Upland lakes of the Carajás region: origin and development through time

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ABSTRACT

Upland lakes (ULs) of the Carajás, southeastern Amazonia, have been intensively studied to their evolution during the Quaternary, as well as the development of the associated biota. In this review, several classical and modern approaches from structural geology to the pollen rain and sedimentary data which cover an area of around 41,300 km^2 were compiled. Multi-elemental geochemistry indicates that the detrital sediments derived from weathered crusts and soils, while the sedimentary organic matter represent autochthonous (siliceous sponge spicules, algae, macrophytes) and allochthonous (C3 plants and freshwater DOC) sources. Modern pollen rain suggests that even small lakes and canga areas can reflect forest signal, which depends on the topographic control and prevailing wind direction on pollen deposition. Integrated data of the sedimentary cores indicate that the active lakes never dried up during the last 50 ka cal BP. However, subaerial exposure occurs on filled lakes such as ST02 Lake during the LGM, LB3 and R2 lakes at the mid-Holocene due to drier paleoclimate conditions. Considering the organic proxies, only LB3 Lake presents expansion of C4 canga (montane savanna) plants since ULs of the Serra da Bocaína does not present siderites. Siderite formation on ULs deposits also points to drier paleoenviromental conditions, interrupting predominantly wet conditions. However, there is no evidence for widespread expansion of savanna into Southeastern Amazonia during the late Pleistocene and Holocene.

Keywords: Amazonia, Upland lakes, Serra dos Carajás, Palaeoenvironmental reconstruction, Quaternary, Geology

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Highlights
- Carajás lakes represents singular ecosystems in Amazon uplands;
- The lakes were formed by structural and dissolution processes during the late Cenozoic;
- Water quality and sedimentary processes are controlled by lake catchment characteristics;
- Multi-proxy approach is more robust (or reliable) for paleoenvironmental reconstructions

1. Introduction

Upland lakes (ULs) in the Brazilian Amazon are singular mid-altitude landforms (from 400 m to 800 m) formed over iron and iron-aluminous lateritic crusts as a result of successive structural processes, weathering (chemical, physical and biological) and erosion cycles under tropical climate conditions (Vasconcelos et al., 1994; Costa et al., 2005; Maurity and Kotschoubey, 1995). These lakes are hydrologically restricted and constitute depositional environments with variable accommodation space for sediment deposition, and accordingly they are classified as active and inactive lake systems, with the latter representing upland swamps (Reis et al., 2017).

The ULs sediments are highly influenced by natural and local characteristics of each catchment basins, including parent rock properties, source-area weathering, rheology, morphology and vegetation cover, as well as the primary productivity of the central basins (Sahoo et al., 2015, 2016a, 2017a). The interrelation of these factors have controlled the geochemical and limnological characteristics of these lakes through time (Sahoo et al., 2017b). In general, ULs present thick Quaternary deposits with relatively continuous records of paleoenvironmental changes, as such observed in the Morro dos Seis Lagos (northwestern Amazonia), Serras de Maicuru and Maraconaí (northestern Amazonia), and dos Carajás (southeastern Amazonia) (Colinvaux et al., 2001; Bush et al., 2004; Sifeddine et al., 2001; Guimarães et al., 2016; Reis et al., 2017).

The western and eastern ULs have provided exceptional records for paleoclimate and paleovegetation modelling, allowing to evaluate the effects of the last glacial and interglacial periods on lakes and vegetation patterns (Colinvaux et al., 2001; Bush et al., 2004; Sifeddine et al., 2001; Reis et al., 2017). In addition, they serve as excellent database for discussions about speciation events throughout the Amazonia (Arruda et al., 2018), However, mismatches between paleoclimate data of western and eastern Amazonia are still recurrent (Reis et al., 2017; Guimarães et al., 2017, 2018a, b), which causes difficulty in analysis and interpretation of past and current vegetation distribution on large spatial scales. For instance, speleothems records suggested that eastern Amazonia was wetter during the mid-Holocene than present (Wang et al., 2017). It contradicts palynological and geochemical data from Serra dos Carajás. Such studies proposed extensive dries up of the upland lakes and dominance of montane savanna (*canga* vegetation) and dry-adapted semideciduous tropical dry forests (SDF), in detriment of humid evergreen tropical forest (HETF) (Absy et al., 1991; Sifeddine et al., 2001; Hermanowski et al., 2014; Reis et al., 2017; Guimarães et al., 2016, 2018b).

Even the drainage basins of the ULs of Amazonia developed on basement lateritic crusts may locally present a great variety of lithotypes, geomorphological settings, and consequently, structural and floristic composition of plant communities (Nunes et al., 2015). The complexity of this system is also responsible for the development of

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different microhabitats in the crusts, with high beta diversity and endemism of plant species (Guimarães et al., 2014; Nunes et al., 2015; Viana et al. 2016).

Palynological and geochemical studies were conducted on upland swamps in this region (Absy et al., 1991; Sifeddine et al., 2001; Cordeiro et al., 2008; Hermanowski et al., 2014; Reis et al., 2017; Guimarães et al., 2016, 2018b), so most of these records may reflect hydrarch succession and basin-filling rather than a paleoclimate signal. ULs may become more similar to terrestrial habitats during negative water balance produced by prolonged hydric stress, which may affect ecological attributes of water-dependent biota (Lopes et al., 2011; Mormul et al., 2015). On the other hand, ULs that remained relatively resilient to these environmental conditions may act as microrefuges for such organisms. Thus, both physical and biological aspects, as well as their dynamic nature, must be carefully evaluated over shorter (annual to decadal) and longer (century to millennial) time scales through an integrated approach using surface or subsurface records from geological, geomorphological, sedimentological, geochemical, limnological, botanical and paleontological prospecting. This is highly recommended for a precise environmental assessment and regional correlation of events, which should be the foundation of any paleoenvironmental reconstruction, since ULs may respond differently under similar paleoclimate change (Guimarães et al., 2018a). In this scenario, this study presents multi-proxy characterizations of the surface and subsurface processes and landforms of ULs, as well as new data and proxies about late Quaternary environmental dynamic of the Carajás region, southeastern Amazonia.

1.1. Regional geological setting

The study site is located in the eastern portion of the Carajás Domain, northeast portion of the Carajás Mineral Province, southeastern Amazonia (Fig. 1), which is an important metallogenic province on a global scale (Tolbert et al., 1971). This province is represented by felsic and mafic granulites (Pium Complex), granodioritic and tonalites (Xingu Complex), which form the Meso-archean basement, and by supracrustals Neo-archean metavolcanic-sedimentary sequences and banded iron formations (BIFs) related to Greenstone Belts of the Itacaiúnas Supergroup (Barros et al. 2010; Costa, 2007; Macambira 2003; Rosière et al. 2005). Sedimentary successions of the Águas Claras Formation were deposited over the Greenstone Belts (Nogueira et al., 1995).

