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ORIGINAL PAPER

The San Nicolás succession of the Cauca paleolake: a late Holocene laminated ria lake record from the Neotropics

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Abstract The stratigraphic, geochemical, and organic matter study of the late Holocene San Nicolás succession of the Cauca paleolake (Santa Fé–Sopetrán pull-apart basin) in the middle Cauca Valley, northern Colombia, suggests that it was deposited in a ria lake environment, at sedimentary accumulation rates in excess of 600 cm ky^{-1} between $\sim$3500 and $\sim$500 yr BP. Laminated deposition occurred, first under *igapo* (black-water), and then under *varzea* (white-water) conditions. The transition occurred ca. 3000 yr BP, a time of major change in El Niño/Southern Oscillation (ENSO) behavior in the Cariaco Basin, thus reflecting the southern migration of the intertropical convergence zone and intensified rain upstream the Cauca Valley. A second, but less conspicuous change occurred ca. 2000 yr BP, which apparently corresponds to the intensified and/or more frequent ENSO activity in the Galapagos Islands. Our contribution describes, for the first time, a ria lake sedimentary succession from the northern Andes and demonstrates the high potential of these hitherto undervalued deposits for the reconstruction of the paleohydrological history of the northern Andes.

Keywords Ria lakes · Late Holocene · Neotropics · Laminated sediments

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Introduction

Only a few Holocene laminated, high resolution, sedimentary successions have been documented in the Neotropics. These include the Cariaco Basin (Venezuela; Peterson et al. 2000), the Pallcacocha Lake, Ecuador (Rodbell et al. 1999; Moy et al. 2002), and the Brainbridge and El Junco Lakes, Galapagos Islands (Riedinger et al. 2002; Conroy et al. 2008). Despite the quality of these unique paleoclimate records, there is a significant gap in our knowledge of the Colombian region. In this region, besides the meridional migration of the intertropical convergence zone (ITCZ), the impact of El Niño–Southern Oscillation (ENSO), and the North Atlantic Oscillation (NAO) phenomena, the northern Andes impose a significant barrier to the interaction between Atlantic and Pacific climate regimes, therefore resulting in climate dynamics that are still poorly understood at centennial to decadal time-scales. The Cauca paleolake sedimentary succession has the potential to fill this gap in information.

Here we explore the San Nicolás sedimentary succession of the Cauca paleolake (6°30′N; 75°50′W, Fig. 1) as a unique potential, high resolution, paleoenvironmental and paleoclimate record for the late Holocene. The sedimentary successions of the Cauca paleolake were formerly recognized in three terraces levels, Obregón (3100 yr BP), San Nicolás (1500 yr BP), and Olaya (800 yr BP), attributed to lacustrine sedimentation as the product of the episodic damming of the Cauca river by landslides in the Liborina region, north of our study site, during the late Holocene

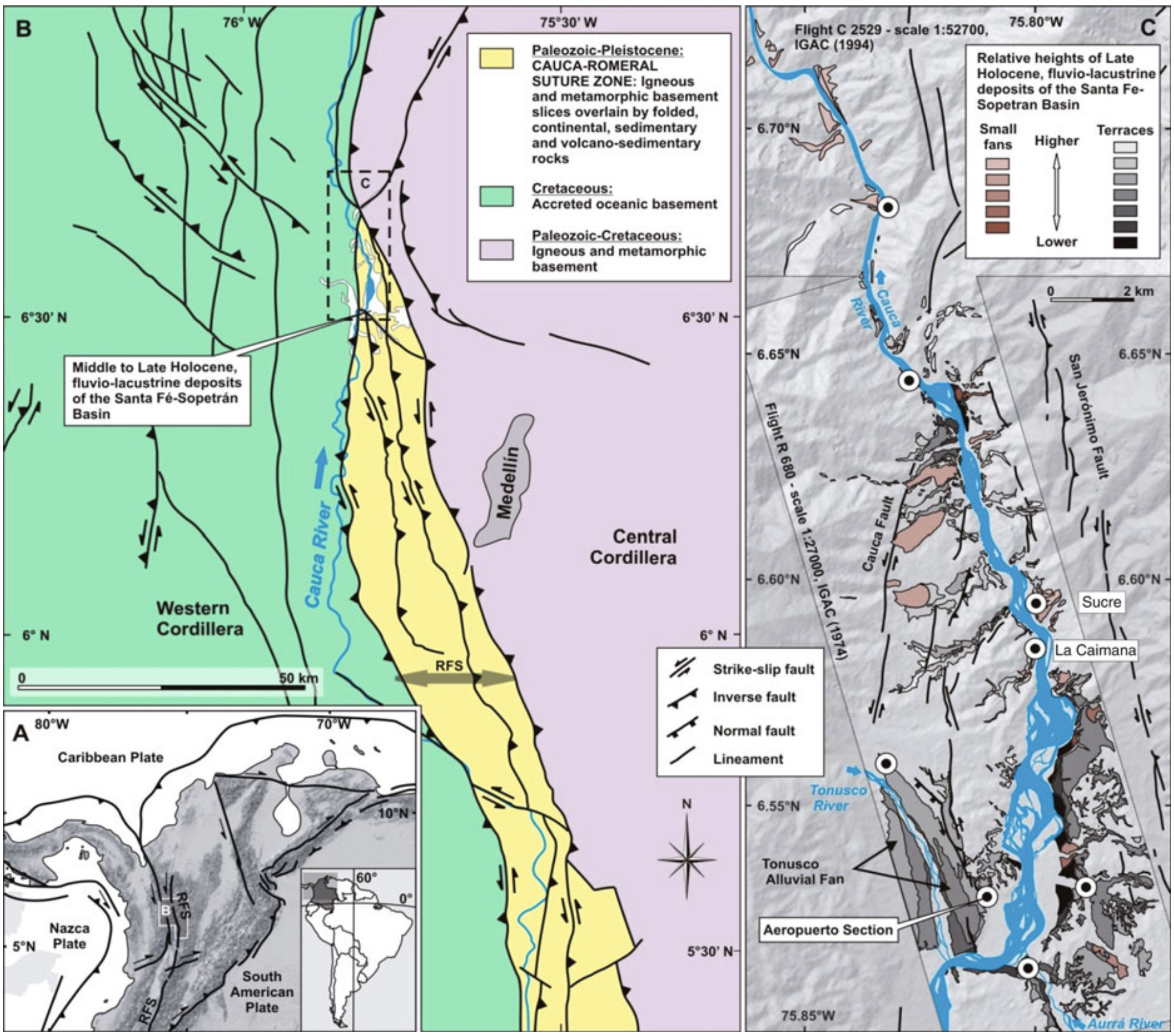


Fig. 1 **a** Neotectonic framework of the Colombian Andes. **b** Simplified geologic map of the middle Cauca Valley. Note the location of Medellín and the Late Holocene fluvio-lacustrine deposits (in *white*) of the Santa Fe–Sopetrán (SF–S) Basin (modified from Mejía et al. 1983 and Gómez et al. 2007). **c** Geomorphological map of the northern part of the SF–S Basin, showing the relative heights of terraces and fans. Note the location of La Caimana and Sucre sections. The San Nicolás-1 well was drilled 100 m south of La Caimana Creek. Flight *numbers* used for mapping are indicated. For further details see Suter et al. (2011)

