Basin morphology, sedimentology and seismic stratigraphy of an upland lake from Serra dos Carajás, southeastern Amazon, Brazil

Morfologia da bacia de drenagem, sedimentologia e sismoestratigrafia de um lago de planalto da Serra dos Carajás, sudeste da Amazônia, Brasil

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Abstract: To understand the sedimentary processes in a lake environment, it is essential to investigate the morphological, sedimentalogical and limnological features of the basin. The present study was developed at Violão Lake, Serra Sul de Carajás. The methodological approach comprises the collection of bathymetric and sedimentary data, and shallow seismic profiles. Lake Violão has a NE-SW elongated guitar-shaped form and ~0.3 km^2 of surface area, with a perimeter of ~2.7 km. The lake presents washing basin morphology and it is marked by a steep margin carved in duricrust outcrops, while the bottom is flat and constituted mainly by muddy sediments. The water column is stratified only during the dry season and it is mixed in the rainy season. Three seismic stratigraphic successions were identified in the lake resting on prominent basal reflector (bedrock), which reaches a maximum depth of ~15 m. Small lobate masses are deposited in the bottom of the lake from underflows, while the central part of the lake is characterized by drape deposition, suggesting that organic-mud sedimentation is associated to pelagic deposition from dilute interflows or overflows. Therefore, the sedimentary processes are strongly regulated by basin morphology, drainage water inflow and thermal stratification of the water column.

Keywords: Upland lake. Sedimentology. Lacustrine sedimentary facies. Amazon.

Resumo: Para compreender os processos sedimentares em um ambiente lacustre, é essencial investigar os processos morfológicos, sedimentares e limnológicos. O presente estudo foi desenvolvido na lagoa do Violão, Serra Sul de Carajás. A abordagem metodológica incluiu a coleta de dados batimétricos, sedimentológicos e sísmicos. A lagoa apresenta forma de violão, alongada na direção NE-SW, ocupando uma área de ~0,3 km^2, com perímetro de ~2,7 km. O lago apresenta uma morfologia de bacia de lavar roupa, com margens íngremes em afloramentos de crosta laterítica ferruginosa. O fundo plano é constituído principalmente por sedimentos lamosos. A coluna de água apresenta uma estratificação térmica somente durante a estação seca, sendo misturada no período chuvoso. Três sucessões sismoestratigráficas foram identificadas no lago, que apresenta uma espessura de sedimentos de ~15 m sobre um refletor basal. Pequenos lóbulos deltaicos são depositados no fundo do lago a partir de correntes de turbidez, enquanto a parte central do lago é caracterizada pela deposição por decantação de sedimentos finos, sugerindo que a de sedimentação da lama orgânica está associada a fluxos intermediários ou superficiais. Portanto, os processos sedimentares são fortemente regulados pela morfologia da bacia, pelo influxo de água de drenagem e pela estratificação térmica da coluna de água.

Palavras-chave: Lagos de altitude. Sedimentologia. Facies sedimentares lacustres. Amazônia.

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INTRODUCTION

Upland lakes over lateritic crusts can only be found in the Brazilian Amazon in Morro dos Seis Lagos (Cordeiro *et al*., 2011), Maicuru-Maraconai (Costa *et al*., 1991), and Serra dos Carajás (Costa *et al*., 2005), in the western and eastern Amazon region, respectively. On the contrary of alluvial lakes, upland lakes over lateritic crusts are hydrologically restricted, located above 350 m above mean sea level (AMSL), and formed by structural and degradation process of lateritic profiles (Maurity & Kotschoubey, 1995), where sinkhole lakes have been developed.

Tropical upland lakes in Amazon Region are considered excellent testimonies to study climate and rainforest changes during the Quaternary (Soubies *et al*., 1991; Sifeddine *et al*., 2001; Costa *et al*., 2005; Hermanowski *et al*., 2012a). Most researches over the last few decades dealt with proxy records from palynology, geochemistry, isotopic analysis and radiocarbon chronology to infer environmental history related to climatic changes during Pleistocene and Holocene (Cordeiro *et al*., 2011; Hermanowski *et al*., 2012b).

The use of multi-proxy approaches based on geochemical, isotopic composition and palynology of superficial sediments from a plateau lake in Carajás were investigated to delineate lithological compositions of sediments, source area weathering, provenance and geochemical processes (Sahoo *et al*., 2015) and source and spatial distribution of pollen and spores (Guimarães *et al*., 2014). Even without influence of the fluvial system, there are several controls on the lake processes driving flow and sedimentary processes, such as basin morphology, changes in the type of sediment and its rate of supply (Blais & Kalff, 1995), limnological parameters (Aguilera *et al*., 2006), water-circulation pattern of the lake (Laval *et al*., 2003), and water-level changes due to variable inflow, precipitation and evaporation (Talbot & Allen, 1996; Bridge & Demicco, 2008; Dietze *et al*., 2010).

The use of an integrated approach was never been applied to investigate sedimentary processes in upland lakes of the Amazon region. Therefore, the combination of basin-morphology, sedimentology, limnological parameters and seismo-stratigraphic studies will improve significantly the knowledge about sedimentary processes in upland lakes. This study in Lake Violão follows a comprehensive morphological, sedimentological and limnological approach to improve understanding of the sedimentary processes and their associated deposits of the upland lakes in the Amazon region.

REGIONAL SETTING

Serra dos Carajás represents a metallogenic province on a global scale (Tolbert *et al*., 1971). This region is recognized as major Archean tectonic province of the Amazonian Craton (Macambira & Lafon, 1995; Rämö *et al*., 2002). The large iron deposits occur associated with the Carajás Formation, a dominant volcano-sedimentary sequence that host significant band-iron formation (Olszewski *et al*., 1989).

The lateritization of the Carajás Formation's rocks occurred under humid climate conditions that allowed the formation of an extensively weathering profile on basic volcanic and iron formations rocks (Maurity, 1993). This alteration mantle is constituted by iron-aluminous laterite, hematitic breccias, ortho and paraconglomerates (Maurity, 1993). With the development of lateritization processes, fragile zones associated with preexisting fractures, sinkhole and lakes can be formed with several caves on their borders (Maurity, 1993; Maurity & Kotschoubey, 1995).

Violão Lake is located in the Serra Sul dos Carajás, more specifically in the S11D (Figure 1). It represents a hydrologically restricted lake that evolved from geochemical and structural processes of the lateritic crusts. The lake is situated in a ridge about 730 m above mean sea level (AMSL), presenting an elongated form along NW-SE direction. Slopes with open forests occur over fractured detritic crust and mafic sills, while montane savanna occupies the largest areas over iron-ore duricrust and detritic crust (Guimarães *et al*., 2014).

The modern climate of this area is tropical humid, with a mean annual temperature of around 26 °C, with around 28 °C during the dry season (June to November). The total annual precipitation ranges from 1,800 to 2,300 mm (Moraes *et al*., 2005), with a total mean and median of around 1,550 mm during the rainy season (December to May) and 350 mm during the dry season (June to November).

MATERIAL AND METHODS

In order to satisfy the requirements of detailed morphological mapping, a multispectral high spatial resolution image of satellite Worldview-2 was acquired on May 19, 2013 (Figure 1). Furthermore, Light Detection and Ranging (LiDAR) data was used for generation of digital terrain model (DTM). The planimetric mapping was referenced to WGS 84 in UTM zone 22.

