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# Environmental changes in the western Amazônia: morphological framework, geochemistry, palynology and radiocarbon dating data

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**ABSTRACT**

The sediments from the Coari lake, a "terra firme" lake sculpted into Plio-Pleistocene deposits, and the Acará lake, a flooding-type lake developed on Quaternary sediments in the floodplain of the mid-Solimões river, in the western Amazônia, Brazil, were studied to investigate the environmental condition of their developing. This study includes mineral composition, geochemistry, Pb isotope, palinology, radiocarbon-age and morphological framework of the lakes obtained from SRTM satellite images. The geological and the environmental conditions in the two lakes are highly variable and suggest that their evolution reflect autogenic processes under humid rainforest condition. Although kaolinite, quartz, muscovite, illite, and smectite are the main minerals in both lakes, the geochemistry indicates distinct source, the Acará lake sediments have higher concentrations of $Al_2O_3$, $Fe_2O_3$, FeO, CaO, $K_2O$, MgO, $Na_2O$, $P_2O_5$, Ba, V, Cu, Ni, Zn, Pb, Sr, Li, Y and La and have more radiogenic Pb than the Coari lake sediments. The radiocarbon ages suggest that at 10160 yr BP the Coari lake started to be developed due to avulsion of the Solimões river, and the Acará lake was formed by the meander abandonment of Solimões river retaining its grass dominated shore at ca. 3710 yr BP.

**Key words:** Pb isotopes, lacustrine environment, paleovegetation, flooding plain, Holocene.

## INTRODUCTION

The current configuration of the middle Solimões-Amazon basin, developed since the Andean uplift during the Pliocene, is characterized by extensive floodplains with several types of lakes that are deposition sites of clay and silt and represent the dominant modern inland sedimentation style (e.g. Hoorn et al. 1995, Mertes et al. 1996, Nanson and Knighton 1996, Hooghiemstra and Van der Hammen 1998). During the evolution of the basin, the position of the channel and the morphology and the size of the fluvial plain of the Solimões-Amazon river has been modified in consequence of the neotectonic movements which may have caused avulsion, new impeded flooplains lakes and island development (e.g. Franzinelli and Latrubesse 1993, Mertes et al. 1996, Costa et al. 2001, Latrubesse and Franzinelli 2002, Bezerra 2003). These changes were also influenced by climate and vegetation cover. Many researchers have associated the savanna and rainforest environment in Amazônia to dry and humid conditions (e.g. Suguio et al. 1985, Van der Hammen and Absy 1994, Van der Hammen and Hooghiemstra 2000, Behling et al. 2001,

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Sifeddine et al. 2001, Behling and Hooghiemstra 2000, 2001).

Investigation on the pollen contents, mineralogy, chemistry, Pb isotope and radiocarbon-age of lake sediments provided a record of the environmental changes and also helped to better understand the climate, the provenance and the geological and biological history of the western Amazônia during the Holocene. In the western Amazônia there are some studies about these aspects (Franzinelli and Igreja 1990, Franzinelli and Latrubesse 1993, Colinvaux et al. 1996, Behling et al. 2001, Latrubesse and Franzinelli 2002, Bezerra 2003, Rossetti 2004). With these purposes, two lakes, Coari and Acará, located at the mid-Solimões river flooded fluvial plain (Fig. 1) were ideal to study the Holocene evolution of the Amazon floodplain sedimentation in the western part of the Brazilian Amazon.

## MATERIAL AND ANALYTICAL TECHNIQUES

Mineralogical, chemical, and palynological analyses of the lake sediments along with the radiocarbon dating were done based on the morphological framework obtained from SRTM satellite images. The sediment samples were obtained using a vibra-coring device. Although several cores were collected, only one of each lake, with more than 1.0 m deep, was recovered. The Coari lake core was sampled in the southern portion of the lake and reached 4.05 m deep while the 1.80 m deep Acará lake core was collected in the southwestern part of the lake (Fig. 1).

Mineralogical and chemical analyses of the lake sediments were carried out on eleven and four samples from the Coari and Acará lakes, respectively. Mineralogical analyses were done by X-ray diffractometry performed in a Shimadzu XRD 6000 device, equipped with a Cu anode at 5° to 60° $2\theta$ intervals. Chemical analyses ($Al_2O_3$, $Fe_2O_3$, $TiO_2$, CaO, $K_2O$, MgO, $Na_2O$, $P_2O_5$, Ba, Mn, V, Co, Cr, Cu, Ni, Zn, Pb, Sr, Zr, Li, Y, Sc, Sb, La, Ag, Be, Mo, As, Bi, Sn and W) in melt and triacid solution were carried out by inductively coupled plasma mass spectrometry, except LOI and Hg, which were analyzed by gravimetry and atomic absorption spectrometry, respectively. Total $SiO_2$ was calculated by subtracting the sum of the oxide percentages from 100%, and FeO by volumetry. Organic carbon was analyzed by volumetry with potassium bychromat solution.

For Pb isotope analysis, 20-40 mg aliquots of sediments were digested in two stages using $HF/HNO_3$ and 6N HCl on a hot plate. Lead was isolated using an HBr anion exchange technique, loaded onto standard Re filaments with a mixture of silica gel and phosphoric acid, and analyzed with VG Sector 54 thermal ionization mass spectrometer running in static multicollection mode. Typical $^{208}$Pb ion beam intensity was ca. 2V with $10^{-11}\,\Omega$ resistors. On the basis of multiple analyses of common Pb standard, NBS-981, samples were corrected 0.12%/amu for instrumental mass fractionation.

Samples collected at 0.5 and 1.3 m deep in Acará lake and at 1.8 m and 3.95 m deep in Coari lake were dated by AMS radiocarbon at the "Pysikalisches Institut der Universitat Erlangen-Nürnberg" in Germany. The calibration of the samples was done using the software found in http://radiocarbon.ldeo.columbia.edu that gives ages in years before present (yr BP).