The weathering of the Itacaiúnas Supergroup due to the tropical paleoclimate conditions of the Cenozoic allowed the development of extensively Fe-Al lateritic crusts from BIFs and metavolcanic rocks (Maurity and Kotschoubey, 1995; Vasconcelos, 1999). The formed crusts underwent a progressive degradation caused by paleoclimate changes, regional uplifting and lowering of the groundwater base levels. Therefore, the weathering reached deeper portions, while intense pseudo-pisolitization occurred in the upper part of the crust. Highly porous and permeable zones developed near the contact with the saprolite horizon due to the mobilization of Si, Fe and Al, and lateral fluxes of underground waters following structural and dissolution features. Subsequently, ULs with caves in their borders were formed according to the evolution of these zones and collapse of the overlying crust (Maurity and Kotschoubey, 1995). ULs only occur in the upper lateritic terrains (plateaus) of the Carajás region at 600 to 760 m altitude, such as Serra dos Carajás (S11 and Norte), do Tarzan, da Bocaína and Leste (Fig. 1).
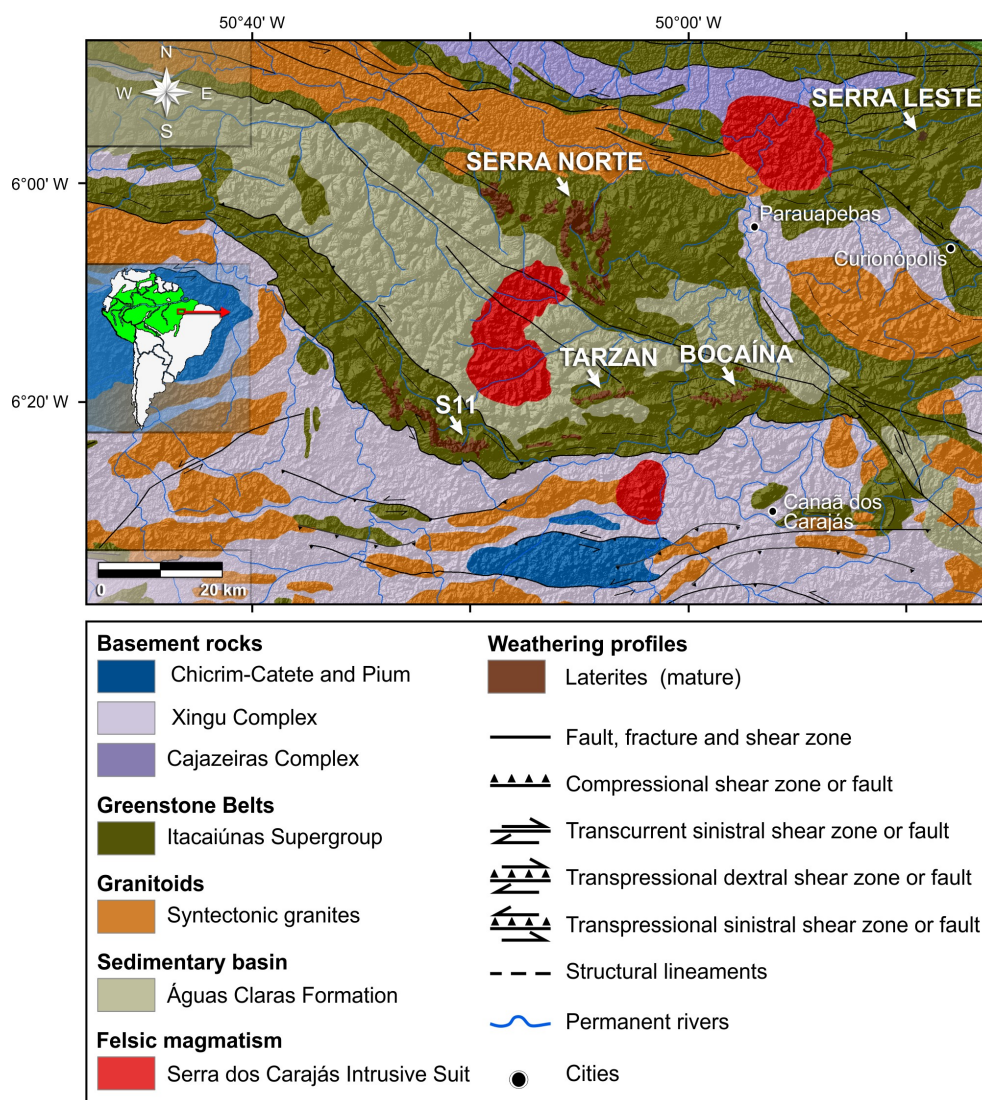
Fig. 1. Geological map showing the main lithological units of the Carajás region in the Brazilian Amazon. The studied lakes are located in the lateritic crusts of the Serra dos Carajás (S11 and Norte), do Tarzan, da Bocaína and Leste.

Considering the influence of structural features in the formation of ULs, the lateritic crusts of the Serra Sul dos Carajás are cut and displaced by sets of E-W, N-S to NE-SW sinistral normal oblique faults. ULs, such as Violão Lake (S11), are strongly controlled by these sets of fractures and their related folds, both in position and shape. Most of these fractures and faults were reactivated as collapse normal faults and occur along the borders of the lake, with a step-down displacement towards its central basin (Souza-Filho et al., submitted). Partial dissolution of the lateritic crust by the run-off and deposition of clastic sediments are in agreement with the major scale lake development (Souza-Filho et al., 2016a).

Based on shallow seismic surveys and sediment cores, it was possible to identify the geometry of sedimentary units deposited in the ULs of the Carajás region (Souza-Filho et al., 2016a). The lake basement is represented by well-defined reflection with no penetration due to total acoustic reflection at the lateritic crust leading to strong

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amplitude lake-bottom multiples. The basal deposits correspond to basinward prograding clinoforms associated with delta fans located near the main drainage inflows. Underflow processes are responsible for carrying fine-grained particles towards the lake depocenter interrupted by siderite beds. The upper deposits are related to massive or structureless mud with some scattered peat fragments. This facies arrangement produces fining and thinning upward cycles. However, cycle thickness may vary if accommodation space is high enough to produce high deposition angles, such those observed on active ULs.

1.2. Regional physiography and climate

The studied ULs are situated in the plateaus of the Serra dos Carajás (Sul and Norte), do Tarzan, da Bocaína and Leste (Fig. 1), inserted into the Itacaiúnas River Watershed (IRW) that drains an area of around 41,300 km² (Souza Filho et al., 2016b). These lakes are active or inactive (filled) depending on the sedimentary filling stage (Guimarães et al., 2017). Considering the main vegetation types, HETF colonize the slopes of the plateaus and are associated with metavolcanic rocks of the Itacaiúnas Supergroup. SDF may be observed over fragile zones of detritic crust and mafic sills in the plateaus. Montane savanna (canga vegetation) occupies the largest areas over lateritic crusts, and it is mainly related to edaphic conditions (Skirycz et al., 2014).

The rainfall regime is characterized by two well-defined seasons, one rainy, regionally known as Amazonian winter, and another dry, which is called Amazonian summer (Lopes et al., 2013). The rainy (November to May) and dry (June to October) seasons are well defined, in which total annual rainfall can vary from 1,545 mm to 1,863 mm during the rainy season and from 159 mm to 321 mm during the dry season (Silva Júnior et al., 2017). The main weather system that affects the rainfall regime during the rainy season in southeastern Pará, in the Itacaiúnas River Watershed region, is the band of convective clouds of the Intertropical Convergence Zone (ITCZ). In the dry season, the rainfall regime is influenced by frontal systems, which are responsible for the convective activity over the eastern Amazon (De Souza et al., 2017). Specifically in the IRW region, the mean value recorded is 27.2°C, with a minimum annual temperature of 26.6°C in January and a maximum annual temperature of 28.1°C in September (Tavares et al., 2018).

2. Research methods

For morphological mapping of the lake basins, worldview-2 multispectral satellite imagery with 2 m resolution and LiDAR (Light Detection and Ranging) data were integrated to produce a digital elevation model (DEM). The images were orthorectified and the resulting digital values were converted to terrain reflectance by the ATCOR algorithm using PCI Geomatica 13. This dataset was used for interpretation of the morphological features and real-time navigation during field surveys, which were supported by a Differential Global Positioning System. The main lithotypes and soil samples were described and collected according to Maurity and Kotschoubey (1995) and Sahoo et al. (2017a).

Bathymetric data and seismic profiling were conducted in the active lakes using a 200 kHz Raytheon DE719E and StrataBox™ SyQuest Echo Sounders, respectively. The bathymetric maps and digital terrain model were designed for planimetric map with 1 m isobaths of interval and 3D view to allow a precise visualization of the lake morphology according to Silva et al. (2018). Based on these maps, 145 surficial (0-10 cm) sediment

samples were collected using a Van Veen Grab sampler. In addition, eleven sediment cores were collected using a Livingstone-type drive rod piston corer (operated over an adapted AIRE Leopard Cataraft) and a Russian peat borer on active and filled lakes, respectively (Table A.1; Figure A.1). Surface and core samples were described according to the classification system of lacustrine sediments of the Global Lake Drilling Program (Schnurrenberger et al., 2003) and facies analysis (Walker, 1992).

Major and minor elements in sediments, soils and crusts were determined in pulverized samples by inductively coupled plasma optical emission spectrometry (ICP-OES) and X-ray fluorescence spectrometry (XRF), while trace elements by inductively coupled plasma optical mass spectrometry (ICP-MS). Data accuracy analysis and statistical treatment were carried out according to Sahoo et al. (2019).

The main vegetation types were defined during field observation and DEM interpretation. See Guimarães et al. (2016) for detailed information about the methodological approach for vegetation survey and palynological analysis of the study site. Fertile material was incorporate in our pollen database (PALIITV). Thus, it helps to calibrate all pollen data of this work. In addition, artificial pollen traps (Gosling et al., 2003) installed along the drainage basin of the LTM2 Lake allowed the evaluation of the annual pollen signal of very small canga areas surrounded by HETF and SDF.

For $\delta^{13}C$ and $\delta^{15}N$ analysis, sediment samples were determined by an elemental analyzer coupled to a Continuous Flow Isotopic Ratio Mass Spectrometer (CFIRMS). Total sulphur (TS) and total organic carbon (TOC) were measured using a LECO CS-300 combustion analyzer. See Sahoo et al. (2017a) for more details about sample preparation and data treatment.

