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Paleodrainage Systems and Connections to the Southern Lacustrine Belt applying Remote Sansing Data, Amazon Coast, Brazil.

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ABSTRACT

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Paleodrainage systems mapped in many regions worldwide reveal important inactive fluvial systems that indicate changes in morphosedimentary, tectonic and environmental processes in different time scales. Two paleodrainage systems were identified north of the Amazon River mouth, associated with the Southern Lacustrine Belt at Cabo Norte. The analyses were performed using data from orbital remote sensors, validated by field information and overflights. The paleodrainage systems show predominant North-South (N-S) and Southwest-Northeast (SW-NE) directions. The N-S system may be connected to an ancient Pleistocene coastline. The SW-NE system is younger, with the same direction as the current river courses and is associated with the genesis of the Araguari River. The paleodrainage alignments of this system in the Northwest-Southeast direction (NW-SE) show the same direction as tectonic lineaments presented from the basement to the continental shelf. The identified paleodrainage systems indicate significant changes in the regional drainage of the Amazonian coastal plain and indicate intense riverbed aggradation processes, which may be associated with neotectonic movements and relative sea level variations during the Quaternary. These are important indicators for the understanding of environmental changes during the Late Pleistocene and Holocene, and may aid in the paleogeographic reconstitution of the Amazon river mouth.

ADDITIONAL INDEX WORDS: *lake, evolution, Amazon mouth, Amazon coast.*

INTRODUCTION

The concept of paleodrainage is associated with large-scale changes in fluvial systems (Conti, 2012). The deactivation of these systems is due to broader environmental processes (Horton, 1945; Bloom, 2004) such as base-level variations, morphosedimentary processes (Conti, 2012), climate changes and tectonics (Benvenuti *et al.,* 2008; Hayakawa *et al.,* 2010; Ghoneim, 2012).

These processes do not always occur as isolated events, and involve changes in the sedimentary supply, topographical and geological configurations, local and regional climate and vegetation cover (Conti, 2012). In the case of meandering rivers, stream diversion leads to oxbow lakes and abandoned meanders (Yang *et al.,* 2015).

Remote sensing data (digital elevation models (DEMs) andoptical and radar sensors) have been widely applied in several regions worldwide for the identification and analysis of paleoenvironmental changes in paleodrainage systems (McCauley *et al.,* 1986; Yang *et al.,* 2015; Paillou *et al.,* 2007; Paillou *et al.,* 2012). However, most of these studies were conducted in arid and semi-arid regions.

In tropical environments with large rivers, such as the Congo and Niger basins (Goudie, 2005; Stankiewicz and Wit, 2006) and the Ganges river basin (Gupta, et al., 2014), studies indicate connections between paleodrainage evolution and the formation of lacustrine systems. In tropical regions of South America, the few studies available are concentrated along the Amazon River system, which is marked by numerous paleodrainages associated with neotectonic processes, resulting in several fluvial captures (Almeida Filho and Miranda, 2007; Hayakawa *et al.,* 2010; Plotzki *et al.,* 2013).

A paleoestuarine system with several paleodrainages located at the Amazon River mouth, in the Marajó archipelago, was recognized by Rossetti *et al.,* 2010 and attributed to the Late Pleistocene. Large paleodrainage systems stand out north Amazon River mouth, concentrated in the North Cape region (Boaventura and Narita, 1974; Silveira, 1998; Jardim *et al.,* 2015). The Late Pleistocene paleodrainage systems located near the coastal plain limit of the crystalline basement indicate the existence of high sea levels between 120,600 and 23,150 years BP (Bezerra *et al.,* 2015). Holocene paleodrainage systems (Silveira, 1998; Jardim, 2015) are distributed throughout the floodplain, influenced by tides (Santos *et al.,* 2009a), and include recent deactivation in the 19th century (Silveira, 1998). These paleodrainage systems indicate significant changes in regional drainage processes due to riverbed aggradation (Boaventura and Narita, 1974), local tectonic and neotectonic movements (Silveira, 1998; Costa *et al.,* 2013), relative sea level variations during the Quaternary (Silveira, 1998; Mendes, 1994)

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and probable relations with significant changes in the Amazon River (Discroll and Karner, 1995).

