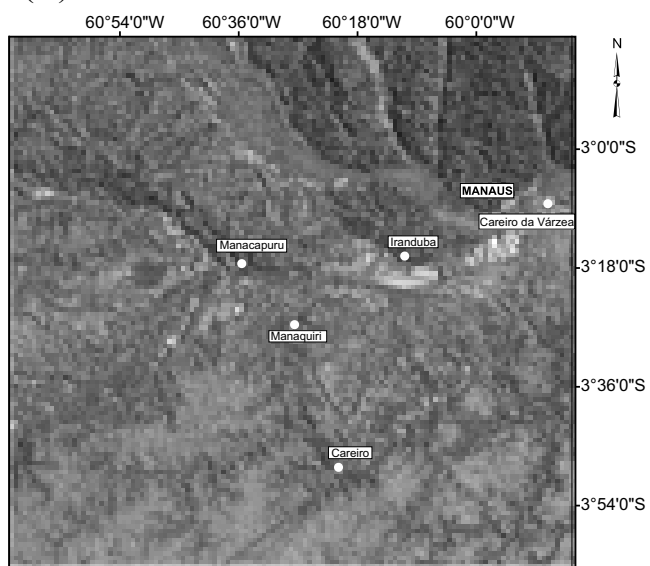
Fig. 2 – Comparison between topographical contour lines obtained from the 1:100.000 topographic charts (A) and those from the SRTM model (B). Contour lines of the topographic charts are at 50 m and 100 m and the ones from the SRTM model are at 35 m, 50 m and 70 m represented in black, white and gray lines, respectively.

and Quaternary sediments. The Alter do Chão Formation is constituted by kaolin-rich, fine to medium-grained red sandstone, locally displaying cross stratification (Caputo et al. 1971). It crops out in the northern part of the study area, at elevations between 50 and 100 m, near Manaus, Iraduba and Manacapuru. This formation has been deposited by a high-energy fluvial system, in hu-

mid climate, when the paleo-Amazon River (known as Sanozama) flew from East to West (Caputo et al. 1971). Dino et al. (1999), based on studies carried out in the region of Fazendinha and Nova Olinda, proposed a subdivision of this unit into a lower Sequence 1 (late Aptian to Albian), characterized by continental deposits formed by meandering fluvial systems that graded into braided



(A)



(B)

Fig. 3 – SRTM model of the southwestern region of Manaus (Amazon-Brazil). In (A) a synthetic shading filter was applied with azimuth 334 and elevation 58. In (B), with azimuth 62 and elevation 53, the latter used for enhancing the main morphostructural elements.

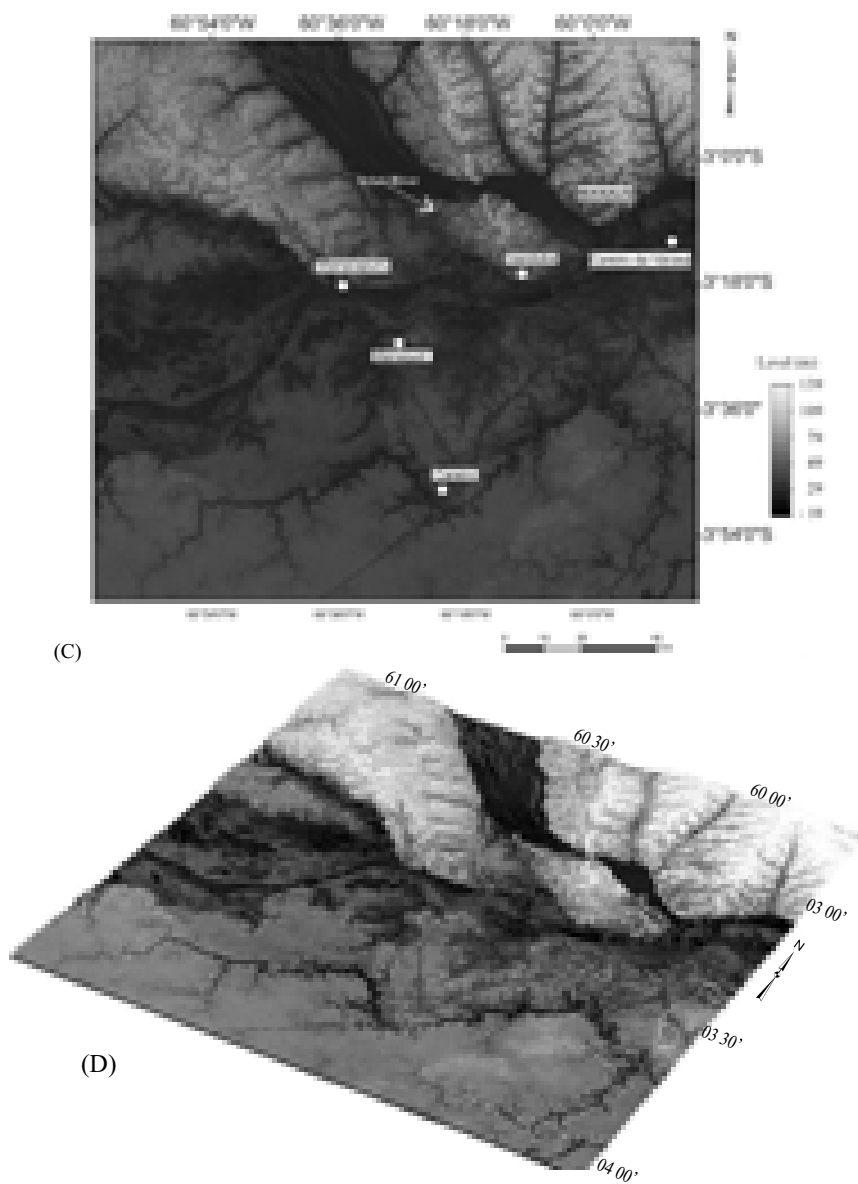


Fig. 3 – SRTM model of the southwestern region of Manaus (Amazon-Brazil). (C) SRTM model with the topographic contour lines (meters). (D) 3-D visualization of the SRTM DEM with a vertical exaggeration of 80 times.

system with eolian reworking; and an upper Sequence 2 (Cenomanian), deposited in a fluvial-deltaic and lacustrine prograding system.