As for the pollen analyses, samples (0.5 $cm^3$) were generally sampled at 10 cm intervals along each core. All samples were treated using standard methods with hydrofluoric acid (47-52%) and acetolysis (Faegri and Iversen 1989). Pollen residues were mounted on slides in a glycerin gelatin medium. A minimum of 300 pollen grains per sample was counted. The pollen sum, excluding aquatic taxa, and fern and moss spores, was the basis for percentage pollen diagrams using TILIA and TILIAGRAPH software (Grimm 1987). The pollen diagrams include percentages of the most abundant pollen and spore taxa, the ecological groups, and the pollen sum. For identification, pollen morphological descriptions published by Absy (1979), Behling (1993), Herrera and Urrego (1996), Hooghiemstra (1984), Roubik and Moreno (1991) and Behling's own reference collection, were used.

## PHYSIOGRAPHY AND MORPHOLOGY OF LAKES COARI AND ACARÁ

The Coari and Acará lakes are presently connected to the Solimões river and are influenced by the seasonal flood pulse, which reaches an annual span of 10 m. In satellite images, the Coari lake exhibits a straight pattern with the Mio-Pleistocene units commonly forming cliffs along its shores (Fig. 1). The Coari lake head is

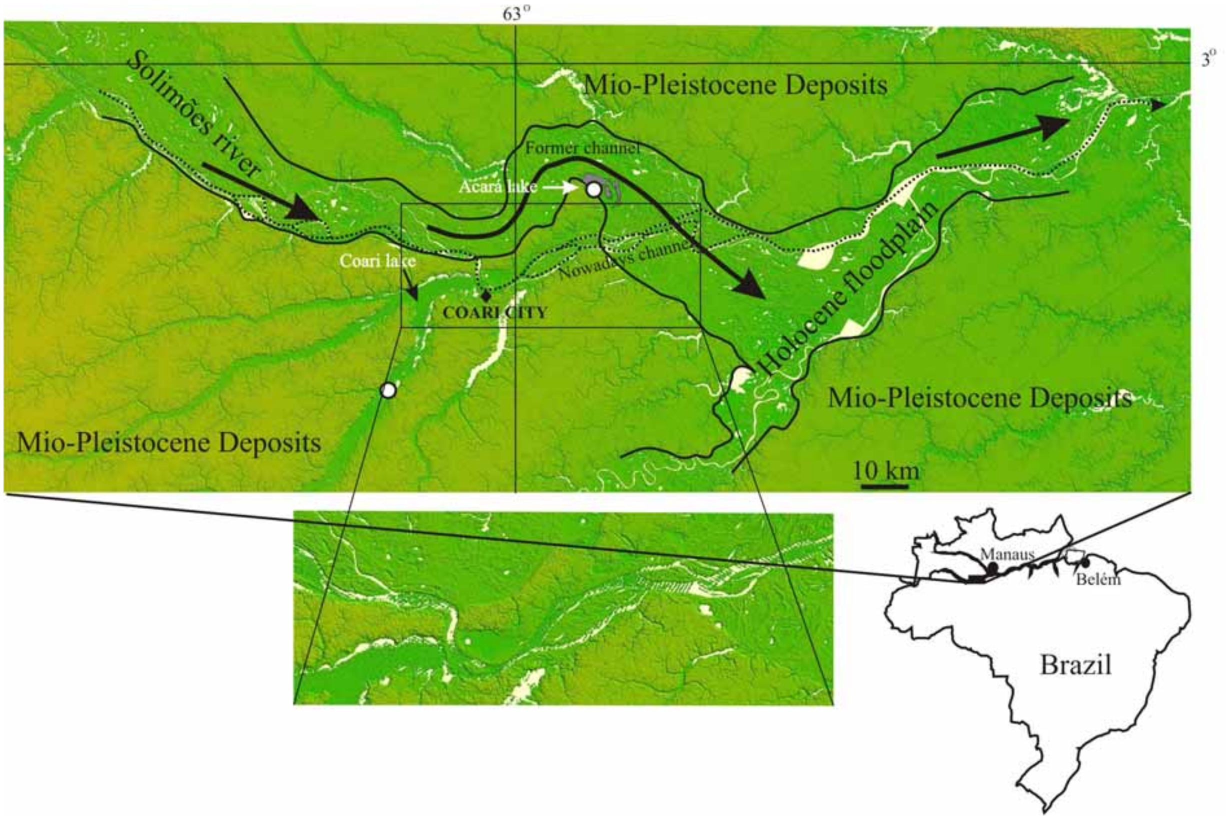


Fig. 1 – The SRTM satellite images with the geographic location of the Coari and Acará lakes and with the former and nowadays Solimões channel configuration. The white dots indicate the position of the cores.

characterized by a flooded meandering pattern that enlarges downstream into a funnel-like geometry barred at its mouth by Holocene deposits which are supplied by the Solimões river. The lake is almost 10 km long and reaches 1 km at its maximum width (Figs. 1 and 2). This type of lake is known as "ria" or "terra firme" in the Amazon region (unflooded upland). The Acará lake, located in the right side of a large meander, is a floodplain or "várzea"-type lake and is characterized by a half-moon-shaped with almost 10 km of maximum width which is limited by Holocene deposits and cliffs of the Mio-Pleistocene units (Figs. 1 and 2).

The morphological framework obtained from SRTM satellite images indicates avulsion of the Solimões river with abandoning of the former channel turning it almost 90° to the south and then runs to east until reach the old floodplain in the downstream portion (Fig. 1) in accordance with the structural lineaments and the tectonic event in the region (Mertes et al. 1996, Latrubesse and Franzinelli 2002, Bezerra 2003, and others). In this process, the Solimões river cuts the Mio-Pleistocene units leaving only a straight tongue between the former and the present channel. It also suggests that the drainage precursor of the Coari lake was longer to east than today and the Solimões river used this portion to develop its new channel. The new channel starts to deposit sediments in the new mouth of the Coari lake that contributes to its enlargement (Fig. 2A) and causes inputs of suspended sediment from the Solimões river. The Acará lake, inside the meander floodplain, was developed after the avulsion in the abandoning meander.

