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Remote sensing applied to decipher the origin of the Marajó Island, northern Brazil

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Abstract. The present study provides a detailed mapping and characterization of paleochannels in the northeasten Marajó Island using remote sensing (i.e., SRTM, Landsat 5-TM and Landsat 7-ETM+). The Arari Lake area is emphasized where a funnel-shaped morphology attributed to a Late Pleistocene paleoestuarine system was recognized previously to the lake development. Remote sensing data reveal that the inner estuary was connected to three fluvial channels that ran from the east/southeast throughout an area currently occupied by the Marajó Bay, implying that this bay did not exist yet by the time the estuarine system was active. Separation of the eastern side of Marajó Island due to establishment of the Tocantins River along northeastward-orientated faults would have interrupted the fluvial inflow, ultimately causing the abandonment of the estuarine system.

Key-words: Remote sensing, Landsat, SRTM, Landscape evolution, Quaternary, Marajó Island, Arari Lake

1. Introduction

The record of paleochannels in the Marajó Island is not new (e.g., RADAM, 1974; Bemerguy, 1981; Porsani, 1981; Vital, 1988), but their mapping and characterization remain to be presented, providing a unique opportunity to raise information for helping reconstructing the paleogeographic evolution of the lowest Amazonas drainage system throughout the Quaternary.

The aim of this paper is provide remote sensing (mostly TM and ETM+ Landsat imagery, and whenever possible, SRTM) information from the northeast of Marajó Island as a tool for recording changes in its physical environments during the Quaternary. The Arari Lake area will be emphasized, because it contains a set of geomorphological features attributed to past drainage systems that provides valuable information for improving our understanding on the origin and evolution of the Marajó Island. The application of remote sensing allows a reconstruction of Quaternary landscape evolution in the lowest Amazonian drainage system and of the succession of events responsible for the recent (thousands of years) separation of the Marajó Island from the mainland.

2. Material and methods

The Arari Lake consists of a north-south elongated feature in the northeast part of the Marajó Island, where it forms a basin encompassing up to 1,900 km^2 that is surrounded by lowlands only 4-6 m high. The water volume in the lake reaches up to $600x10^6$ m^3, but the lake is shallow, being only up to 7 m deep during raining seasons. During dry seasons, there is a reduction in water volume of up to 60%, and the lake might even become totally dry during prolonged dry seasons. To the south, it becomes the headwater for the Arari River, which runs to the southeast draining into the Marajó Bay.

The Arari Lake is located in a region of tropical climate characterized by mean annual temperature of 28^{o}C and precipitation of 2,500 to 3,000 mm/year, 90% of which concentrated between January and July. In Koppen classification, the southern part of the island is described as Af (forest tropical climate) and the remaining areas as Amw' (relatively drier than Af, with dry winters).

The morphological characterization presented in this paper is based on the analysis of Landsat 5-TM (Ref. 224-060 and 225-061, INPE) and Landsat 7-ETM+ (Ref. 223-060 and 223-061, GLCF) images, collected in August/2001.

SRTM-90 m topographic data distributed by USGS were additionally used to help with the interpretations. Given the very low topography of the study area, SRTM data had to be visualized accordingly using customized shade schemes and palettes to efficiently highlight the morphologic features. Color schemes were rearranged to present strong hue transitions near the height of terrain unit boundaries, requiring often adjustments from a local to another. Image interpretation of elevation data was made possible by the use of the software Global Mapper (Global Mapper Software LLC).

3. Morphological characterization

Existing topographic maps available from the study area in the scales of 1:1,000,000 or 1:250,000 (contours spacing of 100 m and 50 m, respectively) indicate no contour lines, since heights vary under these levels. The SRTM data, however, shows heights averaging 4 to 8 m. Occasional features scoring SRTM heights up to 30 m reflect altitude enhancement due to vegetation-relief interactions under the C-band radar altimetry. In fact, actual terrain heights hardly reach 10 m in this region.