Around 1cm^3 of sediment was collected in the surficial and core (at intervals of around 2.5 to 5 m depth) samples for palynological analysis, which was based on classical techniques for palynomorphs extraction including acetolysis (Faegri and Iversen, 1989). Identification were conducted following Guimarães et al. (2018a).

One hundred twenty-four bulk samples of about 1-2 g each were collected for radiocarbon dating (Table A.2), which was performed by an Accelerator Mass Spectrometry (AMS). The age-depth model was made based on *B*ayesian *ac*cumulatio*n* (Bacon) histories for lake and peat deposits (Guimarães et al., 2016; Reis et al., 2017; Blaauw and Christen, 2011), using R as an interface and Intcal13.14c calibration dataset (Reimer et al., 2013).

For limnological study, water samples were collected (surface, middle and bottom of the lake) in both rainy and dry seasons between 2013 and 2016 using Van Dorn water sampler. Sample collection and analysis of various inorganic, organic and bacteriological parameters were carried out by using Bureau Veritas analytical facilities following referred guidelines (EPA 2004; SMEWW 2005; and CETESB 2006). In-site measurement of physico-chemical parameters were carried out using Horiba W-20XD multi sensor probe.

3. Surface geology and geobotany of the catchment basins

The lateritic crusts of the study area have distinct mineralogical assemblages and structural features, rheology and geomorphology, which rule its outcropping. Thus, they may be genetically classified as structured (iron-ore), detrital and Al-rich crusts (Fig. 2).

Structured and detrital crusts were formed by the lateritization of BIFs, and contain hematite, magnetite, goethite and secondarily, quartz and clay minerals. These crusts are generally thick and more resistant to modern weathering, and then, not suitable to soil formation, or forming only Petric Plinthosols (Nunes et al., 2015). In addition, they are

predominant on higher topographical quotas of the study site. On the other hand, crusts formed by the lateritization of mafic rocks (Al-rich crusts) have more clay minerals, as well as gibbsite, especially close to the saprolite horizon. They are less resistant to weathering, and occur on lower quotas than structured and detrital crusts. Thus, these crusts may produce thicker soils (i.e. Ferrasols).
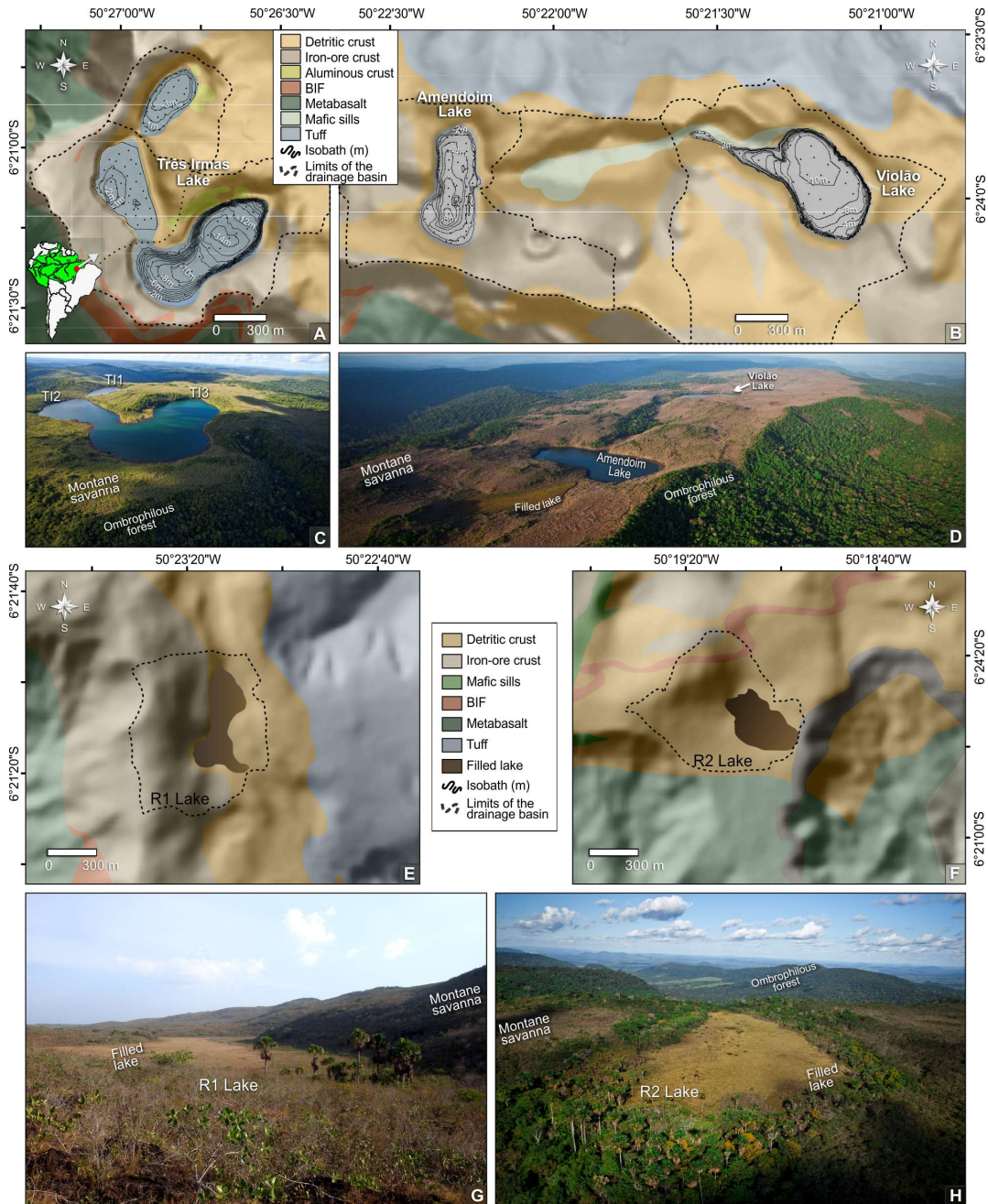

Fig. 2. A-B) Digital elevation model (DEM) integrated with bathymetric data showing western and eastern portion of the Serra Sul Plateau showing the main lithotypes described in the catchment basins of active ULs. Aerial photograph of the C) Três Irmãs, D) Amendoim and Violão Lake. E-F) DEM showing the main lithotypes described in the catchment basins of filled ULs. G-H) Aerial photograph of the filled ULs.

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The variability of lateritic crusts and resulting soils may rule the distribution of modern vegetation due to shallow, patchy and acidic soils with low water-retention and nutrient availability, high insolation and temperature (Skirycz et al., 2014; Schaefer et al., 2016). Therefore, the extensive cover of detrital and structured crusts allowed the widespread development of *canga* vegetation and hindered the colonization of tree species (Fig, 4a-d), such as SDF and HETF (Skirycz et al., 2014; Guimarães et al., 2014; Nunes et al., 2015). This is supported by the elevated foliar δ^{13}C values observed in Amazon *cangas* than in neotropical forests, which indicate a more pronounced water shortage in *cangas* than in forests (Mitre et al., 2018). SDF only occur over structural features and distinct rheological settings of the detrital and structured crusts, while HETF is restricted to soils over Al-rich crusts and mafic sills. The latter is predominant in the slopes of the of the Serra dos Carajás, and locally, on lake borders of the Três Irmãs and Violão lakes (Fig. 2a-d). Palms and macrophytes extensively occur on filled lakes (Fig. 2e-h). The dominant plant species of each physiognomy are described on Table 1.

4. Modern sedimentation patterns: Basin morphology and source-to-sink relationship

Lakes sediments are archives of various proxies that help to understand the local and regional climate. However, the profound interpretation of proxy data derived from lake sediment records requires an in-depth knowledge of the lake-specific modern sedimentological processes and their controlling factors such as rate of weathering, catchment materials and basin morphology (Viehberg et al., 2012; Wenrich et al., 2013; Hasberg et al., 2018). This helps to close the gaps in the knowledge on source-sink interactions through time.

This is particularly interesting for Amazonian ULs, which are located in the Carajás mineral province, as these lakes are best fit for paleoclimate studies (Guimarães et al., 2016, 2017). The active ULs of the Carajás region have mid-altitude ranges (695-725 m), very small surface areas (< 0.5 km^2), shallow to very shallow depths (< 10 m: mean depth), and catchments with relatively high declivities (> 20º and maximum of ~ 60º) (Silva et al., 2018). Violão and Amendoim lakes are separated by an intermediate basin that prevents any surface connection of water among them (Fig. 2b). The catchment of Amendoim Lake was composed by two active lakes (Fig. 2d), but the smaller one located in the western portion was progressively filled by detritic and organic sediments, and nowadays represents a swamp colonized by macrophytes (Guimarães et al., 2017). Once the three lakes of Três Irmãs are connected, the water flow follows the elevation gradient from TI1 to TI3 (Fig. 2c), forming a small waterfall between them (Silva et al., 2018).

