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Late Holocene history of the floodplain lakes of the Cauca River, Colombia

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Abstract We conducted a paleolimnological investigation of late Holocene deposits on a distal, constrained floodplain of the Cauca River, northern Colombia, i.e. the La Caimana sedimentary succession. The record starts sometime between 4,500 and 4,000 cal yr BP, when the first high-energy fluvial events inundated an ancient soil surface. From that time until about 3,260 cal yr BP, a stable and probably seasonal flooding regime was established on the floodplain. From ~3,260 to ~2,800 cal yr BP, ephemeral and shallow swamps developed on the floodplain. Their formation and duration depended on their connection with the Cauca River. From ~2,800 to ~2,400 cal yr BP, fluvial influence became more dominant, establishing a semi-permanent connection between the river and the floodplain. From ~2,400 to 1,400 cal yr BP, episodic formation of ephemeral swamps occurred. During this stage, floodplain lakes displayed high salinity and nutrient concentrations, and possibly alkaline conditions as a consequence of reduced water volume when the connection with the river was reduced or lost completely. A change in the hydrological regime occurred from ~1,400 to ~850 cal yr BP, when high-energy fluvial events were punctuated by periods of reduced flooding that enabled soil formation. Generally, connection with the Cauca River resulted in lake waters with low salinity and nutrient concentration, whereas loss of connection with the river led to lakes with greater salinity and nutrient content. Paleocurrent analyses indicate that flows came predominantly from the Cauca River, suggesting the lakes were formed by the impoundment of La Caimana Creek. The sedimentary succession of La Caimana offers a unique, high-resolution record of the evolution and dynamics of an ancient floodplain of the Cauca River and its aquatic ecosystems.

Keywords Floodplain lakes · Braided river · Paleolimnology · River connectivity · Cauca River · Mid-late Holocene

Introduction

The Cauca River is one of the most important fluvial systems of Colombia. Over 850 km long, it crosses

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most of the country from the mountainous region in the south where it arises. It cuts through a valley between the Western and Central Andean Cordilleras of Colombia and ends in the Magdalena River, in the northern lowlands. The Magdalena, in turn, drains into the southern Caribbean Sea. The Cauca River's fertile floodplains, with their rich soils and highly productive lakes and swamps, are a vital resource for the economic and social development of the country. The high biodiversity and productivity of these lakes is partly generated and maintained by connectivity with the Cauca River during the flooding season (Moreno et al. 1987). Despite their biological and socio-economic importance, these aquatic ecosystems and the hydrological and sedimentological dynamics imposed by the Cauca River, are still poorly understood (Moreno et al. 1987; Montoya and Aguirre 2009). Worldwide, increasing deterioration of rivers and their impact on floodplain ecosystems is a reason for concern, as it is believed that floodplain lakes play a key role in the exchange of nutrients, pollutants and other materials between the river and the floodplain (Gell et al. 2005; Hausmann et al. 2011; Liu et al. 2012).

Recent papers on the paleolimnology of floodplain lakes have focused mainly on meandering rivers (Gell et al. 2002, 2005; Reid and Ogden 2009). These rivers run across extensive floodplains where oxbow lakes or billabongs frequently form from meanders that gradually become isolated from the river channel. Braided rivers, on the other hand, form smaller floodplains. Thus, the aquatic bodies formed in them differ from classical oxbows. Paleolimnological information on floodplain lakes from such braided rivers is scarce. Here, we present a late Holocene limnological and hydrological history of the Cauca River utilizing a sequence of exposed sediments collected where the channel is braided. It was our goal to provide a deeper understanding of the hydrology, sedimentology and ecosystem dynamics of tropical floodplain braided fluvial channels. Our paleoenvironmental inferences are based on detailed analyses of litho-facies and diatoms. Sediments analyzed in this study are exposed in the San Nicolás terrace, formed during an accretional stage of the Cauca River. Previous paleoenvironmental reconstructions from the San Nicolás terrace include: (1) a palynofacies and preliminary diatom analysis, which identified the terrace as a fluvial, shallow, lacustrine depositional environment (García et al. 2011), and (2) a sedimentological and organic geochemical analysis, which suggests that sediments were deposited in riverine-lake environments (Martínez in press). In this study we used diatoms and sedimentological analyses to generate a more robust and detailed paleolimnological reconstruction of the floodplain lakes, with emphasis on paleoecological conditions under the dynamics imposed by the connectivity with the Cauca River.

Study area

The Santa Fe-Sopetrán Basin (Suter and Martínez 2009) is a north-striking, 20-km-long inter-Andean basin located 500 m above sea level (asl), between the Western and Eastern Andean Cordilleras in northern Colombia (Fig. 1). This tectonic setting has been classified an active pull-apart basin (Suter and Martínez 2009; Suter et al. 2011). Once the Cauca River enters the Santa Fe-Sopetrán Basin from the south, the channel becomes braided, whereas outside the basin, it is mainly straight and incises the bedrock. The San Nicolás terrace outcrops along La Caimana Creek, a W-E flowing tributary of the Cauca River, confined between small and steep hills on the metamorphic basement (García et al. 2011). The San Nicolás terrace lies stratigraphically between an older level, terrace I, and a modern one, terrace III (Page and Mattsson 1981) (Fig. 1). The succession of terraces I, II, and III may be related to stages of tectonic quiescence (incision) and activity (accumulation) in the Santa Fe-Sopetrán Basin. Mapping of the area revealed a grain-size zonation, with conglomeratic sediments south of the basin (upstream) and finely laminated clays and silts in the north (downstream) (Fig. 1).