According to the geologic map of Brazil (Bizzi et al. 2001), the areas located to the west of Manacapuru and to the south of the Solimões River are characterized by outcrops of the Içá Formation. This unit is unconformable with the Alter do Chão Formation and comprises interlayered sandy and muddy deposits, formed in an alluvial system. The occurrence of the Içá Formation in this region is controverse (controversial?), with many authors considering only the Solimões Formation (Costa et al. 1978, Lourenço et al. 1978). Rossetti et al. (2005) consider that the Içá Formation has a Plio-Pleistocene age, based on the fact that this unit overlies unconformably the Solimões Formation (Miocene).

Quaternary sediments occur along the Amazon River and its tributaries and consist of fluvial sand and mud formed in meandering bars, floodplains, crevasse splays, abandoned meanders and lakes setting (Nascimento et al. 1976, Costa et al. 1978, Latrubesse and Franzinelli 2002). In the southwest area of the city of Manaus, Latrubesse and Franzinelli (2002) recognized an ancient alluvial plain dominated by point bars, a barred floodplain and a floodplain dominated by channels along of the Amazon River. The ancient alluvial plain occurs in low, sandy terraces. The barred floodplain is characterized by a large area with lakes comprising mostly grey to grey-greenish and mottled (yellowish) mud exhibiting bioturbation and plant debris. Secondly, levees, crevasse splays and various delta systems occur. There is a predominance of the sand fraction in the channel-dominated floodplains, where the main features are channels, active sand bars, levees, inactive islands and a system of abandoned channels.

Quaternary sediments in the Ariáú River region, located between the towns of Manacapuru and Iranduba, comprise light grey to mid-grey sand and mud that locally intergraded with sand layers up to 1m thick. Soares et al. (2001) recognized three levels of terraces, related to the Paraná do Ariáú River, situated between 30 m and 50 m above sea level, interpreted as having being formed on subsiding blocks (Fig. 5). These resulted from tectonic processes associated to normal faults, as explained by Silva (2005). Three boreholes in this area indicated

a minimum thickness of 60 m for these Quaternary sediments (Silva 2005). Drainage patterns such as rectangular and trellis suggest a strong structural control (Howard 1967). Moreover, the landforms exhibit ruptures on the relief, rectilinear scarps, smooth surfaces and block tilting, being located on a lower topographical level.

Quaternary sediments in the Cacau-Pirêra area, located at the confluence of the Negro and Solimões rivers, consist of mud and cross stratified sand related to crevasse splays and abandoned channels. Those deposits occur in subsurface up to a depth of 20 m overlying the Alter do Chão Formation.

Several studies have proposed a tectonic control for the evolution of the Amazon River system in the study area during the Quaternary (Costa et al. 2001, Bemerguy et al. 2002, Igreja and Franzinelli 2002, Silva 2005). Other studies have also shown that tectonic processes were responsible for the formation of several Quaternary sediments along the Amazon River outside the study area (P.E.L. Bezerra et al. unpublished data).

Costa and Hasui (1997), applying the neotectonic model of Hasui (1990) for the Brazilian Platform, defined an E-W dextral strike-slip tectonic model for the Amazon region, after the opening of the Atlantic Ocean. This was reflected in Eastern Amazon by a Miocene-Pliocene and Quaternary tectonic episodes.

According to the relief classification proposed by Projeto Radambrasil (Nascimento et al. 1976, Costa et al. 1978), the Rio Trombetas-Rio Negro Dissected Plateau or Negro-Jari Plateau encompasses the Alter do Chão Formation. The area to the south of the Amazon River is included into the western domain of the Amazon Lowered Plateau and the Central Amazon Depression, and consists of the deposits of the Içá Formation (Bizzi et al. 2001). Finally, the Amazonian floodplain comprises the Quaternary sediments in the floodplain of the Solimões-Amazon rivers, at topographic levels up to 25 m.

MORPHOSTRUCTURAL ANALYSIS

The relief of the study area presents distinct characteristics in the northern, southern, and central portions. In the northern portion, which includes the towns of Manaus, Iranduba and Manacapuru, the relief is relatively high. It comprises well dissected, small to medium-