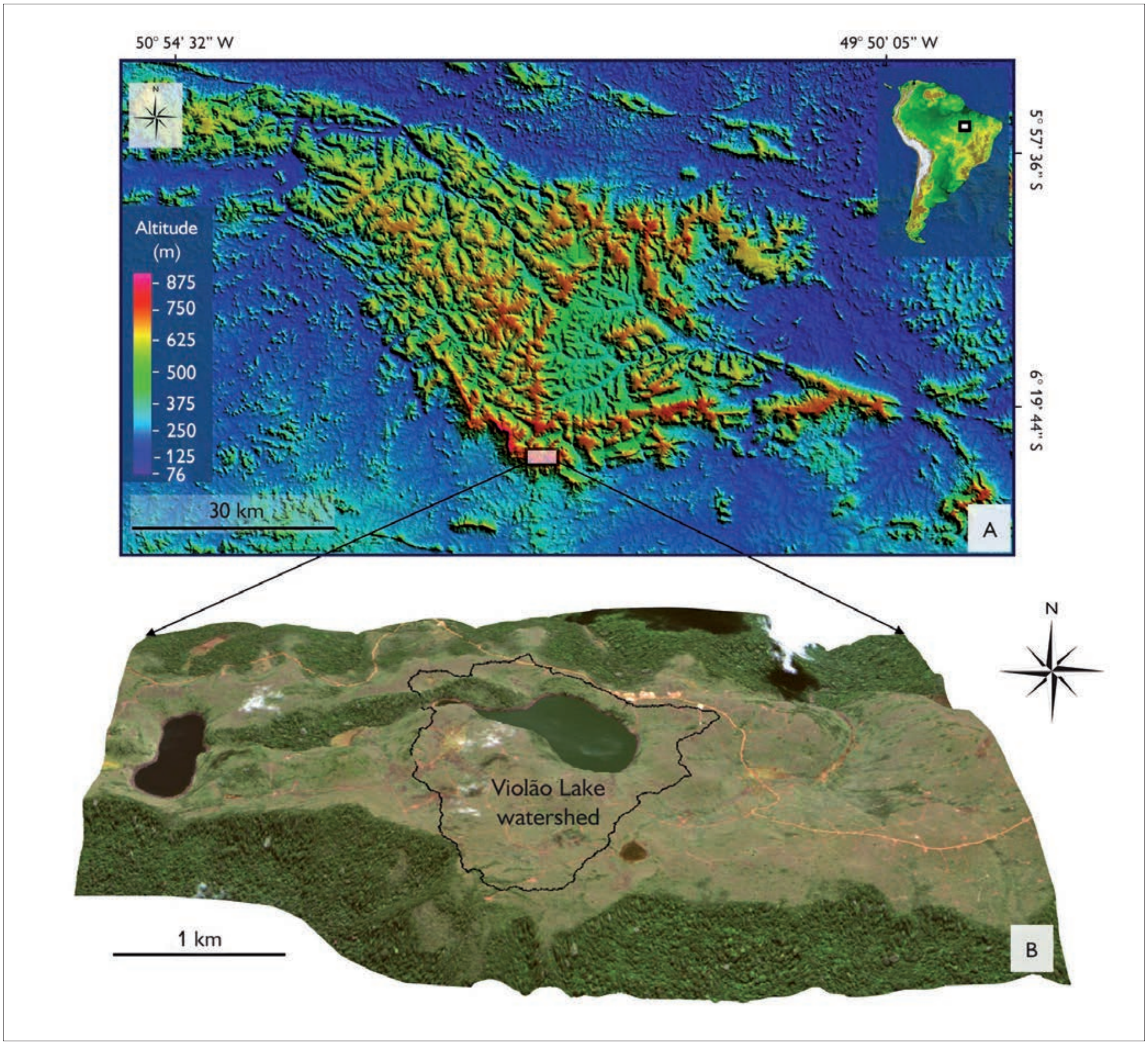

Figure 1. A) Location map of the Lake Violão basin and its catchment in the context of the Serra dos Carajás, southeastern Amazon region in SRTM3-color hillshade; B) 3D visualization of Lake Violão in the Serra Sul S11D viewed in WorldView-2 image color composition 5R3G1B.

The bathymetric map was generated from 107,388 sampling points in a total of 29 km of bathymetric lines gotten in September 2012. The integrated acquisition of bathymetric and Differential Global Positioning System (DGPS) data were based on Hypack 6.2b software. The points were interpolated using Kriging geostatistical method in Surfer 11 software. The bathymetric map and digital terrain model were designed for planimetric map with 1 m isobaths of interval. The integration of bathymetric data with LiDAR topography allowed a 3D visualization of the Lake Violão bottom morphology and adjacent emerge areas (Figure 2). Morphometric parameters and indexes were calculated to the lake level zero in September 2012.