Materials and methods

Fieldwork

The terrace was described from an outcrop in La Caimana Creek (Fig. 1). The outcrop was cleared of vegetation and weathered sediment to guarantee that a fresh exposure was studied. A detailed outcrop description, with extensive lateral and vertical coverage, was done to complement the stratigraphic information presented in García et al. (2011) and Martinez et al. (in press). Detailed measurements of bed thickness and grain size were taken, paleocurrent readings were obtained, and observations of color and

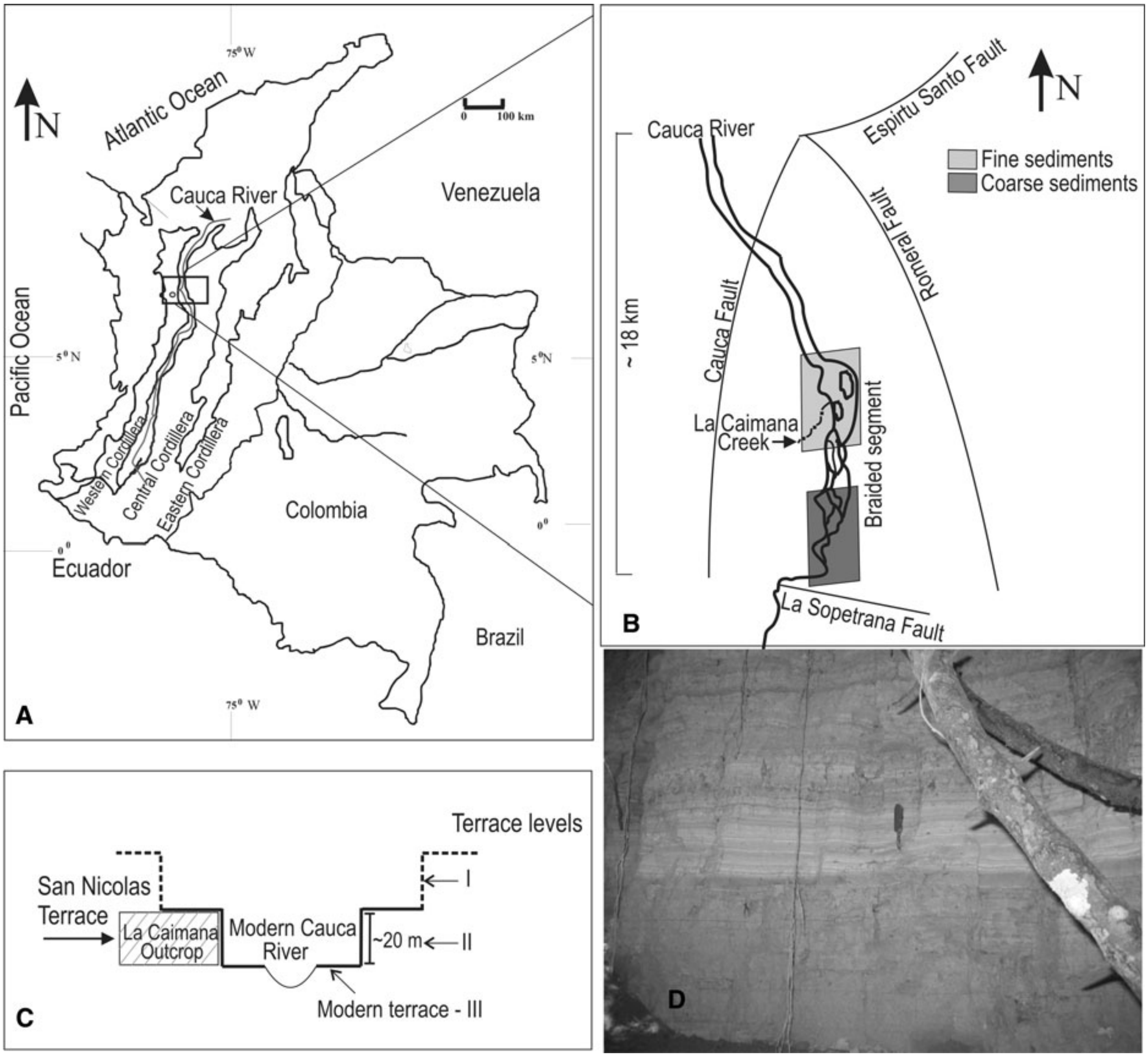

Fig. 1 **a** Map of Colombia showing the Cauca River and the study area (rectangle in the Northwest part of Colombia between the Eastern and Central Andean Cordilleras). **b** General tectonic setting of the basin and location of the study area along La Caimana Creek. **c** Stratigraphic position of the San Nicolas Terrace (Terrace level II) in relation to the other terrace levels I and III. **d** Photo of the studied section of the San Nicolas terrace showing the nature of the sediments and fine-scale lamination

sedimentary structures were recorded. Sediment samples were taken for both pollen (García et al. 2011) and diatom analysis.

Radiocarbon dating

A chronologic model for the San Nicolás Terrace was presented in García et al. (2011) and later reviewed by Martínez et al. (in press). For the La Caimana section, twelve bulk sediment samples were dated using accelerator mass spectrometry (AMS) at the University of Tokyo and one AMS date was obtained on a bivalve shell at the University of Laval. Radiocarbon dates were calibrated using OxCal 4.1 (Martínez et al. in press). Dates are presented as calendar years before present (cal yr BP).

Diatoms

About 0.3 g dry sediment was diluted in 40 ml distilled water and 0.6 ml aliquots were directly mounted on a cover slip and glued with Zrax (R.I. 1.7) for microscope

Table 1 Radiocarbon dates of La Caimana section (modified from Martínez et al. in press). *Dates used in the age-depth model

Sample	Above base (cm)	Lab Code	^{14}C yrs BP	BC/AD (95.4 %)-2 sigma	cal yr BP
LC-01	228	12246	5,235 ± 50	4,231–3,962 BC	6,045
LC-03	326	12247	5,705 ± 110	4,788–4,347 BC	6,518
LC-04*	435	12248	2,965 ± 50	1,374–1,025 BC	3,150
LC-05*	511	12700	2,970 ± 135	1,496–847 BC	3,122
LC-06*	597	13126	2,435 ± 45	755–403 BC	2,529
LC-07	630	12701	3,765 ± 50	2,397–2,028 BC	4,163
LC-08*	717	12702	2,395 ± 50	752–389 BC	2,521
LC-09	837	13127	2,985 ± 45	1,381–1,056 BC	3,169
LC-10*	935	13128	1,945 ± 130	352 BC–382 AD	1,920
LC-11	1,065	13129	2,695 ± 195	1,376–399 BC	2,838
LC-12	1,522	13130	4,000 ± 50	2,836–2,346 BC	4,541
LC-13	435	ULA3244	1,460 ± 15		1,344