The vegetation surrounding the Coari lake is a "terra firme" forest (unflooded upland) and the Acará lake is a "várzea" forest (seasonally inundated). The tree species; Flacourticeae, Bombacaceae, Rubiaceae, Bignoniaceae, Combretaceae, Euphorbiaceae, Vitaceae, Caparidaceae, Sapotaceae, Lauraceae, Tiliaceae, Moraceae, Leguminoceae-Mimosoideae, Polygonaceae, Cecropiaceae,

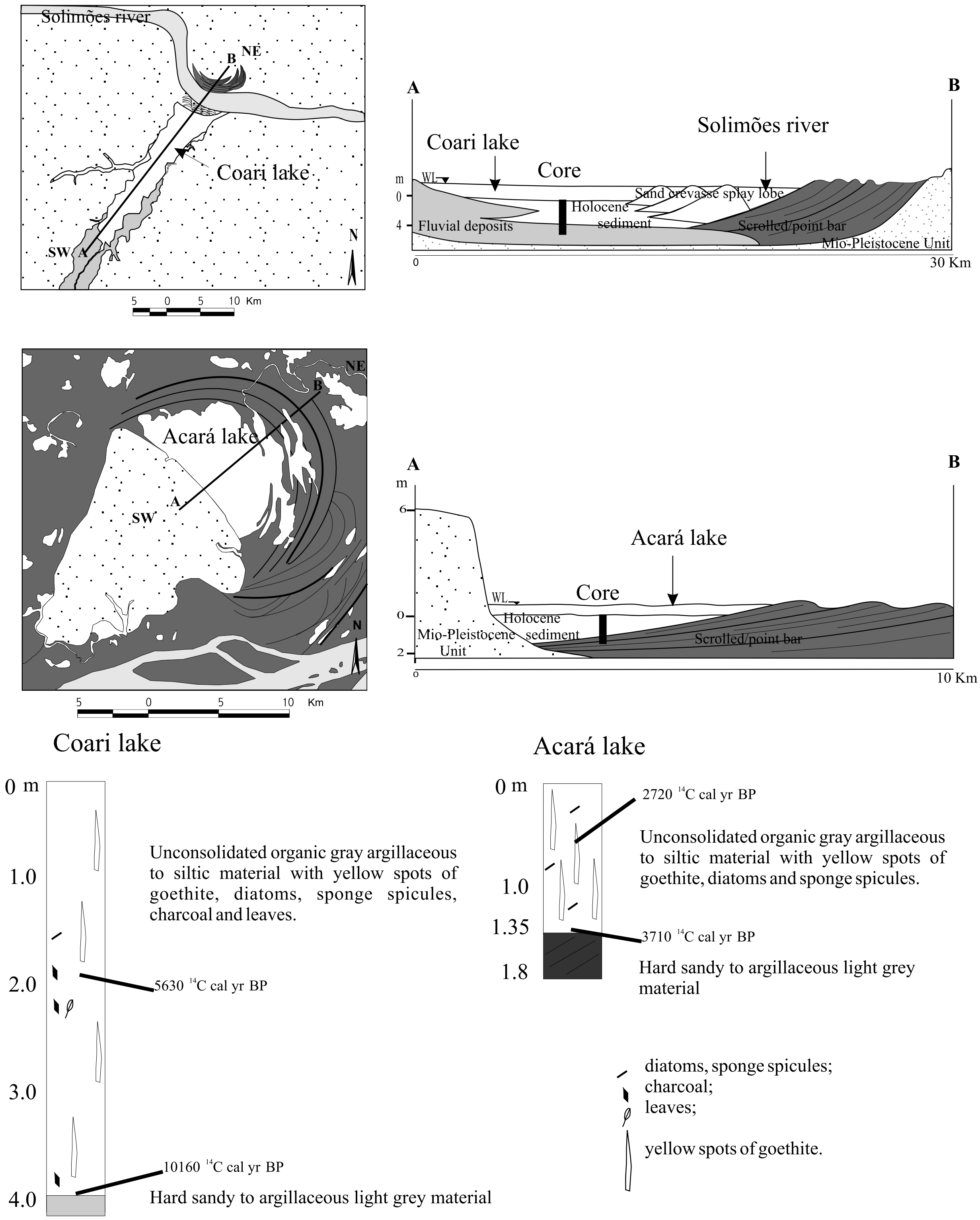


Fig. 2 – The lakes systems and descriptions of the cores profiles.

Fabaceae, Lecythidaceae, Myristicaceae, Annonaceae, Anacardiaceae, Dichapetalaceae, and Apocynaceae are common to the study region (Wittmann et al. 2004). Some Poaceae, Cyperaceae, Asteraceae and a few other herbs comprise the lake shore vegetation. On the other hand, the vegetation of the Coari lake is enriched in Poaceae which is characteristic of large areas of floating meadows. This flora is favored by the climate conditions in the region with temperatures between 25°C and 28°C and rainfall of ~3,000 mm/yr.

## COMPOSITION OF THE SEDIMENTS

The lowermost section in both cores is comprised of hard sandy to argillaceous light grey material while the upper portions are homogeneous and consist of unconsolidated organic gray argillaceous to silty material with yellow mottles of ferruginous material (Fig. 2). In the Coari lake, small pieces of charcoal and leaves are common. Kaolinite and quartz are the main mineral constituents, and goethite, muscovite, illite, and smectite occur in small quantities in all samples (Fig. 3). Rare siderite concretions, diatoms and Si-sponge spicules occur in the upper sediments. The presence of only 20.3° $2\theta$ kaolinite XRD reflections show its lower order in the B axis which it is an indicative of a detritus origin and/or iron incorporation.