(Page and Mattsson 1981). Ruiz et al. (2005) provided a preliminary description of the San Nicolás succession and stressed its potential as a high-resolution paleoenvironmental record. In accompanying papers we: (1) suggest that the formation of the terrace deposits is not due to landslides, but to subsidence in the Santa Fe–Sopetrán pull-apart Basin (Suter and Martínez 2009; Suter et al. 2011) and, (2) document the palynofacies content of the San Nicolás succession in response to hydrological connectivity with the Cauca River and climate dynamics in northern South America (Garcia et al. 2011). Here we synthesize these data, add detailed stratigraphic, and geochemical information, and demonstrate that the San Nicolás succession of the Cauca paleolake was deposited in a ria lake environment (Baker 1978; Dumont 1996; Schumm et al. 2000) where fluvial dynamics were very important, besides some tectonic control. Furthermore, we suggest that the San Nicolás succession, similarly to the Amazon system, was deposited in *igapó* (black-water) to *varzea* (white-water) environments from ~3.5 to ~1 ka. These environmental settings have not been recognized in the large valleys of the northern Andes, despite their potential as target areas for high-resolution paleoclimate studies.

Studies on modern braided fluvial systems have shown that extreme flooding events, on rivers like the Mississippi and Saskatchewan, do not leave any appreciable sedimentological evidence on their floodplains, because of their wide extent (Gomez et al. 1995; Magilligan et al. 1998; Sambrook Smith et al. 2010). This is different than flooding events on constrained floodplains, such as ria lake environments, where a thick sedimentary record is expected to be preserved. Here we document the San Nicolás succession of the Cauca paleolake, which we interpret as the product of sedimentation in a ria lake environment akin to those widely studied, from the physical and biological point of view, in the Amazon basin. Furthermore, we highlight the potential that exists to extract paleoclimate information from the background sedimentological signal in the thick ria lake deposits of the San Nicolás succession.

Climatology and hydrology of the present Cauca Valley

Presently, climate in the Cauca Valley, as in most of the northern Andes, is dominated by a bimodal regime: two rainy seasons during March–May and October–November and two dry seasons during December–March and June–August (Poveda et al. 2006). This results from the convergence of the trade winds along the ITCZ, which migrates meridionally. Conversely, the presence of the Andes results in a very dynamic atmospheric system producing meso-scale convective cells and high precipitation, mostly on the western and eastern flanks of the Western and Eastern Cordilleras, respectively.

In the Pacific, the westerly low-level Choco jet, whose intensity is controlled by the sea-surface temperature gradient between the cold tongue (south of the equator) and the Panama Basin, annually shifts with the ITCZ and inter-annually with the ENSO phenomenon (Poveda and Mesa 2000; Poveda et al. 2011). The Choco jet is forced by orographic lifting to deliver most of its moisture on the western flank of the Western Cordillera, thus producing a rain shadow or "dry island" effect on the inter-montane Cauca and Magdalena Valleys. However, through the Mistrato pass, located at 5°N on the Western Cordillera, some moisture reaches the Cauca Valley particularly between September and October when the ITCZ is in the north (Poveda and Mesa 2000). This has an important effect on the middle Cauca Valley, and the Cauca paleolake, the subject of the present study.

Total annual precipitation in the Cauca basin is 1887 mm with 243 mm during the maximum month (Restrepo et al. 2005a). Furthermore, there is a direct relationship between precipitation, induced by the negative phase of ENSO, and water discharge (2,373 $m^3\ s^{-1}$), and suspended sediment yield (49.1 Mt a^{-1}) in the Cauca River (Restrepo et al. 2005a). The Cauca hydrographic basin, that covers 59,615 km^2 and extends from 2°N to >8°N (Restrepo et al. 2005b), and runs northward, is the recipient of the influence of the ITCZ on its annual path, and the ENSO phenomenon inter-annually. This would make the reconstruction of the mean position of the ITCZ in the Cauca paleolake for the past difficult. Conversely, the ENSO phenomenon, which equally influences northern South America, from the Ecuadorian Andes to the Cauca Valley will leave a signal over the entire Cauca basin (Garreaud et al. 2009). Even though during ENSO events the ITCZ is displaced southward of its mean position, and rainfall decreases, it returns to average conditions during +2 year (Poveda et al. 2006).

The Cauca Valley runs along the Cauca–Romeral Fault system that is a major structural suture between the Western Cordillera, of Cretaceous oceanic origin, and the Central Cordillera, of Paleozoic–Mesozoic plutonic origin (Cediel et al. 2003). In the northern Cauca Valley the Cauca–Romeral System Fault is inverse, sinestral, and braided. This suggests that the Santa Fé–Sopetrán depression is a pull-apart basin, limited by the NW–SE Sopetrana, the NE-SW Cauca, and the N–S San Jerónimo Faults (Fig. 1; Suter and Martínez 2009; Suter et al. 2011). The Santa Fé–Sopetrán depression is partly filled with late Holocene fluviolacustrine sediments. As for the present, and because the middle Cauca Valley is a steep and narrow valley, the Cauca river is entrained and mostly braided. Therefore, it has a high bed load, and is relatively unstable (Schumm 1981, 2005; Schumm et al. 2000). Under the present high pressure anthropogenic scenario, when erosion and deforestation is extensive (Restrepo et al. 2005a), the detailed geomorphology of the Cauca river is unrepresentative of natural conditions in pre-Hispanic times and, therefore, will not be considered further.

Methods

This study is based on detailed photo-interpretation and geologic and stratigraphic mapping. The sedimentary succession of the San Nicolás terrace was studied along: (1) La Caimana Creek and, (2) the San Nicolás-1 core, on the western side of the valley. A complementary section was studied at Sucre, on the eastern side of the valley (Fig. 1). Outcrop and core samples were retrieved by means of the box sampling method (Mangili et al. 2005), and rotary drilling, respectively. Both sets of samples were then transported to the laboratory and stored at 4 °C to prevent oxidation and degradation of organic matter, and then cut longitudinally.