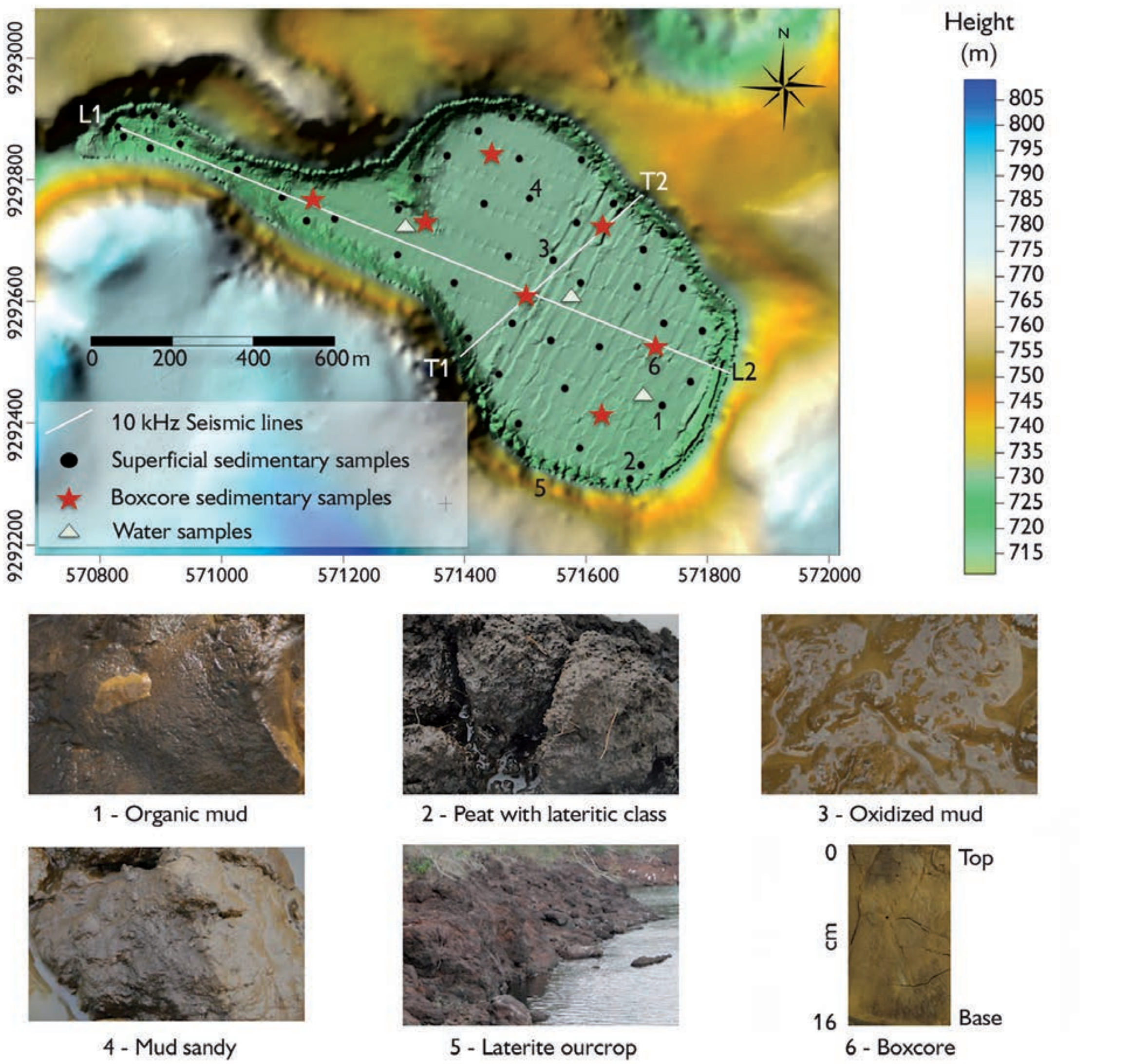

Figure 2. Integration of bathymetric data with LiDAR topography showing a 3D visualization of the Lake Violão bottom morphology and adjacent emerge areas. Note the location of 10 kHz seismic track lines, superficial, box-core sedimentary and water samples. Facies classification of the superficial sedimentary deposit based on clastic and organic description, laterite outcrop and shallow box-core are also present in this figure. Photos: P. W. M. Souza-Filho.

Based on the bathimetric data, three sampling points were used to determine in-situ the water temperature profile in September 2012 (dry season) and April 2013 (rainy season) using a Water Quality Monitoring System (Horiba W-20XD) (Figure 2).

A total of forty-three surficial sediment samples were collected from Lake Violão using a Van Veen Grab sampler. Six undisturbed sub-surficial samples were also collected using a box corer sampler (Figure 2). For a quantitative evaluation of the inorganic components, around 20 g of bulk samples were treated with hydrogen peroxide to remove organic matter, followed by a dispersion process with sodium pyrophosphate solution in an ultrasonic bath. Thereafter, grain size analyses were carried out in a Mastersizer 2000 with hydro dispersion unit to obtain information about particle grain-size distribution.

The sediments were characterized based on Wentworth (1922) and Folk & Ward (1957) classification. Following the lacustrine classification of Schnurrenberger *et al*. (2003), the sedimentary facies of these samples were analyzed including the grain-size, macroscopic features, texture and color (Figure 2). Considering the organic components, around 10 g of bulk sample were used for the analysis of total organic carbon (TOC) by a LECO CS-300 combustion analyzer.

For radiocarbon dating, ~2 g of bulk sample was chemically treated to remove eventual presence of younger organic fraction (fulvic and/or humic acids) and carbonates. The sediment organic matter was analyzed in an Accelerator Mass Spectrometry (AMS) at the Beta Analytic facilities (Miami-FL, USA). Radiocarbon ages are expressed as cal. year B.P. normalized to a $\delta^{13}C$ of -25 ‰ Pee Dee Belemnite (PDB) (Stuiver & Polach, 1977). The radiocarbon ages were calibrated to ages B.P. using Calib 7, Intcal13.14c calibration dataset with an error of 2σ (Reimer *et al*., 2013). The sedimentation rates were calculated based on the ratio between the depth intervals (mm) and the mean time range.

In addition to echo sound profiling, a shallow water seismic reflection survey were carried out using a StrataBox™ Marine Geophysical Instrument of the SyQuest, operating in a frequency of 10 KHz, with sedimentary strata resolution of 6 cm to penetration up to 40 m and depth resolution of 0.1 m. The StrataBox profiler was also coupled in the same Trimble DGPS. The maximum bottom set depth was around 20 m, with DC Gain of 20 dB and bottom triggered of 1.5 dB in the. Transverse and longitudinal lines were acquired in Violão Lake (Figure 2).

The mapping of seismic reflection changes (sequence boundary, unconformities, such as onlap, downlap and toplap structures) and geometry of the seismic stratigraphic units were recognized by standardized methods (Vail & Mitchum, 1977; Catuneanu *et al*., 2009), which allowed the identification of three depositional units throughout the basin.

RESULTS

LAKE MORPHOLOGY

Lake Violão has a NE-SW elongated guitar-shaped form. The lake presents washing basin morphology and it is marked by a steep margin scoured in duricrust outcrops, while the bottom is flat and constituted mainly by muddy sediments. As illustrated in Figure 3, four morphological sectors were recognized in Violão Lake.

Zone A is located in the most western sector of the lake that presents a flat, shallow (< 2.5 m in depth) and ellipsoidal area (200 x 100 m) associated to embedded drainage, linked to Zone B, which is characterized by a narrow and elongated channel in NW-SE direction. Zone B connects shallower area of the basin (~1 m in depth) with deeper zone (~10.5 m in depth), where is possible to observe a fan sedimentation inside the lake.

Zone C constitutes the central sector of the lake, defined by steep margin up to 8 m in depth, followed by a flat bottom that reaches 10 m in depth. Zone D is situated in the eastern sector of the lake also characterized by steep margin followed by a deltaic sedimentation in the northwest direction, whose water depth ranges from 7.5 to 9.5 m. The lake has a surface of around 0.3 km^2, a perimeter of 2.7 km, a maximum NW-SE fetch of 1.1 km and a maximum NE-SW width of 0.46 km. Bathymetry reveals a current lake volume of 1.8 million m^3.

Based on bathymetric data, we calculated several morphometric parameters and indexes that are presented in Table 1. Based on the values of area and volume, the Violão is classified as a small lake (Tundisi & Matsumura Tundisi, 2008). The relative depth of the lake suggested that there is a vertical circulation in response to thermic stratification. Based on volume development index, the lake presents a concave form, and can be classified as a lake in "U" shape (Von Sperling, 1999), what is evidenced in the Figure 3.

VERTICAL WATER TEMPERATURE AND SECCHI DEPHT

The vertical water temperature of Lake Violão is mainly oscillated in the dry season from around 29 °C in the surface waters, decreasing to 28 °C and 26 °C at 3 to 5.2 m depth, respectively. From this point, the temperatures declined to around 25 °C at 9 m depth. During the wet season, the vertical temperature profile is almost constant varying from ~28 °C to 27 °C. The Secchi depth reached 2.2 m and 3.3 in the dry and rainy season, respectively (Figure 4).

SEDIMENTARY FACIES

In the Violão Lake, water level oscillates according precipitation regime. From January to April, the water level ranges from 722.4 to 722.9 m, rising to 723.3 m in May, thereafter dropping to its lowest level with 720.9 m in October, and rising again to 722.2 m during December (Sahoo *et al.*, in press). Hence, bedrock outcrops can be observed in its margins during the dry season. In the same way, the connection between the northwestern borders becomes restricted (Figure 5A).

Table 1. Morphometric parameters of Lake Violão based on Tundisi & Matsumura Tundisi (2008).