The multi-proxy geochemical analyses of surface sediments of these lakes, soils and lithotypes of their catchments, supplemented by statistical methods, evaluated the major factors such as catchment lithology, source area weathering, transport, and depositional processes that influencing the modern sedimentation in the lakes (Sahoo et al., 2015, 2016a, 2017a, 2019). The results show that detritic sediments are mainly enrichment of Fe_2O_3 and P_2O_5 and Se when compared to upper continental crust (UCC). High Chemical Index of Alteration (CIA), Mafic Index of Alteration (MIA) and Index of Laterization (IOL) values indicate intense chemical weathering at source areas, however, similar values between soils and catchment rocks indicates the weathering transformation between them and its erosion led to its deposition as sediment into the lakes (Sahoo et al., 2017a).

PCA analysis shows 5 major groups of geochemical association (Fig. 3a), with the major detritic groups being similar to catchment basin laterites (Sahoo et al., in 2019). The Ti-Zr-Hf-Y-Nb-HREEs (Gp-1) corresponds to resistant minerals, which possibly remained stable during lateritization, while different behavior of LREEs (Gp-2) relative to HREE indicates their relative mobility during laterite formation and reprecipitation by REE bearing minerals. The Al-Sc-V-Cr association (Gp-3) in sediments reflects the signature of country rock, such as metavolcanic components. TOC-SO3-Hg-Se (Gp-4) is controlled by organic matter, while Fe-P-Mo-As-Zn (Gp-5) in sediments is influenced by Fe-oxyhydroxide precipitation.
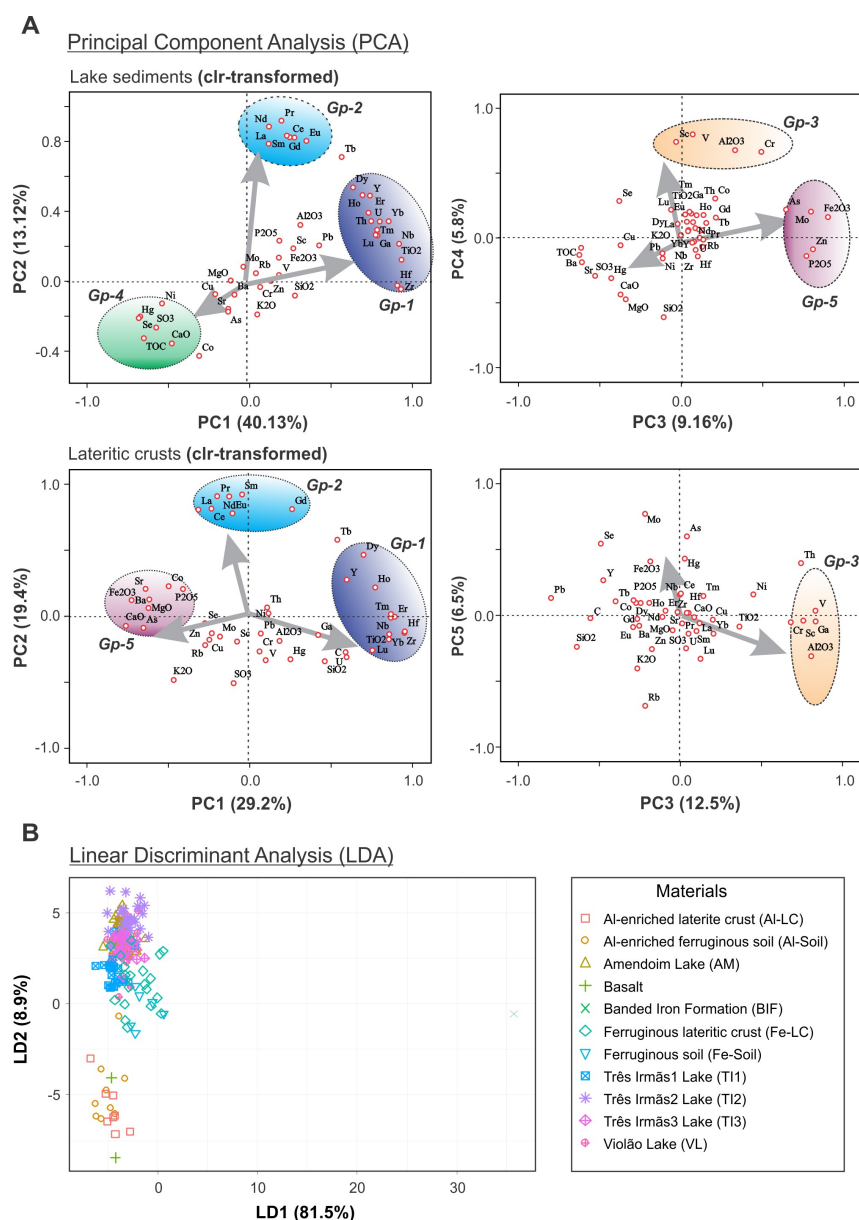

Fig. 3. Principal component analysis (PCA) biplot of PC1 vs PC2 and PC3 vs PC4 for all lake sediments and catchment lateritic crusts, based on centered log-ratio (clr) transformed data, showing the different geochemical associations and the major detritic signatures similar between them (A); and Linear discriminate analysis (LDA) showing the distribution of lake sediments with

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relationship with catchment basin materials (B) (modified from Sahoo et al., 2019).

The detritic association of Gp 1, 2 and 3 similar with catchment rocks indicates a strong influence of catchment basin lithology and laterization process. Multivariate analysis such as Linear Discriminant Analysis (LDA) further indicates that detritic sediments are not directly derived from the parent rocks (Fig. 3b), but are well correlated with the underlying weathered crusts (mainly ferruginous) and soils, while ferruginous laterite crusts are the major source of detrital sediments. This inference clearly demonstrates that lake sediments can be a potential tool for identifying and describing catchment processes and basin lithology.

The geochemical proxies further support the interpretation of depositional conditions and revealed that sediments are deposited under oxic depositional enrichment (Sahoo et al., 2015, 2016a), and the elements in sediments have less post-depositional changes, despite having high enrichment of TOC and Fe. All these fundamental knowledge of the modern lake sedimentary processes of Amazonian ULs and its lake catchment interactions thus can provide a crucial insight for the interpretation of source-sink relationships and paleoclimate reconstruction in future studies.

Principal component analysis (PCA) performed on centred log transformed (clr) data was evaluated the relationships of the geochemistry of the bottom sediments among filled lakes (Fig. 4). In general, sediments from each zone show distinguished characteristics. Bocaína (LB) lakes were mostly differentiated from others as they loaded weakly on PC1 and negatively on PC2. It is related to the lateritic crusts of this area that were formed mostly from metavolcanic rocks. Thus, the lake sediments have higher concentrations of Al, Ti, Cr, V, Sc and associated elements. Filled lakes of the Serra Sul have widely varied in geochemical compositions, part of the samples positively loaded PC1 and part of loaded on PC2. This is mostly associated with Fe as well as Si, indicating that the crusts developed mainly from iron formations, which have significant concentrations of Fe, while Si contribution from BIF. Sediments from ST02 Lake show mostly negatively loading on PC1 and positively on PC2. This is partly associated with Fe suggesting that the crusts are similar with Serra Sul, but the high enrichment of Co, Cu, Mo, P, Cr and P in these sediments indicates strong influence of mafic rocks, which is not exactly similar with Bocaína.
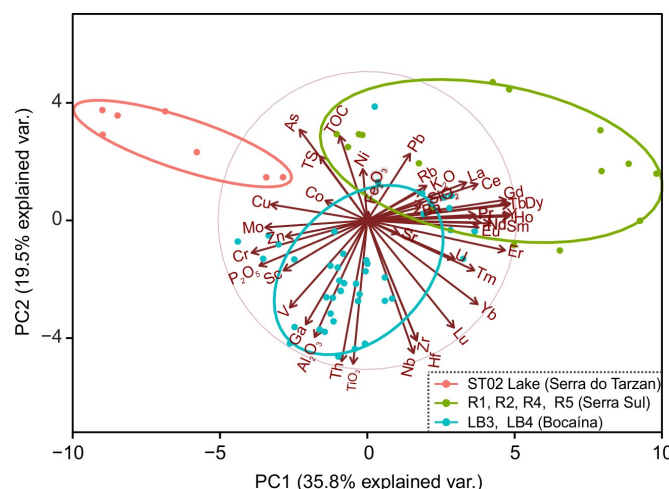

Fig. 4. Principal component analysis (PCA) performed on centred log transformed (clr) data for all filled lakes (sediment cores).