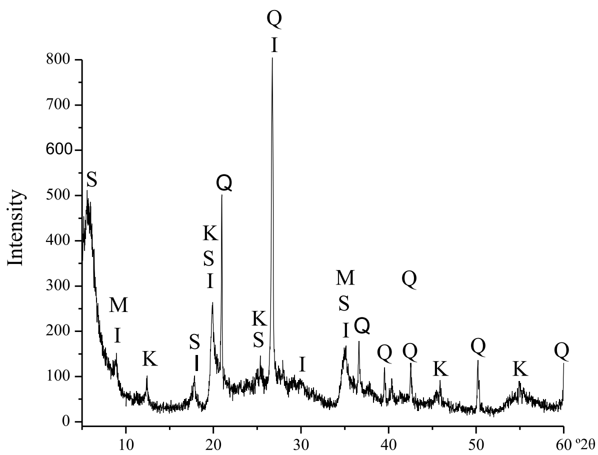


Fig. 3 – The XRD diagram of the lake sediments. S – smectite, M – muscovite, I – illite, K – kaolinite and Q – quartz.

The bulk chemical composition of the Acará lake sediments contain higher $Al_2O_3$, $Fe_2O_3$, FeO, CaO, $K_2O$, MgO, $Na_2O$ and $P_2O_5$ contents compared to the Coari lake sediments which contain higher $SiO_2$ (Table I). It is also possible differentiate the sandy to argillaceous sediment in the lowermost section of the Coari lake with higher contents of $SiO_2$ and lower of almost all the other elements, from the gray argillaceous to silty material upward. The chemical differentiation between lower and upper lake sediment is less perceptible in Acará lake, it has in the lower portion higher $SiO_2$, CaO and $Na_2O$ contents, upward the FeO, MgO and $P_2O_5$ contents increase while the $Al_2O_3$ content does not vary considerably. Carbon content in lakes sediments from both cores (i.e. leaves and charcoal fragments) varies from 5% to 38% indicating significant variation in organic matter input (Table I). The sediments bear low contents of trace-elements as compared to bulk crustal values, particularly on what refers to Mn, V, Cu, Zn, Pb, Sr, Sc, La and Hg (Table I). The Ba, V, Cu, Ni, Zn, Pb, Sr, Li, Y and La concentrations are higher in Acará lake than in Coari lake. Most trace-element concentrations increase upward except Co, Ni, Y, Sb, and La in Coari lake and Co, Ni, Sr, and La in Acará lake (Table I). Acará lake sediments are homogeneous in the distribution of trace element contents (except Mn from 762 to 133 ppm) but in Coari lake, Ba, Mn, Zn, Pb, Y and Sc show a variation of over 100%. Most trace-elements (V, Co, Cu, Ni, Zn, Pb, Sr, Zr, Li) appear to be associated with occurrence of muscovite, illite, smectite, goethite and siderite. Table II shows the most significant correlation factors for trace elements against the major constituent oxides of those minerals ($K_2O$, MgO and $Fe_2O_3$). Correlations with kaolinite and quartz is less significant (r=<0.7).

### LEAD ISOTOPIC COMPOSITION

The lead isotopic composition ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$) is different for each lake (Table III and Fig. 4); the Acará lake sediments show higher isotope homogeneity and are more similar to the Pleistocene and Holocene Amazon fan muds (McDaniel et al. 1997, 1998) while the Coari lake sediments are less radiogenic and yield a wider range of Pb isotope values. Moreover, the Pb isotopic composition of the Coari lake shows some similarity to those in the suspended sediment of the Modern Amazon (Asmerom and Jacobsen 1993, Allègre et al. 1996).