Area in zero quota (A)	0.27 km^2
Volume in zero quota (V)	1,814,356 m^3
Perimeter in zero quota (P)	2,784 m
Fetch (L_{max})	1,120 m
Maximum width (Wd_{max})	460 m
Maximum depth (Z_{max})	10.5 m
Average depth in zero quote (Z)	6.62 m
Relative depth in zero quote (Zr)	1.8%
Development index of margin (Ds)	1.42 m
Development index of volume (Dv)	2.85 m

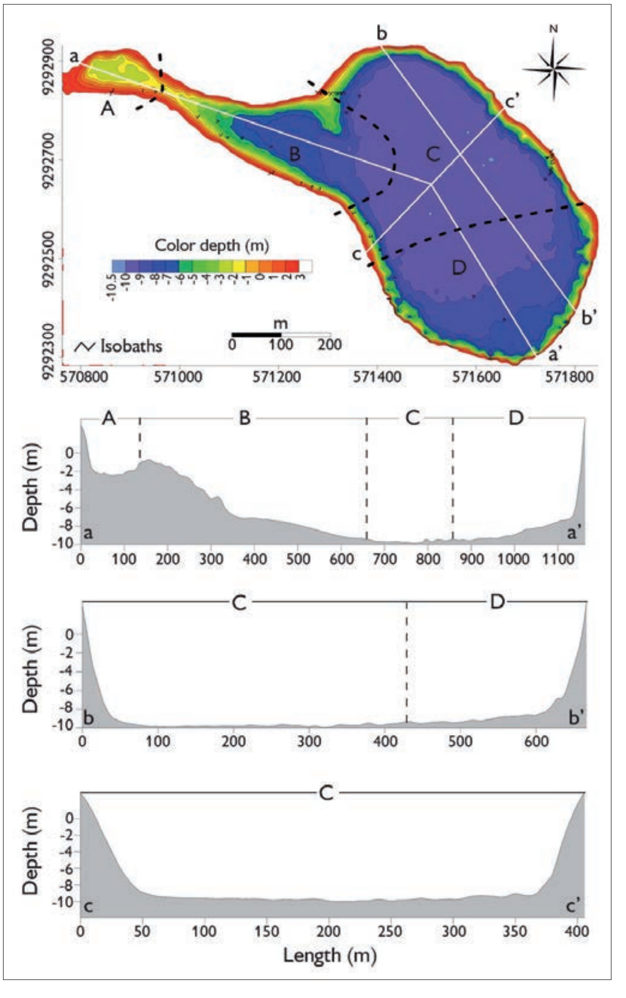

Figure 3. Bathymetric chart of Lake Violão. Observe topographic profiles and morphological zonation of the study area.

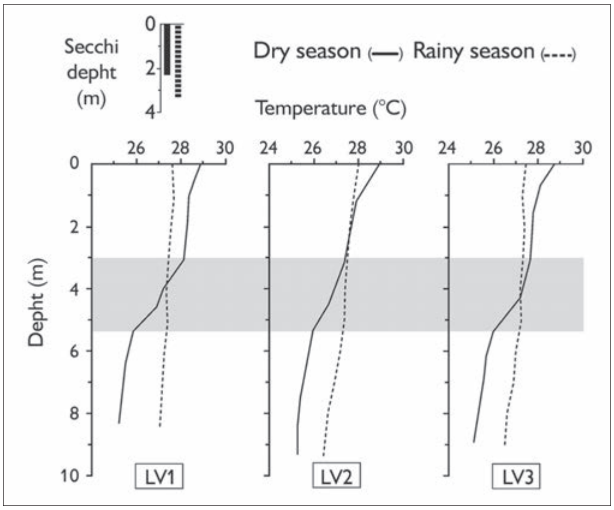

Figure 4. Thermic profiles and Secchi depth of Lake Violão. Observe the water column stratification in dry season and no stratification in wet season.

Clastic sediments can be found in the deeper portions of the lake, mainly represented by very to extremely poorly sorted coarse silts. Very poorly to poorly sorted coarser grained deposits (very fine to fine sands) are restricted to the southeastern (SE) and northwestern (NW) portion of the lake. In general, these sediments are rich in total organic carbon (TOC) with maximum concentrations (44 to 20%) in NW portion of the lake, while moderate (36 to 15%) and lowest TOC (~10%) concentration were registered in SE and central portion of the lake, respectively (Figure 5B).

Using the classification of the clastic and organic sediments, five sedimentary facies were identified in the lake bottom (Figure 5C): bedrock outcrops, peat with lateritic clasts, mud sandy, organic mud and slightly oxidized mud (Figure 2).

Based on the box cores descriptions, the uppermost sedimentary facies present less than 1 m thick, and it is generally massive with some scattered vegetable debris. Additionally, coarse-grained deposits of the SE and NW portions of the lake locally may contain small-scale ripple cross-lamination. Organic mud was dated at 1820-1690 cal yr B.P, at 16 cm depth, which corresponds a sedimentation rate of 0.09 mm/yr.

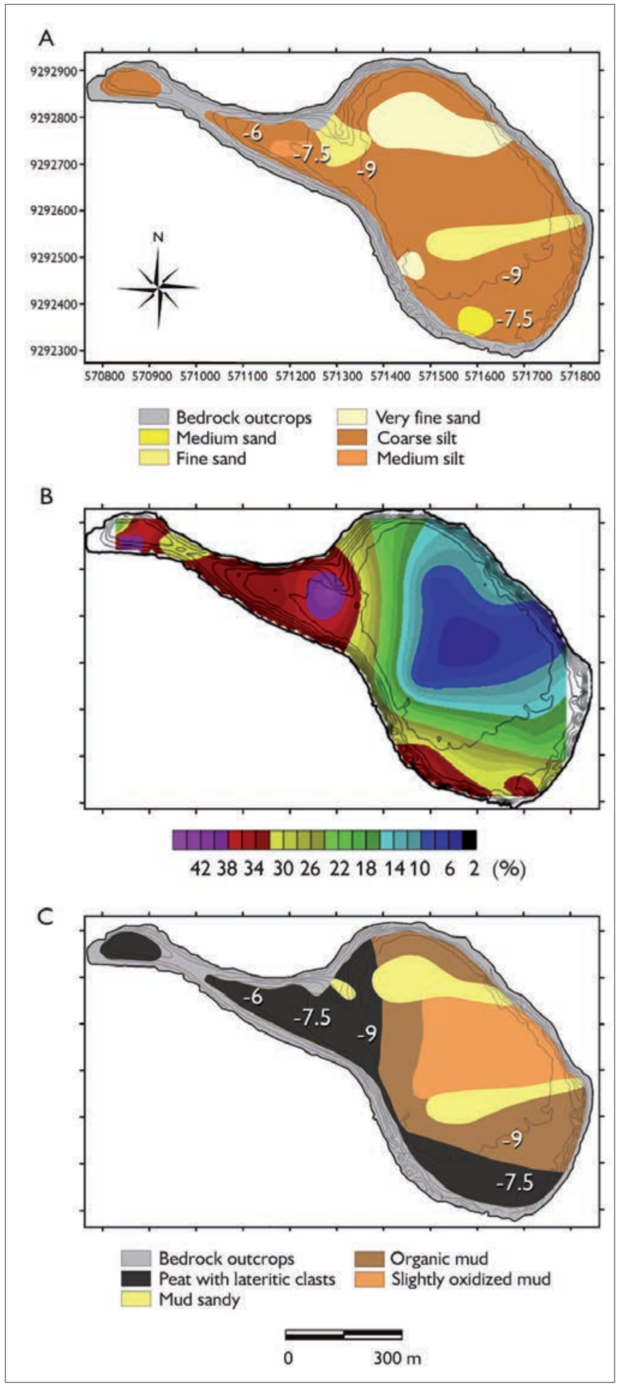

Figure 5. Sedimentological description of the surficial sediments of Lake Violão: A) classification of the clastic sediments based on Folk & Ward (1957); B) concentration of the total organic carbon (TOC) of the bulk sediment in percentages; C) facies classification of the uppermost sedimentary deposit based on clastic and organic description. Black lines represented the isobaths in meters.