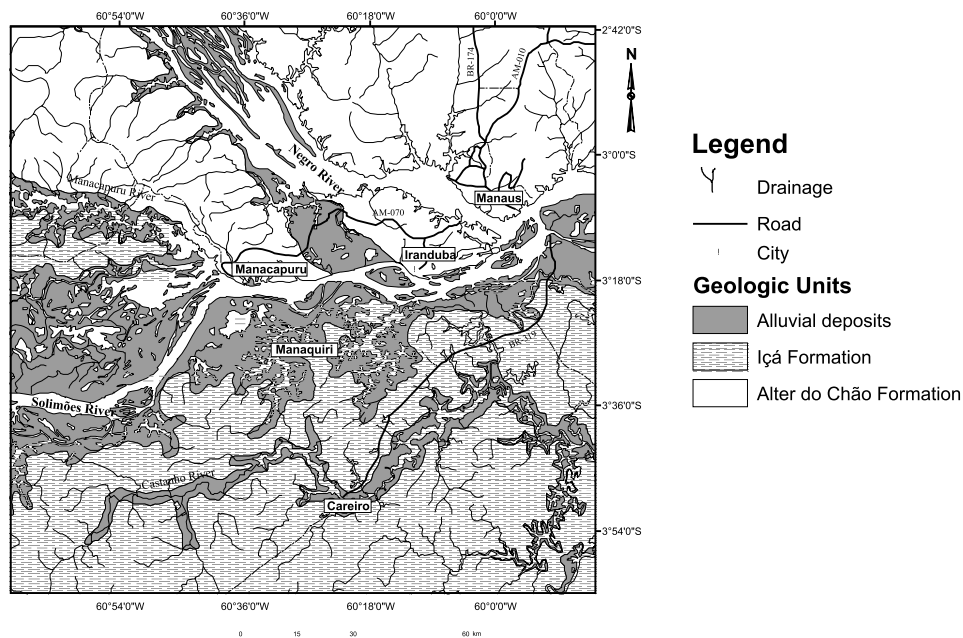


Fig. 4 – Geological map of the study region (1:2,500,000) according to Bizzi et al. (2001).

sized hills up to 100 m in height. To the north of Manacapuru, the relief is more preserved from erosion, with medium elevations (about 50 meters) and sub-horizontal tops. Close to the rivers, however, the relief changes to well-dissected and small forms, defining a characteristic topographic alignment (Fig. 3C). The Ariáú River region, between Iraduba and Manacapuru, includes a flat surface with levels not higher than 50 m, often flooded and covered by Quaternary sediments.

The region to the south of the Solimões River, in the central area, corresponds to the Amazon Lowered Plateau, and comprises the towns of Careiro and Manauquiri. Its relief is low (around 50 m), with flat and dissected tops and poorly-evolved drainage. In this region, the Castanho River marks the boundary between two lowered surfaces. On its left margin, on the outskirts of Manauquiri, heights are typically below 30 m, whereas the right margin exhibits altitudes between 30 m and 50 m. This configuration of the relief shows a gentle

unlevelling that may reach up to 20 m. Moreover, this surface is in the same level of the Solimões River plain, getting mixed up with terraces of the Negro River, Ariáú River and of the right margin of the Manacapuru River. This unlevelling between the two surfaces becomes more conspicuous when visualized through a 3-D model of the DEM with high vertical exaggeration (Fig. 3D).

The Solimões River floodplain comprises an area where the Quaternary sediments are distributed according to the migrations of the river's channel. The heights of the countless types of alluvial deposits (meander bars, natural levee, etc.), usually submerged under the rivers' high waters, do not exceed 25 m. The relief of this region shows a group of tectonic landforms: fault scarps, asymmetric valleys and terraces, depressions and anomalous drainage patterns (such as rectangular types, meandering forms, and drowned rivers). These features form an asymmetric relief arrangement, which includes structural highs and lows, found on several of the relief com-

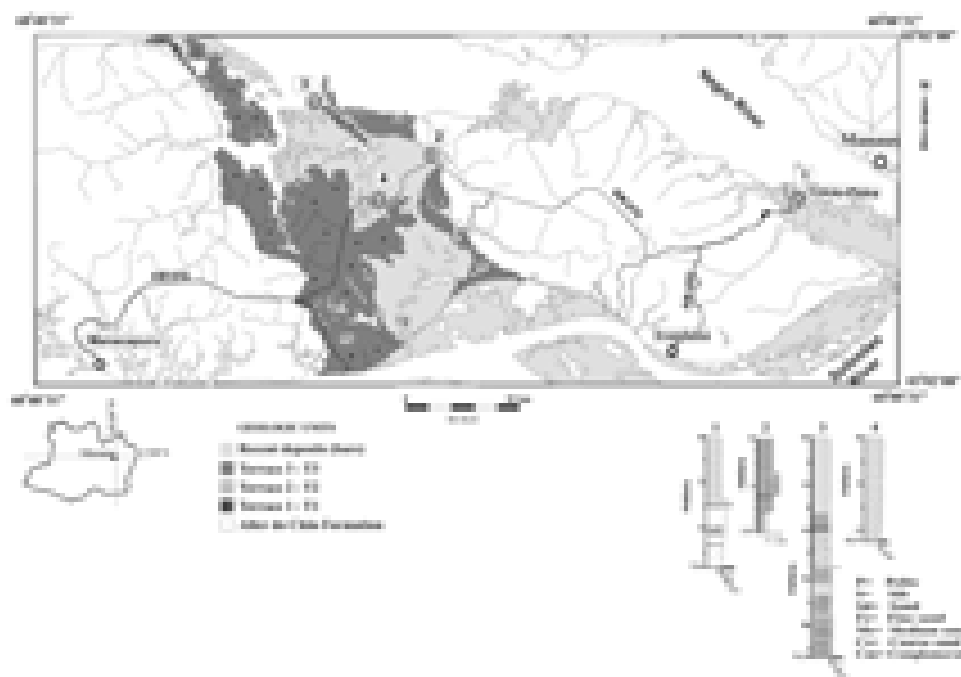


Fig. 5 – Geological map with the location of the Iranduba and Ariáú region with stratigraphic sections. Points 1, 2, 3 and 4 correspond to the respective sedimentological profiles. Modified from Soares et al. (2001).

partments that occur in the Amazonia Plain.

The Negro River Fault is an important structure mentioned by several authors, including Sternberg (1950), Andrade and Cunha (1971), and Igreja and Franzinelli (2002). This fault controls the margins of that river for more than 70 km and it is easily recognized on maps and satellite images as sets of rectilinear scarps on both margins of the river. Its extension may be noted in the western region of the Ariáú River, in the contact between the Quaternary sediments and the Alter do Chão Formation. It is possible that this fault extends towards the Careiro region, forming the various NW-SE lineaments seen in this region (Silva 2005). According to Cordani et al. (1984), the Negro River Fault is a possible extension of structures of the Amazonian Craton, suggesting that they were reactivated during the Palaeozoic and Cenozoic times (Fig. 6A e B).