analysis. Samples were not digested with H_2O_2. Sampling for diatom analysis was done systematically, ensuring diverse lithologies were examined. At least 300 valves were counted per sample (Battarbee 1986). Samples for analysis of modern diatoms were collected from water and submersed plants in the Cauca River, La Caimana Creek, and in swamps and soils in the modern floodplain in May and June 2010. Samples were transported to the soils laboratory of EAFIT University and processed according to Battarbee (1986). For diatom identification and ecology, the following references were used: Evans (1958), Patrick and Reimer (1966), Lowe (1974), Foged (1978), Hoffmann (1989), Fritz et al. (1991), Torgan and Biancamano (1991), Krammer and Lange-Bertalot (1991, 1999, 2000), Moro and Fürstenberger (1997), Watanabe and Asai (1999), Gaiser and Johansen (2000), Servant and Servant Vildary (2003), Lauriol et al. (2006), and Poulícková and Hašler (2007). The diatom stratigraphic diagram and cluster analysis were produced with Tilia and Tilia Graph (Grimm 1987). Modern assemblages recovered from soils and swamps were used to interpret the paleoenvironmental conditions.

Results

Radiocarbon dates

Radiocarbon results show two clusters of dates. Older dates are attributed to reworking of organic matter. Younger dates are considered to be from organic matter in situ (Martínez et al. in press) (Table 1, Fig. 2). The age model was therefore built using the younger dates (Fig. 2). The date on the bivalve shell, given its very young age, is considered an outlier. The dates for the diatoms zones and reconstructed environmental periods were estimated from the linear regression line obtained for the age model (Fig. 2). According to this age model, sediment accumulation started sometime between ~4,500 and 4,000 cal yr BP and ended ~850 cal yr BP. Average linear accumulation rate was on the order of ~614 cm/kyr.

Modern diatoms and hydrological conditions

Nitzschia cf. *palea, Navicula* sp. and *Achnanthes* spp. occur at La Caimana Creek and the Cauca River. This modern assemblage does not resemble any of the fossil assemblages and therefore cannot be used in the environmental reconstruction. Similarity in species composition between the data from the two sites is evidence of the influence the Cauca River has on the La Caimana tributary. This influence is directly observed during the rainy season when the river floods into La Caimana Creek. Diatoms from modern soils and ephemeral swamps are dominated by *Navicula mutica*, *N. confervacea* and *N. contenta,* species that also occur in the fossil assemblages. These taxa were thus used in the environmental reconstruction as indicators of aerial/terrestrial or very shallow-water conditions.

Diatom zones

Of 73 prepared samples, only 28 had the minimum number of 300 valves for inclusion in the statistical analysis (Battarbee 1986). Two additional samples, however, with counts of only 250 valves, were included because they came from key levels, 558 and 1,094 cm. The paleolimnological reconstruction is thus based on 30 samples. Diatoms were grouped according to their ecology, i.e. planktonic, benthic, epiphytic, facultative planktonic and aerophil/terrestrial. Four diatom zones were identified using CONISS (Fig. 3).

Diatom zone 1 (264–515 cm above base; ~3,260–2,800 cal yr BP)

This zone is composed of planktonic species *Aulacoseira granulata,* with increasing abundances towards the top of the zone (1–49 %) and isolated peaks of *Aulacoseira ambigua* (40 %) and *Cyclotella meneghiniana* (15 %). Facultative planktonic *Synedra ulna* is present throughout (5–15 %). The terrestrial species *Orthoseira dendroteres* (4-11 %), *Orthoseira roeseana* (3–12 %), *Navicula mutica* (1–6 %) and *Navicula goeppertiana* (3–6 %) are more abundant at the base of the zone. Epiphytic species *Gomphonema gracile* peaks at the top (1–14 %). Other epiphytic and benthic species are present, although with low values, i.e. *Cocconeis* aff. *pediculus* (2–7 %), *Cocconeis placentula* (2–6 %), and *Nitzschia amphibia* (1–9 %).

Diatom zone 2 (515–790 cm above base; ~2,800–2,400 cal yr BP)

This zone is dominated by the planktonic species *A. granulata* (14–80 %). Epiphytic species *Pinnularia gibba* and *Pinnularia maior* peak at the top of the zone with 36 and 9 %, respectively. Facultative planktonic species such as *Fragilaria nanana*, also peak (20 %) towards the top, whereas *S. ulna* is present throughout the zone (3–14 %). Diatoms were not preserved in the middle of the zone.

Diatom zone 3 (790–1,450 cm above base; ~2,400–1,350 cal yr BP)

This zone is dominated by the benthic species *N. amphibia* (42–90 %). The planktonic species *A. granulata* is present throughout the zone (2–19 %), though it is more common in the middle and top. Epiphytic *G. gracile* is present at relatively low values (1–13 %), with the higher values at the bottom of the zone. *Synedra ulna* and *P. gibba*, which are facultative planktonic and epiphytic species, respectively, are present throughout the zone, with slightly higher values towards the top (1–14 %). Single peaks of epiphytic *Amphora ovalis* (27 %), *Achnanthes* cf. *suchlandti* (7 %), and the planktonic species *C. pseudostelligera* (5 %) are recorded. Other taxa with percentages ~5 % include *Navicula leptiostrata, N. minuta*, *Pinnularia braunii, P. gibba*, and *Rhopalodia gibba.* Diatoms were not preserved at the beginning and top of the zone.

Diatom zone 4 (1,450–1,700 cm above base; ~1,350–850 cal yr BP)

This zone is dominated by the benthic species *N. amphibia* (3–47 %). Other species that occur throughout include the facultative planktonic *S. ulna* (5–11 %), the epiphytic *C.* aff. *pediculus* (1–6 %) and *G. gracile* (1–9 %), and *A. granulata* (1–11 %). *Pinnularia maior* and *P. viridis* are common at the base of the zone (8–9 %). Other species peak in this zone, such as the terrestrial *N. confervacea* (33 %) at the base, and the facultative planktonic *Fragilaria capucina* (18 %) at the top. Diatoms were not preserved at the beginning of the zone.