SEISMO-STRATIGRAPHY

Late-Quaternary sediments reach average thickness of around 11 m in Violão Lake. In the entire sedimentary infill, three seismic stratigraphic units were recognized in the most of the seismic transects, which were defined as units I, II and III from older to youngest (Figures 6 and 7). The seismo-stratigraphic units are resting on prominent basal reflector (bedrock), which can be traced over most of the areas. This reflector extends from outcrops in the boundary of the lake to at least 20 m below lake level (bll), forming an irregular surface with steep slope relief in the margin and flat bottom morphology, characterized by enclosed depression, similar to a washing basin.

The lowermost seismo-stratigraphy Unit I is present in almost all seismic transects throughout the basin, constituting the basal infill. It represents a basinward prograding clinoform package in downlap over bedrock reflector at around 18 m bll (Figure 5 and 6). The upper boundary of Unit I is defined by a toplap that seems to be massive with strong changes between high and low acoustic impedance, geometrically truncating both sub-units throughout the basin.

The seismo-stratigraphy Unit II occurs throughout the lake basin and is characterized by continuous, relatively homogeneous and spaced plane-parallel reflection sequence of high accoustic impedance contrast. Unit II displays an approximately constant thickness of 5 m and it may reach maximum thickness of around 7 m within the depocenter (Figures 6 and 7).

The upper most Unit III drapes the lower units throughout the basin, onlapping the lake margin and in concordance to the top of the Unit II. It seems to be massive with some scattered vegetable debris. Unit III is underlying to strong seismic reflector and its top occurs at least from 8 m to 10 m bll. It constitutes a thinner seismo-stratigraphy unit with around 1 m thickness (Figures 6 and 7).

TROPICAL UPLAND LAKE SEDIMENTATION

The basin morphology of Violão Lake seems to be associated to collapse faults. Seismic track lines show collapse normal faults that bound the margin of the lake (Figures 6 and 7). The geometry of seismo-stratigraphy depositional units allows the interpretation of the sedimentary basin infilling.

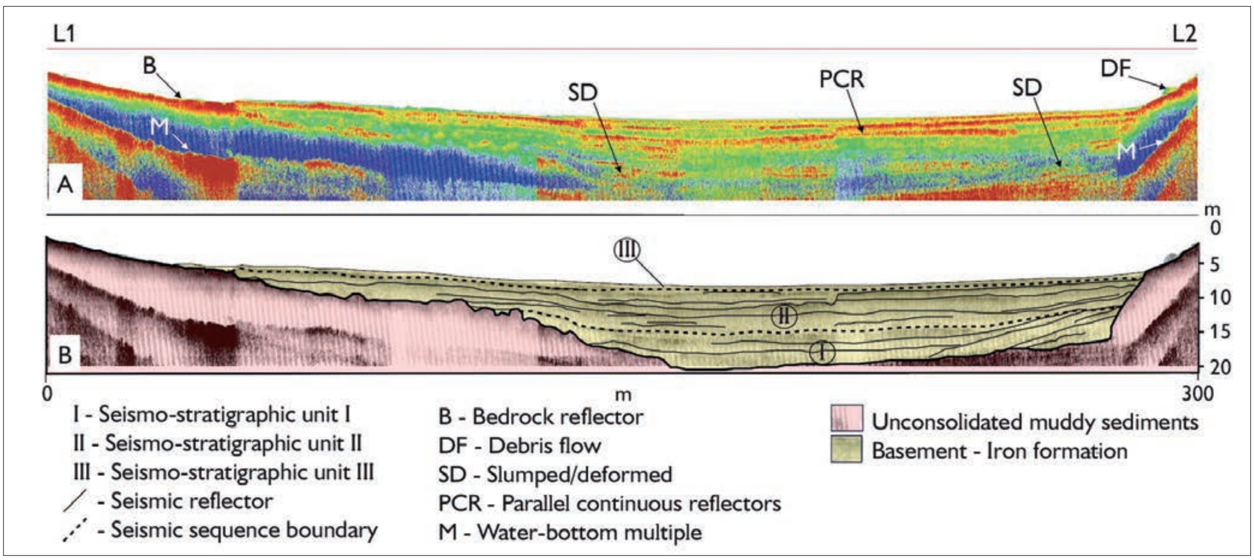

Figure 6. A) Longitudinal seismic transects in a northwest-southeast direction showing several morphologic levels, depositional units, basement and multiples reflectors and fault lines in upper; B) seismo-stratigraphic interpretation. Location map of seismic profiles are represented in Figure 1.

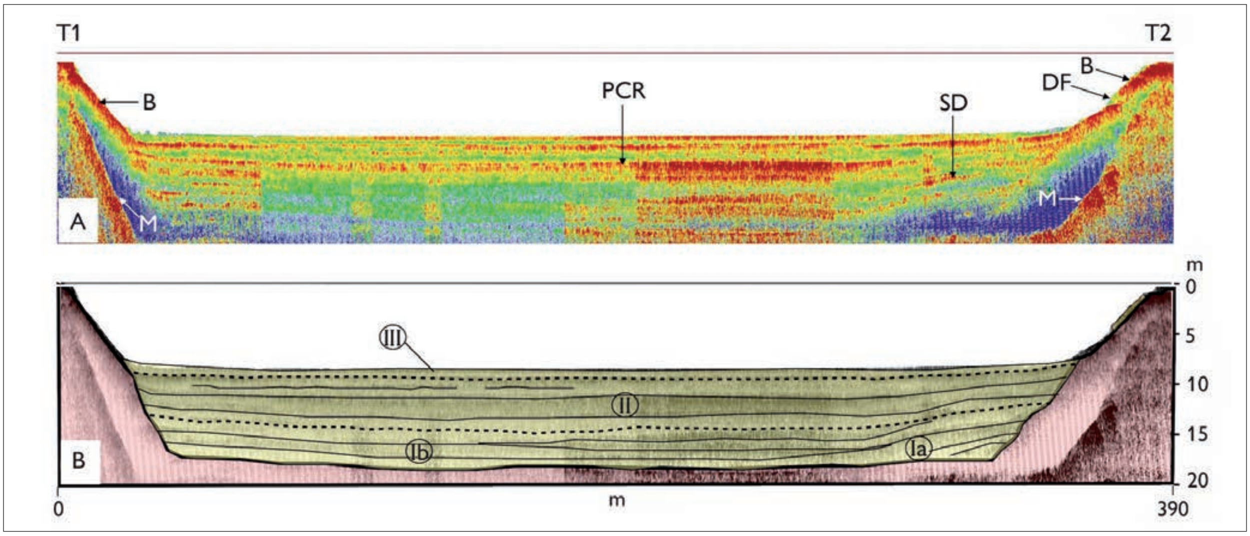

Figure 7. A) Transversal seismic transects in a northeast-southwest direction showing several morphologic levels, depositional units, basement and multiples reflectors and fault lines in upper; B) seismo-stratigraphic interpretation. Legends: B = bedrock reflector; DF = debris flow; SD = slumped/deformed; PCR = parallel continuous reflectors; M = water-bottom multiple; Ia = seismo-stratigraphic unit Ia; Ib = seismo-stratigraphic unit Ib; II = seismo-stratigraphic unit II; III = seismo-stratigraphic unit III. Location map of seismic profiles are represented in Figure 1.