**TABLE I**
**Major chemical composition in weight % and trace-elements in ppm except Hg in ppb.**

| | Coari lake | | | | | | | | | | | Acará lake | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample (m) | 0.10 | 0.40 | 0.80 | 1.2 | 1.6 | 2.0 | 2.4 | 2.8 | 3.2 | 3.6 | 4.05 | 0.4 | 0.8 | 1.3 | 1.6 |
| $SiO_2$ | 76.20 | 76.77 | 74.15 | 69.28 | 71.67 | 72.75 | 71.79 | 70.62 | 72.34 | 73.51 | 88.12 | 64.06 | 63.29 | 58.85 | 68.24 |
| $Al_2O_3$ | 9.64 | 9.64 | 10.58 | 10.58 | 11.72 | 9.26 | 10.01 | 11.90 | 10.96 | 10.39 | 6.80 | 11.90 | 11.15 | 11.34 | 11.15 |
| $Fe_2O_3$ | 2.00 | 1.72 | 2.29 | 2.29 | 2.86 | 1.86 | 2.14 | 3.00 | 2.57 | 2.29 | 1.03 | 5.00 | 7.58 | 8.44 | 6.29 |
| FeO | 0.29 | 0.43 | 0.29 | 0.43 | 0.57 | 0.57 | 0.43 | 0.14 | 0.43 | 0.29 | 0.14 | 0.86 | 0.86 | – | 0.29 |
| $TiO_2$ | 0.97 | 0.92 | 0.92 | 0.85 | 1.00 | 0.88 | 0.90 | 1.18 | 1.00 | 0.90 | 0.58 | 0.78 | 0.78 | 0.75 | 0.80 |
| CaO | 0.03 | 0.04 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.03 | 0.01 | 0.03 | 0.36 | 0.41 | 0.39 | 0.56 |
| $K_2O$ | 1.19 | 1.18 | 1.13 | 1.20 | 1.45 | 1.08 | 1.20 | 1.45 | 1.45 | 1.33 | 0.81 | 1.69 | 2.05 | 1.81 | 1.81 |
| MgO | 0.33 | 0.33 | 0.35 | 0.38 | 0.25 | 0.27 | 0.35 | 0.33 | 0.41 | 0.41 | 0.15 | 1.08 | 0.91 | 0.85 | 0.71 |
| $Na_2O$ | 0.12 | 0.12 | 0.11 | 0.12 | 0.11 | 0.09 | 0.11 | 0.12 | 0.13 | 0.13 | 0.11 | 0.12 | 0.39 | 0.31 | 0.80 |
| $P_2O_5$ | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.09 | 0.07 | 0.07 | 0.02 | 0.11 | 0.18 | 0.18 | 0.09 |
| PF | 9.45 | 9.22 | 10.41 | 15.21 | 10.88 | 13.74 | 13.42 | 11.30 | 11.03 | 10.95 | 2.35 | 14.88 | 13.26 | 17.09 | 9.55 |
| C | 8.69 | 11.74 | 8.20 | 38.21 | 36.17 | 15.63 | 19.48 | 4.73 | 7.37 | 15.09 | 3.61 | 17.28 | 11.41 | 30.74 | 3.22 |
| Ba | 234 | 242 | 176 | 306 | 369 | 208 | 252 | 244 | 423 | 310 | 178 | 370 | 342 | 265 | 298 |
| Mn | 103 | 116 | <100 | 135 | 187 | 111 | 156 | 214 | 212 | 201 | 135 | 133 | 267 | 227 | 762 |
| V | 97 | 90 | 113 | 118 | 137 | 120 | 111 | 163 | 138 | 127 | 37 | 227 | 174 | 192 | 135 |
| Co | 13 | 13 | 12 | 14 | 19 | 15 | 16 | 20 | 18 | 18 | 19 | 19 | 23 | 24 | 26 |
| Cr | 62 | 61 | 71 | 65 | 89 | 68 | 64 | 90 | 81 | 77 | 30 | 87 | 83 | 79 | 66 |
| Cu | 17 | 16 | 20 | 24 | 31 | 19 | 19 | 21 | 21 | 20 | 9.8 | 118 | 58 | 74 | 46 |
| Ni | 13 | 13 | 15 | 19 | 23 | 17 | 18 | 21 | 19 | 18 | 22 | 50 | 37 | 39 | 32 |
| Zn | 42 | 31 | 31 | 160 | 78 | 63 | 43 | 54 | 69 | 66 | 33 | 143 | 139 | 144 | 124 |
| Pb | 52 | 52 | 67 | 67 | 88 | 45 | 56 | 93 | 72 | 61 | 28 | 117 | 83 | 95 | 68 |
| Sr | 48 | 49 | 43 | 52 | 41 | 29 | 40 | 40 | 54 | 51 | 27 | 97 | 96 | 84 | 106 |
| Zr | 101 | 91 | 91 | 77 | 94 | 76 | 79 | 103 | 93 | 88 | 68 | 123 | 106 | 102 | 100 |
| Li | 31 | 31 | 27 | 40 | 46 | 36 | 36 | 47 | 34 | 34 | 14 | 57 | 50 | 47 | 38 |
| Y | 5.5 | 5.6 | 8.1 | 9.2 | 15 | <3 | 3.4 | 9.5 | 8.5 | 6.5 | 5.6 | 31 | 19 | 20 | 15 |
| Sc | 8.8 | <3 | 12 | 12 | 17 | 5.5 | 6.6 | 14 | 12 | 10 | 3.3 | 21 | 15 | 17 | 15 |
| Sb | 12 | 14 | 19 | 15 | 26 | <10 | < 10 | 19 | 10 | <10 | 10 | 21 | 16 | 14 | 14 |
| La | <20 | <20 | <20 | 20 | 26 | <20 | <20 | <20 | <20 | <20 | <20 | 38 | 35 | 35 | 34 |
| Hg | 122 | 131 | 149 | 246 | 131 | 122 | 114 | 140 | 105 | 114 | <50 | <50 | <50 | 19122 | 114 |

Ag, Be and Mo <3; As <10; Bi, Sn and W <20.

**TABLE II**
**The most significant correlation factors.**

| | $K_2O$ | MgO | $Fe_2O_3$ |
|---|---|---|---|
| $Al_2O_3$ | 0.75 | 0.56 | 0.56 |
| $Fe_2O_3$ | 0.92 | 0.86 | 1.00 |
| $P_2O_5$ | 0.86 | 0.81 | 0.92 |
| V | 0.82 | 0.83 | 0.73 |
| Co | 0.75 | 0.59 | 0.79 |
| Cu | 0.71 | 0.93 | 0.74 |
| Ni | 0.76 | 0.91 | 0.81 |
| Zn | 0.72 | 0.76 | 0.74 |
| Pb | 0.75 | 0.71 | 0.63 |
| Sr | 0.88 | 0.93 | 0.87 |
| Zr | 0.77 | 0.77 | 0.63 |

## PALYNOLOGICAL CONTENT

Figure 5 shows the most frequent taxa found in the sediment from the Coari lake. The lowermost section of the core is characterized by low tree and shrub pollen contents (25-40%), as well as, a high amount of herb pollen (max 75%), especially from Cyperaceae, Poaceae I (which is small-sized and bears a small annulus) and from Poaceae II. Upward, herb pollen content decreases and represents only 10-20% of all the pollen in the core. Asteraceae pollen content is relatively high in the middle part of the core. Amazonian tree and shrub pollen become less frequent (∼70%) in the upper portion of the core, as well. Several taxa is relatively well-represented (e.g. Moraceae/Urticaceae, *Mabea*), while others are abundant only at specific levels (e.g. Bombacaceae, *Salix*, *Amanoa*). A sequence of maxima for different taxa start with Bombacaceae, *Salix*, *Alchornea*, and include Moraceae/Urticaceae, *Amanoa* the *Macrolobium*-type and the cf. *Symmeria*-type. Aquatic taxa (a few pollen grains of *Sagittaria*) and fern spores (shown only as sums in the diagram) are almost absent or play a minor role, respectively. There is one common unknown pollen type in the upper section of the core.