In the Ariáú River region, some landforms suggest

the occurrence of block movements, such as parallel and rectangular patterns in the course of the Acajutuba River (right margin of the Rio Negro River), aligned confluence of tributaries and also the asymmetry of the drainage between the blocks (long and short segments). An example of drainage asymmetry is the anomalous trellis pattern of the Acajutuba stream, enclosed to the scarp of the Negro River (Fig. 6B). The parallel disposition of the watershed between the Acajutuba and Miriti streams and the asymmetric valleys of the Miriti and Manacapuru rivers, along the NW-SE direction, are associated to interfluvial zones on the relief.

Other NW-SE lineaments are observed in the Iranduba and Cacao-Pirêra region (Fig. 6B). These relief lineaments represent steep scarps with altitudes of about 50 m, similar to those located on the western limit of the city of Manaus, and are responsible for the rectangular geometry of the Iranduba area (Irlanduba Block). The

Irاندوبا Block is bounded by Cacau-Pirêra and Irاندوبا lineaments, forming the island where Irاندوبا is located. In the central portion of the block, the relief shows residual dissected hills with sub-horizontal tops that stand out in the landscape and may be visualized in the DEM (Fig. 3C and D).

Between the scarps of the Negro and Irاندوبا rivers there is a depressed region with altitudes up to 50 m, with terraces formed on Quaternary sediments, together with Quaternary sediments from the Ariáu River plain, both confined among Cretaceous deposits of the Alter do Chão Formation. In that sector, the Ariáu River, that links the Negro and Solimões rivers, lies asymmetrically on the plain due to the migration of the channel towards east. The asymmetry of the channels is also evident in the Acajituba River. Close to the scarp of the Negro River it presents a trellis pattern, as well as anomalous confluence of its tributaries. The depressed area is controlled by the Negro River's Fault. Farther west, in the region of Manacapuru, the homonymous river lies oriented NW-SE and presents asymmetric channels and drowned mouth (the Manacapuru lake). The morphostructural arrangement shows unlevelled areas, with strong relief asymmetry, characterized by tectonic landforms and drainage anomalies associated to the Negro River Fault.

Castanho River is the main tributary of the Solimões River in the southern portion, showing a rectangular pattern associated with ENE-WSW and NW-SE lineaments and drowned-type drainage anomalies (Figs. 3C, D and 6B). The extensive areas of still waters representing drowned rivers are called "lakes", such as the Castanho Lake. In this area, the formation of drowned channels is associated with relief lineaments, which in turn are responsible for the development of the rectangular pattern of the channels. The strong asymmetry of the tributary channels indicates that the surface is slightly lowered, dipping gently northward. Tributaries of the Castanho River also exhibit an arrangement parallel to the lineaments ENE-WSW. The rectangular drainage pattern observed in the Castanho River region is controlled by NW-SE lineaments (Fig. 6A).

Along its fluvial plain, the Solimões River shows straight segments with former bar and meander situated in asymmetric positions (Fig. 6B). To the southwest of

Manacapuru, the river suddenly changes its course from E-W to NNE-SSW, for nearly 50 km. That region embraces a wide low area, with a flat relief which does not surpass 27 m, dominated by a series of lakes, such as the Cabaliana, Padre, Sacambu and Manacapuru, as well as present and ancient bar deposits of the Solimões River. The boundaries of the alluvial plain sediments are marked by NE-SW and E-W relief lineaments.

This extensive lowered region narrows down near Manacapuru, where the river suddenly changes the direction of its course. P.E.L. Bezerra et al. (unpublished data) mentioned the existence of a series of tectonic depressions which control the Quaternary sedimentation along the channel of the Solimões River. Silva (2005) described several strike-slip and normal faults and transtensive tectonic basins along the left bank of the Solimões River between Coari and Manaus. Among these basins, the Manacapuru pull-apart basin stands out, with its peculiar rhombohedral form.

In the stretch between Manacapuru and Manaus, the Solimões River follows an approximate E-W course for about 70 km (Fig. 6B). In that stretch the river shows evidences of erosion in both, the meander bars and the deposits from the Alter do Chão and Içá formations. Thus, an area with a wide and another with a narrow floodplain becomes evident along the river. The paleogeographic reconstruction shows that the Solimões River presented an E-W orientation on this entire sector, possibly with meandering characteristics. Through the analysis of SRTM and Landsat images, a lineament map was produced (Fig. 6A), showing the relationship between the morphostructural anomalies and main structural features (Fig. 7).

In Figure 7 a conspicuous set of lineaments can be observed in the older units (Alter do Chão and Içá formations), showing an even distribution in four directions (NE-SW, NW-SE, E-W and N-S). The analysis of these lineaments reveals that they represent sheaves or fracture zones. The E-W fractures are the most frequent ones and have also longer accumulated length, in spite of presenting no significant landscape elements. Fractures along N50E and N30-60W are frequent, whereas those in the N-S direction are less so. The coincidence of the mapped fracture systems with the described tectonic landforms allowed the characterization of conspic-