Lithofacies and paleocurrents

The sedimentary succession in La Caimana creek rests on a regional unconformity marked by a paleosol developed on top of a consolidated, mass-wasting deposit. This unconformity follows the paleo-topography and is higher, both topographically and stratigraphically, on the west part of the outcrop. The first 14 m, from base to top (Fig. 4), are composed of cm-scale laminated silt and clay, with a few fine-grained, cross-bedded sand beds. Three massive clay beds, a few cm thick and with root traces, occur at 0.3, 12.5 and 14 m. A coarsening-upward clay to silt bed is identified ~4 m from the bottom. Laminae vary in color, ranging from orange, to brown, dark grey, and white to light grey. Coal and gypsum laminae, and a bivalve in life position were found in this lithofacies. The top 4 m of the section are composed of fining-upward silts and sand beds dissected by small

Table 2 Ecological preferences of dominant and common diatoms used in the paleolimnological reconstruction

Common species	Ecology	Reference
Achnanthes suchlandti	(1) pH indifferent	(1) Moro and Fürstenberger (1997)
	(2) Oligotrophic, circumneutral, low-med electrolyte content	(2) Krammer and Lange-Bertalot (1991)
Amphora ovalis var. *affinis*	(1) Littoral, periphytic, epiphytic, alkaliphil, indifferent to salinity	(1) Moro and Fürstenberger (1997)
		(2) Krammer and Lange-Bertalot (1999)
	(2) Littoral, cosmopolitan, med electrolyte content, slightly brackish water	
Aulacoseira granulata	(1) Planktonic, fresh and brackish water	(1) Torgan and Biancamano (1991)
	(2) Well mixed water, moderately eutrophic, moderately alkaline	(2) Sala et al. (1999)
	(3) Turbulent conditions	(3) Kilham (1973)
	(4) In surface sediments from the modern lake (1.5 m depth)	(4) Vélez et al. (2005a)
Cocconeis placentula	(1) Epiphytic on aquatic plants circumneutral to alkaline	(1) Patrick and Reimer (1966)
	(2) Littoral, epiphytic, periphytic, tolerant to a wide range of pH and salinity	(2) Moro and Fürstenberger (1997)
Fragilaria capucina	(1) Freshwater slightly alkaline, salt indifferent	(1) Patrick and Reimer (1966)
	(2) Littoral, planktonic, tychoplanktonic	(2) Moro and Fürstenberger (1997)
Fragilaria nanana	(1) Oligohalob., planktonic, pH indifferent	(1) Moro and Fürstenberger (1997)
	(2) Disperse to rare in plankton of oligotrophic lakes	(2) Krammer and Lange-Bertalot (2000)
Gomphonema gracile	(1) Littoral, occasionally planktonic, low nutrient content, indifferent to pH and conductivity	(1) Patrick and Reimer (1966)
Navicula confervacea	(1) Aerophil or shallow water, prefers soft warm water	(1) Patrick and Reimer (1966)
	(2) pH: 4,6-6, low conductivities	(2) Sala et al. (2002)
	(3) On soils from the modern floodplain	(3) Personal observation
Navicula contenta	(1) Terrestrial on wet moss	(1) Krammer and Lange-Bertalot (1999)
	(2) Tolerates periods of drought	(2) Lauriol et al. (2006)
	(3) On soils from the modern floodplain	(3) On soils from the modern floodplain
Navicula mutica	(1) Often as aerophil	(1) Krammer and Lange-Bertalot (1999)
	(2) Soil samples, brackish conditions or sublittoral areas, damp surfaces, common in soils and caves	(2) Poulícková and Hašler (2007)
		(3) On soils from the modern floodplain
	(3) On soils from the modern floodplain	
Nitzschia amphibia	(1) Periphytic, alkaliphil, alkalibiont, salt indifferent	(1) Lowe 1974
	(2) Eutrophic, hard water	(2) Moro and Fürstenberger (1997)
	(3) Not attached (floating, free motile)	(3) www.craticula.ncl.ac.uk
Orthoseira roeseana	(1) Aerophil, common in caves,	(1) Gaiser and Johansen (2000)
	optimum depth 2.2 cm	(2) Poulícková and Hašler (2007)
	(2) Aerophil on rock faces, bryophytes, alkaline areas	
Orthoseira dendroteres	Terrestrial, optimum depth 2.2 cm	Gaiser and Johansen (2000)
Pinnularia braunii	(1) Water with low electrolyte content	(1) Patrick and Reimer
	(2) Epiphytic	(2) Moro and Fürstenberger (1997)
Pinnularia gibba	(1) On plants from littoral ponds, acidic water	(1) Patrick and Reimer
	(2) Oligotrophic to eutrophic, mainly periphytic	(2) Moro and Fürstenberger (1997)
Pinnularia maior	(1) On plants from littoral ponds, acidic water	(1) Patrick and Reimer (1966)
	(2) Oligotrophic waters	(2) Moro and Fürstenberger (1997)
Synedra ulna	(1) Facultative planktonic	(1) Gell et al. (2005)
	(2) Freshwater	(2) Patrick and Reimer (1966)

channels. Massive clay beds of a few cm, up to a meter, and with root traces, are more common in the top part. The upper meter, composed of fine laminated silt and clay, is similar to the bottom part of the section, except for the presence of small, sand-filled channels.