The pollen data from the Acará lake is marked by a high amount of herb pollen (around 80%) throughout the record, especially from Poaceae I, some Cyperaceae and *Alternathera*, and a few Asteraceae and Amaranthaceae/Chenopodiaceae (Fig. 5). Trees and shrubs are poorly represented in the lake deposits and do not vary markedly. Moraceae/Urticaceae, *Alchornea*, cf. *Symmeria*-type are the most common pollen types, followed by Myrtaceae, Cecropia, Melastomataceae/Combretaceae, *Mabea*, and some other less significant taxa. Aquatic taxa are represented by just a few pollen grains from *Sagittaria*. Fern spores are also very scarce.

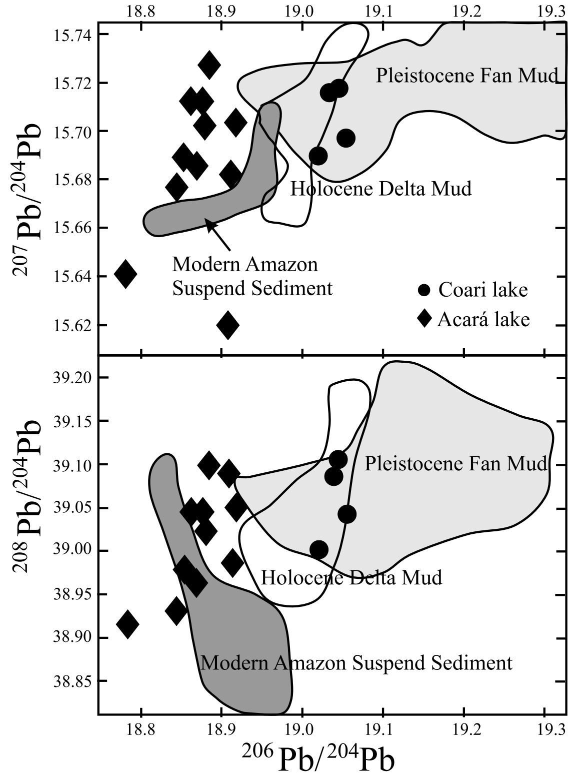


Fig. 4 – The Pb isotope composition. The data are compared to the Pb-isotopic ratios of the Pleistocene fan mud (McDaniel et al. 1997), the Holocene delta mud (McDaniel 1998), and modern suspended sediment of Amazônia (Allégre et al. 1996, Asmerom and Jacobsen 1993).

## RADIOCARBON DATING AND $\delta^{13}C$

Two AMS radiocarbon dates from each lake provide important information about the timing of lacustrine sedimentation (Table IV, Fig. 2). Sediment samples taken at 1.8 m and 3.95 m core depths from the Coari lake yielded ages of 4910±52 $^{14}C$ yr BP or 5630 cal yr BP and 8975±59 $^{14}C$ yr BP or 10160 cal yr BP respectively. Yet, sediments collected at 0.55 m and 1.3 m core depths in the Acará lake yielded ages of 2586± 50 $^{14}C$ yr BP or 2720 cal yr BP and 3457±46 $^{14}C$ yr BP or 3710 cal yr BP, respectively. The plant $\delta^{13}C$ data

**TABLE III**
**The $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ isotopes ratios.**

| | Coari lake | | | | | | | | | | | Acará lake | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample (m) | 0.10 | 0.40 | 0.80 | 1.20 | 1.60 | 2.00 | 2.40 | 2.80 | 3.20 | 3.60 | 4.05 | 0.40 | 0.80 | 1.30 | 1.60 |
| $^{206}Pb/^{204}Pb$ | 18.911 | 18.917 | 18.887 | 18.786 | 18.846 | 18.865 | 18.870 | 18.884 | 18.856 | 18.878 | 18.920 | 19.040 | 19.058 | 19.021 | 19.047 |
| Error | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 | ±0.023 |
| $^{206}Pb/^{207}Pb$ | 1.211 | 1.206 | 1.201 | 1.201 | 1.202 | 1.201 | 1.203 | 1.203 | 1.202 | 1.202 | 1.205 | 1.211 | 1.214 | 1.212 | 1.212 |
| Error | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 |
| $^{206}Pb/^{208}Pb$ | 0.484 | 0.485 | 0.483 | 0.483 | 0.484 | 0.483 | 0.484 | 0.484 | 0.484 | 0.484 | 0.484 | 0.487 | 0.488 | 0.488 | 0.487 |
| Error | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 | ±0.001 |
| $^{207}Pb/^{204}Pb$ | 15.622 | 15.683 | 15.729 | 15.643 | 15.679 | 15.713 | 15.687 | 15.703 | 15.690 | 15.712 | 15.705 | 15.718 | 15.698 | 15.690 | 15.719 |
| Error | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 | ±0.028 |
| $^{208}Pb/^{204}Pb$ | 39.089 | 38.985 | 39.097 | 38.913 | 38.929 | 39.044 | 38.961 | 39.022 | 38.976 | 39.044 | 39.048 | 39.086 | 39.042 | 39.001 | 39.104 |
| Error | ±0.094 | ±0.094 | ±0.094 | ±0.093 | ±0.093 | ±0.094 | ±0.094 | ±0.094 | ±0.094 | ±0.094 | ±0.094 | ±0.094 | ±0.094 | ±0.094 | ±0.094 |