The morphological features of the Arari Lake area are, in general, characterized by an abundance of channellized features, particularly well preserved and promptly mapped on Landsat images by an intricate meandering drainage network that resemble those observed in many modern Amazonian basins (**Figures 1A-C**). SRTM data reveal that the topography crossing the paleochannels is relatively higher when compared to the surrounding areas, in general with an average gradient of 10-11 m, but which can reach up to 20 when associated with larger paleochannels (**Figure 1D**). Accompanying fieldwork showed that this gradient is, in great part, exaggerated due to vegetation. This is because the terrains corresponding to the paleochannels consistently contain arboreal elements, in contrast to the prevailing grasslands over the surrounding areas. Radar C band, used for the acquisition of SRTM-90 m, refers to wavelengths that are able to penetrate dense canopies without reaching the ground (Le Toan *et al.*, 1992). The number, height and architecture of individuals are determinants of the radiation penetration into the canopies. Thus, in a thick tropical forest cover, information on SRTM data refers to the surface and near surface of the canopy. Despite this canopy effect, field observations also revealed that there is, in fact, a very smooth, convex relief that can reach up to 2-3 m high over the paleochannel areas. These slightly higher lands were favorable for the development of arboreal vegetation as they can escape from frequent floods that inundate the entire area during wet seasons.

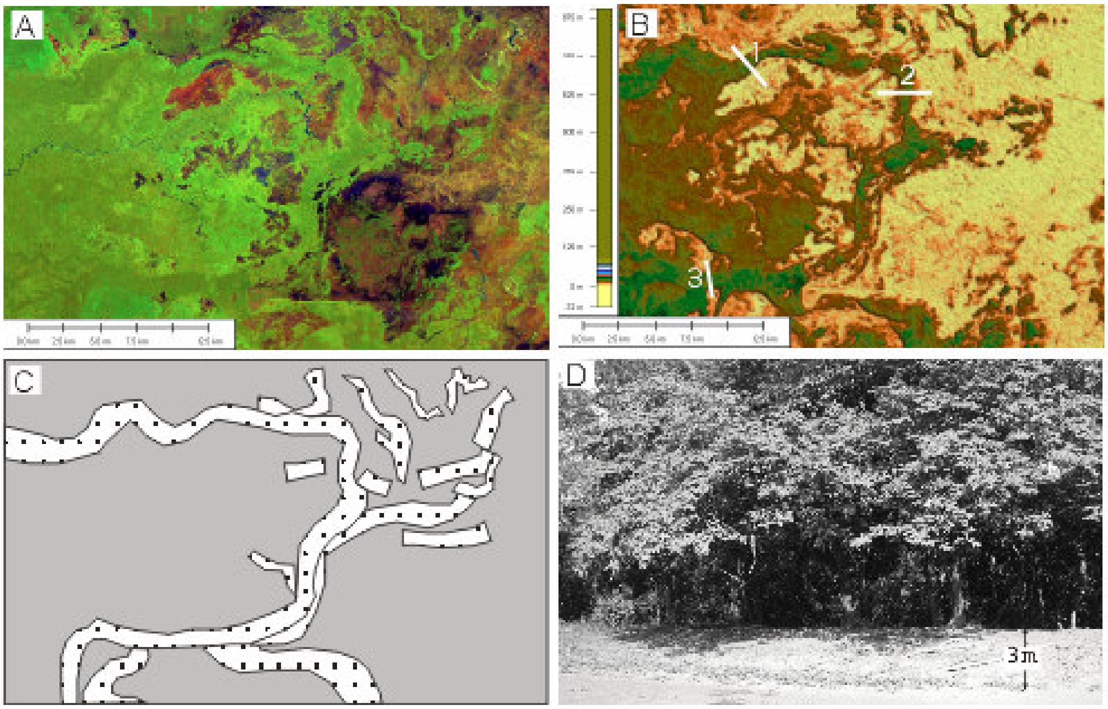

Figure 1: Characterization of the paleochannels in the study area based on Landsat 5(R), 4(G), 3(B) composition (A) and SRTM (B) data. C) Drawing over the data presented in A and B, highlighting the elongated, meandering morphologies attributed to paleochannels. D) Profiles transversal to a paleochannel morphology characterized by a SRTM relief gradient of up to 20 m relative to surrounding areas, resulting from combination of smooth topography and vegetation.

A particular feature of interest is that the Arari Lake, rather than representing an isolated structure, appears as the central part of a larger channeled morphology (**Figures 2A,B, 3A-C**). The lake dominates the modern landscape, occurring near the locality of Santa Cruz do Arari (**Figure 2B**), where it is part of the most important drainage basin of the island. It is remarkable that the lake area, established upon a north/south elongated depression averaging 4 km wide and 25 km long, configures the center of a much larger, funnel-shaped structure that reaches as much as twice the lake length (**Figures 2A,B**). The southern portion of the funnel coincides with the main, deeper lake body. In the southern edge, the funnel shaped structure is bent to east/northeast, as it becomes progressively narrower, and slightly sinusoidal, when it grades into a complex of meandering paleochannels (**Figures 3A-C**). Three main branches of this paleochannel are recognized (see 1 to 3 in **Figure 2B**).