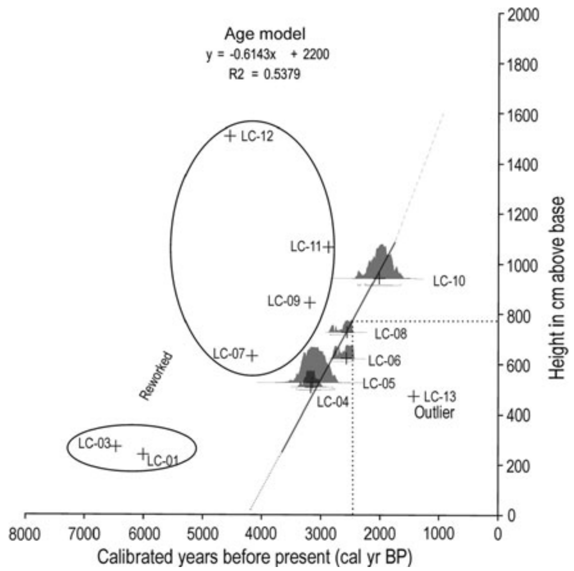

Fig. 2 Age model for the studied section showing the cluster of old and young dates, the outlier and an example (*dash lines*) of how we estimated the age for the sample at 790 cm above base (modified from Martínez et al. in press)

About 33 paleocurrent readings were taken from different depths in the section to determine the directions of the flow. Rose diagrams (Fig. 4) show that the currents flowed predominantly to the southwest and northwest.

Discussion

Diatoms

Dominance of epiphytic and terrestrial species at the base of diatom zone 1 (~3,260–2,800 cal yr BP) indicates the presence of ephemeral swamps with abundant plants. The increase in planktonic species, mainly *A. granulata*, at the top of diatom zone 1 and bottom of diatom zone 2 (~2,800–2,400 cal yr BP), suggests a change from ephemeral to more permanent ponds, where turbulence was maintained by longer connectivity with the Cauca River. Pond waters were presumably low in nutrients and acidic. The increase

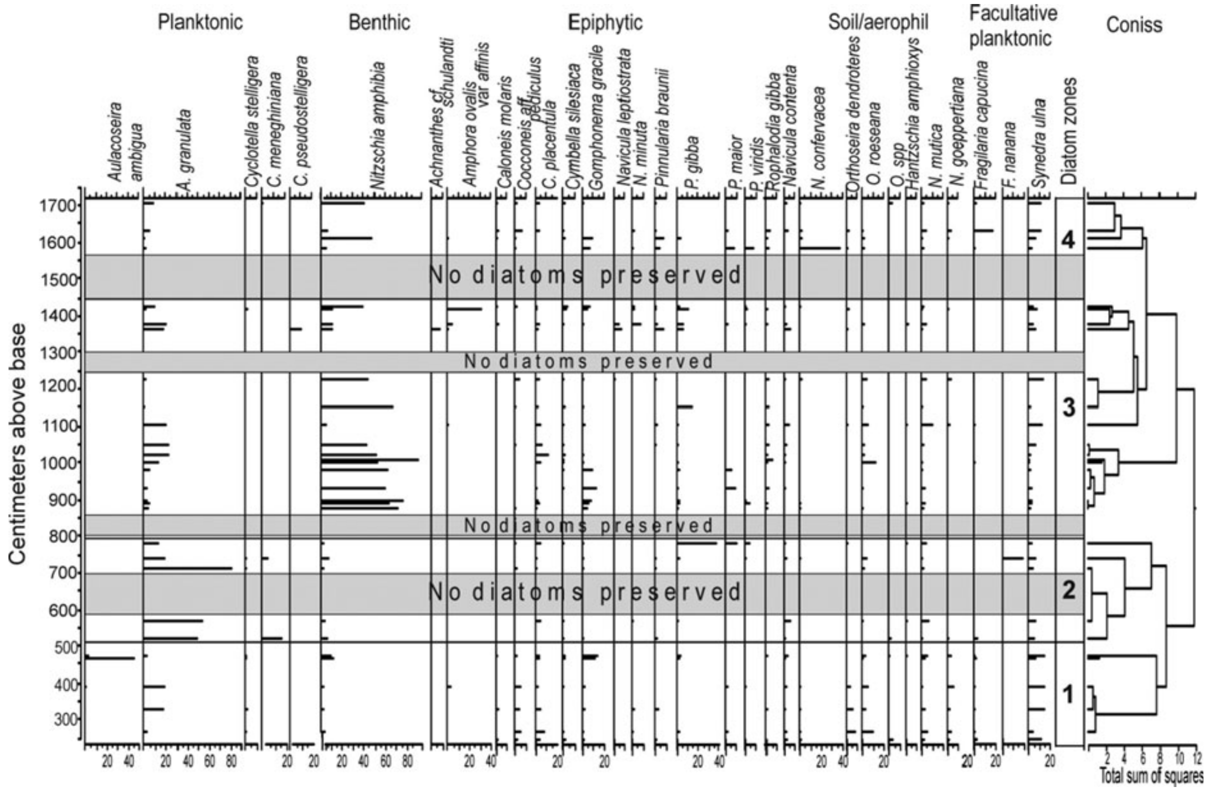

Fig. 3 Stratigraphic distribution of the diatom taxa and their grouping according to their ecology