The chronology of La Caimana Creek, the San Nicolás-1 core, and the Sucre sections are based on 32 radiocarbon (accelerator mass spectrometry, AMS^{14}C) analyses on bulk sediment samples. Samples were retrieved from the outcrop by means of Shelby cores in order to minimize weathering effects and sample contamination. Analyses were done at the University of Tokyo, the Australian National University, and SUERC (Scottish Universities Environmental Centre), respectively. Calibrated age ranges were determined from the University of Oxford Radiocarbon Accelerator Unit calibration program (OxCal4.1). Therefore, in the present paper all ages indicated refer to calibrated years before present (cal yr BP).

Dried sediments were sieved and the <200 μm fraction was used for organic stable isotope and element concentration analyses. Bulk sediments were weighed into tin capsules and combusted in an elemental analyzer (NC2500, Carlo Erba, Italy) at 1080 °C in the presence of chromium oxide and silvered cobalt oxide in a continuous helium flow. The combustion gases were reduced by passing over copper wires at 650 °C and water vapour was trapped with $Mg(ClO_4)_2$. N_2 and CO_2 were separated in a GC column at 45 °C and then passed via a ConFloII interface into the isotope ratio-mass spectrometer (Delta Plus, Thermo-Finnigan, Germany). For organic carbon isotope analyses of La Caimana Creek sediments, the effect of decalcification was tested, as described in Mayr et al. (2005), by weighting samples in silver capsules and treating them with 5 % and thereafter 20 % HCl on a heating plate (70 °C) as well as decalcification in centrifuge tubes with 5 % HCl in a water bath at 50 °C for 6 h and subsequent rinsing with deionized water.

Carbon and nitrogen contents were determined from the peak area versus sample weight ratio of the samples and calibrated with certified elemental standards. A lab-internal organic standard (Peptone) was used for final isotopic calibrations. Organic isotope ratios are reported as δ-values in ‰ deviation relative to international standards (AIR for nitrogen and VPDB for carbon). Analytical precision typically was 0.1 ‰ for both $\delta^{13}C$ and $\delta^{15}N$ (one standard deviation). All element concentrations given are weight percentages relative to dry weight and have an analytical error of less than 5 % of the given value.

Results

The San Nicolás succession at La Caimana Creek, the San Nicolás-1 core, and the Sucre II section

The sedimentary succession of the San Nicolás terrace varies between 19.7 m at La Caimana Creek, and 25 m at Sucre II (Fig. 2). Stratigraphic differences observed on the three sections are explained by

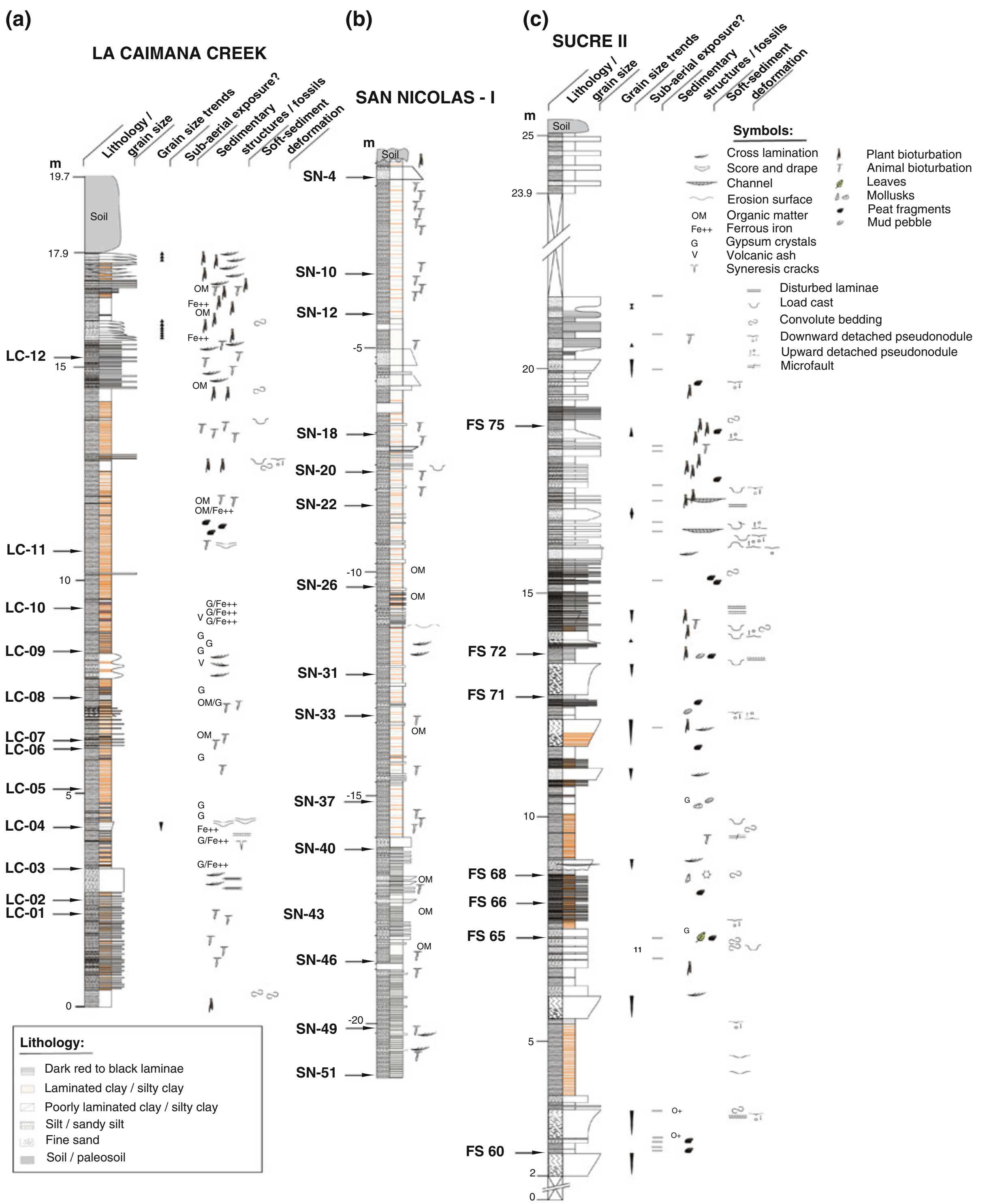


Fig. 2 Stratigraphic sections of **a** La Caimana Creek, **b** the San Nicolás-1 core, and **c** Sucre II. Note the location of AMS^{14}C samples (LC, SN, and FS), and the conspicuous increase in plant bioturbation at the expenses of animal bioturbation, and grain size, *upward* in the succession

basement irregularities, weathering of the outcrops, and varying lateral extent.