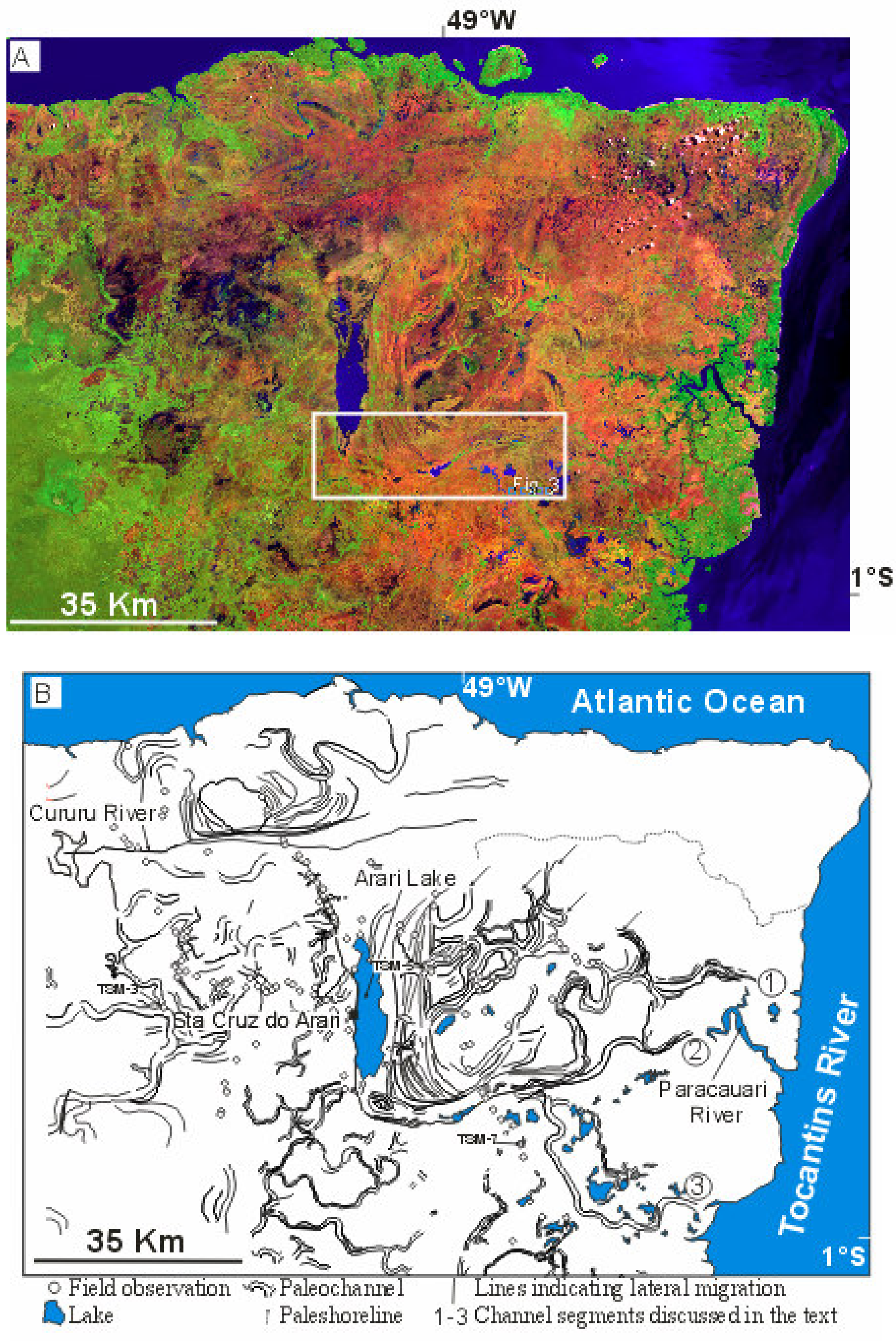

Figure 2: Landsat 5(R), 4(G), 3(B) composition from the northeast of Marajó Island (A), with the corresponding map indicating the morphological features discussed in the text (B) Arrows in the northeast of the Arari Lake indicate places where the paleochannels are sharply interrupted.