The evolution of the paleodrainages located in the North Cabe region originated large and complex lacustrine systems (Boaventura and Narita, 1974), connected to the Araguari river floodplain north of the Amazon River mouth. These lacustrine systems were subdivided by Silveira (1998) into three belts: the Southern Lacustrine Belt (SLB), the Eastern Lacustrine Belt (ELB) and the Western Lacustrine Belt (WLB). However, the morphogenesis relationships of lacustrine systems and paleodrainages with the current drainage network have not yet been adequately clarified.

In this context, this study aims to clarify the origin of SLB paleodrainages, constituted by Botos, Comprido de Cima, dos Ventos, Lodão, Mutuco and Comprido de Baixo lakes (Figure 1A, B). The results may aid in understanding the geological and geomorphological framework and paleogeographic reconstruction of the Amazon River mouth region.

METHODS

A mosaic of airborne radar images (X-band) from the Goodyear Mapping System 1000 (GEMS-1000) was used herein, as well as six scenes from the Phased Array type L-band SAR/Advanced Land Observing Satellite (PALSAR/ALOS) orbital radar, and Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM). In addition, a scene (path/row 225/059) from the Land Remote Sensing Satellite (LANDSAT 7), Enhanced Thematic Mapper Plus (ETM +) sensor was also used. Collateral and ancillary information from field work and previous database were applied for remote sensing data interpretation.

Filtering

The Enhanced FROST adaptive filter (Frost *et al.,* 1982) was used to enhance the morphological features and attenuate the effect of speckle noise of ALOS PALSAR images. One of this filter´s characteristics is the fact that it preserves the average value of the homogeneous areas, maintaining an adequate signal-to-noise ratio while preserving the edge structure of radar images. A 3x3 pixel window size used was chosen, since it presents superior performance for the preservation of the morphological features of the region, as applied by Jardim et al. (2010).

Mosaic construction and co-registration

The PALSAR/ALOS images were mosaicked by using six scenes, applying the nearest neighbour interpolation method. The mosaic elaborated by Silva *et al.,* (2011) was used for the GEMS-1000 data.

The PALSAR/ALOS and GEMS-1000 images were co-registered using the LANDSAT 7 ETM+ satellite (225/059) and the mosaic pixels were resampled to 30 m, in order to assume the same spatial characteristics as the base image. The root mean square error (RMSE) did not exceed 1 pixel (Table 1).

Multi-sensor analysis and photointerpretation

All remote sensing data were set using the Universal Transverse Mercator (UTM) system and WGS84 Datum, integrated into a Geographic Information System (GIS), in which the overlay, correlation and analysis of the interpreted features of the images was performed. The features were extracted manually in the form of vectors, applying relief feature photointerpretation principles (Guy, 1966). Information on texture, colour and context relationships were considered according to Jensen's (2009) guidelines for the interpretation of the optical sensor scene features.

Concerning the radar images, texture, geometry, hue and pattern elements were used. DEM/SRTM data were used in order to highlight variations regarding the relative height of the terrain, and a colour palette at 1 m intervals was applied.

Relative chronology and morphometric measurements

A relative chronology was used to trace the events responsible for paleodrainage formation. The identified paleodrainages were sequentially by chronological priority. Each paleo-feature alignment was numbered in ascending order, from oldest to newest.

The paleo-feature alignments can be found from the contact of the coastal plateau and the hill units of the crystalline basement to the coastal plain, towards the current coastline. Most alignments are discontinuous, forming multiple segments.

Morphometric measurements concerning the maximum and minimum paleodrainage lengths and their widths were carried out, in order to estimate the dimensions of ancient riverbeds and compare them with the current rivers in the region. Subsurface data from 3 and 12 kHz seismic profiles were applied for channel depth estimation.

RESULTS

The identified paleodrainage systems cover an area comprising approximately 823 km², with two preferred directions: N-S and SW-NE.

N-S Paleodrainage System

This system is embedded in two terraces, at approximate topographic altitudes of 30 m and 10 m (Figure 2A), presenting three well-defined and poorly-segmented alignments (L1, L2 and L3). The paleodrainages comprising this system are located between the coastal plateau to the west and the coastal plain to the east, encompassing the Botos and Comprido de Cima lakes. They display a maximum length of approximately 36 km and a width of up to 4 km. In the northern portion, the paleodrainage alignments follow the lake borders, while in the Southern portion they reach near the left Araguari river margin (Figure 2B).