Three seismic stratigraphic successions were identified in the lake resting on prominent basal reflector (bedrock), which reaches a maximum depth of around 15 m bll. The lowermost seismo-stratigraphic succession (SSS I, up to 5 m thick) is in downlap over bedrock reflector and it is characterized by progradational succession, deposited by downslope gravitational flows from oversteepened delta fronts under shallow water condition.

A second seismo-stratigraphic succession (SSS II, up to 7 m thick) occurs throughout the lake basin and is characterized by continuous and spaced plane-parallel reflectors, typical of repetitively bedded muds most likely deposited by overflow or interflow. A thin Holocene succession (SSS III, < 1 m) seems to be massive and distributed throughout the lake surface with drape morphology (Figures 6 and 7).

Considering overflow or interflow processes, it must occur in stratified water column with a well-defined thermocline. In this way, the vertical temperature profile of Lake Violão during the dry season exhibits a stratification of water column mainly in response to the development of a metalimnion (Figures 4 and 8). This zone is marked by a decrease of temperature of 1 ºC per meter depth. However, a complete mixing of the water column may occur during the rainy season following the decrease of temperature in the surface waters due to high cloud cover.

The relative density of the inflow and lake waters, and the vertical water density distribution control the nature of inflow into the lake (Weirich, 1986). The lake and its watershed basin morphology control the inflow of sediment into the lake related to underflows (turbidity currents) processes. Wind-driven surface currents can be most effective in the distribution of suspended sediments, especially in the Violão Lake where there is minimal density of contrast between inflow and lake waters. Similar processes were found in great lakes, such as Brienz Lake in the Switzerland (Sturm & Matter, 1978) and Waterton Lake in Canada (Eyles *et al*., 2000).

The grain-size distribution in the lake reflects the energy near the bottom, which is directly related to bottom morphology and marginal rocky outcrop. On the marginal rocky outcrop flow detrital sediments from the hill into the lake that are well identified in seismic profiles, as debris flow deposits (Figure 6). Small lobate masses constituted by peat with lateritic clasts are deposited from underflows. These deposits are interpreted as product of downslope slumping or debris flow, which form small deltaic deposits (Figure 9).

Deltaic deposits were observed closed to the main drainage comprised of mud sandy sediments, whose origin is also related to underflow process. The sedimentation in the central part of the lake is characterized by drape-like geometry, suggesting that organic mud sedimentation is associated to pelagic deposition from dilute interflows or overflows (Figure 9), in metalimnion and epilimnion zones, respectively. In contrast, progradation of organic material with laterite clasts represent the main sediment input from the drainage of the watershed basin. Deltatic reflection pattern suggests the continuation of the intermittent drainage contribution into the lake. Prograding deltaic deposits are also typical of tectonic lakes (Dietze *et al*., 2010) and sediment-starved glaciated lake basin (Eyles *et al*., 2000).

Estimates of annual accumulation rates in organic mud deposits were calculated in 0.09 mm/yr in the Violão Lake. At present, the lake has no significant input of sediment from overflow or interflow. Comparing with other lakes developed over lateritic crusts, Hermanowski *et al*. (2012a, 2012b) and Sifeddine *et al*. (2001) presented modern sedimentation rates of around 0.20 mm/yr for the Cachoeira Lake and 0.15 mm/yr for the CSS 2 Lake, in the Serra Sul dos Carajás, northwest from the Violão Lake. In the Serra Norte dos Carajás, 41 km northward from the Violão Lake, Cordeiro *et al*. (2011) presented higher rates with around 0.70 mm/yr. On the other hand, Morro dos Seis Lagos in the western Amazonia present lower sedimentation rates varying from 0.01 mm/yr to 0.02 mm/yr (Colinvaux *et al*., 1996, 2000).

The differences in sedimentation rates may be mainly related to the morphology and lithology of each catchment basin (Takehara *et al*., 2014; Sahoo *et al*., 2015). Despite the catchment basins, the Carajás lakes present lateritic crusts formed by the alteration of ferriferous formations, which provide higher resistance to weathering processes (Maurity & Kotschoubey, 1995), and larger drainage areas. In such condition, more material can be available to be transported to the lake basin. Also, the vegetation of this plateau is partially represented by deciduous forests. This typology loses their leaves seasonally, contributing to the formation of relatively thicker organic horizons on soils and components to the lake sediments (Guimarães *et al*., 2014).

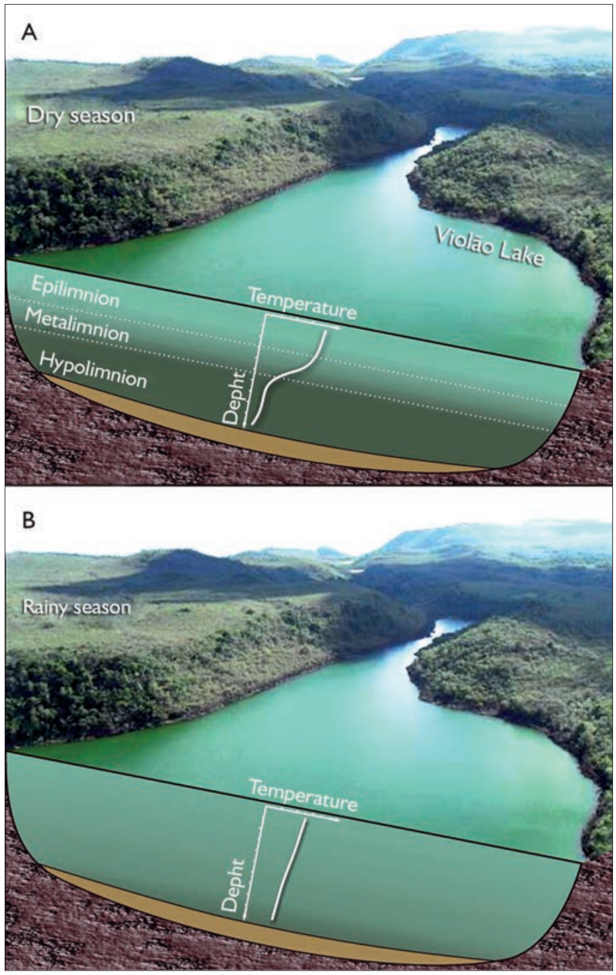

Figure 8. Seasonal changes in water stratification in Lake Violão during September 2012 (dry season) and April 2013 (rainy season).