5. Environmental influences on limnology and water quality

In closed lake basin, local geology and seasonal climate are the major factors controlling the physical and chemical characteristics of waters such as temperature, thermal stratification, lake levels and nutrient availability (Catalan and Rondon 2016; Sahoo et al., 2017b). These parameters can have a significantly influence on lake trophic states, phytoplankton assemblage as well as the overall planktonic abundance (Molisani et al., 2010). To address these issues, Sahoo et al. (2017b) presents the first integrative approach of limnological study on the ULs in the Carajás region. The results show that waters were mostly acidic in nature (avg. pH 4.9–5.9), with high total Fe (up to 1.52mg/L) and low SO_4 and other metal concentrations. Low pH can be explained by the absence of base and by the ferruginous lateritic nature of the catchment, as well as high sedimentary organic carbon which releases CO_2 and H_2S by bacterial decomposition that make the water acidic (Wetzel, 2001). The main reason behinds the high levels of Fe is the weathering and erosion of ferruginous soils and laterites crusts. The chemical compositions of these lakes indicate catchment geology is one of the dominating factors influencing water chemistry.

These ULs are shallow, weakly stratified (Fig. 5a), and classified as polymictic type, which controlled vertical mixing of limnological parameters (Sahoo et al., 2017b). Although water quality index (WQI) shows good water quality and high similarity among the studied lakes, the trophic state of these lakes varied significantly from ultra-oligotrophic to eutrophic states (Fig. 5b), with lower values observed for Amendoim Lake (Sahoo et al., 2017b). High trophic states are due to nutrient concentrations, mainly TP (total phosphorous), promoting algal growth. Sources of TP for these lakes are associated with the presence of mafic rocks, and caves with high guano volume (Sahoo et al., 2016b, 2017b). Although, Chl-a and cyanobacteria are mainly influenced by nutrients such as TP, this is not the case for these lakes, rather they are controlled by additional factors such as seasonal climate conditions, specificities of catchment lithology and lake morphology (Sahoo et al., 2017b).

Phytoplankton taxa in the lakes are characterized by small chroococcales groups and desmids together with filamentous algae, more commonly observed in the dry season. Phytoplankton composition also varied among lakes based on differences in water depth and nutrient concentration, which may be regulated, by local factors such as lake depth, nutrient status that may influence the degree of biological response (Sahoo et al., 2017b). This study outcome contributes to understand the common limnological characteristics of Amazonian ULs and its role in controlling geochemical distribution of elements and diagenetic process in sediments.
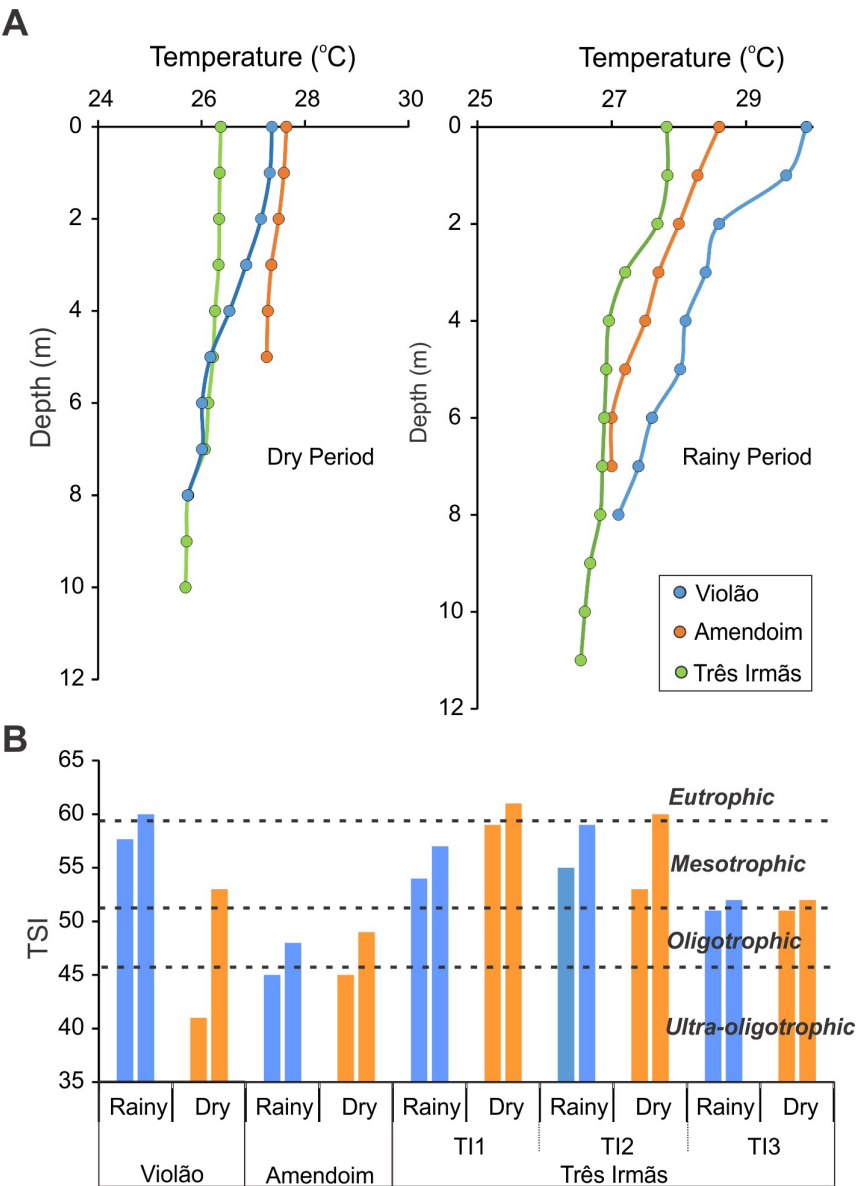
Fig. 5. Vertical temperature profile in Violão, Amendoim and Três Irmãs lakes during the dry and rainy seasons showing the thermal stratification of the lakes (A), and Trophic State Index (TSI) of the lakes during both dry and rainy seasons showing the significant variation of trophic state between lakes (modified from Sahoo et al., 2017).

6. The role of isotopes in understanding the sources of sediment organic matter

Sources of organic matter to ULs may be highly variable deriving from vegetation cover of the catchment and central basins, as well as lacustrine primary and secondary productivity (Sahoo et al., 2017a). Morphology and morphometry are important attributes for controlling trophic state of ULs of the Carajás region. The mid-altitudinal ranges, very small catchment area and shallow to very shallow central basins make these ULs sensible to eutrophication processes (Silva et al., 2018). Very shallow central basins are favorable to *in-situ* development of macrophytes. Thus, modern sediments