L1 is located at the contact between the plateau and the coastal plain, with a maximum length of 23 km. It marks a terrace at approximately 20 m in altitude on the left bank of the Botos Lake (Figure 2B), which is confined to a depression between alignments L1 and L2 (Figure 2A, B).

L2 is located between Botos Lake and Comprido de Cima Lake, on a terrace at approximately 10 m in altitude, with a maximum length of 36 km. This alignment defines the west border of Comprido de Cima Lake (Figure 2B).

L3 comprises an lenght of approximately 30 km. In the southern portion, near the Araguari River, the alignment deflects SW towards L2, following the same direction of one of the meanders of the current Araguari river. In the northern direction, the alignment plunges SE-NW, towards the edge of a small lake, where it loses its continuity (Figure 2B). Subsequently, this alignment borders the east margin of Comprido de Cima Lake.

SW-NE Paleodrainage System

The paleodrainages of the SW-NE system are more extensive and numerous than those of the N-S system. Their features are entirely inserted on the coastal plain (Figure 3A) and are distributed from the eastern part of the Comprido de Cima Lake, bordering the Lodão and Mutuco lakes, extending to the extreme northeast of the area. Five alignments (L3, L4, L5, L6 and L7) are noteworthy in this paleodrainage system, all continuous, with maximum length up to 45 km and maximum width of 3 km.

L3 begins at the N-S system, extends throughout this system and corresponds to the first alignment of this set of paleodrainages. It originates in the southwest portion, between the Comprido de Cima and Mutuco lakes, following a straight line, forming a westbound curve to dos Ventos Lake. Subsequently, this alignment follows in a straight line towards the northeast when near Lodão Lake. At this point, another parallel alignment also appears, identified as L3, which could define another margin of this paleodrainage, bordering the western portion of the Lodão Lake (Figure 3A). Several segments of this alignment were recorded at the northeastern end of the area (Figure 3C). A smaller secondary system in a NW-SE direction truncates this alignment in its west portion.

The paleodrainage segments of the L4 alignment begin in the southwest region of Mutuco Lake, with two parallel paleomeander features, with a maximum length of about 28 km. These alignments define the oxbow feature of Mutuco Lake (Figure 3D). In the NE direction, both alignments converge, meandering alignments and isolated meanders (Figure 3A, C).

L5 is located between the Mutuco and Comprido de Baixo lakes (Figure 3A, D), with approximately 9 km in length. The alignment is marked by two curved and isolated segments bordering small isolated and elongated lakes with a W-E direction (Figure 3D), present east of Mutuco Lake.

L6 is located in the NE portion of the analysed area, approximately 20 km in length. The segment of this alignment is straight, forming isolated meanders as it moves in the NE direction. At the end of the segment it straightens out again (Figure 3A, C). Like alignments L4 and L5, it borders a series of small residual lakes arranged in an E-W direction, comprising an area from 2 to 20 km². These lakes are located in more humid areas on the coastal plain, where the radar images show a slightly darker tone (Figure 3C).

L7 is formed by two parallel segments in a SW-NE direction, almost 10 km in length, which define the two margins of a paleodrainage (Figure 3A, D). These alignments are intercepted by the Comprido de Baixo Lake.

DISCUSSION

The results of this work indicates the existence of two paleosystem in the studied region.

Paleosystem I Pre-Araguari

The N-S paleodrainage system is probably associated with an ancient coastline oriented in that direction, defining the contact between the crystalline basement and the coastal plain. This paleo-coast follows the same orientation as the regional alignments.

The L1 alignment would represent evidence of an older primary coastline, currently marked by an inactive cliff built at the plateau margin (Figures 2A, B). This cliff would mark the paleo-coastline assembled during the Holocene transgression, at approximately 7,000 years BP (Silveira, 1998). Bezerra et al., (2015) evidenced the existence of a Late Pleistocene unit (Itaubal Formation). This Formation constitutes part of the plateau and hill relief (Figura 2A). The relative positioning of this geological formation and the morphological features found in this study corroborate the Holocene age for the N-S system. Radiocarbon dating carried out at the base of core samples by Jardim (2015) determined an age of approximately 8,000 years old at the top of the paleodrainage sequence.

The genesis of the Paleosystem I Araguari would be associated with the same event responsible for the change of direction of the Tartarugal paleo-river, as described by Silveira (1998) (Figures 2A, B). This event was responsible for the obstruction of the mouth Rivers that flowed cutting off the crystalline basement in the W-E direction. Probably, changes in the base level created the N-S direction drainages (Figure 2B) cutting off the previous drainage E-W system in the Pleistocene.