Dark red to black laminated clays are dominant all over the San Nicolás succession. However, color is only reliably recorded in the San Nicolás-1 core compared to the outcrop sections where weathering has significantly altered it. In the San Nicolás-1 core, color varies from greenish dark grey (10BG4/1) to bluish grey (5B6/1) at the base to dark red (2.5YR3/6) and yellowish brown (2.5Y3/6) moving upward in the section until 16 mbt (m below the top) when the grey colors are less frequent and are replaced by yellowish light brown (2.5Y6/4), reddish brown (7.5YR4/3), grey (10YR5/1), and white (5Y8/1), among others. This change in color reflects organic matter (OM) content as will be shown below.

Silt laminae are conspicuous at the base and the top of La Caimana Creek, whereas fine grained sands are restricted to its top. An analogous pattern is observed in the San Nicolás-1 core. By contrast, fine-grained sands are more common in the Sucre II section. Gypsum crystals, normally associated with ferric iron, as well as three conspicuous volcanic ash layers, which are ryolitic in composition, are present at La Caimana Creek.

Weathering at the La Caimana and Sucre II sections has enhanced color contrast, thus allowing the visualization of sedimentary structures; among them, cross lamination, syneresis cracks, and "scour and drape". The latter are wave macro-structures about 1 m wide, which are covered by drapping laminae. Aside from these structures, a number of soft sediment deformation structures, such as load cast and convolute bedding, are common. The significance of the latter, at the Aeropuerto section (Fig. 1), are attributed to seismic activity and are fully discussed in Suter et al. (2011).

The base of the San Nicolás succession is mostly dominated by animal bioturbation, as compared to its top where plant bioturbation is conspicuous, particularly in La Caimana and Sucre II sections. However, animal bioturbation in any case is not high enough to destroy lamination. Vertical burrows <0.8 cm in diameter and internally containing spreiten structures are conspicuous in the lower part of the succession, whereas horizontal burrows occur sporadically all through the succession. They are assigned to the *Scoyenia* and *Mermia* ichnofacies, respectively (Buatois and Mangano 2009). Few macrofossils (leaves and mollusks) were found, as well as some diatoms, sponge spicules, and zoosporic fungi (*Chytridiales*). The latter were found inside some diatom frustules.

Chronology of the San Nicolás succession

Except for the lowermost and the uppermost parts of the sections where there is no chronologic control due to the absence of enough OM for radiocarbon analysis, there are enough data to group radiocarbon ages from the sedimentary succession of the San Nicolás terrace in two sample families in the three sections. These are labeled as "young" and "old" (Table 1; Fig. 3). Age models for the "young" samples are consistent in the three sections and most particularly in the Sucre II section. Consequently, "old" ages are considered as the product of reworking of OM. Two reasons support our inference: (1) a high percentage of altered phytoclasts are dominant in the "old" samples and (2) reworked samples probably came from the underlying Obregón terrace (Garcia et al. 2011). Despite differences in the calibrated distributions between the San Nicolás core and La Caimana and Sucre II sections, linear interpolation equations are analogous. Furthermore, if we extrapolate these tendencies, the top of the sedimentary succession would be hundreds of years old. Therefore, the succession apparently ranges in age between ~3500 and <500 cal yr BP and was deposited at an accumulation rate that exceeded ~600 cm kyr^{-1} (Fig. 3). Limitations in age models are imposed by the various sources of organic matter and hydrological connectivity of the tributaries with the Cauca river, aside from the proximity of each site to the various sources of older organic matter (Garcia et al. 2011). The young outliers in La Caimana Creek section might be the result of deep infiltration of humic or fulvic acids from overlying strata due to weathering processes.

Terrace deposit patterns and paleocurrent directions of the San Nicolás succession

Mapping of the terrace deposits, or its geologic contact with the igneous to metamorphic basement, reveals a dendritic pattern (Figs. 1, 4). Paleocurrent measurements on cross laminae at terrace outcrops on each tributary, reveal a unimodal to bimodal direction pattern for most of the northern locations. This is the

Table 1 Radiocarbon analyses of sediment samples from the Cauca paleolake at La Caimana Creek, San Nicolás-1 core, and Sucre sections

Sample	cm	Lab code	^{14}C yrs BP	Unmodelled (BC/AD)		Cal yrs BP
				From	To (95.4 %)	
La Caimana Creek		MTC no.				
LC-01	228	12246	5,235 ± 50	−4,231	−3,962	6,046.5
LC-03	326	12247	5,705 ± 110	−4,788	−4,347	6,517.5
LC-04	435	12248	2,965 ± 50	−1,374	−1,025	<u>3,149.5</u>
LC-05	511	12700	2,970 ± 135	−1,496	−847	<u>3,121.5</u>
LC-06	597	13126	2,435 ± 45	−755	−403	<u>2,529.0</u>
LC-07	630	12701	3,765 ± 50	−2,397	−2,028	4,162.5
LC-08	717	12702	2,395 ± 50	−752	−389	<u>2,520.5</u>
LC-09	837	13127	2,985 ± 45	−1,381	−1,056	3,168.5
LC-10	935	13128	1,945 ± 130	−352	382	<u>1,920.0</u>
LC-11	1,065	13129	2,695 ± 195	−1,376	−399	2,837.5
LC-12	1,522	13130	4,000 ± 50	−2,836	−2,346	4,541.0
San Nicolás core		SSAMS no.				
SN-4	−84	9924	5,860 ± 100	−4,482	−4,493	6,687.5
SN-10	−335	9,920	2,600 ± 70	−914	−513	2,663.5
SN-12	−415	9,921	3,980 ± 40	−2,618	−2,347	4,432.5
SN-18	−678	9,927	3,940 ± 40	−2,568	−2,299	4,383.5
SN-20	−764	9929	4,580 ± 40	−3,500	−3,104	5,252.0
SN-22	−852	9930	1,790 ± 20	136	324	<u>1,856.0</u>
SN-26	−1,035	9931	2,500 ± 20	−772	−540	<u>2,606.0</u>
SN-31	−1,226	9918	2,660 ± 30	−896	−793	<u>2,794.5</u>
SN-33	−1,321	9919	1,720 ± 30	245	397	<u>1,629.0</u>
SN-37	−1,512	9923	2,320 ± 30	−482	−233	<u>2,307.5</u>
SN-40	−1,623	9925	3010 ± 30	−1,384	−1,130	<u>3,080.0</u>
SN-46	−1,979	9926	1,990 ± 30	−41	59	1,900.0
SN-49	−2,015	9932	2,680 ± 20	−896	−802	<u>2,799.0</u>
SN-51	−2,123	9917	1,760 ± 20	224	344	1,666.0
Sucre section		SUERC no.				
FS-60	250	29264	1,875 ± 30	60	230	1,805.0
FS-65	730	29260	2,040 ± 30	−120	30	<u>1,955.0</u>
FS-66	810	29259	1,940 ± 30	−20	130	<u>1,895.0</u>
FS-68	870	29258	1,860 ± 30	80	240	<u>1,790.0</u>
FS-71	1,275	29257	1,235 ± 30	680	880	<u>1,170.0</u>
FS-72	1,368	29256	2,750 ± 30	980	820	2,030.0
FS-75	1,865	29255	1,555 ± 30	420	580	1,450.0