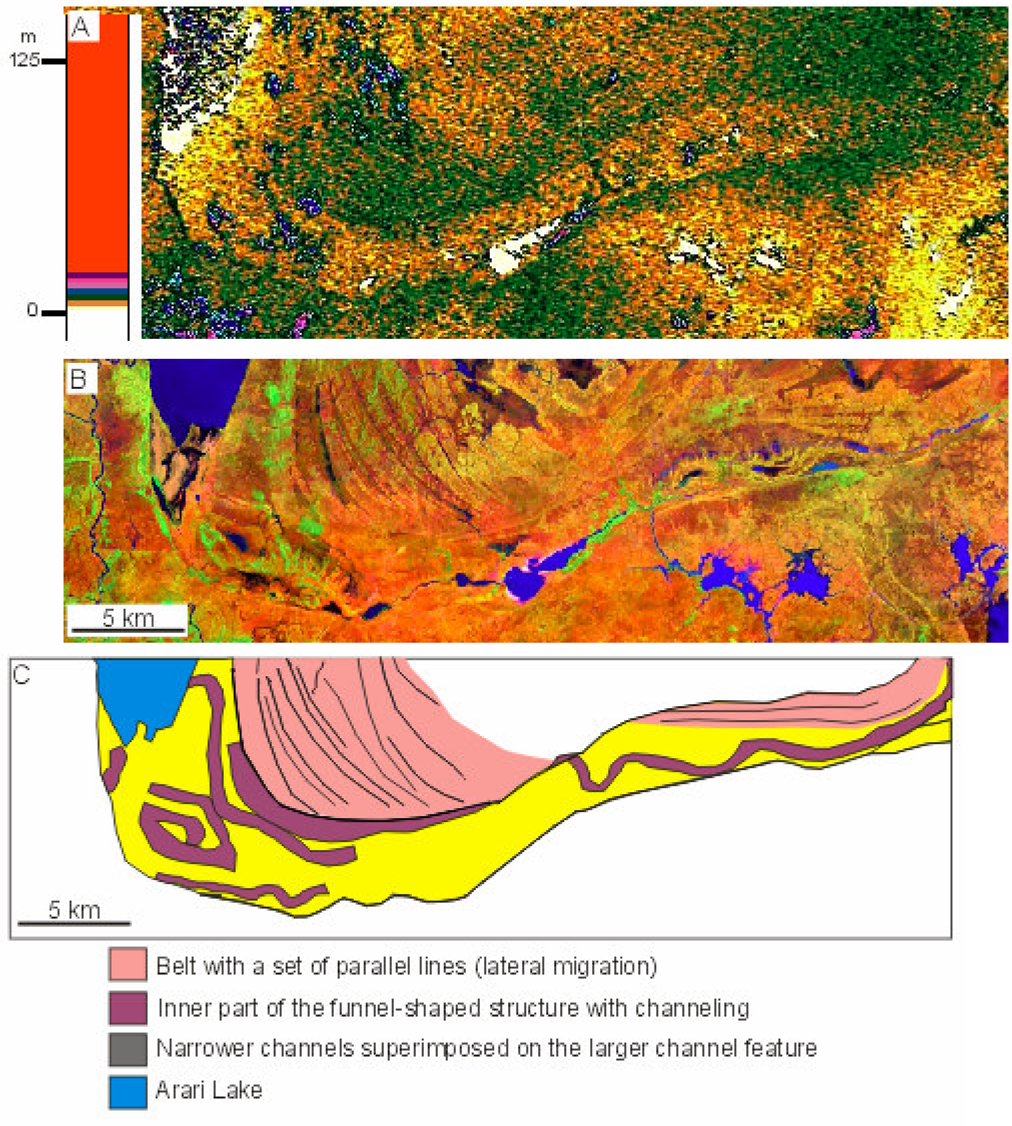

Figure 3: A-C) Detail of the southernmost portion of the funnel-shaped structure attributed to represent the scar of a middle estuarine depositional setting as seen in the SRTM (A) and Landsat (B) 5(R), 4(G), 3(B) composition, as well as the corresponding drawing (C). See figure 2 for location.