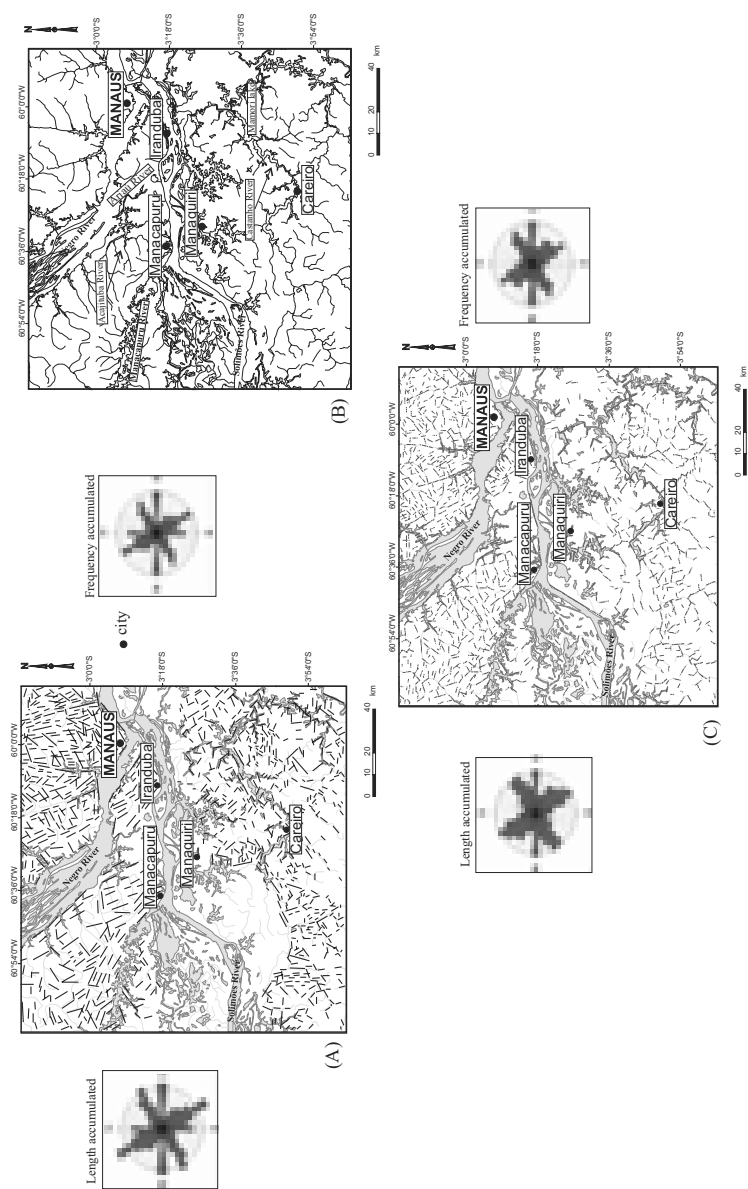


Fig. 6 – (A) Relief lineament map obtained from the analysis on Landsat ETM + image with rose diagrams (accumulated frequency and length). (B) Drainage lineament map with rose diagram.

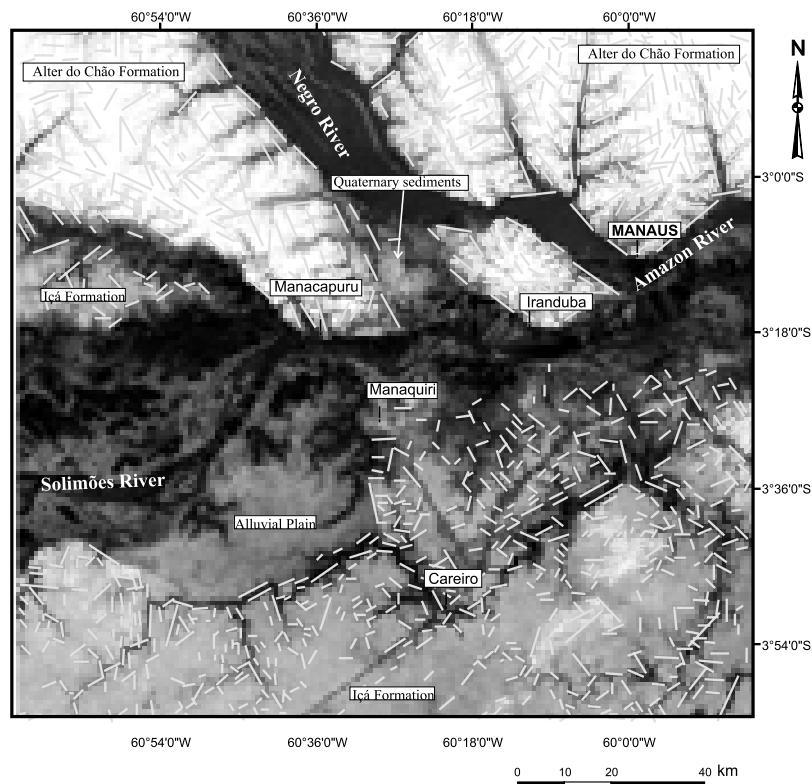


Fig. 7 – Relief lineaments overlaid to the SRTM DEM.

uous tectonic lineaments along different directions. In the NW-SE direction the interpreted lineaments were named Manaus, Cacao-Pirêra, Iranduba, Negro River, Miriti, Manacapuru River and Manaquiri. Along NE-SW the lineaments are: Castanho River, Castanho River-lake Mamori, Acajituba and Solimões River (Padre lake). Finally, along E-W the lineaments are: Paricatuba, Manacapuru-Iranduba, lineaments of Careiro and southern Castanho River (Fig. 8).