Calibrated C-14 ages with OxCal 4.1. "Young" cal ages used in the age model are underlined. Depth in cm above the base for the La Caimana and Sucre sections. For the San Nicolás-1 core it is below the top

MTC, University of Tokyo (Japan); *SSAMS*, The Australian National University; *SUERC*, Scottish Universities Environmental Research Centre

case of the La Caimana and Sucre sections which indicates that sediments were mainly supplied to the tributaries from the Cauca river. By contrast, a more complex pattern is evident in the southern part of the basin, which is possibly related to the activity of the Sopetrana Fault (Fig. 4).

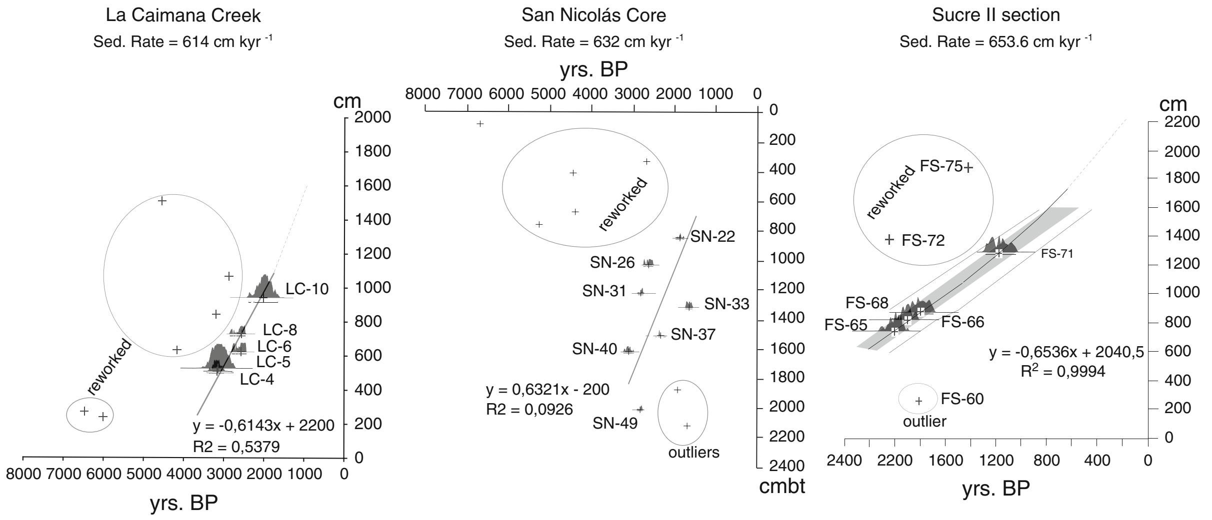
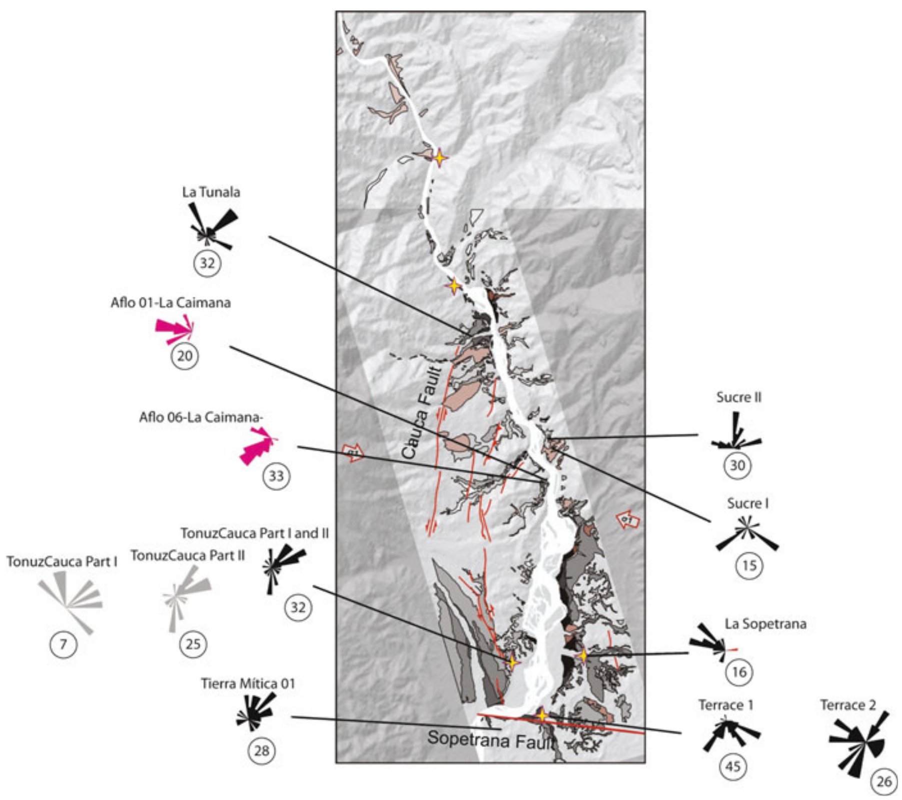


Fig. 3 Age models for La Caimana Creek, the San Nicolás core and the Sucre II section. based on AMS^{14}C calibrated dates (cal yr BP; see Table 1 for details). *Grey* histograms represent calibrated distributions. Note that in all cases sediment accumulation rates are larger than 613 cm ky^{-1}, and that samples above the *curves* are attributed to reworking