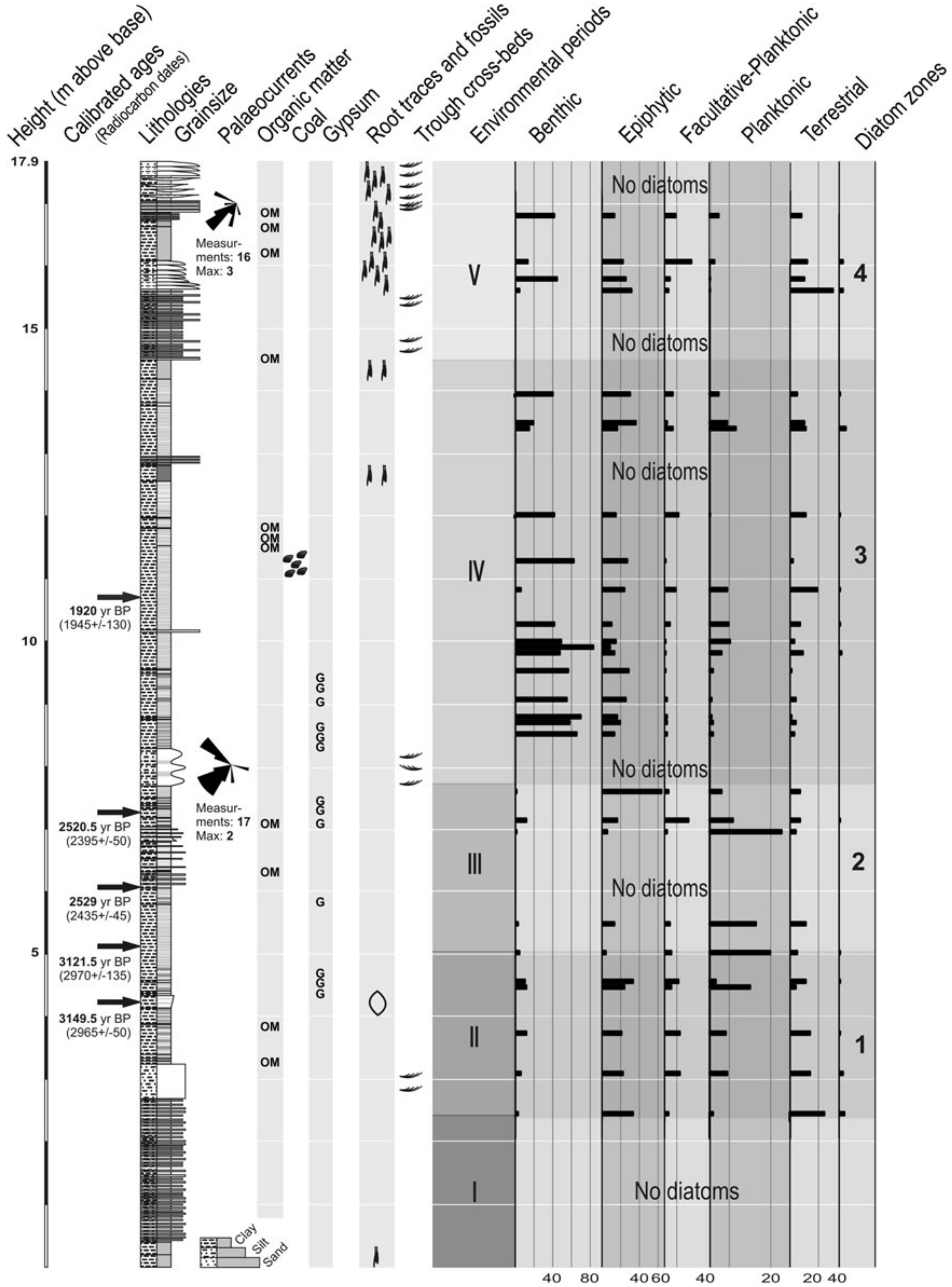

Fig. 4 Integrated analysis of the La Caimana section. From *left* to *right* scale in m, calibrated ages, lithology and grain size, organic matter, gypsum content, sedimentary structures, diatom assemblages, diatom zones and paleoenvironmental periods

in planktonic diatoms and decrease in epiphytic taxa in zone 2 compared to zone 1 probably reflects a decrease in plants, which suggests deeper-water conditions. *Aulacoseira granulata* is a robust planktonic species that requires turbidity and well-mixed conditions to remain suspended in the upper water column (Kilham 1973; Liu et al. 2012). It inhabits lakes and rivers of a wide range of trophic conditions, from oligotrophic (Vélez et al. 2005a, b) to eutrophic (Gómez et al. 1995; Torgan and Biancamano 1991; Sala et al. 1999), and a wide range of salinities (Torgan and Biancamano 1991; Fritz et al. 1991). Several paleolimnological studies from floodplain lakes (Gell et al. 2002, 2005; Reid and Ogden 2009; Liu et al. 2012; Grundell et al. 2012) suggest that *A. granulata* is common to dominant in the lake's plankton during stages of lake–river connectivity. Although this taxon is now absent from the Cauca River, it was the single most common taxon in the sediments from the Pliocene and Pleistocene Zarzal Formation (Sandoval 1953), which is a stratigraphic unit that outcrops along the Cauca River, south of the study area, and is characterized by diatomite layers formed during several episodes of impounding of the Cauca River and its tributaries (Neuwerth et al. 2006). The diatomites are composed mainly of *A. granulata* (95 %) (Sandoval 1953), which indicates that during the remote past, this taxon inhabited the river. Its absence from the Cauca River today could be a consequence of increased sediment load from deforestation in the basin or eutrophication of the water, as observed by Liu et al. (2012). Given the hydrodynamic requirements of *A. granulata* and its abundance in the paleo-Cauca River, we use it as an indicator of periods during which floodplain waters were connected with the river.

A change in the limnological conditions of the floodplain lakes is reflected by the change in diatom community composition at the beginning of zone 3 (~2,400–1,350 cal yr BP). The record is dominated by *N. amphibia,* with the presence of *G. gracile* and *C. placentula,* which are benthic, epiphytic species that inhabit alkaliphilous and eutrophic waters. These taxa suggest the presence of permanent lakes with abundant macrophytes and high-pH, nutrient-rich waters. The decrease in *A. granulata,* particularly towards the top, suggests that although pulses from the river occurred, they did not last long, as this taxon does not attain high relative abundances in zone 3. Dominance of the salt-tolerant species *N. amphibia*, and the peaks in *Amphora ovalis* and *Achnanthes* cf. *suchlandti* (Lowe 1974; Krammer and Lange-Bertalot 1991), suggest that the water experienced periods of high salinity as a consequence of evaporation. Dominance of few taxa in zone 3, and the isolated peaks of some species, suggest that evaporitic conditions were ecologically stressful. With the onset of zone 4 (~1,350–850 cal yr BP), which is generally similar to zone 3, planktonic taxa decreased while terrestrial and facultative planktonic types increased. This suggests that the floodplain ponds that formed were colonized by macrophytes, but desiccated quickly as water pulses from the river diminished.

Lithofacies

The massive gray clay beds of a few cm up to a meter, with roots, are classified as paleosols (Retallack 2001; Miall 2010). The fine laminated clay and silt facies indicate sediment deposition from suspension, carried by low-energy floods, possibly sheet floods, typical of floodplains (Miall 1996; Nichols 2007). Presence of gypsum indicates solute saturation in the water column and deposition under evaporitic conditions. Coarsening-upward, cross-bedded silt and sand beds suggest bed load transport events of increasing energy, probably formed during storms (Miall 1996), whereas fining-upward silt and sand beds are suggestive of waning flows.