The deactivation of the Paleosystem I (N-S) left as a record the Botos and Comprido de Cima lakes, whose alignments cross the current left margin of Araguari River. Thus, these lakes could be related to another older fluvial system other than the Araguari River. Thus, the mentioned lakes would not constitute records for the migration of the Araguari River, as proposed by Boaventura and Narita (1974).

Paleosystem II Araguari

The Paleosystem II was part of an ancient meandering drainage system, probably active in the Holocene.

The alignments of continuous paleodrainages in a SW-NE direction indicate a lateral migration from NW to SE (Figure 3A). Neotectonic processes may have conditioned this drainage network migration direction (Boaventura and Narita, 1974; Silveira, 1998), which would have been responsible for changes at the local base level, deactivating the N-S direction drainages, and shifting their courses to the SW-NE direction.

The migration of this drainage system in a NW-SE direction corroborates the interpretation by Souza (2010), which suggests the presence of tectonic compartments associated with this direction, formed by tectonically active basement blocks. These blocks would have conditioned the positioning and maintenance of Lodão and Mutuco lakes, as well as a series of small, unnamed lakes oriented in a NW-SE direction.

The Paleosystems and Current Processes

The results presented herein and literature analyses indicate that the deactivations of the fluvial systems continue from the Late Pleistocene until today.

Paleodrainage development is related to continuous changes in local and probably regional base levels, due to the existence of neotectonic processes (Costa *et al.,* 2013, Silveira, 1998), as well as a high sedimentary supply from the Amazon river which has increased over time, especially in recent years (Martinez *et al.,* 2009). The presence of macrotides with tidal bores results in the input of Amazon sediments to estuarine systems (Santos *et al.,* 2016a). In addition, the Amazon River mouth region is located on a low-relief coastline that allows for the existence of continuous processes of riverbed aggradation (Boaventura and Narita, 1974; Silveira, 1998; Santos, 2006).

This change in the base level is still developing, as evidenced by the closure of the of the Araguari river mouth in 2014 (Santos *et al.,* 2016a). Anthropogenic processes, like cattle activities, intensify these morphological changes (Santos, 2006) and represent a new force (Anthropocene) in the generation of new paleochannels.

The dimension and morphology of the identified paleodrainage systems are comparable to the current drainage systems found in the Amapá state coastal plain, such as the Araguari River. This river is about 3 km wide at its mouth and contributes an average flow of 2,617 m³/s (Matos *et al.,* 2011) to the Atlantic Ocean. Geophysical data allow for the estimate that some paleodrainages in these systems had maintained the same form and depth of the Araguari River, therefore they would present similar discharges during their active period.

CONCLUSIONS

This study revealed the existence of two paleosystems formed during the Holocene in the study area. New paleodrainages, not yet identified in the scientific literature, were recorded. The results provide new information in the elucidation of part of the physiographic evolution at the Amazon River mouth. Geological and geophysical investigations are necessary to track the paleogeographic evolution and to understand climate change history in the region.

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Table list

Table 1. Root mean square error (RMSE) *after registration between mosaics.*

IMAGE/ YEAR	Resolution (m)	RMS (pixel)	Linear Error (m)	Linear Error (km)	Error (km^2)
GEMS-1000 (1972)	30	0,95	28,5	0,0285	+/- 0,0008
PALSAR/ ALOS (2008)	30	0,97	29,1	0,0291	+/- 0,0008

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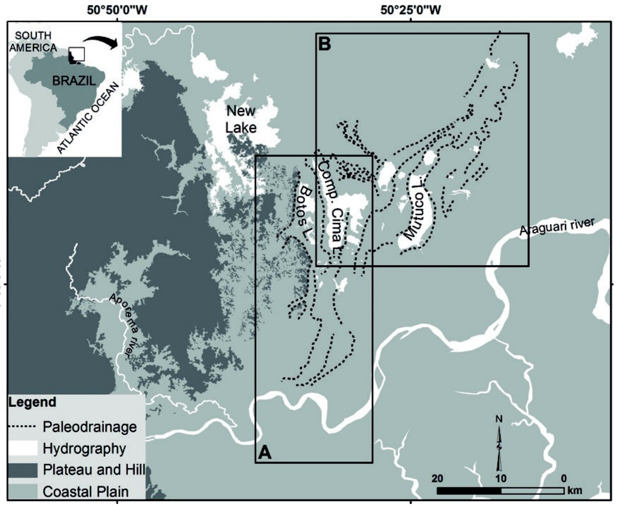

Figure 1. Study area displaying the identified paleodrainage systems.