Fig. 4 Paleocurrent trends (unimodal to bimodal) measured at the tributaries of the Cauca river. The number of measurements at each point are indicated (*circles*). Dendritic *grey* patterns are terrace deposits as in Fig. 1



Geochemical analyses of the San Nicolás-1 core and La Caimana Creek successions

The C/N ratios of bulk sediments at the La Caiman Creek section were as low as 1.7 indicating a considerable fraction of inorganic nitrogen, whereas decalcification in centrifuge tubes and subsequent rinsing revealed on average 0.44 % lower δ^{13}C values indicating negligible carbonate contents in the sediment. These results rather demonstrate that inorganic nitrogen was removed by the HCl treatment and washing procedure. After this procedure, the correlation of TOC and TN of La Caimana sediments is similar to that of the non-weathered San Nicolas borehole sediments. Given this similarity we restrict our discussion to the geochemisty of the San Nicolás-1 core sediments. Organic carbon isotope (δ^{13}C) measurements, which vary between −24 and −17 ‰, when graphed against C/N values reveal a mixed source of organic matter, apparently closer in origin to C3 land plants and lacustrine algae than to C4 plants (Fig. 5). The C/N ratios point to a high fraction of algal organic matter, but could also indicate soil organic matter, which also can have C/N ratios close to 10 (Mayr et al. 2009).

These, and other geochemical proxies are better visualized stratigraphically (Fig. 6) where δ^{13}C values steadily increase upward in contrast to organic %C and total %N that decrease. In fact, the decrease in organic %C is reflected in the steady decrease in grey colors from bottom to top in the sedimentary succession in

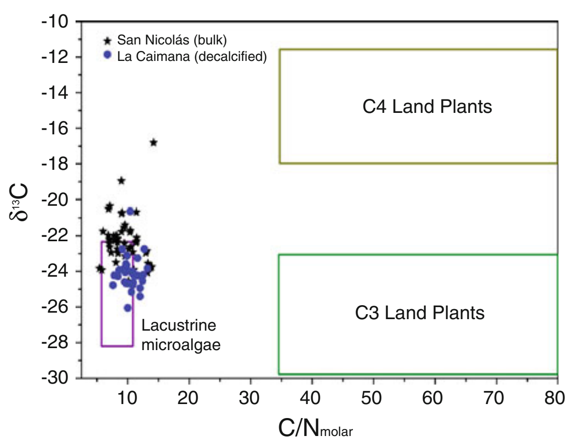


Fig. 5 San Nicolás-1 core. Geochemical analyses (C/N–δ^{13}C diagram; Meyers 1994; Meyers and Lallier-Vergès, 1999). Note the mixture between lacustrine microalgae, C3, and C4 plants

the San Nicolás-1 core. By contrast, C/N and δ^{15}N do not appear to change systematically. A lack of correlation is observed between C/N and %C and δ^{15}N, compared to %C against %N whose line of correlation goes through the origin (Fig. 7).

Stratigraphic trends in %C and total N, and δ^{13}C at San Nicolás core are analogous to trends in charcoal concentration and altered lignocellulose debris (Altered LcD; Fig. 6). The gelified lignocellulose debris—gelified amorphous organic matter ratio (G-LcD/G-AOM) do not show a systematic pattern (Fig. 6). Of major interest is the change in the percentage abundance of the geochemical and palynodebris proxies at 1,600 cm (ca. 3000 yr BP), which coincides with the change in color from greyish to reddish. This change, however, does not coincide with a change in grain size (Fig. 2).

Discussion

As indicated above, the stratigraphic differences observed in the three sections can be explained by weathering of the outcrops, and varying sedimentological differences. However, during flooding events there should be similar sedimentary records on both sides of the valley analogously to the hydrological and biological connectivity observed in modern floodplains. That is to say the flood pulse concept (Junk et al. 1989; Junk and Wantzen 2004; Thomaz et al. 2007). Differences might be due to the closeness of each particular site to the basement, steepness and length of the tributaries, among other causes.

We discard the landslide model (Page and Mattsson 1981) as a possible damming mechanism for the ~2500 yr time interval represented by the stratigraphic succession of the San Nicolás terrace on the basis of: (1) the large water hydraulic power of the braided middle Cauca river, which runs constrained in a narrow and steeply sided (~40°) valley, would erode any landslide barrier in less than a century, and (2) the absence of proxies indicative of a deep water body or a permanent lake. As for the former there are examples in historical times of large landslides, like the 30×10^3 m^3 Chirapotó event, located about 100 km south, which blocked the main course of the Cauca river on December the 12th, 1970 to be eroded in less than an hour (Uribe and Sanchez 1987). Furthermore, there is other possible evidence, which

