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Late Holocene tectonic influence on hydrology and vegetation patterns in a northern Amazonian megafan

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ABSTRACT

The factors that control the heterogeneous canopy of the Amazonian rainforest have long been a topic of interest for research. Among all hypotheses, changes in landscape due to geological processes have been increasingly defended. Large areas of open vegetation in the northern Amazonian lowlands are confined to paleolandforms created by the abandoning of megafan depositional systems. Previous investigations related the megafan sedimentation in this region to Late Pleistocene-Holocene tectonic reactivations. However, the influence of neotectonics on both the Amazonian megafans and associated vegetation cover remains to be further investigated. We studied a depression preliminarily noticed in the south-central sector of one Amazonian megafan (i.e., Viruá megafan) aiming to determine if its genesis was due to recent tectonic subsidence after the megafan abandoning. The investigation combined morphostructural, hydrological and remote sensing reflectance analyses, as well as characterization of floristic communities in the modern and ancient environments based respectively on field inventories and palynological data. The results indicated a nearly 10-km long and rectangular-shaped area having straight margins paralleling NNE/SSW-trending regional structural lineaments. Hydrological analysis suggests that this area experiences the largest floods during wet seasons, a condition compatible with the topographic data that revealed a smoother gradient of ~3 m comparing this area with others from the megafan plain. In the studied depression, numerous forest patches are arranged as sets of parallel straight lines trending consistently in the NE/SW direction. The patches have spectral values that differ significantly from other forest patches over the megafan surface, being compared to those of seasonally-flooded forests, such as igapós and várzeas, that surround the megafan paleolandform. In addition, a forest patch within the depression revealed trees physiologically adapted to tolerate submersion 6 to 7 months per year, which is also a characteristic of the inundated forests external to the megafan. These data altogether led us to conclude that the studied depression consists of a shallow subsiding basin formed by tectonic reactivations in the mid/late Holocene. Tectonic instability at around 2 cal kyr BP further disturbed this system by creating NE/SW-trending lakes and leading to the replacement of seasonally-flooded forests by grasslands. Thus, tectonic activity in a relatively recent geological time must be accounted when analyzing plant distribution in the Amazonian wetlands.

1. Introduction

Changes in the modern (ter Steege et al., 2003; Miles and Phillips, 2004) or past (Absy et al., 1991; Pessenda et al., 2001) climate and in soil properties (e.g., Phillips et al., 2003; Tuomisto et al., 2003; Ruokolainen et al., 2007; Higgins et al., 2011) have been commonly proposed as main controls of plant distribution in the Amazonian lowlands. However, paleoenvironmental changes over a relatively recent geological time are also reflected in the modern vegetation cover. Thus, analyzing the distribution of modern plants in the context of geological history helps understand the factors that affect plant distribution. In particular, how sedimentary processes have acted to modify the physical environment in order to make it suitable for the growth of particular plant communities is a topic still in need of further

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investigation. This theme can be approached with the analysis of palimpsest morphologies and sedimentary archives.

The influence of geological processes on plant distribution was already emphasized in previous publications (e.g., Butler et al., 2003; Salovaara et al., 2004; Rossetti et al., 2005; Tuomisto, 2007; Rossetti et al., 2010; Amaral et al., 2011; Rossetti et al., 2012a; Rossetti et al., 2012b; Kiedrzynski et al., 2015). In particular, geological characteristics have been indicated as fundamental for the creation of heterogeneous substrates that have contributed to add new plant species to the Amazonian rainforest (e.g., Salo et al., 1986; Räsänen et al., 1987; Terbourgh and Andresen, 1998; ter Steege et al., 2006; Higgins et al., 2011; Mendonça et al., 2014). In this context, many paleolandforms representative of ancient fluvial depositional environments over this region are occupied by white-sand vegetation in contrast with the surrounding rainforest (e.g., Rossetti et al., 2005; Amaral et al., 2011; Bertani et al., 2015; Rossetti et al., 2010; Rossetti et al., 2012a). This sclerophyllous vegetation consists of forests, grasslands and shrublands mostly specialized to sandy soils (Bongers et al., 1985; Adeney et al., 2016). In addition to fluvial paleolandforms, the distinctive Amazonian white-sand vegetation also occur over numerous discontinuous and triangular-shaped megafan deposits (cf. Nichols and Fisher, 2007; Chakraborty and Ghosh, 2010) of a wide wetland in the Negro-Branco basin of northern Brazil (Rossetti et al., 2012a; Rossetti et al., 2012b; Zani and Rossetti, 2012; Rossetti et al., 2014a). These deposits were formed by distributary (i.e., downstream divergent) drainage networks active in the Late Pleistocene and Holocene in areas currently occupied by the Amazonian tributary (i.e., downstream convergent) systems.