Orange coloration is interpreted as the product of oxidation of organic matter, as observed in thin sections and halos around root traces. Oxidized fungal spores inside diatom frustules are common features. Oxidation most likely occurred when the sediments were exposed to aerial/subaerial conditions (Stephen Bend pers. commun.). Contrary to the oxidized organic matter, we interpret the coal and dark-clay laminae, rich in organic matter, as indicative of rapid burial or anoxic conditions, probably occurring at the bottom of stagnant water bodies. Small channels, fining-upward sand laminae and thick paleosols, which are more common in the top 4 m of the sedimentary succession, suggest a change in the hydrological and sedimentological regime, from a "stable" floodplain dominated by low-energy flows to a floodplain dissected by streams of higher energy. The river-pulse frequency decreased, as there was enough time between floods for soils to form. Paleocurrent analysis indicates that these high-energy flows

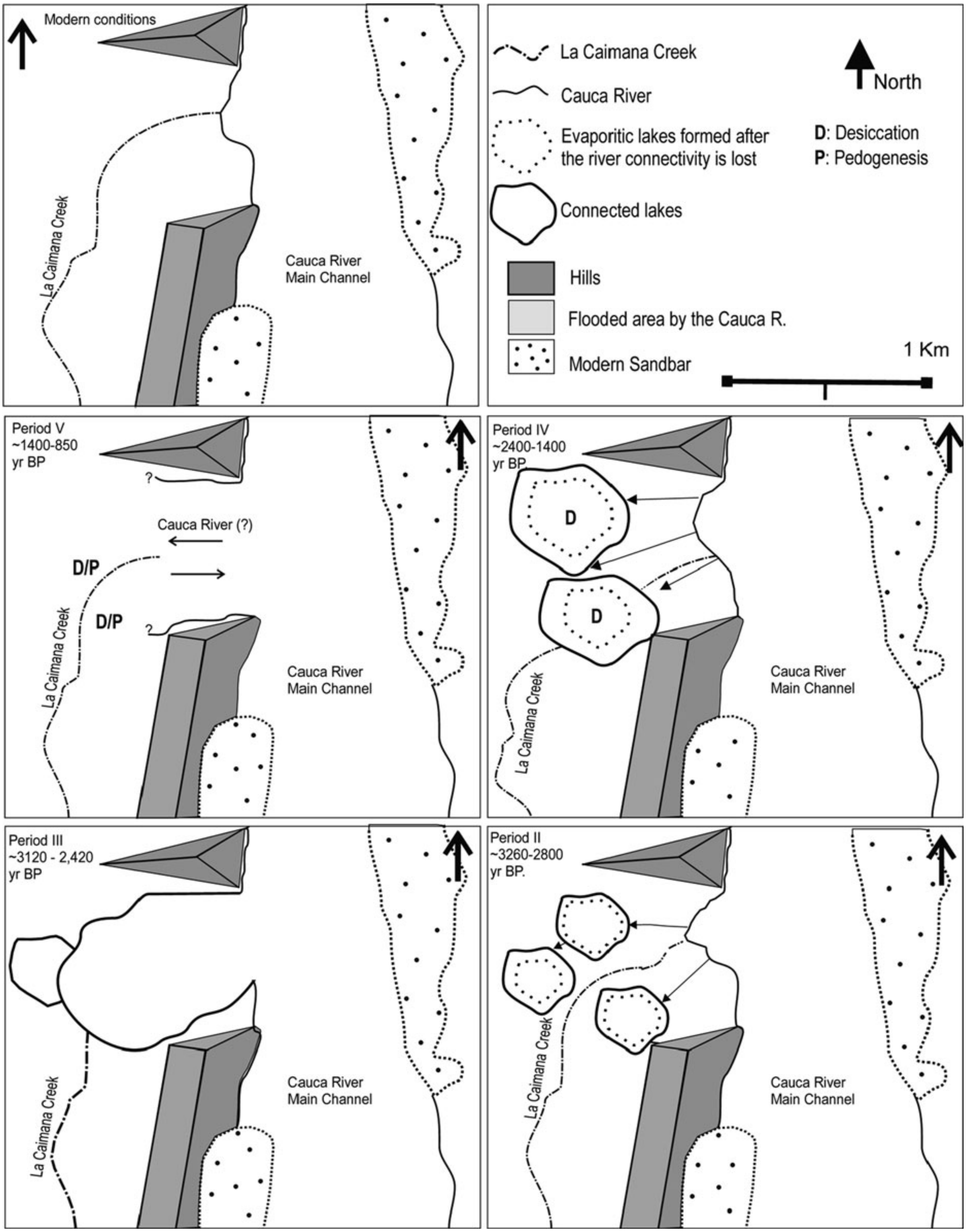

Fig. 5 Evolution of the floodplain lakes, as reconstructed in this study. Modern conditions are presented in the *top left*, with older conditions, period II, in the *bottom right*

came from the east and entered La Caimana tributary. This could indicate either a more energetic Cauca River that eroded its own floodplain, or a westward migration of the main channel. Paleocurrent analysis indicates that sediments from this succession were deposited by flows coming from the Cauca River (Martínez et al. in press).

Integrated paleoenvironmental reconstruction

Integration of lithofacies, diatom and chronologic data allowed identification of five environmental periods in the Cauca River floodplain between about 3,750 and 850 cal yr BP (Fig. 5):

Period I: ~(4,500) 4,000–3,260 cal yr BP (0–264 cm above base). This period records the beginning of floodplain sedimentation. At that time, hydrological conditions changed from infrequent flooding, as indicated by the thick paleosols, to frequent flooding, as indicated by laminated silts. No diatoms were recovered.