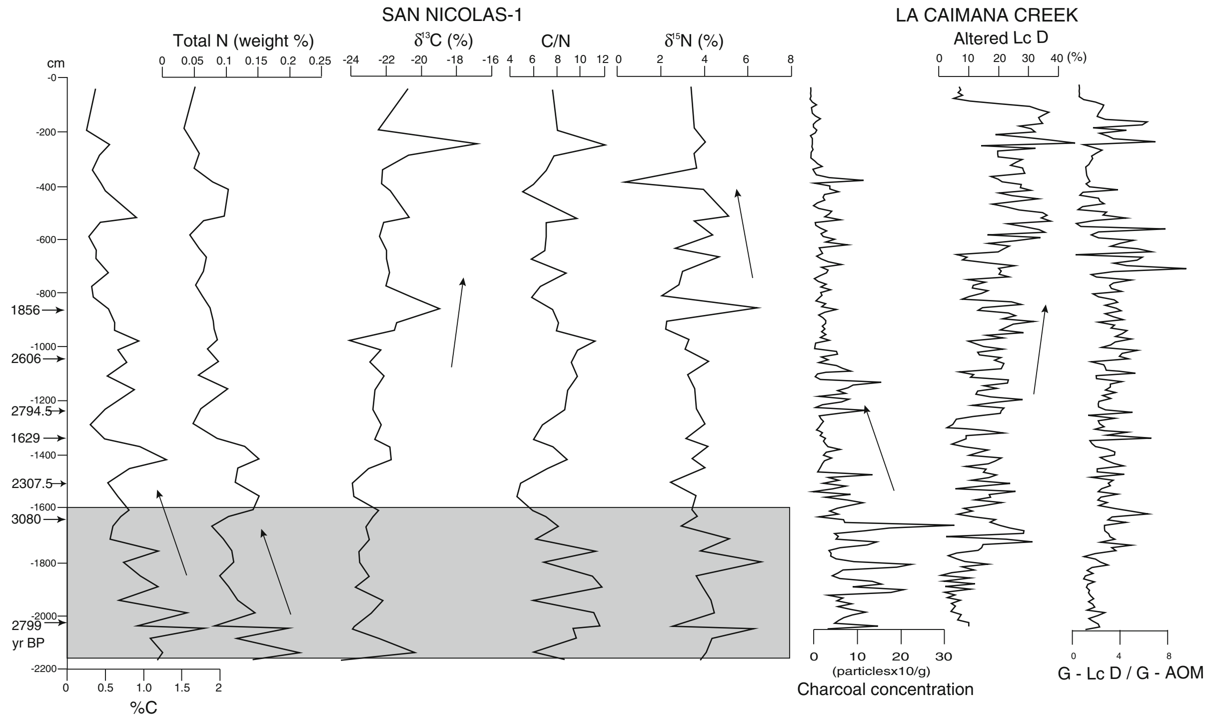


Fig. 6 Geochemical analyses of %C, total %N, δ^{13}C, C/N and δ^{15}N at the San Nicolás-1 core compared to selected optical indices of organic matter at the Caimana Creek (Garcia et al. 2011). Note the decreasing trends of %C, Total %N, and charcoal concentration in contrast to the increasing trends in δ^{13}C and altered lignocellulose debris (Lc D). The *shadow rectangle* indicates the interval where *grey colors* predominate

suggests that damming of the Cauca river might have occurred temporarily. This is the case of the volcanic ash layer which most probably came from the Machin volcano (4°29′N; 75°22′W), the most active of the northern Andes during the late Holocene (Mendez 1989). The ash would have arrived to the Cauca paleolake site either floating passively or damming temporarily the Cauca river upstream ca. 2400 yr BP. Therefore, it is unlikely that the northern Liborina landslides might have been able to dam the Cauca river for decades.

As for the reconstruction of paleobathymetric conditions, Garcia et al. (2011) report the diatoms *Aulacoseira granulata* (Ehrenberg) Simonsen and *Synedra ulna* (Nitzsch) Ehrenberg, among others, which are common in La Caimana Creek section and are suggestive of shallow water depths. Of interest is *A. granulata*, which supports a fluvial connectivity with the Cauca river, where this species is living today. As indicated above, both *Mermia* and *Scoyenia* ichnofacies occur in the San Nicolás succession, thus evidencing the episodic flooding of the Cauca river tributaries. The former would represent animal grazing during maximum flooding, compared to the latter which would represent grazing during low level stages of the Cauca river (in accordance with Buatois and Mangano 2009). However, under this highly dynamic connectivity scenario and the very large sediment accumulation rates, straightforward paleobathymetric inferences, following Buatois and Mangano (2009) cannot be made, and possibly are not applicable.

The high sediment accumulation rate of the laminated San Nicolás succession, its shallow water character, paleocurrent directions, and biological connectivity with the Cauca river (Garcia et al. 2011) suggest that the sedimentary infilling of the tributary valleys occurred as a consequence of the hydrological dynamics of the Cauca river, that is to say. The ria lake model that predicts that during flooding events the main river prevents tributaries to deliver water and their sediment load to the main course thus resulting in the vertical aggradation of sediments (Dumont 1993, 1996; Schumm et al. 2000; Archer 2005). Ria lakes are highly dynamic (and

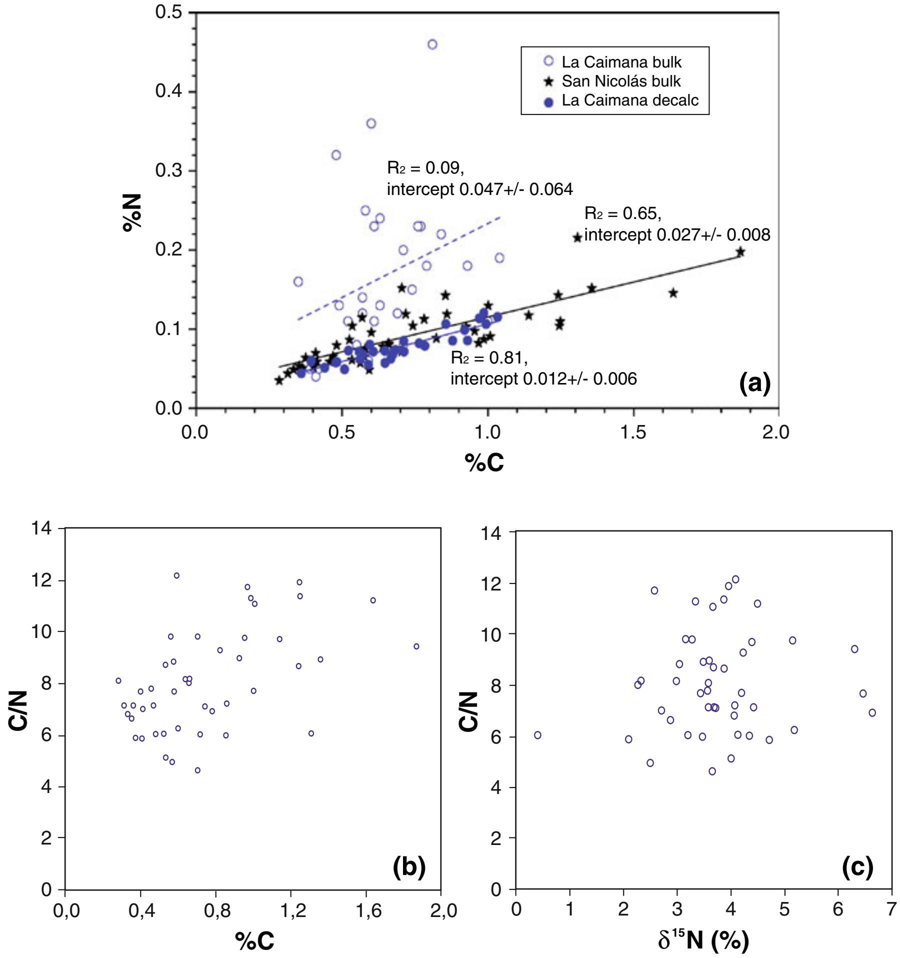


Fig. 7 San Nicolás-1 core. Comparison between: **a** %N and %C, **b** C/N and %C, and **c** C/N and $\delta^{15}N$. Note how the correlation between %N and %C goes through the origin, whereas C/N against %C and $\delta^{15}N$ do not show any correlation

seasonal) systems. Laminae, therefore, have a dual origin, lacustrine and fluvial. When the Cauca river floods it yields silt and fine-grained sands to the tributaries, as evidenced by the paleocurrent patterns (Fig. 4). Conversely, when flooding ceases ria lakes start to dry out and clay sedimentation occurs on the tributaries. Even today during the rainy season, and La Niña years, the Cauca river floods its tributaries resulting in shallow water bodies (ria lakes), whose depth and geometry is controlled by topography, water discharge, and sediment yield.