As the Arari Lake becomes shallower northward, the opposed side of the funnel-shaped structure enlarges substantially, varying from 10 to 40 km wide in its middle and outer reaches, respectively. Paleochannels are scarce in this area and, when present, they are not clearly traceable. Towards the southeastern edge of the Marajó Island, all paleochannels disappear rapidly in points distant circa 30 to 50 km from the modern coastline.

5. Discussion

The present study focused on remote sensing of the Arari Lake area confirmed that paleochannels are the most impressive geomorphogical features in the northeast of Marajó Island. The typical meandering geometry of individual channels, as recognized in many previous works and described in more detail herein, does not leave any doubts on the attribution of the described features to paleodrainages, as they resemble channels from many modern drainage basins. Channel widths, measured from Landsat and SRTM data are also consistent with large channel systems similar to many modern Amazonian rivers.

The funnel-shaped structure associated with the Arari Lake is intriguing and leads to invoke that this is a reminiscent of a distinct depositional system developed previously to the lake establishment. Previous works had suggested that the Arari Lake is a modern expression of an ancient, much larger lake setting (Porsani, 1981; Vital, 1988). The data presented herein, however, lead to invoke a paleoestuarine system, rather than a large paleolake, in the area now occupied by the Arari Lake. This is suggested with basis on the fact that the modern lake is in physical continuity with a much larger structure characterized by a funnel-shaped morphology, which is a typical geometry for many tidal-dominated estuarine settings (e.g., Dalrymple *et al*., 1990, 1992). The opening of the funnel to the north indicates the position of an east to west-orientated paleocoast (see a hatched line with indication of the paleoshoreline in **Figure 2B**). The narrowing of the funnel morphology in its inner reaches, located to the south, and its linkage to paleochannel systems to the east, conform to the morphology of estuarine settings.

Based on the foregoing discussion, it can be proposed that the Arari Lake is a relatively young morphological feature in the Marajó Island. The lake parallels a much larger ancient structure displaying shape typical of a paleoestuarine system, which is confirmed by our ongoing sedimentological data obtained from cores. Our unpublished radiocarbon datings from these cores show also that the main evolution of this estuary took place already in the late Quaternary. Sandy channel fill successions displaying ages that vary from >40,200 ^{14}C yr B.P. to a depth of almost 120 m to 30,360 (+/-250) ^{14}C yr B.P. and 7,900 (+/-40) ^{14}C yr B.P. upward led to suggest that at least a major part of this estuarine paleovalley might have been filled by high volumes of sands deposited in large fluvial channels in a relatively recent, i.e., late Quaternary time. This would explain why this feature is preserved so perfectly in the modern landscape, despite the strong tropical weathering.

Considering that a substantial fluvial sand supply to the paleoestuary mapped in the northeastern Marajó Island remained active during the latest Pleistocene/earliest Holocene, some questions arise concerning to the paleogeography of the study area. This is because the position of the three branches of paleochannels that fed the estuary from northeast/southeast requires a continental inflow in an area now occupied by the Marajó Bay (see **Figure 2B**). Thus, if the interpretations are correct, then the Tocantins River could not have existed yet by the time this estuary was active when the Marajó Island was still connected to the mainland.

A tectonic genesis is claimed as the most likely trigger mechanism for the establishment of this paleoestuary, based on the many features attesting tectonic activity in the Marajó Island during the Quaternary (Bemerguy, 1981; Bemerguy, 1997; Costa *et al*. 2002). Four sets of tectonic lineaments have been recognized in the Marajó Island (i.e., NNW/N/NNE-SSE/S/SSW, NW-SE, NE-SW and E-W/ENE-WSW/ESE-WNW), which coincide with a tectonic pattern observed in many other areas located at the mouth of the Amazon (RADAM 1974; Bemerguy 1981; Bemerguy *et al*. 2002; Costa and Hasui 1997). Hence, it is proposed that as the Tocantins

River became established, the water supply at the estuary head was cut off, causing stagnation of the depositional setting, with its consequent abandonment. Subsequently, the water started to accumulate, promoting the development of the Arari Lake.

Therefore, the present integration of remote sensing and sedimentological data lead to the conclusion that the northeastern Marajó Island was a place of great dynamism concerning to the development of its depositional environments during the Quaternary. Changes in the physical setting were frequent, and they appear to have been, at least in great part, motivated by tectonics. As tectonics took place, many channels had their courses deviated, resulting in a network of abandoned drainage that is nicely preserved on the modern landscape.

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