Period II: ~3,260–2,800 cal yr BP (264–515 cm above base; diatom zone 1). At the beginning of this period, a single high-energy flood occurred, followed by a decrease in hydrologic energy and establishment of a low-energy flooding regime. The diatom assemblage suggests that ephemeral, shallow swamps of low conductivity, low pH, and low nutrient concentration frequently formed in the floodplain, and that their existence depended on connectivity with the Cauca River. The increase in epiphytic diatoms and gypsum towards the end of this period suggests an increase in plant coverage and development of evaporitic conditions as a result of decreased frequency of river pulses. Coarsening-upward clay beds, with sharp basal and top contacts, suggest that another high-energy flood event occurred around 3,150 cal yr BP. At the end of the period, lacustrine conditions with connectivity to the Cauca River were established, as indicated by the diatom assemblage.

Period III: ~2,800–2,400 cal yr BP (515–790 cm above base; diatom zone 2). At the beginning of this period, swamps maintained a connection with the river and were colonized by plants. Increasing high-energy events and thus riverine influence occurred in the middle of the period, ~2,530 cal yr BP, after which low-energy flood conditions returned.

Period IV: ~2,400–1,350 cal yr BP (790–1,410 cm above base; diatom zone 3). At the beginning of this period, the floodplain was under the influence of high-energy flows, reflected by three discrete sand layers. This riverine influence gradually decreased, allowing the formation of large swamps or lakes of alkaline waters and high nutrient concentration, with abundant macrophytes. Towards the middle part of this period, ~1,920 cal yr BP, connectivity with the river was re-established for a short time, as indicated by the increase in planktonic taxa and sand laminae. After ~1,920 cal yr BP, connectivity was lost again and evaporitic conditions developed, followed by complete desiccation and soil formation. During the evaporitic phases, the water was alkaline and saline, as indicated by the dominance of *N. amphibia, G. gracile* and the greatest abundance of *A. ovalis* and other *Amphora* species. Preservation of organic matter and coal laminae in the sediments suggests that anoxic waters developed, probably as a consequence of poor water circulation, as the river influence diminished. Absence of diatoms in the samples may have been caused by poor preservation, or more likely, lack of production caused by a long dry period on the floodplain indicated by a paleosol layer. After this dry period, connectivity was re-established for a short time, allowing evaporitic swamps to form once again. Fluctuations in the connectivity with the river throughout this period are also inferred from the mixed character of organic matter, an increase in amorphous organic debris, and a decrease in altered phytoclasts and charcoal (García et al. 2011).

Period V: ~1,350–850 cal yr BP (1,410–1,694 cm above base; diatom zone 4). This period records a change in the hydrological regime of the floodplain. High-energy and high-frequency flood events, indicated by the coarser sediments and fining-upward beds, were interrupted by longer periods of quiet conditions that led to plant colonization and pedogenesis, as indicated by the paleosols and abundance of terrestrial diatoms. Epiphytic and benthic (*N. amphibia*) diatoms suggest that ephemeral and evaporitic swamps developed for short times.

Conclusions

Sediments from the La Caimana succession, Colombia, yielded a unique record of the evolution and dynamics of the ancient floodplain of the Cauca River and its aquatic ecosystems. It is the first such record for the northern Neotropics. The diatom record indicates that swamps and ponds on the floodplain were formed as a result of connectivity with the Cauca River. During periods of connection, these water bodies had low concentrations of salts and nutrients, and possibly achieved considerable water depths. When the river connection was lost, the swamps were subject to evaporitic conditions that led to the reduction of the water volume, with associated increases in salinity and nutrients.

The environmental periods identified in this study document the evolution of the floodplain, from its formation sometime after ~3,750 cal yr BP, to the establishment of lakes and swamps that were probably fed by seasonal flows of low energy. Establishment of a fluvio-lacustrine regime was identified by García et al. (2011) at ~3,150 yr BP, on the basis of an increase in altered phytoclasts. The origin of floodplain sediments is still uncertain. Page and Mattsson (1981) attributed the origin of the sediments of the San Nicolás terrace to mega-slides that impounded the Cauca River north of the basin. The confluence of faults north of the basin could also have played a role, by changing the equilibrium profile of the river, generating an accretional phase. The cause(s) of the onset and cessation of this depositional phase still need to be investigated. A switch in the limnological conditions of the floodplain water bodies is recorded after ~2,800 cal yr BP, when they changed from ephemeral swamps to permanent evaporitic lakes of larger extent and when littoral plant communities developed. García et al. (2011) identified fluctuations in river connectivity taking place by ~2,730 cal yr BP. These changes could be explained as a change from *igapó*- to *várzea ria*-type lakes that occurred at ~3,000 cal yr BP, as isotopically identified by Martínez et al. (in press). The decrease in total N, C and C/N values, the shift in average values of δ^{13}C, from −24 to −22 ‰, along with lower values of ligno-cellulose debris, are interpreted as a switch from *igapó* (black waters with a light sediment load) to *várzea* (white waters with a heavier sediment load) lacustrine environments (Martínez et al. in press). The increase in sediment load could have been the result of anthropogenic deforestation, an increase in precipitation, or both. Early Holocene human activities ~400 km south of the study area have been reported (Vélez et al. 2005a). The hydrologic change recorded shortly after ~2,400 cal yr BP towards higher-energy fluvial conditions could be a reflection of periodic damming of the La Caimana tributary caused by the Cauca River carrying a heavier sediment load, and thus forming the *várzea*-type lakes (Martínez et al. in press). After ~1,350 cal yr BP, the floodplain was characterized by less frequent high-energy flows that formed ephemeral evaporitic swamps, and created conditions for pedogenesis. The increase in gelified, amorphous organic matter by ~600 cal yr BP (García et al. 2011), is indicative of aerobic diagenesis, thus supporting the interpretation of frequent aerial exposure events.

The change in lithofacies between periods I and II, and the absence of diatoms in period I, could be explained by the prevalence of low-productivity black waters at the beginning of the record, as is normally the case in *igapó*-type lakes (Putz 1997). Different from billabongs or oxbow lakes, where lacustrine sedimentation occurs for longer time as the lake deepens, the water bodies of the braided paleo-Cauca River never achieved much depth, and as a consequence, the sediments themselves do not suffice as a tool for identification of lacustrine phases. For that purpose, diatom analysis was required.

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