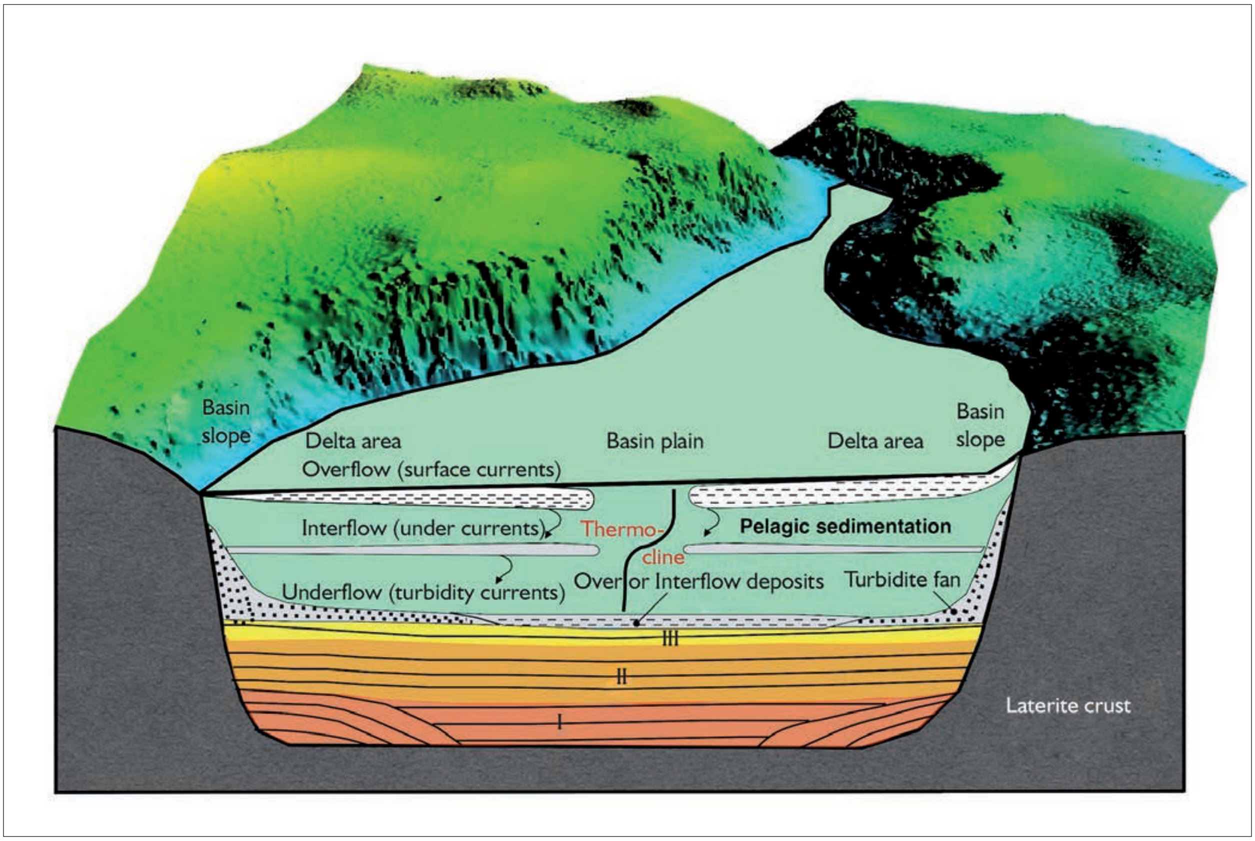

Figure 9. Sedimentation mechanisms in Violão upland Lake.

CONCLUDING REMARKS

Washing basin morphology, drainage water inflow and annual thermal stratification of the water column exert major influence on the sedimentary processes and patterns of Quaternary sedimentation in the tropical upland Violão Lake. The integration of these three characters is responsible for generation of under and inter-flows, while winds on lake surface control the overflows. Three seismo-stratigraphic units were identified in the lake. This study suggests that Lake Violão contains a complete record of late Quaternary deposit, providing detailed insights into climate and environmental changes in eastern Amazon.

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REFERENCES

AGUILERA, X., S. DECLERCK, L. DE MEESTE, M. MALDONADO & F. OLLEVIER, 2006. Tropical high Andes lakes: a limnological survey and an assessment of exotic rainbow trout (*Oncorhynchus mykiss*). **Limnologica - Ecology and Management of Inland Waters** 36(4): 258-268.

BLAIS, J. M. & J. KALFF, 1995. The influence of lake morphometry on sediment focusing. **Limnology and Oceanography** 40(3): 582-588.

BRIDGE, J. & R. DEMICCO, 2008. Lakes. In: J. BRIDGE & R. DEMICCO (Ed.): **Earth surface processes, landforms and sediment deposits**: 462-472. Cambridge University Press, New York.

CATUNEANU, O., V. ABREU, J. P. BHATTACHARYA, M. D. BLUM, R. W. DALRYMPLE, P. G. ERIKSSON, C. R. FIELDING, W. L. FISHER, W. E. GALLOWAY, M. R. GIBLING, K. A. GILES, J. M. HOLBROOK, R. JORDAN, C. G. S. C. KENDALL, B. MACURDA, O. J. MARTINSEN, A. D. MIALL, J. E. NEAL, D. NUMMEDAL, L. POMAR, H. W. POSAMENTIER, B. R. PRATT, J. F. SARG, K. W. SHANLEY, R. J. STEEL, A. STRASSER, M. E. TUCKER & C. WINKER, 2009. Towards the standardization of sequence stratigraphy. **Earth-Science Reviews** 92: 1-33.

COLINVAUX, P. A., P. E. DE OLIVEIRA, J. E. MORENO, M. C. MILLER & M. B. BUSH, 1996. A long pollen record from lowland Amazonia: forest and cooling in glacial times. **Science** 274(5284): 85-88.

COLINVAUX, P. A., P. E. DE OLIVEIRA & M. B. BUSH, 2000. Amazonian and neotropical plant communities on glacial time-scales: the failure of the aridity and refuge hypotheses. **Quaternary Science Reviews** 19(1-5): 141-169.

CORDEIRO, R. C., B. TURC, A. SIFEDDINE, L. D. LACERDA, E. V. SILVA FILHO, B. GUEIROS, Y. P. POTTY, R. E. SANTELLI, E. O. PÁDUA & S. R. PATCHINELAM, 2011. Biogeochemical indicators of environmental changes from 50 Ka to 10 Ka in a humid region of the Brazilian Amazon. **Palaeogeography, Palaeoclimatology, Palaeoecology** 299(3-4): 426-436.

COSTA, M. L., L. R. FONSECA, R. S. ANGÉLICA, V. P. LEMOS & R. L. LEMOS, 1991. Geochemical exploration of the Maicuru alkaline-ultramafic-carbonatite complex, northern Brazil. **Journal of Geochemical Exploration** 40(1-3): 193-204.

COSTA, M. L., M. S. CARMO & H. BEHLING, 2005. Mineralogia e geoquímica de sedimentos lacustres com substrato laterítico na Amazônia. **Revista Brasileira de Geociências** 35(2): 165-176.

DIETZE, E., B. WÜNNEMANN, B. DIEKMANN, B. AICHNER, K. HARTMANN, U. HERZSCHUH, J. IJMKER, H. JIN, C. KOPSCH, F. LEHMKUHL, S. LI, S. MISCHKE, F. NIESSEN, S. OPITZ, G. STAUCH & S. YANG, 2010. Basin morphology and seismic stratigraphy of Lake Donggi Cona, north-eastern Tibetan Plateau, China. **Quaternary International** 218(1-2): 131-142.

EYLES, N., J. I. BOYCE, J. D. HALFMAN & B. KOSEOGLU, 2000. Seismic stratigraphy of Waterton Lake, a sediment-starved glaciated basin in the Rocky Mountains of Alberta, Canada and Montana, USA. **Sedimentary Geology** 130(3-4): 283-311.