Tectonic reactivation was claimed as the main reason for past changes in Amazonian rivers (Bezerra, 2003; Souza-Filho et al., 1999; Almeida-Filho and Miranda, 2007; Lombardo, 2014; Rossetti et al., 2014b; Cremon et al., 2016). This factor may have also been important to determine the origin of the Amazonian megafans, as shown by the detailed work integrating sedimentological, chronological and morphostructural data in one of these megafans (i.e., the Viruá megafan) (Rossetti et al., 2012b). The proposed tectonic influence on the northern Amazonian megafans was further addressed in a recent publication focusing surface and subsurface surveys, which revealed the megafan depositional locus in a tectonically-triggered subsiding basin (Rossetti et al., 2015). The tectonic evidence was provided by numerous morphostructural anomalies (see (Rossetti, 2014) for a review), including the lateral displacement of megafan paleolandforms by strike-slip faults (Rossetti et al., 2014a). Such displacement implies in a tectonic reactivation post-dating the mid-Holocene, i.e., following the megafan abandoning. Investigations aiming characterize the imprint of tectonic disturbance on the Amazonian megafan surfaces, as well as determine its effect on the vegetation cover, might contribute to advance understanding the factors that have controlled plant distribution in a changing Amazonian environment over time.

The main goal of the present work was to investigate the surface of one Amazonian megafan in order to detect environmental changes that could be related to geologically recent tectonic disturbances with ability to impact floristic patterns. We focused on the south-central sector of the Viruá megafan (Fig. 1A, B) located at the left margin of the Branco River and so far the best known Amazonian megafan (e.g., Rossetti et al., 2012a; Rossetti et al., 2012b; Rossetti et al., 2014a). Similarly to other megafans of the region, the surface of the Viruá megafan is typified by patchy white-sand forest mixed with grasslands and shrublands (Rossetti et al., 2012a; Zani and Rossetti, 2012; Cordeiro et al., 2016). A south-central sector of this megafan (Fig. 1B) caught the attention due to the highest concentration of forest patches. We tested the hypothesis that this area consists of a local depression formed on the megafan surface by tectonic subsidence after the megafan abandoning. Our investigation analyzed morphostructures, hydrology, remote sensing reflectance, floristic communities based on field inventories and pollen from the sedimentary record. This integrated survey allowed to characterize the forest types in space and time and analyze their relation to the physical environments. We present a multidisciplinary exploration for elucidating the impact of recent active tectonics on the establishment of some Amazonian white-sand vegetation while also explaining the origin of this dissimilar vegetation within the Neotropical rainforest.

2. Geological context and physiography

The Viruá megafan is one out of many megafan paleolandforms that characterize an outsized depressed wetland of northern Amazonia (Rossetti et al., 2014a; Fig. 1A), inserted in the *Pantanal Setentrional* Basin (Santos et al., 1993; Rossetti et al., 2012b). This basin formed by tectonic subsidence during the Quaternary (Rossetti et al., 2016). Climate in this region is tropical, with monthly temperatures ranging from 26 °C to 33 °C (Radambrasil, 1976), average annual rainfall is 1800 mm, well-defined dry season between December and March, and wet season between June and September. Severe droughts occur every five to seven years, regulated by the El Niño and La Niña cycles, when this wetland turns into a dryland (personal observation).

The Viruá megafan is a 45 km-long and 25 km-wide (nearly 1000 km^2) triangular-shaped feature (Fig. 1B). It dips slightly to the west and southwest, with a slope variation of $< 15\ cm\ km^{-1}$ (Zani and Rossetti, 2012). Sedimentary deposits are mostly sands locally interbedded with silts and muds. They formed in distributary channels, overbank sand sheets, aeolian dunes and small lakes (Rossetti et al., 2012b). The megafan deposits intercept older, i.e., Mid-Late and Late Pleistocene deposits (Rossetti et al., 2015). Radiocarbon dating indicates active sediment deposition at least since the latest Pleistocene (i.e., up to 38.2-36.6 cal kyr BP) and megafan abandoning in the mid-Holocene (Rossetti et al., 2012a).

Similar to other megafans of northern Brazilian Amazonia, much of the Viruá megafan deposits are occupied by white-sand vegetation (Anderson, 1981) consisting of grassland, shrubland, woodland and forest. These vegetation types are in sharp contact with surrounding areas of terra firme, alluvial, igapó and várzea forests. The white-sand vegetation is a low-diversity forest dominated by light-demanding trees adapted to poorly-drained and poorly-structured sandy soils (Mendonça et al., 2014) that occur in scattered patches over the Viruá megafan (Cordeiro et al., 2016).

3. Methods

The morphological characterization was based on the digital elevation model derived from the Shuttle Radar Topography Mission (SRTM-DEM). We used the 30-m spatial resolution (1 arc sec) C-band InSAR-Interferometric Synthetic Aperture Radar elevation (SRTM). Other remote sensing images included the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture (PALSAR) radar, Landsat–5/TM Thematic Mapper and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). PALSAR images had a pre–processing level of 1.5. Optical images were processed applying R (red) G (green) B (blue) color image compositions. The morphological characterization was completed with the help of 1 m-resolution TerraSAR-X images and high resolution optical images obtained from Google Earth™ and WebGLEarth™.

The hydrological analysis required precise and reliable altimetry data, which are sparse in Amazonia. SRTM-DEM has been mainly used in hydrological studies. However, vertical variations lower than 1 m cannot be correctly on these data, which restricts their use in large flat areas. For the hydrological characterization of the study area we used optical imagery derived from Landsat Enhanced Thematic Mapper (TM +) sensor onboard of the Landsat 7 satellite. Optical images can detect flooding conditions in non-forested areas or in areas where trees are widely spaced. In both cases, there is a noticeable spectral response difference between wet and dry habitats. We predicted the flooding depth and the relative height above the maximum inundation quote