Morphostructural features along the NW-SE direction comprise fault scarps, aligned interfluvies, asymmetric patterns of the channels and the linear course of the Negro River. They confirm that this river is controlled by a normal fault zone, as suggested by Silva (2005). This is also the case of the Quaternary sediments

at low topographical level, thought to be tectonically-controlled by normal faulting associated with the Iranduba, Cacao-Pirêra and Manacapuru lineaments. Some authors referred to the Negro River region as “the Negro River *Graben*”, later interpreted by Igreja and Franzinelli (2002) as a northeasterly tilted hemi-graben. However, these authors analyzed the supposed graben only along the margins of that river. The evidence presented in this work indicates that this lineament comprises a set of normal faults, which extend beyond the margins of the Negro River until the Ariáú River region, forming graben and horst structures.

The structure (R.N. Damião et al., unpublished data) that led to erroneously suggest this feature to be a dome corresponds to a fault scarp approximately parallel to the

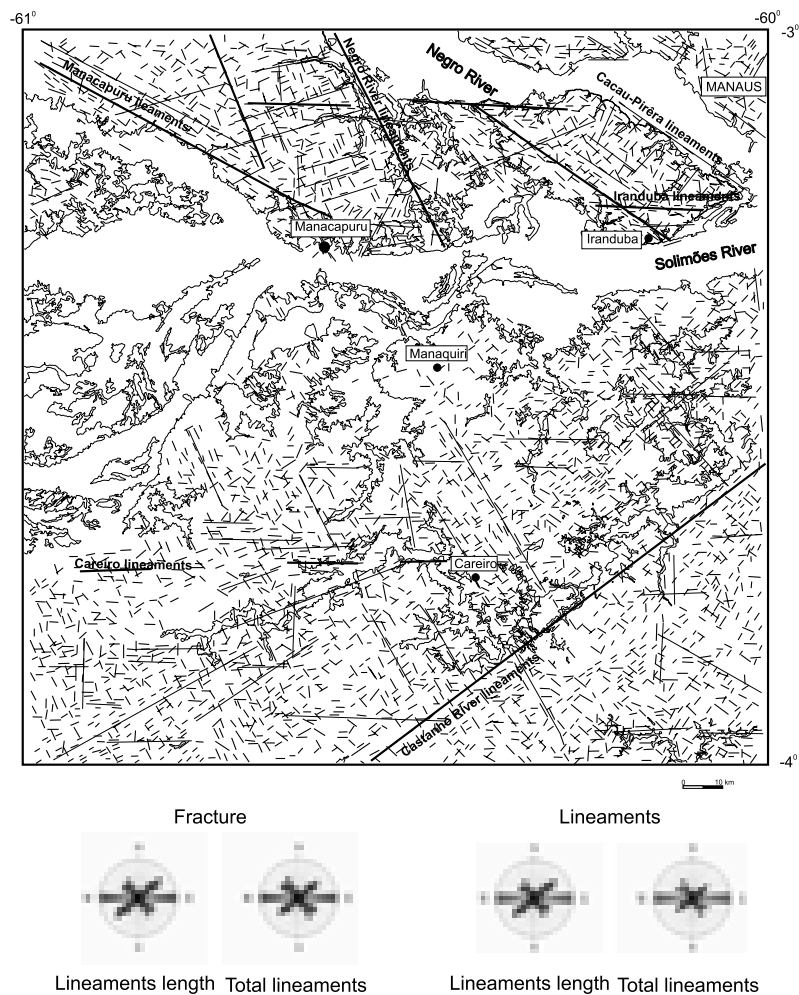


Fig. 8 – Lineament map of the study region from the integration of relief and drainage features obtained from Landsat TM images. Rose diagrams show the directions of the lineaments.

left edge from the Negro River fault. The extension of this structure may be observed further north, in the region of the Cuieiras River.

The NE-SW lineaments seem to have imposed significant control on the deposition of Quaternary sediments along the straight segments of the Solimões River.

Furthermore, these lineaments show up as remarkably dissected zones, as in the Manacapuru region. In the region located south of the Solimões River there is a subsiding area associated with normal faults. Previous work by Igreja and Franzinelli (2002) and Silva (2005) referred to these NE-SW lineaments respectively as

transference, normal and dextral strike-slip faults. Those authors showed that these lineaments are associated with a strike-slip system.

The E-W and N-S lineaments are more difficult to characterize because their morphostructural expression does not indicate the associated kinematics. The most significant E-W feature is the Paricatuba lineament, representing the northern boundary of the Ariáú River. In addition, other E-W lineaments may be seen cutting the topography in the region of Manacapuru and Iranduba and in the south of the Careiro region (Fig. 8). The N-S structures are less expressive, represented by scarce sets of lineaments on the region west of Manaus, in Manacapuru and east and west of Careiro. Based on the regional tectonic model proposed by Hasui (1990), E-W faults have been interpreted as dextral strike-slip faults, whereas those along the N-S direction as normal faults dipping to the west (Igreja and Franzinelli 2002).

As a result of the morphotectonics analysis presented here, three tectonic compartments were recognized in the study area (Figs. 8 and 9). The first compartment comprises the northern portion of the area, encompassing the cities of Manaus, Iranduba and Manacapuru, and includes the asymmetric graben of the Ariáú River (Fig. 9A and B). The western limit of this graben is represented by the scarp of the Negro River Fault scarp, coinciding with the contact between Cretaceous and Quaternary units.