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from active and filled ULs may present distinct signatures of the carbon and nitrogen isotopes (Fig. 6a-d).
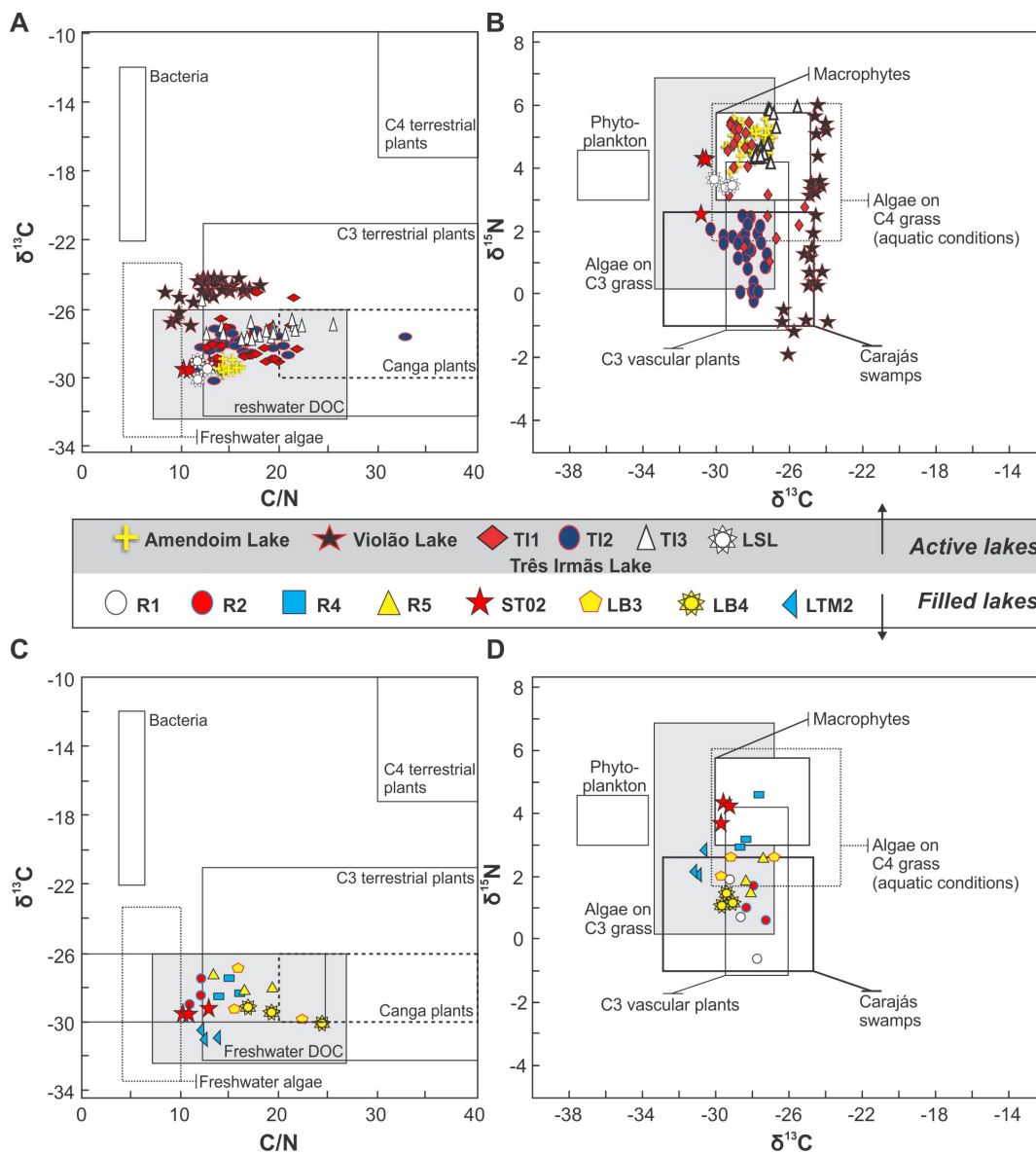

Fig. 6. Binary plot of (a) $\delta^{13}C$ vs. C/N and (b) $\delta^{15}N$ vs. $\delta^{13}C$ of the surficial sediments of the active ULs, and (c) $\delta^{13}C$ vs. C/N and (d) $\delta^{15}N$ vs. $\delta^{13}C$ of sediment cores from filled ULs of the Carajás region (fields based on Deines, 1980; Boutton, 1991; Hamilton and Lewis, 1992; Thornton and McManus, 1994; Meyers, 1997; Brenner et al., 1999; Troxler and Richards, 2009; Smith et al., 2012; Sahoo et al., 2015, 2016a, 2017a; Reis et al., 2017),

The $\delta^{13}C$ and $\delta^{15}N$, and C/N data from surficial sediments of the Violão Lake indicate that the organic matter comes from the siliceous sponge spicules, algae, and C3 vascular forest plants (Sahoo et al., 2015). The latter is dominant in the shallower portion of this lake (arm), with more impoverished $\delta^{15}N$. Considering the Amendoim Lake, the stable isotopic compositions are quite homogeneous, and suggest organic sources composed of submerged macrophytes and palms (Sahoo et al., 2016a). More

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diversified sources occur in the Três Irmãs Lake. The isotopic and elemental signatures are indicative of C3 plants, macrophytes and freshwater DOC, while TI2 Lake has a lower influence from aquatic organic matter, quite similar with the arm of Violão Lake based on $\delta^{15}N$ values (Fig. 6a, b).

Filled lakes developed over structured and detrital (R1, R2, R4, R5) and Al-rich crusts (ST02, LB3, LB4, LTM2) are mainly composed by organic matter derived from freshwater DOC, C3 plants and algae, while canga plants are less represented or its signals are diluted with other organic sources (Fig. 6c, d). Enriched values of $\delta^{15}N$ indicate slightly higher aquatic influence on LTM2 and ST02 lakes. More impoverished values of $\delta^{13}C$ occur in LTM2. This site is located into a very narrow plateau with an area of around 0.033 km^2 surrounded by HETF. HETF has more profound soils with higher water availability than lateritic crusts. Adaptations to seasonal droughts makes canga plants be characterized by higher water shortage, and consequently, more enriched values of $\delta^{13}C$ than HETF (Mitre et al., 2018). Thus, the signal from HETF must be predominant in the sedimentary organic matter of LTM2 Lake.

7. Modern pollen rain using ULs sediments

Edaphic conditions developed in the plateaus of the Carajás region lead to the formation of islands of canga plants, structurally and compositionally different from the surrounding matrix, with a large number of endemic species (Skirycz et al. 2014; Nunes et al., 2015). Any comparisons with other savanna physiognomies should consider pollination strategies related to environmental conditions (Guimarães et al., 2018a). The pollen signal of HETF may overlap the signal of small savanna due to high production and enhanced dispersal capacity, but this is not always true.

The modern pollen rain of Violão Lake was evaluated using surficial sediments shows significant differences regarding its spatial distribution (Guimarães et al., 2014). Pollen from canga vegetation is predominant in the lake, occurring in eastern and western portions. Pollen grains from HETF and SDF are concentrated in its arm, while algae spores are mainly observed in the central portion. The comparative analysis between floristic inventories of the catchment basin and modern pollen rain indicates that pollen from canga plants are brought into Lake Basin from 'regional' sources (outside the basin). On the other hand, pollen grains from HETF and SDF represent local sources (inside the basin).

Modern pollen rain based on Amendoim Lake, located ~1 km eastward and 20 m below the mean altitude of the Violão Lake (Fig. 2), shows that pollen from HETF and SDF are dominant on surficial sediments, despite the widespread abundance of canga plants in its drainage basin. This suggests the role of topographic control and prevailing wind direction on pollen deposition (Guimarães et al., 2017). In the same way, one-year (2015-2016) of pollen data collected from artificial traps installed along the drainage basin of the LTM2 Lake reveal did not indicate overlaps of pollen signal between vegetation types (Fig. 7). These findings based on surficial lake sediments and artificial traps contradict the assumption of D'Apolito et al. (2018) that a clear savanna signal will only be acquired in sites with a large extension of this vegetation type.
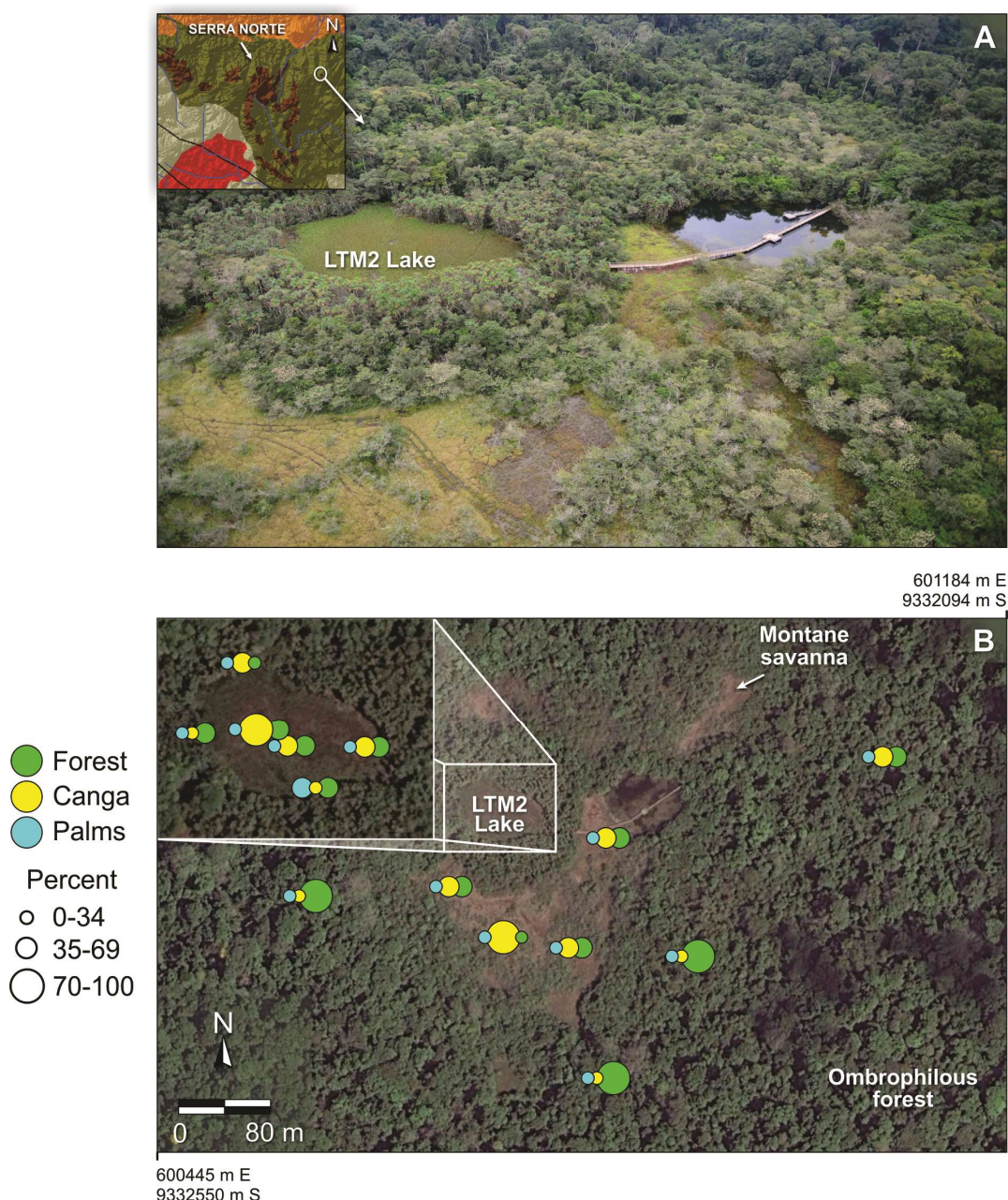
Fig. 7. Modern pollen rain of catchment basin of the LTM2 Lake, Serra Norte dos Carajás (a), showing the annual contribution (in %) of grains from forest, canga and palms (b).