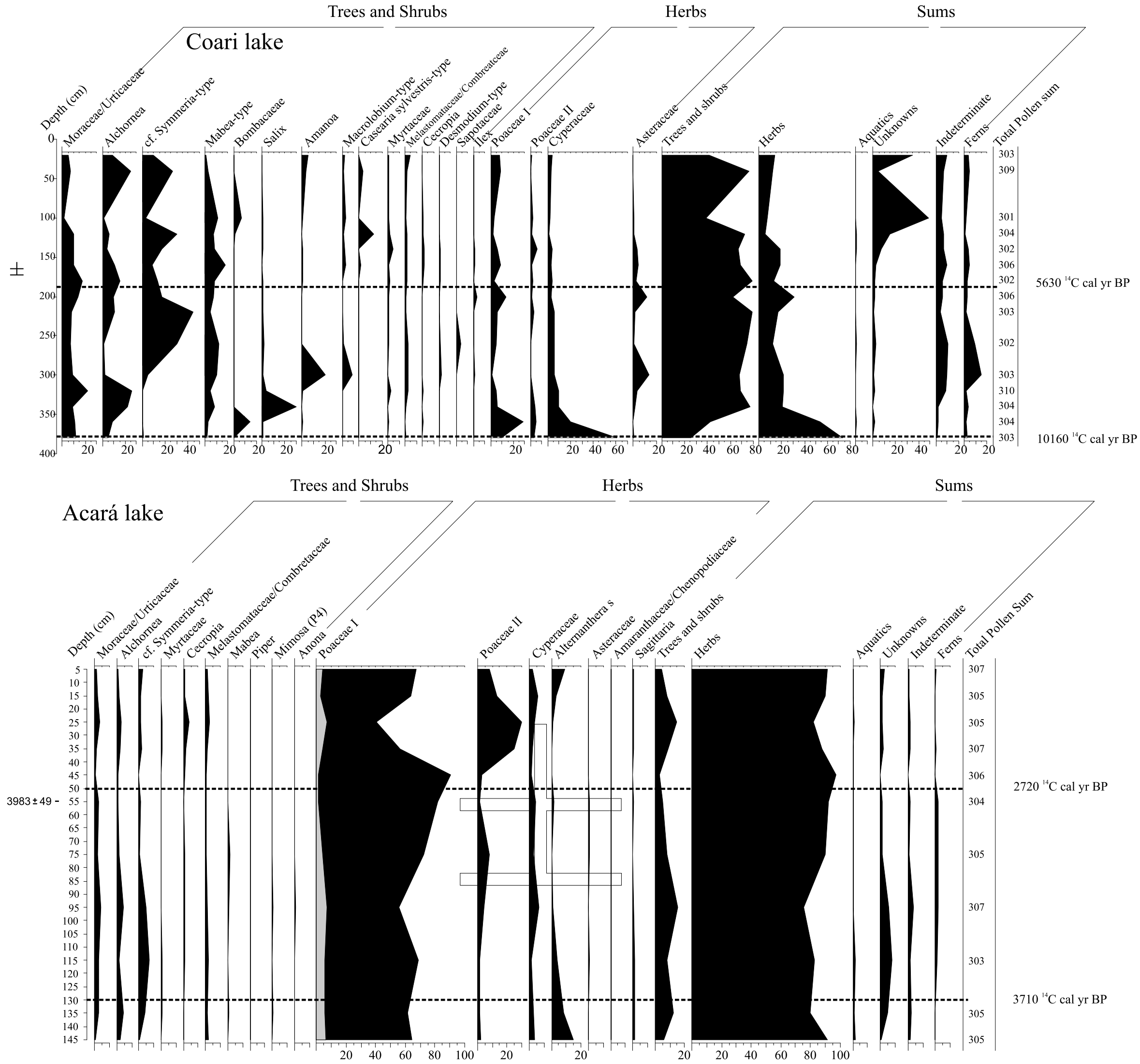


Fig. 5 – The pollen percentage diagrams.

has values ranging from –30.8‰ to –27.7‰ typical of $C_3$ plants, which reflect the organic matter contribution from surrounding forest vegetation accumulated in the lakes with a few contribution of herb vegetation.

## DISCUSSION AND CONCLUSIONS

The morphological framework of the floodplains and the composition of the sediments with their physical, mineralogical and chemical characteristics allow us to make important considerations about the environment where the Coari and Acará lakes were developed.

The sharp break in the sediment types from sandy to argillaceous in the bottom to organic gray argillaceous to silty material in the upper portion of the cores in both lakes, suggests changes in the environmental dynamic, as well as changes in the sources of the sediments which is better identified in the Coari lake. The organic gray argillaceous to silty material in the upper portion of the cores indicates that over the fluvial sediments a stagnated condition might have developed in a typical lake environment. This environment promoted the deposition of the fine-grained lacustrine sediments rich in kaolinite, illite and smectite in opposition to the sandy to argillaceous fluvial material enriched in quartz. Siderite concretions, product of iron oxide reduction, are absent in the sandy to argillaceous material and may be associated to seasonal water table fluctuation or mixing

**TABLE IV**
**The amount of modern carbon, age and $\delta^{13}$C of the organic matter.**

| Sample | Lab number | PMC | PMC error | $^{14}$C yr BP | Calendar age (cal yr BP) | $\delta^{13}$C |
|---|---|---|---|---|---|---|
| Acará – 0.5 m | 6564 | 72.47 | 0.45 | 2586±50 | 2720 | –27.7 |
| Acará – 1.3 m | 9614 | 65.03 | 0.37 | 3457±46 | 3710 | –30.8 |
| Coari – 1.8 m | 6563 | 54.27 | 0.35 | 4910±52 | 5630 | –29.3 |
| Coari – 3.95 m | 9615 | 32.72 | 0.24 | 8975±59 | 10160 | –30.3 |

of oxygenated meteoric water in a stagnant lake conditions (Aslan and Autin 1996). This finding reinforces a shallow and probable lake depositional environment to the organic gray argillaceous to silty material in the upper portion of the cores. Accumulations of leaves, sponge spicules, and diatoms were produced by biological and metabolic activities of plants and animals while the existence of charcoal fragments suggest fire associated with dry periods or human activities.