The second morphotectonic compartment is located on the right margin of the Solimões River and corresponds to the area with flat relief and rectangular drainage patterns. This compartment is marked by relief lineaments and aligned drainage channels following the NW-SE and NE-SW directions. The lineaments along these two directions induce a parallel arrangement of the drainage and relief, such as the fault scarp of Castanho River and portions of the watersheds of its tributaries. They also control stretches of that river and produce conspicuous drainage anomalies. The development of a typical rectangular pattern and the remarkable relief asymmetry, marked by escarpments, point out to the existence of two blocks unlevelled by about 30 m, similar to the Ariáú depression. The morphostructural features associated with this compartment also include anomalous parallel drainage patterns, drowned portions of Castanho and

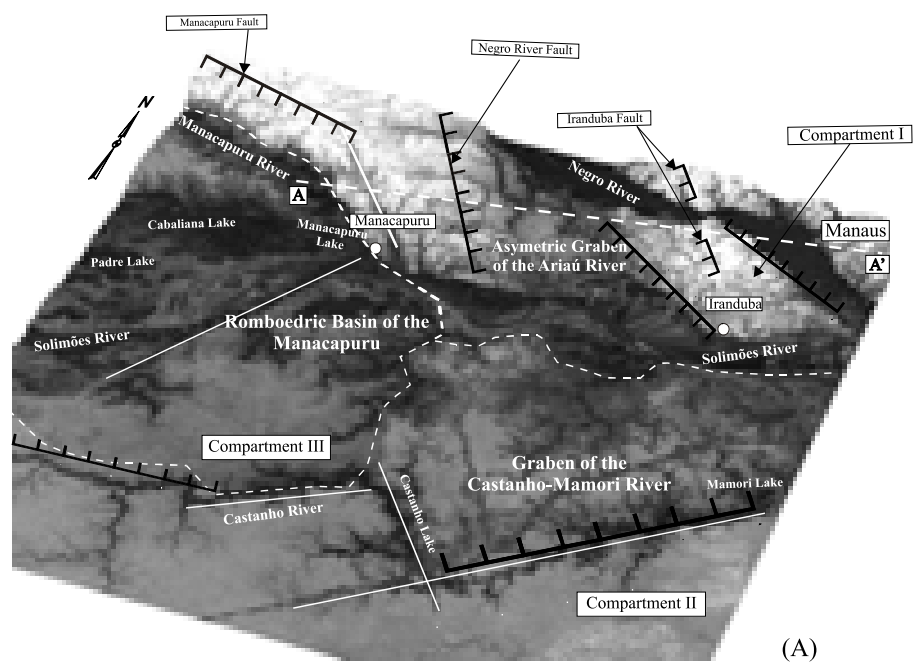
Mamori lakes, anomalous bends and channel asymmetry (Fig. 9A). The relief elements and drainage anomalies show a significant structural control of the present alluvial sedimentation. The extensive abandoned deposits on the left bank of the Solimões River result from the migration of the channel from NW to S-SE leading to the present asymmetric position.

The third compartment is located west of Manacapuru and is represented by the alluvial plain of the Solimões River. That area comprises part of the Purus Rhombohedral Basin localized in western of this region (Silva 2005).

The paleogeographic reconstruction shows that the Iranduba region, bounded by the Cacau-Pirêra and Iranduba lineaments, was once part of the left margin of the Negro River (Fig. 10A). The ancient channel of the river was probably narrower and flowed along the Ariáú depression and, from there, into the Solimões River (Fig. 10B). The proto-channel of the Negro River opened by normal faulting that formed the Negro River Graben. This process made possible the development of sedimentation at the confluence of the Negro and Solimões rivers, where the Ariáú River is situated today. The continuous movement of the E-W binary produced the NW-SE faulting observed west of Manaus and at Cacau-Pirêra and Iranduba, resulting in the formation of fault scarps (Fig. 10C). Normal faulting generated an opening into which the Negro River was captured, thus changing its flow direction from south to east and south-east, abandoning the channel where the Ariáú river currently lies (Fig. 10D). This E-W lineament played an important role in the capture process observed in this area. The presence of ancient bar deposits indicates that the Solimões River had meanders and was probably orientated towards E-W, as currently seen between Manacapuru and Manaus (Fig. 10E). The migration of the Solimões River towards southeast would be the result of tectonic processes, associated with the formation and evolution of the Manacapuru Rhombohedral Basin (Fig. 10).

CONCLUSIONS

The main tectonic compartments of the western Amazon Basin near Manaus were interpreted by means of morphotectonic analysis, supported by orbital InSAR (SRTM) and optical (Landsat ETM+) images and field



Schematic geologic section A - A'

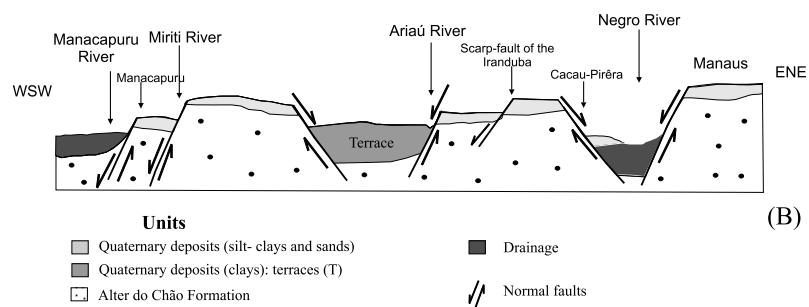


Fig. 9 – (A) 3-D model (vertical exaggeration of 80 times) with the main morphotectonich compartments of the region to the southwest of Manaus. (B) geological section (without scale) between compartments I and II.