Amendoim Lake is the unique active and oligotrophic lake of this region (Sahoo et al., 2016b). This trophic condition favored the widespread development of *Isoetes cangae*, which only occurs in this lake (Pereira et al., 2014; Caldeira et al., 2018). In addition, this species is very well represented on surficial sediments by its microspores (Guimarães et al., 2017). Thus, the use of *Isoetes* microspores as a proxy for low water levels, eutrophic and drier paleoclimate conditions must be used with caution.

These studies clearly indicate the importance of understanding (1) the ways in which modern pollen grains are transported into lakes, (2) the relationship between pollen and regional or local vegetation signals, (3) the modern vegetation types considering a clear

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taxonomic and ecological determination, coupled with a robust pollen database of the studied site. This approach should precede any effort for paleovegetation reconstruction.

8. ULs sediments: implication for paleovegetation and paleoenvironmental changes

Previous palynological studies in sediment cores collected from filled ULs of the Serra Sul dos Carajás indicated drier glacial conditions of the late Pleistocene (Absy et al., 1991; Hermanowski et al., 2012), based on high and low abundance of canga (Poaceae, *Borreria*, Asteraceae, among others) and forest taxa (e.g. *Alchornea/Aparisthmium*, Moraceae and *Celtis*), respectively. However, these canga taxa in Carajás were generally over-represented (Guimarães et al., 2018a). In edaphically conditioned areas, such as those observed for canga vegetation of Carajás, most of the plants lose their leaves and do not produce flowers during drier months (June to September), remaining in an almost dormant state to save energy due to strong hydric stress (Sahoo et al., 2016b). Thus, high abundance of pollen from over-represented taxa did not directly indicate expansion of canga plants under drier conditions. In addition, all previous work on Carajás was conducted on swampy grasslands, so most of these records may reflect hydrarch succession and basin-filling rather than a paleoclimate signal (Guimarães et al., 2018a). Considering the effects of diagenesis on glacial deposits of these lakes, siderite beds commonly occur in down-profile and are timely correlated with the supposed savanna (canga) expansion (Absy et al., 1991; Soubies et al., 1991; Guimarães et al., 2016; Reis et al., 2017).

Siderites in ULs of Carajás are associated with post-depositional processes where biologically mediated diagenesis degraded organic material, converting ferric to ferrous iron and generating CO_2 that caused massive siderite precipitation (Guimarães et al., 2016). It also influences elemental and isotopic composition of the bulk organic matter (Meyers and Teranes, 2001), as well as strongly degrade biopolymer components, producing selective preservation of pollen grains (Guimarães et al., 2018a). Thus, plants that produce large quantities of pollen, and those that produce high resistant grains may prevail in pollen assemblages (Reis et al., 2017).

This suggests that other proxies must be carefully integrated and analyzed with pollen data to understand paleoenvironmental and paleoclimate conditions of this region. Furthermore, ULs of Carajás region has different geomorphological setting (Silva et al., 2018), which influences sediment yield and geochemical characteristics, resulting from complex basin processes from sources to sinks of the sediments.

Active lakes (Três Irmãs, Violão and Serra Leste) do not present problems with hydrarch succession and basin-filling in their deposits. Absence of woody roots and physical or geochemical indicators of subaerial exposure indicate that these lakes never dried up during the last 50 ka cal BP. Based on geochemical proxies, the detrital fraction (Al and Ti) provides insight about climatic conditions prevailing in source areas and mechanisms involved in the transport of materials within the basin (Guimarães et al. 2016). When rainfall is strong enough it can cause high erosion and high detrital input to lakes (Oliveira et al., 2009), as shown by an increase of Al and Ti. Ti and K are typically associated with clays and increase in the Ti/K suggest high amounts of weathered clay minerals deposited during high water stands and wetter periods (Hodell et al., 1998). Therefore, Al/K and Ti/K are very well correlated and slight increased values seems to be fitted with Heinrich Stadials (HS) 1-3. This may be attributed to an increased precipitation due to a strengthening of the South American summer monsoon due to a change in the Atlantic interhemispheric sea surface temperature (SST) gradient

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(Zhang et al., 2016), also affecting eastern Amazon. It interrupted a generalized drier period in the beginning of the LGM until around 13 ka cal BP (Fig. 8). Carbon and nitrogen isotopes indicates continuous predominance of C3 plants and freshwater DOC, except for Violão Lake that presented more enriched values throughout the late Pleistocene until 20 ka cal BP. This may be indicative of the presence of siderite nodules (Guimarães et al., 2016; Reis et al., 2017), which massively formed in the Violão Lake at around 30 to 35 ka cal BP, and dilution with algae on C4 grass environment (aquatic conditions).
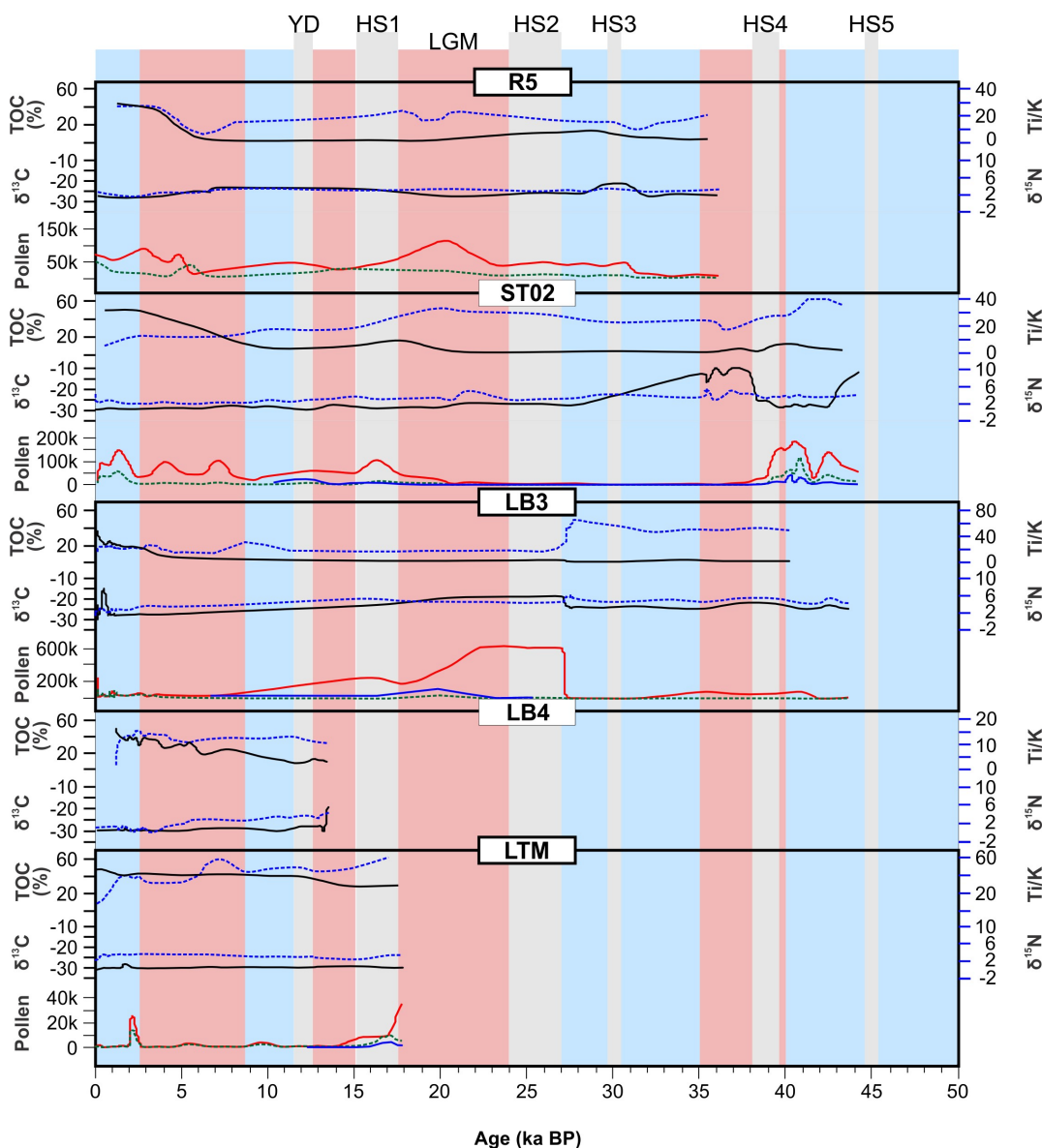