FOLK, R. L. & W. C. WARD, 1957. Brazos River bar: a study in the significance of grain size parameters. **Journal of Sedimentary Petrology** 27(1): 3-26

GUIMARÃES, J. T. F., P. W. M. SOUZA-FILHO, R. ALVES, E. B. SOUZA, F. R. COSTA, L. S. REIS, P. K. SAHOO, C.-L. O. MANES, R. O. SILVA JÚNIOR, D. OTI & R. DALL'AGNOL, 2014. Source and distribution of pollen and spores in surface sediments of a plateau lake in southeastern Amazonia. **Quaternary International** 352: 181-196.

HERMANOWSKI, B., M. L. COSTA & H. BEHLING, 2012a. Environmental changes in southeastern Amazonia during the last 25,000 yr revealed from a paleoecological record. **Quaternary Research** 77(1): 138-148.

HERMANOWSKI, B., M. L. COSTA, A. T. CARVALHO & H. BEHLING, 2012b. Palaeoenvironmental dynamics and underlying climatic changes in southeast Amazonia (Serra Sul dos Carajás, Brazil) during the late Pleistocene and Holocene. **Palaeogeography, Palaeoclimatology, Palaeoecology** 365-366: 227-246.

LAVAL, B., J. IMBERGER, B. R. HODGES & R. STOCKER, 2003. Modeling circulation in lakes: spatial and temporal variations. **Limnology and Oceanography** 48(3): 983-994.

MACAMBIRA, M. J. B. & J.-M. LAFON, 1995. Geocronologia da Província Mineral de Carajás: síntese dos dados e novos desafios. **Boletim do Museu Paraense Emílio Goeldi, série Ciências da Terra** 7: 263-288.

MAURITY, C. W., 1993. **Evolução recente da cobertura de alteração no platô N1 – Serra dos Carajás**: 1-95. Dissertação (Mestrado em Geologia) – Universidade Federal do Pará, Belém.

MAURITY, C. W. & B. KOTSCHOUBEY, 1995. Evolução recente da cobertura de alteração no Platô N1 – Serra dos Carajás-PA. Degradação, pseudocarstificação, espeleotemas. **Boletim do Museu Paraense Emílio Goeldi, série Ciências da Terra** 7: 331-362.

MORAES, B. C., J. M. N. COSTA, A. C. L. COSTA & M. H. COSTA, 2005. Variação espacial e temporal da precipitação no estado do Pará. **Acta Amazonica** 35(2): 207-214.

OLSZEWSKI, W. J., K. R. WIRTH, A. K. GIBBS & H. E. GAUDETTE, 1989. The age, origin, and tectonics of the Grão Pará Group and associated rocks, Serra dos Carajás, Brazil: archean continental vulcanism and rifting. **Precambrian Research** 42(3-4): 229-254.

RÄMÖ, O. T., R. DALL'AGNOL, M. J. B. MACAMBIRA, A. A. S. LEITE & D. C. OLIVEIRA, 2002. 88 Ga oxidized A-Type granites of the Rio Maria Region, eastern Amazonian Craton, Brazil: positively anorogenic. **Journal of Geology** 110: 603-610.

REIMER, P. J., E. BARD, A. BAYLISS, J. W. BECK, P. G. BLACKWELL, C. BRONK RAMSEY, C. E. BUCK, H. CHENG, R. L. EDWARDS, M. FRIEDRICH, P. M. GROOTES, T. P. GUILDERSON, H. HAFLIDASON, I. HAJDAS, C. HATTÉ, T. J. HEATON, A. G. HOGG, K. A. HUGHEN, K. F. KAISER, B. KROMER, S. W. MANNING, M. NIU, R. W. REIMER, D. A. RICHARDS, E. M. SCOTT, J. R. SOUTHON, C. S. M. TURNEY & J. VAN DER PLICHT, 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50000 years cal. BP. **Radiocarbon** 55(4): 1869-1887.

SAHOO, P. K., P. W. M. SOUZA-FILHO, J. T. F. GUIMARÃES, M. S. SILVA, F. R. COSTA, C.-L. O. MANES, D. OTI, R. O. SILVA JÚNIOR & R. DALL'AGNOL, 2015. Use of multi-proxy approaches to determine the origin and depositional processes in modern lacustrine sediments: Carajás Plateau, Southeastern Amazon, Brazil. **Applied Geochemistry** 52: 130-146.

SAHOO, P. K., J. T. F. GUIMARÃES, P. W. M. SOUZA-FILHO, R. O. SILVA JÚNIOR, G. PESSIN, B. C. MORAES, P. F. P. PESSOA, T. M. RODRIGUES, M. F. COSTA & R. DALL'AGNOL, in press. Hydrological and limnological characteristics of upland lakes of the southeastern Amazon. **Environmental Earth Sciences**.

SCHNURRENBERGER, D., J. RUSSELL & K. KERRY, 2003. Classification of lacustrine sediments based on sedimentary components. **Journal of Paleolimnology** 29(2): 141-154.

SIFEDDINE, A., L. MARTIN, B. TURCQ, C. V. RIBEIRO, F. SOUBIES, R. C. CORDEIRO & K. SUGUIO, 2001. Variations of the Amazonian rainforest environment: a sedimentological record covering 30,000 years. **Palaeogeography, Palaeoclimatology, Palaeoecology** 168(3-4): 221-235.

SOUBIES, F., K. SUGUIO, J. C. LEPRUN, M. SERVANT, B. TURCQ, M. FOURNIER, M. DELAUNE & A. SIFEDDINE, 1991. The Quaternary lacustrine deposits of the Serra dos Cajajás (state of Pará, Brazil) – ages and other preliminary results. **Boletim IG-USP. Publicação Especial** (8): 223-243.

STUIVER, M. & H. A. POLACH, 1977. Discussion: reporting of 14C data. **Radiocarbon** 19(3): 355-363.

STURM, M. & A. MATTER, 1978. Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents. In: A. MATTER & M. E. TUCKER (Ed.): **Modern and ancient lake sediments**: 147-168. International Association of Sedimentology (Special Publication, 2), Oxford.

TAKEHARA, L., M. ALMEIDA & F. SILVEIRA, 2014. Mineralogical aspects of Morro de Seis Lagos deposit (Amazonas, Brazil). **Geophysical Research Abstracts** 16: EGU2014-12709-1. Available at: <http://meetingorganizer.copernicus.org/EGU2014/EGU2014-12709-1.pdf>. Access on: June 23rd, 2014.

TALBOT, M. R. & P. A. ALLEN, 1996. Lakes. In: H. G. READING (Ed.): **Sedimentary environments**: processes, facies and stratigraphy: 3rd ed.: 83-124. Wiley-Blackwell, New York.

TOLBERT, G. E., J. W. TREMAINE, G. C. MELCHER & C. B. GOMES, 1971. The recently discovered Serra dos Carajás iron deposit, northern Brazil. **Economic Geology** 66(7): 985-994.

TUNDISI, J. G. & T. MATSUMURA TUNDISI, 2008. **Limnologia**: 1-631. Oficina de Textos, São Paulo.

VAIL, P. R. & R. M. MITCHUM, 1977. Seismic stratigraphy and global changes of sea level. Part 1: Overview. **AAPG SpecialVolumes** 26: 51-52.

VON SPERLING, E., 1999. **Morfologia de lagos e represas**: 1-137. DESA/UFMG, Belo Horizonte.

WEIRICH, F. H., 1986. A study of the nature and incidence of density currents in a shallow glacial lake. **Annals of the Association of American Geographers** 76(3): 396-413.

WENTWORTH, C. K., 1922. A scale of grade and class terms for clastic sediments. **The Journal of Geology** 30(5): 377-392.