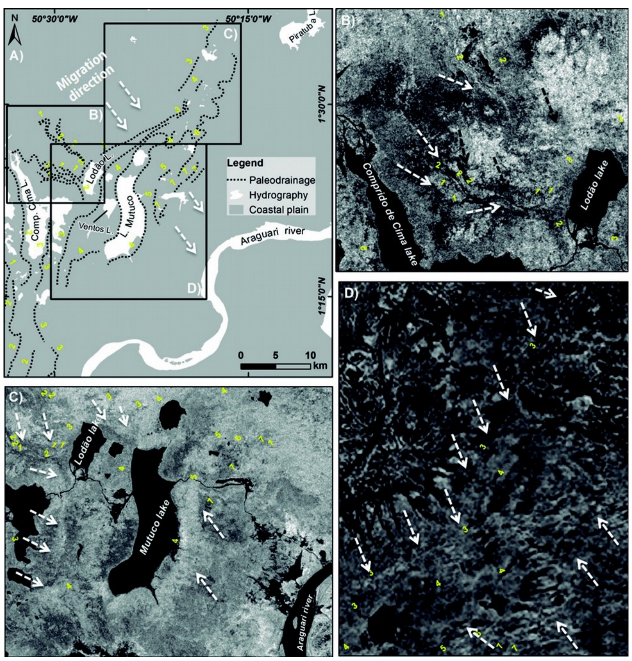

Figure 3. SW-NE Paleodrainage system. A) Map displaying the alignment segments of the SW-NE paleodrainage features; B) L-band radar image with identification of the paleodrainage tributaries in the NW-SE direction; C) X-band radar image highlighting the paleodrainage lines in the SW-NE direction, with a series of small lakes that assist in identifying these paleo-features; D) L-band radar image with identification of the SW-NE paleodrainages that follow Lodão and Mutuco Lakes.

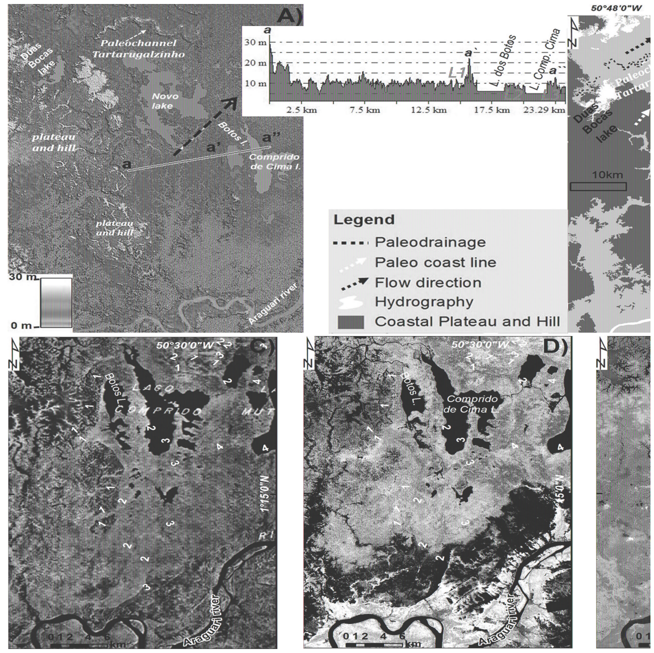

Figure 2. The N-S paleodrainage system and morphological units. A) DEM/SRTM highlighting differences in relative altitude, pointing out the topographic profile a, a', a''; B) Map highlighting the identified units and morphological features and the direction of the ancient paleodrainage flows; C) X-band radar image indicating evidence of N-S paleodrainages, transversal to the Araguari River, highlighted in the rectangle displayed in figure B; D) L-band radar image indicating evidence of the N-S paleodrainages, transversal to the Araguari River, highlighted in the rectangle displayed in figure B; E) LANDSAT 7 ETM+ image, coloured composition 7R 4G 3B showing evidence of the N-S paleodrainages, transversal to the Araguari River, highlighted in the rectangle displayed in figure B.