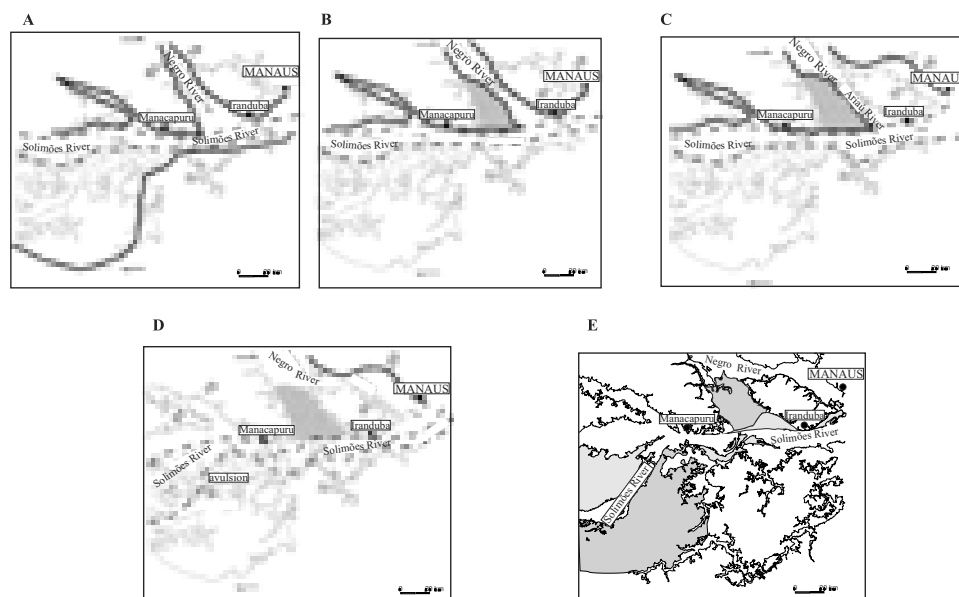


Fig. 10 – Paleogeographic model of the study region. In (A) the first stage where the Negro River passed into the region of the Ariáú River. (B) The normal fault of the Negro River (left margin) evolved also on the right margin enlarging the basin (C). The diversion of the Negro River to the east was the result of E-W fractures, following the fulfillment of the channel at Ariáú; (D) The E-W Solimões River formed meanders in the western portion. (E) The last stage shows the current morphology of the region.

observations. The combination of modern remote sensing technologies and three-dimensional visualization tools enabled a detailed characterization of the relief and drainage patterns of this region, unveiling subtle terrain features related to Cenozoic tectonics of the western Amazon Basin. The tectonic compartments were named Ariáú Graben, Castanho-Mamori Graben and Manacapuru Basin.

The Ariáú Graben corresponds to an asymmetric depression, where unlevelled Quaternary deposits are bounded by the NW-SE Negro River Fault. Morphostructural features recognized in association with the Ariáú Graben, include terraces, fault scarps, drainage asymmetry and anomalies, such as rectangular and trellis patterns, beheaded stream and drowned rivers.

The Castanho-Mamori Graben is a NE-SW rectangular asymmetric feature located at the right margin of the Solimões River. Its main tectonic boundary is

the Castanho Fault, also orientated towards NE-SW and plunging NW, controlling the course of the Castanho River. Morphostructural features recognized in association with this graben include relief anomalies, such as fault scarps of the Castanho River, rectangular drainage patterns and drowned rivers which formed Mamori, Castanho and Janauacá lakes. These features are interpreted mostly as the result of faulting along NW-SE, NE-SW and N-S, represented by the relief and drainage lineaments along the same directions.

The Manacapuru Basin corresponds to the depression where lake Cabaliana-Padre was formed and depicts a rhombohedral geometry. It is bounded to the north and south by E-W strike-slip faults and to the east and west by NE-SW normal faults, plunging NW and SE. In this area, the sudden change of the course of the Solimões River is caused by faults, marking the boundary of the Manacapuru Basin.

The results presented in this paper strengthen the important role of neotectonics in controlling the fluvial morphology and sedimentation processes of the western Amazon Basin. The configuration of relief patterns and drainage networks, as well as the spatial distribution and characteristics of Quaternary sediments in the region located southwest of Manaus, are unmistakably associated with the Cenozoic tectonic compartments here defined.

ACKNOWLEDGMENTS

The authors would like to thank the Dr. Giorgio Basili of the Universidade Estadual de Campinas, who reviewed parts of the manuscript. A.P. Crósta and N. Morales acknowledge Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for research grant 305203/2003-7 (APC) and 307526/2003-8 (NM).

RESUMO

Uma investigação do controle tectônico da morfologia fluvial e dos processos sedimentares de uma área localizada a sudoeste da cidade de Manaus, na Bacia do Amazonas, foi conduzida a partir do uso de dados de sensores remotos orbitais. Nessa região, o baixo gradiente topográfico representa o principal obstáculo para a análise morfotectônica usando métodos convencionais. O uso de dados de sensores remotos pode contribuir significativamente para superar essa limitação. Desse modo, dados de sensoriamento remoto, compreendendo modelo digital de elevação (DEM) obtido pelo Shuttle Radar Topographic Mission (SRTM) e imagens Landsat TM, foram utilizados para essa investigação. Técnicas avançadas de processamento de imagem foram empregadas para realce de imagens topográficas e sua elaboração tridimensional, permitindo desse modo, a interpretação dos elementos morfotectônicos. Isso permitiu o reconhecimento de principais compartimentos tectônicos, diversas feições morfoestruturais e formas de relevo relacionadas à evolução neotectônica dessa porção da Bacia do Amazonas. Feições como escarpas de falha, padrão anômalo na drenagem, alinhamentos de relevo, vales e divisores d'água foram realçados nas imagens como notáveis lineamentos ao longo das direções NE-SW, NW-SE, E-W e N-S. Essas feições foram associadas à geometria de estruturas do tipo horste e gráben alternados, este último preenchido por unidades sedimentares recentes. A interpretação morfotectônica usando essa técnica mostrou-se eficiente e permitiu o reconhecimento de novas feições tectônicas as quais foram denominadas de

Gráben Assimétrico Ariaú, Bacia Romboédrica de Manacapuru e Gráben Castanho-Mamori.

Palavras-chave: morfotectônica, morfoestrutura, neotectônica, Bacia do Amazonas.

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