This change in the deposition environment is also demonstrated by the geochemical pattern where most of the trace elements are more concentrated in the lacustrine sediments. Moreover, the geochemical patterns of the sediments from the two lakes are different (i.e. higher concentration of $Al_2O_3$, $Fe_2O_3$, FeO, CaO, $K_2O$, MgO, $Na_2O$, $P_2O_5$, Ba, V, Cu, Ni, Zn, Pb, Sr, Li, Y and La in the Acará lake and the Pb isotopic composition of the Acará lake is more radiogenic and shows a narrow range compared to the Coari lake). Their geochemical differences are attributed to their geological environment; the Coari lake developed in a "terra firme" Mio-Pleistocene units with inputs from the modern suspended sediment of Solimões river while the Acará lake, an Holocene "várzea"-like, is more isolate, being the Holocene bank the main source of sediments (Fig. 1). The high homogeneities in the $SiO_2$ and $Al_2O_3$ contents, that reflect the quartz and kaolinite proportion in the sediments of the lakes, point out a source and a paleoenvironmental stability during their development.

The AMS radiocarbon dates indicate that the depositional rate of the sedimentation decreased toward the present time for both lakes, from 0.047 to 0.032 cm/yr in the Coari lake and from 0.080 to 0.018 cm/year in the Acará lake. This decreased depositional rate is consequence of the set up of the lacustrine environment. The higher depositional rate for the Coari lake is consequence of the erosion of the cliffs along its shores and by the proximity to the Solimões river, which is the main source influx of sediments. The radiocarbon dates suggest that if the stagnant environment in the Coari lake would have started by 8975 $^{14}$C yr BP or 10160 cal yr BP the avulsion of the Solimões river would be immediate earlier. The probable age for the Acará lake 3457 $^{14}$C yr BP or 3710 cal yr BP, indicates when the abandonment of the Solimões river meander was completed.

The avulsion of the Solimões river barring and enlarging the Coari lake causes the water level to rise flooding the open exposed banks up to the rainforest boundaries. This causes greater change in the vegetation surrounding the lake. The herbs, especially Cyperaceae and Poaceae I, that colonized the exposed, nonflooded lake shore and bank were sudden substituted by tree and shrub pollens of Bombacaceae, *Salix*, *Alchornea*, Moraceae/Urticaceae that changed to *Amanoa*, *Macrolobium*-type, and cf. *Symmeria*-type. The Acará lake, developed by 3457 $^{14}$C yr BP or 3710 cal yr BP maintains an open exposed banks condition where herb pollen is the main type.

Although the pollens indicate vegetation variability with prevalence of the Amazonian tree and shrub pollens for the Coari lake and herbs for the whole Acará lake, the $C_3$ are an indicative of the forest vegetation for the two lakes. These data suggest that the herbs, especially Cyperaceae and Poaceae I, colonized the exposed, nonflooded lake shore and banks as is usually found nowadays in Amazonia in a forest environment condition. The argillaceous to silty material upper cores, indicative of the low erosional rate, is in accordance with a prevalence of forest vegetation. As the two lakes are less than 100 km way, we can point out forest environment in the region of the Coari-Acará lakes and therefore humid condition since 8975 $^{14}$C yr BP or

10160 cal yr BP. Similar environment was found for the Calado lake located 150 km far way (Behling et al. 2001). Nevertheless variable environmental condition were detected in the Amazonia during the time, drier in the central portion between 4000 and 3500 $^{14}$C yr BP and 2100 and 700 yr $^{14}$C BP (Absy 1979) and in 4000 $^{14}$C yr BP (Moreira et al. 2009) but also humid in 6000 and 2500 yr $^{14}$C yr BP in the east (Behling and Costa 2000), in the west since 8280 $^{14}$C yr BP (Behling et al. 2001) and in the central Amazonia in 4600 $^{14}$C yr BP (Irion et al. 2006). These insights suggest that the evolution of both lakes may reflect autogenic processes under humid rainforest condition and their geochemical and palynologic history are consequence of local environmental conditions.

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## RESUMO

Os sedimentos do lago Coari, de ambiente de terra firme e esculpido nos depósitos do Plio-Pleistocenos, e o Acará, típico lago de várzea e ambos formados nos sedimentos quaternários da planície de inundação do médio Solimões, no oeste da Amazônia, Brasil, foram estudados para investigar as condições ambientais durante sua formação. Este estudo inclui dados da composição mineralógica, química, isótopos de Pb, palinologia, datações de radiocarbono e a configuração morfológica dos lagos obtida por imagens SRTM. As condições geológica e ambiental dos lagos variam e sugerem que suas evoluções refletem processos autogenéticos em condições de floresta úmida e chuvosa. Embora caulinita, quartz, muscovita, illita e esmectita sejam os principais minerais em ambos os lagos, a geoquímica indica fonte distinta, os sedimentos do lago Acará têm maior concentração de $Al_2O_3$, $Fe_2O_3$, FeO, CaO, $K_2O$, MgO, $Na_2O$, $P_2O_5$, Ba, V, Cu, Ni, Zn, Pb, Sr, Li, Y e La e têm mais Pb radiogênico que os sedimentos do lago Coari. As idades de radiocarbono sugerem que há aproximadamente 10160 anos AP o lago Coari iniciou o desenvolvimento devido a avulsão do rio Solimões, enquanto o lago Acará foi formado devido ao abandono de meandro do rio Solimões e retendo o domínio das gramíneas nas suas praias há aproximadamente 3710 anos AP.

**Palavras-chave:** isótopos de Pb, ambiente lacustre, paleovegetação, várzea, Holoceno.

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