Fig. 8. Generalized profile of the geochemical (Al/K with black line, Ti/K with blue-dashed line), isotopic (δ^{13}C with black line, δ^{15}N with blue dashed line), and pollen (canga vegetation with red line, forest with green line and cool-adapted taxa with blue line) data of active (3 Irmãs, Violão and Serra Leste) and filled (R1, R2, R4, R5, ST02, LB3, LB4 and LTM) lakes. Light blue and red vertical bars represent wet and dry lacustrine phases in the ULs of Carajás

according to Sifeddine et al. (2001), Guimarães et al. (2016, 2018b), Reis et al. (2017). Divided in 2 parts.

High Al/K and Ti/K values infer high amount of weathered clay minerals deposited during the high water stands and wetter period in the Holocene deposits of the active lakes, except for the relatively low ratios around the mid-Holocene (Fig. 8). In general, Increase of Al/K and Ti/K ratio is an indication of high amounts of weathered clay minerals, which can be deposited during high water stands and occurred during wetter periods. This will also be favored during the cycling of dry to wet period. During Dry periods, occasional rainfall leads to weathering and these materials transported during heavy rainfall event. Additionally, pollen data of the Serra Leste covering the last 15 ka cal BP showed that canga vegetation and forests concomitantly contracted and expanded in a cyclic pattern during the last 5 ka cal BP. This is a clear indicative of the predominance of a strong millennial climate seasonality.

Filled lakes over structured and detrital (R1, R2, R4, R5) and Al-rich crusts (ST02, LB3, LB4, LTM2) are more influenced by the basin-filling effect. In this way, the establishment of modern swampy conditions (final filling stage) varied according sites. These conditions were attained in the R1, R5, ST02 and LTM2 lakes around 10 ka cal, while R2 and LB3 lakes at 5 ka cal BP, and R4 and LB4 at 2 ka cal BP, which is clearly observed from their TOC, carbon and nitrogen isotopic profiles (Fig. 8). The detrital fraction of these cores follows the cycles of lake level and paleoclimate changes in Carajás region, with good records for the LGM and mid-Holocene, as described by relatively low Ti/K. However, differently from the active lakes, the Ti/K profiles between the late Pleistocene and Holocene deposits of the filled lakes cannot be compared since the latter was represented by modern swampy condition. In other words, swamps developed on lakes under low accommodation space when accommodation angle (measured between lake margins and depocenter) decreases at a point restricting to the deposition of detrital materials from runoff to lake margins.

Dryness with subaerial exposure of lacustrine deposits were observed on ST02 Lake during the LGM, and on LB3 and R2 lakes during the mid-Holocene. However, C4 plants were never predominant in the Carajás region, except for the LB3 area that record canga expansion with C4 plants during the LGM, without siderite influence (Fig. 8). Siderites were formed between around 35 to 30 ka cal BP on R5 and ST02 lakes, and during the LGM on R1 and R2 lakes. Serra da Bocaína Lakes do not present iron carbonates such as siderite, which may be related by the different depositional conditions as well as lower abundance of Fe in crust, which leads to lower aqueous iron (Lemos et al., 2007; Kimberley 1989).

Cool-adapted taxa widespread developed along the Carajás region and occurred all over the late Pleistocene until around 7 ka cal, with higher abundance observed before 40 ka cal BP. This is not indicative that colder periods occurred during this period. In fact, most of the LGM deposits were not suitable for high pollen concentration due to the sediment redox condition influenced by diagenetic changes, except for the LB3 Lake that recorded higher abundance of cool-adapted taxa during LGM.

The Interpretation of speleothem data from Paraíso cave in eastern Amazonia indicate wetter climate conditions than present at around 6 ka cal BP (Wang et al., 2017). This contradicts a long set of paleoclimate studies in the Carajás region, that indicates dominance of montane savanna and SDF during the mid-Holocene under drier climate conditions (Absy et al., 1991; Sifeddine et al., 2001; Cordeiro et al., 2008; Hermanowski et al., 2014; Guimarães et al., 2016, Reis et al., 2018; Guimarães et al., 2018b). Assumptions about the Holocene pollen assemblage of Carajás only reflect

canga vegetation with small signals from HETF, then reflecting local changes on the plateau itself and making difficult any regional scale vegetation changes (Smith and Mayle, 2017), must be viewed with caution. Smith and Mayle (2017) authors based their assumptions on the modern pollen rain of the Violão Lake (Guimarães et al., 2014), while the modern pollen rain of the Amendoim Lake shows the opposite, with predominance of the pollen signal from HETF (Guimarães et al., 2017). Thus, it depends on the topographic position of each lake, wind direction among others factors (Guimarães et al., 2018a).

Drier mid-Holocene on Carajás region was proposed by Sifeddine et al. (2001), Cordeiro et al. (2008), Guimarães et al. (2016), Reis et al. (2018), Guimarães et al. (2018b) mainly based on multi-elemental and organic isotope geochemistry with strong indications of hydric deficit, low weathering and sedimentation rates. In addition, LB3 and R2 lakes (~ 40 km distant from each other) were sub aerially exposed during this period with full formation of iron oxides and mud cracks (Figure A.2). The drier mid-Holocene event was widespread indicated along the southern tropics (Cross et al. 2000; Seltzer et al. 2000; Mayle and Power 2008; Cordeiro et al. 2008; Guimarães et al. 2012; Prado et al. 2013), and by numerical simulations (Maksic et al., 2018). This may be a consequence of low insolation, which induced a less effective land–sea contrast, reducing South Atlantic Convergence Zone intensity and weaker South American Monsoon System (SAMS) (Prado et al., 2013; Maksic et al., 2018).

9. Conclusions

The multidisciplinary research approach compiled in this review helps to clarify some key doubts about the formation of the Carajás, as well as the apparent mismatches of plant and paleoclimate dynamics during the last 50 ka cal BP. The ULs were formed by structural and dissolution of the lateritic crusts during the late Cenozoic, and possibly start to fill with sediment during the Quaternary. The study of the modern environments of deposition allowed the calibration of the down-profile data from lake deposits. Thus, it is possible to relate detritic facies with predominant chemical weathering and peat facies with swampy conditions, high primary productivity or macrophytes development under ultra-oligotrophic conditions, depending of the accommodation space. The cyclical pattern of the sediment deposition with alternating beds of mud, peat and siderites reveals that paleoclimate seasonality was stronger during the Holocene than the previous epoch, which was clearly evidenced by stratigraphy, multi-elemental and isotope geochemistry, and pollen data. ULs were strongly influenced by drier paleoclimate conditions of the LGM and mid-Holocene with very low detrital inflow, subaerial exposure of lake deposits and large formation of siderites (late Pleistocene). However, there is no signal of widespread expansion of savanna during the studied period.

Supplementary Material: Table A.1. General description of the surface sediment samples and sediment cores collected from the upland lakes of the Carajás region; **Table A.2.** Radiocarbon dates (AMS) of the samples from Carajás region; **Figure A.1.** Graphic sedimentary Log of the active lakes: LTI3 (3 Irmãs-S11), LV2 (Violão-S11), LSL (Serra Leste); and inactive lakes: R1, R2, R4 and R5 (S11). Continued; **Figure A.2.** Graphic sedimentary Log of the inactive lakes:ST2 (Serra do Tarzan), LB3 and LB4 (Serra da Bocaína), LTM2 (Lagoa Trilha da Mata-Serra Norte).

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