In addition to the damming of tributaries by hydrological and sedimentological mechanisms, it has been proposed that tectonics also produces similar sedimentary environments (Schumm et al. 2000). On the basis of the northern tapering shape of the Santa Fe–Sopetrán Basin, direction of faults, and paleocurrent directions, we do not discount some tectonic control on the deposition of the San Nicolás succession in combination with the hydrological dynamics of the river. This appears more evident in the southern part of the basin where paleocurrent directions are widespread and there is a swampy area against the Sopetrán Fault, which suggests increased subsidence in this part (Fig. 1). Furthermore, it appears that sedimentation of the San Nicolás succession, and other terrace levels, was controlled by the activity of the Cauca Fault, which in turn controlled the local base level of the Cauca river in the Santa Fe–Sopetrán Basin.

Ria lakes in the Amazon basin are classified into two categories, *igapó* and *varzea*. *Igapó*, or black-water lakes, occur over the Guyana shield (Rio Negro system) and are characterized by their high organic matter content (humic and fulvic acids) and low productivity, whereas *varzea*, or white-water lakes, occur over the high Amazon (Solimoes river system) and are characterized by their high sediment load and high productivity (Sioli 1984; Putz 1997). In *igapó* environments, biological productivity increases in the floodplain during the flooding season or lentic phase (Castillo 2000).

When comparing *igapó* with *varzea* lakes, there is an increase in bacterial content, dissolved oxygen, particulate (POC) and dissolved organic carbon (DOC), pH, Fe, SiO_2 and PO_4, from the former to the latter. Conversely, light penetration and $SO_4^{=}$ are larger in *igapó* lakes (Rai and Hill 1980). This might explain the occurrence of gypsum crystals in the lower part of La Caimana succession.

Of interest, the C/N ratios, as measured in DOC, are larger in tributaries with a large aerobic degradation of the fulvic acid fraction and lower lignin levels (St. John and Anderson 1982; Ertel et al. 1986). As shown in Fig. 6, C/N ratios exceed 8 and correspond to a lower percentage of altered ligno-cellulose debris, thus suggesting *igapó*-like paleonvironmental conditions for the lower part of the San Nicolás succession. The low total N values and its inverse trend with altered ligno-cellulose debris (Fig. 6) suggest that the contribution of the latter to the N pool was minor (Talbot 2001). Furthermore, the positive linear correlation between total %N and organic %C intersecting the origin (Fig. 7) suggests that $\delta^{15}N$ measurements are exclusively related to organic %N (Talbot 2001).

Carbon isotope ($\delta^{13}C$) values are more positive than those measured for the Amazon river, which are −26.8 to −30.1 ‰, and −27.4 to −29.9 ‰ for fine and coarse particulate organic carbon, respectively. Black waters showing the more negative values (Quay et al. 1992).

The inverse linear relationship between organic $\delta^{13}C$ and $\delta^{15}N$ curves (Fig. 6) is analogous to the pattern observed in Florida lakes for the past few 100 years, which has been interpreted as indicative of increasing trophic states (Brenner et al. 1999). This is in agreement with our interpretation for a *varzea* type environment for the uppermost part of the succession.

Even though the change from a *igapó* to a *varzea* environment seems to occur steadily, the change in color from grey to yellowish brown at −1,600 cm, or ca. 3000 yr BP, suggests otherwise. Before this, $\delta^{13}C$ is rather constant and is −23.5 ‰, whereas C/N, $\delta^{15}N$, and charcoal concentration show high frequency fluctuations around 8, 4 ‰, and 150 particles/g, respectively.

Interestingly, the 3000 yr BP limit coincides with a major change in the ENSO behavior in the Cariaco Basin when El Niño became stronger and precipitation was reduced to switch to a phase of increased ENSO variability and higher precipitation (Haug et al. 2001; Rull 2005). This change seems to coincide with a wet period in the Yucatan Peninsula (Curtis et al. 1996; Mueller et al. 2009). Furthermore, the increase in altered ligno-cellulose debris ca. 2000 yr BP in La Caimana Creek might reflect human occupation and deforestation upstream the Cauca Valley (Behling et al. 1998; Wille et al. 2000; Vélez et al. 2005). A similar date for human occupation has also been reported for the lower Magdalena Valley where the Cauca river ends (Berrio et al. 2001). On the other hand, the abundance of charcoal particles coincides with a period of dry forest elements before ca. 3000 yr BP in Teta-2 site in the upper Cauca Valley (Berrio et al. 2002). The whole charcoal pattern at La Caimana Creek is analogous to the one reported for Lake Miragoane in Haiti (Higuera-Gundy et al. 1999).

The observed two-step, 3000 and 2000 yr BP, pattern is analogous to a number of sites in northen South America which have been attributed to a background climate condition (Conroy et al. 2008). The latter, in particular, has been interpreted as the result of warmer/wetter conditions in the Galápagos Islands, when El Niño intensified and/or became more frequent (Conroy et al. 2008).

Conclusions

The stratigraphic, geochemical, and organic matter content of the late Holocene San Nicolás succession, complemented by microfossil data, suggest that it was deposited in a ria lake environment in the Santa Fe–Sopetran pull-apart basin between ∼3500 and ∼500 yr BP. Deposition occurred, first under *igapo* (black-water), and then under *varzea* (white-water) conditions. The transition occurred ca. 3000 yr BP, a time of major change in the ENSO behavior in the Cariaco Basin, thus reflecting the southern migration of the ITCZ and intensified rain upstream the Cauca Valley. A second, but less conspicuous change occurred ca. 2000 yr BP which apparently corresponds to the intensified and/or more frequent ENSO activity in the Galapagos Islands. Our contribution demonstrates the high potential of these hitherto undervalued ria lake deposits for the reconstruction of the paleohydrological history of the northern Andes, although obtaining a reliable chronology is a challenge in these environments.

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